A9.1 Hydrodynamic Modelling

1 Introduction

1.1.1 This appendix contains the hydrodynamic modelling reports that have been prepared for the proposed scheme as follows:

- Hydrodynamic Model Calibration and Validation Report (Section 2);
- Hydrodynamic Impacts Initial Assessment (Section 3); and
- Suspended Sediment Plume Modelling (Section 4).

1.1.2 For the purposes of this report, the Forth Estuary is taken to extend from approximately 6km upstream of Stirling to the Forth Road Bridge and Forth Rail Bridge. The Firth of Forth extends from the Forth Road Bridge and Forth Rail Bridge to the North Sea beyond a line from Fife Ness to the Isle of May.

2 Coastal Hydrodynamic Model Calibration and Validation

2.1 Introduction

2.1.1 As the Main Crossing sub-structures are in the water body (the Firth of Forth), it was considered necessary to assess the impacts of the Main Crossing structure on the hydrodynamics in the estuary and Firth of Forth both during construction and following construction.

2.1.2 A numerical modelling study has been undertaken to assess the hydrodynamics and predict potential effects the Main Crossing may have, both during and following construction. A three dimensional (3D) model of the upper and lower estuaries centring on the Main Crossing corridor was constructed to simulate the complex flow pattern and tidal interactions within the Firth of Forth, in order to inform the assessment of the potential effects of the proposals on the European sites in or near the Forth Estuary and Firth of Forth due to the presence of the structures in the water.

2.1.3 A coastal model will need to address the following issues:

- To determine the hydrodynamics (time series of water level, current speed, phasing and direction) over the model area at several depths, for the Baseline Condition and any scenarios such as bridge pier construction, final configuration of the piers and any mitigation measures.
- To determine the suspended sediment concentrations over the model area, for the Baseline Condition and any scenarios such as bridge pier construction, final configuration of the piers and any mitigation measures.

2.2 Approach and Methods

Modelling

2.2.1 A 3D hydrodynamic model using industry standard MIKE3 Flexible Mesh (FM) finite volume modelling package developed by DHI has been constructed to understand the behaviour of the current flow and fluid mixing in the Firth of Forth and Forth Estuary.

2.2.2 Modelling 'components' investigated include: hydrodynamics, temperature changes, salinity and density (as a function of both temperature and salinity).

2.2.3 The MIKE3 FM modelling system is based on a flexible mesh approach developed for applications within oceanographic, coastal and estuarine environments. Intrinsic to MIKE3 is the Hydrodynamic Module which is the basic computational component of the entire MIKE3 modelling system.

2.2.4 The computational basis of the software relies on the numerical solution of the 3D incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and hydrostatic pressure. The model takes into account the continuity, momentum, temperature, salinity and density equations and is closed by a turbulent closure scheme. In the horizontal domain, both Cartesian and Spherical coordinates can be used (a Cartesian coordinate system has been adopted for the present model as this is considered the most appropriate). The free surface is simulated using a sigma-coordinate transformation approach which avoids the problem of drying and wetting of the shoreline which is known to cause numerical instabilities and erroneous results in numerical models with irregular boundaries/shorelines.

2.2.5 The spatial discretisation of the governing equations is performed using a cell-centred finite volume method. The spatial domain is discretised by subdivision of the continuum into non-overlapping elements/cells. In the horizontal plane an unstructured grid is used while in the vertical domain a structured discretisation is used. The elements can be prisms or bricks whose horizontal faces are triangles and/or quadrilateral elements, respectively. Triangular elements have been adopted as they fit well to any shoreline shapes.

2.2.6 For the time integration a semi-implicit approach is used where the horizontal terms are treated explicitly and the vertical terms are treated implicitly. The use of an explicit method placed a limitation on the time step interval used.

2.2.7 The 3D model was used to represent and predict the estuarine hydrodynamic processes (water level, current magnitude, phasing and direction) for three scenarios – existing condition (baseline), during the bridge construction and post construction i.e. in operation.

2.2.8 The development of the 3D model was undertaken in six stages:

- Establishment of the area of interest or possible influence within the Forth Estuary and Firth of Forth, and extraction of both land and marine model boundaries from known records.
- Construction of the model's 3D mesh representing the baseline scenario, i.e. existing condition.
- Collection and correlation of all relevant and readily available data required for constructing the model including bathymetry, time series of water level, current, wave and wind data from the Forth.
- Calibration and validation of the baseline model hydrodynamics against historical hydrodynamic data.
- Revision of the baseline model to represent the construction phase and post construction configurations, and comparison of the impact on hydrodynamic processes against the baseline case.
- Incorporation and simulation of any mitigation measures which may be required to alleviate environmental or ecological impacts.

2.2.9 The hydrodynamic model can provide the basis for simulation, if necessary, of other hydro-environmental processes such as suspended sediment plume movement, bed sediment transport and water quality issues.

2.2.10 In addition to 3D hydrodynamic modelling, wave modelling of the study area using the SWAN software from open domain was undertaken. This modelling assesses the percentage of time during which construction activities could be restricted due to severe wave conditions predicted.

Extent of Current Model of Firth of Forth

2.2.11 The extent of the model is shown in Diagram 1 This extent was chosen in order that the model has reasonable coverage of the Natura 2000 sites under consideration in the ES and on the basis of the availability of suitable boundary data. Some of the Natura 2000 sites local to the Main Crossing are shown in Diagram 2.

Diagram 1: Area of Interest for Proposed Scheme Coastal Modelling

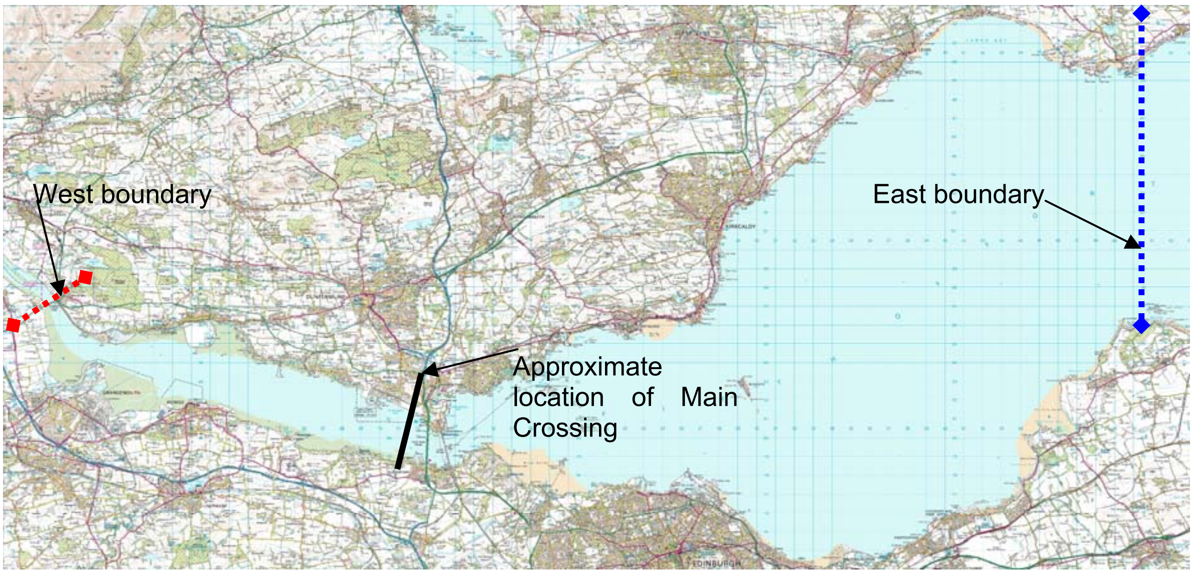
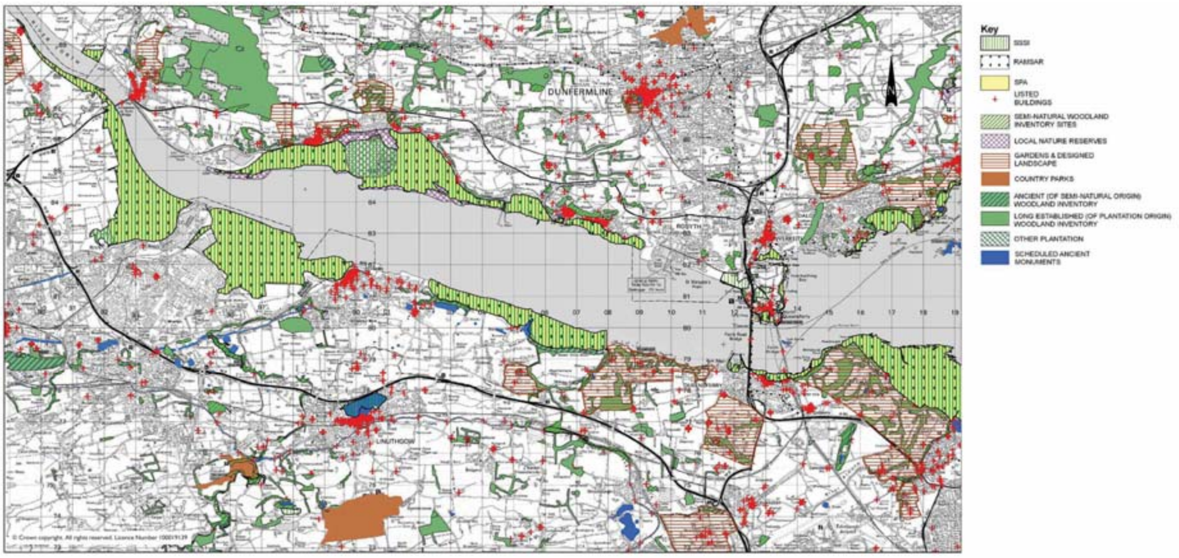


Diagram 2: SPA and Ramsar Sites in the Forth Estuary



2.2.12 The modelled area shown in the OS map in Diagram 1 is contained within land boundaries to the north and south and open water boundaries to the east and west.

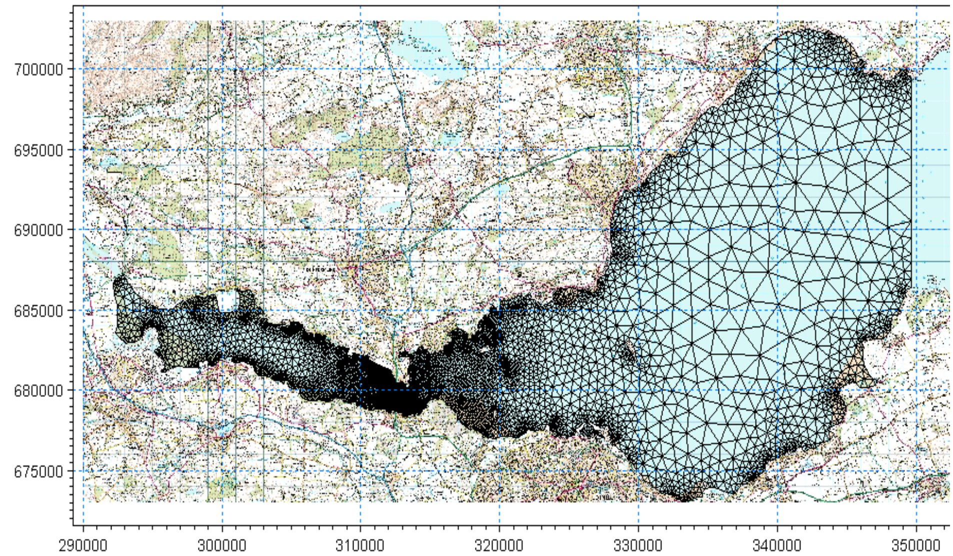
2.2.13 The western boundary lies on a line drawn between NT 292360, 686900 and NT 292890, 687160 (in Red). The boundary is located just downstream of the existing Kincardine Bridge. At this location the boundary width is about 590m.

2.2.14 The eastern boundary lies on the 349600 grid line (in blue). Its north-most point is Elie Ness 699280N and the south-most point is at Eyebroughy 686420N, near the island of Fidra. The boundary width is about 12,860m.

2.2.15 The distance from the eastern to the western boundary is 57,240m. As well as the need to include all potentially affected Natura 2000 sites, another reason for the wide distance between the west and east boundaries is to reduce the influence of the open water boundary conditions exerting unrealistic influence on the hydrodynamics at the Main Crossing area.

2.2.16 The model surface is covered by an unstructured mesh comprising almost 16,000 triangular finite elements, through 5 sigma layers over the water depth. The total number of elements used is just under 80,000 and the number of node points on each layer is 8820. The model mesh is shown in Diagram 3. It is noted that the plan is distorted because of non-identical scaling in the X and Y directions.

Diagram 3: Proposed Scheme Coastal Model Mesh

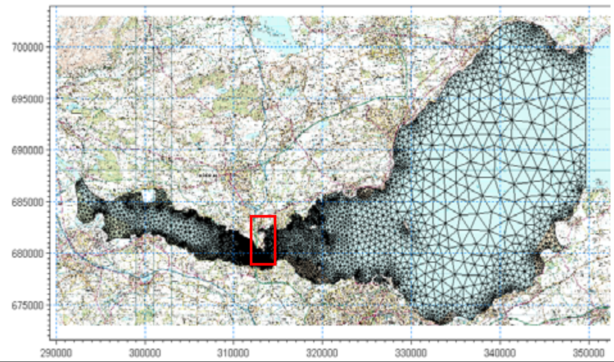
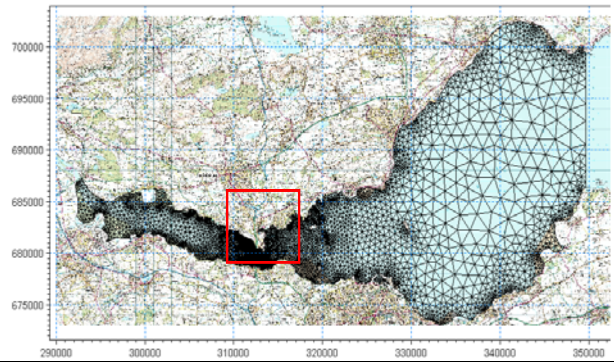
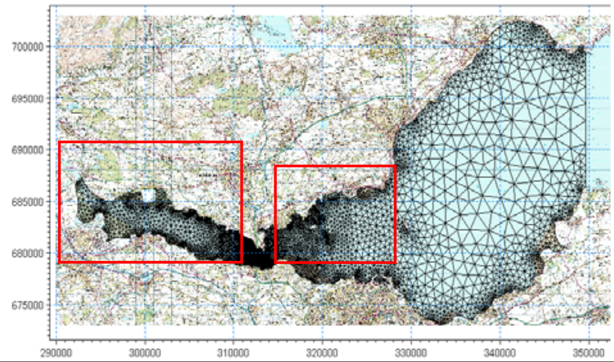
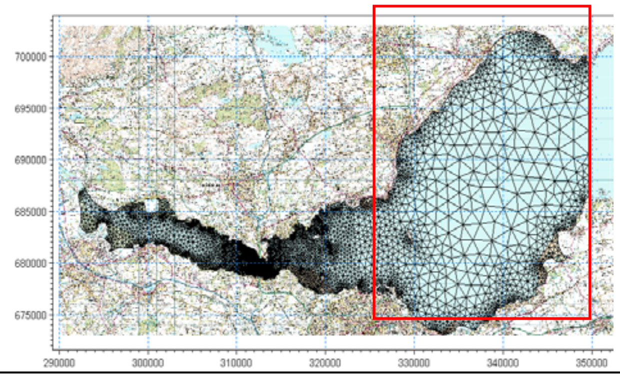


2.2.17 The vertical layers in the model have thicknesses ranging from zero (or a few millimetres) to about 15 m, as the maximum water depth is about 80m. Due to the mathematical formulation of the finite volume element and the sigma coordinate system used in the vertical direction, wetting and drying following each tidal event at the mudflats/shoreline will not cause any of the computational difficulties which can occur with traditional finite difference schemes.

2.2.18 Four large intertidal embayments full of soft mud flank the Forth Estuary between Kincardine and the Forth Road Bridge and Forth Rail Bridge. The mudflats are designated conservation areas on account of their unique geomorphology, ecology and bird-life. These tidal flats are flooded at high water and significantly affect water circulation patterns in the estuary. Excessive erosion or deposition on the flats would affect circulation patterns and may have detrimental consequences elsewhere in the estuary. The model cell sizes in these sensitive areas have been reduced to provide adequate resolutions for the hydrodynamics on these mudflats.

2.2.19 Various spatial resolutions have been imposed on the mesh according to the level of detail required for the simulations, as described in Table 2.1.

Table 2.1: Coastal Model Mesh Resolutions

Model Area	Smallest Element length	Minimum Element centre-to-centre distance
	5~15m	3~10m Required to study the detailed hydrodynamics around the bridge piers.
	30 ~ 70m	20 ~ 45m Rosyth channel and between bridge piers, existing bridges, and mudflats.
	100 ~ 450m	50 ~ 300m Areas upstream and downstream of bridge piers and mudflats.
	1000 ~ 2000m	500 ~ 1000m Eastern boundary, Firth of Forth.

2.2.20 The central area where the bridge piers are situated, the navigation channels and some of the mudflats have been represented by relatively small elements, while the areas to the eastern and western boundaries are covered by large size elements. One of the main purposes of the large boundary elements is to transfer the known boundary conditions (such as water level and current) from the model boundary to the central area of interest.

2.2.21 Diagrams 4 to 6 show the varying resolutions of the model computational mesh.

Diagram 4: Coastal Model Mesh – Western Section

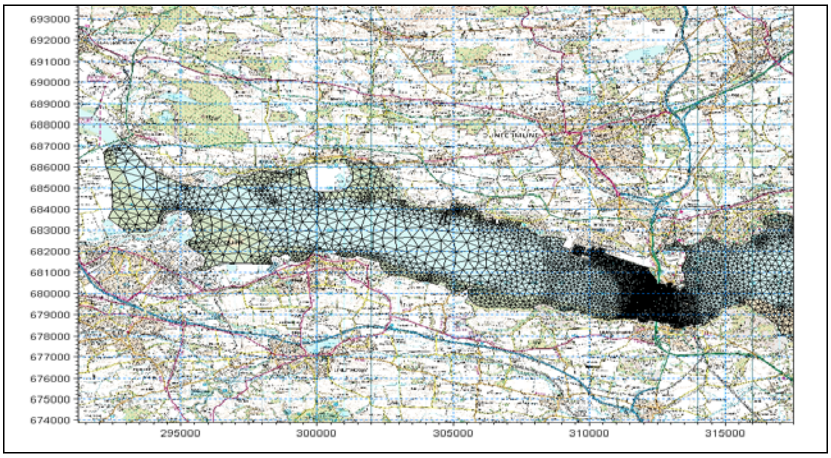


Diagram 5: Coastal Model Mesh – Central Section

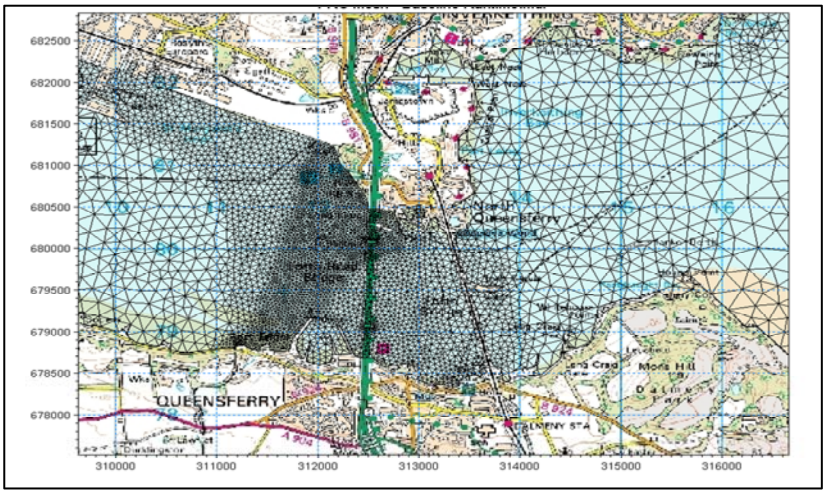
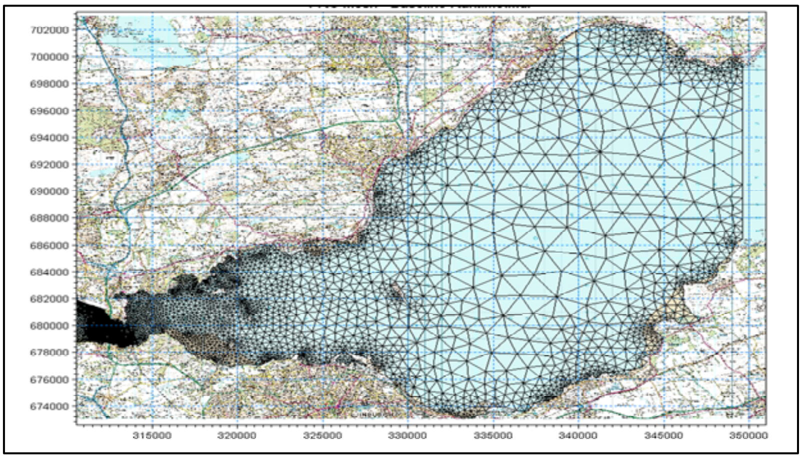


Diagram 6: Coastal Model Mesh – Eastern Section



Tides and Currents

2.2.22 Tides in the Forth Estuary are semi-diurnal. The mean spring and neap tidal range at a number of sites within the model domain are provided in Table 2.2.

Table 2.2: Average Spring and Neap Tidal Ranges

Location	Easting	Northing	MHWS (mCD)	MHWN (mCD)	MLWN (mCD)	MLWS (mCD)	Chart Datum (CD) relative to Ordnance Datum (Newlyn) OD(N)
Kincardine	293222	687304	5.8	4.5	1.7	0.5	2.85 m below OD(N)
Grangemouth	295207	683544	5.7	4.5	1.9	0.5	2.75 m below OD(N)
Rosyth	309706	681359	5.8	4.7	2.2	0.8	2.95 m below OD(N)
Granton	324186	677369	5.6	4.5	2.1	0.8	2.90 m below OD(N)
Leith	327305	677315	5.6	4.4	2	0.8	2.90 m below OD(N)
Burntisland	323278	684806	5.6	4.5	2.1	0.8	2.85 m below OD(N)
Kirkcaldy	328654	695846	5.3	4.1	1.8	0.6	
Methil	338026	699411	5.6	4.4	2.1	0.9	2.90 m below OD(N)
Fidra	351327	686252	5.4	4.2	2	0.8	

2.2.23 A notable feature of the tides in the estuary region between Rosyth and Kincardine is the presence of double high and low waters, known locally as the lackie tide that result in a prolonged period of weak currents around the time of slack water (Elliot & Clarke 1998). These features diminish with distance upstream in the upper estuary. It is thought that they result from an amplified sixth tidal harmonic produced by the shallow water effects within the estuary.

2.2.24 Tidal movements are the dominant flows in the estuary with freshwater influence a relatively small component.

2.2.25 Typical peak tidal velocities recorded off Rosyth are 0.7 to 1.1m/s on the ebb tide and 0.4 to 0.7m/s on the flood tide, depending on the tidal range. Flood currents are stronger on the north side of the estuary and ebb currents stronger on the south side. This is primarily due to the estuary bathymetry.

2.2.26 Tidal currents turn approximately 1.5 hours before High Water (HW) off Rosyth, with this time interval decreasing with distance upstream.

2.2.27 It is noted that the shift between Chart Datum and Ordnance Datum (Newlyn) varies slightly from location to location across the Forth. The majority of data available for this study (including Admiralty Charts and UKHO predicted water levels) are quoted with respect to Chart Datum. To avoid over-complicating the modelling, Chart Datum has been assumed throughout with level data provided with reference to Ordnance Datum, converted to Chart Datum according to the Rosyth variation, hence

mOD(N) = 2.95mCD.

Freshwater Inputs

2.2.28 The annual mean discharge from all rivers entering the Forth Estuary is approximately 66m^3/s (Lindsay et al, 1996). The tidal flux through the estuary (crossing a north-south line drawn between Rosyth and South Queensferry) is estimated by the hydrodynamic model to be about 20,000m^3/s during the high water of spring tide, which means the freshwater inputs are only about 0.33% of the maximum tidal flux. During the high water associated with a neap tide, the model predicts a much reduced tidal flux of 4,000m^3/s. The proportion of freshwater input is increased to 1.65%.

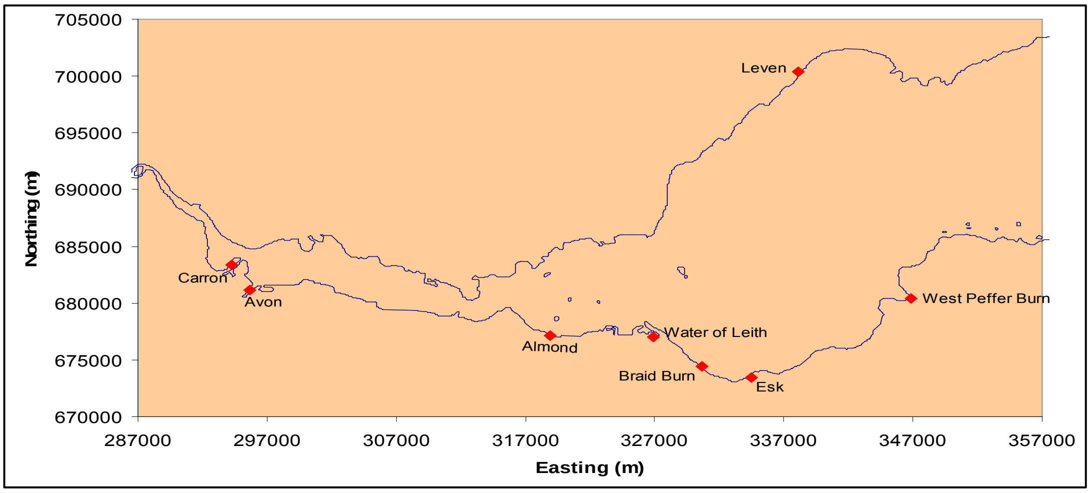
2.2.29 It is considered that these small freshwater inputs will have a negligible impact on the estuary hydrodynamics even though they may possess a much lower salinity and/or different water temperature than the seawater. However, they may be important when considering suspended sediments and water quality, as they may carry a high proportion of the sediment loads and pollutants from land into the estuary.

2.2.30 Within the model domain, there are nine major rivers contributing to the discharge. Table 2.3 shows the breakdown of all in-flows. This data has been obtained from SEPA's website as mean daily flow data was not available from SEPA at the time of the modelling. The locations of the freshwater inputs are shown in Diagram 7. Due, to their close proximity, the flow from Bonny Water at Bonnybridge is combined with the River Carron in the model's freshwater inputs.

Table 2.3: Mean Freshwater Input

Location	Grid Reference	Easting Northing	Mean Flow (m^3/s)
Leven at Leven	37 (NO) 369 006	338153 700360	6.45
Almond at Craigiehall	36 (NT) 165 752	318882 677163	6.03
Esk at Musselburgh	36 (NT) 339 723	334505 673472	4.26
Avon at Polmonthill	26 (NS) 952 797	295673 681158	4.12
Carron at Headswood	26 (NS) 832 820	294269 683371	3.45
Water of Leith at Murrayfield	36 (NT) 228 732	326909 677021	1.49
Bonny Water at Bonnybridge	26 (NS) 824 804	combine with Carron	1.31
Braid Burn at Liberton	36 (NT) 273 707	330639 674418	0.18
West Peffer Burn at Luffness	36 (NT) 489 811	346829 680393	0.14

Diagram 7: Freshwater Input Locations



Model Boundary Conditions

2.2.31 The model has two open boundaries: one in the west immediately downstream of Kincardine Bridge, and the other in the east, on a line across the estuary near Fidra Island.

2.2.32 It is necessary to define the variation of water level or velocities along these open water boundaries. These hydrodynamic boundary conditions are required to enable the model to calculate the variation of water levels and velocities within the modelled area.

2.2.33 The eastern model boundary is set as a water level boundary because not enough data of acceptable quality can be identified to define the discharge/flux or the current velocity and directions across such a wide stretch of open water and throughout the water depth.

2.2.34 The boundary at Kincardine can be set as either a water level, or as a flow boundary. Normally the boundary would be set as a flow condition because more stable model predictions often result through the combination of one flow and one water level boundary. However, as the model extent is large and the separation between the two open water boundaries is wide enough to prevent a clash of flow patterns, utilising water level boundary conditions on both boundaries is feasible and more convenient.

2.2.35 It is noted that the coastal model for the proposed scheme will only predict the fluvial and tidal currents based on inputs from its open water boundaries and freshwater inputs. The model does not predict wave and surge effects unless the appropriate boundary conditions and wind regimes are available as part of the input conditions.

Calibration Stages and Calibration Areas

2.2.36 The calibration of the hydrodynamics has been undertaken in two stages.

2.2.37 The first stage is to demonstrate the overall stability of the model. The model has been run with the calibration boundary condition and initial conditions using typical values of the model parameters under a range of time-step intervals. This is to assess the Courant number and the Courant-Friedrichs-Levy (CFL) stability parameter, which should be less than 0.5 and 1.0, respectively, to preserve numerical stability. The calibration results found the maximum Courant number to be 0.36 and the CFL to be 0.72, which meets the stated stability criteria.

2.2.38 The model is able to replicate consistent flow patterns within the model domain and in synchronisation with the timing of the high and low water cycles of the boundary water level time series, with wetting and drying of the mudflats flanking the estuary. The model also proved to be able to simulate the repeated wetting and drying processes in the mudflat and some of the shoreline areas without showing any numerical instability.

2.2.39 In order to demonstrate the model's ability to predict the overall flow patterns in the Firth of Forth and Forth Estuary, model predictions have been compared to the collated data point measurements/predictions in terms of water levels, current speed and direction, and their phasing.

2.2.40 For ease of assessment of the calibration results, the calibration points are divided into three groups, according to their locations in the Firth of Forth/Forth Estuary: Upstream (of the Main Crossing), Central (close to the Main Crossing), and Downstream (of the Main Crossing) areas:

- Upstream – Grangemouth, SN023F.
- Central –Rosyth, Granton, Burntisland, SN023A, SN023B, SN023D, SN023G, SN023J.
- Downstream – Leith, Kirkcaldy, Methil, Gullane, Port Seton, SN023C, SN023E, SN023H, SN023I, SN023K, SN023L.

Calibration and Validation Guidelines

2.2.41 The Foundation for Water Research (FWR) published a report "A Framework for Marine and Estuarine Model Specification in the UK" (Foundation for Water Research, 1993) providing guidelines to statistically assess model performance. These guidelines include:

- Levels to within ±0.1 m at the mouth, ±0.3 m at the head (or to within 15% of spring tidal ranges or 20% of neap tidal ranges);
- Current speeds to within ±0.2 m/s, or to within ±10-20% of the observed speed;
- Current directions to within ±20 degrees; and
- Timing of high water at the mouth to within ±15 minutes; ±25 minutes at the head.

2.2.42 The reference document also states that "it is accepted that these criteria might be too testing for all regions of the modelled area and that a less stringent expectation might thus be that these conditions should be satisfied for 90% of the position/time combinations evaluated."

2.2.43 The model has been successfully calibrated and validated according to the above guidelines.

2.3 Baseline Conditions

2.3.1 The following information is required for hydrodynamic modelling:

- Coastline details for sensitive locations;
- Bathymetric data within the model area;
- Hydrodynamics data – time series of tide levels, water velocities and flow directions;
- Wind data;
- Sediment and soil data;
- Pier details for the Forth Rail Bridge, Forth Road Bridge and Main Crossing; and
- Main Crossing pier construction method and sequence.

Coastline Details of Sensitive Locations

2.3.2 Coastline details are primarily taken from relevant published OS maps and Admiralty Charts.

2.3.3 The mudflat outlines of the Natura 2000 sites have been incorporated into the model. Some rock features and islands such as Long Craig and Beamer Rock which become exposed during parts of the tidal cycles, and existing bridge piers are treated as obstructions to flows. Due to their changing outlines in high and low water levels, the average contours have been adopted in the model mesh.

Bathymetric Data

2.3.4 Bathymetric levels have been determined from data taken from two sources.

Available Bathymetric Survey Data

2.3.5 Osiris was commissioned to carry out two surveys under two contracts: “Setting Forth: Second Forth Road Bridge & Associated Road Links, Geophysical Investigation” (Osiris, 1993), and under the “Replacement Crossing Study - Geophysical Survey” (Osiris Projects Report No. C7028. October 2007 and February 2008).

2.3.6 The initial survey carried out in 1993 comprised a bathymetric survey, sidescan sonar, seismic reflection and magnetometer surveys. A second survey comprising a seismic refraction survey was carried out in October 2007. The surveys have covered route corridors C and D identified in the Forth Replacement Crossing Study (Jacobs et al., 2007). Route corridor D has now been selected for the new bridge.

2.3.7 The coverage of the 1993 survey extends a little closer to the shore on both the north and south sides of the Firth of Forth than the 2007 survey. The coverage of each of the surveys upstream and downstream of the crossing corridor varies. The 1993 bathymetric survey included the part of Beamer rock exposed at low tide whereas this has not been included in the 2007 survey. Both the 1993 survey and Phase 1 of the 2007 survey encountered acoustic masking over large parts of the selected Main Crossing corridor which has limited the areas where information relating to stratigraphy and rockhead levels below the seabed has been obtained.

2.3.8 2,676,170 scatter bathymetric data points have been extracted from the Osiris surveys.

Relevant UK Hydrographic Office (UKHO) Admiralty Charts

2.3.9 UKHO gave permission to perform digitising of the three Admiralty Charts – 734 (1999), 736 (1992) and 737 (1999) to extract the bathymetry data.

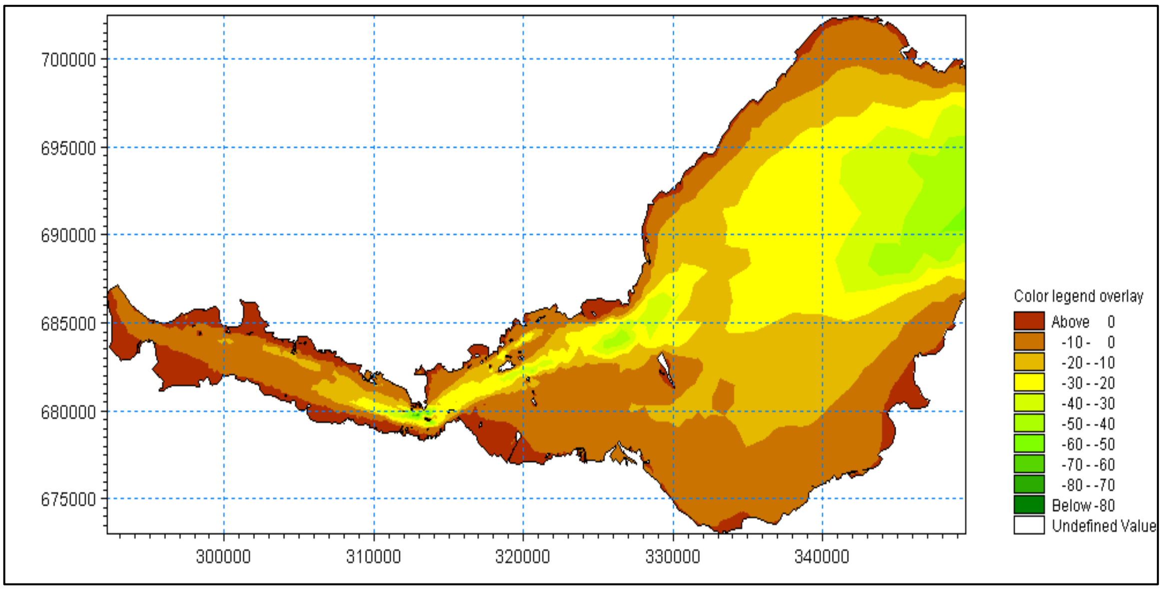
2.3.10 It is noted however, in respect of their age and their intended purpose for use in navigation, bed levels presented on these charts are anticipated to be relatively inaccurate. The charts provide no information on bed level change (either natural or engineered) since the charts were produced. Moreover, as the charts are intended for navigation purposes, they typically present conservative (shallow) estimates of the underlying bed levels.

2.3.11 A total of 129,163 data points have been digitised from the three Admiralty Charts. Table 2.4 shows the composition of the bathymetric data points.

Table 2.4: Bathymetry Data Used in the 3D Model

	Max Depth (mCD)	Min Depth (mCD)	No. of data points	
Osiris Survey	6.6	-52.03	2,676,170	95.4%
UKHO	8	-76	129,163	4.6%
Total No. of bathymetric data points			2,805,333	

Diagram 8: The Proposed Scheme Coastal Model Bathymetry



2.3.12 More detailed realisation of the bathymetric levels is shown in Diagrams 9 and 10.

Diagram 9: The Proposed Scheme Coastal Model Bathymetry – Western and Central Section

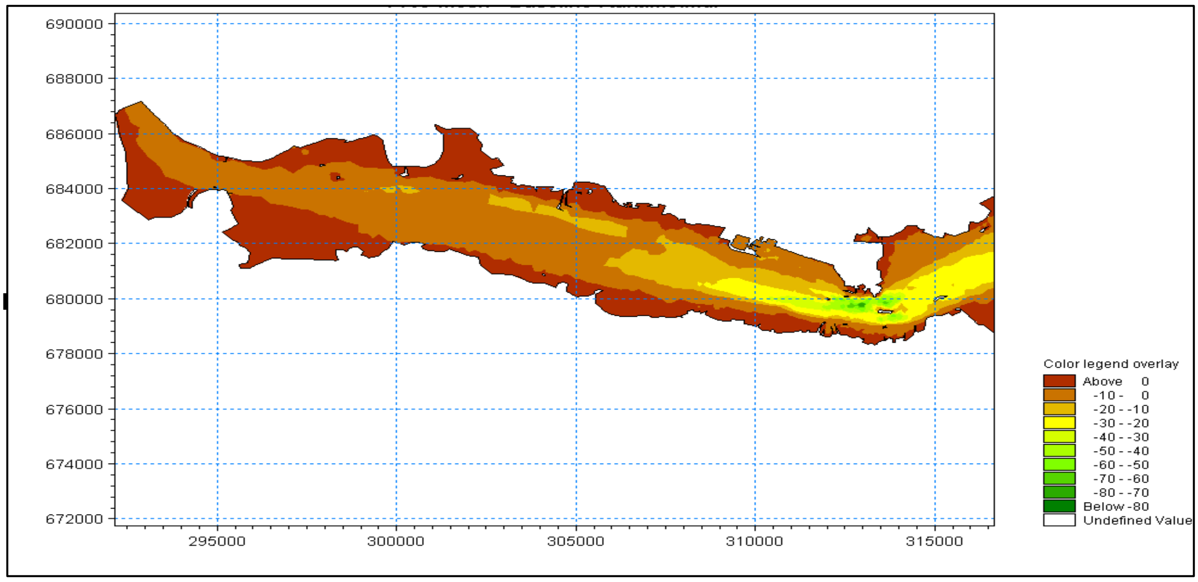
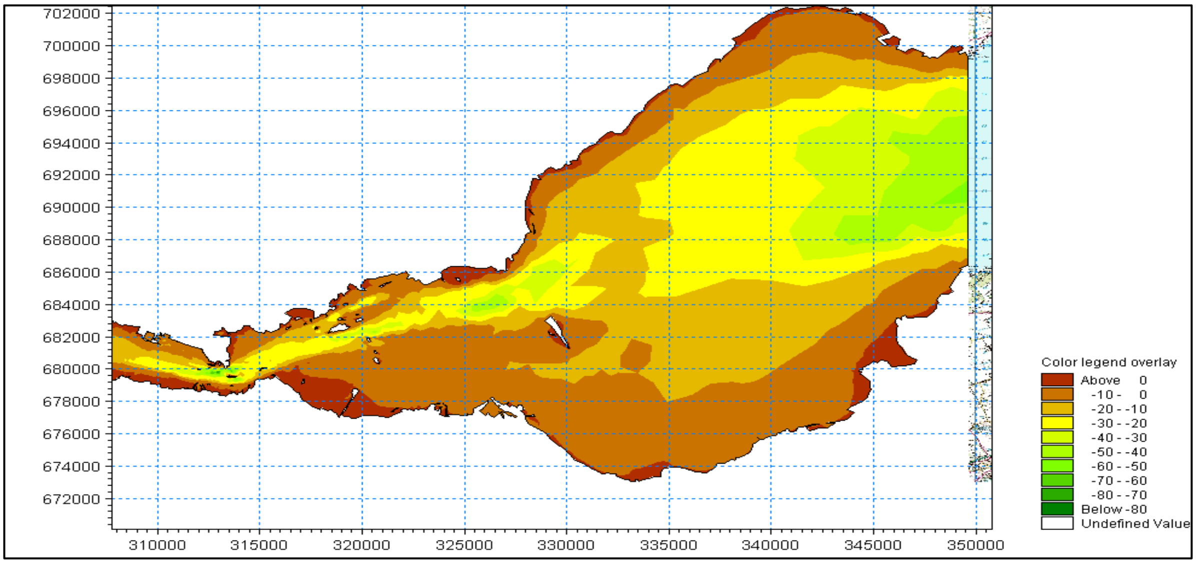


Diagram 10: The Proposed Scheme Coastal Model Bathymetry – Central and Eastern Section



2.3.13 The model mesh with bathymetry is shown in Diagram 11, with the detailed central part shown in Diagram 12.

Diagram 11: The Proposed Scheme Coastal Model Mesh and Bathymetry

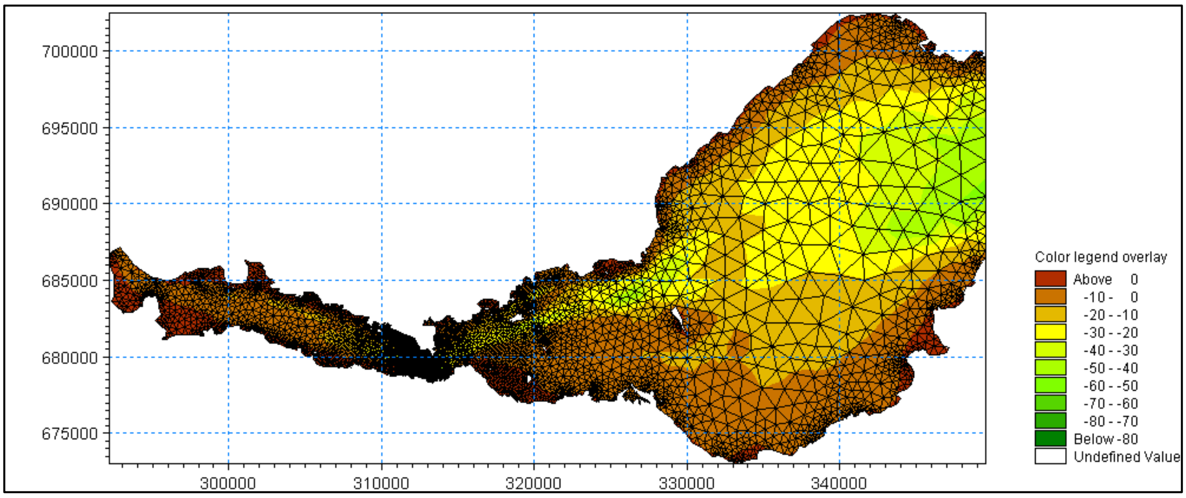
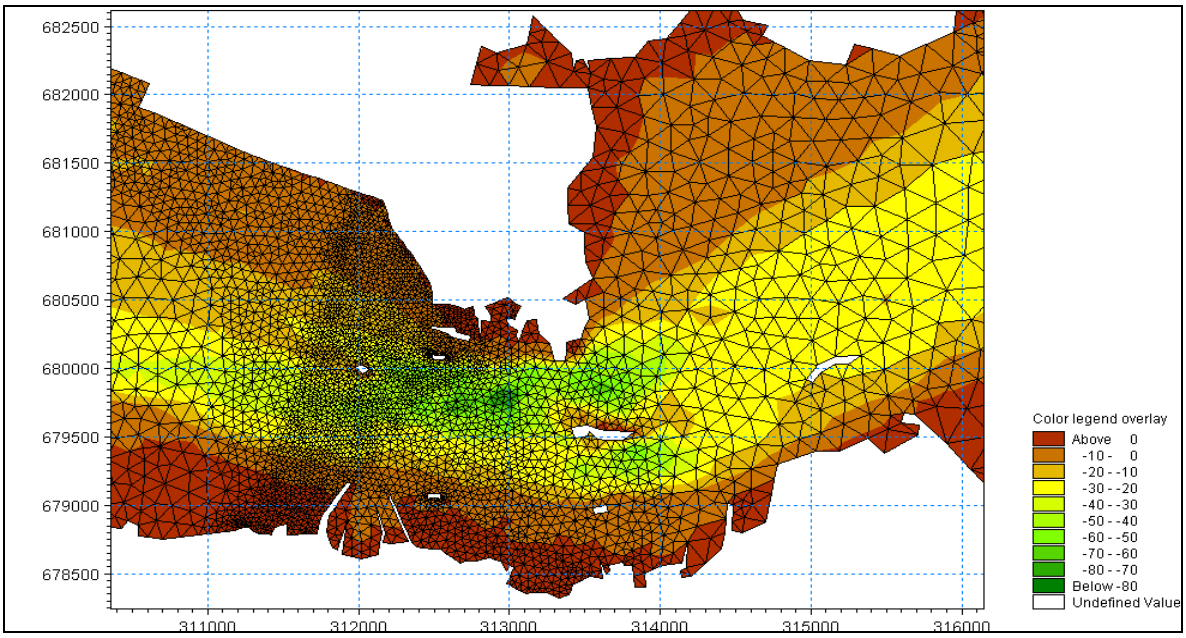
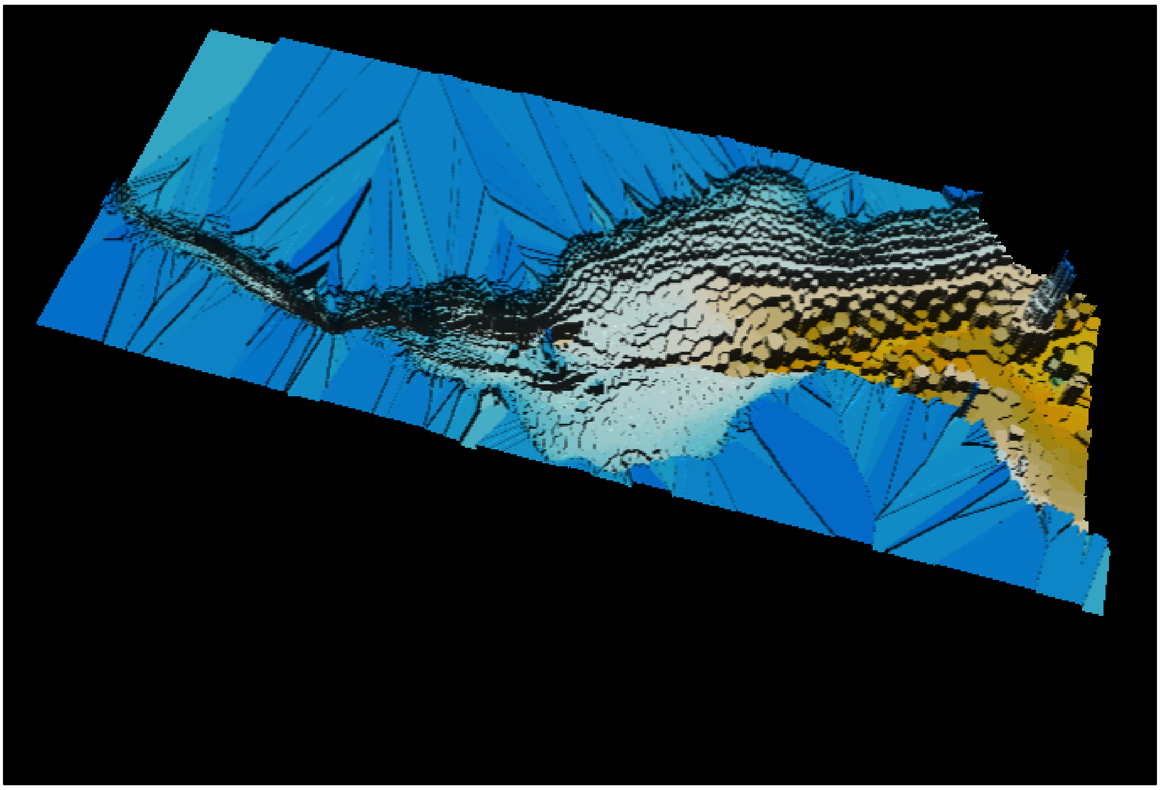


Diagram 12: The Proposed Scheme Coastal Model Mesh and Bathymetry – Central Section



2.3.14 A pseudo-3D representation of the model domain is shown in Diagram 13, giving an idea of the under-water terrain.

Diagram 13: Pseudo-3D Representation of the Model Terrain



Boundary Data

2.3.15 There are two open water boundaries in the model.

2.3.16 Water level time series have been applied to both the western and eastern boundaries. The approach is very similar to that adopted by Hyder in their Longannet 2D hydrodynamic model (Hyder Consulting, 2007), which has been approved by SEPA.

2.3.17 The UKHO TOTALTIDE model has been adopted to predict the required time series data of water levels for Kincardine and Fidra as our open water boundary conditions. This software is based on data from Admiralty charts and tidal stream atlases. Its predictions are based on actual measurements over at least a 12-hour period at each site.

Initial Data

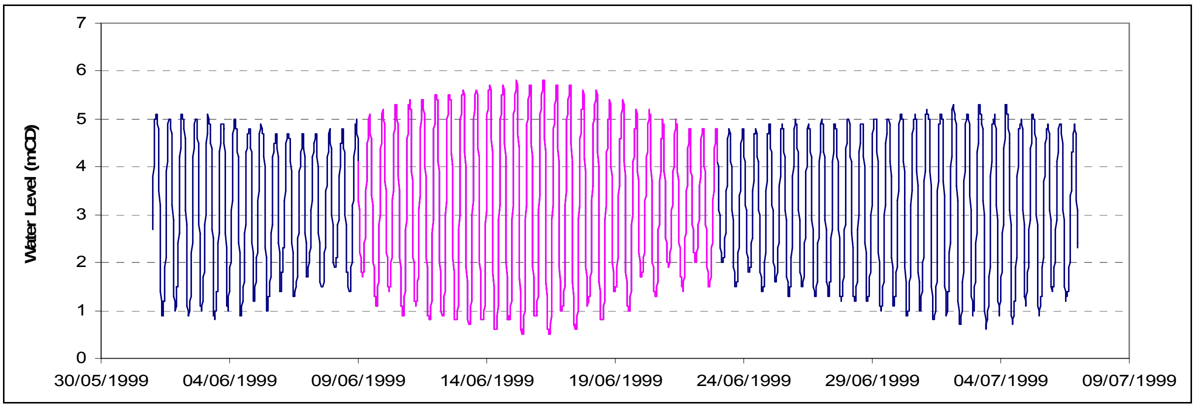
2.3.18 To run the model, a set of initial data (water level and the current speed components in the three principal directions: U, V and W) over the whole model domain is required. In order to overcome this requirement the average of the two boundary water levels as the initial water level over the whole and initially very small current speeds in all directions has been adopted. In addition, the model simulation is allowed to run for four hours to let the model settle and allow any errors from incorrect initial conditions to be minimised, before any results are extracted for analysis.

Data for Calibration

2.3.19 The following data has been collated for model calibration purposes:

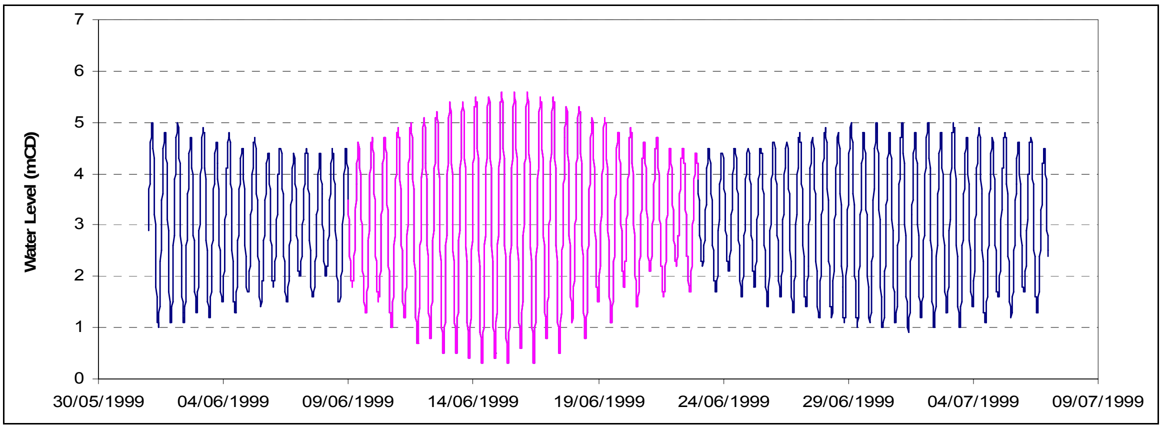
- Time scale for calibration: Spring Tide= 09/06/1999 06:00:00 to 22/06/1999 23:30:00.
- Water Level Boundary Time series data
  i. Kincardine = obtained from UKHO TOTALTIDE program.

Diagram 14: Kincardine Water Level Times Series – Western Boundary Condition



ii. Fidra = obtained from UKHO TOTALTIDE program

Diagram 15: Fidra Water Level Times Series – Eastern Boundary Condition



2.3.20 For calibration against the predicted results, the following datasets for points within the model domain have been obtained:

- The Port Seton survey carried out by HR Wallingford and Lyndhurst Oceanographics in 1999 (Lyndhurst Oceanographics, 1999), as part of the Edinburgh Coastal Strategy Marine Survey. The survey collected water level, current and wind data by means of the deployment of an offshore tide gauge, two recording current meters and an Acoustic Doppler Profiler (ADP). Data was collected on both spring and neap tides at the following locations:

  i. Gullane – water level and current.

  ii. Port Seton – current and wind.

