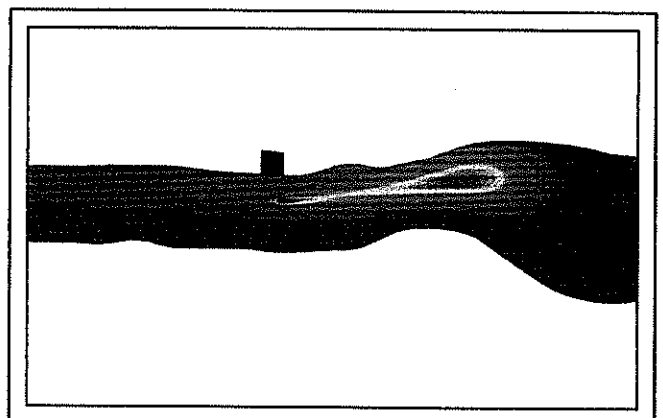
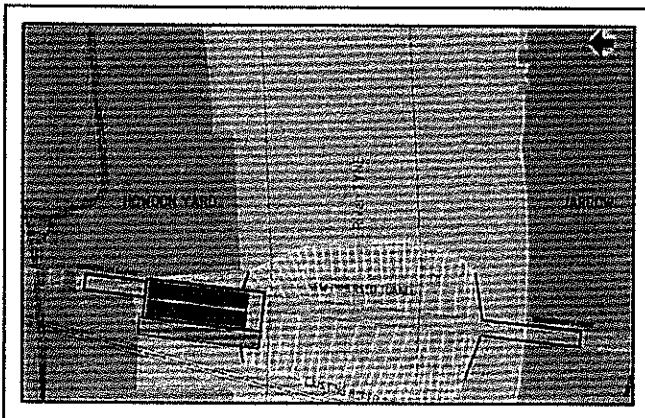