- In order to obtain sufficient data points to perform the calibration, time series water level from the TOTALTIDE program of the following locations has been obtained:

  i. Burntisland, Grangemouth, Granton, Kirkcaldy and Methil.

- Time series of water level at Leith (measurements) were obtained from the BODC, and at Rosyth (predictions) from Service Hydrographique et Océanographique de la Marine (SHOM).

- For current time series data (speed and direction), the TOTALTIDE prediction at 12 locations SN023A to SN023L were obtained.

- For wind data, the measured wind at Port Seton recorded during the 1999 marine survey by HR Wallingford and Lyndhurst Oceanographics has been used. The wind is measured at 10 m above sea level so there is no need to make any adjustment for use in modelling.

- Fluvial flow rates have been based on mean flow rates obtained from SEPA's website and as shown in Table 2.3 and Diagram 7. Daily mean flow time series data was received from SEPA following the calibration process and therefore it was not possible to incorporate them in the model calibration.
- For temperature and salinity, the water temperature has been assumed to be constant, at 15 °C and salinity of 32 (in practical salinity units PSU) for sea water and 0 for freshwater.

2.3.21 The use of predicted data from other software/models to calibrate and validate the model has been applied successfully in the past, noticeably the 1993 HR Wallingford study (HR Wallingford, 1993), the Upper Forth Crossing Modelling Study in 2001 by Babtie Group (2001) and the Longannet 2D model by Hyder in 2007 (Hyder Consulting, 2007).

2.3.22 The available water level measurement/prediction locations are shown in Diagram 16 and the available current velocity measurement and prediction locations in Diagram 17.

2.3.23 The tidal streams for the above 12 TOTALTIDE locations together with some of the water level prediction sites are also shown in UKHO website, as shown in Diagram 18. All the data used for calibration are summarised in Table 2.5.

Diagram 16: Available Water Level Measurement/Prediction Points

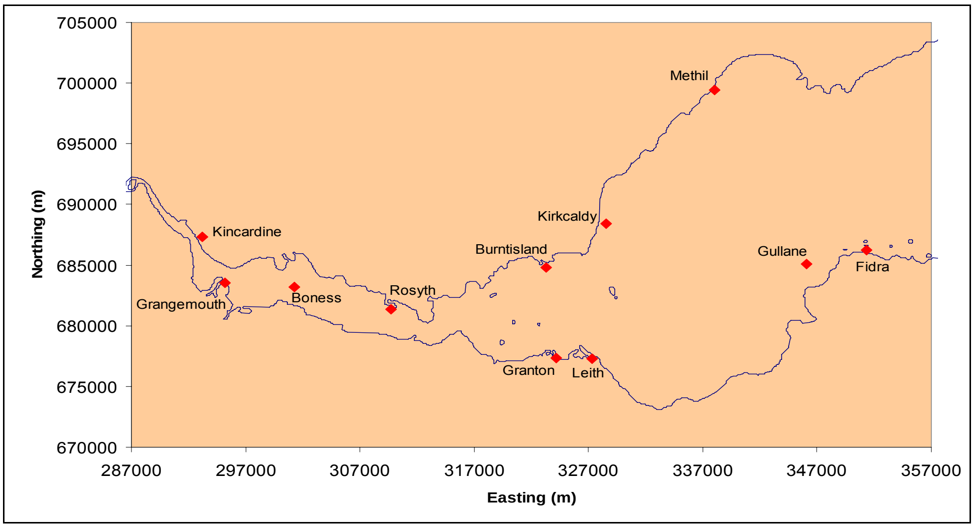


Diagram 17: Available Current Velocity Measurement/Prediction Points

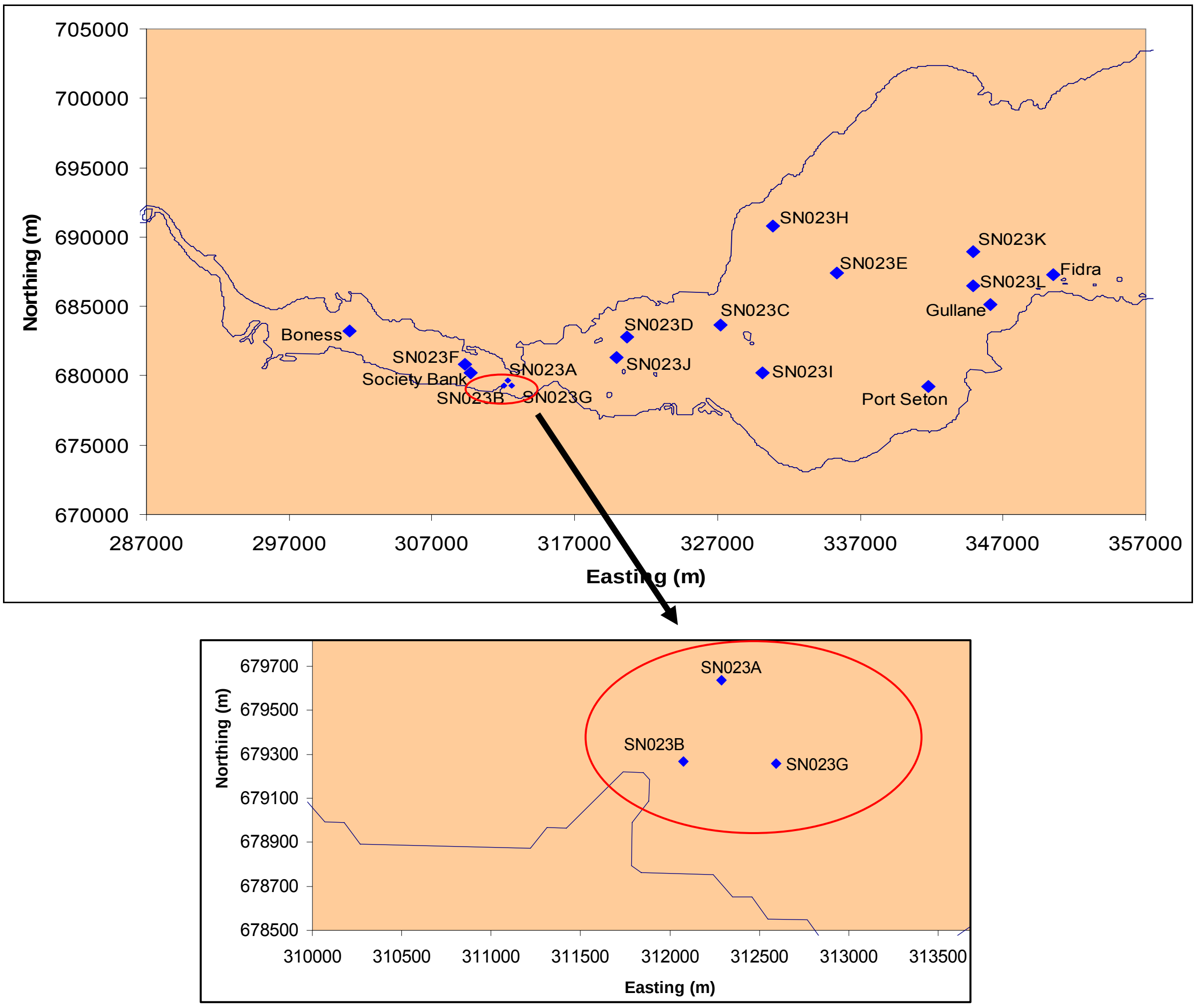


Diagram 18: Tidal Streams and Water Level predictions from TOTALTIDE

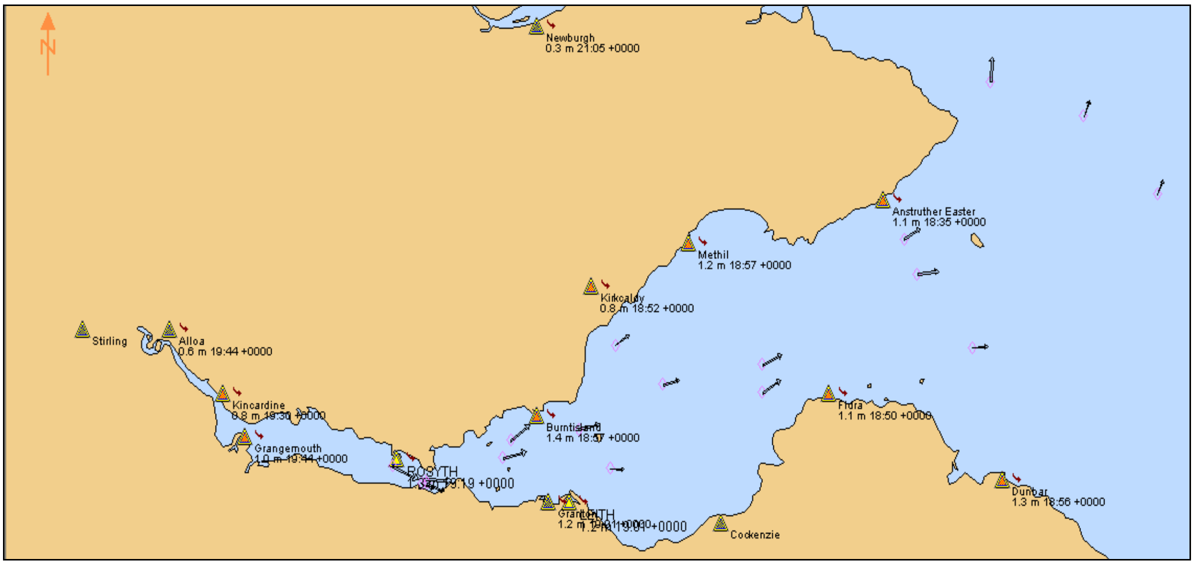


Table 2.5: Summary of Calibration Data

Calibration Time Period Spring Tide = 09/06/1999 06:00:00 to 22/06/1999 23:30:00 = 14 days or 336 hours			
Boundary Conditions Western Boundary – Kincardine – Water Level Eastern Boundary – Fidra – Water Level			
Location	**Water Level**	**Current (speed, Direction)**	**Wind**
Kincardine	TOTALTIDE		
Fidra	TOTALTIDE		
Gullane	Survey	Survey	
Port Seton		Survey	Survey
Burntisland	TOTALTIDE		
Grangemouth	TOTALTIDE		
Granton	TOTALTIDE		
Kirkcaldy	TOTALTIDE		
Methil	TOTALTIDE		
Leith	BODC		
Rosyth	SHOM		
SN023A		TOTALTIDE	
SN023B		TOTALTIDE	
SN023C		TOTALTIDE	
SN023D		TOTALTIDE	
SN023E		TOTALTIDE	
SN023F		TOTALTIDE	
SN023G		TOTALTIDE	
SN023H		TOTALTIDE	
SN023I		TOTALTIDE	
SN023J		TOTALTIDE	

Calibration Time Period Spring Tide = 09/06/1999 06:00:00 to 22/06/1999 23:30:00 = 14 days or 336 hours			
SN023K		TOTALTIDE	
SN023L		TOTALTIDE	

Wind = Port Seton wind time series data applied to whole model domain.

Freshwater inputs = 9 rivers based on the mean flows in SEPA website.

Temperature = 15 °C for all water, at all times.

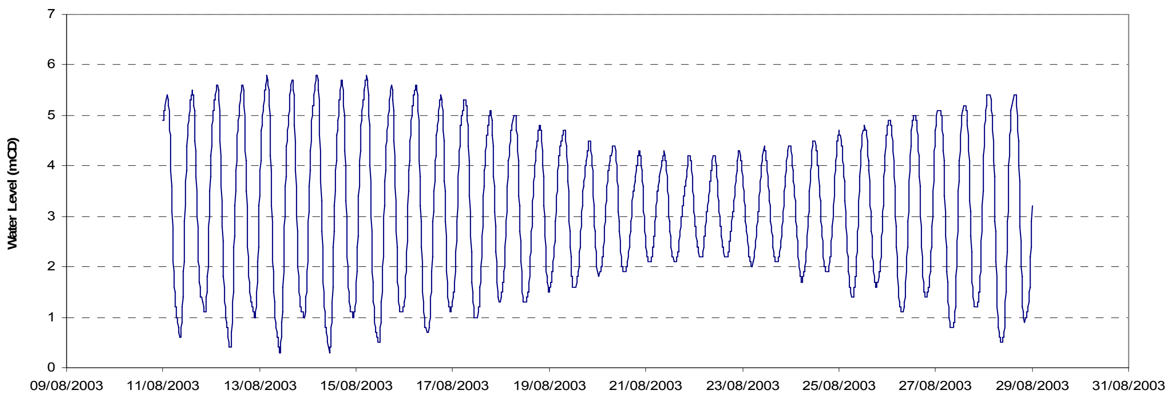
Salinity = 0 for freshwater and 32 for seawater in PSU.

Data for Validation

2.3.24 The following data have been collected for model validation purposes:

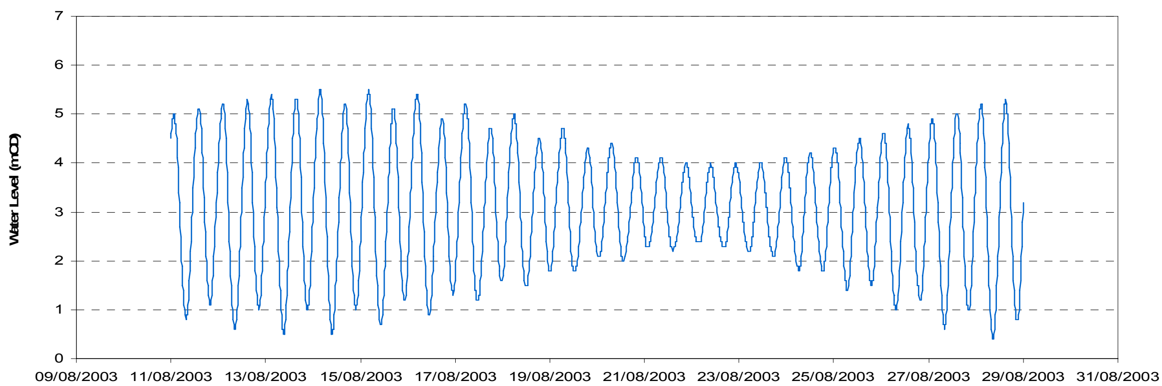
- Time scale for validation
  i. Neap Tide = 11/08/2004 06:00:00 to 28/08/2003 23:30:00.
- Water Level Boundary Time series data
  i. Kincardine = obtained from UKHO TOTALTIDE program.

Diagram 19: Kincardine Water Level Times Series – Western Boundary Condition



  ii. Fidra = obtained from UKHO TOTALTIDE program

Diagram 20: Fidra Water Level Times Series – Easter Boundary Condition



2.3.25 For validation against the predicted results, the following data points within the model domain have been obtained:

- Water level time series data at Boness from 11/8/2003 to 26/8/2003, provided by SEPA.

- Time series of water level at Rosyth were obtained from Proudman Oceanographic Laboratory tidal prediction program POLTIPS.
- Time series water level from the TOTALTIDE program of the following locations:
  i. Burntisland, Grangemouth, Granton, Kirkcaldy, Leith and Methil.
- For current time series data (speed and direction), the SEPA supplied measurement time series at Boness and Society Bank were used.
- For wind data 5-minute interval anemometer data from March 1994 to February 2008 has been obtained from Forth Estuary Transport Authority (FETA).

2.3.26 The FETA anemometer is located at about 72m above water and consequently this data set is not ideal when the wind speed at 10m above sea level is required. Without the temperature profile associated with the measured wind data, it is difficult to transpose the wind data to a height of 10m above sea level which is required for hydrodynamic modelling. As a consequence this data source was not used for model calibration, however due to a lack of other sources of wind data for the validation period it has been necessary to use this data set.

2.3.27 Freshwater inputs are the same as the calibration case, by adopting the mean flow rates as shown in Table 2.6. The locations of the freshwater inputs are shown in Diagram 7.

2.3.28 Temperature and salinity are assumed the same as in calibration, in which temperature in the water is constant, at 15 °C and salinity is 32 for sea water and 0 for freshwater in PSU.

2.3.29 The available water level measurement/prediction locations are shown in Diagram 16 and the available current velocity measurement and prediction points in Diagram 17.

2.3.30 The tidal streams for the above 12 TOTALTIDE locations, together with some of the water level prediction sites are also shown in TOTALTIDE map, as shown in Diagram 18.

2.3.31 All the data used for validation are summarised in Table 2.6.

Table 2.6: Summary of Validation Data

Calibration Time Period Spring Tide = 11/08/2004 06:00:00 to 28/08/2003 23:30:00 = 18 days or 432 hours			
Boundary Conditions Western Boundary – Kincardine – Water Level Eastern Boundary - Fidra – Water Level			
Location	**Water Level**	**Current (speed, Direction)**	**Wind**
Kincardine	TOTALTIDE		
Fidra	TOTALTIDE		
Boness	SEPA	SEPA	
Society Bank		SEPA	
Burntisland	TOTALTIDE		
Grangemouth	TOTALTIDE		
Granton	TOTALTIDE		
Kirkcaldy	TOTALTIDE		
Methil	TOTALTIDE		
Leith	BODC		
Rosyth	POLTIPS		
Forth Road Bridge			FETA
SN023A		TOTALTIDE	
SN023B		TOTALTIDE	

Calibration Time Period Spring Tide = 11/08/2004 06:00:00 to 28/08/2003 23:30:00 = 18 days or 432 hours			
Boundary Conditions Western Boundary – Kincardine – Water Level Eastern Boundary - Fidra – Water Level			
Location	**Water Level**	**Current (speed, Direction)**	**Wind**
SN023C		TOTALTIDE	
SN023D		TOTALTIDE	
SN023E		TOTALTIDE	
SN023F		TOTALTIDE	
SN023G		TOTALTIDE	
SN023H		TOTALTIDE	
SN023I		TOTALTIDE	
SN023J		TOTALTIDE	
SN023K		TOTALTIDE	
SN023L		TOTALTIDE	

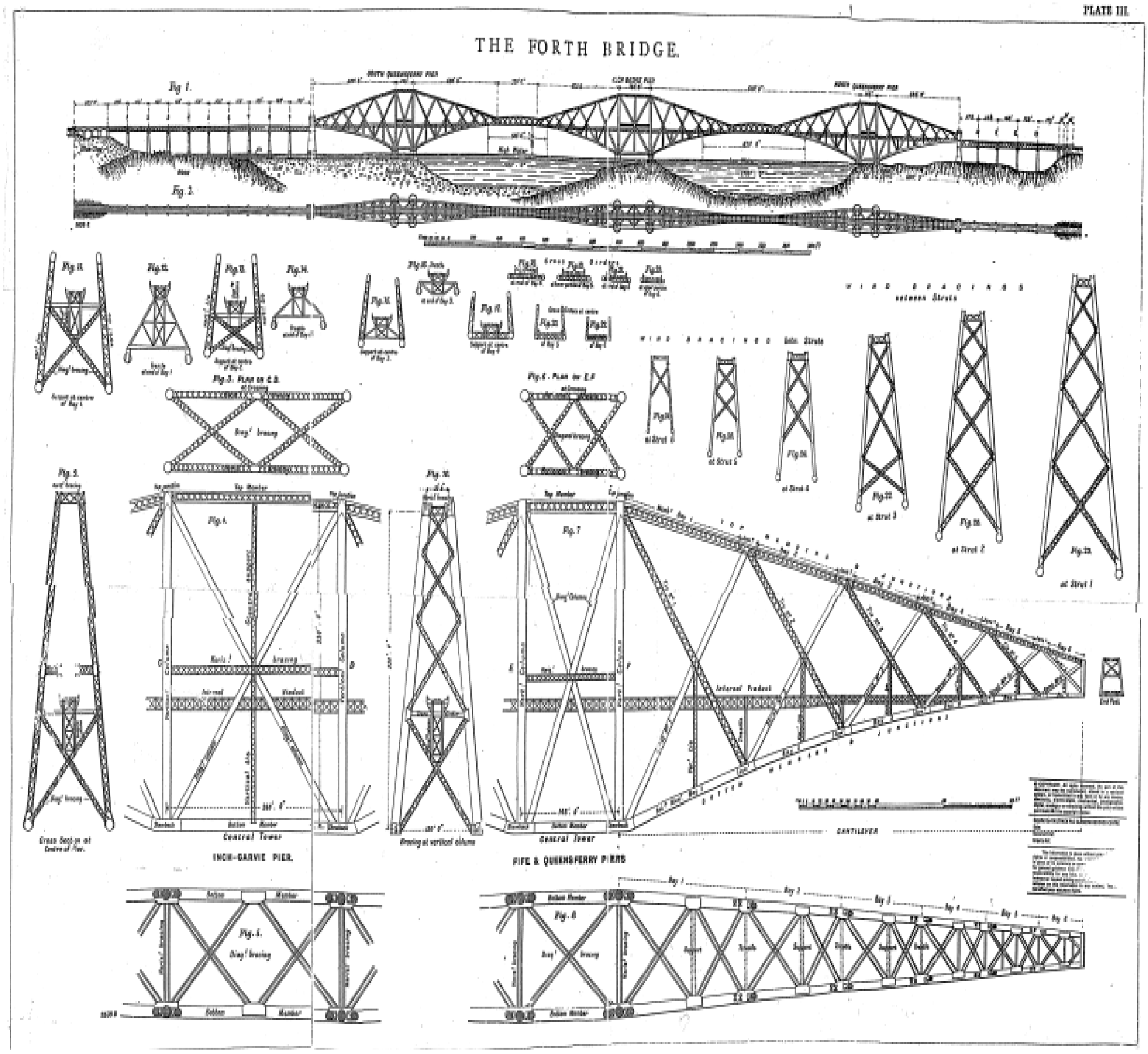
Wind = Forth Road Bridge wind time series data applied to whole model domain.
Freshwater inputs = 9 rivers based on the mean flows in SEPA website.
Temperature = 15 °C for all water, at all times.
Salinity = 0 for freshwater and 32 for seawater in PSU.

Pier Details for the Forth Rail Bridge, Forth Road Bridge and the Main Crossing

2.3.32 To represent bridge piers associated with the Forth Rail Bridge and Forth Road Bridge and other structures (such as physical constraints) located within the Forth channel and represented in the 3D model, details of the structural geometry and location is required.

2.3.33 The following information has been obtained regarding the existing piers of the Forth Rail Bridge, as shown in Diagram 21.

Diagram 21: Forth Rail Bridge Old Drawings



2.3.34 Dimensions and locations of the bridge towers for the Forth Road Bridge, including the ship impact protection have also been obtained and represented in the model. These features have been represented within the model's computational mesh as permanent obstructions.

2.3.35 As this report is focused on the model verification process for the existing (baseline) condition, the nature and arrangement of the Main Crossing piers has not been considered at this stage.

Sediment and Soil Data

2.3.36 The model is developed primarily for the prediction of hydrodynamics in the Firth of Forth and Forth Estuary. Water quality investigations such as nutrients, microbiological and heavy metals and sediment transport processes have not been included in the model calibration and validation as only the hydrodynamic effects are simulated.

2.3.37 The hydrodynamic model has not considered the type and nature of the seabed sediments and their engineering properties, particularly in relation to deposition, scouring, re-suspension and flocculation. If further hydrodynamic impact assessment on the sea bottom current speed indicates that the natural sediment transport processes in the Forth Estuary and Firth of Firth could be substantially modified or disrupted by the Main Crossing construction temporary works or by the presence of the Main Crossing permanent structures, consideration would be given to modelling sediment transport processes.

2.3.38 Although sediment and soil data are not required for hydrodynamic modelling, a seabed friction parameter either defined as bed roughness height or a quadratic drag coefficient is required. As both of these are notional values in some empirical formulae, they do not relate to the actual depth or size of the seabed sediments/layer.

2.4 Hydrodynamic Model Validation

Validation Areas

2.4.1 As with the calibration stage, the validation points are divided into three groups, according to their locations in the Firth of Forth for ease of consideration: Upstream (of the Main Crossing), Central, and Downstream (of Main Crossing) areas:

- Upstream – Grangemouth, Boness, Society bank, SN023F;
- Central – Rosyth, Granton, Burntisland, SN023A, SN023B, SN023D, SN023G, SN023J; and
- Downstream – Leith, Kirkcaldy, Methil, Gullane, Port Seton, SN023C, SN023E, SN023H, SN023I, SN023K, SN023L.

Validation in Upstream Area

2.4.2 The results of the four sites in the upstream area are shown in Diagrams 22 to 26.

Diagram 22: Grangemouth Water Level – Data vs Model Prediction

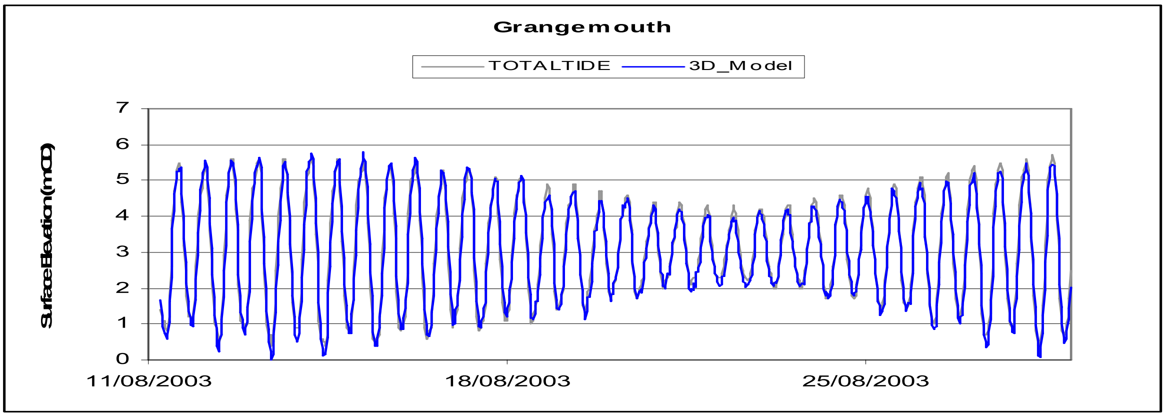


Diagram 23: Boness Water Level – Data vs Model Prediction

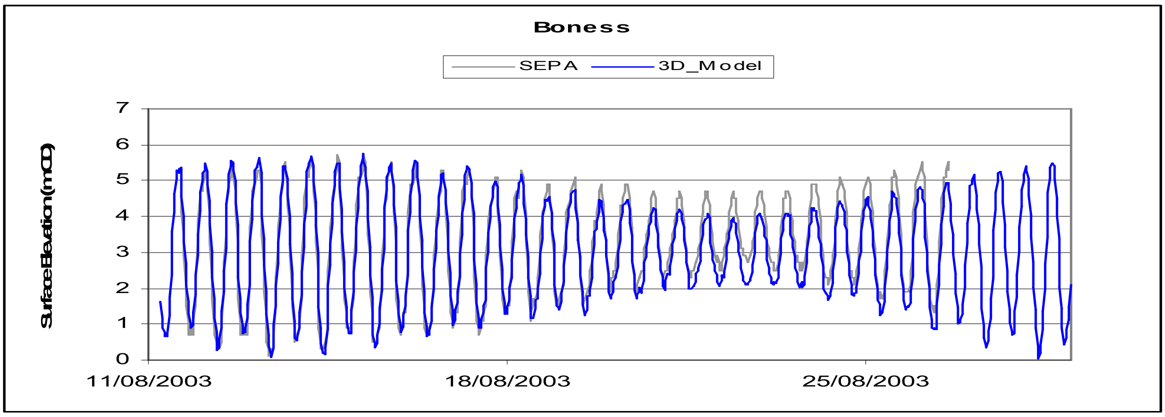
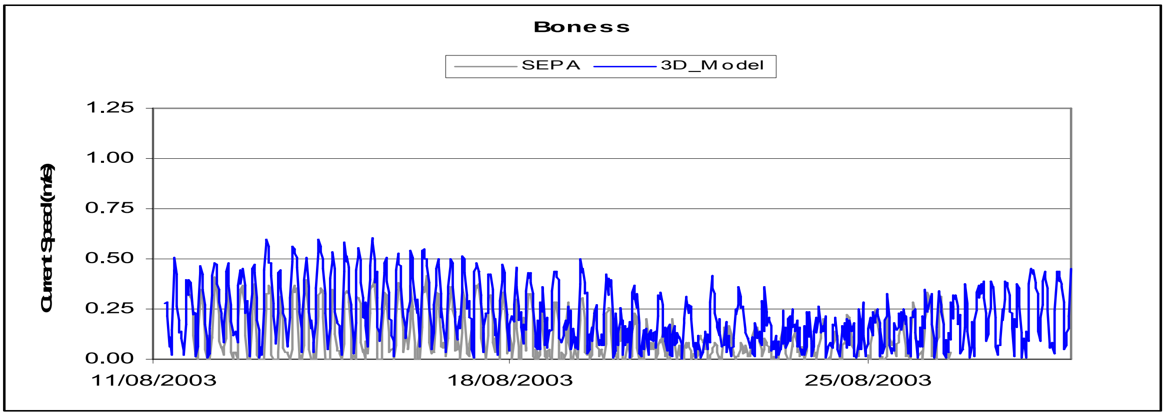


Diagram 24: Bo'ness Current – Data vs Model Prediction



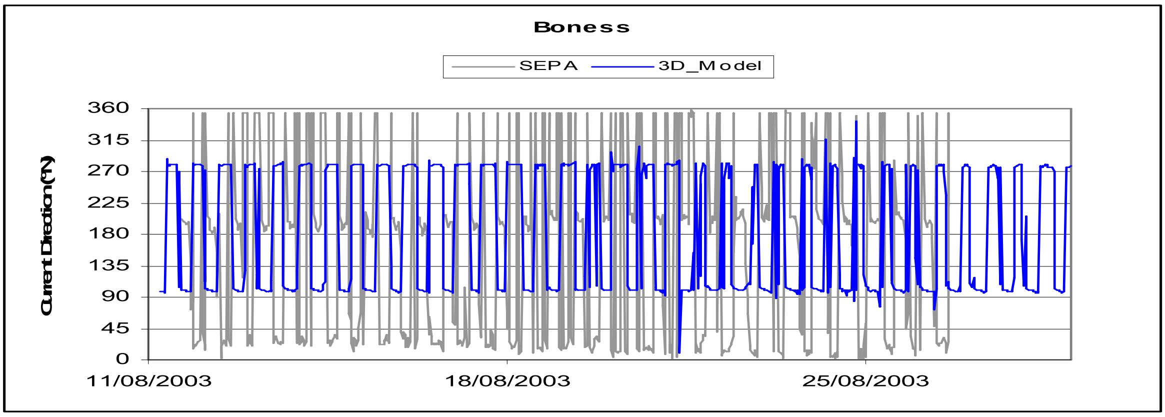


Diagram 25: Society Bank Current – Data vs. Model Prediction

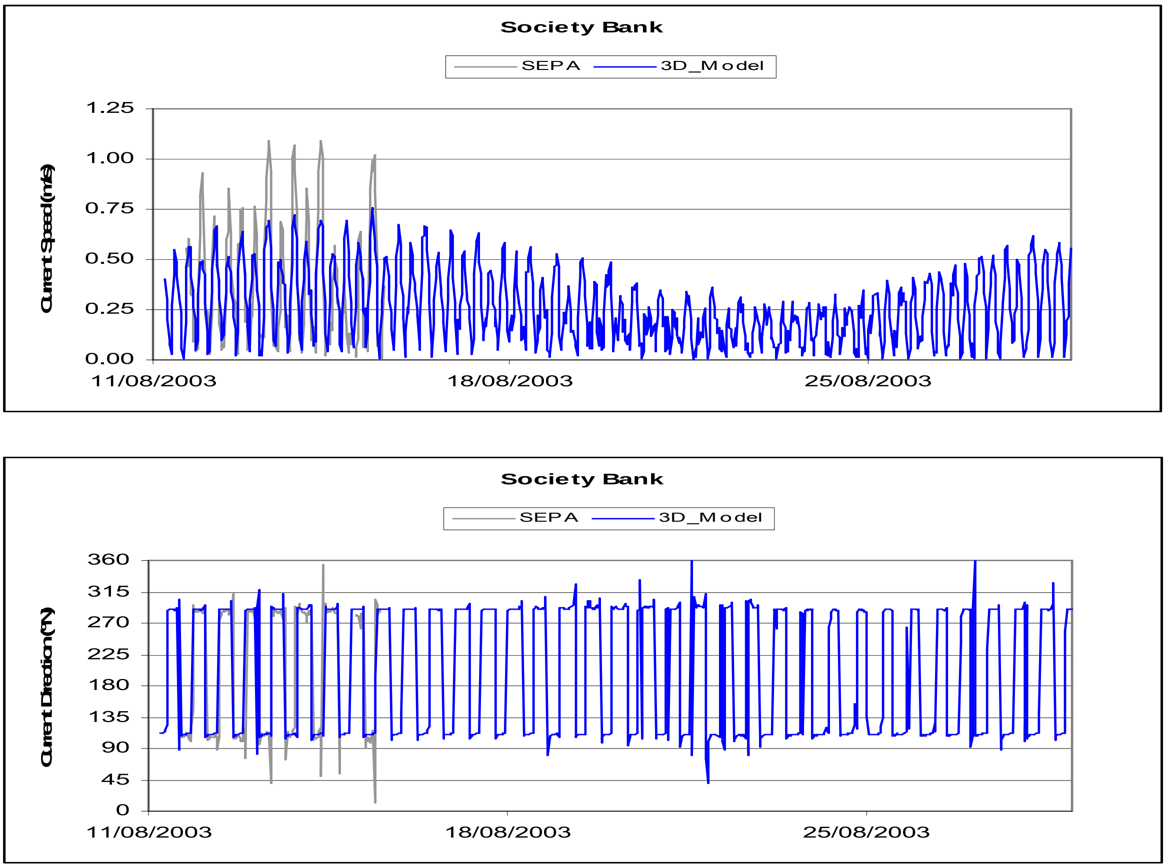
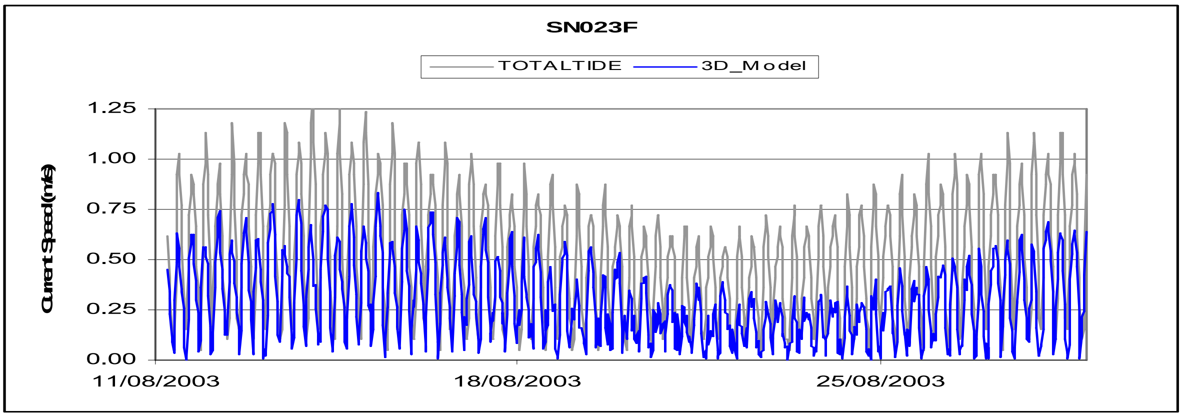
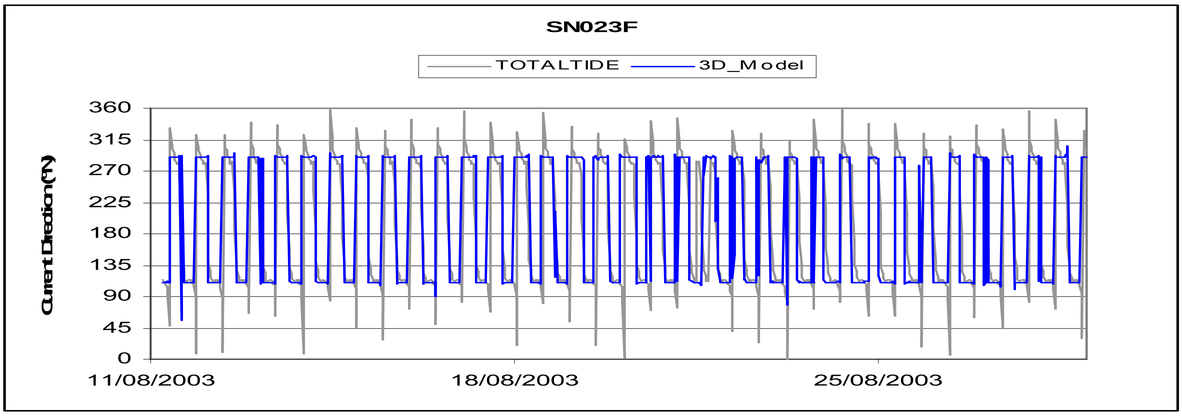


Diagram 26: SN023F Current – Data vs Model Prediction





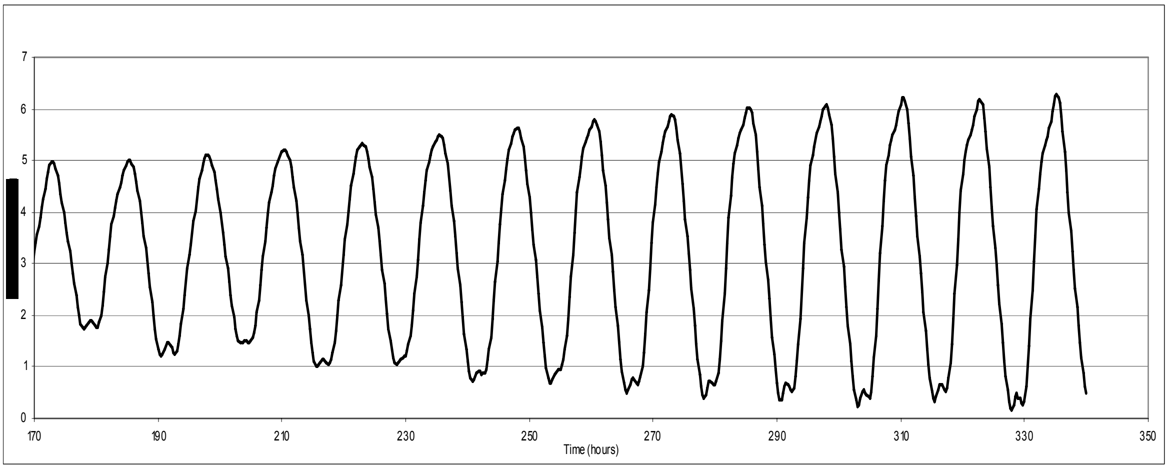
2.4.3 The following observations for the upstream area validation are made:

- The model water level prediction at Grangemouth is very good, and there is a reasonable correlation between model predictions and measurements at Boness.
- Apart from Boness, phasing of water level and speed in the other three sites match very well.
- The current directions at Society Bank and SN023F match very well.
- The current speed is under-predicted at SN023F.
- The current data at Boness appears to be unreliable, with the directions clearly incorrect, and hence this data set has been discounted.
- The current speed is under-predicted at Society Bank but the current direction is a good match. The Society Bank current speed was given at four different depths (or levels) by SEPA, without any reference datum. The speeds at depth appear to exceed those closer to the surface some of the time. This is contrary to the usually expected current profile where flow speeds decrease the closer to the seabed the measurements are taken. This may point to problems in data recording. The reliability of Society Bank SEPA data is uncertain.
- According to a note attached with the Society Bank data from SEPA, it was recommended to discard the data above a certain depth and it was also commented that the velocities are unrealistically high; there may also have been a possible signal strength problem during data recording. Therefore the Society Bank velocity data have been discarded but the current directions have been retained for validation purposes.

2.4.4 The hydrodynamic model can also simulate the existence of lackie tides in the estuary upstream of Rosyth.

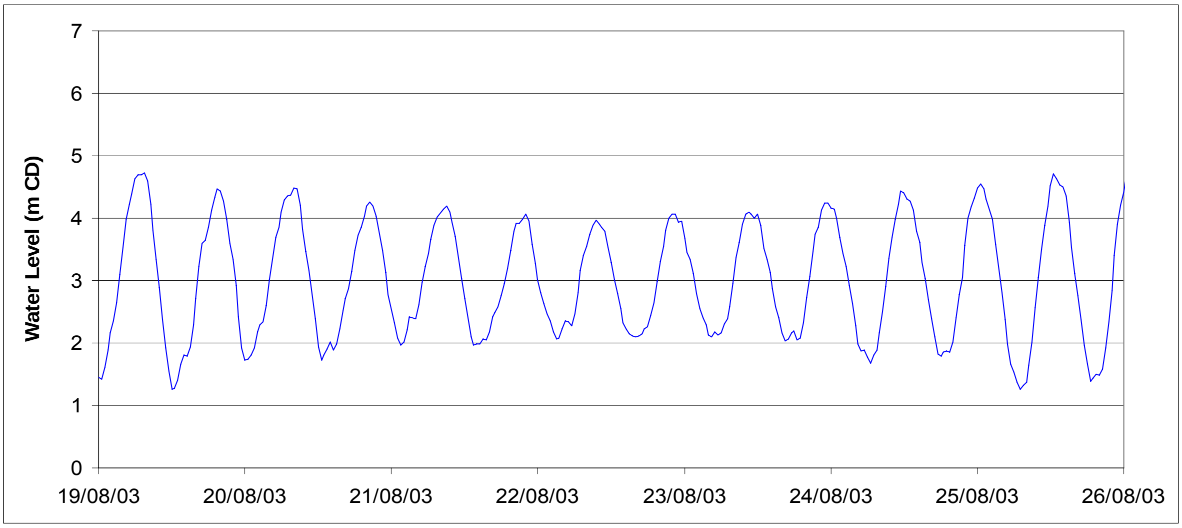
2.4.5 Diagram 27 shows the water level time series at Kincardine Bridge generated by the SEPA East MIKE11 clearly showing the lackie tide pattern. The plot covers about seven days of data.

Diagram 27: Water Level at Kincardine Bridge Simulated by SEPA East MIKE11 Model



2.4.6 The hydrodynamic model has been able to replicate the lackie tide behaviour in the estuary. Diagram 28 is a shorter plot of the neap tide water levels at Boness (refer to Diagram 23), which is not too far downstream of Kincardine. Even though the plot is for an entirely different time period to Diagram 27, the lackie tide pattern is clearly present.

Diagram 28 Water Level at Boness Simulated by the Hydrodynamic Model



Validation in Central Area

2.4.7 The results of the four sites in the upstream area are shown in Diagram 29 to Diagram 36.

Diagram 29: Rosyth Water Level – Data vs Model Prediction

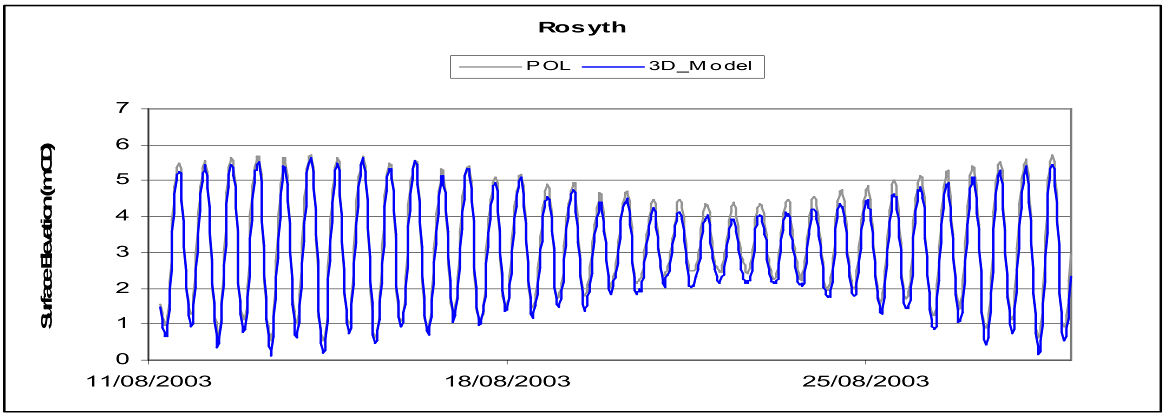


Diagram 30: Granton Water Level – Data vs Model Prediction

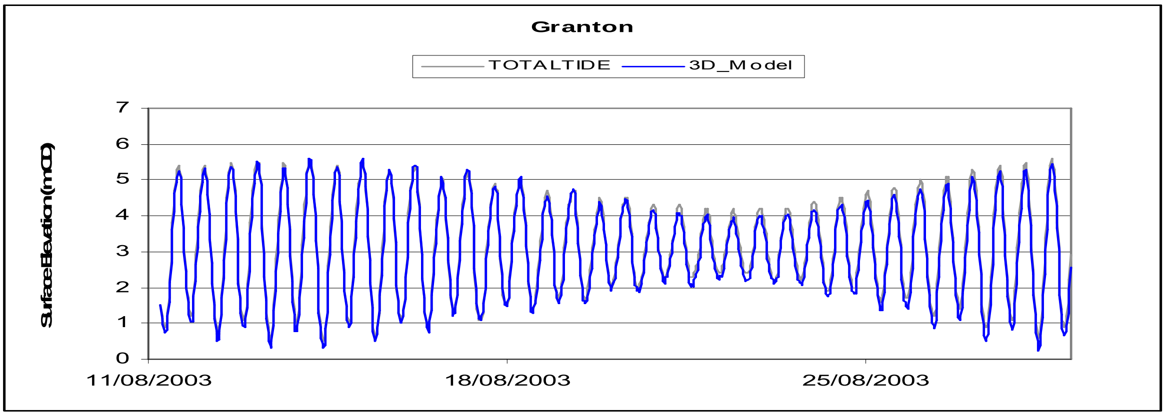


Diagram 31: Burntisland Water Level – Data vs Model Prediction

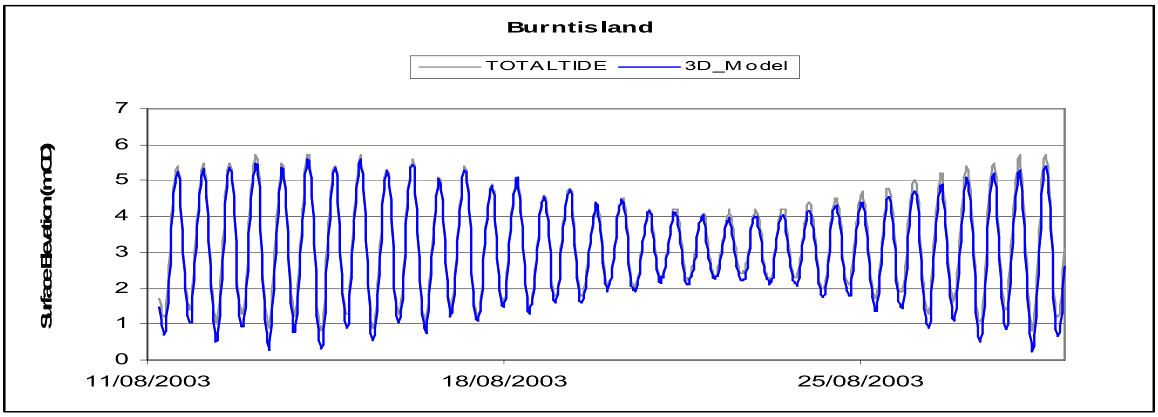
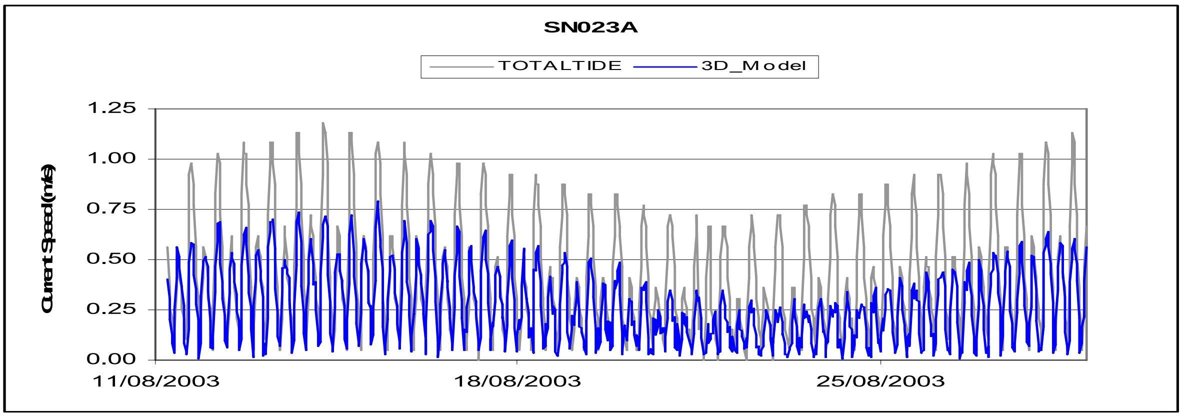


Diagram 32: SN023A Current– Data vs Model Prediction



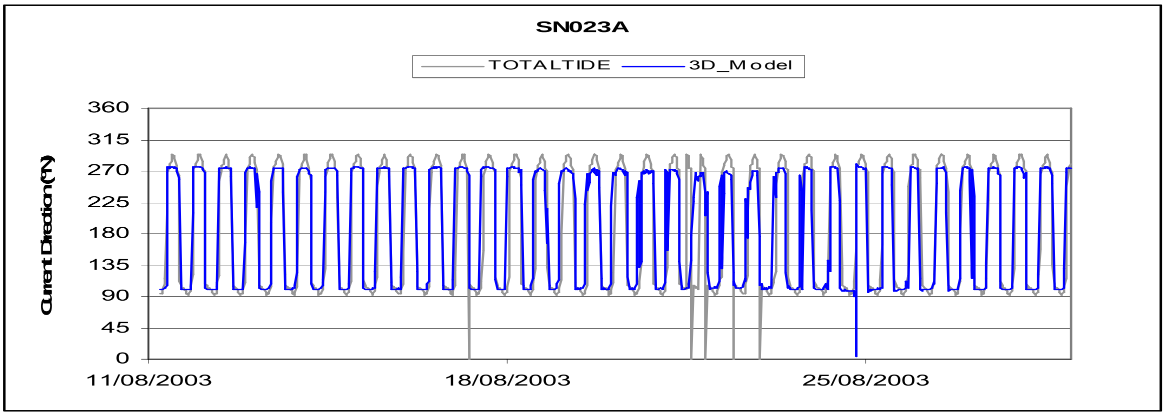
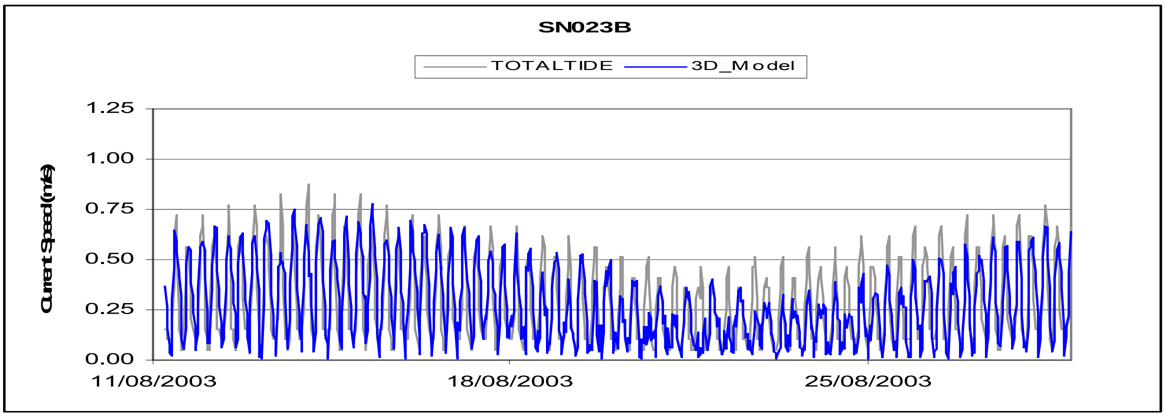


Diagram 33: SN023B Current– Data vs Model Prediction



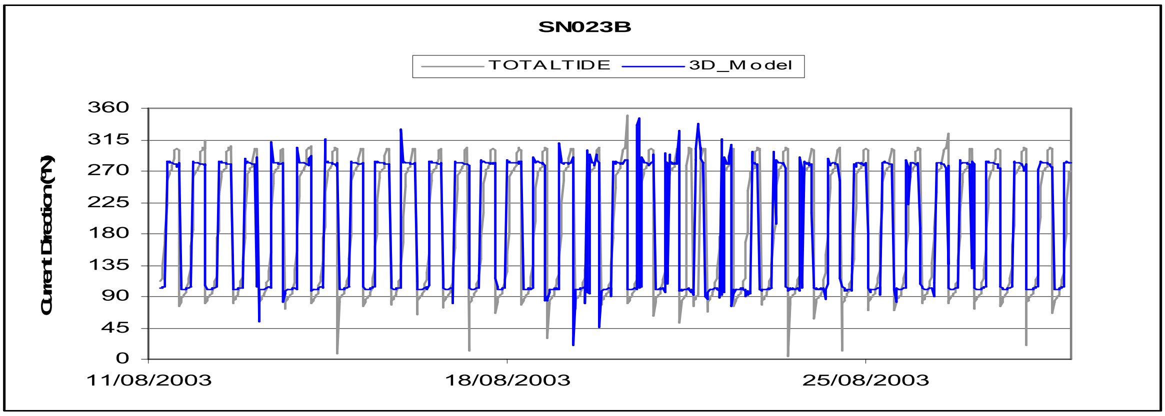
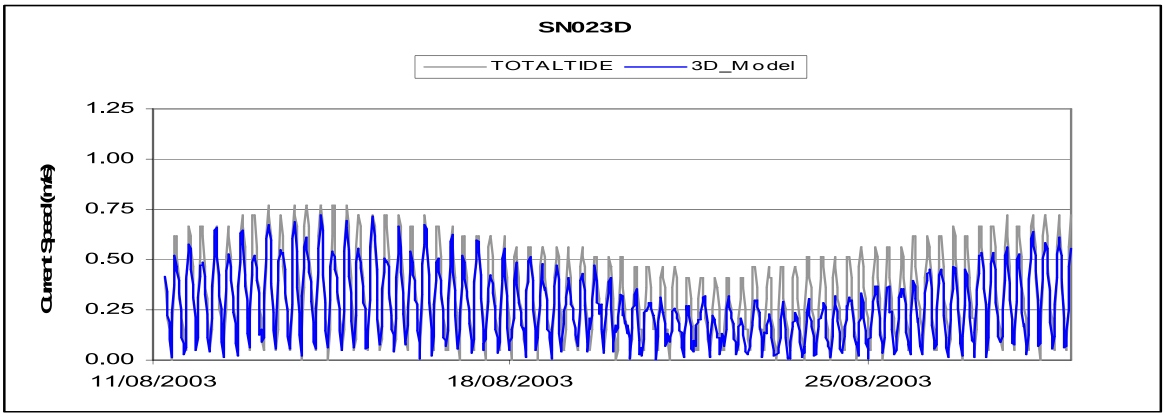


Diagram 34: SN023D Current– Data vs Model Prediction



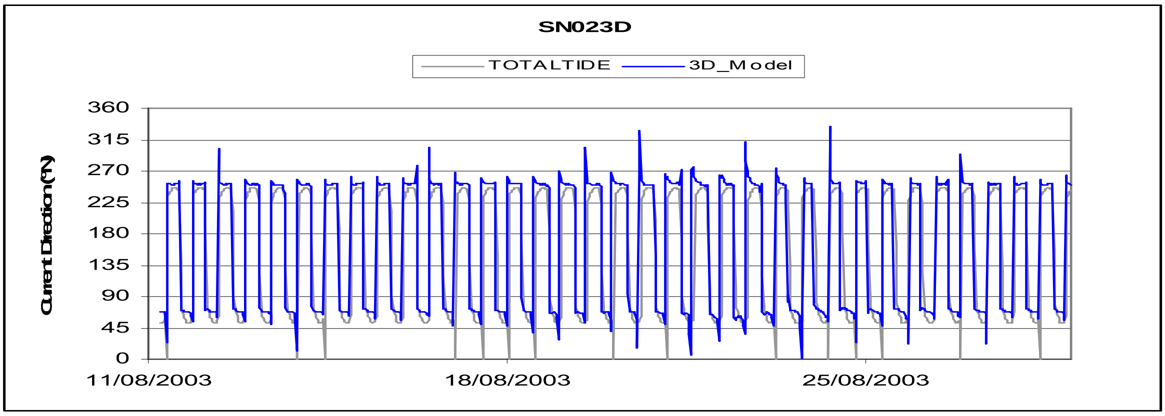
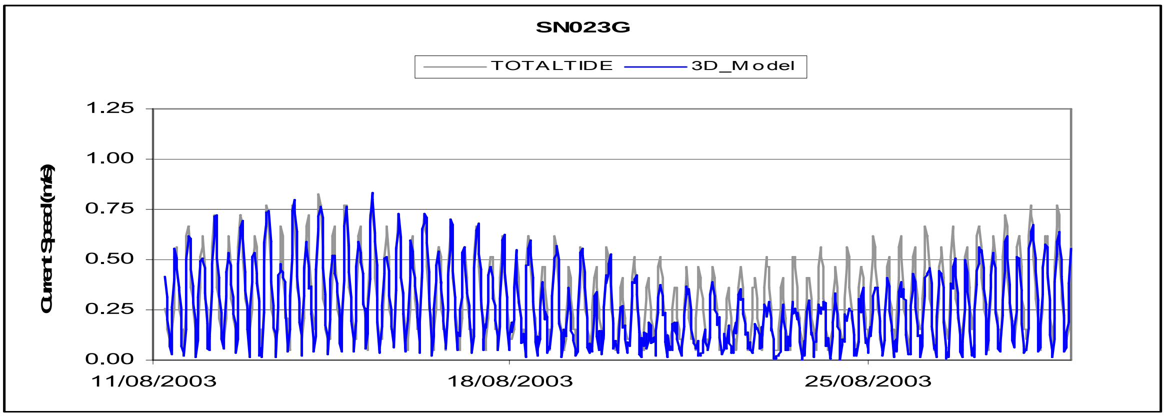


Diagram 35: SN023G Current– Data vs Model Prediction



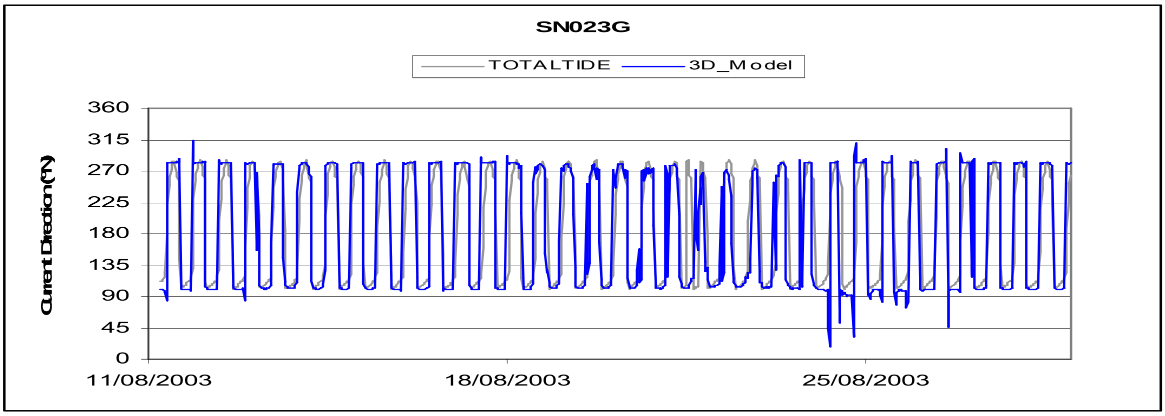
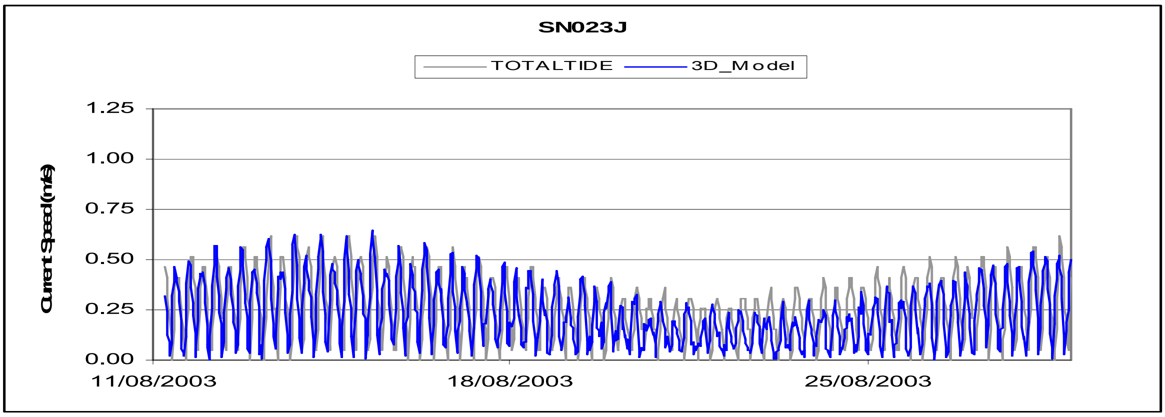
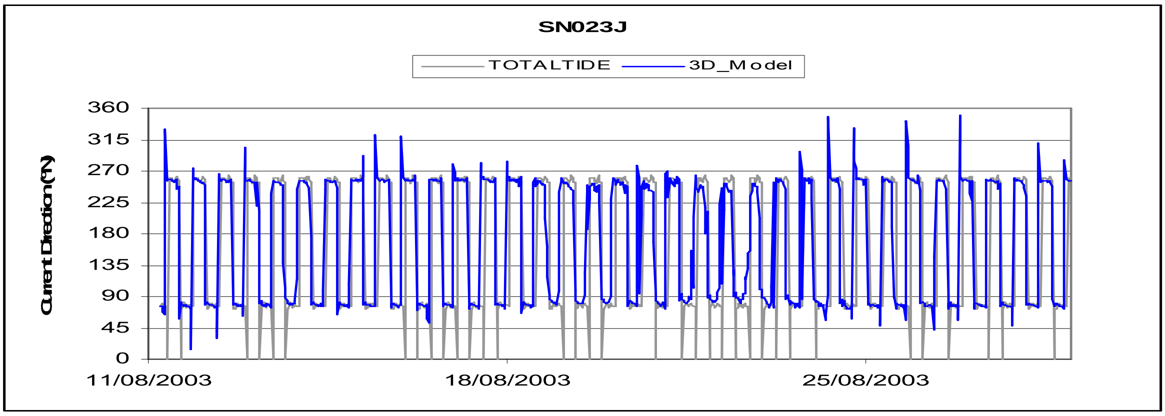


Diagram 36: SN023J Current– Data vs Model Prediction





2.4.8 The following observations for the central area validation are made:

- The water level prediction is very good.
- Phasing of water level and speed are very good.
- The current direction matches very well.
- As in the calibration, the current speed is under-predicted at one site (SN023A) but a very good correlation occurs at the other four sites. SN023A is close to the deepest part of the Queensferry narrows but is surrounded by several large bridge piers and outcrop islands. No re-circulation pattern is observed throughout the water column in this area and the flow is reasonably uniform. For the same reason as SN023F, the divergence of current speed between the (faster) TOTALTIDE prediction and the (slower) FRC model prediction could be due to changes in the bathymetry levels in this location since the tidal stream measurement for SN023A were taken in the 1960s. The FRC model has the benefit of some survey data in the area taken in 1993 and 2007. The more accurate and deeper seabed levels used by the FRC model may result in a slower current speed in SN023A. A good match in speed phasing and flow direction at this location both support this conclusion.
- The two neighbouring diamonds SN023B and SN023G are considered good matches in terms of current speed, phasing and direction. Due to their locations in relatively shallow waters, the potential change in bathymetry levels since the tidal stream measurements used in TOTALTIDE could be small and hence the similarity in the predictions.
- The current predictions are generally good at the other four sites but in the middle of the neap tide periods between 21and 25 August 2003, the 3D model under-predicted. It is known that in general modelling is less accurate in predicting neap tide conditions.

Validation in Downstream Area

2.4.9 The results of the nine sites in the downstream area are shown in Diagrams 37 to 45.

Diagram 37: Leith Water Level – Data vs Model Prediction

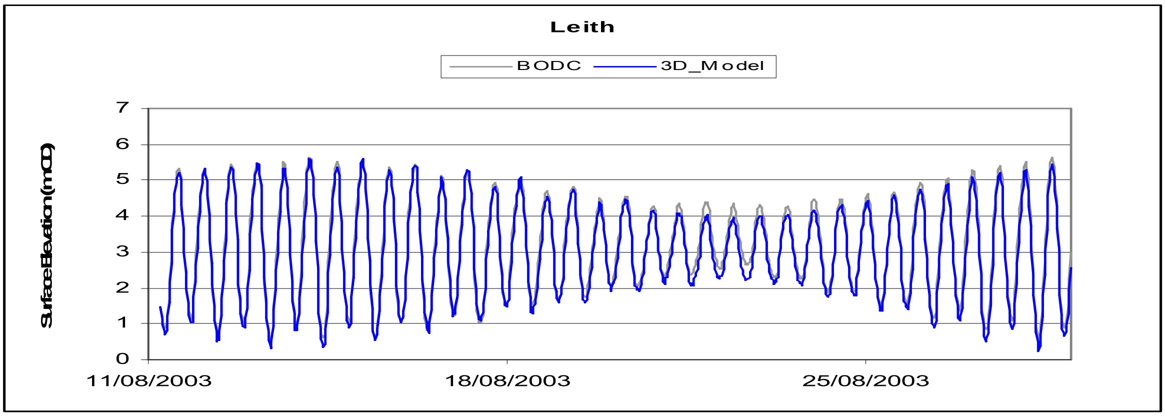


Diagram 38: Kirkcaldy Water Level – Data vs Model Prediction

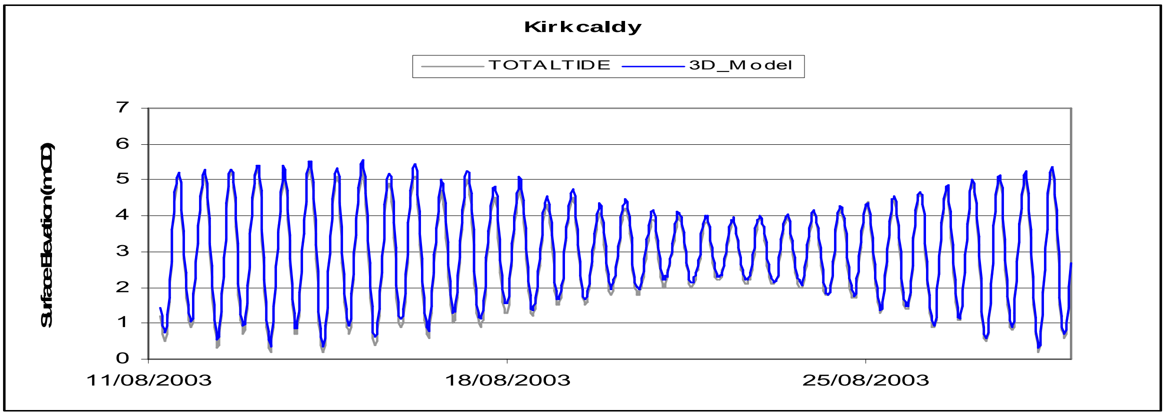


Diagram 39: Methil Water Level – Data vs Model Prediction

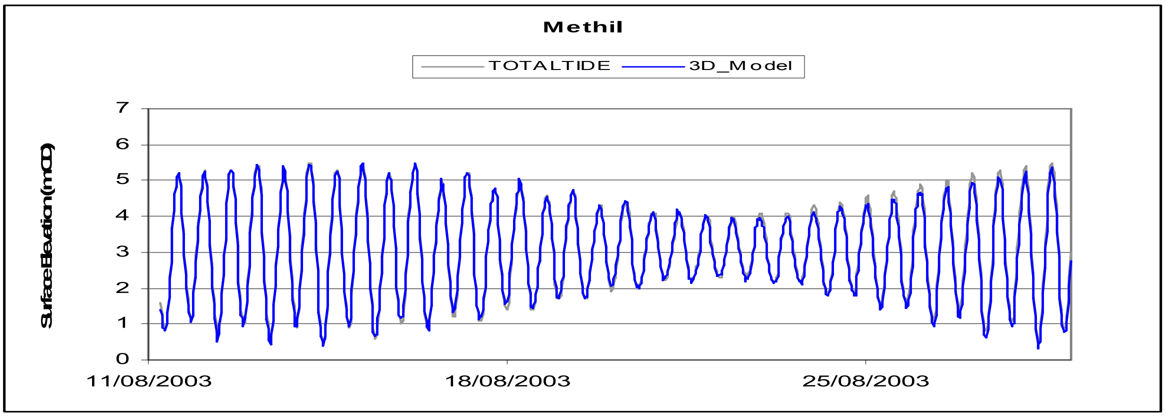
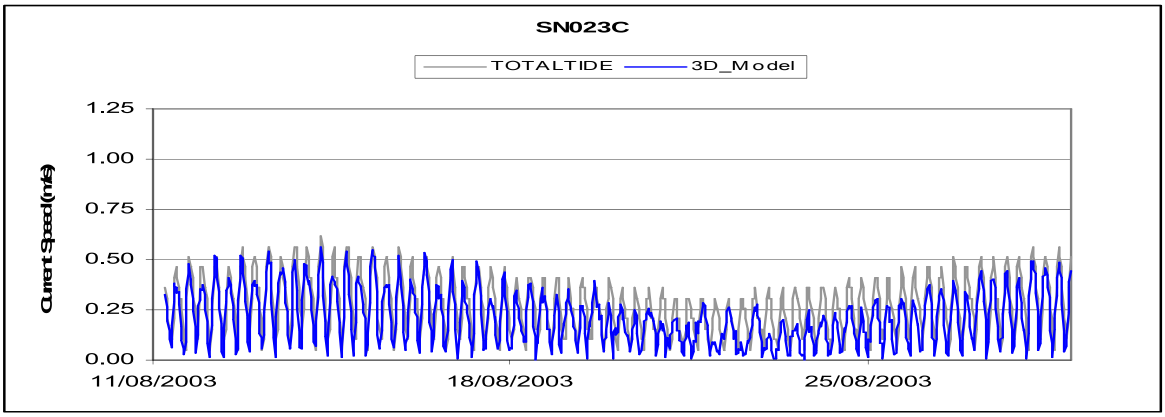


Diagram 40: SN023C Current – Data vs Model Prediction



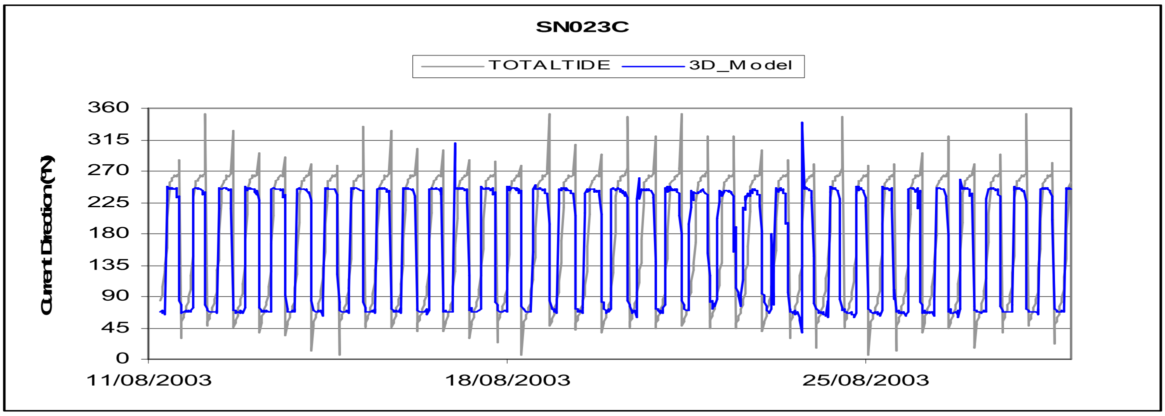
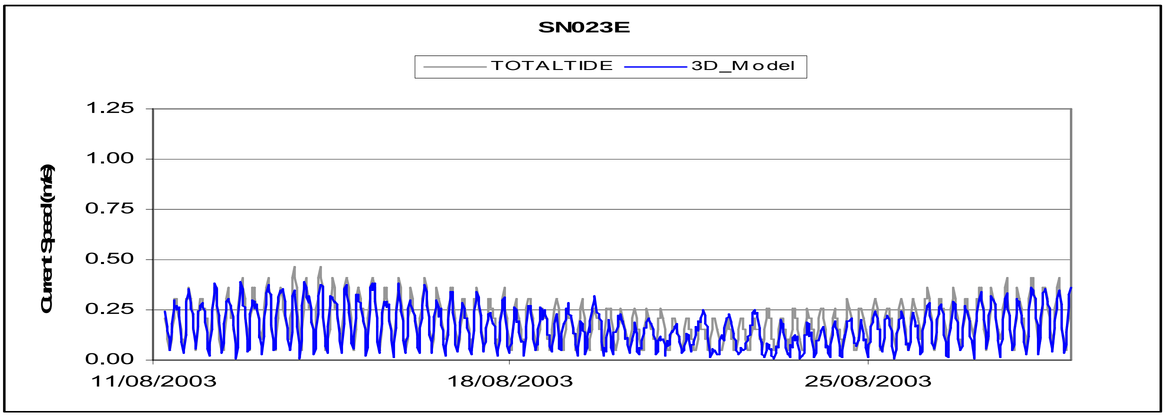


Diagram 41: SN023E Current – Data vs Model Prediction



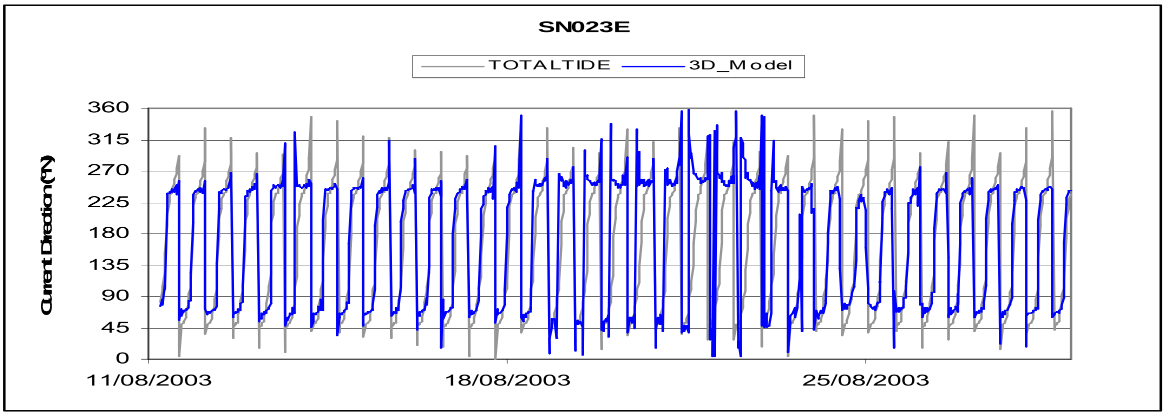
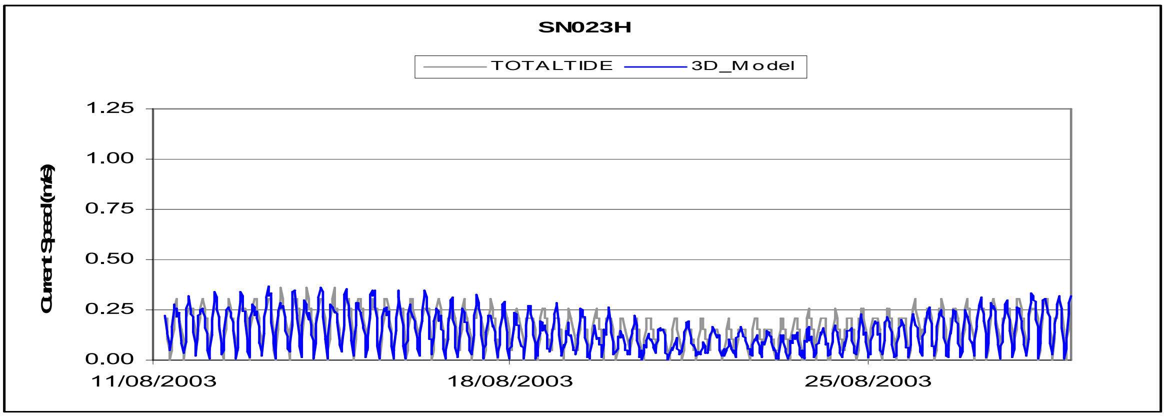


Diagram 42: SN023H Current – Data vs Model Prediction



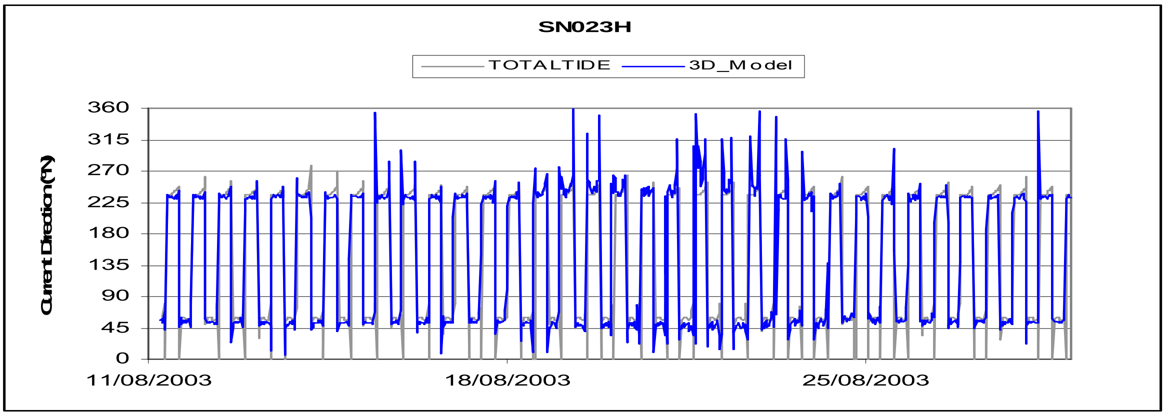
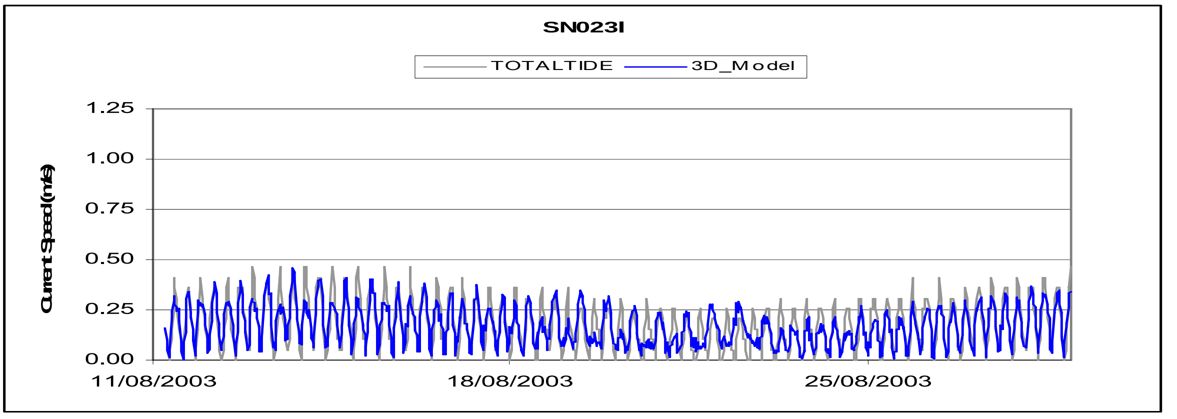


Diagram 43: SN023I Current – Data vs. Model Prediction



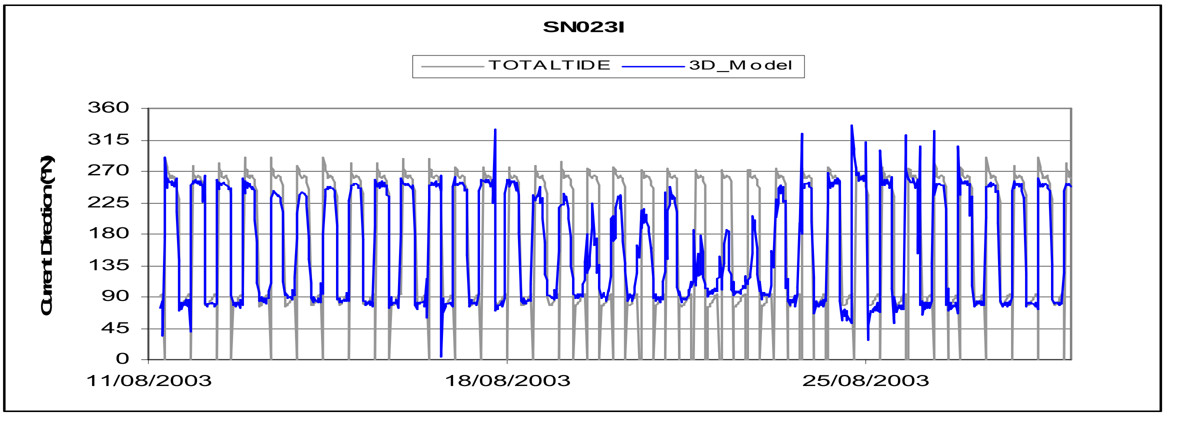
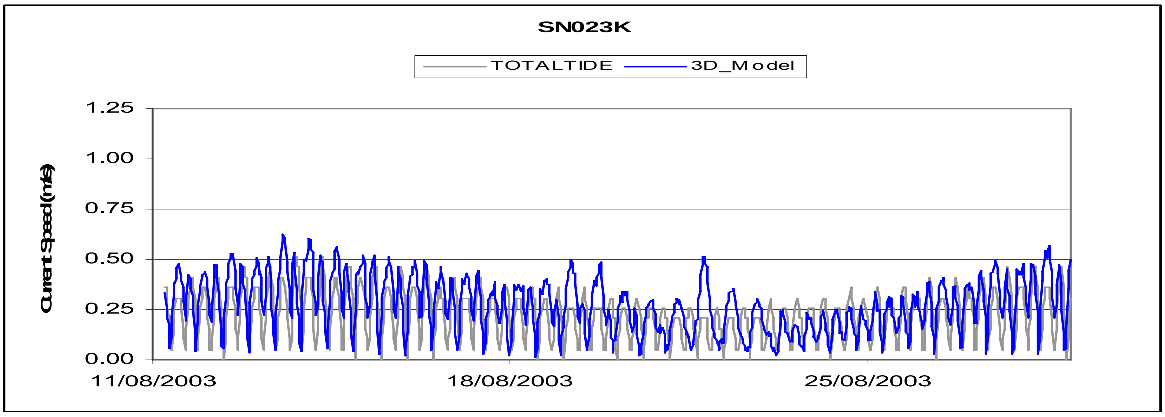


Diagram 44: SN023K Current – Data vs Model Prediction



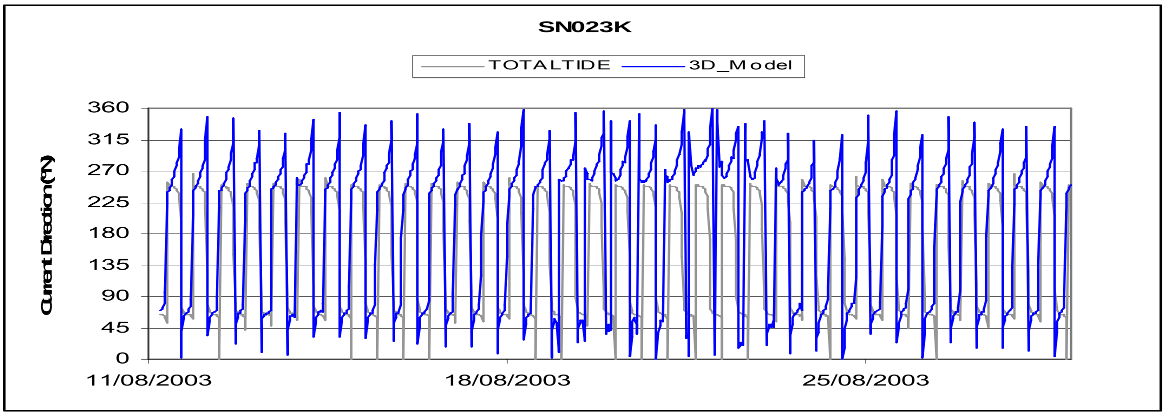
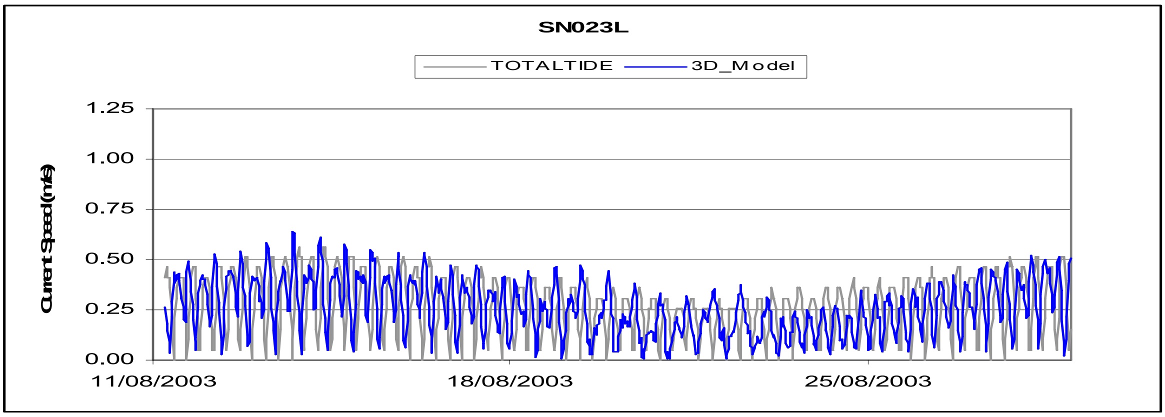
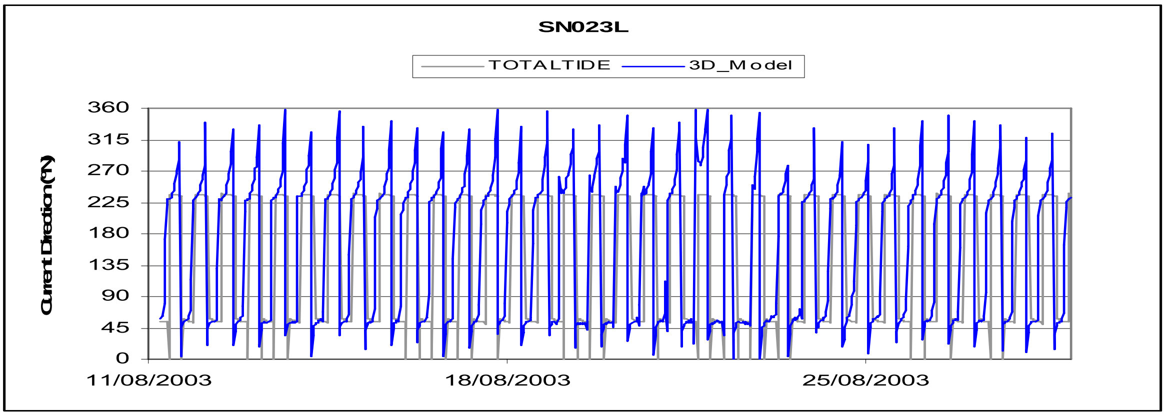


Diagram 45: SN023L Current – Data vs. Model Prediction





2.4.10 The following observations for the central area calibration are made:

- The water level prediction is very good.
- Phasing of water level and speed are very good.
- The current direction matches very well except that the TOTALTIDE data exhibits a lot of random and quick turning currents before the main tide turns.
- The current speed is over-predicted at only one site (SN023K), as in the calibration but is good in the other six sites. The location of SN023K is in an open area of the Firth of Forth quite close to the east boundary. The combination of boundary and wind effects (different winds regimes used) will definitely play a significant role in the divergence between the current predictions by TOTALTIDE and the FRC model.
- The error in the TOTALTIDE prediction of SN023H as seen in the calibration does not occur in this validation. The TOTALTIDE error may be confined to spring tide only.

Statistical Analysis of Model Validations

2.4.11 The rms error from the water level predictions excluding the suspected Boness data is on average 0.21m, and the rms error from the current speed predictions excluding Society Bank is 0.14 m/s.

2.4.12 The error in the current speed is slightly larger than that in calibration (0.12m/s) but it is well known that modelling neap tides is less accurate than spring tides as the stronger energy available in spring tides allows better mixing and more uniform flow than in neap tides.

2.4.13 In addition, the wind data applied to the whole model domain may have contributed to some degree to inaccuracies in the model predictions due to the difficulties with transposing the FETA wind data from 72m to 10m above sea level. It is also likely that the wind data (speed and direction) may be inaccurate due to the sheltering effect of the existing Forth Road Bridge deck. The effect of the wind field and its friction factor has a considerable influence on the top layer current velocity. The wind friction factor value and wind set up period have been selected from several trial runs of the model to give the least rms errors.

2.4.14 The accuracy of the model prediction in terms of water level, velocity and direction are considered to be acceptable and within the modelling guidelines presented in the Foundation for Water Research document (1993).

2.5 Conclusion

2.5.1 Although there are a small number of minor issues regarding velocity matching against the 2D data, such as over and under-prediction at one site respectively on the upstream and downstream area of the Main Crossing, the majority of the current speed predictions, particularly in the central part of the model domain centred at the new bridge, correlate very well. The average rms error of current speed of 0.14 m/s is within the "±0.2 m/s" FWR guideline.

2.5.2 The predicted water levels and current directions have matched all the surveyed, TOTALTIDE and other available predictions. The average rms error for water level is only 0.21 m, which is between the "±0.1 m at the mouth, ±0.3 m at the head" FWR guideline.

2.5.3 The phasing of both water level and velocity are found to be very accurate. This is perhaps not that surprising as although depth-averaged (by simple arithmetic averaging or vector averaging) 3D predictions may not match perfectly 2D predictions, phase timing does not involve any spatial errors.

2.5.4 Considering the limits in terms of data availability and the difficulties involved in collecting and assembling such a large quantity of data required for 3D modelling, the hydrodynamic matching through both the calibration and validation processes covering 14 days of spring tide cycles and 18 days of neap tide cycles is considered reasonably accurate. It is considered that the model is able to reproduce the complex flow and tide patterns in the Firth of Forth and Forth Estuary.

3 Hydrodynamic Impacts Initial Assessment

3.1 Introduction

3.1.1 A three dimensional coastal hydrodynamic model of the Firth of Forth and Forth Estuary has been constructed as part of the proposed scheme. The model extends from Kincardine in the west to Fidra in the east (Diagram 1), and has been calibrated and validated against surveyed hydrographic data as well as water levels and currents predicted by other industry standard programs over the full spring and neap tidal cycles occurring in different years.

3.1.2 The main purpose of the proposed scheme hydrodynamic model, as presented in this report, is to permit quantitative assessment of the hydrodynamics and predict any potential effects the new bridge may have on the existing hydrodynamic regime, both during and following construction, in the Firth of Forth and Forth Estuary. The capability of the model to simulate the complex flow pattern and tidal interactions within the model domain can inform the assessment of the environmental impacts of the proposals in relation to the European sites in the Forth Estuary and Firth of Forth which could be affected by the presence of structures or changes in the local physical environment.

3.1.3 The coastal hydrodynamic model is able to predict water levels and tidal currents, as well as flow patterns within the model domain for given boundary, wind and other input parameters. The model, in its current form, is not able to consider the many complex processes of sediment transport such as seabed scouring, sediment deposition, flocculation and re-suspension in the water body without further calibration and validation of the model parameters against background levels and seasonal variations. It is nevertheless possible to infer the changes in sedimentation patterns on the seabed (scour and deposition) by studying the changes in the hydrodynamics – specifically the changes in the seabed (bottom) current speed – from its baseline, i.e. existing, condition before any bridge construction activities are carried out.

3.1.4 The purpose of this initial report is to demonstrate the likelihood of any scouring and/or sediment deposition in the vicinity of the Main Crossing corridor in terms of changes in the bottom current speed. It is based on initial modelling of four spring tide cycles. Subsequent to this report, further more detailed modelling will be carried out.

3.1.5 This report presents the changes in hydrodynamic conditions in the Firth of Forth and Forth Estuary at two different stages of the proposed scheme, namely:

- The temporary works stage when the seabed is dredged at specific locations to allow installation of pile caps for the piers and towers and temporary bunds are placed on existing seabed or mudflats to allow construction works to be carried out on dry ground.
- The permanent works stage when all the piers and towers of the Main Crossing are in their final design dimensions and locations, and all the obstructions or voids created during construction are removed and/or reinstated.

3.1.6 Using the calibrated and validated hydrodynamic model, the bottom current speeds in the above two scenarios as well as in the Baseline Condition are computed over a period of 48 hours (approximately four tidal cycles during spring tides) and the changes (presented as either an increase or decrease in current speed) derived. The general changes in bottom speed in a wider area and any hotspots (more significant changes) are shown in the form of output plans as well as in time series at a number of points on ten transects across the Firth of Forth. The result will inform and help to decide on whether there is any need for carrying out sediment transport modelling in the Firth of Forth and Forth Estuary.

3.2 Approach and Methods

Methodology

3.2.1 A 3D hydrodynamic model using industry standard MIKE3 Flexible Mesh (FM) finite volume modelling package developed by DHI has been constructed. The model can be used to predict the changes in flow hydrodynamics at the seabed within the model domain.

3.2.2 Three different hydrodynamic conditions have been considered:

- baseline condition;
- temporary works condition; and
- permanent works condition.

3.2.3 The model predicts the current speeds in each of the three conditions during a period of 48 hours (i.e. approximately four tidal cycles during spring tides). The current speeds at the bottom layer of the model (the model has five layers in the vertical direction) are most relevant for the inference of sediment transport patterns, so the results from this bottom layer are extracted in each time step computation.

3.2.4 It is assumed that the spring tide is the more severe tidal event for sediment transport as it is associated with both the higher and lower seawater levels, greater energy flux in the water and faster tidal currents than the neap tide. As such, the following spring tide event for the model hydrodynamic simulation has been selected:

- 14 June 1999 22:00:00 to 17 June 1999 00:00:00.

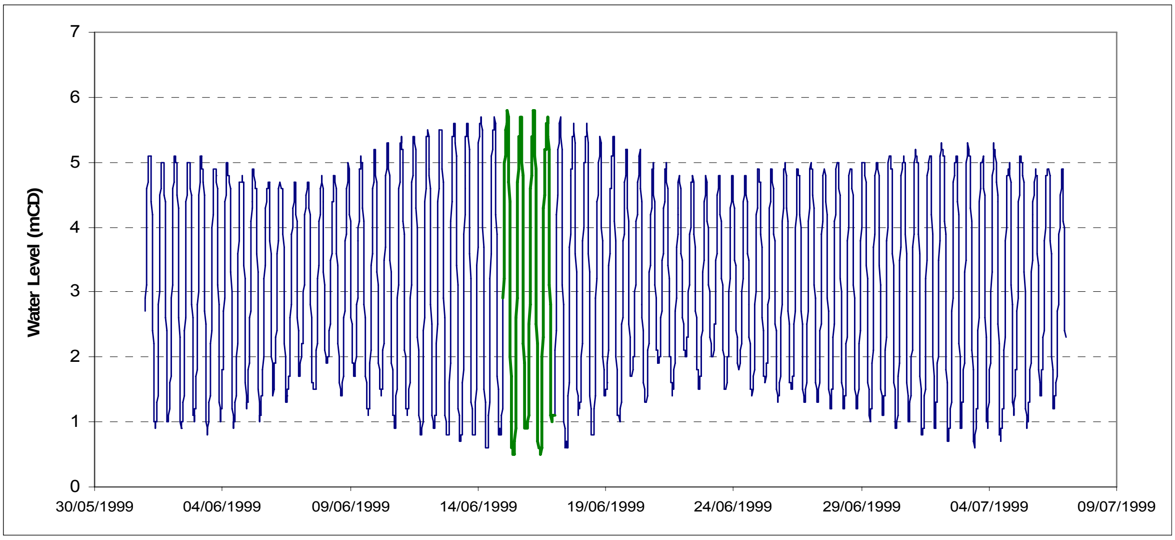
3.2.5 The first two hours of simulation allow the model to settle before the results are used. The remaining simulation period covers 2 days or 48 hours of spring tides.

3.2.6 The 3D model has been constructed to represent about 57km of the Firth of Forth and Forth Estuary centred approximately on the location of the Main Crossing. The horizontal model domain is covered by a mesh comprising about 16,000 triangular shape finite elements of varying sizes, orientation and angles. The model's vertical dimension is represented by five sigma layers, in equidistant distribution, which means that each layer may have a thickness ranging from zero to about 15m (the maximum water depth in the model is about 80m). Most of the small vertical thicknesses (or water depths) are found in the mudflats flanking both the south and north banks of the Firth of Forth.

Input Data

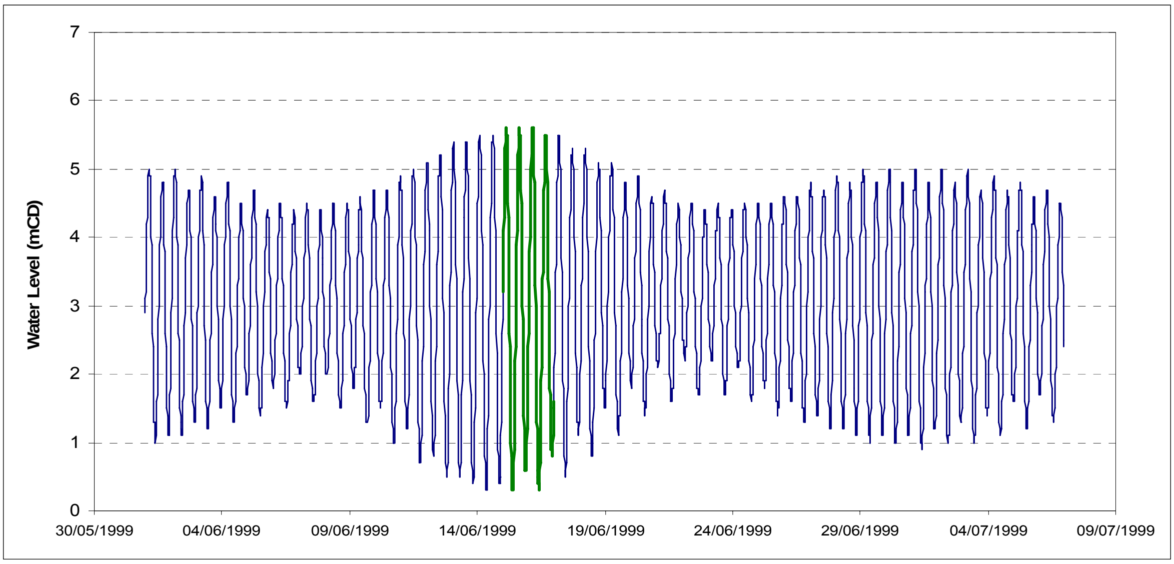
3.2.7 The western boundary of the proposed scheme model uses the Kincardine water level time series generated by the UKHO TOTALTIDE, as shown in Diagram 46. The trace in green covers the required simulation period of 2 days (48 hours or about 4 tidal cycles).

Diagram 46: Kincardine Water Level Time Series for Western Boundary Condition



3.2.8 On the eastern boundary of the model, the water level time series at Fidra is used as the boundary condition, as shown in Diagram 47.

Diagram 47: Fidra Water Level Time Series for Western Boundary Condition



3.2.9 To model the effect of wind over the model domain, measured wind data from Port Seton recorded during the 1999 marine survey by HR Wallingford and Lyndhurst Oceanographics (Lyndhurst Oceanographics, 1999) has been included in the model. The wind speed and direction are shown in Diagrams 48 and 49, respectively. The traces in green cover the required simulation period.

Diagram 48: Wind Speed (in m/s) at Port Seton for Hydrodynamic Modelling

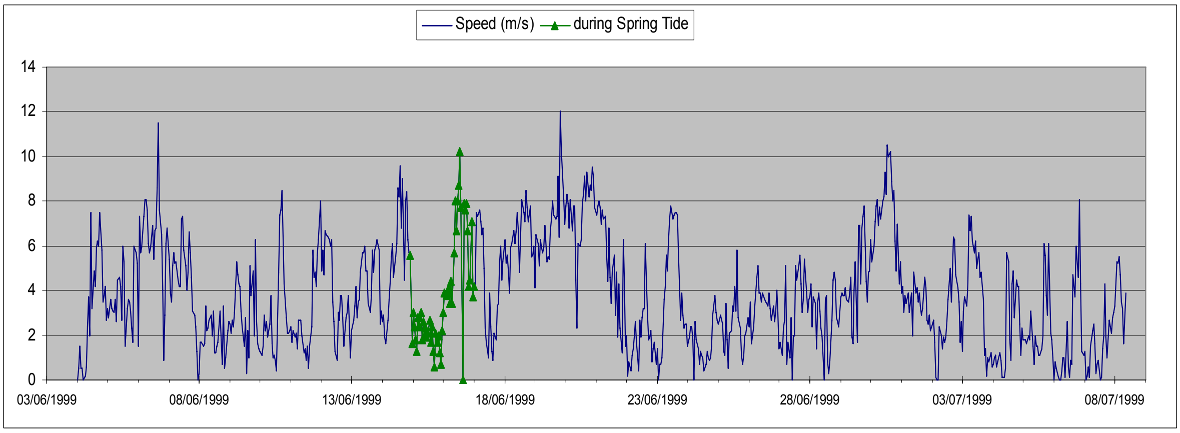
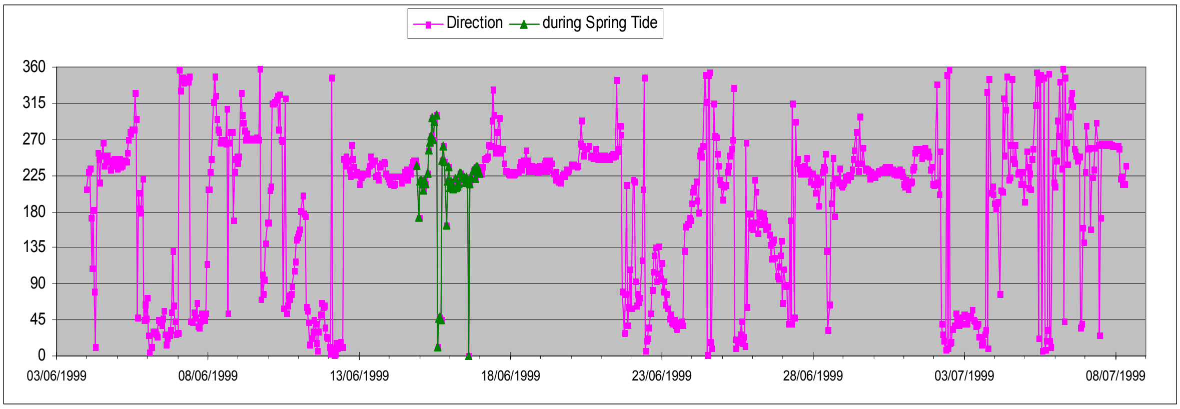


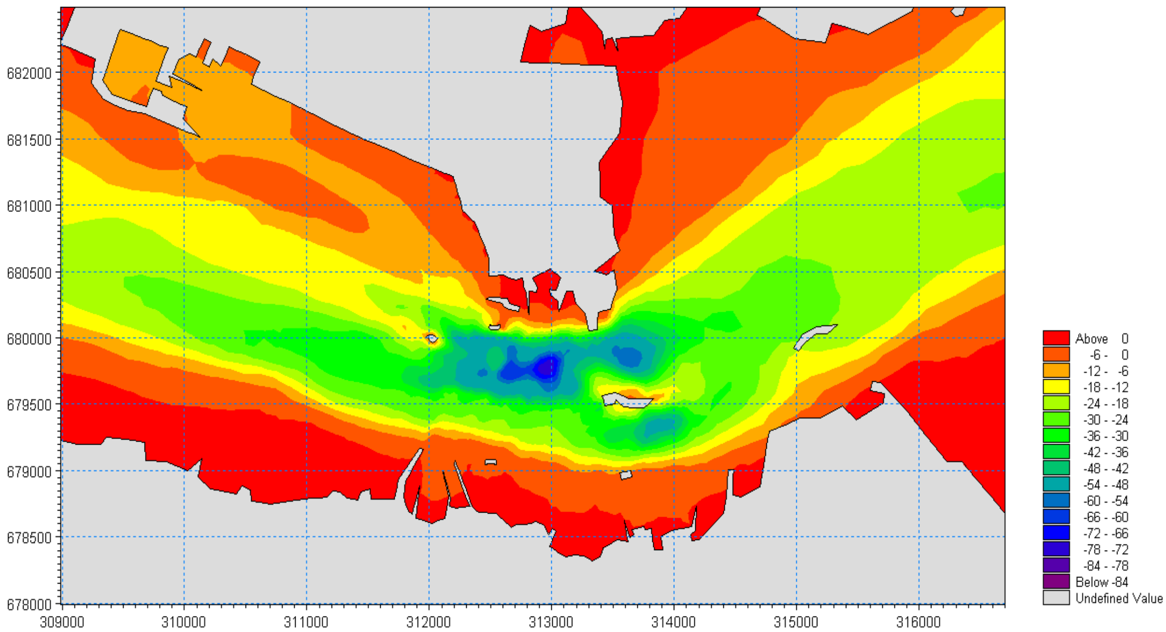
Diagram 49: Wind Direction (in degree from TN) at Port Seton for Hydrodynamic Modelling



3.3 Baseline Conditions

3.3.1 A realisation of the modelled baseline conditions is shown graphically in Diagram 50. The colour key displays bathymetry in metres Chart Datum (mCD). The model has been run for the baseline computational mesh and for the simulation duration and boundary conditions as described in the previous chapter. Only a small portion of the model domain (7.5km) is shown to centre on the Main Crossing corridor. Note that the display is distorted as the X- and Y-scaling is not identical.

Diagram 50: Model Realisation for Baseline Condition



Temporary Works Condition

3.3.2 All the temporary works activities have been compressed into a single stage for the purposes of this preliminary hydrodynamic assessment. It is anticipated that the following work activities would be undertaken during the construction phase over a period of several years.

- Temporary bunds above water level for piers S5 and S6 at the southern end of the bridge – These bunds are modelled as land boundaries extending into the estuary, thereby creating an obstruction on the mudflats to the east of Port Edgar.

- Dredged pockets for the foundations of piers S1, S2, S3 and S4 – The bathymetry of the four rectangular shape foundations have been deepened to their final depths to reflect the dredged profiles.
- South Flanking Tower (ST) would be located on the existing seabed – As there is no change to the bathymetry, this bathymetry has not been altered at this location.
- Central Tower (CT) would be founded on the existing Beamer Rock – It is understood that the excavation will be within the existing Beamer Rock outline with no change to the surrounding bathymetry. Therefore the model bathymetry has not been altered at this location.
- North Flanking Tower (NT) will have a long dredged strip for barge access and foundations – The dredged profile and level have been represented within the model.
- North pier (N1) will have a dredged pocket for to facilitate provision of its foundations – Local bathymetry under the proposed foundations has been modified within the model to represent this deeper level.