New Tyne Crossing Hydraulic Modelling Report



**POSFORD
DUVIVIER**

Posford Duvivier
Rightwell House
Bretton
Peterborough PE3 8DW
United Kingdom

Tel +44 (0) 1733 334455
Fax +44 (0) 1733 262243



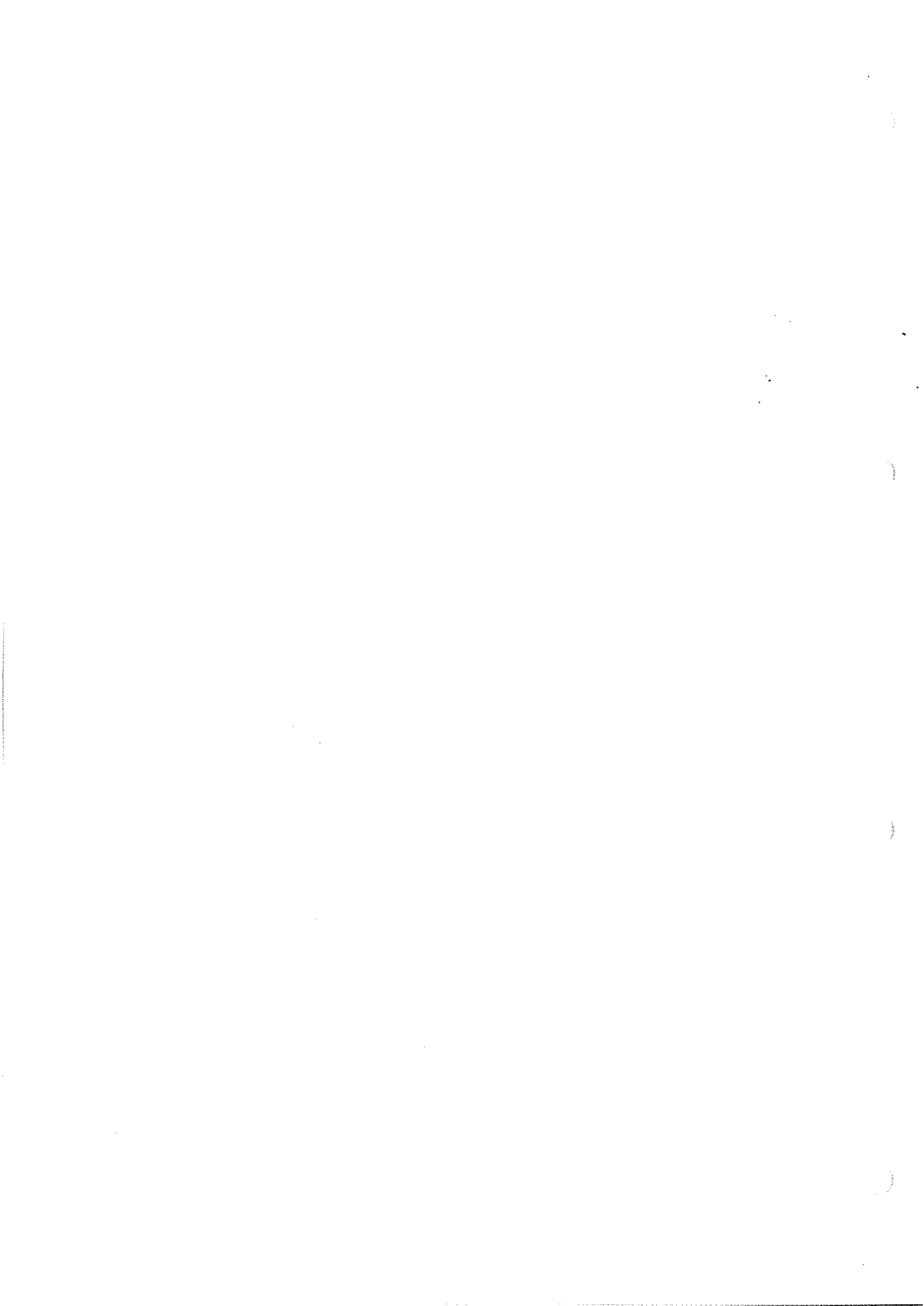
**NEW TYNE CROSSING
HYDRAULIC MODELLING REPORT**

MARCH 2001

Revision	Date	Prepared	Checked	Reviewed	Approved	Status
0	9 March 2001	Keming Hu Duncan Winn <i>Keming Hu Duncan Winn</i>	Tim Fay <i>Tim Fay</i>	Noel Beech <i>Noel Beech</i>	Tim Fay <i>Tim Fay</i>	Final

Prepared by:

Posford Duvivier Ltd.
Rightwell House
Bretton
Peterborough
PE3 8DW



CONTENTS

- 1. Introduction**
 - 2. Extent of Modelling and Techniques adopted**
 - 3. Input Data**
 - 3.1 Hydrographic Survey**
 - 3.2 Bathymetry**
 - 3.3 Bed Sampling**
 - 3.4 Dredging Records**
 - 3.5 Fluvial Flows**
 - 4. Model Setup, Calibration and Verification**
 - 5. River Flows and the Effect of the Temporary Structures**
 - 5.1 Tidal and Fluvial Flows**
 - 5.2 Effect of Temporary Structures**
 - 6. Modelling of Dredging and Backfilling Operations**
 - 6.1 Introduction**
 - 6.2 Dredging Activities Modelled**
 - 6.3 Period of Modelling of Dredging and Tidal Conditions**
 - 6.4 Suspended Sediment Concentrations Caused by Dredging**
 - 6.5 Backfilling**
 - 6.6 Sediment Transport and Description**
 - 7. Model Limitations and Accuracy**
 - 7.1 Hydrostatic Assumptions**
 - 7.2 Effects of Turbulence**
 - 7.3 Uncertainty of Sediment Size**
 - 8. Conclusions**
- References**
- Figures**
- Appendices**
- A Description of Used Models**
 - B POTA Dredging Records**
 - C Bed Materials**
 - D Sediment Release from Dredging Operations**
 - E Modelling Results of the Suspended Sediment Concentration**
 - F Modelling Results for the Sediment Deposition**