3.3.3 A schematic of the temporary works is shown in Diagram 51 and a model realisation of the activities in Diagram 52. The two inserts in Diagram 52 show the footprints of the dredged pockets at the five piers and North Flanking tower, and the temporary (dry) bund outlines.

Diagram 51: Temporary Works Activities

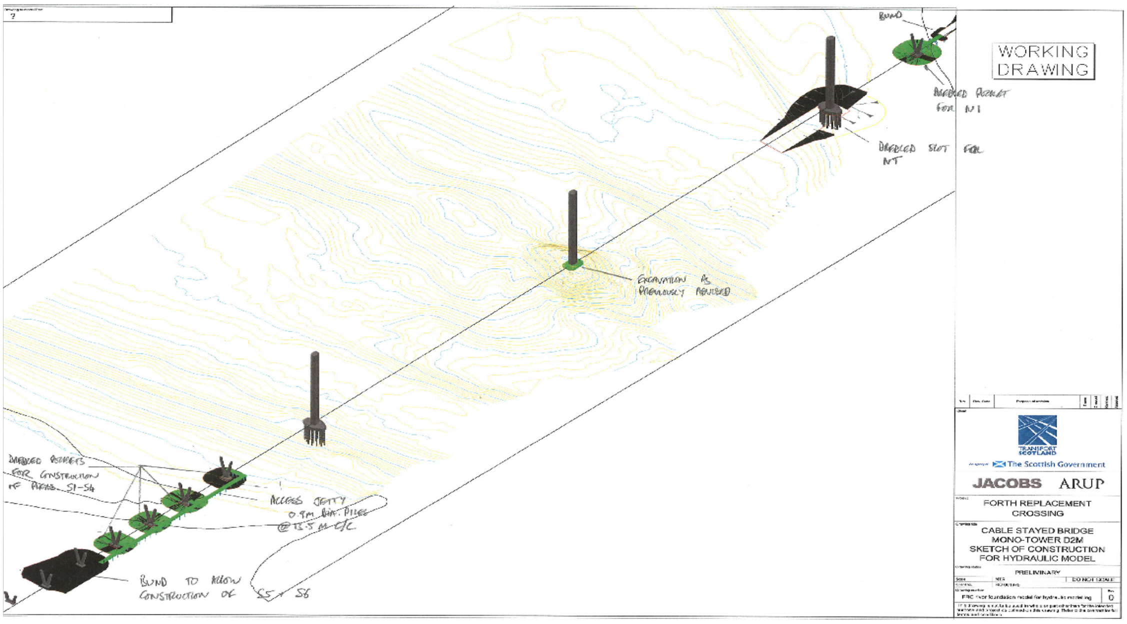
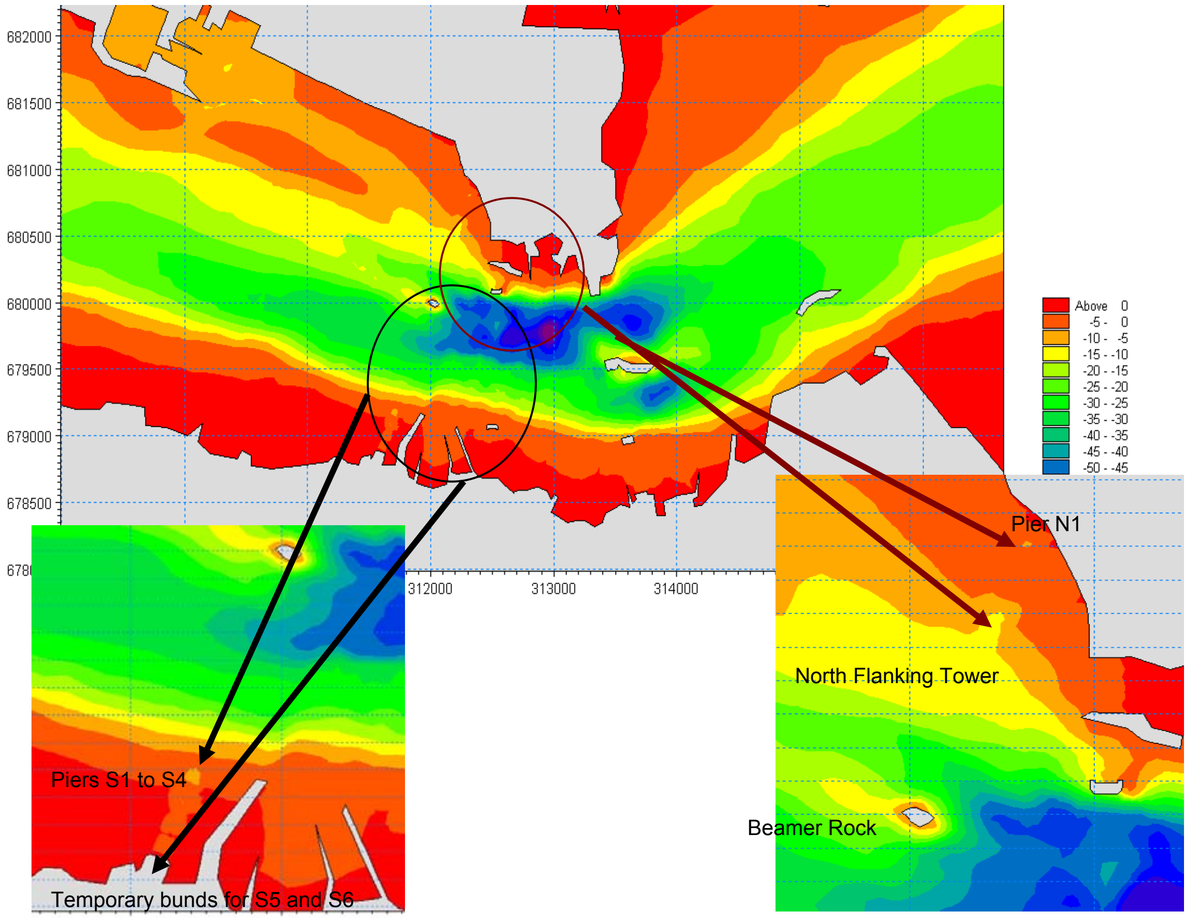


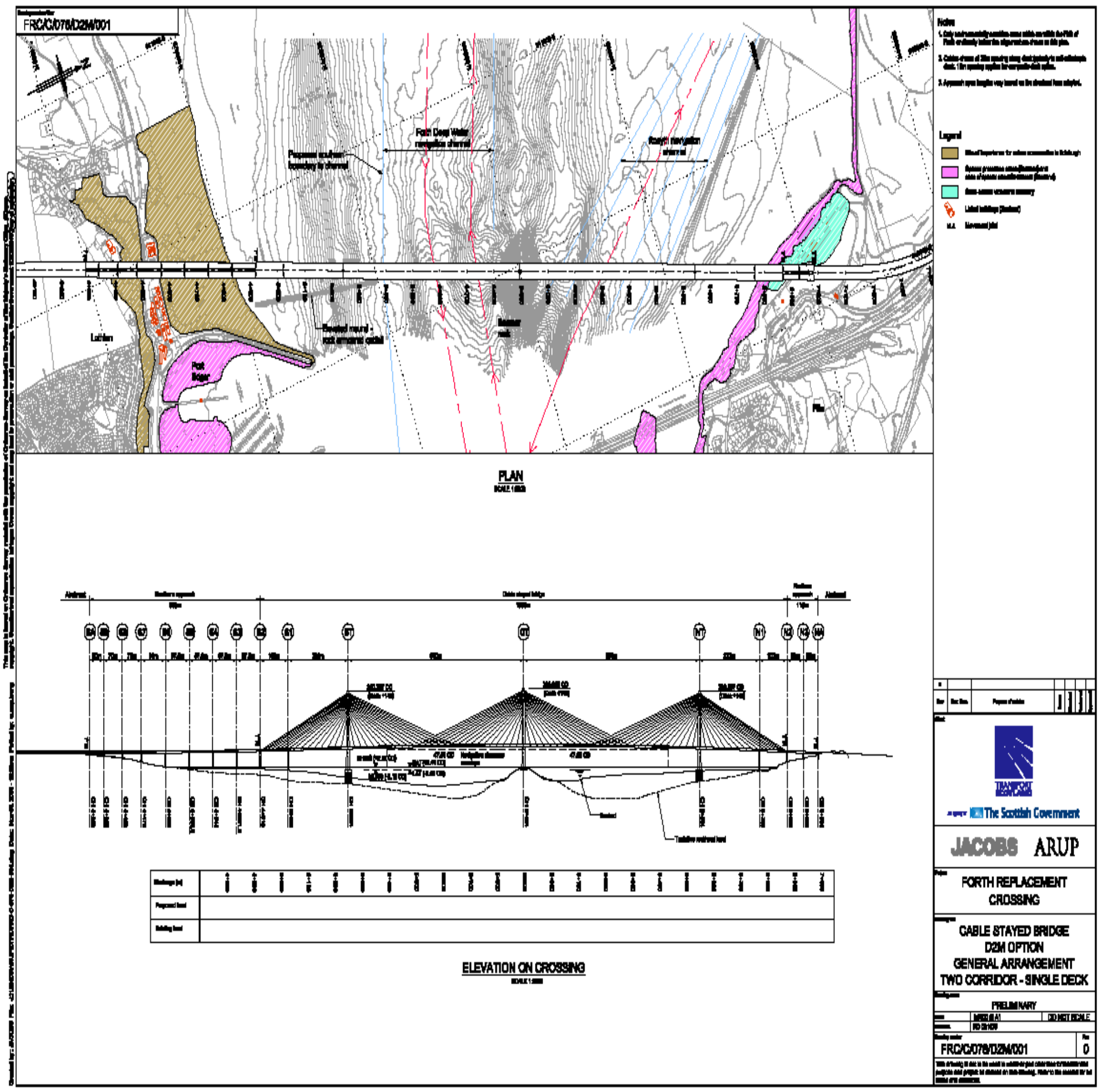
Diagram 52: Model Realisation for Temporary Works Condition



Permanent Works Condition

3.3.4 The permanent works consist of six piers in water on the south side, one pier in water on the north side, the central tower, and the north and south flanking towers, as shown in Diagram 53.

Diagram 53: Permanent Works Activities



3.3.5 The seven piers (one in the north and six in the south) are modelled with the pier stems as obstructions in the water column (from seabed extending up to a level above still water level). It is understood that the pile caps will be located below seabed level.

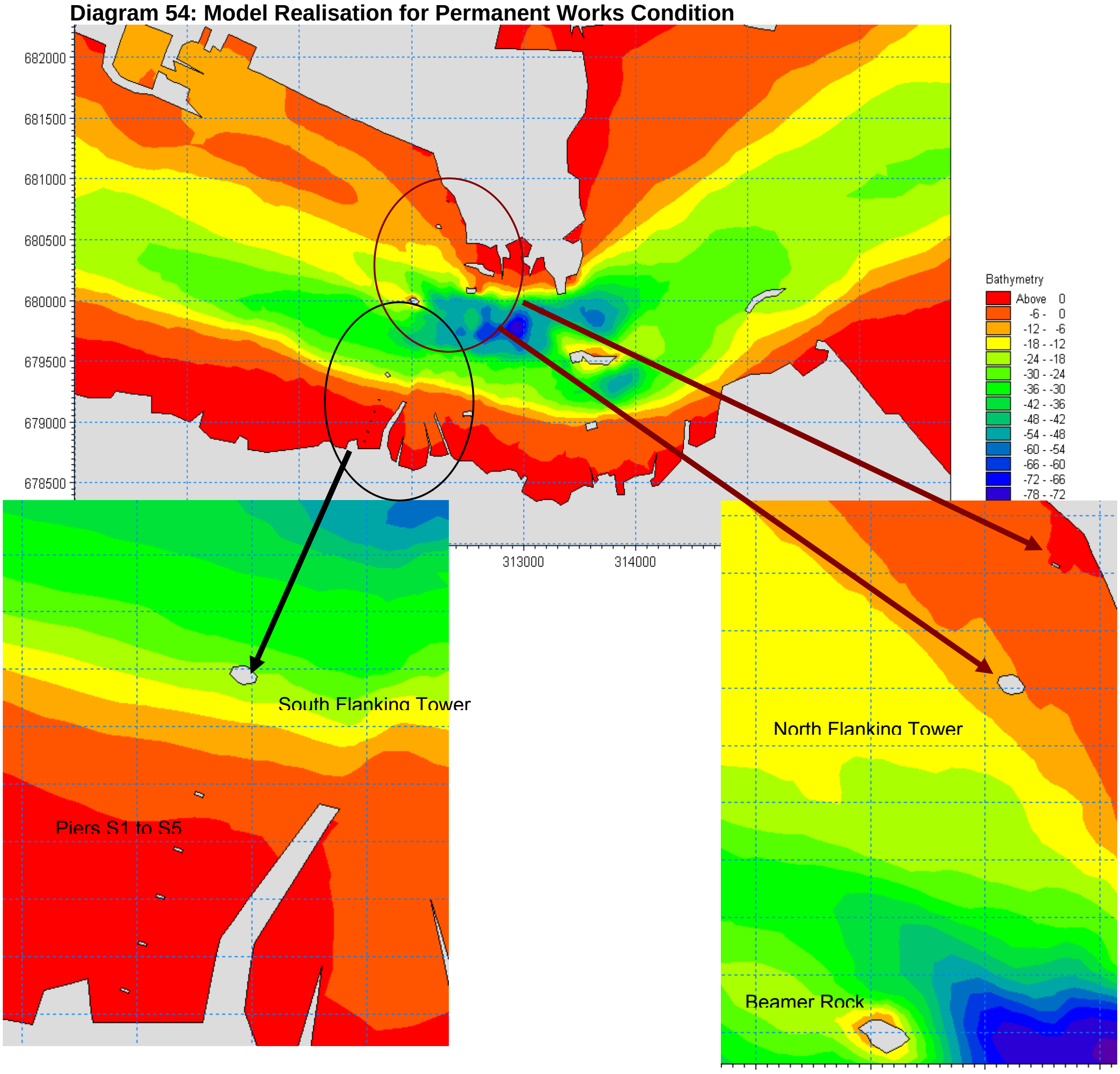
3.3.6 The Central Tower is sited on the existing Beamer Rock. It is assumed at this stage that the footprints of the tower pile cap and tower stem are completely contained within the Beamer Rock outline under all tidal conditions. There is thus no requirement to model the hydrodynamic impacts of the Central Tower in the permanent works.

3.3.7 The North and South Flanking Towers are modelled with the pile cap dimensions protruding from seabed to above water level. It is recognised that the tower stems will be slimmer than the pile caps but for simplicity in this preliminary hydrodynamic assessment, modelling the piles cap dimensions all the way from seabed to above water level is considered to be a worst case scenario.

3.3.8 Diagram 54 shows the model realisation of the permanent works scenario. The two inserts show the footprints of the two flanking towers and the six piers. Pier S6 on the south side is landward of the shoreline (above high water spring) and hence outside the model domain.

3.3.9 The Baseline Conditions section will also identify the sensitivity in accordance with the criteria established.

Diagram 54: Model Realisation for Permanent Works Condition



3.4 Hydrodynamic Modelling Results

Current Speeds at the Bottom Layer

3.4.1 The changes in the hydrodynamics, specifically the differences in the average current speeds at the seabed predicted by the proposed scheme hydrodynamic model, are presented in this chapter.

3.4.2 Computation of the hydrodynamics is carried out for each depth layer. These may include the water layer thickness, which when all five layers are added together contributes to the overall water depth in that computational finite element. The other parameters computed are the three spatial components of the current velocity, known as U, V and W. Essentially, each finite element in individual water layer will have its own velocity components, from these the current speed and direction can be derived.

3.4.3 In order to precisely derive the changes in current speed at any finite element cell, vector subtractions and the re-combination of the differences in all three spatial components of the current speeds from two different model scenarios would be required. This is because the velocity vector in different scenarios, even at the same depth and location, may point to a different direction. The normal procedure is to carry out subtraction of the three speed components and then combine them to form the new vector, i.e. √[(U1-U2)2 + (V1-V2)2 + (W1-W2)2] but the numerical result will always be positive (because of the quadratic and square root operations), which will not indicate if there is an increase or decrease in bottom speed.

3.4.4 Therefore, in this assessment of the hydrodynamic impacts from the temporary and permanent works, only the algebraic difference between the average speeds in two separate model scenarios is performed to obtain an indication of the changes.

The Effect from Different Computational Meshes

3.4.5 Three scenarios have been modelled to represent the baseline, temporary works and permanent works conditions (see Section 3.3: Baseline Conditions).

3.4.6 It is a feature of the flexible mesh computational model that every time there is a change in the model representation whether it is a new obstruction or clearance, a change in the bathymetry, a change in the model's internal or external boundaries, or even a change in the triangulation settings, a different computational mesh is produced. The change in the mesh composition affects the number of finite elements, nodes and their spatial locations, upon which computation of all the hydrodynamic parameters are carried out.

3.4.7 In order to compare the modelling results correctly, the hydrodynamic values from different scenarios need to be compared at the same points but different meshes may not produce the results at the exact points required. Therefore, before exact point by point subtraction/comparison from different simulations can be carried out, interpolations of the model results from different meshes are necessary. This can give rise to small interpolation errors in the subtraction of the average speeds from different model scenarios, which has been referred to as background noise.

3.4.8 Considering the nominal current speed on the mudflats varies between 0 (during slack water or dry period) and 0.5m/s most of the time during spring tide, with a maximum speed of up to 0.75m/s over a very short duration, it is considered that a background noise of about 10% of the speed values could be artificially generated by the interpolation process. Therefore, ±0.05m/s is recommended to be taken off the speed difference from the scenarios comparison. The results from the first simulation time step (time step of 0) of the baseline scenario and the temporary works (or permanent works) scenario, i.e. before any flow is initiated, should indicate no change in current speed anywhere in the model domain. Based on the results from this initial time step, it is confirmed that 0.05m/s should be taken off when the bottom speed difference shows an increase and added back if a speed decrease is detected. This is required in order to normalise the results such that there is no change in the bottom current speeds.

3.4.9 It is also noted that the modelling accuracy is dependent on the accuracy of the driving data (such as wind, boundary and initial conditions) and of those used for calibration/validation of the hydrodynamic model. In terms of water levels, the model should be accurate to two decimal places, i.e. to 1cm or 0.01m, as most of the data used are given in either two or three decimal places.

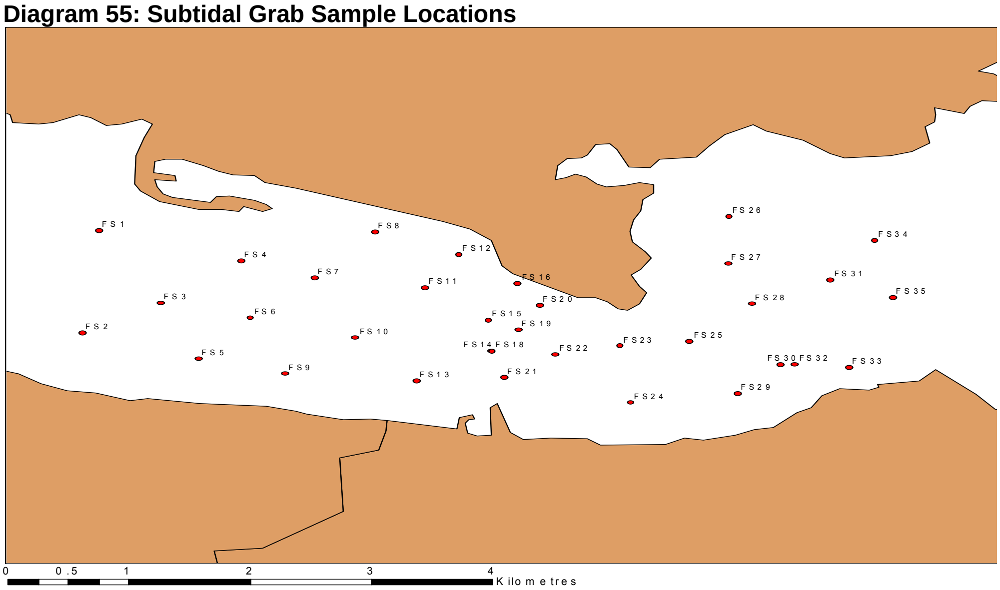
3.4.10 As for current velocity (or speed), the measurements or prediction used for calibrating and validating the hydrodynamic model are quoted to three decimal places, such that the model velocity result should be accurate to at least two decimal places.

Sediment Properties in the Subtidal and Intertidal Areas near the Proposed Scheme Corridor

3.4.11 There is very little up-to-date information available about the nature and properties of the seabed sediments in the Firth of Forth and Forth Estuary. Due to the dynamic nature of the Forth estuarine environment and extensive dredging and dumping activities over the years, the use of seabed sediment data more than 10 years old may give potential misleading results for sediment transport studies.

3.4.12 On 20 May 2008 Jacobs Arup carried out a subtidal sampling exercise around the Main Crossing corridor. Thirty-five grab samples were planned and 34 eventually taken in locations shown in Diagram 55.

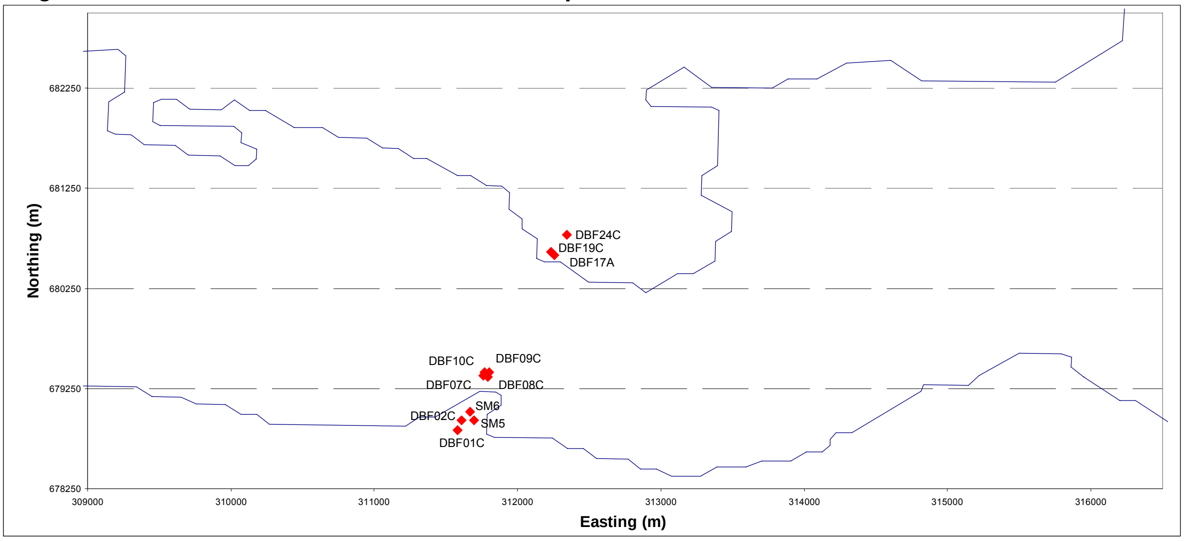
Diagram 55: Subtidal Grab Sample Locations



3.4.13 However, these grab samples were taken for the purposes of ecological assessment. Grab sampling is not an ideal method for determining sediment particle size distributions and material classification/fraction (such as clay, silt, sand and gravel) for the purposes of interpretation of sediment transport.

3.4.14 In the summer of 2008, Jacobs Arup initiated a marine GI contract to determine the underlying geology and geotechnical properties under the pier/tower locations which also included collection of some borehole samples on the seabed. Eleven marine boreholes close to the proposed scheme corridor provided four intertidal samples and eight subtidal samples, as shown in Diagram 56.

Diagram 56: Subtidal and Intertidal Borehole Sample Locations



3.4.15 The samples taken consist of sediments found on the seabed penetrating to 1m depth. Given the method of sampling, it is not possible to confirm if the samples are entirely representative of the seabed, however it is possible to determine the general material fractions making up the top 1m layer and this appears to consist of predominantly silts and sands as shown in Table 3.1. The subtidal boreholes are highlighted in yellow.

Table 3.1: Subtidal and Intertidal Borehole Samples Material Fractions

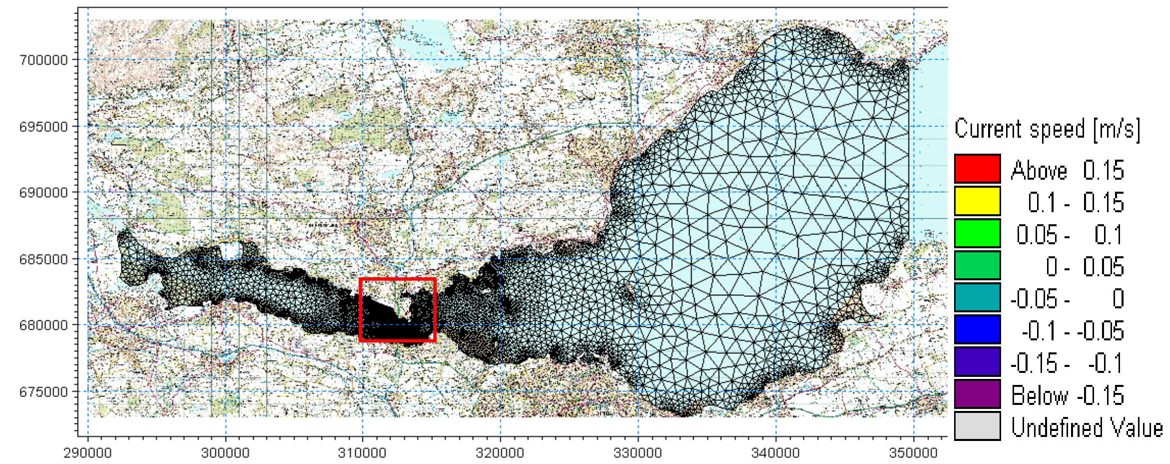
Sample No	Easting	Northing	Subtidal/ Intertidal	Clay	Silt	Sand	Gravel
DBF01C	311582	678834	Intertidal	7	17	50	26
DBF02C	311609	678931	Intertidal	9	43	40	8
DBF07C	311760	679381	Subtidal	6	82	12	0
DBF08C	311793	679368	Subtidal	12	66	20	2
DBF09C	311803	679411	Subtidal	13	78	9	0
DBF10C	311770	679411	Subtidal	38	51	10	1
DBF17A	312258	680586	Intertidal	7	22	69	2
DBF17A-deeper	312258	680586	Intertidal	23	74	2	1
DBF19C	312233	680617	Intertidal	22	57	21	0
DBF24C	312343	680785	Intertidal	2	10	85	3
SM5	311696	678935	Intertidal	19	45	29	6
SM6	311667	679017	Intertidal	9	33	57	1

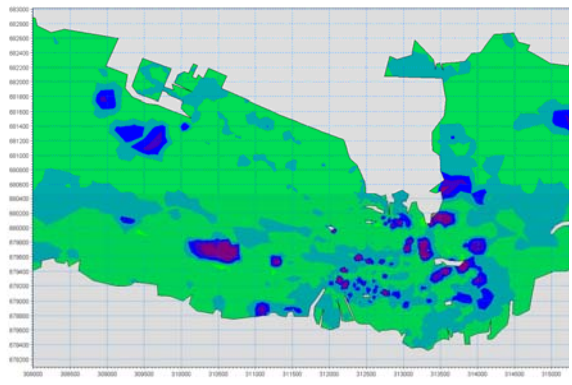
2D Graphical View of the Hydrodynamic Changes – Temporary Works Stage vs Baseline Condition

3.4.16 Diagram 57 shows a series of snapshots of the difference in bottom layer current speeds (algebraically subtracted) between the ‘Temporary Works’ and ‘Baseline Conditions’ scenarios. Only a 7.5km stretch of the Firth of Forth and Forth Estuary centred on the proposed scheme Corridor is shown in the snapshots to focus on the changes upstream and downstream of the proposed temporary works, otherwise any change hotspots will not show up in sufficient detail. Changes in bottom speed outside of this 7.5km stretch are less significant.

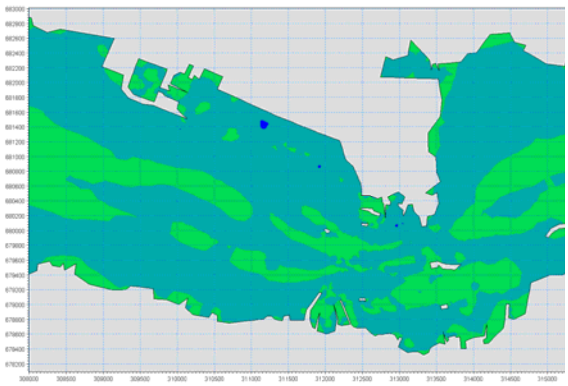
3.4.17 The total period simulated for the spring tide is 48 hours. The time between each snapshot is approximately two hours (about 1/6 of a tidal cycle). A positive value shown in the graphical display denotes a faster current speed in the Temporary Works Condition than in the Baseline Condition, and vice versa.

Diagram 57: Snapshots of Bottom Current Changes between Temporary Works and Baseline Conditions over a 48-hour Period

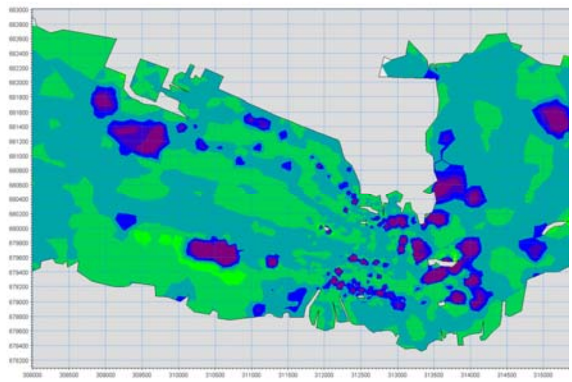




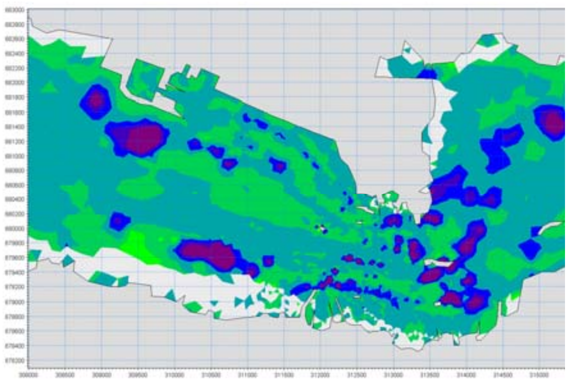
+2 hours after simulation, rising (flood) tide



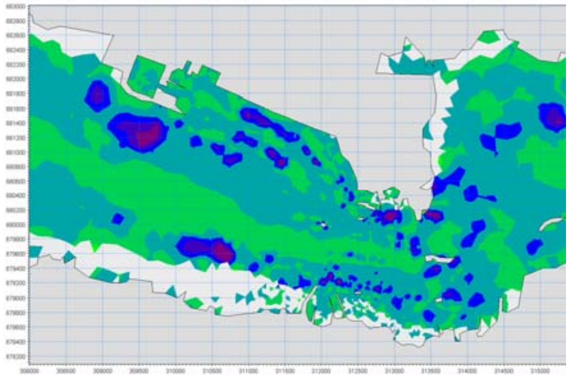
+4 hours, high water



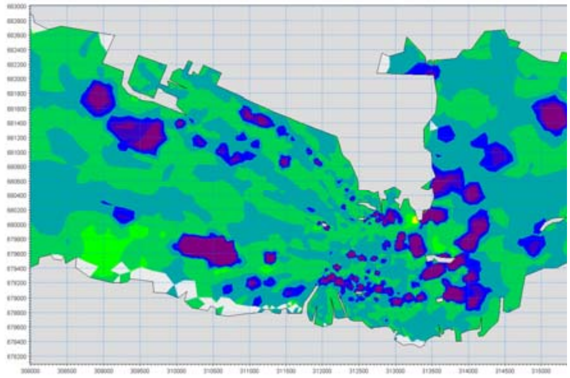
+6 hours, ebb tide



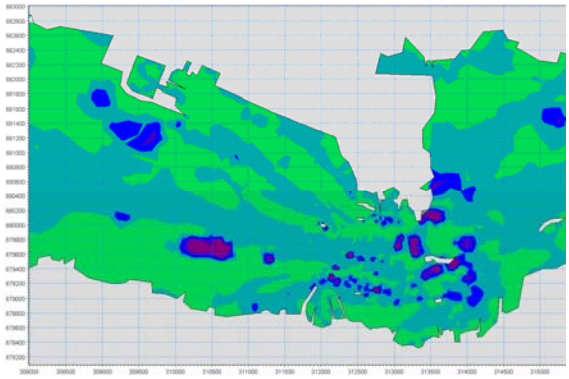
+8 hours, low water



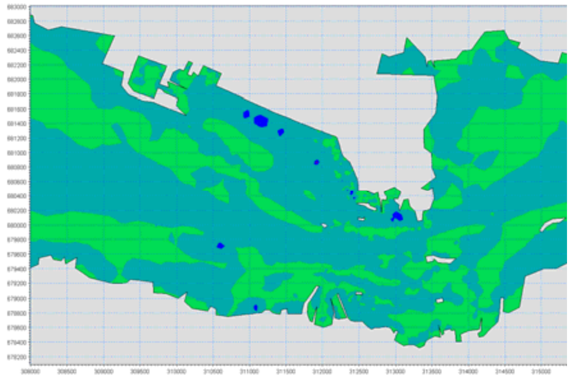
+10 hours, low water



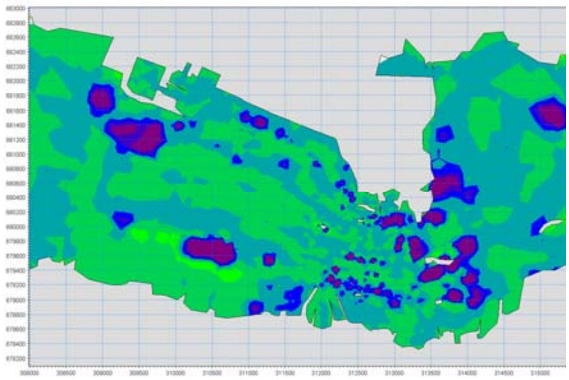
+12 hours, flood tide



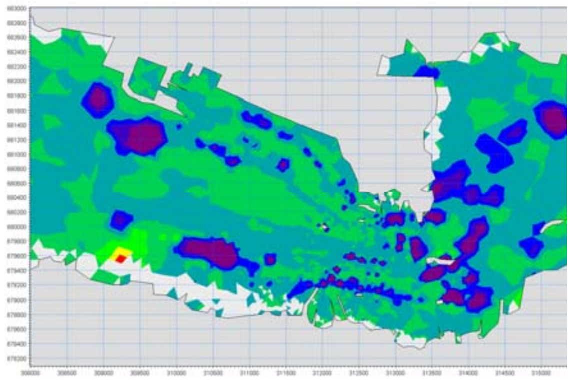
+14 hours, almost reaching high water



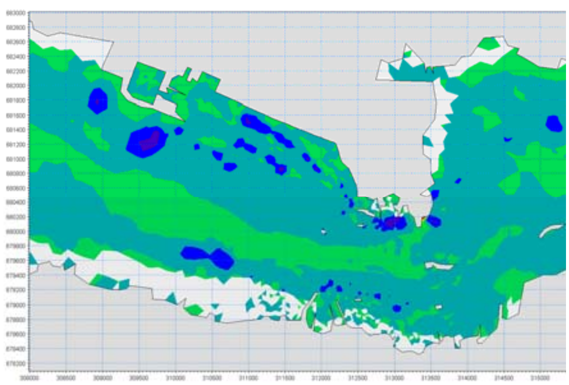
+16 hours, high water



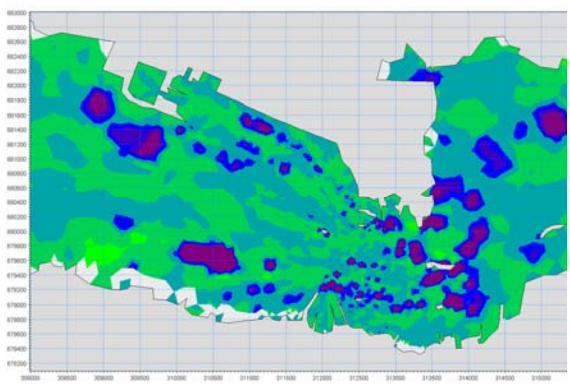
+18 hours, ebb tide



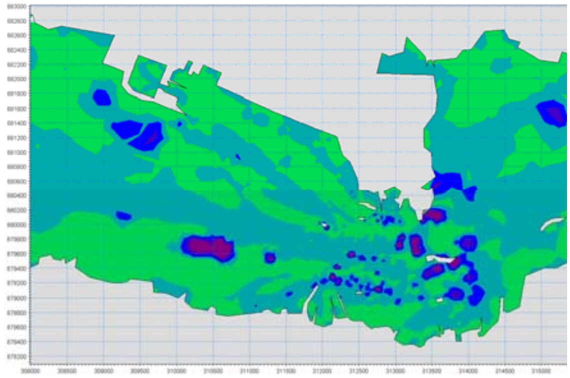
+20 hours, low water

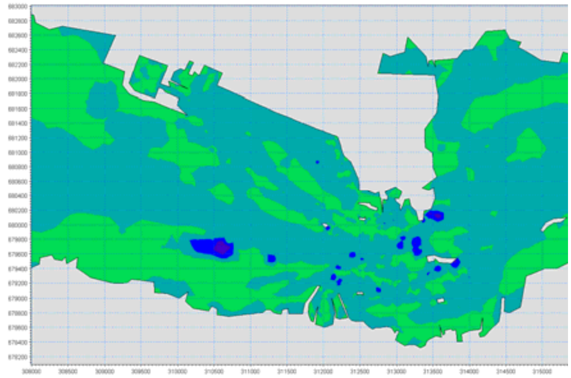


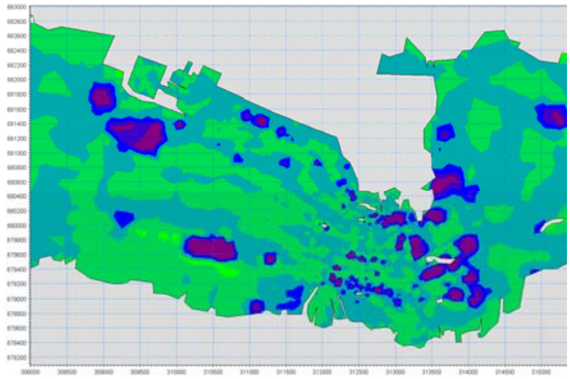
+22 hours, low water

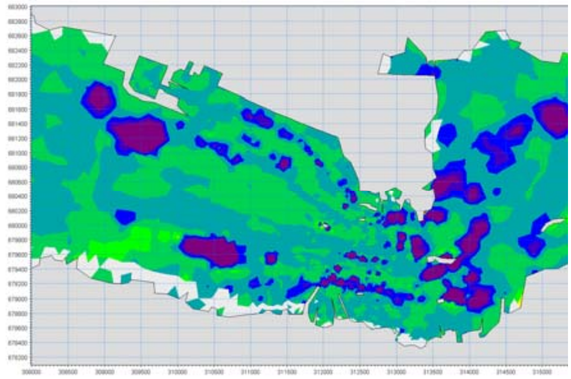


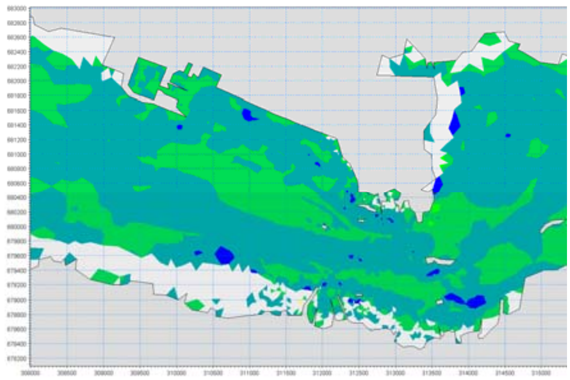
+24 hours, flood tide

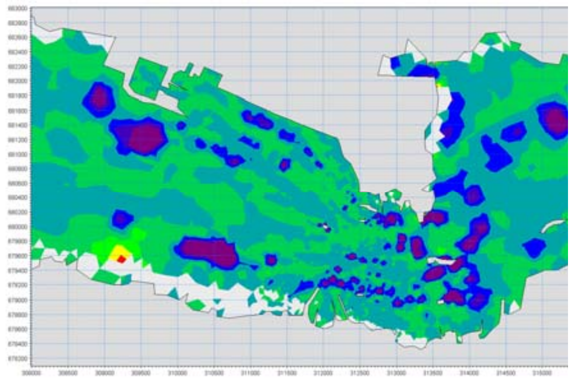

+26 hours, almost reaching high water

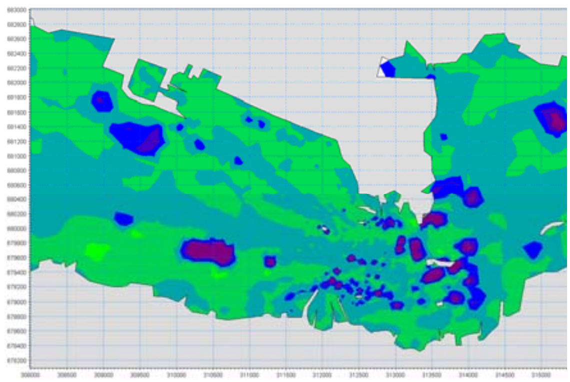

+28 hours, high water

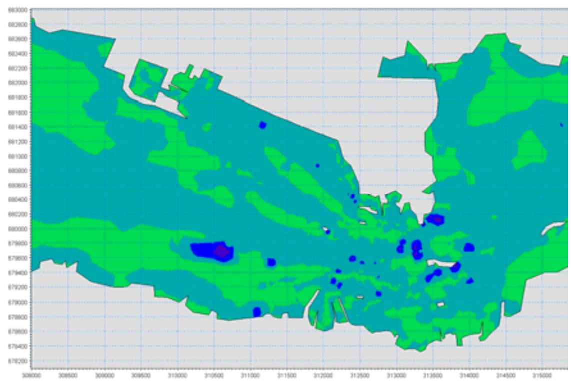

+30 hours, ebb tide

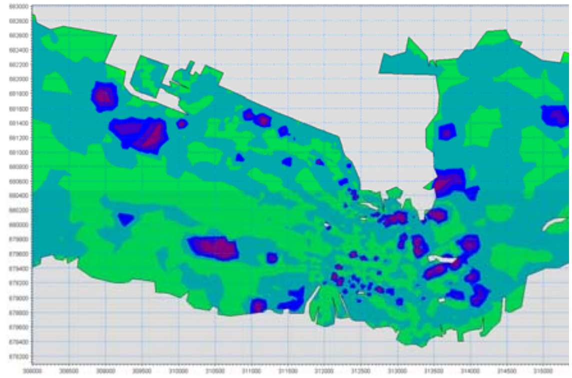

+32 hours, almost reaching low water


+34 hours, low water

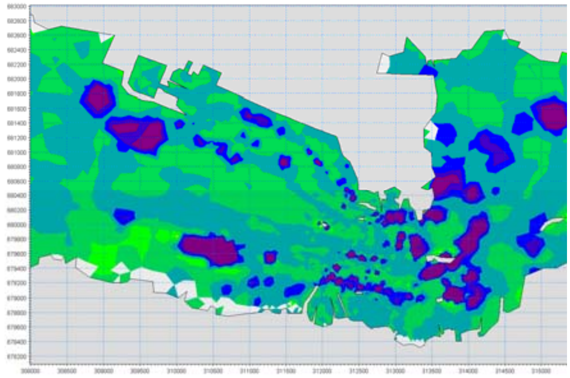

+36 hours, low water


+38 hours, flood tide

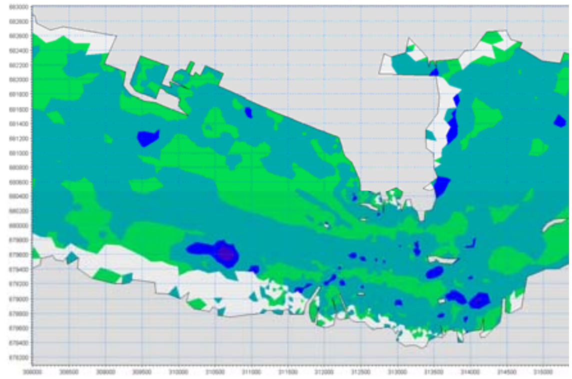

+40 hours, high water



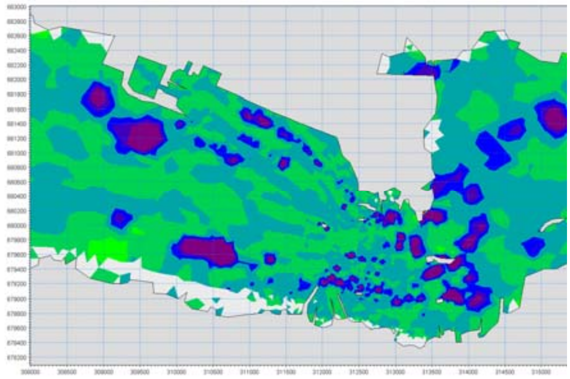
+42 hours, high water, starting ebbing



+44 hours, almost reaching low water



+46 hours, low water



+48 hours, low water

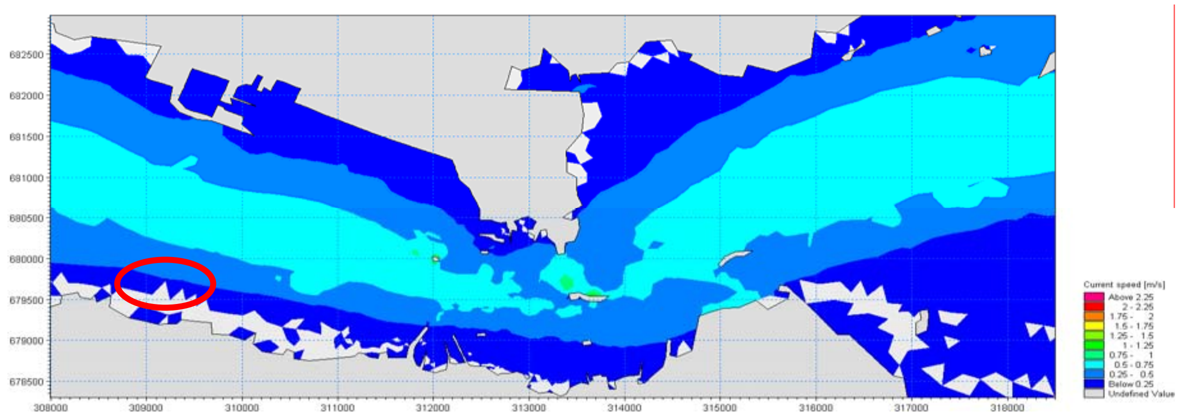
3.4.18 The snapshots presented in Diagram 57 show that there are generally large areas of very small speed increases and decreases over the 7.5km stretch. These changes are in the order of ±0.05 m/s. After adjusting for background noise due to interpolation errors, there is practically no change at all. (The snapshots show the actual algebraic subtraction without any adjustment because of difficulty in automating the background noise subtraction for both positive and negative speed change values).

3.4.19 Many speed reduction hotspots are found on the seabed layer of the water body. These are shown as blue and maroon coloured blots in the snapshots. These hotspots occur principally in ebb/flood tides and sometimes at low water, but rarely in high water. It is therefore concluded that this sort of speed reduction is a transient phenomenon during the ebb/flood tides and any potential deposition as a result of slower bottom speed could be removed or reversed within the timeframe of a single tidal cycle; as such they do not pose any concern in terms of potential changes to sediment transport behaviour caused by the Temporary Works.

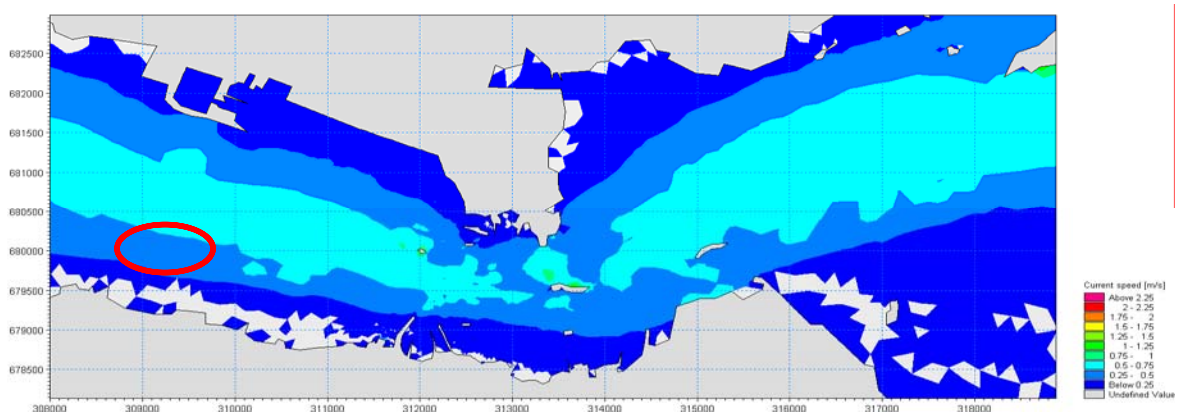
3.4.20 It is noted that there is one speed increase hotspot near the south shoreline of the Firth of Forth between Abercorn Point and Society Bank (E309280, N679544), at +20 hours and +36 hours, during ebb tide and low water. The bathymetry in this area is about 1m CD, suggesting a possible intertidal location. The appearance of the hotspot is only for a very short time, possibly less than two hours.

3.4.21 Diagrams 58 and 59 show the predicted actual bottom velocity at +20 hours and +36 hours for the Baseline and Temporary Works scenarios. The identified speed increase hotspot is inside the red line.

Diagram 58: Baseline and Temporary Works Scenarios Bottom Speed at +20 hours

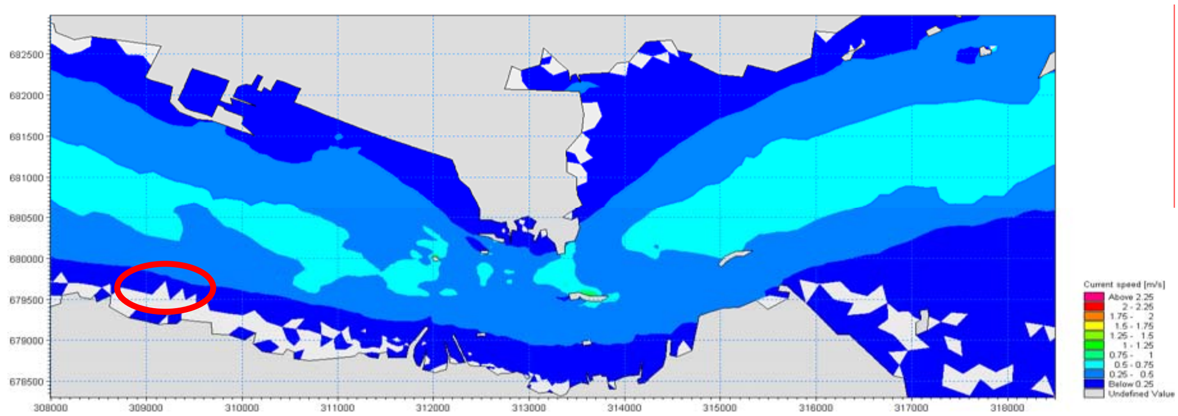


Baseline Condition, Time = +20 hours low water

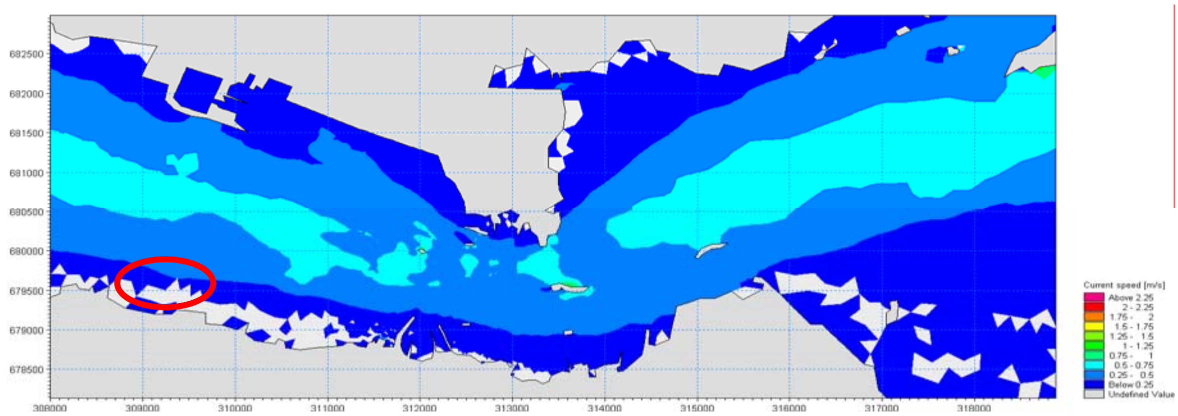


Temporary Works Condition, Time = +20 hours low water

Diagram 59: Baseline and Temporary Works Scenarios Bottom Speed at +36 hours



Baseline Condition, Time = +36 hours low water



Temporary Works Condition, Time = +36 hours low water

3.4.22 Both Diagrams 58 and 59 clearly show that at +20 hours and +36 hours, the supposed speed increase hotspot location is mostly dry under the Baseline scenario. The increase in bottom speed is a direct result of the area being wetted again as a result of the temporary works, at a numerical value of between 0.15m/s and 0.2m/s.

3.4.23 Diagram 60 shows the general bed nature along the shoreline in the vicinity of this hotspot.

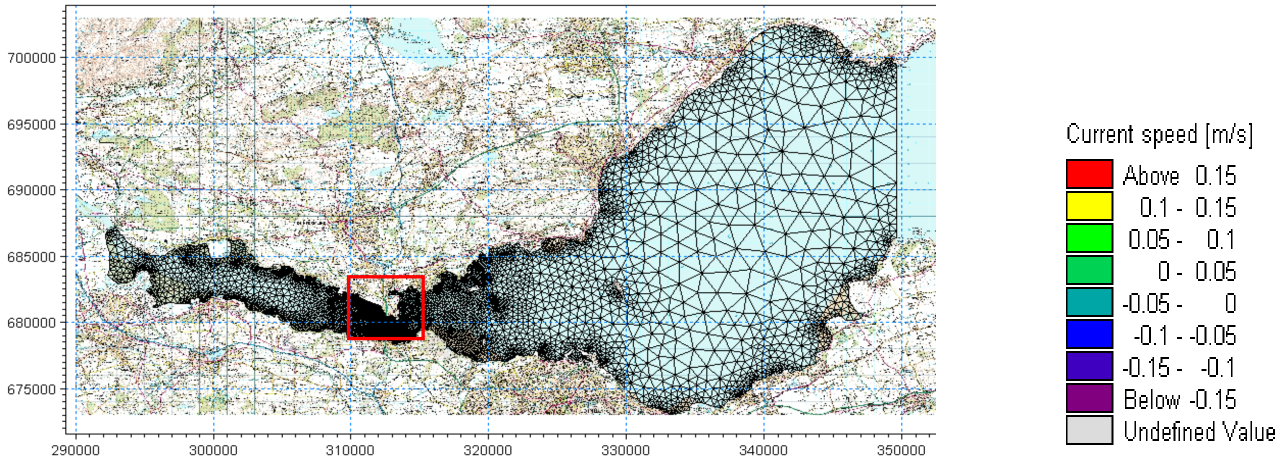
Diagram 60: Bed Materials on the South Shore of the Firth of Forth between Abercorn Point and Society Point

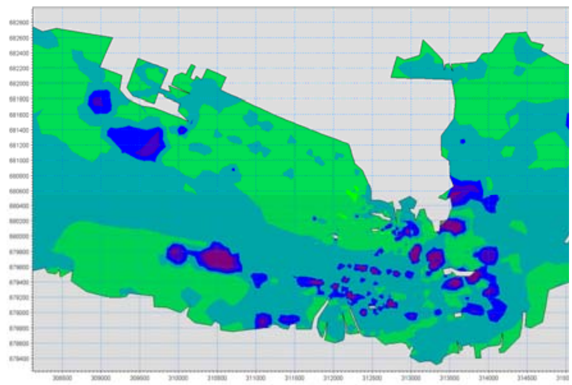
3.4.24 It is considered that these increases in bottom speed over such a short period within the tidal cycle are not significant, particularly when considering the rocky/cobbly and sandy nature of the shore along the coastline at this location, which is unlikely to suffer significant threat of increased erosion and morphological change under such minimal and short term velocity changes.

2D Graphical View of the Hydrodynamic Changes – Permanent Works Stage vs Baseline Condition

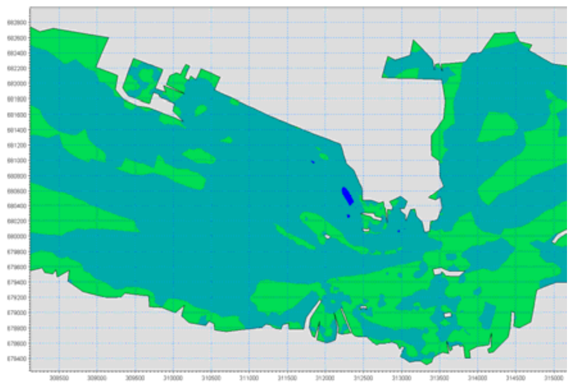
3.4.25 Snapshots of the difference in bottom layer current speeds (arithmetically subtracted without any background noise adjustment) between the permanent works and baseline conditions are shown in Diagram 61. Positive values denote a faster current speed in the permanent works condition than in the baseline condition, and vice versa.

Diagram 61: Snapshots of Bottom Current Changes between Permanent Works and Baseline Conditions over a 48-hour Period

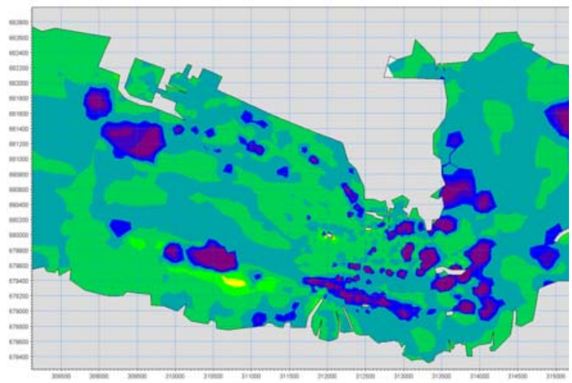




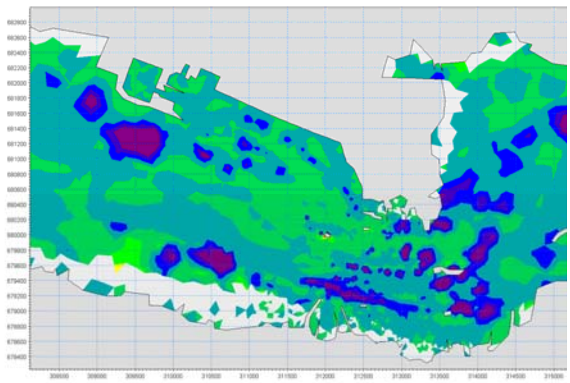
+2 hours after simulation, rising (flood) tide



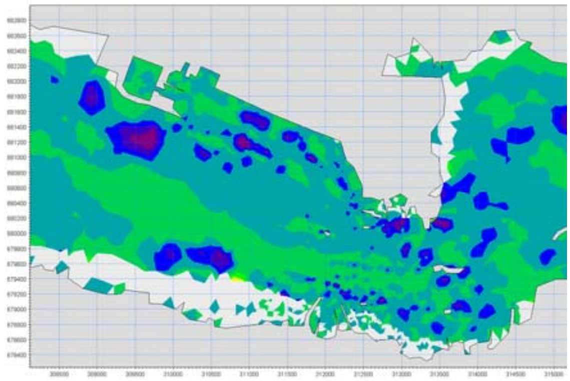
+4 hours, high water



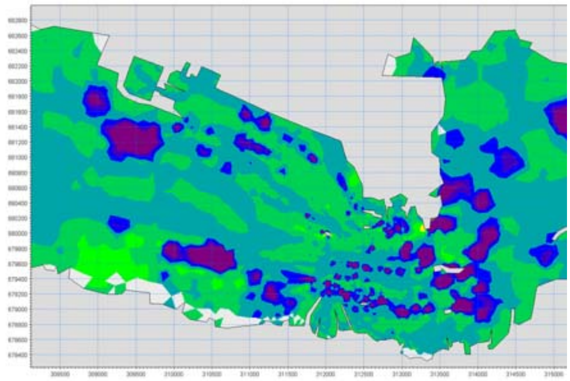
+6 hours, ebb tide



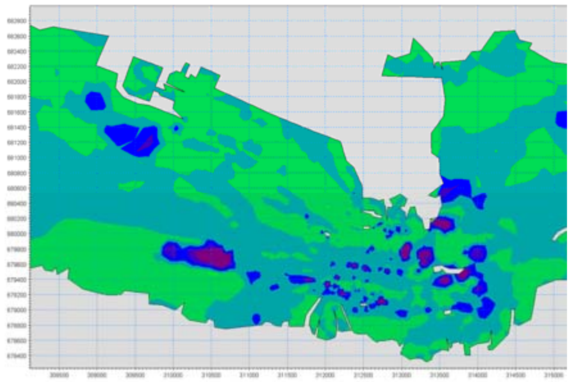
+8 hours, low water



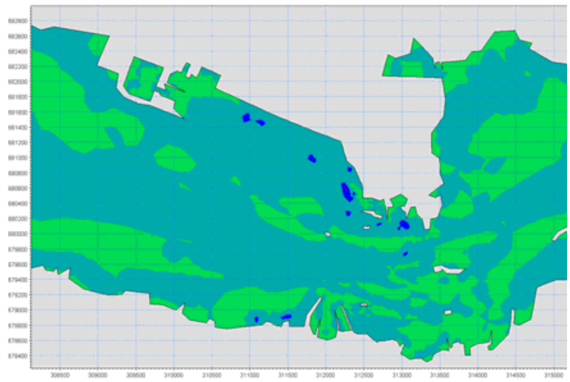
+10 hours, low water



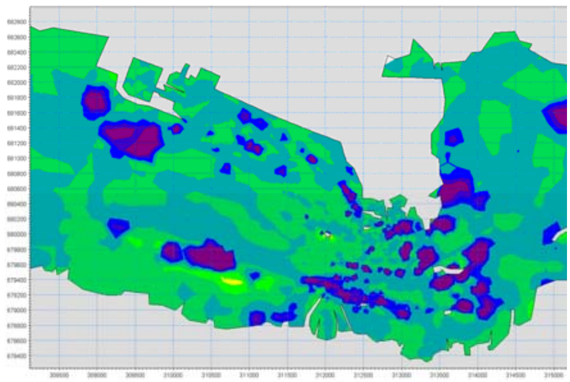
+12 hours, flood tide



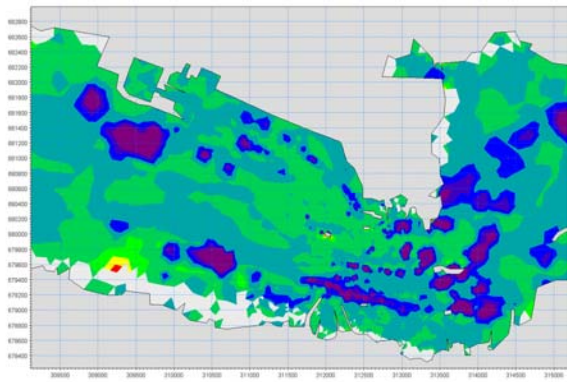
+14 hours, almost reaching high water



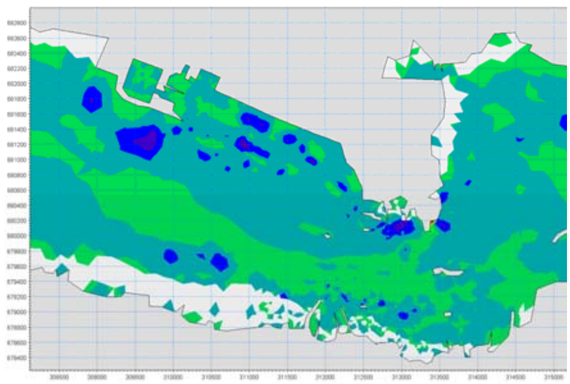
+16 hours, high water



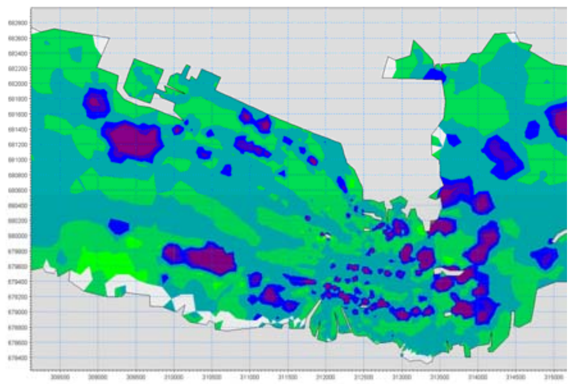
+18 hours, ebb tide



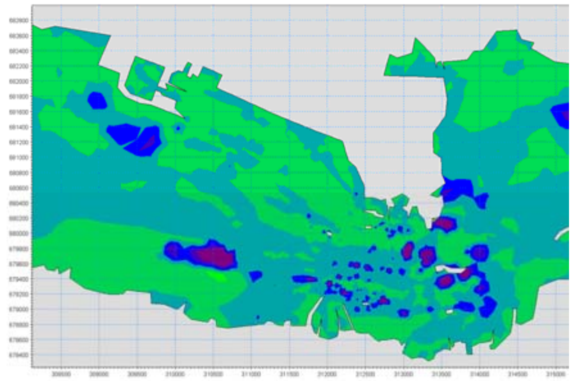
+20 hours, low water

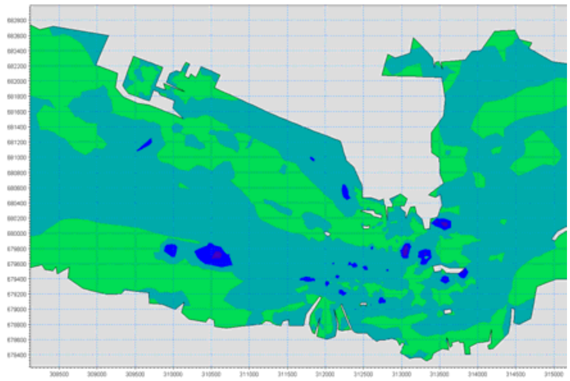


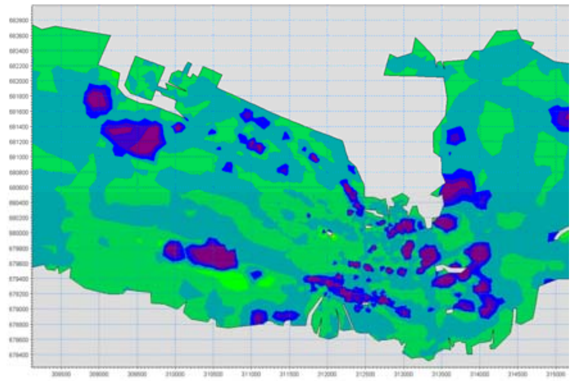
+22 hours, low water

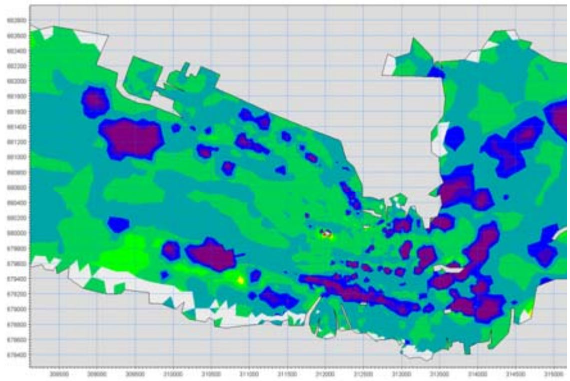


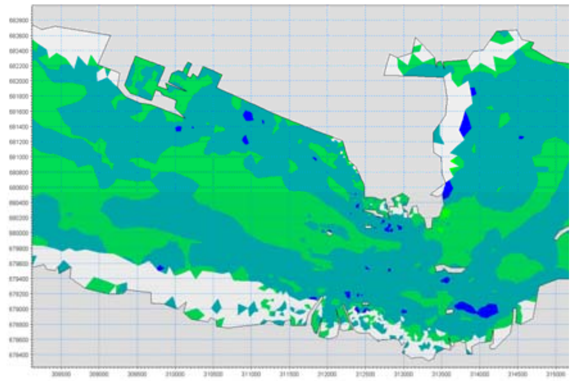
+24 hours, flood tide

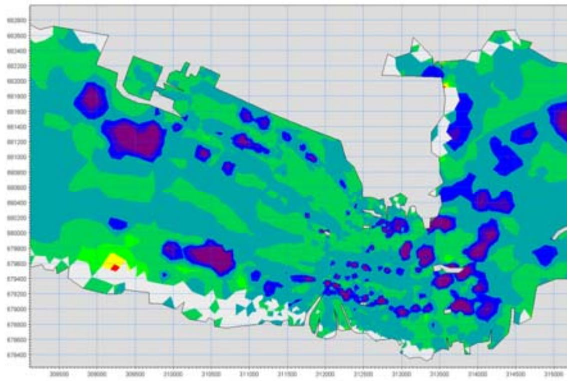

+26 hours, almost reaching high water

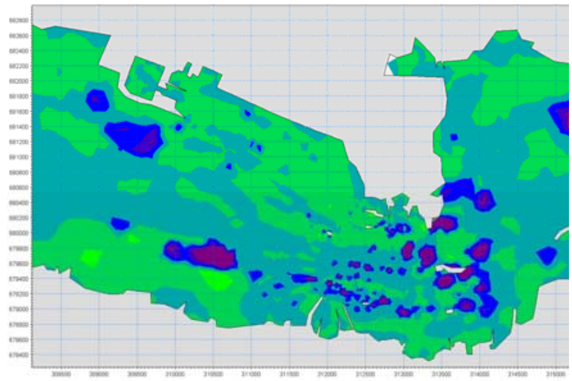

+28 hours, high water

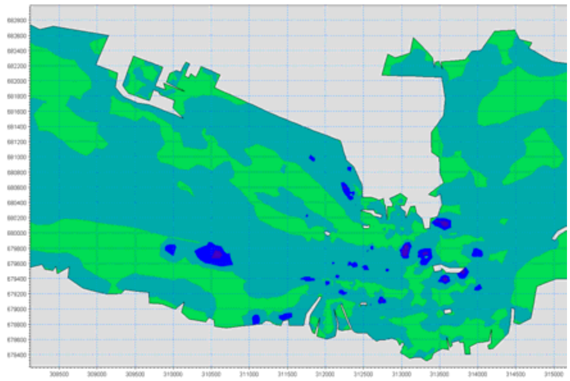

+30 hours, ebb tide

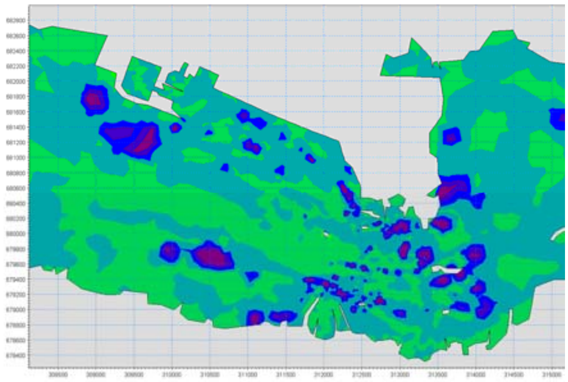

+32 hours, almost reaching low water


+34 hours, low water

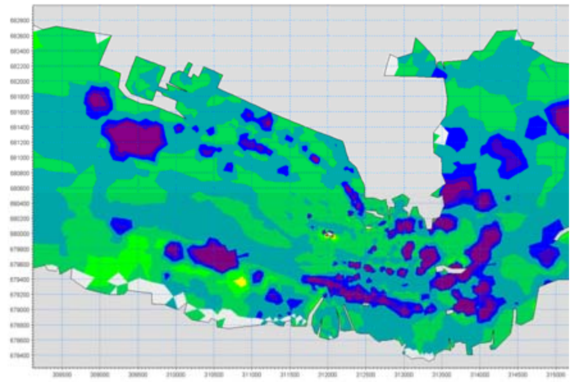

+36 hours, low water


+38 hours, flood tide

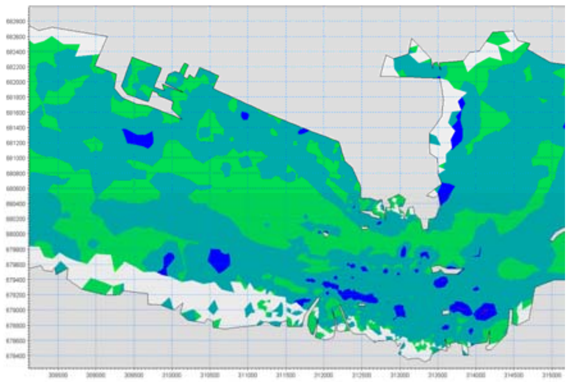

+40 hours, high water



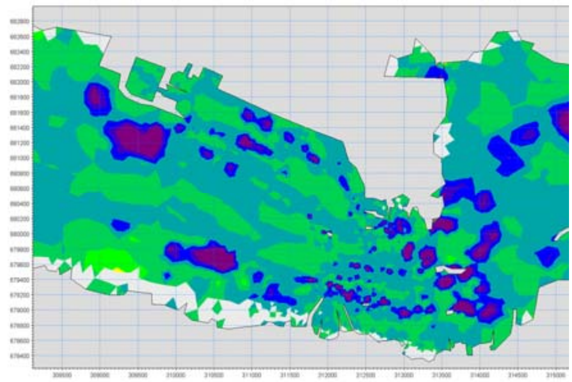
+42 hours, high water, starting ebbing



+44 hours, almost reaching low water



+46 hours, low water



+48 hours, low water

3.4.26 Compared to the baseline condition, the snapshots in the permanent works conditions show widespread increases in bottom speeds in the main channel area but the numerical value is small, in the order of 0.05m/s. After the deduction of the recommended background noise of 0.05m/s, this is reverted to no change at all.

3.4.27 Many speed reduction hotspots are found on the seabed layer of the water body. These are shown as blue and maroon coloured blots in the snapshots. These hotspots occur principally in ebb/flood tides and sometimes at low water, but rarely in high water. It is therefore concluded that this sort of speed reduction is a transient phenomenon and any potential deposition as a result of slower bottom speed could be removed or reversed within the timeframe of a single tidal cycle; as such they do not pose any concern in terms of potential changes to sediment transport behaviours caused by the permanent works.

3.4.28 It is noted that there is one speed increase hotspot near the south shoreline of the Firth of Forth between Abercorn Point and Society Bank (E309280, N679544), at +20 hours and +36 hours, during ebb tide and low water, as in ‘temporary works vs. baseline condition’. The reason for the occurrence of this hotspot is the same as stated in paragraph 3.4.22, i.e. wetting of a previously dry location (in the baseline condition) caused by the permanent works.

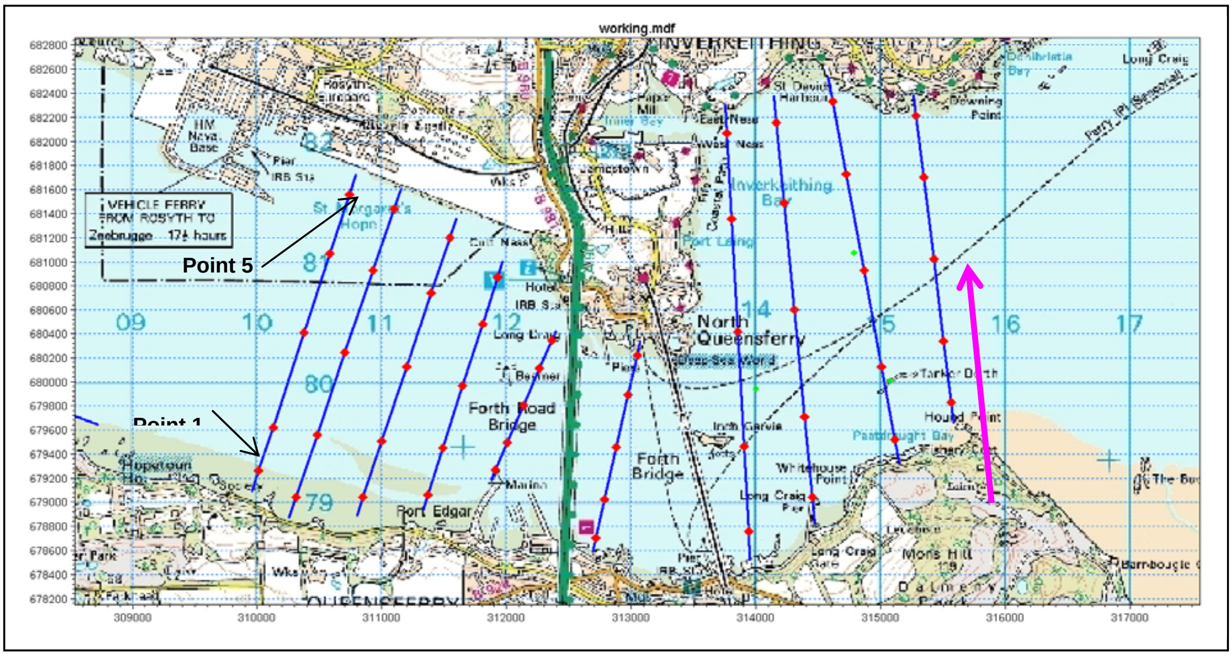
3.4.29 It is considered that these increases in bottom speed over such a short period within the tidal cycle are not significant, particularly when considering the rocky/cobbly and sandy nature of the shore along the coastline at this location, which is unlikely to suffer significant threat of increased erosion and morphological change under such minimal and short term velocity changes.

3.5 Transect Time Series of the Hydrodynamic Changes

3.5.1 It is recognised that the low resolution of the 2D snapshots presented in Diagrams 57 and 61 may conceal some localised changes in the current speeds.

3.5.2 To investigate this further, 10 transects in the vicinity of the proposed scheme corridor, with five points on each transect, as shown in Diagram 62, have been overlain for the purposes of picking up any detailed changes.

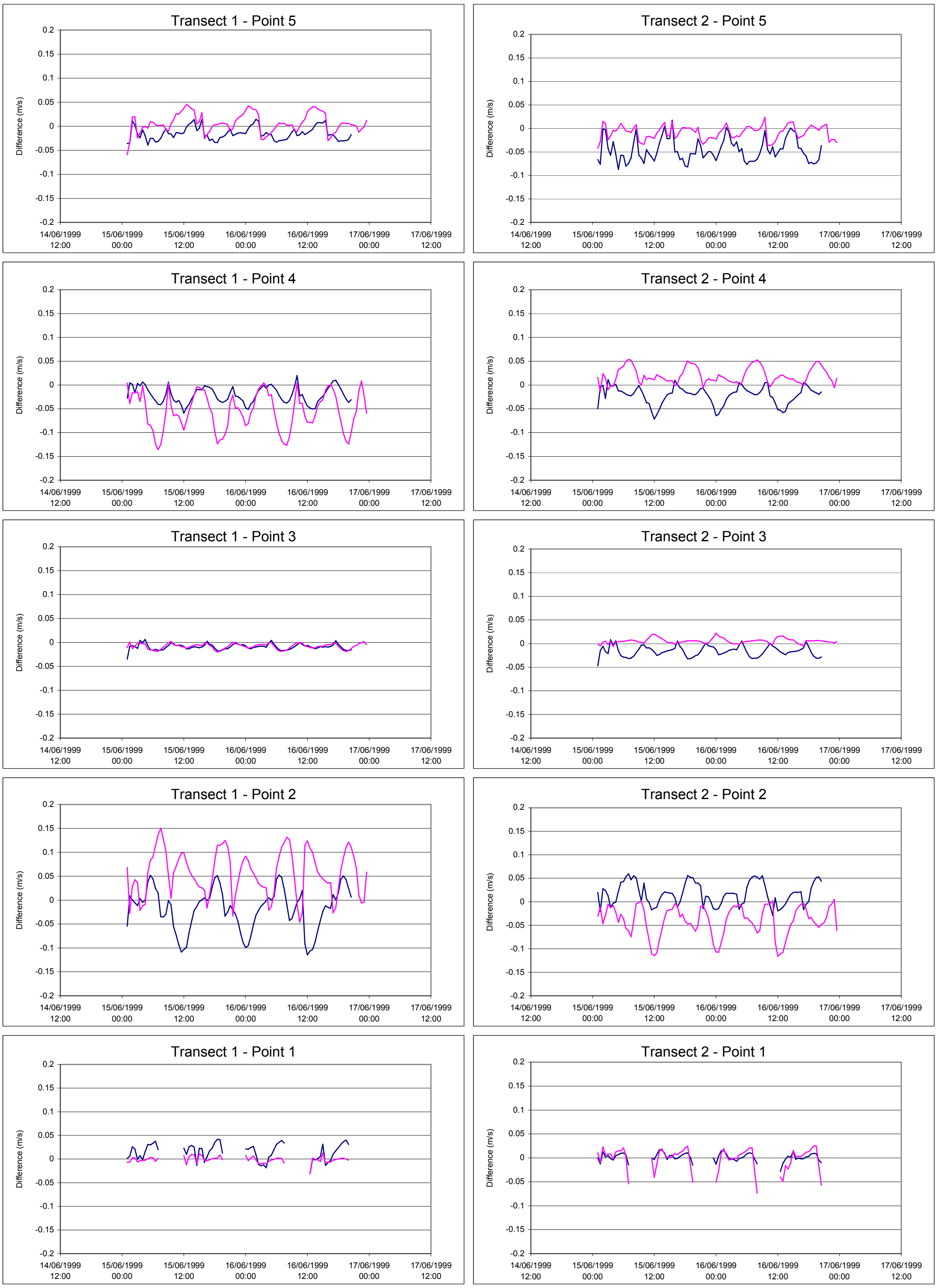
Diagram 62: Transects for Predicted Current Monitoring



Transect No. 1 2 3 4 5 6 7 8 9 10

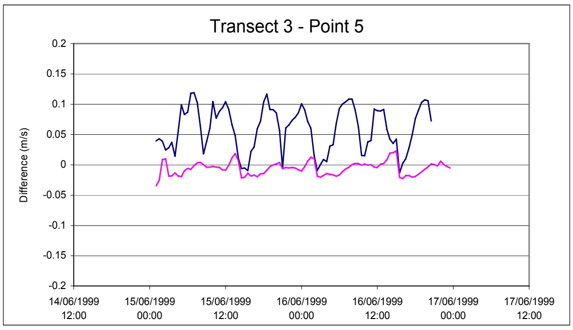
3.5.3 Time series plots of the current speed differences for the temporary works condition against baseline condition, and permanent works condition against baseline condition are shown in Diagram 63. A positive value denotes a faster current speed in the changed condition than in the baseline condition, and vice versa. A gap in the plot may signify a dry period in the location (intertidal point).

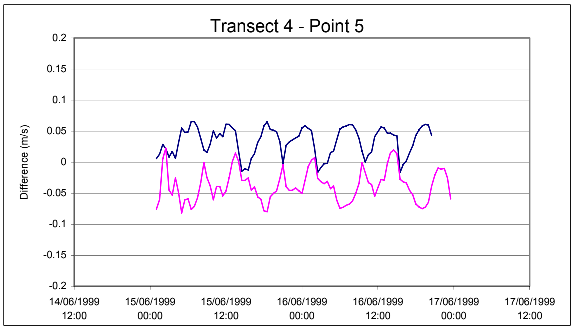
Diagram 63: Time Series Plots of Current Speed Defences

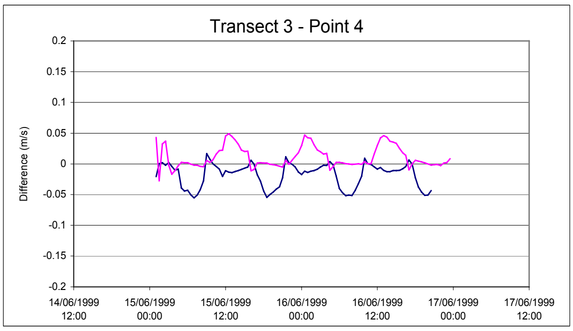


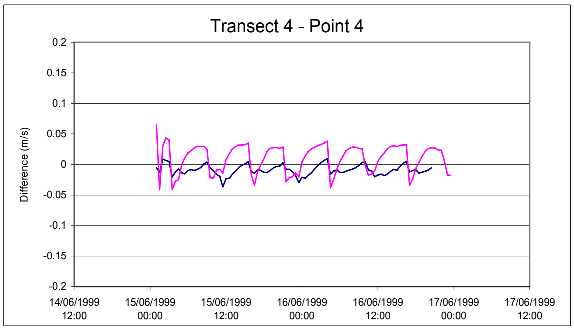
Temporary Works Condition minus Baseline Condition

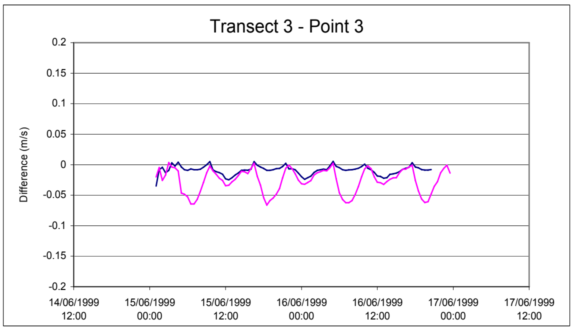
Permanent Works Condition minus Baseline Condition

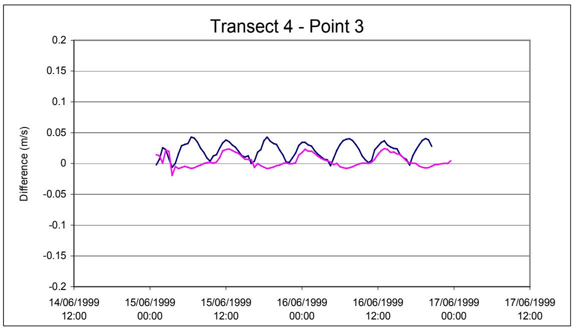


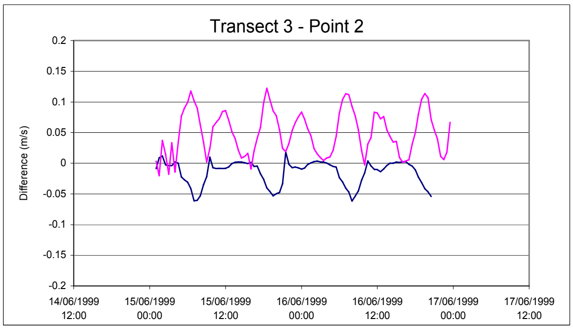


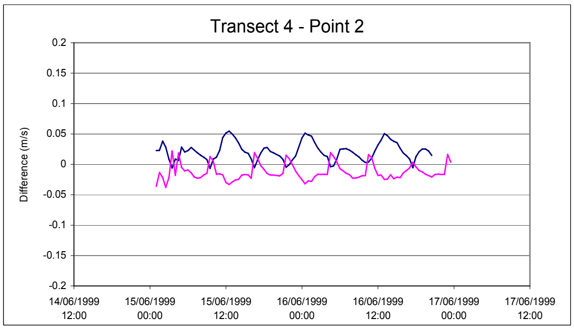


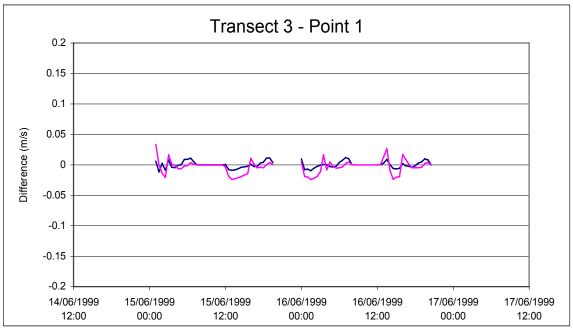


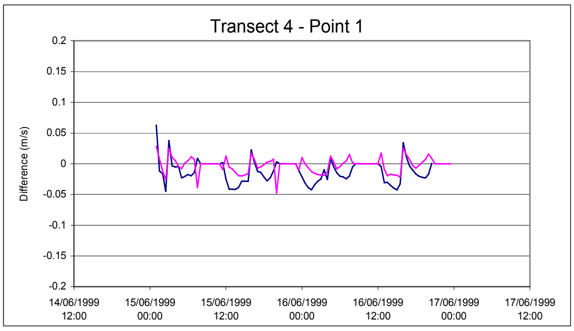






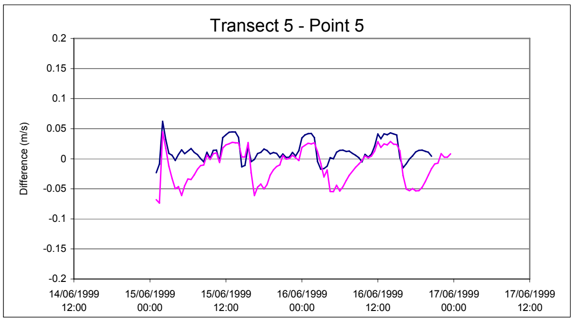


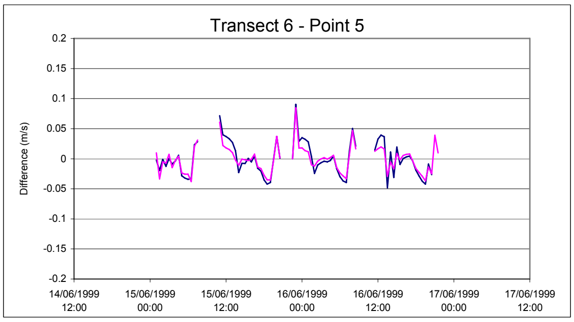


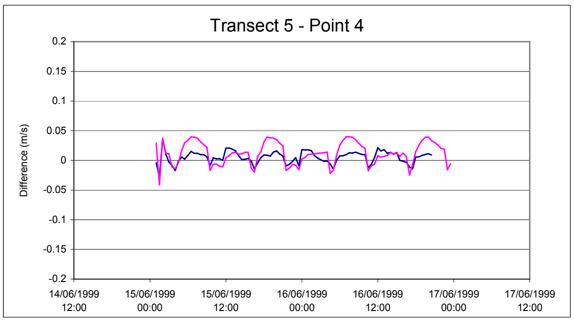


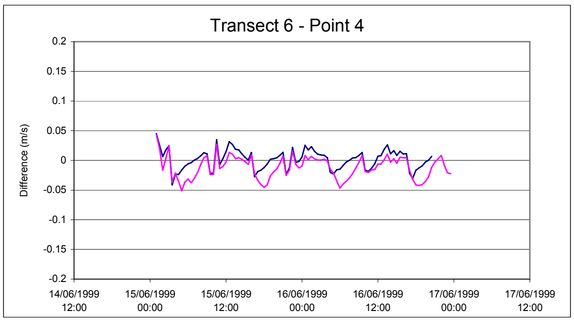
Temporary Works Condition minus Baseline Condition

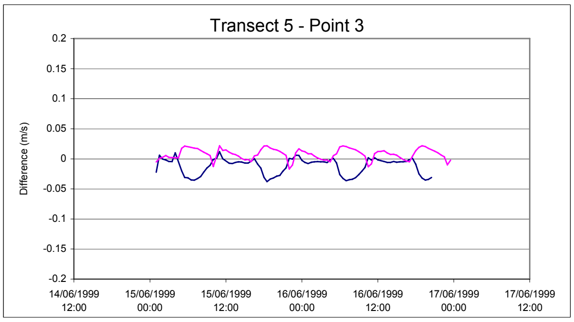
Permanent Works Condition minus Baseline Condition

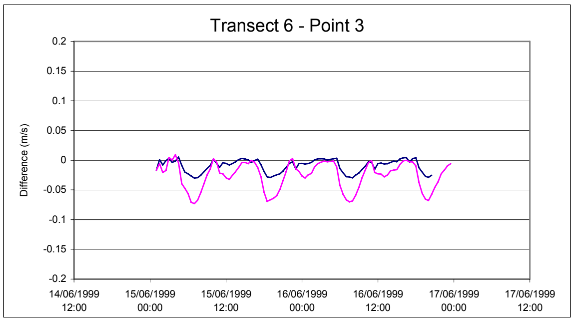


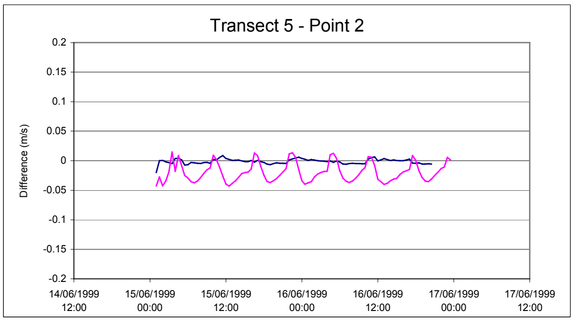


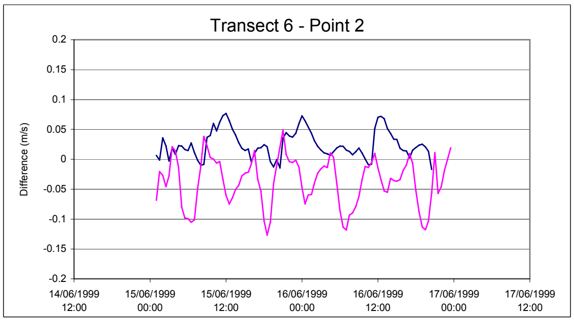


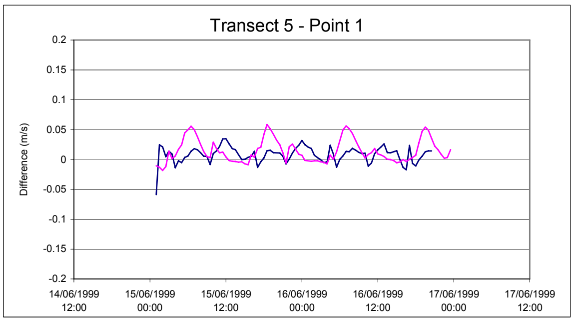


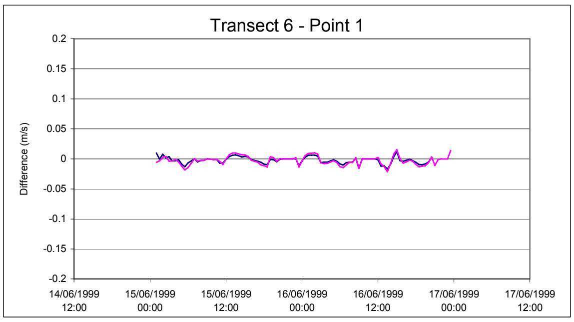






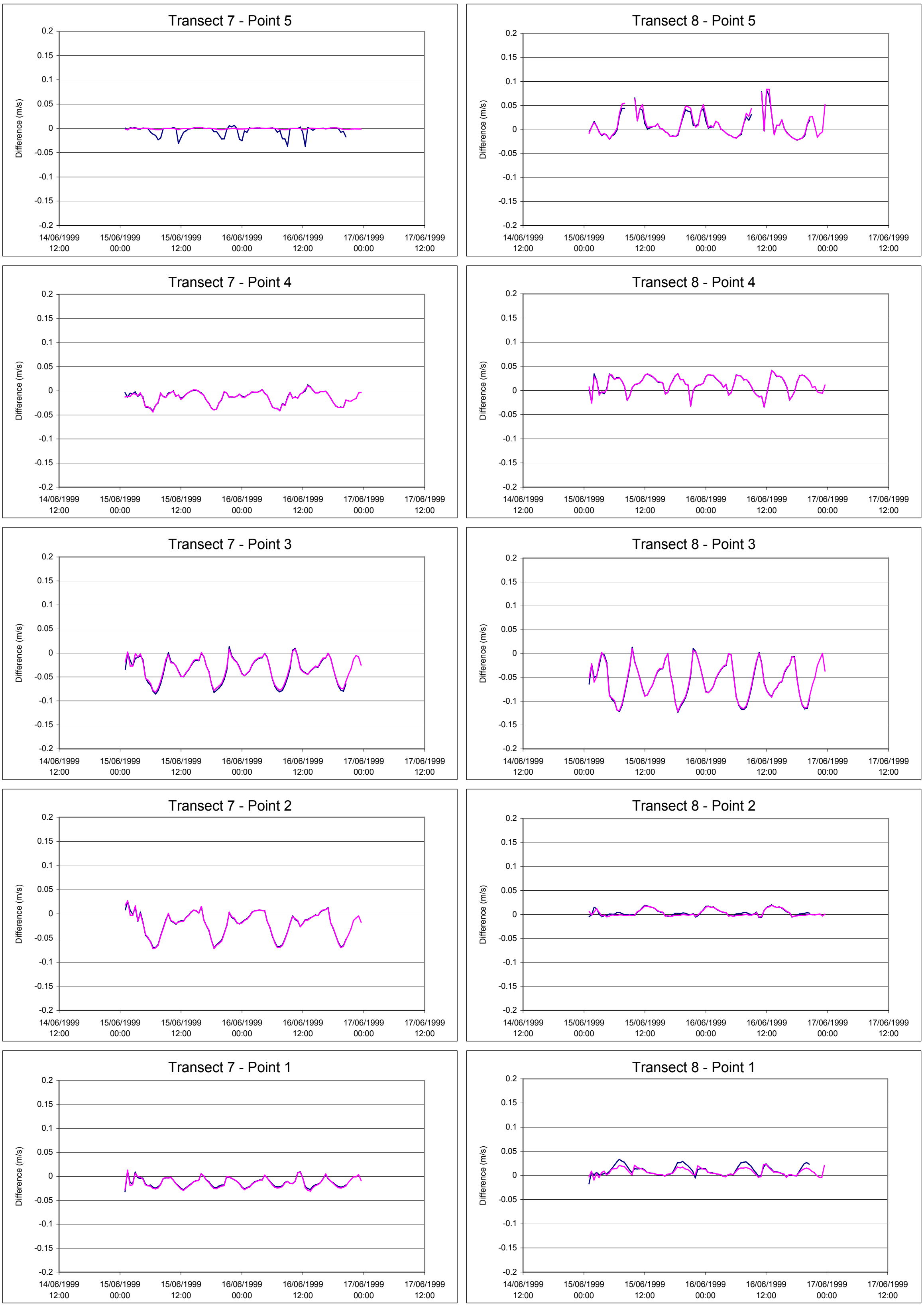






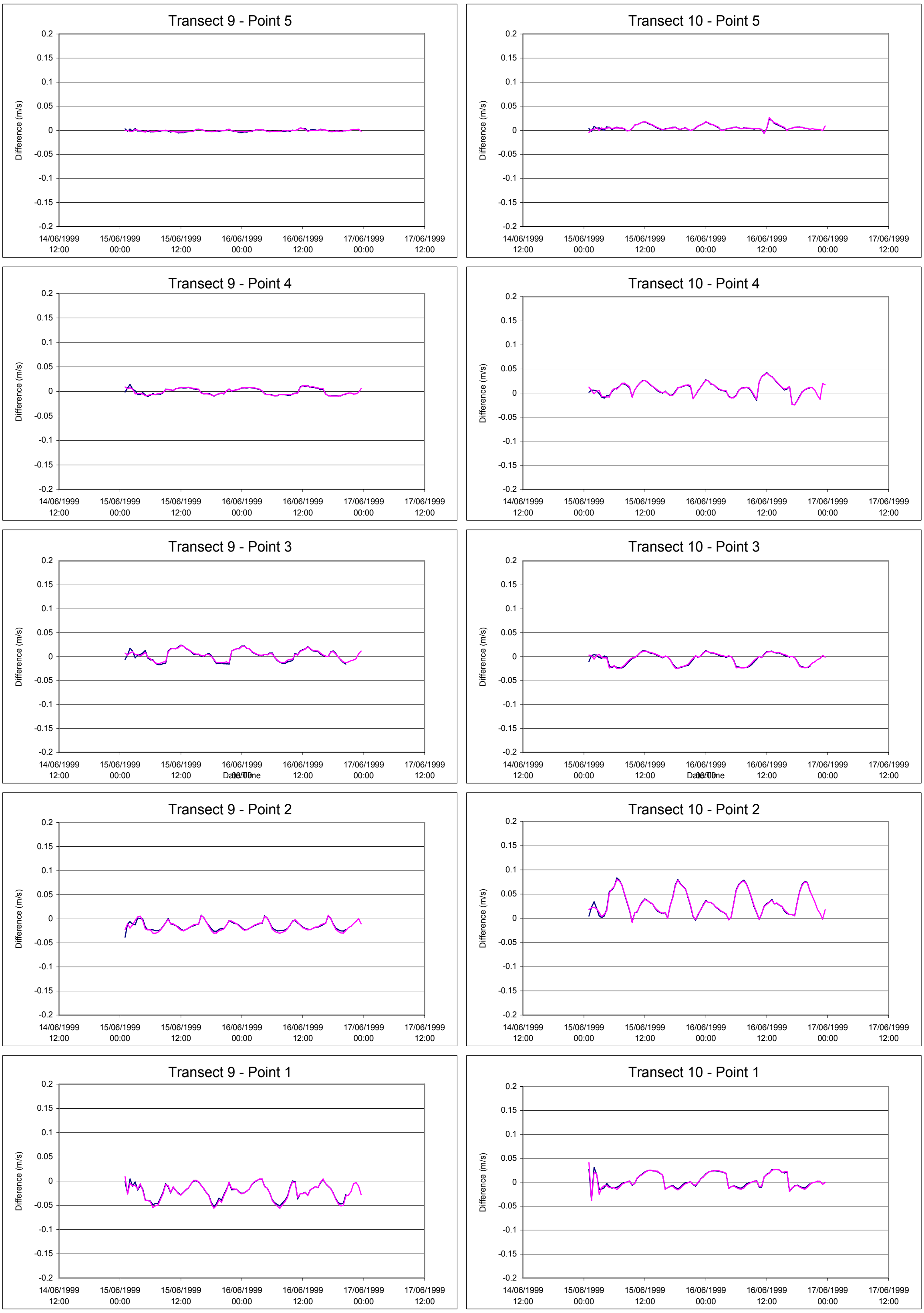
Temporary Works Condition minus Baseline Condition

Permanent Works Condition minus Baseline Condition



Temporary Works Condition minus Baseline Condition

Permanent Works Condition minus Baseline Condition



Temporary Works Condition minus Baseline Condition

Permanent Works Condition minus Baseline Condition

3.5.4 It is noted that most of the speed differences picked up by the transect points are within the range of ±0.05m/s, with the maximum difference being 0.15m/s. As recommended in paragraph 3.4.8, the background noise of ±0.05m/s should be taken off from the calculations. This will leave a maximum speed impact of ±0.1m/s in a very small number of areas, and no impacts (in terms of change in bottom speeds) in most areas.

3.6 Conclusion

3.6.1 The proposed scheme hydrodynamic model is able to provide quantitative assessment of the hydrodynamics and predict the potential effects the Main Crossing may have on the existing hydrodynamic regime, both during and following construction, in the Firth of Forth and Forth Estuary. Although the model is presently not able to consider the many complex processes of sediment transport, it is nevertheless possible to infer the changes in sedimentation patterns on the seabed (scour and deposition) by considering the changes in the seabed (bottom) current speed from its baseline, i.e. existing, condition before any bridge construction activities are carried out.

3.6.2 The model has been used to provide initial predictions of the current speeds during a 48 hour time period (representing approximately four tidal cycles during spring tides) in each of the three conditions: baseline, temporary works and permanent works. It has been assumed that the spring tide is the more severe tidal event for sediment transport as it is associated with both the higher and lower seawater levels, greater energy flux in the water and faster tidal currents than the neap tide. Therefore, although this report is based on initial predictions, it is considered to provide a robust assessment, as worst case conditions have been modelled.

3.6.3 Subsequent, to this report, further more detailed hydrodynamic modelling will be undertaken. This will include modelling of suspended sediments during the temporary works phase.

3.6.4 As the current speeds at the bottom layer of the model are most relevant for the inference of sediment transport patterns, the results from this bottom layer have been extracted in each time step computation. The simulation period covered two days or 48 hours of spring tides.

3.6.5 The hydrodynamic results have been presented as a series of snapshots of the bottom speed changes in two-hour intervals. These snapshots show that there are generally large areas of very small speed increases and decreases. After adjusting for background noise due to interpolation errors, there is practically no change at all.

3.6.6 For the temporary works and permanent works scenarios, a number of predicted speed reduction hotspots are found on the seabed layer of the water body but they occurred principally in ebb/flood tides and sometimes at low water, but rarely during high water. It is concluded that this sort of speed reduction is a transient phenomenon during the ebb/flood tides and any potential deposition as a result of slower bottom speed could be removed or reversed within the timeframe of a single tidal cycle; as such they do not pose any concern in terms of potential changes to sediment transport behaviour.

3.6.7 One speed increase hotspot is predicted near the intertidal area between Abercorn Point and Society Bank on the south shore of the Forth. The appearance of this hotspot is only for a very short time, at +20 hours and +36 hours, during ebb tide and low water, possibly for less than two hours. The maximum increase in bed velocities is up to 0.15m/s to 0.2m/s.

3.6.8 Further checks of the bottom speed at this speed increase hotspot revealed that at +20 hours and +36 hours, the hotspot location is mostly dry under the baseline scenario. The increase in bottom speed is a result of the area being wetted again caused by the presence of temporary works or the permanent works. It is considered that the small increases in bottom speed are not significant, particularly when considering the rocky/cobbly and sandy nature of the shore along the coastline at this location. Consequently, the shore is unlikely to suffer significant threat of increased erosion and morphological change under such minimal and short term velocity changes.

3.6.9 The results presented in this report demonstrate that no significant hydrodynamic impacts, specifically changes in bottom current speeds, would be caused by the temporary works and permanent works. The model predicts that the wider area would see negligible or no change.

3.6.10 Based on interpretation of the bottom speed changes predicted by the hydrodynamic model, it is concluded that effects would be negligible and there would be no discernible changes in sediment movement patterns within the model domain (the Firth of Forth and Forth Estuary). Consequently, it is not considered necessary to model the sediment transport process.

4 Suspended Sediment Plume Modelling

4.1 Introduction

4.1.1 A numerical modelling study has previously been undertaken to assess the hydrodynamics and predict potential effects the new bridge may have, both during and following construction. In the study, a three dimensional (3D) model of the upper and lower estuaries centring on the new bridge corridor was constructed to simulate the complex flow patterns and tidal interactions within the Firth of Forth, in order to inform the assessment of the potential effects of the proposals on the European sites in or near the Forth Estuary and Firth of Forth due to the presence of these sub-structures in the water. The results of the study including details of the model construction, calibration and validation processes, as well as the hydrodynamic impacts due to the bridge construction and permanent works have been collated into two reports:

- Coastal Hydrodynamic Model Calibration and Validation Report (refer to Section 2).
- Hydrodynamic Impacts Initial Assessment Report (refer to Section 3).