NEW TYNE CROSSING

HYDRAULIC MODELLING REPORT

1. Introduction

The objective of the hydraulic modelling study of the River Tyne is to facilitate the reference design for an Immersed Tube Tunnel in relation to:

- the impact of the construction works on the existing environment
- the hydraulic conditions likely to be encountered during construction
- the impact of the construction works on the flood defence standard

The information derived in the hydraulic modelling study is to be used to demonstrate the impact of the works on the estuary and to determine the optimum construction procedures. The potential impact on the estuary may include:

- adverse impact on fish and fisheries owing to increased suspended sediment concentration in the river during the dredging and backfilling operation.
- contaminated sediment transported to and settled on the Site of Special Scientific Interest (SSSI) area at the mouth of the river (Figure 1).
- change of tidal flow regime caused by the temporary works and its impact on the sediment transport regime.
- the backwater effect caused by the temporary works during the construction and its impact on the flood defence standard.

In addition to the backwater effect, the increased velocity at the tunnel site caused by the temporary works may cause difficulty in manoeuvring and positioning the concrete tunnel elements, and accelerate re-siltation in the trench.

To study the above impacts, numerical models C-DIVAST and STM were set up, calibrated and used to simulate the tide flow and sediment transport regime for various scenarios including different tides, fluvial flows, sediment size and dredging locations.

2. Extent of Modelling and Techniques Adopted

The required extent of the hydraulic model is determined by the potential travel distance and the dilution of any suspended sediment which may be released into the watercourse as a result of the construction works. However until the hydraulic modelling has been completed it is unclear what the full potential sediment travel distance and the suspended sediment concentration may be.

The River Tyne is tidally influenced from the mouth of the river up to a weir near Wylam which is located approximately 7.7km upstream from Newburn Bridge. The overall length of tidal influence is approximately 38km. A model over the full length of tidal influence was considered to be not justifiable as the scale of the construction impact of the immersed tube tunnel could be adequately determined by a more limited extent of the model.

The New Tyne Crossing model extends approximately 12.5 km along the Tyne from the mouth to Low Walker. The tunnel site is approximately 7.5km and 5km away from the upstream and downstream boundaries respectively. The downstream boundary was extended to the river mouth in order to cover the SSSI area, a mud flat located between the north bank and the navigation channel at the mouth (Figure 1).

The hydrodynamic modelling uses a platform model called C-DIVAST. It was developed by Professor R A Falconer of Cardiff University and has been used extensively in the UK and elsewhere in the world and is well proven through its extended applications in both industrial and academic fields. The model operates on the finite difference method to represent hydrodynamic behaviour. The model uses a "curvilinear grid" which enables it to follow complex boundary shapes such as river bends, with higher accuracy. The model is used principally to evaluate tidal regimes i.e. the patterns of flows in a given water body. The output from the model has direct application to river regime studies, construction condition studies and as the principle input into further process studies, in particular sediment transport.

The water velocities and water levels which were derived from the C-DIVAST model, were used to drive an added-on quasi three-dimensional sediment transport model (STM) developed by Posford Duvivier. STM utilises an advanced numerical scheme for particle transport provided by C-DIVAST to simulate suspended-load, bed-load sediment transport and consequent bed level changes. More details about C-DIVAST and STM can be found in Appendix A of this report.

3. Input Data

3.1 Hydrographic Survey

A hydrographic survey of the river was commissioned to obtain tidal level data, currents and suspended sediment measurements^[1]. Tidal observations were obtained to provide the boundary conditions for the operation of the numerical hydrodynamic model, and velocity and suspended sediment measurements were used for the calibration of the model.

One tide gauge was set up at Low Walker and uninterrupted tidal readings were obtained for a 67 hour period (13:42 6th April - 08:57 9th April). Tide measurements were continuous with instantaneous readings taken every 5 minutes. The tidal elevation at the river mouth was recorded by a permanent tide gauge at North Shields, and the data was provided by Port of Tyne Authority (POTA).