4.1.2 These two reports were submitted to some of the stake-holders including SEPA, Marine Scotland (formerly Fisheries Research Services) and SNH for comments. A meeting was held in January 2009 to discuss the contents presented and conclusions drawn in these two reports.

4.1.3 Following the acceptance of the reports by all parties attending the meeting during which the validity and appropriateness of the 3D model for simulating/predicting the complex hydrodynamics of the estuary and Firth of Forth were implicitly confirmed, it was agreed that the model should be used to further investigate the formation and spread of suspended sediment plumes during the course of the dredging, piling, temporary bund placing/removal activities planned for the construction of the tower/pier foundations.

<u>Objectives of Suspended Sediment Plume Modelling</u>

4.1.4 Suspended sediment plume modelling is required to inform these studies of the possible changes in water turbidity or suspended sediment concentration levels in the Firth of Forth and Forth Estuary before and during construction. During operation, it is not considered that there would be any changes to the turbidity levels due to the presence of the bridge sub-structures in the water as previous hydrodynamic modelling results suggested that there will be negligible changes to the flow regimes that would cause disturbance of the seabed sediments.

4.1.5 Elevated turbidity or suspended sediment concentration levels in the water columns could have the following impacts:

- Ecological – The feeding habits of small sea birds such as terns could be adversely affected.
- Ecological – Choking or disturbing the normal travel pathways of migratory fishes such as salmon and lamprey.
- Geomorphological – Suspended sediments may be washed onto the shoreline by tidal movements or by the advection/dispersion processes, which could result in a thin layer of fine materials deposited on the shallow bed surface that could affect the normal functioning of the bio-system in the inter-tidal zone.

- Water Quality – The suspended sediments derived from the seabed sediments may release heavy metals and other harmful substances which are normally attached to or locked onto the sediment particles, into the water body in a soluble form, resulting in temporary elevated concentrations locally in the surrounding water.
- Visual Impacts – The increase in water turbidity may give the public an impression of temporary fouling of the water.

4.1.6 The concentrations of suspended sediments in the water columns before commencement of any construction activities relating to the bridge foundations will be described here as the Background Level.

4.1.7 Consequently, a suspended sediment plume model will need to address the following issues:

- To determine the suspended sediment concentrations (as spatial distributions) over the model area at specific month of the year (it is reckoned that natural background concentration levels change according to seasons, with higher concentrations in the water during winter because of high fluvial discharges and heavy sediment loads from land, and comparatively lower concentrations in the dry summer season). These concentrations are the Background Level.
- To determine the suspended sediment concentrations over the model area, for scenarios of bridge tower/pier foundations construction, at the same month as that considered for the Background Level. Both spatial distributions and time series concentrations at selected monitoring points would need to be collected for detailed assessment.

4.2 Modelling Software

4.2.1 A 3D hydrodynamic model using industry standard MIKE3 Flexible Mesh (FM) finite volume modelling package developed by DHI has been constructed to understand the behaviour of the current flow and fluid mixing in the Firth of Forth and Forth Estuary.

4.2.2 Modelling 'components' being investigated include hydrodynamics, temperature changes, salinity and density (as a function of both temperature and salinity), and the transport (in term of advection and dispersion processes) of conservative, i.e. non-decaying, matter such as suspended sediments in the water columns.

4.2.3 The MIKE3 FM modelling system is based on a flexible mesh approach developed for applications within oceanographic, coastal and estuarine environments. Intrinsic to MIKE3 is the Hydrodynamic Module which is the basic computational component of the entire MIKE3 modelling system, as it provides the hydrodynamic basis for the Transport Module.

4.2.4 The Transport Module calculates the transport of materials, i.e. thermal particles/heated water and suspended sediment tracers, governed by the flow conditions found in the hydrodynamic calculations.

4.2.5 The computational basis of the software relies on the numerical solution of the 3D incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and hydrostatic pressure. The model takes into account the continuity, momentum, temperature, salinity and density equations and is closed by a turbulent closure scheme. In the horizontal domain, both Cartesian and Spherical coordinates can be used (a Cartesian coordinate system has been adopted for the present model as this is considered the most appropriate). The free surface is simulated using a sigma-coordinate transformation approach which avoids the problem of drying and wetting of the shoreline which is known to cause numerical instabilities and erroneous results in numerical models with irregular boundaries/shorelines.

4.2.6 The spatial discretisation of the governing equations is performed using a cell-centred finite volume method. The spatial domain is discretised by subdivision of the continuum into non-overlapping elements/cells. In the horizontal plane an unstructured grid is used while in the vertical domain a structured discretisation is used. The elements can be prisms or bricks whose horizontal faces are triangles and/or quadrilateral elements, respectively. Triangular elements have been adopted as they fit well to any shoreline shapes.

4.2.7 For the time integration a semi-implicit approach is used where the horizontal terms are treated explicitly and the vertical terms are treated implicitly. The use of an explicit method placed a limitation on the time step interval used.

4.3 Methodology and Modelling Approach

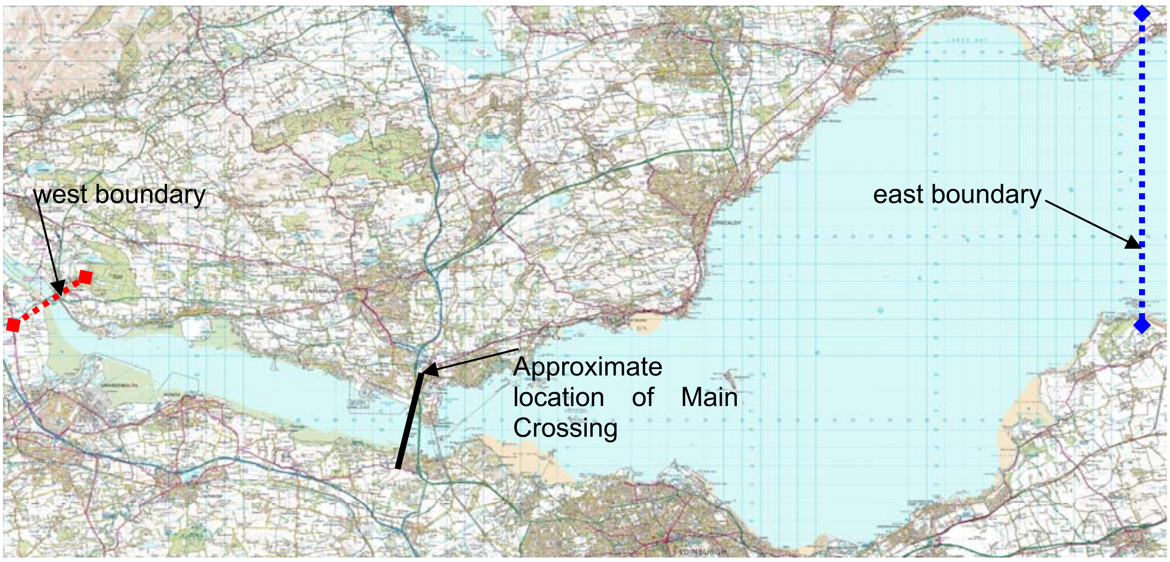
Hydrodynamic Modelling

4.3.1 This section sets out the methodology and general approach for modelling the construction impacts of the proposed bridge crossing on the Forth Estuary and Firth of Forth, specifically in terms of the impacts on hydrodynamics (water levels and tidal currents) and suspended sediment plumes.

4.3.2 To assess the impacts of the construction of the proposed Main Crossing and its permanent presence on the hydrodynamics in the Forth, a 3D hydrodynamic model representing a large area of the Forth Estuary using DHI MIKE3 FM modelling software has been constructed.

4.3.3 The extent of the model is shown in Diagram 64. This extent was chosen in order that the model has reasonable coverage of the Natura 2000 sites considered in Chapter 10 (Terrestrial and Freshwater Ecology) and Chapter 11 (Estuarine Ecology), and on the basis of the availability of suitable boundary data.

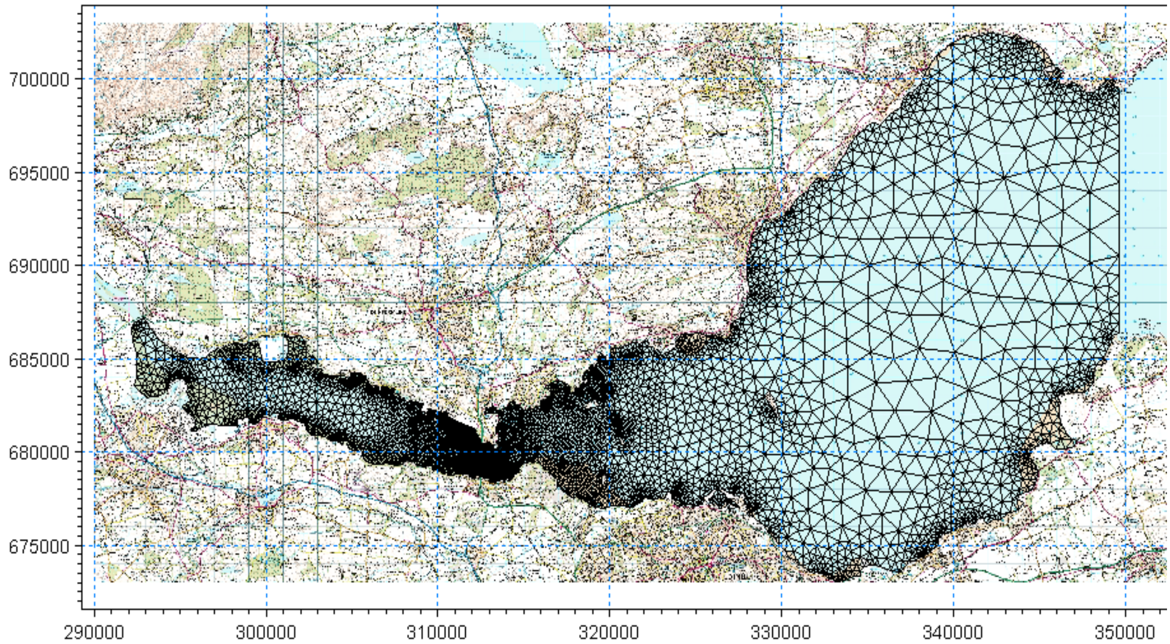
Diagram 64: Area of Interest for FRC Coastal Modelling



4.3.4 The modelled area shown in the OS map in Diagram 64 is contained within land boundaries to the north and south and open water boundaries to the east and west.

4.3.5 The model surface is covered by an unstructured mesh comprising almost 16,000 triangular finite elements, through 5 sigma layers over the water depth. The total number of elements used is just under 80,000 and the number of node points on each layer is 8,820. The model mesh is shown in Diagram 65. It should be noted that the plan is distorted because of non-identical scaling in the X and Y directions.

Diagram 65: Proposed Scheme Coastal Model Mesh



4.3.6 The hydrodynamic model has been calibrated and validated (see Section 1.2) against a range of recorded data obtained from several recognised sources and predicted tidal results produced by the UKHO TOTALTIDE model.

Suspended Sediment Plume Modelling

4.3.7 Modelling of the suspended sediment plume is by means of the Transport Module in the MIKE3 FM software. The hydrodynamic basis on which the Transport Module is run is provided by the Hydrodynamic Module described in Section 3.

4.3.8 The Hydrodynamic Module considers the effects of tidal and fluvial flows as well as wind forcing, temperature and salinity (these two latter parameters allow the computation of density using the UNESCO equation of state) and buoyancy forcing.

4.3.9 The two important modelling parameters in the Hydrodynamic Module which will affect the advection of suspended sediments are the horizontal and vertical Eddy Viscosities. During calibration and validation of the hydrodynamic model, the best values for these two parameters were found to be:

- Horizontal Eddy Viscosity = Smagorinsky formulation, 0.675 m^2/s constant; and
- Vertical Eddy Viscosity = Constant Eddy formulation, 0.6 m^2/s constant.

4.3.10 In the Transport Module, the dispersion of the suspended sediments is characterised by yet another two modelling parameters: Horizontal and Vertical Dispersion coefficients.

4.3.11 These two dispersion coefficients can be formulated by means of known coefficients derived from dye release tests or back-analysis of the performance of existing discharge scheme. It is however difficult to derive generally applicable values for the dispersion coefficients, particularly for a very wide area and varying water depths.

4.3.12 Alternatively, the dispersion coefficient can be considered as the product of a length scale and a velocity scale using Reynolds analogy. In shallow waters the length scale can often be taken as the water depth, while the velocity scale can be a typical current speed. In this way the Scaled Eddy

Viscosity formulation can be used when the measured dispersion coefficients are not available, such that the dispersion coefficient is calculated as the eddy viscosity used in the solution of the flow equations multiplied by a scaling factor.

4.3.13 As stated in the MIKE3 manual, the scaling factor can be estimated by $1/\sigma T$, where σT is the Prandtl number. Values of the scaling factors in the order of 1 are usually recommended.

4.3.14 With the lack of more reliable information, it is therefore proposed to adopt the Scaled Eddy Viscosity formulation for both the horizontal and vertical dispersion coefficients and a scaling factor of 1.0 has been applied to both.

4.3.15 The formation and movement of sediments in the water columns may include the processes of suspension, flocculation, settlement, re-suspension and bed load transport. In this study, modelling of the suspended sediment plumes considered only the single process of suspension with the assumption that all the sediment particles suspended in water will remain in suspension. It is true that re-suspension of bed sediments during tidal changes will add to the concentration but this will be more or less offset by the amount of sediment undergoing the processes of flocculation and settlement. Overall, the assumption of perpetual suspension may in fact over-estimate the amount of sediments in the water column, particularly during slack water conditions.

4.4 Construction Activities

4.4.1 Thirteen construction activities have been identified for the purposes of this suspended sediment plume assessment. It is anticipated that the following activities would be undertaken during the construction phase over a period of several months.

Construction Activities 1 and 2

4.4.2 Temporary bunds would be erected on the inter-tidal zone for piers S5 and S6 at the southern end of the bridge. The activities may include removal of the weak sediments by dredging for the bund foundations, placement of soils from land to build the bunds, and subsequent removal of the bund and reinstatement of the foreshore/inter-tidal area after the two piers have been constructed. Details are as follows:

- Total volume of bund for placement and removal is 27,000m^3;
- Placement period programme is 2 months; and
- Removal period is also expected to be 2 months.

Construction Activities 3 to 6

4.4.3 Dredged pockets for the foundations of piers S1, S2, S3 and S4. The seabed bathymetry of the four rectangular shape foundations are to be deepened to their final depths to reflect the dredged profiles.

Construction Activities 7 to 9

4.4.4 Areas between piers S1/S2, S2/S3 and S3/S4 will need to be dredged generally to provide access for dredging vessel and plant to reach the S1 to S4 locations. Details are as follows:

- A total of 120,000 m^3 of material to be dredged including all other dredged areas (temporary bunds, S1 to S4, general access dredging, NT and N1);
- Excavation expected over a 50 day period; and
- The maximum dredging rate at any one location is expected to be 120 m^3 per hour, assuming only one dredging vessel is in operation at any one time.

Construction Activity 10

4.4.5 Foundations for South Flanking Tower ST would be located on the existing seabed. There is no change to the bathymetry. Only piling activity will be undertaken. Details are as follows:

- piling period start in May 2012 to complete in June 2013, over 13 months;
- 52 piles are proposed in total, essentially carried out as a continuous process;
- 16 piles each at north and south flanking towers. Five marine approach viaduct piers (S1 to S4, and N1) with 4 piles at each;
- total piling spoil is estimated at 12,500m^3 (5 x 4 + 2 x 16 piles @240m^3 per pile). This includes piling for all towers/piers;
- 1 day drilling per pile (maximum rate). 52 days of drilling for piles, evenly distributed over a 13-month period; and
- extraction of pile arisings are not expected to continue for more than 18 hours in any 24-hour period.

Construction Activity 11

4.4.6 Foundations for Central Tower CT would be founded on the existing Beamer Rock. It is understood that the excavation will be within the existing Beamer Rock outline with no change to the surrounding bathymetry. Only excavation of the blasted materials is expected. The work may be above or below water depending on the prevailing tidal states. Details are as follows:

- Total volume of rock excavation is 11,000m^3;
- Excavation and blasting operations programmed over 88 days;
- Excavation expected to be on-going over 33% of this period. Say, 6 days drilling and blasting followed by 3 days of excavation, 18 hours a day of actual excavation;
- Removal over 88 days/9 = 9.77 stages. 9.77x 18 hours per day = 176 hours total; and
- 2.5% silt clay fraction (and a further 2.5% sand gravel fraction) may be lost during excavation.

Construction Activity 12

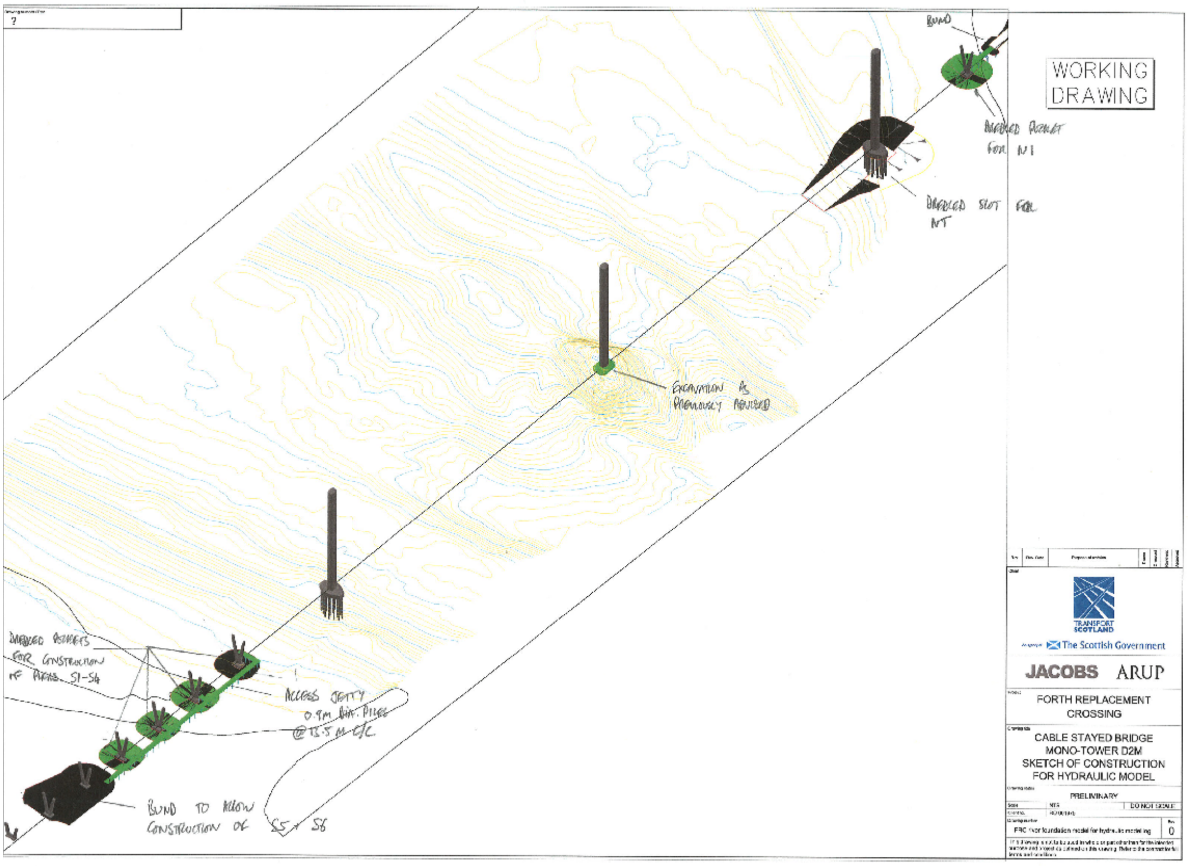
4.4.7 Foundations for North Flanking Tower NT will have a long dredged strip for barge access as well as for the foundations.

Construction Activity 13

4.4.8 North pier N1 will have a dredged pocket to facilitate provision of its foundations. Local bathymetry under the proposed foundations will be deepened.

4.4.9 A schematic of the construction works is shown in Diagram 66 and the various stages of the construction activities are summarised in Table 4.1.

Diagram 66: Construction Activities Schematic



4.4.10 Two different working hour periods have been assumed for the construction activities, with an 8-hour day for the temporary bunds at piers S5 and S6, and an 18-hour day for the rest of the construction activities.

4.4.11 The 8-hour day is from 0800 to 1600 hours, and the 18-hour day has two 3-hour breaks to allow shift changes etc. in between 0600 and 0900, and 1800 and 2100 hours.

Table 4.1: Schedule of Construction Activities

Location	Setting Out Coordinates		Construction Activity	Activity Duration	Foundations Base Level	Working Hours
	Easting	Northing		Days	mCD	
Pier S6	311548	678758	Temporary Bund dredging of weak materials placement/removal	Placement /removal 2 months each	onshore, above MHWS	8
Pier S5	311578	678839	Temporary Bund dredging of weak materials placement/removal		Inter-tidal	8
Pier S4	311609	678920	Dredging and piling	4	-4.05	18
Pier S3	311640	679002	Dredging and piling	4	-4.55	18
Pier S2	311671	679085	Dredging and piling	4	-5.05	18
Pier S1	311708	679182	Dredging and piling	4	-6.55	18
Floating crane access between S1 and S4			General dredging		-1.55	18
South Flanking Tower	311786	679389	Piling	16	Existing seabed	18
Central Tower (Beamer Rock)	312015	679997	Drilling, Blasting and Excavation	Over 88 days Excavation over 33% of time 6 days drilling and blasting 3 days of excavation Carried out in about 10 stages		18
North Flanking Tower	312244	680606	Dredging and piling	16	-11.55	18
Pier N1	312322	680812	Dredging and piling	4	-5.05	18

4.5 Suspended Sediment Budget

4.5.1 The bed density used in MIKE3 is defined as dry density, by the following formula:

$$\rho_d = \frac{\text{dry mass of grain from the sample}}{\text{volume of sample with a mixture of sediment and seawater}}$$

4.5.2 Typical bed densities for different sediment types are recommended in DHI's Sediment Transport Modelling Manual and are shown in Table 4.2.

Table 4.2: Typical Dry Densities of Seabed Sediments

Sediment Type	Dry Density (kg/m^3)
Freshly deposited (1 day), fluff mobile fluid mud	50-100
Weakly consolidated (1 week), fluid stationary mud	100-250
Medium consolidated (1 month), deforming cohesive bed	250-400
Highly consolidated (1 year), stationary cohesive bed	400-550
Stiff mud (10 years), stationary cohesive bed	550-650

4.5.3 Laboratory results from grab samples and marine borehole data taken at the crossing area suggested that the dry density is about 550kg/m^3 on average.

4.5.4 A bulk density of 1,600kg/m^3 has been adopted in the dispersion modelling by the Middle Bank project (ERM, 2008). The Middle Bank project took eight samples during 135 minutes of the dredging operation, and it was found that the average suspended sediment concentration in the overspill seawater is 14,080mg/l. About 5.1% of the solid was overspilled with the maximum loss being 7.1%.

4.5.5 In an influential lecture at a seminar on dredged material assessment in 2008, Drs. Schroeder and Gailani of the US Army Corp of Engineers stated that sediment re-suspension is often less than 1% of mass of fine grained fraction of the sediment dredged, while the loss of fine grain mass of dredged sediment to water column by mechanical dredged methods (either open or water tight) is in the range of 0.2 to 9%.

4.5.6 Based on the above, it is thus proposed to adopt the following parameters for the suspended sediment plume modelling:

- bulking density of sediment = 1,600kg/m^3;
- dry density of sediment = 550kg/m^3, converting to concentration = 550,000mg/l; and
- concentrations of suspended sediments in surface overspill = 14,080mg/l, i.e. dry density = 14.08kg/m^3.

4.5.7 Percentage loss (material released from dredging and piling etc):

- dredging, bottom loss = 9% (maximum value based on an open dredging bucket);
- dredging, surface overspill = half of bottom loss, 4.5%;
- piling, bottom loss = 2%;
- piling, surface overspill loss = 0, assuming the piling arisings are left in place or there is little or no loss during extraction;
- excavation, bottom loss = 2.5%;
- excavation, surface overspill loss = 1.25%; and

- temporary bund placement/removal loss = 2%.

4.5.8 Table 4.3 presents a break-down of the materials expected to be released during the construction activities.

Table 4.3: Break-down of Released Materials

Location	Sediment Composition	Maximum volume of Materials to be removed	% released to water column	Total amount of material released to water column	Release duration over 3 days of simulated tide event
Pier S6 Pier S5		Dredging = 6,000m^3 Placement/ removal = 27,000m^3	Max dredging rate 120m^3/h 4.5% loss overspill 9% below water 2% for placement/removal	Dredging 540m^3 below water Dredging 270m^3 above water Placement/removal 540 m^3 /2 = 270m^3 as half of the area is dry over 60 days	Continuous for 3 days, 8 hours per day
Pier S4	50% silt/clay 24% fine sand	Dredging = 10,000 m^3 Piling = 4 x 240 = 960m^3	Max dredging rate 120m^3/h 4.5% loss overspill 9% below water 2% piling loss	Dredging 900m^3 below water Dredging 450m^3 above water Piling 19.2m^3 (each pile loss 4.8m^3/d)	Continuous for 3 days, 18 hours per day
Pier S3		Dredging = 9,800 m^3 Piling = 4 x 240 = 960m^3	Max dredging rate 120m^3/h 4.5% loss overspill 9% below water 2% piling loss	Dredging 882m^3 below water Dredging 441m^3 above water Piling 19.2m^3	Continuous for 3 days, 18 hours per day
Pier S2	96% silt/clay 2% fine sand	Dredging = 11,500m^3 Piling = 4 x 240 = 960m^3	Max dredging rate 120m^3/h 4.5% loss overspill 9% below water 2% piling loss	Dredging 1035m^3 below water Dredging 517.5m^3 above water Piling 19.2m^3	Continuous for 3 days, 18 hours per day
Pier S1	79% silt/clay 17% fine sand	Dredging = 9,800 m^3 Piling = 4 x 240 = 960m^3	Max dredging rate 120m^3/h 4.5% loss overspill 9% below water 2% piling loss	Dredging 882m^3 below water Dredging 441 m^3 above water Piling 19.2m^3	Continuous for 3 days, 18 hours per day
Floating crane access between S1 and S4		30,000m^3	Max dredging rate 120m^3/h 4.5% loss overspill 9% below water	2,700m^3 below water 1.350m^3 above water	Continuous for 3days, 18 hours per day
South Flanking Tower		240m^3 per pile piling = 16 x 240 = 3,840 m^3	2% loss below water	76.8m^3	Continuous for 3 days, 18 hours per day

Location	Sediment Composition	Maximum volume of Materials to be removed	% released to water column	Total amount of material released to water column	Release duration over 3 days of simulated tide event
Central Tower (Beamer Rock)	2.5% silt/clay and a further 2.5% sand/gravel fraction lost during excavation	11,000m^3	2.5% during excavation below water 1.25% loss overspill	275m^3 over 10 stages 10 x 3 days x18 hours = 275 / 540 = 0.51m^3/h	Continuous for 3 days, 18 hours per day
North Flanking Tower	48% silt/clay 28% fine sand	Dredging = 33,000m^3 Piling = 16 x 240 = 3,840m^3	Max dredging rate 120m^3/h 4.5% loss overspill 9% below water 2% piling loss	Dredging 2,970m^3 below water Dredging 1485m^3 above water Piling 76.8m^3	Continuous for 3 days, 18 hours per day
Pier N1	44% silt/clay 21% fine sand	Dredging = 10,000m^3 Piling = 4 x 240 = 960m^3	Max dredging rate 120m^3/h 4.5% loss overspill 9% below water 2% piling loss	Dredging 900m^3 below water Dredging 450m^3 above water Piling 19.2m^3	Continuous for 3 days, 18 hours per day

4.5.9 Three days of tidal conditions for spring tide and neap tides in June 1999 comprising about three tidal cycles each have been modelled to predict the fate of the plumes. As none of the 13 construction activities is shorter than three days, it is apparent that not all the dredging and piling operations can happen in the time frame. It is therefore decided that only the worst operation, i.e. the one which releases the most sediments (generally dredging) would be modelled. Table 4.4 below gives a further break-down of the release rates and the release concentrations input to the model.

Table 4.4: Released Rates Input to the Suspended Sediment Plume Model

Location	Average Release Rate (in-situ volume)	Mass Rate Input to Model	Concentration Input to Model
Pier S6 Pier S5	Dredging 10.8m^3/h below water overspill 5.4m^3/h above water placement/removal 0.5625m^3/h	Dredging 1.65kg/s below water overspill 0.021kg/s above water placement/removal 0.086 kg/s	550,000mg/l bottom 14,080mg/l overspill
Pier S4	Dredging 10.8m^3/h below water dredging 5.4m^3/h above water piling 0.27m^3/h	Dredging 1.65kg/s below water overspill 0.021kg/s above water piling 0.041kg/s below water	550,000mg/l bottom 14,080mg/l overspill
Pier S3	Dredging 10.8m^3/h below water dredging 5.4m^3/h above water piling 0.27m^3/h	Dredging 1.65kg/s below water overspill 0.021kg/s above water piling 0.041kg/s below water	550,000mg/l bottom 14,080mg/l overspill
Pier S2	Dredging 10.8m^3/h below water dredging 5.4m^3/h above water piling 0.27m^3/h	Dredging 1.65kg/s below water overspill 0.021kg/s above water piling 0.041kg/s below water	550,000mg/l bottom 14,080mg/l overspill
Pier S1	Dredging 10.8m^3/h below water dredging 5.4m^3/h above water piling 0.27m^3/h	Dredging 1.65kg/s below water overspill 0.021kg/s above water piling 0.041kg/s below water	550,000mg/l bottom 14,080mg/l overspill
Floating crane access between S1 and S4	Dredging 10.8m^3/h below water dredging 5.4m^3/h above water	Dredging 1.65kg/s below water overspill 0.021kg/s above water	550,000mg/l bottom 14,080mg/l overspill
South Flanking Tower	Piling 0.27m^3/h	Piling 0.041kg/s	550,000mg/l bottom
Central Tower (Beamer Rock)	Excavation 0.51m^3/h Spill (-50%) 0.255m^3/h	Excavation 0.08kg/s Spill 0.001kg/s	550,000mg/l bottom 14,080mg/l overspill

Location	Average Release Rate (in-situ volume)	Mass Rate Input to Model	Concentration Input to Model
North Flanking Tower	Dredging 10.8m^3/h below water dredging 5.4m^3/h above water piling 0.27m^3/h	Dredging 1.65kg/s below water overspill 0.021kg/s above water piling 0.041kg/s below water	550,000mg/l bottom 14,080mg/l overspill
Pier N1	Dredging 10.8m^3/h below water dredging 5.4m^3/h above water piling 0.27m^3/h	Dredging 1.65kg/s below water overspill 0.021kg/s above water piling 0.041kg/s below water	550,000mg/l bottom 14,080mg/l overspill

4.5.10 As mentioned in the last page, the items in Table 4.4 which are in shown in grey colour are not modelled because they cannot co-exist with the other operations and they also tend to impact less.

Data Requirement and Availability

List of Data Requirements

4.5.11 The following information is required for suspended sediment plume modelling:

- release rates and concentrations from the construction activities;
- temperature and salinity in the fluvial input and in the water body within the model area; and
- suspended sediment concentrations in the fluvial inputs and in the water body within the model area.

Existing Data

Release rates and concentrations from the construction activities

4.5.12 Tables 4.3 and 4.4 provide a detailed break-down of the required data.

Temperature and salinity in the fluvial input and in the model area

4.5.13 SEPA has provided temperature data at Inchkeith and River Almond.

4.5.14 As the modelling is to be driven by the spring and neap tide data in the month of June 1999, only the data values in June or around that month were extracted from the SEPA data. The average temperature values are found to be:

- fluvial temperature (river water based on River Almond) = 15.6°C; and
- seawater temperature (at Inchkeith) = 12°C.

4.5.15 Salinity (PSU or ppt) data between year 2000 and 2008 at the following locations were also provided by SEPA. The following values are the average of those in and near June over the years:

- Kincardine = 26;
- Longannet = 28;
- Dog Rock = 30;
- Black Ness = 31;
- Inchcolm = 32;
- Inchkeith = 34; and
- Methil = 34.

4.5.16 The above temperature and salinity data were extracted from a very small and sparse set of spot samples collected irregularly in intervals between two or more months. Only those data in or near June were used as they are relevant and useful to the modelling period.

4.5.17 There is no salinity data for the fluvial inputs. It is therefore assumed that the PSU for freshwater is 0.

Suspended sediment concentrations in the fluvial inputs and in the model area

4.5.18 Some suspended sediment and salinity data for Kincardine, Longannet, Dog Rock, Black Ness, Inchcolm, Inchkeith and Methil were provide by SEPA. Apart from Kincardine (which was collected in 2 separate days, over about 12 hours on each day), all are spot data (there was no depth and time information) taken a few months apart each time, during 2000 to 2008.

4.5.19 It is known that SEPA and Dr. Alan Elliott (University of Wales) had conducted a test at the Forth Road Bridge site. Some turbidity data were recorded but these data do not have any calibration done to convert the turbidity units (NTU) to concentration (in mg/l) values.

4.5.20 Some turbidity data in a few locations within the model domain for the year 1999 were located from past projects along the Edinburgh coast. Again, there was no calibration to the actual suspended sediment concentrations was carried out, so these results are not useful for modelling purposes.

4.5.21 Marine Scotland (formerly FRS) kindly provided the Middle Bank reports for reference. The Middle Bank site location is sheltered between Inchkeith (to its East) and three small islands (Inchmickery, Cow and Calves, and Oxcars) to its west. The navigation channels are on its north and south. The natural/baseline suspended sediment concentration should be quite low because of its geographical location. In fact, previous modelling carried out by HR Wallingford adopted a background level of about 10mg/l.

4.5.22 The mean daily discharge figures for the 9 main rivers within the model domain were provided by SEPA but only River Almond has suspended sediment concentration, of 4.1mg/l. It is proposed to assume this concentration for all fluvial inputs.

4.5.23 The following suspended sediment concentration values are the average of those provided by SEPA in and near June in the years between year 2000 and 2008:

- Kincardine = 130mg/l;
- Longannet = 16mg/l;
- Dog Rock = 12mg/l;
- Black Ness = 10mg/l;
- Inchcolm = 11mg/l;
- Inchkeith = 6mg/l; and
- Methil = 5mg/l.

4.5.24 The concentration level at Middle Bank is given as 9mg/l (ERM, 2008).

Marine Survey and Sampling

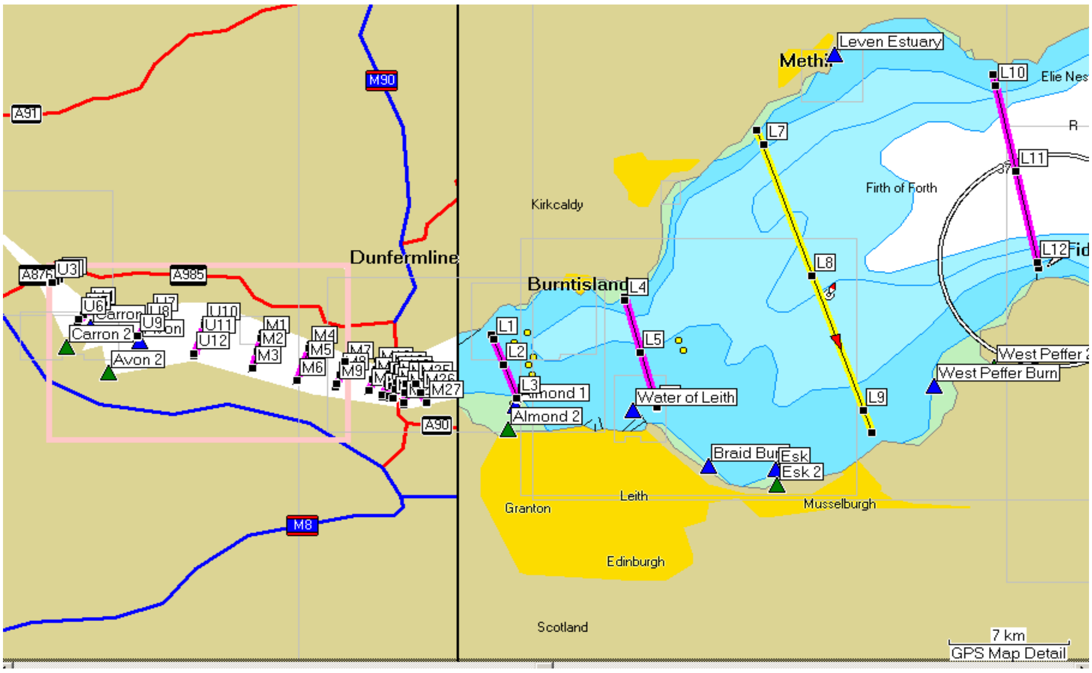
4.5.25 A two-day survey to collect temperature, salinity and turbidity data over the model domain was commissioned by Transport Scotland. The survey was carried out on 18 and 19 March 2009.

4.5.26 51 marine samples along a number of transects in three regions of the Firth of Forth and estuary: Upper Region upstream of Crossing (U-series samples), Middle Region near to the Crossing (M-series samples) and Lower Region downstream of the Crossing (L-series samples), and 8 fluvial samples were taken. Although these are spot samples taken at only one time, on each location the values at several water depths were obtained.

4.5.27 A small number of water samples were also taken to the laboratory to determine the actual concentration such that a correlation between turbidity and concentration was made possible in several area of the model domain.

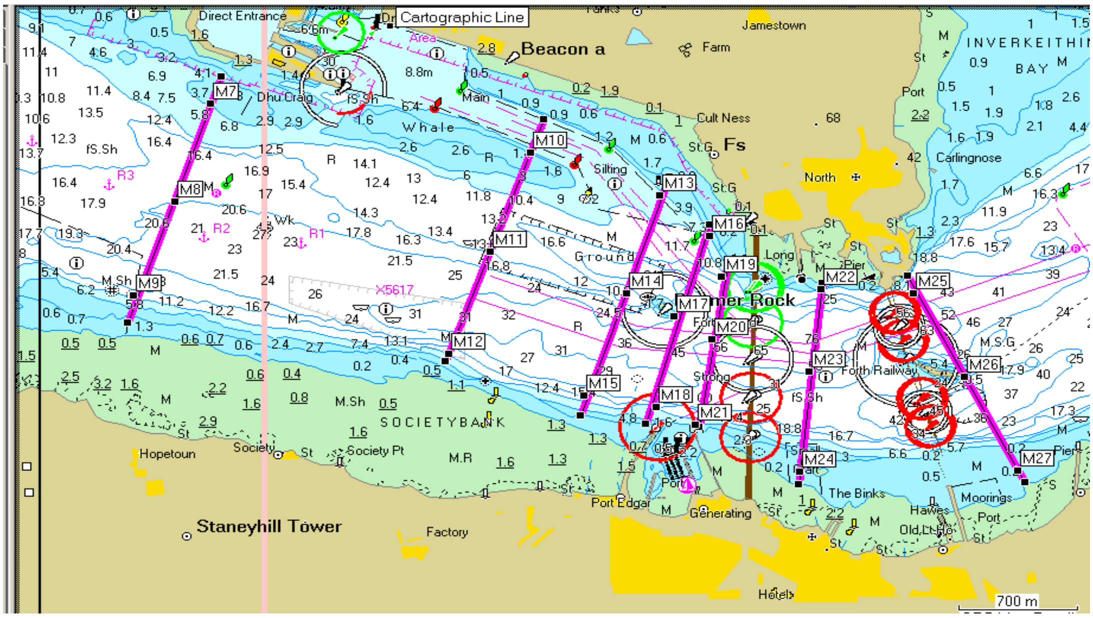
4.5.28 The sampling locations are shown in Diagram 66 and the results are illustrated in Table 4.5.

Diagram 66: Marine Survey Sample Locations



Upper region upstream of Crossing

Lower region downstream of Crossing



Middle region near the Crossing

4.5.29 The sample names with prefix 'U' denote the upper region, 'M' for the middle region near the Crossing, and 'L' for lower region, downstream of the Crossing.

4.5.30 A few samples taken in the lower region did not produce useful results, as well as sample points at Rivers Esk and West Peffer. These are shown in grey colour cells in Table 4.5.

Table 4.5: Marine Survey Results

Sample	Temperature °C		Salinity PSU		Turbidity NTU		Concentration mg/l	
Sites	Max	Min	Max	Min	Max	Min	Max	Min
U1	8.0	7.7	18.3	13.6	21.1	18.6	33	29
U2	7.7	7.0	28.2	13.9	24.3	19	39	30
U3	8.0	7.1	25.5	14.3	30.3	25.8	49	41
U4	6.9	6.8	31.0	28.2	12.5	11.7	19	18
U5	7.3	6.9	28.9	16.0	15.4	12.8	24	20
U6	7.9	7.1	27.0	13.0	12.7	10.9	20	17
U7	7.3	6.7	31.9	19.6	8.7	7.9	13	12
U8	7.4	6.4	32.7	21.7	11.5	8.7	18	13
U9	7.4	6.5	32.1	18.7	9.5	6.4	14	9
U10	8.6	6.3	33.0	28.8	23.8	5.2	38	7
U11	7.7	6.4	32.9	24.6	16.2	5.2	25	7
U12	7.8	6.6	31.7	24.1	7.8	4.7	12	6
M1	7.7	6.2	33.4	25.4	13.9	3.2	22	4
M2	7.4	6.3	33.2	24.8	15.3	4.9	24	7
M3	7.4	6.5	32.1	22.2	15.8	8	25	12
M4	7.4	6.1	33.8	28.3	7.6	3.3	11	4
M5	7.4	6.1	33.9	26.4	8.1	2.1	12	2
M6	7.2	6.4	33.0	24.7	5.8	3.6	8	5
M7	7.1	6.1	34.2	28.6	9.7	4.1	15	5
M8	7.1	6.0	34.4	28.6	4.4	1.2	6	1
M9	7.2	6.1	34.3	28.5	10	2	15	2
M10	7.1	6.3	33.4	29.2	3.3	2.3	4	2
M11	6.9	6.0	34.3	29.5	3.2	1	4	0
M12	7.2	6.0	34.3	28.6	4.6	1.6	6	1
M13	7.1	6.1	34.2	29.4	1.9	1	2	0
M14	7.1	6.0	34.5	29.5	1.8	1	2	0
M15	7.0	6.0	34.4	28.9	2	1.3	2	1
M16	7.4	6.2	33.8	30.6	3.7	3.5	5	4
M17	6.9	6.1	34.3	31.1	4.2	2.8	6	3
M18	6.5	6.2	33.9	30.6	4.5	2.7	6	3
M19	7.5	6.1	34.0	30.1	6.1	3.7	9	5
M20	7.2	6.1	34.2	30.1	5.3	3.1	7	4
M21	7.5	6.2	33.5	29.2	4.5	3.7	6	5

Sample	Temperature °C		Salinity PSU		Turbidity NTU		Concentration mg/l	
Sites	Max	Min	Max	Min	Max	Min	Max	Min
M22	7.0	6.2	33.8	31.4	3.7	3.2	5	4
M23	7.1	6.1	33.9	30.3	4.7	3.2	6	4
M24	7.4	7.3	29.7	29.3	5.3	4.6	7	6
M25	6.9	6.3	33.7	32.4	2.7	1.8	3	2
M26	7.0	6.1	33.9	30.6	3.6	2.6	5	3
M27	7.2	7.1	30.6	30.3	4.8	3.9	7	5
L1	6.6	6.1	34.1	32.5	3.5	2.3	4	2
L2	6.9	5.9	34.6	32.6	2.6	1.7	3	1
L3	6.8	6.5	33.0	32.9	3.2	2.3	4	2
L4	6.3	5.9	34.8	34.4				
L5	6.4	6.2	33.8	33.5				
L6	6.6	6.5	33.3	32.8				
L7	6.3	6.0	35.0	34.9				
L8	6.1	5.9	35.1	34.8				
L9	6.4	6.1	34.4	34.2	1.2	1	1	0
L10	5.9	5.9	34.9	34.9				
L11	6.1	5.8	34.9	34.5				
L12	6.2	6.1	34.8	34.4				
Almond	8.5	7.7	32.1	31.2	37.9	25.4	61	41
Avon	7.9	7.1	28.0	17.2	7.3	6.3	11	9
Braidburn	7.0	6.9	33.8	33.8	3	2	4	2
Carron	8.0	7.4	27.2	9.1	12.5	9.3	19	14
Esk	6.7	6.7	33.9	33.9				
Leven	6.4	6.4	34.8	34.4	2.1	1	2	0
Water of Leith	6.8	6.6	33.4	25.7	1.6	1	1	0
West Peffer	7.2	7.2	33.9	33.9				

Background Temperature, Salinity and Suspended Sediment Levels

4.5.31 Background temperature, salinity and suspended sediment concentration maps have been generated based on all the available data. The three maps (Diagrams 67, 68 and 69) show the spatial variations in these three parameters within the model domain. It is however noted that, due to a lack of data throughout the water column, it was not possible at this stage to consider variations in the vertical direction, such that the same background temperature, salinity and concentration values are applied throughout the water depth.

Diagram 67: Background Temperature Map

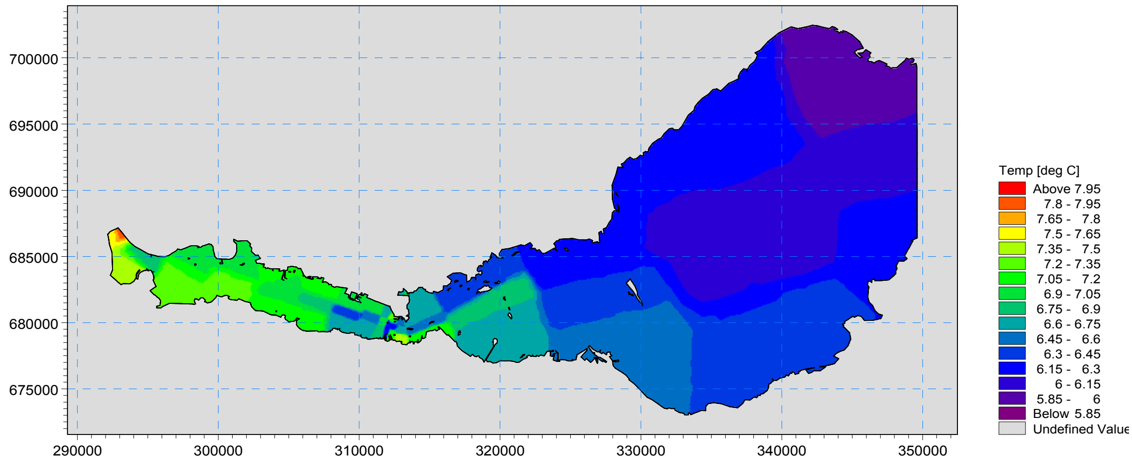


Diagram 68: Background Salinity Map

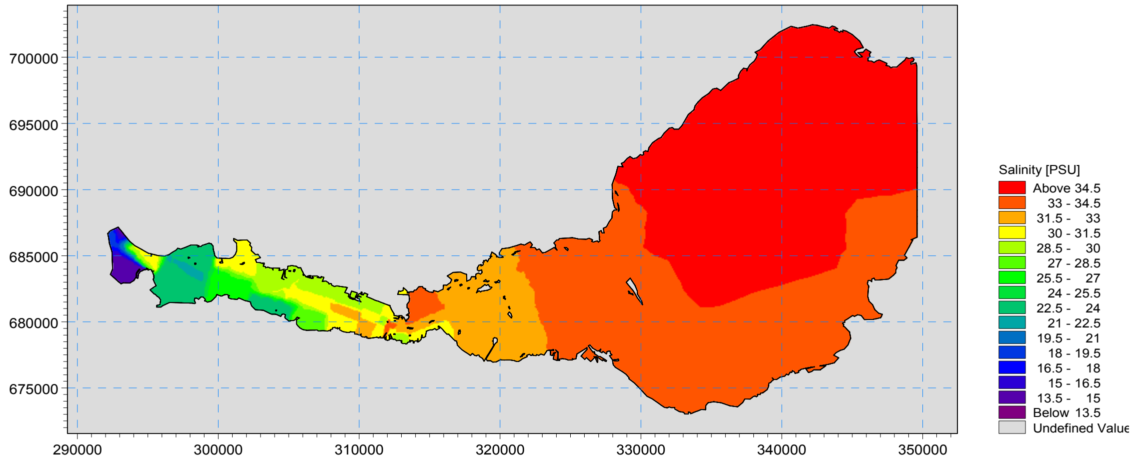
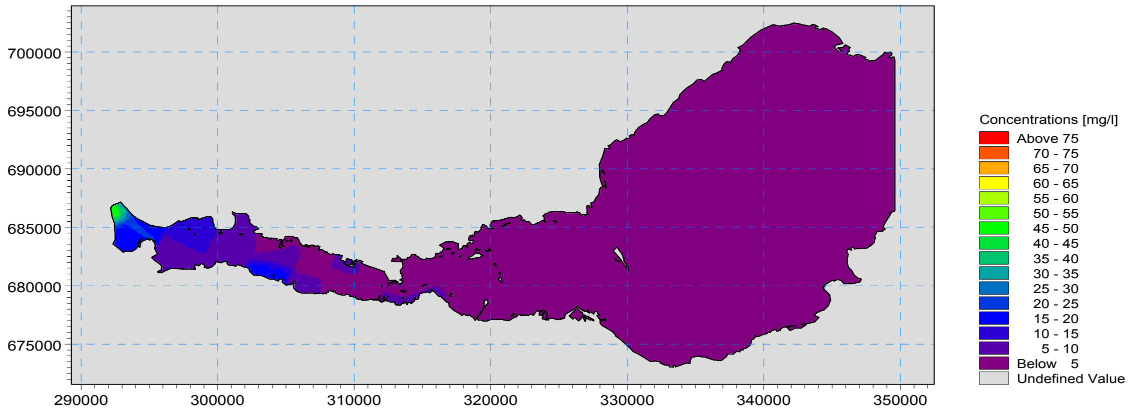


Diagram 69: Background Suspended Sediment Concentration Map



Suspended Sediment Plume Modelling Scenarios

4.5.32 Modelling was carried out for two 3-day periods in June 1999 to cover 3 cycles of the spring tide and neap tide conditions

- Spring Tide – 14 to 17 June 1999; and
- Neap Tide – 21 to 24 June 1999.

4.5.33 It was noted in the SEPA report (2000) that migratory fish including salmon, river lampreys and sea lampreys could be migrating during May, and Long Craig Island which is part of the Forth Islands SPA and SSSI, also provides habitat for nesting and roosting terns from May until July. Therefore potential effects on these species include habitat (intra-tidal water column) disturbance through the discharge of suspended sediments during construction needs to be considered. This is the main reason for modelling the tidal event and construction timing in June. The other reason for choosing the above time period in June for simulation is because good and reliable survey records of the tidal current and wind data are available. In addition, the hydrodynamic model was calibrated using the June 1999 spring tide data.

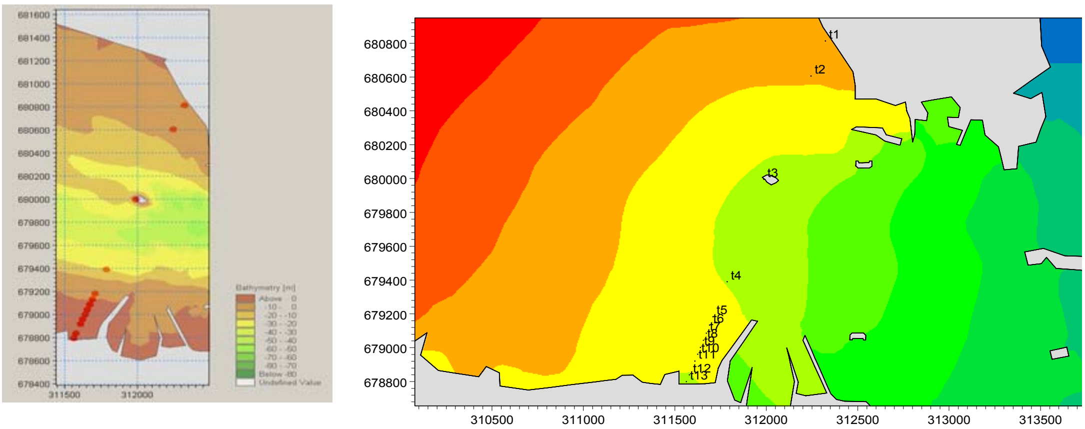
4.5.34 Thirteen construction activities have been identified (refer to paragraph 4.4.1). The simulation will be for each activity so that their individual impacts can be assessed without any interference from each other.

4.5.35 It is however noted that the South Flanking Tower ST and the North pier N1 are some distance apart; in order to save computation effort, the two activities are combined and simulated in one single run. Table 4.6 lists the simulation scenarios and their locations (centre point) are shown in Diagram 70.

Table 4.6: Simulation Scenarios for Suspended Sediment Plume Modelling

Scenario	Construction Activity
S1	Pier S1 dredging, both bottom release and surface overspill.
S1/S2	Access dredging between S1 and S2, bottom release and surface overspill.
S2	Pier S2 dredging, both bottom release and surface overspill.
S2/S3	Access dredging between S2 and S3, bottom release and surface overspill.
S3	Pier S3 dredging, both bottom release and surface overspill.
S3/S4	Access dredging between S3 and S4, bottom release and surface overspill.
S4	Pier S4 dredging, both bottom release and surface overspill.
S5	Bund foundations dredging at S5, both bottom release and surface overspill.
S5/S6	Bund foundations dredging between S5/S6, only bottom release (shallow).
ST & N1	Piling at ST, bottom release only. Pier N1 dredging, both bottom release and surface overspill.
CT	Central Tower CT excavation, both bottom release and surface overspill.
NT	North Flanking Tower NT dredging, both bottom release and surface overspill.