Data was obtained for a 13 hour period (06:30 - 19:30 8th April) on the strength and direction of the currents at three sections to provide data for the calibration of the hydrodynamic models (Figure 1). Bottles of water samples were taken concurrently with current measurements and analysed in a laboratory for the levels of suspended sediment concentration to enable calibration of the sediment transport model.

Nine current measurements were taken simultaneously at three locations namely Low Walker, the tunnel site and North Shields Fish Quay. An acoustic Doppler Current Profile (ADCP) transect covered a 13 hour period to obtain current speed and direction through a spring tide. Currents were recorded every 30 minutes. At each location, velocities at 20%, 60% and 80% of water depth below the surface were derived from ADCP profiles.

Water samples were taken simultaneously with currents measurements at the centre of the navigation channel at Low Walker, the tunnel site and North Shields Fish Quay every 30 minutes and at three vertical levels, i.e. 20%, 60% and 80% of water depth.

The measured depth-averaged suspended sediment concentration varied from 15 ppm to 45 ppm on the date of the survey.

3.2 Bathymetry

POTA provided riverbed sounding data obtained in 1999. The data covered the entire navigation channel within the modelled area. The bathymetry in other areas was digitized from Admiralty Chart (No.1934), which was obtained in the period of 1990-1998 except the SSSI area where the bed level was surveyed in 1960. The combined bathymetry is presented in contours shown in Figure 2.

3.3 Bed Sediment

Preliminary ground investigation was commissioned and 7 boreholes were drilled in the river (Figure C.1). Multi-layer sediment data including the particle size distribution was analysed at these sites. The data shows that sediment sizes vary

significantly among these 7 locations. D_{50} of the surface layer varies from 10 μm to 300 μm . The results of sedimentation analysis for these 7 locations can be found in Appendix C of this report.

3.4 Dredging Record

POTA's dredging records were available for the period of 1989-2000. The records were used to verify the mathematical model by comparing it with simulated bed level changes. However, the dredging records do not contain the information of the exact dredging area and duration of each dredging operation, and the property of sediment being dredged. The dredging records can be found in Appendix B.

3.5 Fluvial Flows

The Environment Agency provided recorded daily flow data at gauging stations Bywell (River Tyne), Rowlands Gill (River Derwent), Team Valley (River Team) and Craghall (River Ouseburn). The data set covers a 15 year period (1985-1999). In addition, one month daily flow data at these four gauging stations was also provided for April 2000 in which month the hydrographic survey was carried out.

The University of Durham derived a return-period curve of daily flow for the River Tyne^[3] (Figure 3). It was estimated that 1 in 10 year daily flow for the River Tyne is approximately 1,060 m^3/s .

4. Model Setup, Calibration and Verification

4.1 Model Setup

The hydrodynamic model was driven by two open boundaries, the seawards boundary at the river mouth near the pier heads and the boundary at Low Walker. Initially, water elevation data was used at both boundaries. At the seaward boundary, the tidal elevation data recorded at North Shields was used, adjusted to take account of the tidal phase lag between North Shields and the seaward boundary. It was found that a 3.5 minute phase lag gave the best results during the calibration.

The seaward boundary was chosen to be approximately 600m away from the pier heads (Figure 4). The purpose of this extension was to improve the model accuracy and numerical stability by avoiding the strong turning currents at the pier heads.

In the model, a curvilinear grid was used (Figure 4). Between North Shields Fish Quay and Low Walker, 36 grids were used cross-sectionally; and 60 grids were used in the river mouth area between North Shields Fish Quay and the seaward boundary. Longitudinally, in total, 1000 grids was used. To include a pocket area at Howdon, an additional 9×10 grid was attached to the main grid. The grid sizes vary from place to place due to the nature of curvilinear grid. At the tunnel site, grid sizes are approximately 10m×10m (Figure 5).

Bed levels of each grid were provided by a digital terrain model based on the bathymetric data supplied by POTA and the Admiralty Chart (see Section 3.2).