Diagram 70: Locations for the Modelled Scenario Centre Points



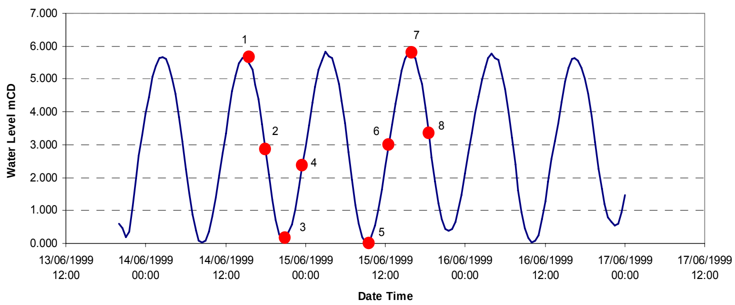
t1 = N1, t2 = NT, t3 = CT, T4 = ST, t5 = S1, t6=S1/S2, t7 = S2, t8 = S2/S3, t9 = S3, t10 = S3/S4, t11 = S4, T12 = S5, t13 = S5/S6.

<u>Spring Tide Results</u>

4.5.36 Modelling results are output in half hour intervals. Obviously there are too many results and plots to include in the report and careful selection is thus necessary. It is therefore proposed that Spring tide simulation results are shown for eight representative tidal states as follows:

Diagram 71: Representative Spring Tidal States for Modelling Results

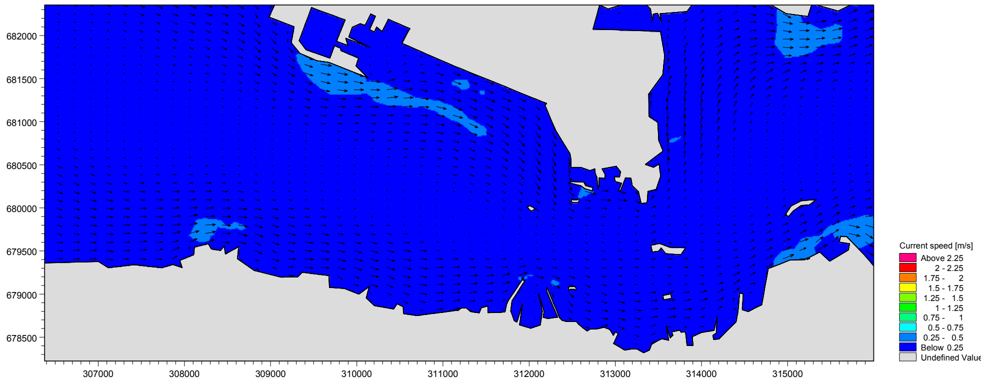
1. High tide, slack water
2. Ebb tide, fast water
3. Low tide, slack water
4. Flood tide, fast water
5. Low tide, slack water
6. Flood tide, fast water
7. High tide, slack water
8. Ebb tide, fast water



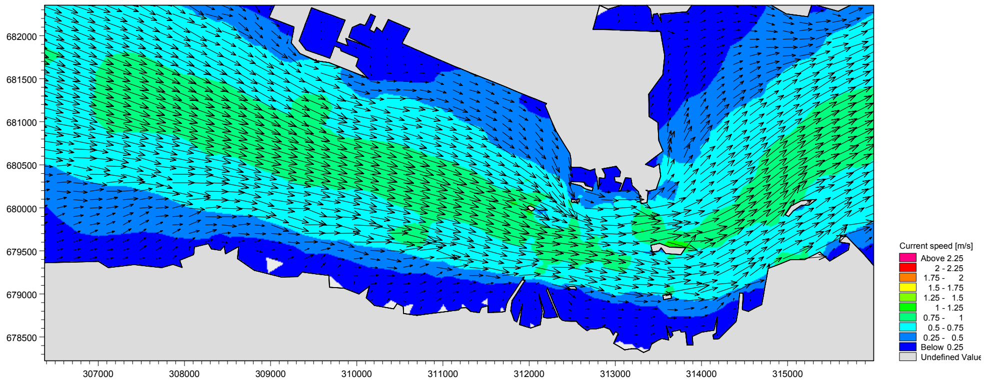
4.5.37 Tidal currents and their flow patterns for these 8 states near to the Main Crossing are shown in Diagram 72.

Diagram 72: Spring Tide Currents and Flow Patterns

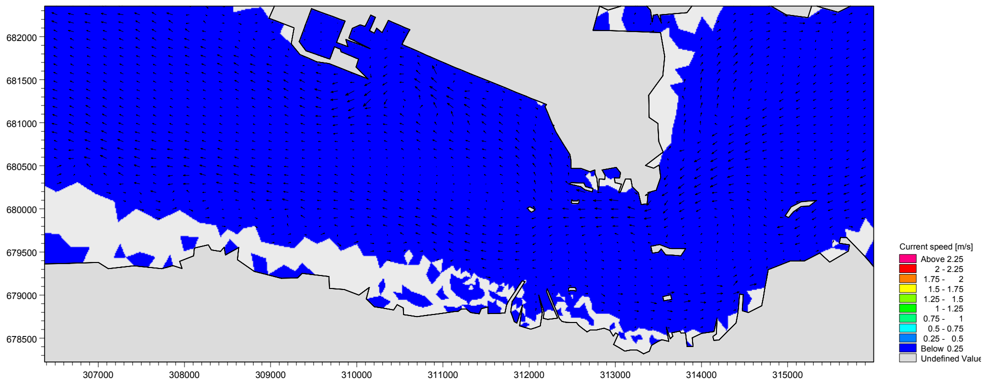
1. High tide, slack water



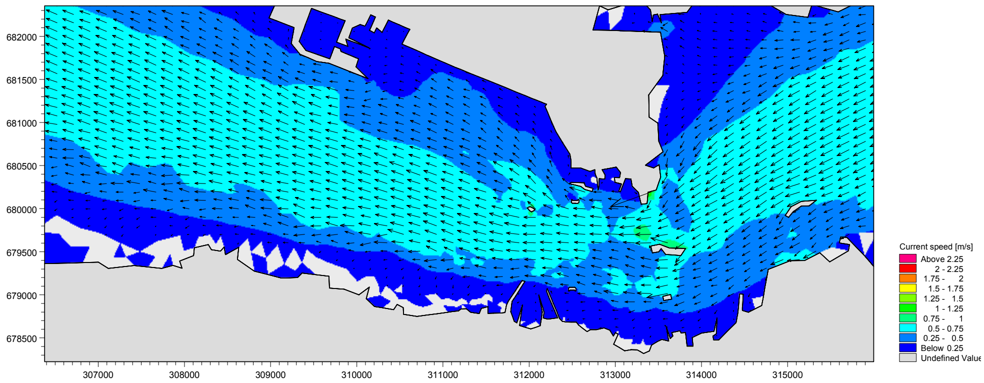
2. Ebb tide, fast water



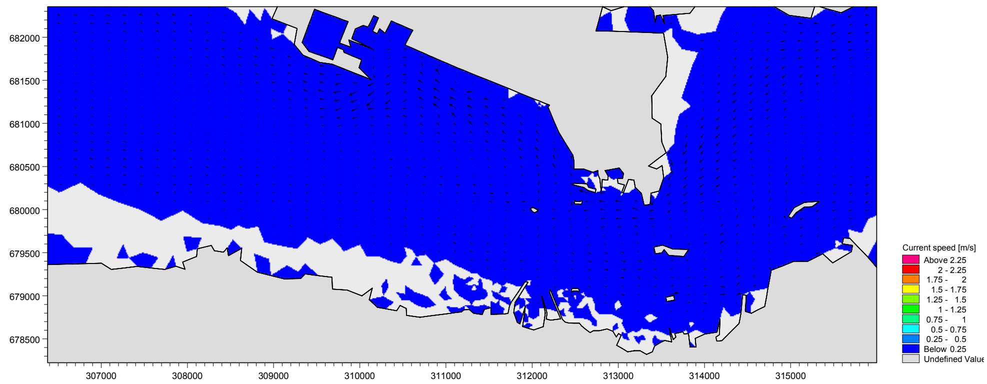
3. Low tide, slack water



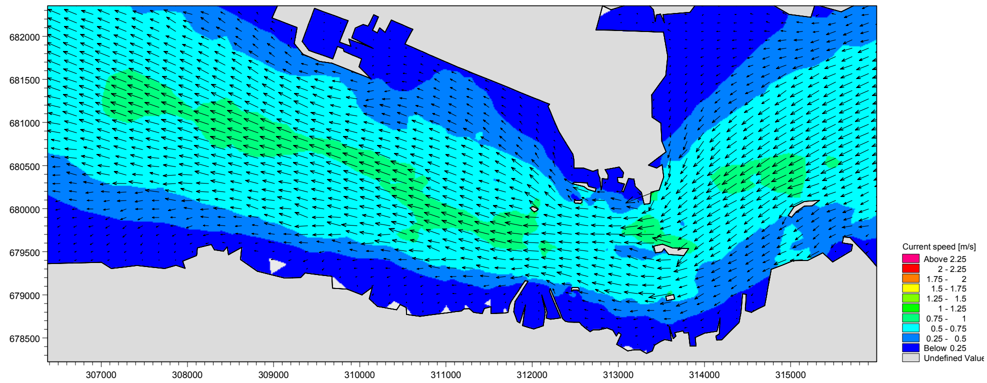
4. Flood tide, fast water



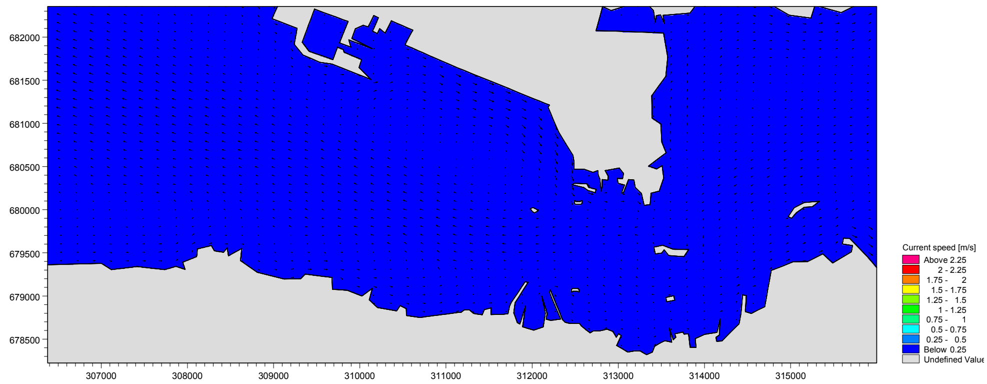
5. Low tide, slack water



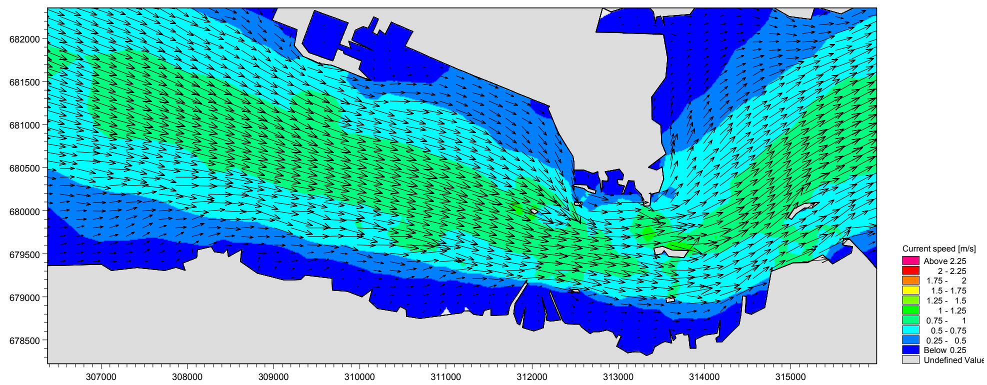
6. Flood tide, fast water



7. High tide, slack water



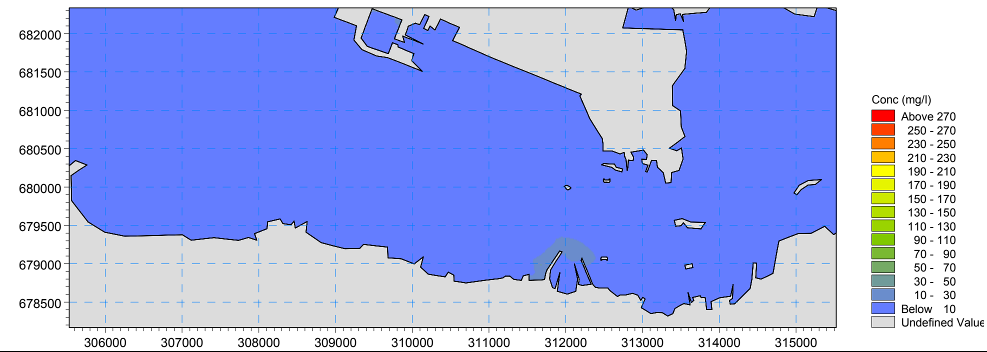
8. Ebb tide, fast water



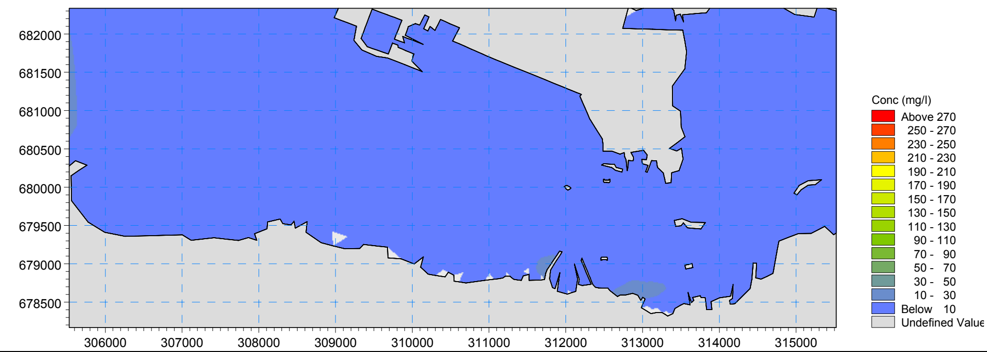
4.5.38 Colour contour plots of the suspended sediment concentration levels at water surface caused by the construction activities were prepared. Three locations are shown in Diagrams 73 and 74: Scenario S3 for its middle location on the south between Piers S1, S2 and Piers S4 and S5; Scenario ST for its central location on the Forth channel; and Scenario N1 for its close proximity to the shore on the north.

Diagram 73: Suspended Sediment Concentration Levels at Water Surface for Scenario S3 at Spring Tide (Pier S3 Dredging, both Bottom Release and Surface Overspill)

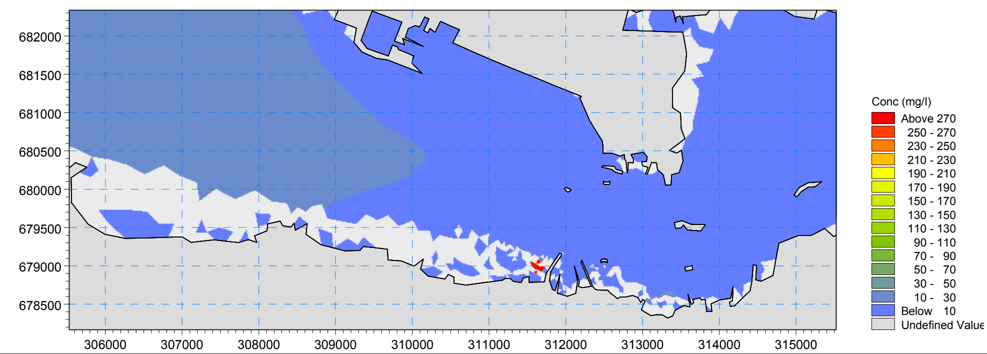
1. High tide, slack water



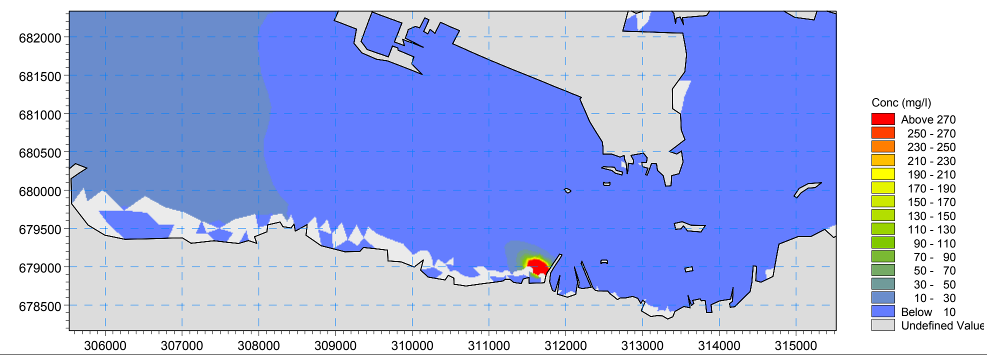
2. Ebb tide, fast water



3. Low tide, slack water



4. Flood tide, fast water



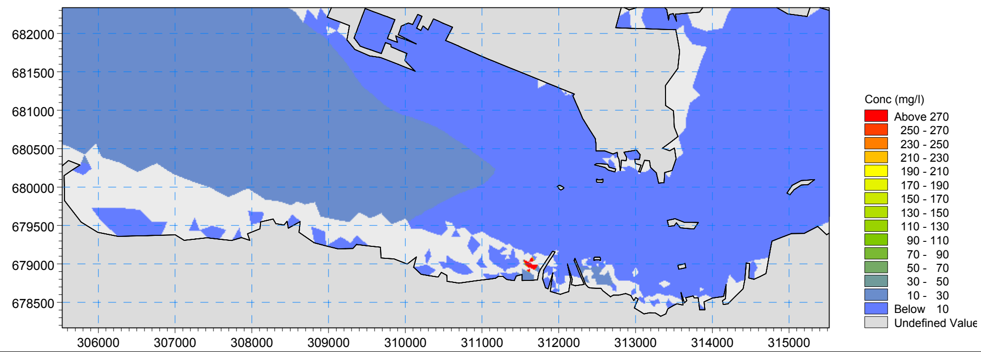
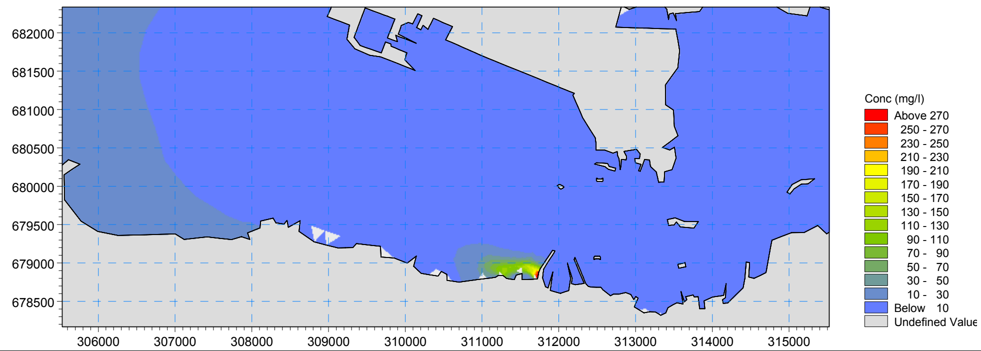
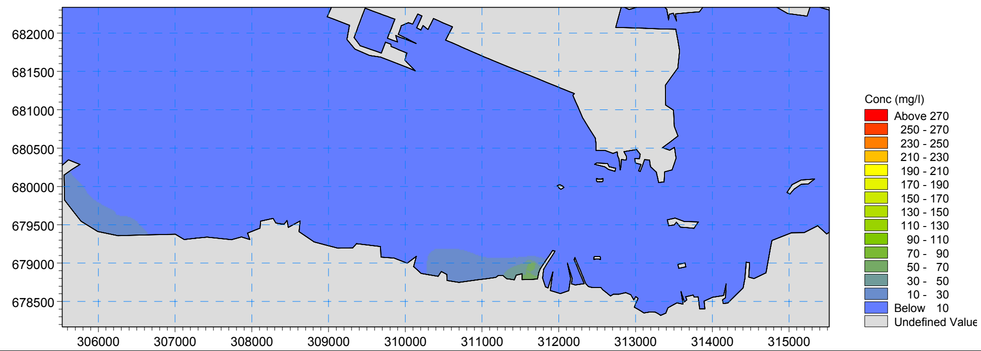
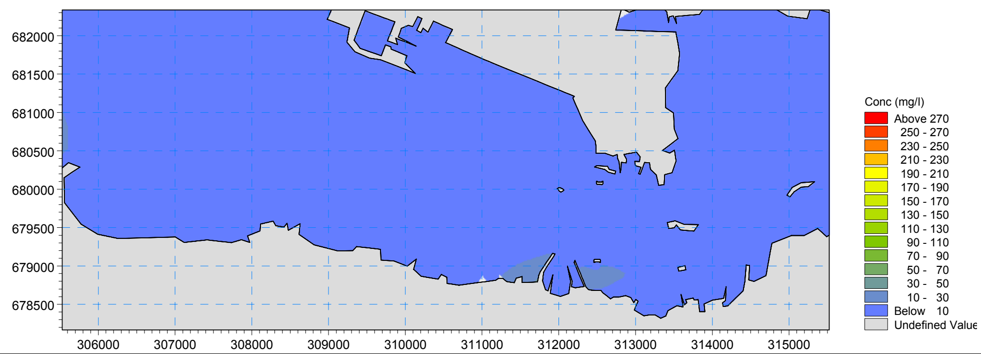
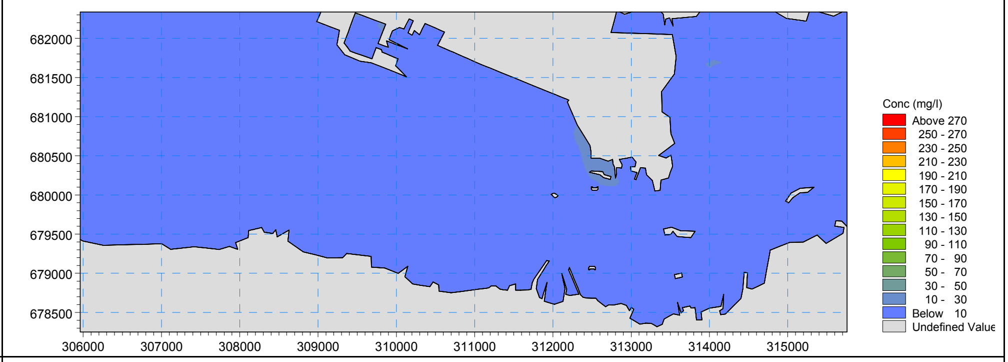
5. Low tide, slack water	
6. Flood tide, fast water	
7. High tide, slack water	
8. Ebb tide, fast water	

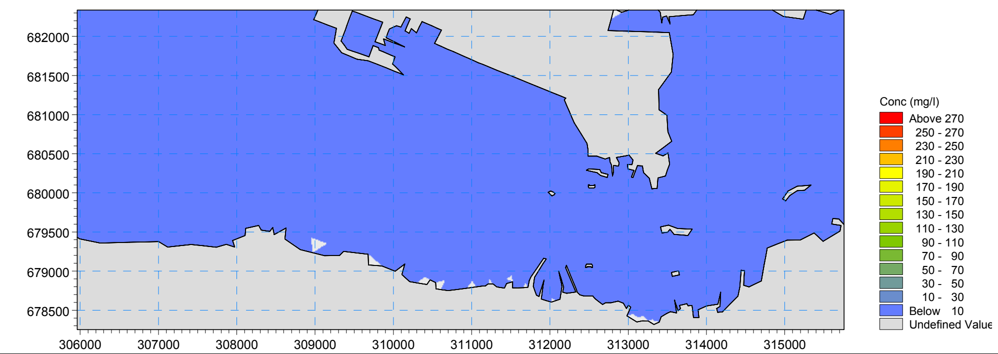
Diagram 74: Suspended Sediment Concentration Levels at Water Surface for Scenarios ST & N1 at Spring Tide (Piling at ST, Bottom Release Only; Pier N1 Dredging, both Bottom Release and Surface Overspill)

N.B. This scenario combines with releases from ST and N1, therefore the results showed elevated levels of suspended sediment on both the northern shore and in mid channel of the Forth)

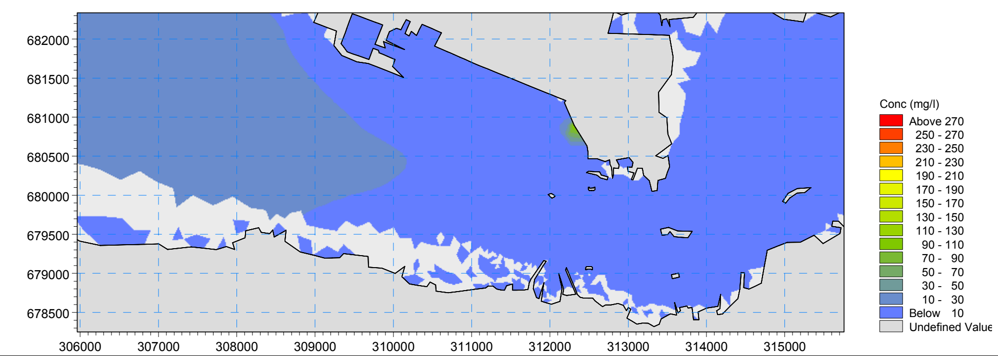
1. High tide, slack water



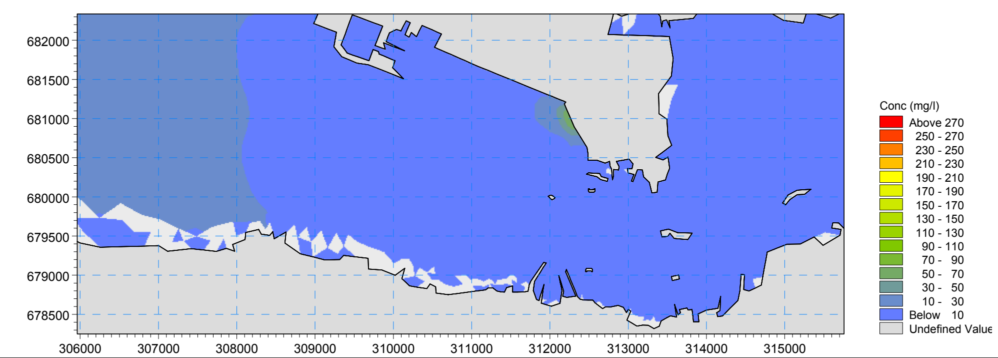
2. Ebb tide, fast water

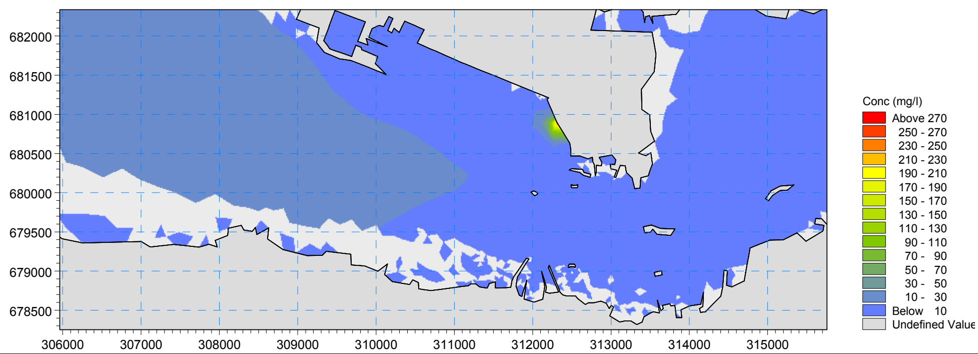
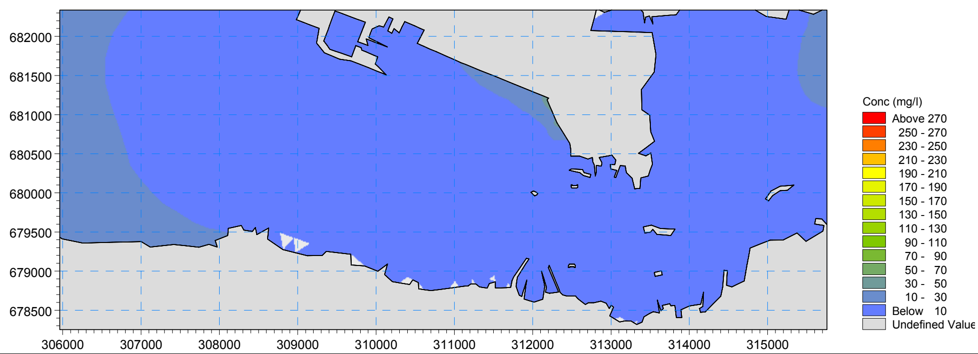
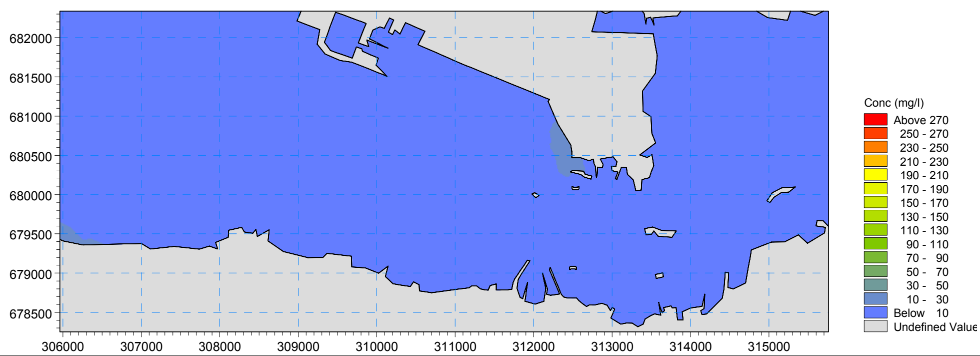
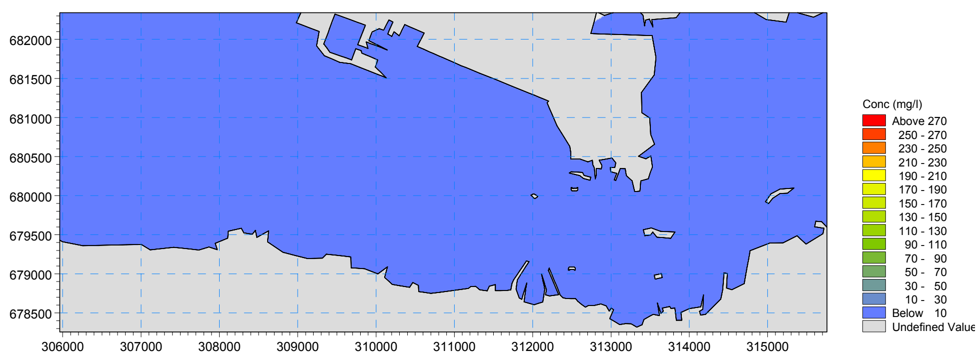


3. Low tide, slack water



4. Flood tide, fast water



5. Low tide, slack water	
6. Flood tide, fast water	
7. High tide, slack water	
8. Ebb tide, fast water	

4.5.39 In addition, nine monitoring points are also chosen to record the time series concentration levels in these locations. The nine monitoring points are arranged in a star pattern, with two bursts at 50m and 150m respectively from the centre of each of the construction activity:

- t1 = centre of the concentration activity
- t2 to t4 = 50m from the construction activity, in NE, SE, SW and NW directions
- t5 to t9 = 150m from the construction activity, in E, S, W and N directions

4.5.40 These nine points are shown in the result plots associated with each modelling scenario to indicate their respective locations. Diagrams 75 to 77 show a typical arrangement of the monitoring points for Scenarios S3, ST and N1.

Diagram 75: Star Pattern Arrangements for Monitoring Points in Scenario S3

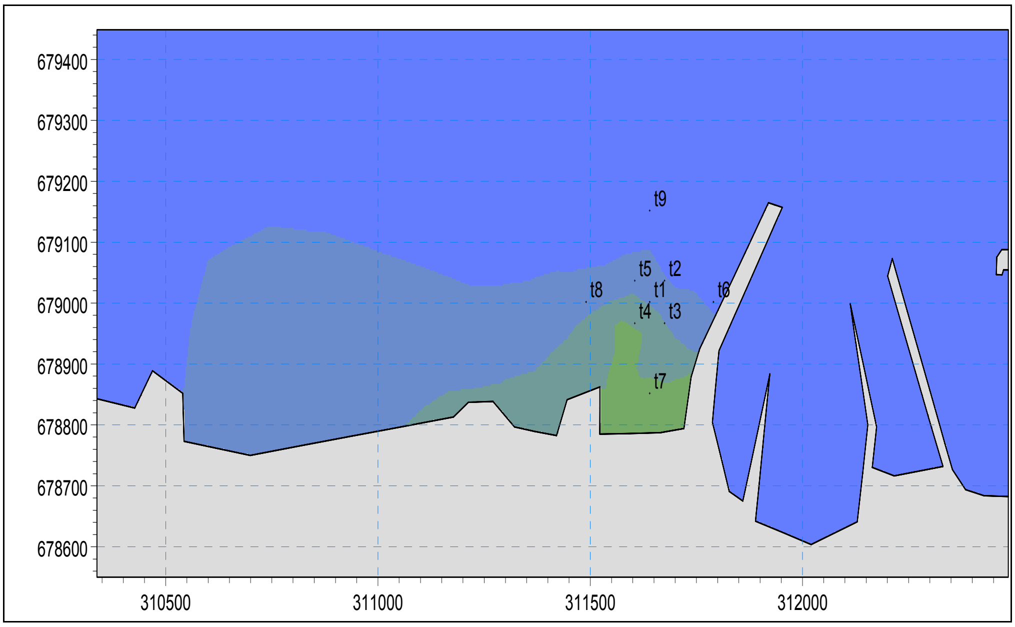


Diagram 76: Star Pattern Arrangements for Monitoring Points in Scenario ST

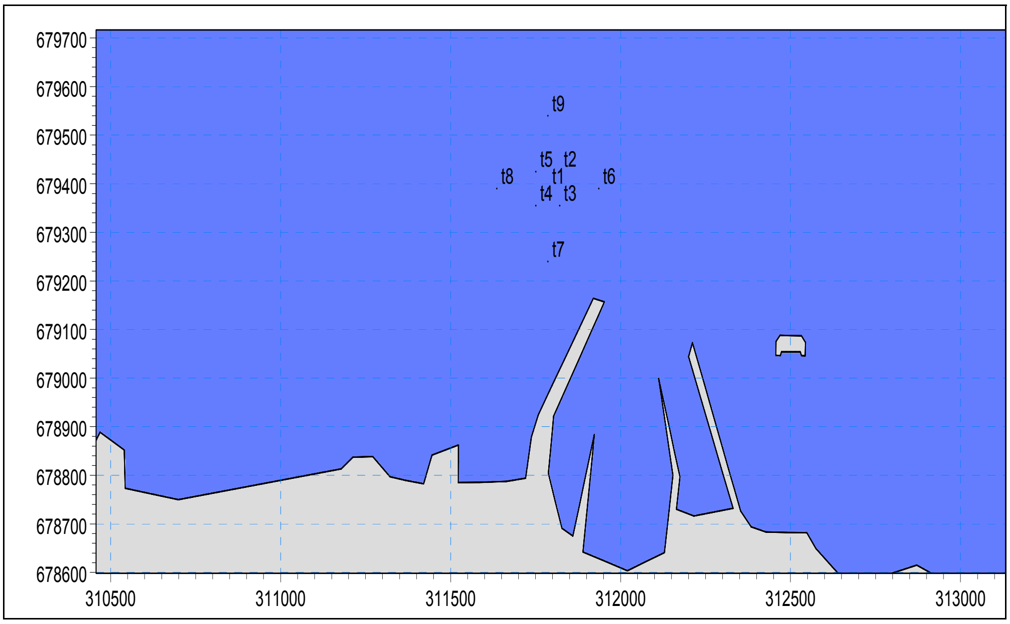
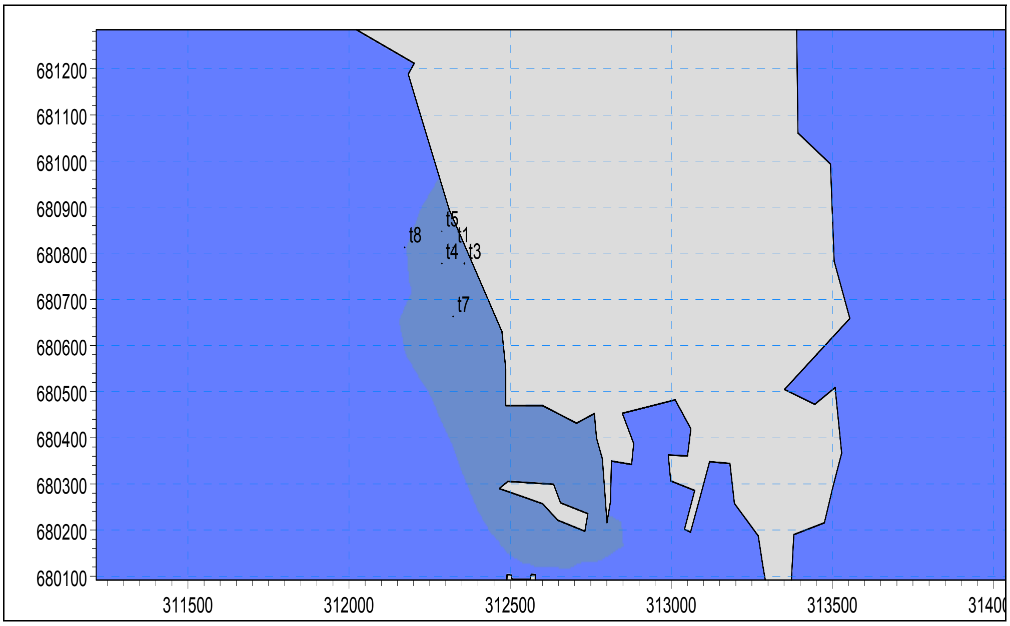


Diagram 77: Star Pattern Arrangements for Monitoring Points in Scenario N1



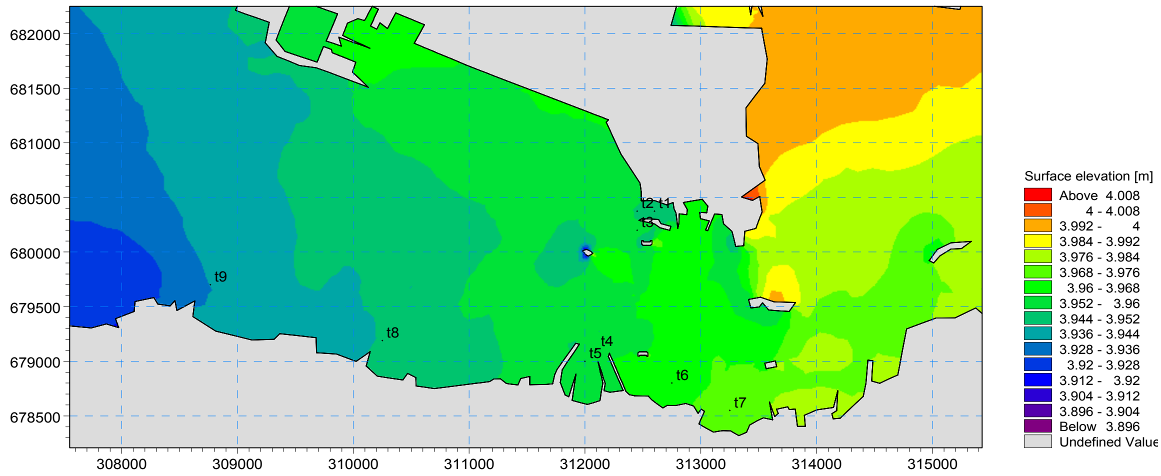
4.5.41 A further nine monitoring points (Diagram 78) are taken to assess the changes in concentrations levels at the following sensitive locations.

Table 4.7: Locations of Additional Points to Monitor Changes to Concentration Levels

Point*	Location	Easting	Northing
t1	Long Craig 1 (North)	312600	680375
t2	Long Craig 2 (Northwest)	312450	680375
t3	Long Craig 3 (Southwest)	312450	680200
t4	Port Edgar Entrance	312100	679110
t5	Port Edgar Marina	312000	679000
t6	South Queensferry 1, The Binks	312750	678800
t7	South Queensferry 2, The Craigs	313250	678550
t8	Society Point	310250	679190
t9	Abercorn Point	308765	679700

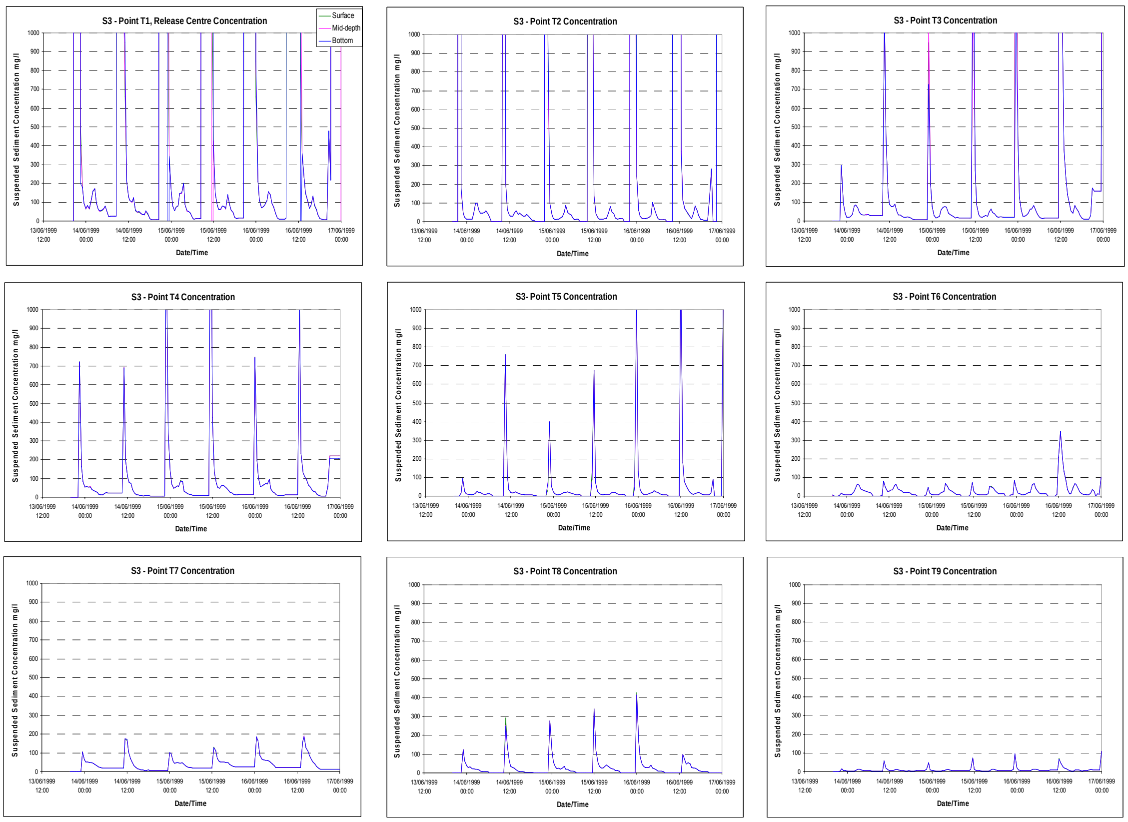
Note: MIKE3 software does not allow user specified point names, so the names t1 to t9 are the same as the 9 points star pattern around each construction activity.

Diagram 78: 9 Additional Monitoring Points for Assessing Changes to Concentration Levels



4.5.42 The suspended sediment concentrations at the respective monitoring points under Scenarios S3, ST and N1 are shown in Diagrams 79, 80 and 81.

Diagram 79: Suspended Sediment Concentrations under Scenario S3 at Spring Tide (Pier S3 Dredging, both Bottom Release and Surface Overspill)



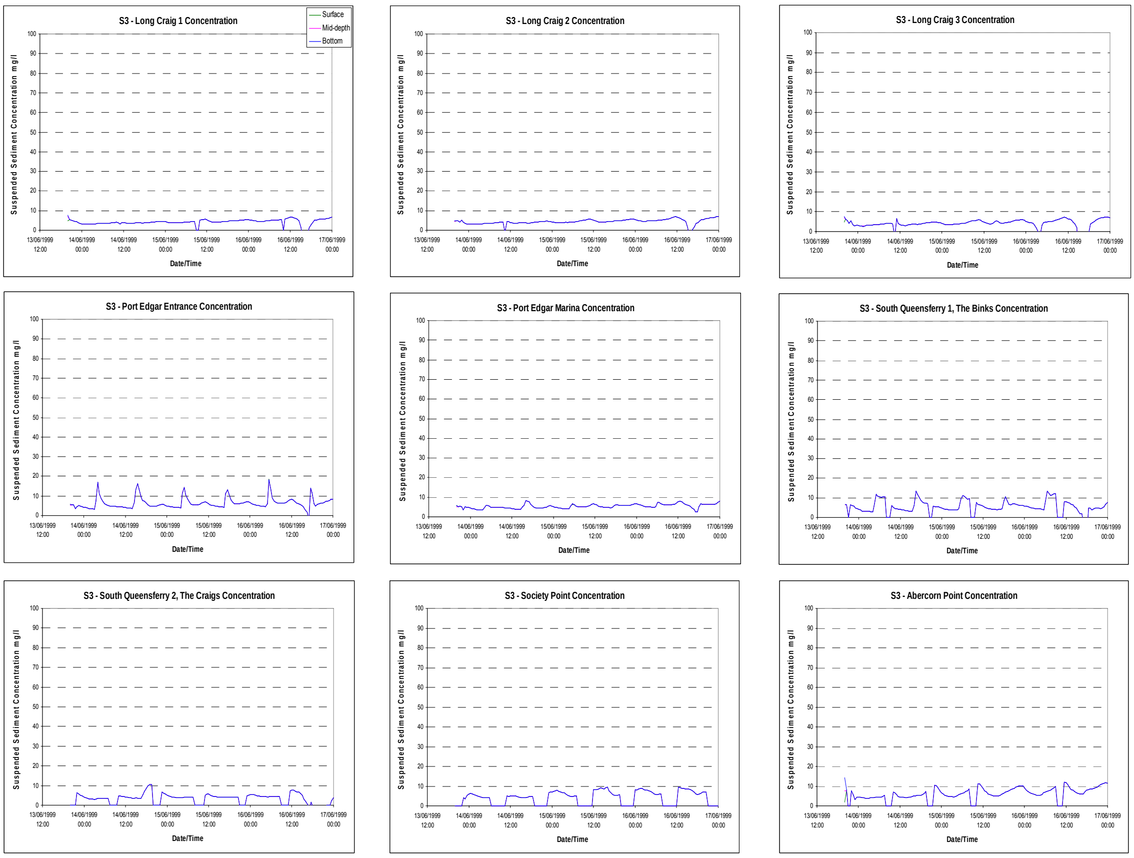


Diagram 80: Suspended Sediment Concentrations under Scenario ST at Spring Tide (Piling at ST, Bottom Release Only)

N.B. This scenario combines with releases from ST and N1, therefore the results showed elevated levels of suspended sediment on both the northern shore and in mid channel of the Forth

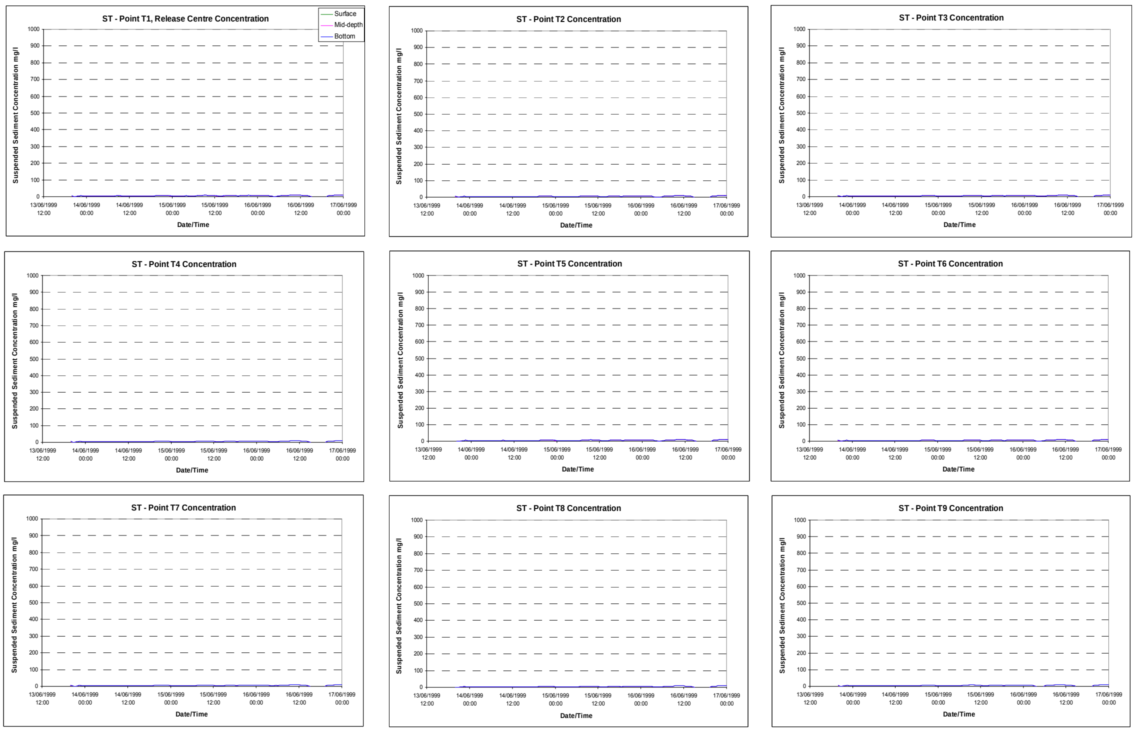
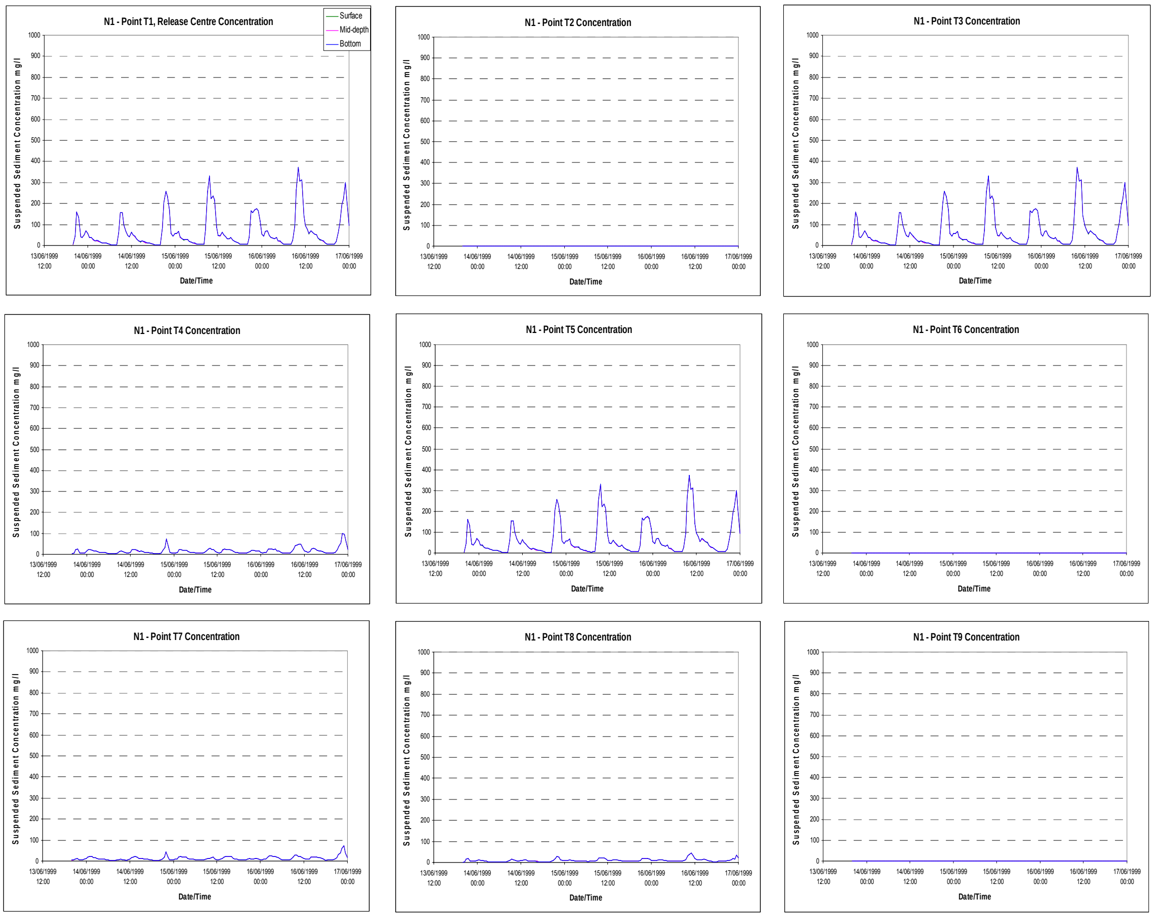


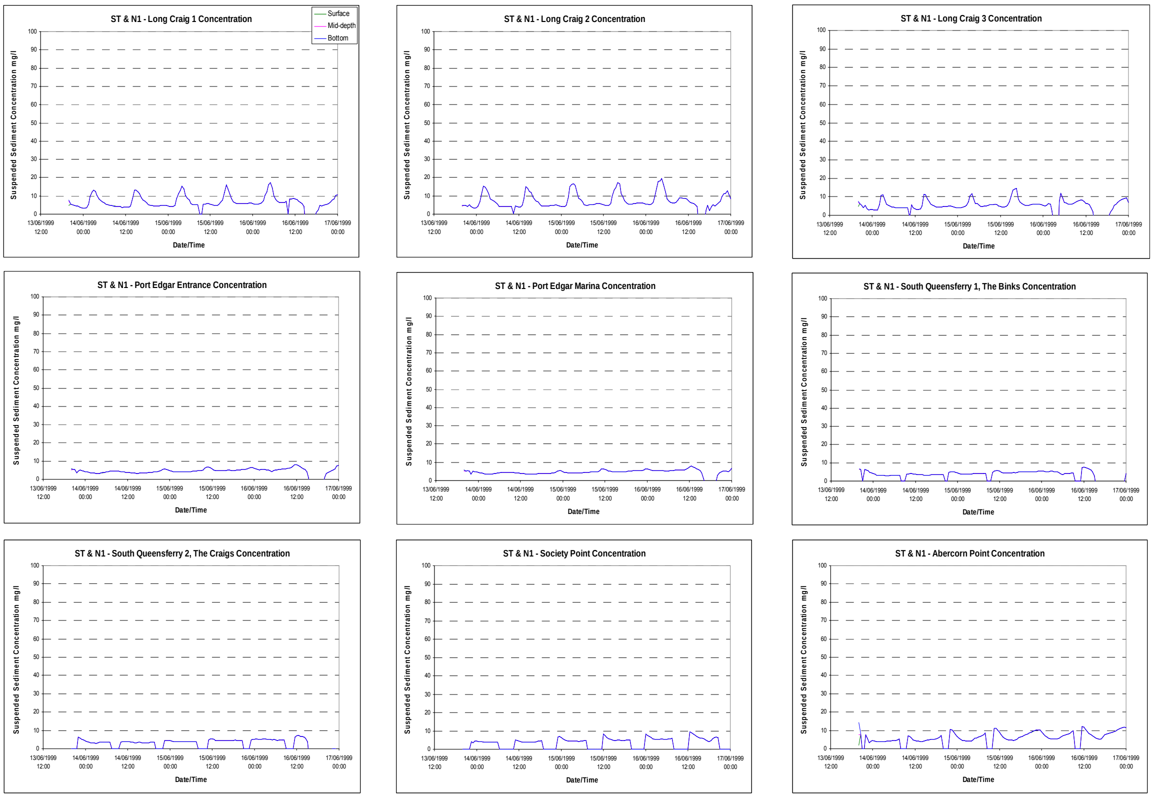
Diagram 81: Suspended Sediment Concentrations under Scenario N1 at Spring Tide (Pier N1 Dredging, both Bottom Release and Surface Overspill)

N.B. This scenario combines with releases from ST and N1, therefore the results showed elevated levels of suspended sediment on both the northern shore and in mid channel of the Forth



4.5.43 Construction activities at both the South Flanking Tower ST and the North Pier N1 together contributed to the suspended sediment concentrations at the following locations shown in Diagram 82. However, due to their proximities, it is considered that the impacts on Long Craig are primarily from Pier N1 and the other locations close the south shore are due to South Flanking Tower ST.

Diagram 82: Suspended Sediment Concentrations under Scenario ST and N1 at Spring Tide



4.5.44 The 3D modelling is capable of computing the concentration levels at different water depths. It was however shown by the results that the difference in concentrations at the top (surface) layer and the bottom (seabed) layer is relatively minor. Only in a few scenarios and for a very short time did some of the results show a difference of more than 15mg/l. The reason for the imperceptible difference is probably due to the relatively shallow water depth existing in many of the pier locations and/or good mixing/dispersion in the vertical direction. The other reason could be that both bottom release and surface overspill from both ends of the water column allow a fast equalisation of the suspended sediment concentrations throughout the water depth.

4.5.45 In order to focus on the impacts from the construction activities close to the Main Crossing, the plots only show an area from about 5.5km upstream of the Main Crossing to about 4.0km downstream of it.

4.5.46 In the plots, the concentration levels are colour coded within 20mg/l bands. Grey colour represents land and white colour is dry up area in the sea.

4.5.47 For all the activities in the south, the results showed that concentrations were generally high at the centres of the sediment release points but declined rapidly at a distance of 150m, to about 150mg/l or less, causing relatively very little impacts to the surrounding water. The highest concentration was during low tide and slack water.

4.5.48 In Scenarios S1 to S6, the plume tended to travel most during flood tides, pushing westward towards Society Pont and Abercorn Point although the increase in concentration is minor, at less than 13mg/l. In ebb tides, the plumes passed Port Edgar and deposited at South Queensferry, but again the increase in concentration is quite low, about 10mg/l.

4.5.49 In the middle of the Firth of Forth, activities ST and CT caused virtually no change to the suspended sediment concentrations in the water because the amount of sediment released is so low and the water depth, as well as the current speed, is the largest.

4.5.50 On the north side of the Firth of Forth, activity NT has a very low and localised impact, with a concentration of less than 100mg/l even at the centre of release. The plume was quickly diluted before it could reach St. Margaret's Hope marsh.

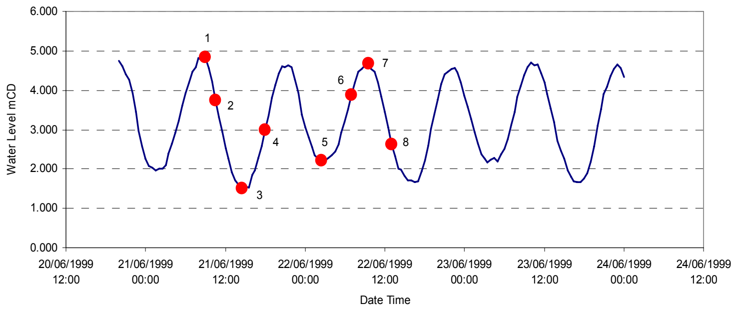
4.5.51 The north pier N1 is very close to the shoreline. The plume seemed to hug along St. Margaret's Hope marsh on the northwest of the activity centre during flood tides and spread towards Long Craig at its southeast at high tides and/or ebb tides. The concentration is up to 300mg/l at a distance of 150m but a mere 20mg/l maximum at Long Craig.

Neap Tide Results

4.5.52 The Neap tide simulation results are also shown for eight representative tidal states.

Diagram 83: Representative Neap Tidal States for Modelling Results

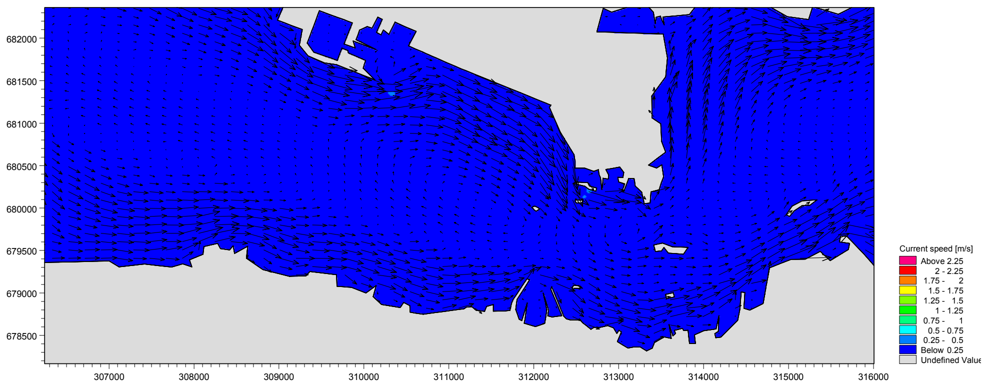
1. High tide, slack water
2. Ebb tide, fast water
3. Low tide, slack water
4. Flood tide, fast water
5. Low tide, slack water
6. Flood tide, fast water
7. High tide, slack water
8. Ebb tide, fast water



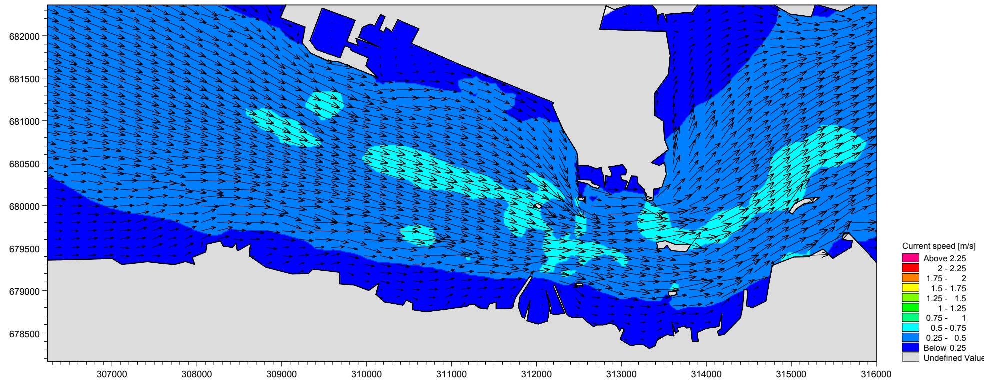
4.5.53 Tidal currents and their flow patterns for these eight states near to the Main Crossing are shown in Diagram 84.

Diagram 84: Neap Tide Currents and Flow Patterns

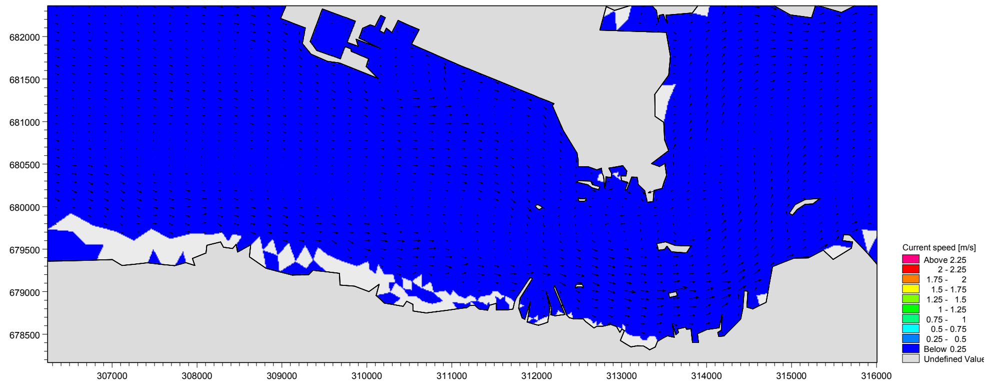
1. High tide, slack water



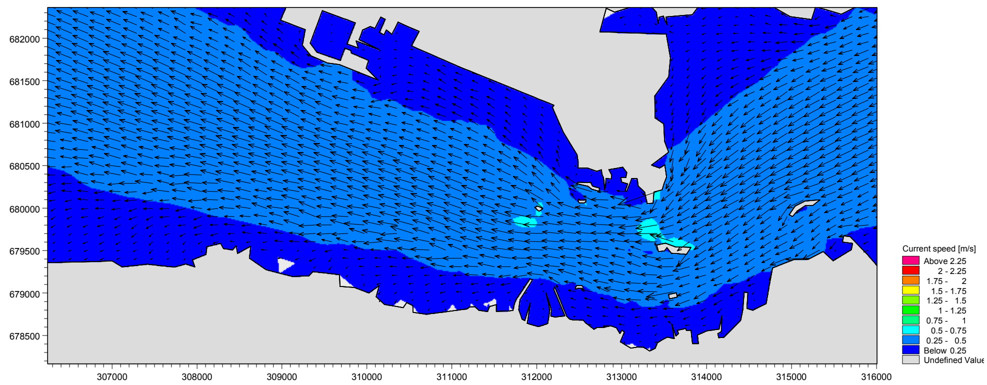
2. Ebb tide, fast water



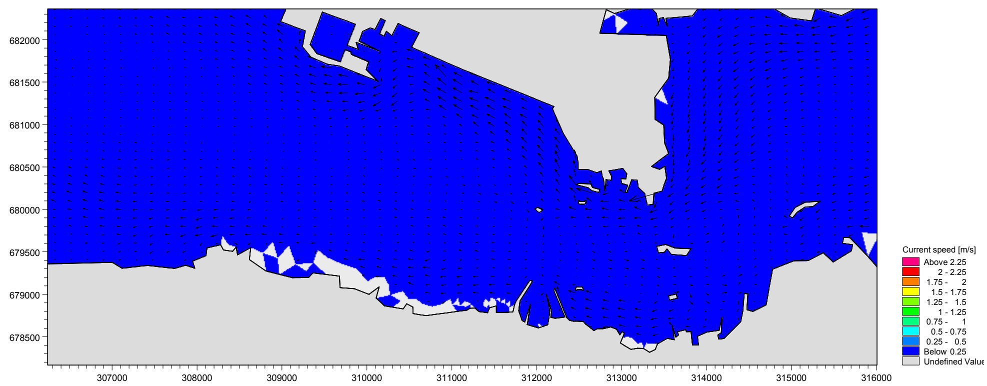
3. Low tide, slack water



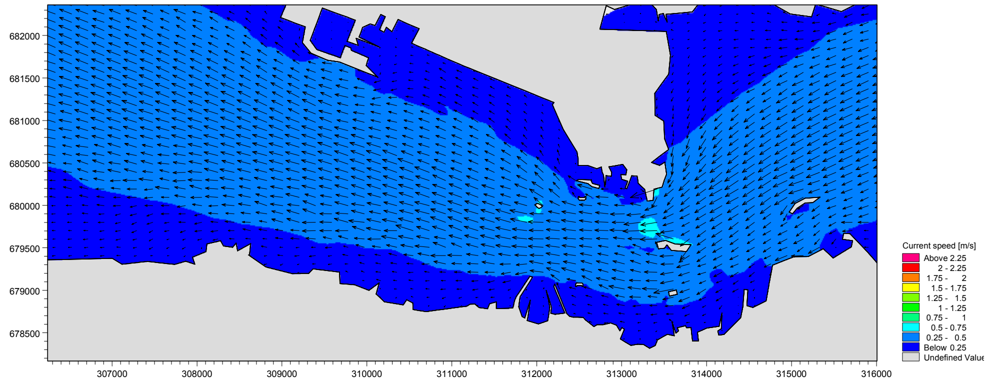
4. Flood tide, fast water



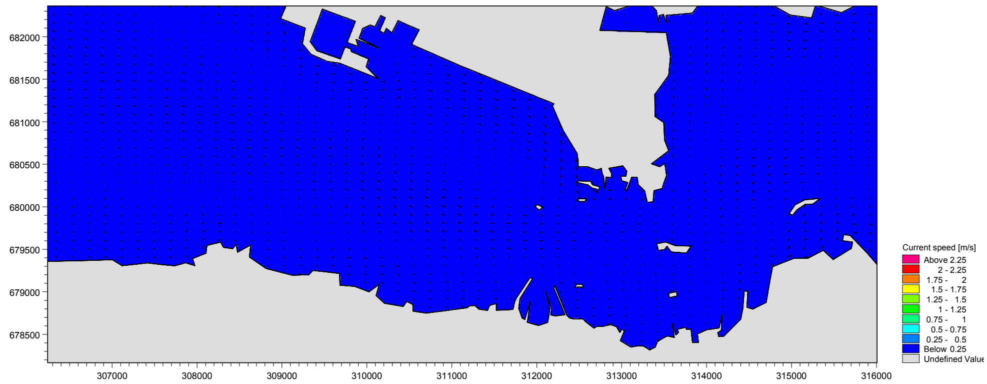
5. Low tide, slack water



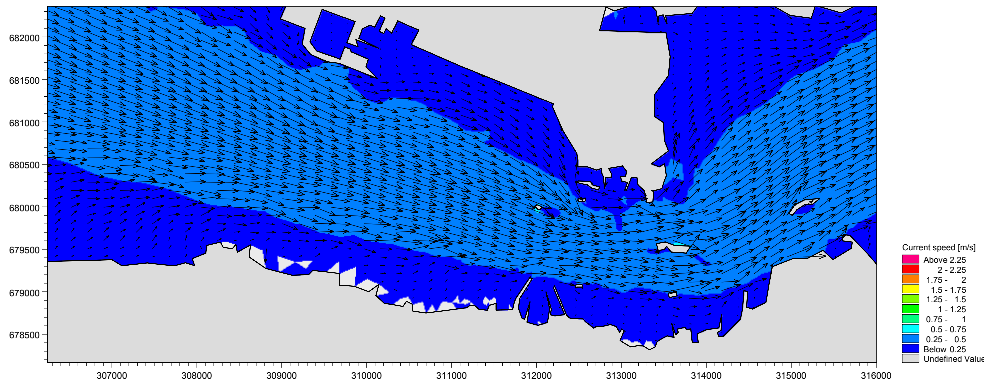
6. Flood tide, fast water



7. High tide, slack water



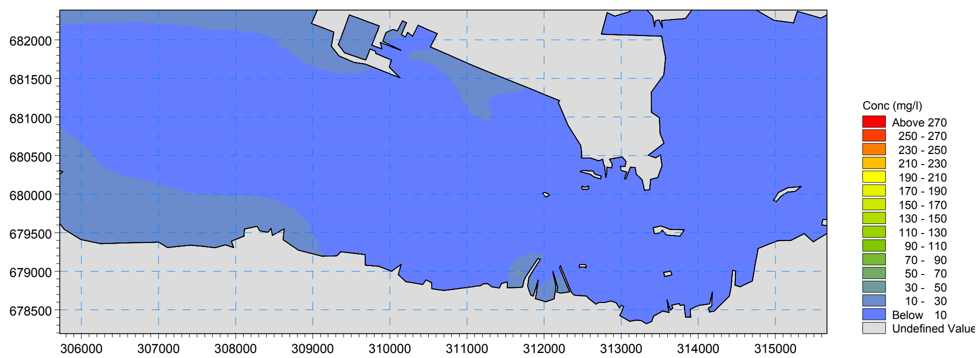
8. Ebb tide, fast water



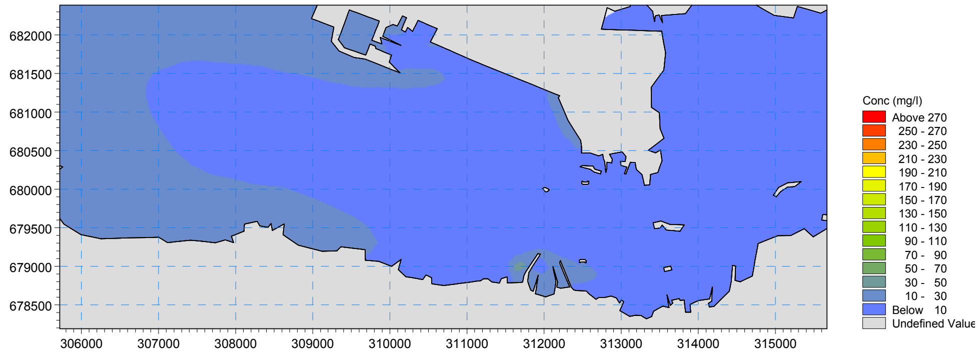
4.5.54 Colour contour plots of the suspended sediment concentration levels at water surface caused by the construction activities are shown in Diagrams 85 and 86.

Diagram 85: Suspended Sediment Concentration Levels at Water Surface for Scenario S3 at Neap Tide (Pier S3 Dredging, both Bottom Release and Surface Overspill)

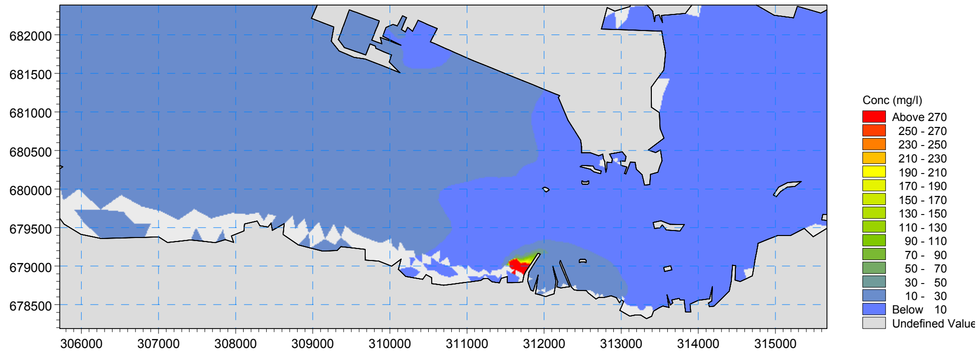
1. High tide, slack water



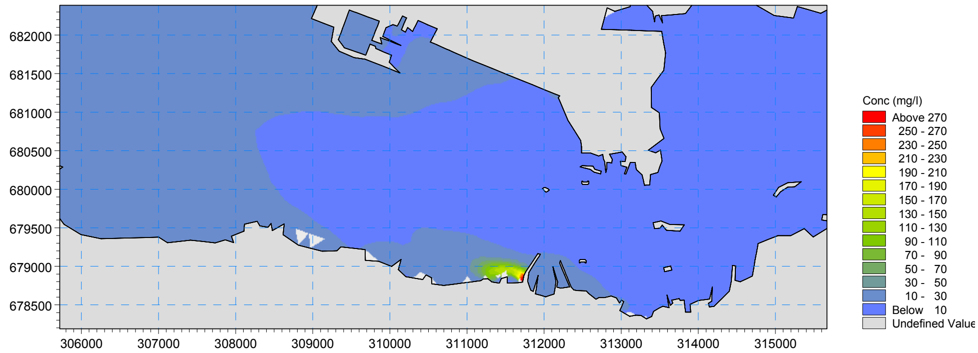
2. Ebb tide, fast water



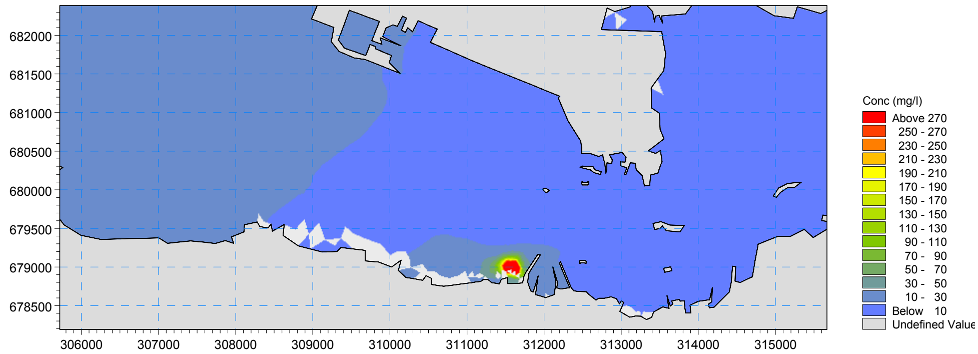
3. Low tide, slack water



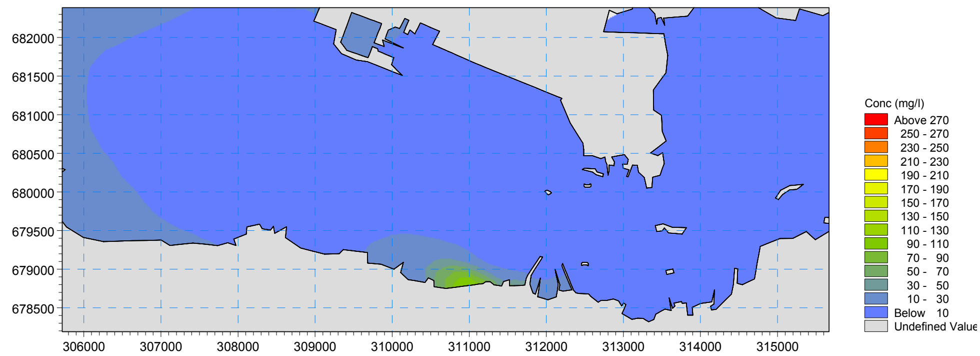
4. Flood tide, fast water



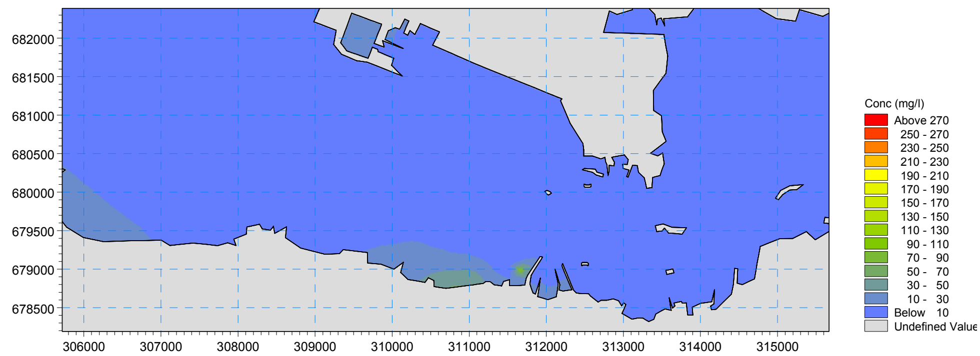
5. Low tide, slack water



6. Flood tide, fast water



7. High tide, slack water



8. Ebb tide, fast water

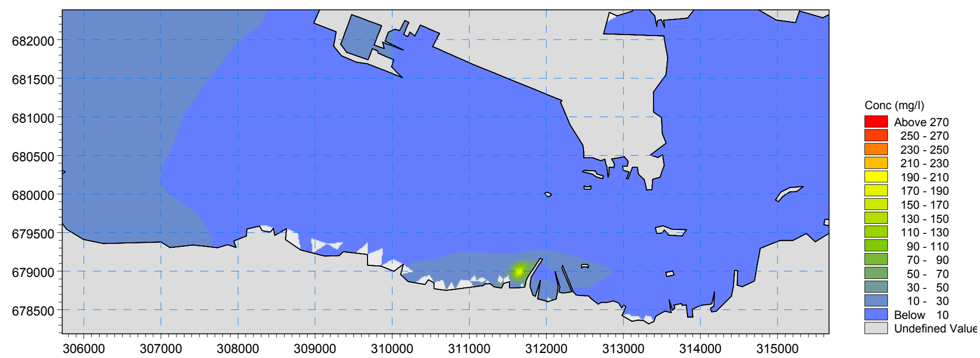
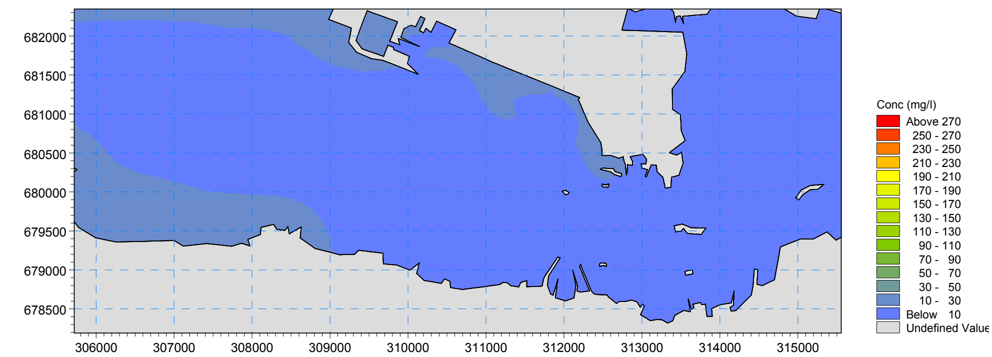


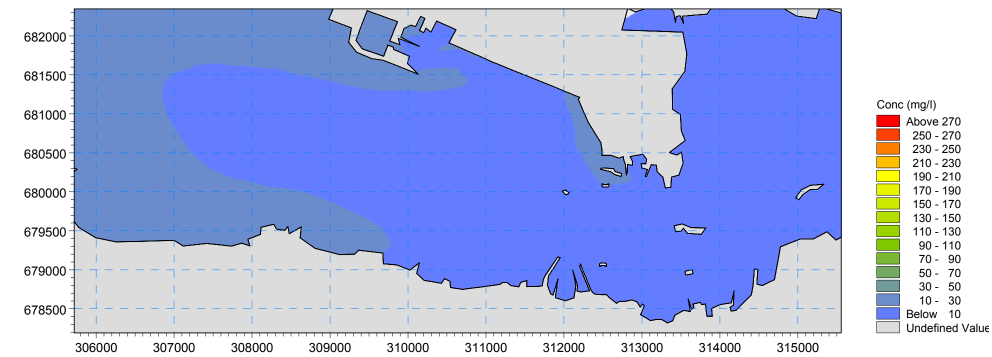
Diagram 86: Suspended Sediment Concentration Levels at Water Surface for Scenarios ST & N1 at Neap Tide (Piling at ST, Bottom Release Only; Pier N1 Dredging, both Bottom Release and Surface Overspill)

N.B. This scenario combines with releases from ST and N1, therefore the results showed elevated levels of suspended sediment on both the northern shore and in mid channel of the Forth).

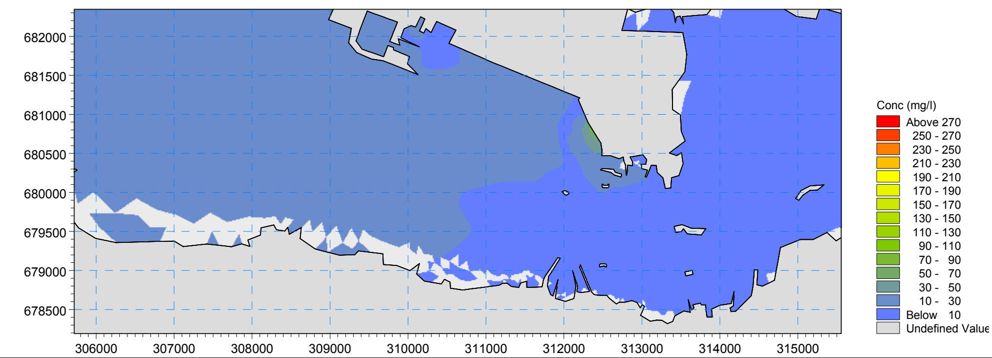
1. High tide, slack water



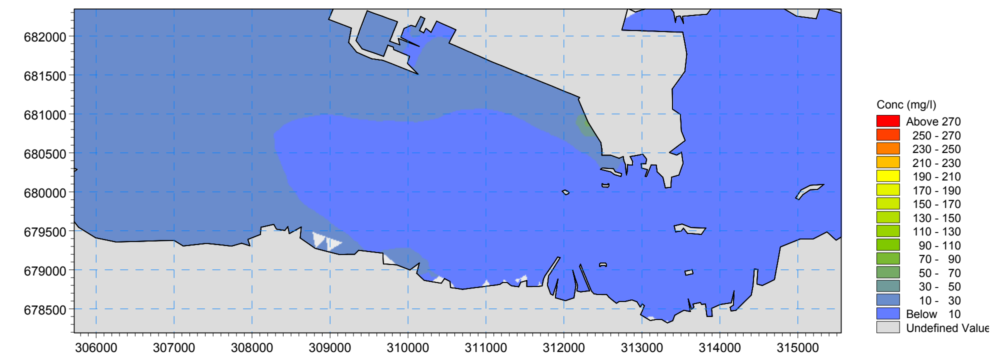
2. Ebb tide, fast water

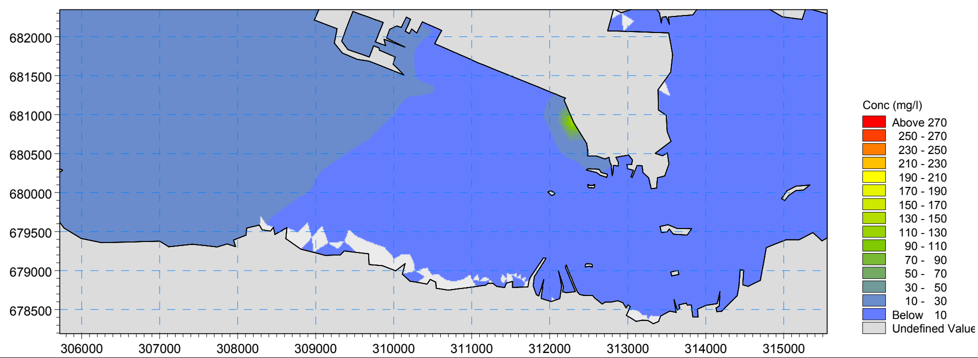
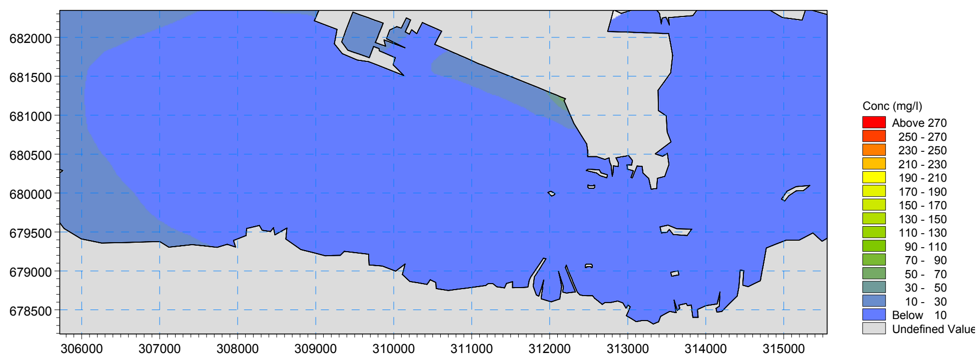
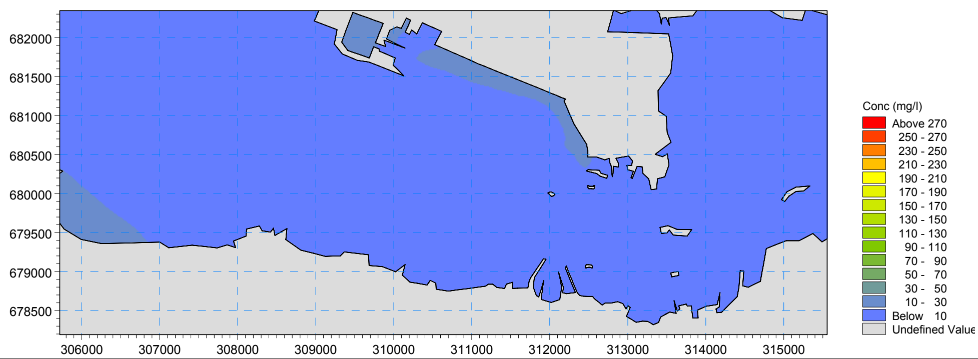
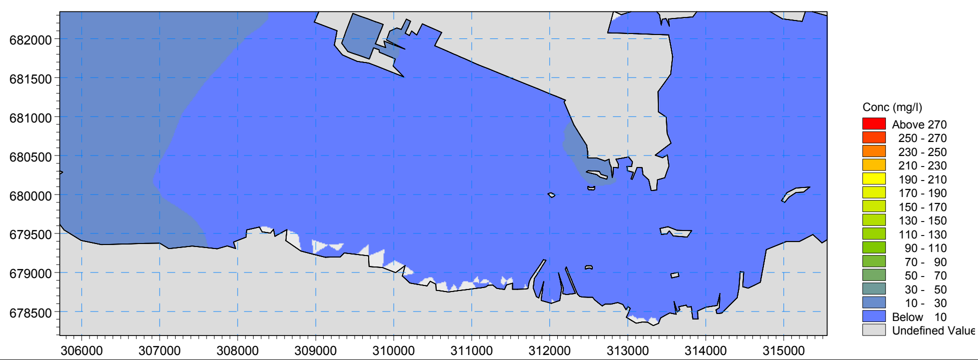


3. Low tide, slack water



4. Flood tide, fast water



5. Low tide, slack water	
6. Flood tide, fast water	
7. High tide, slack water	
8. Ebb tide, fast water	

4.5.55 The suspended sediment concentrations at the respective monitoring points under Scenarios S3, ST and N1 are shown in Diagrams 87 to 89.

Diagram 87: Suspended Sediment Concentrations under Scenario S3 at Neap Tide (Pier S3 Dredging, both Bottom Release and Surface Overspill)

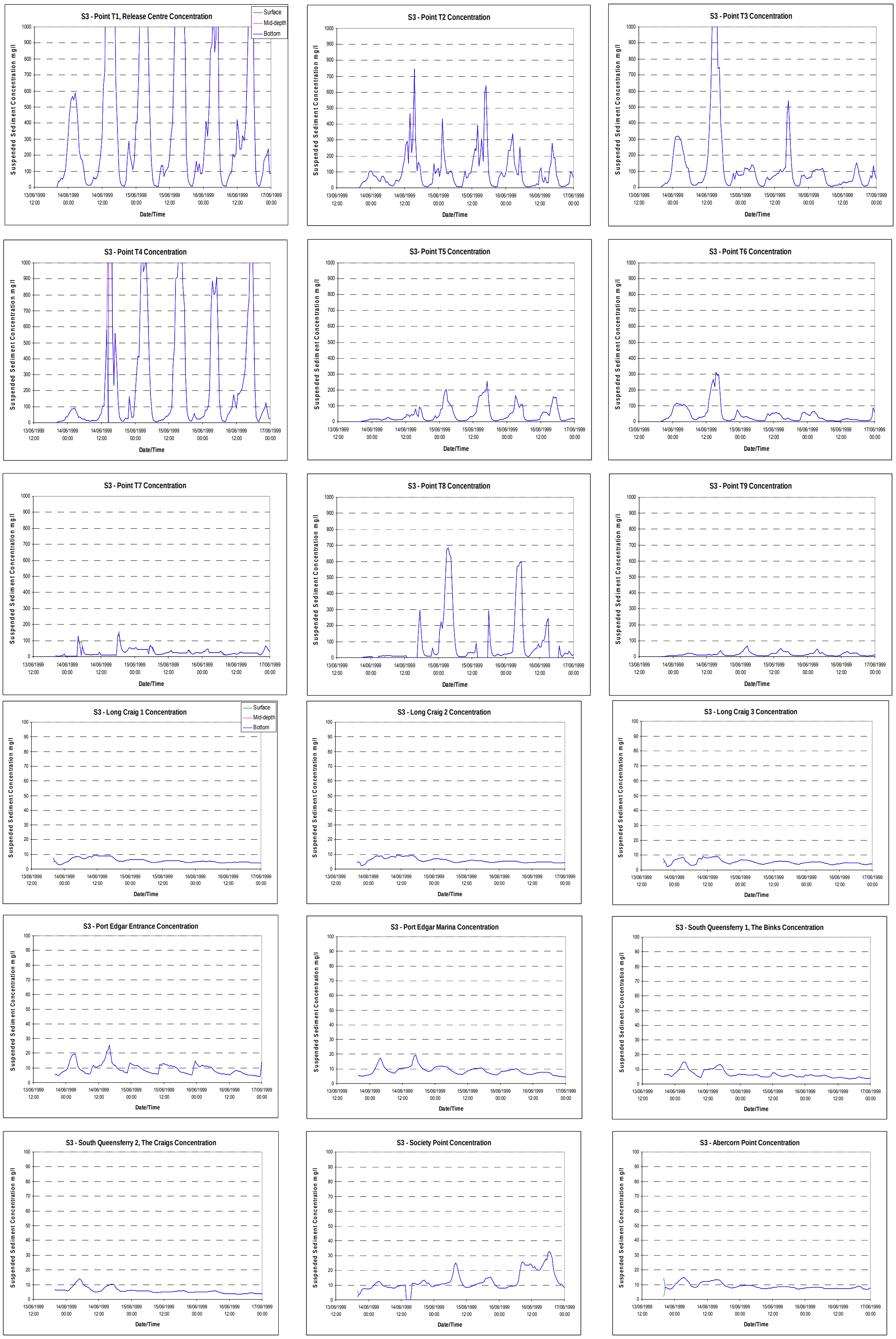


Diagram 88: Suspended Sediment Concentrations under Scenario ST at Neap Tide (Piling at ST, Bottom Release Only)

N.B. This scenario combines with releases from ST and N1, therefore the results showed elevated levels of suspended sediment on both the northern shore and in mid channel of the Forth.

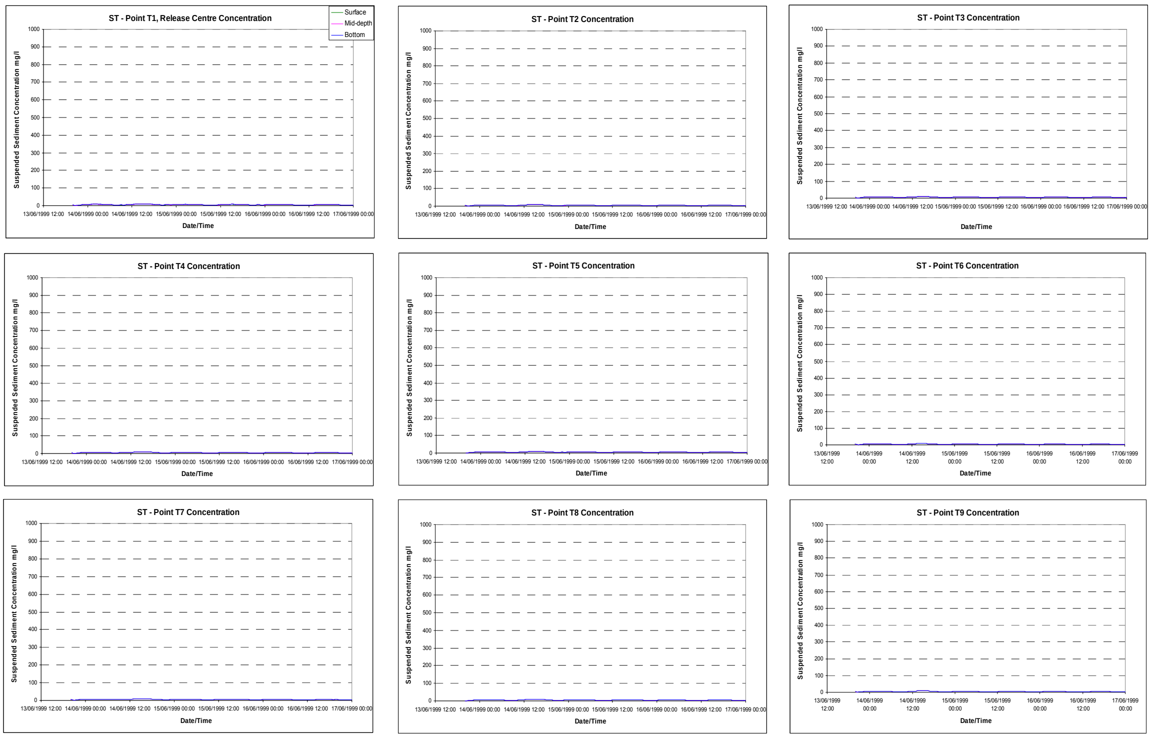
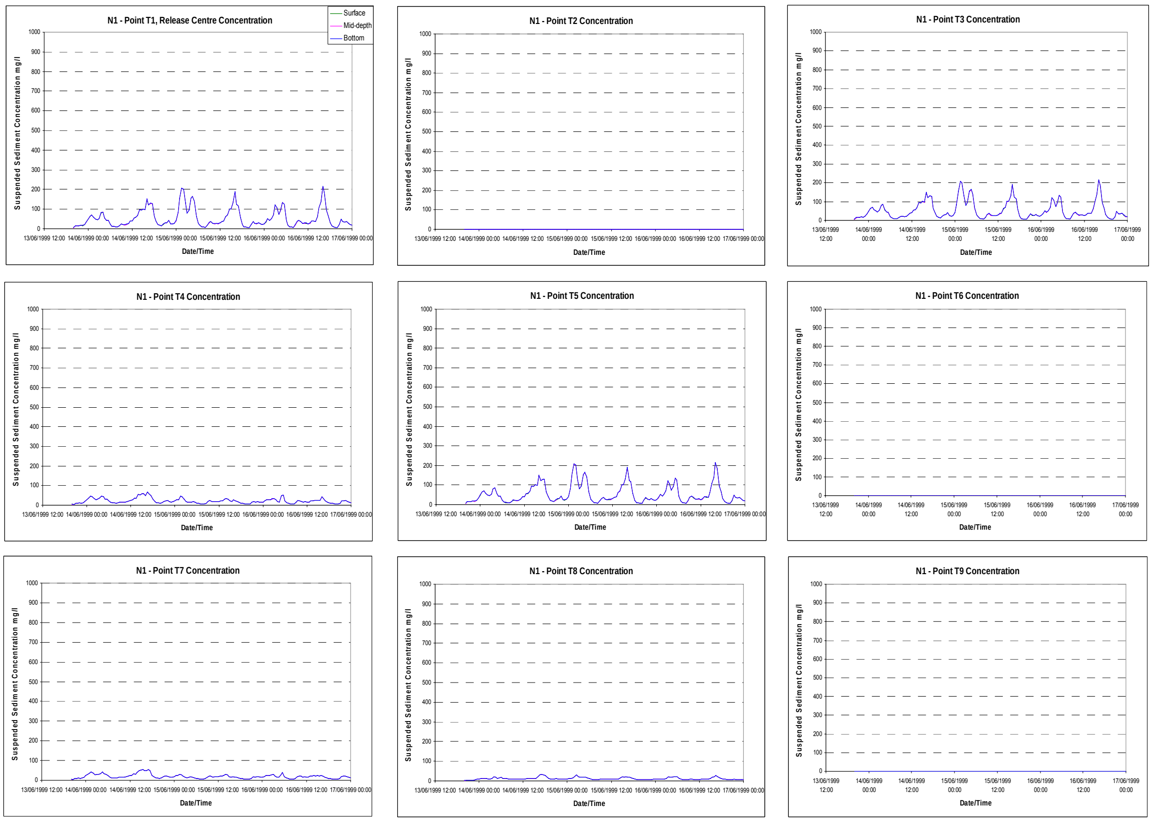


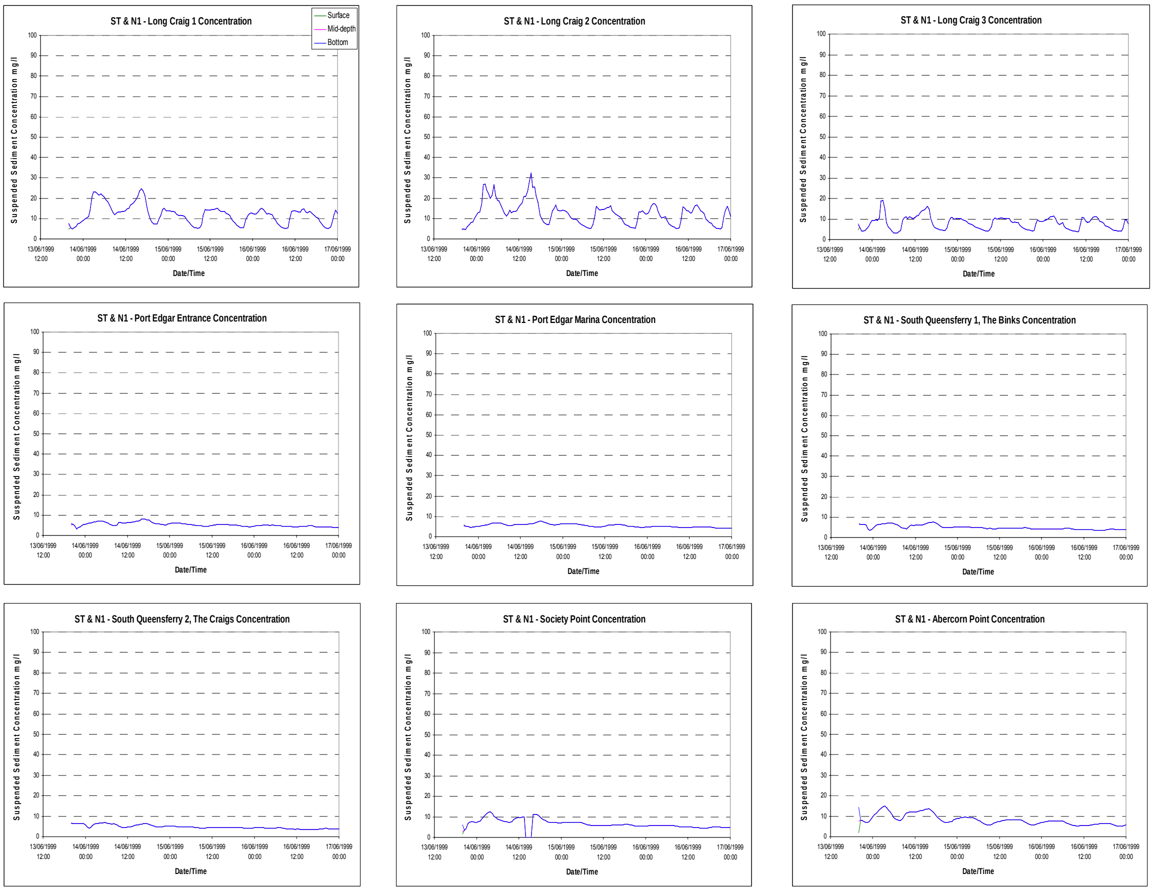
Diagram 89: Suspended Sediment Concentrations under Scenario N1 at Neap Tide (Pier N1 Dredging, both Bottom Release and Surface Overspill)

N.B. This scenario combines with releases from ST and N1, therefore the results showed elevated levels of suspended sediment on both the northern shore and in mid channel of the Forth.



4.5.56 Construction activities at both the South Flanking Tower ST and the North Pier N1 together contributed to the suspended sediment concentrations at the following locations shown in Diagram 90. However, due to their proximities, it is considered that the impacts on Long Craig are primarily from Pier N1 and the other locations close the south shore are due to South Flanking Tower ST.

Diagram 90: Suspended Sediment Concentrations under Scenario ST and N1 at Neap Tide



4.5.57 The Neap tide results showed very similar plume patterns as those scenarios in Spring tide but with lower peak concentrations. However, the peak concentrations seemed to linger on a lot longer than in Spring tide and although at a lower concentrations, their effects are felt longer in the water and dispersed slower.

4.5.58 The impacts at the nine additional monitoring points are almost no different to those from Spring tide, i.e. very minor.

4.6 Conclusion

4.6.1 A suspended sediment plume modelling has been carried out on the basis of the coastal hydrodynamic model that was used to study the complex flow patterns in the Firth of Forth and estuary in the presence of temporary and permanent works from the proposed scheme.

4.6.2 The suspended sediment plume modelling aims to predict the impacts on the water body from all the construction activities expected from building of the new Forth Replacement Crossing. The concentration levels of suspended sediments before and during the construction works, specifically those activities which are likely to disturb the seabed sediments and contribute to significant release of materials throughout the water column. Thirteen construction activities have been identified including all dredging and piling works for the three main towers and seven piers, general dredging for access between the piers, foundations for temporary bunds and the placement/removal of the earth bunds on the foreshore and inter-tidal zones on the south approach of the crossing.

4.6.3 Extensive amount of temperature, salinity and suspended sediment data over the large model domain are required to define the suspended sediment plume model. Data were received from a variety of sources including SEPA, Marine Scotland, past projects and literature reviews. A 2-day marine survey was conducted to supplement the data requirements. Spatial maps of temperature, salinity and suspended sediment concentrations have been produced from these data sources and applied as background conditions for the modelling.

4.6.4 Two 3-day periods in June 1999 covering a spring tide and a neap tide of three tidal cycles each were modelled for the sediment releases from each of the 13 construction activities and their results produced in colour contour plots as well as time series concentration level traces at 9 monitoring points centering on the release activity. The objective is to monitor the change in concentration levels within two zones: 50m and 150m from the centre. A further 9 monitoring points were also chosen at some sensitive receptors to study the level of suspended sediments from the construction activities. These receptors include the south shore locations at South Queensferry, Port Edgar, Society Point and Abercorn Point. There are three points around Long Craig Island on the north shore.

4.6.5 The results for all the activities in the south (Piers S1 to S6 and all general access dredging) showed that concentrations were generally high at the centres of the sediment release points but declined rapidly at a distance of 150m, to about 150mg/l or less, causing relatively very little impacts to the surrounding water. The highest concentration was during low tide and slack water. The plume tended to travel most during flood tides, pushing westward towards Society Pont and Abercorn Point although the increase in concentration is relatively mild, at less than 13mg/l. In ebb tides, the plumes passed Port Edgar marina and deposited at South Queensferry, but again the increase in concentration is quite low, about 10mg/l.

4.6.6 The two construction activities at the central tower CT and the south flanking tower ST in the middle of the Forth channel caused virtually no change to the suspended sediment concentrations in the water. This is due to the low volume of sediment released, relatively deep water, together with high magnitude current speed.

4.6.7 On the north side of the Firth of Forth, construction activity at the north flanking tower NT has a very low and localised impact, with a concentration of less than 100 mg/l even at the centre of release. The plume is predicted to quickly dilute before reaching St Margaret’s marsh.

4.6.8 Finally, the plume from the north pier N1 seemed to hug alone St. Margaret’s Hope marsh on the northwest of the activity centre during flood tides and spread towards Long Craig island on its southeast direction at high tides and/or ebb tides, as the pier location is very close to the shoreline. The concentration is up to 300mg/l at a distance of 150m but a mere 20mg/l maximum at Long Craig.

4.6.9 In conclusion, the suspended sediment concentration is generally very high at the centre of the construction activities, particularly in S3 to S6 locations. The shallow water depth and low current speed in this area, and the natural barrier introduced by the Port Edgar western breakwater contribute to a local confinement of the released sediments during slack water but seemed to act as a guide to deflect the plume over to South Queensferry at ebb tides.

4.6.10 At a distance of 150m from the activity centres, all the concentrations declined quickly, to less than 300mg/l for a very short time. In the context of the Forth, it is noted that the daily mean suspended solids at SEPA’s Alloa monitoring station in 1999 reached 750mg/l (Wallingford, 1993).

4.6.11 The results demonstrated that the raised concentration levels are a temporary phenomenon, and the water column is likely to revert to its background levels in relatively short time after the stoppage of the construction activity.

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