After calibration, flow data was used at the landward boundary for various scenario tests. The flow data for a spring tide was derived by operating C-DIVAST using the recorded tidal elevation data at Low Walker. Flow boundary data for a neap tide with normal fluvial flow and a spring tide with 1:10 year fluvial flow were derived by the use of a control volume model.

The control volume model covers an area between Low Walker and the weir, the tidal limit near Wylam. The model calculates the water level changes in the controlled area in response to a constant fluvial flow input and tidal water exchange at Low Walker. The tidal water exchange at Low Walker is calculated according to the change of the sea level and the water level in the controlled area. The control volume model can be seen as a simplified tidal model which ignores the flow details within the controlled area. The tidal volume of the controlled area was obtained from the Admiralty Chart, and the longitudinal bed profile extracted from the report by University of Durham^[3] for the area between the limit of the Admiralty Chart and the weir.

4.2 Model Calibration

The calibration process includes the adjustment of boundary conditions (phase lag and datum correction), treatment of "flooding and drying", determining friction and turbulence coefficients, and the optimisation for computational time-step etc.

The measured velocities at nine locations and suspended sediment concentration at the tunnel site on 8th April 2000 were used to calibrate the model. The calibrated results are presented in Figures 6-9. The results show a fairly good agreement between computed and measured velocities. For the sediment transport model, it was necessary to make a choice regarding sediment size. D_{50} values varied between 10 μm to 300 μm at the tunnel site, and there was no sediment data available elsewhere within the boundaries of the model. After an iterative process was carried out it was found that when D_{50} was set at 25 μm the computed suspended sediment matches fairly well with the measured rates, (see Figure 9). The calibrated key parameters are presented in Table 1.

Table 1: Calibrated Key Parameters for the New Tyne Crossing Model

Parameters		Settings
Flooding and drying		Switched on; minimum depth=0.2 m
Surface wind stress		Switched off
Turbulence		Zero-equation method; eddy coefficient=1.0
Bed friction		Colebrook-White equation method; roughness height=0.025m
Time steps	Hydrodynamic	0.5 seconds
	Sediment transport	1.0 seconds
Phase Lag between the seawards boundary and North Shields		3.5 minutes
Geometry standard deviation of bed material (σ_s)		3.5

4.3 Model Verification

The calibrated model was used to simulate bed shear stress and bed level changes for the existing conditions. The sediment transport model used a uniform sediment size for the whole model area, as there was no information on the sediment size in areas away from the tunnel site. However, in spite of this problem, by comparing the simulated bed level changes with the dredging records, results were found to be reasonably good.

Firstly, bed shear stress was computed. The computed bed shear stresses are presented as contours of mean and peak bed shear stress in Figures 10a-d. Bed stress has a close relationship with erosion and accretion of the river bed. When bed stress is higher than the critical shear stress, the bed material is likely to be lifted into bed-load transport or further, into suspended-load transport. Although the status of erosion also depends on the saturation of sediment concentration in suspension, and the status of deposition also depends on the availability of suspended sediments. Nevertheless, the bed shear stress provides a good indication of erosion and accretion.

The critical bed shear stresses of different sized sediments are listed in Table 2. It should be noted that the table assumes that sediment is non-cohesive. Critical shear stress for fine sediment, e.g. clay and silt, may be much higher subject to their consolidation status and mixture with coarse material. By comparing this table to the bed shear stress, an indication of the largest erodable sediment size may be obtained.

The peak bed shear stress contours (Figures 10a and 10b) show that the navigation channel is “self-cleaning” except at the Swinging Area and at the mouth of the river, due to expansion of the channel width. The mean bed shear stress contours (Figures 10c and 10d) confirm that the river channel upstream of the Swinging Area is “self-cleaning” with mean bed shear stress above 0.5 N/m^2 which is equivalent to sediment size of 1mm (D_{50}). The water stagnation areas were identified in the Swinging Area, the section in front of the former North Shields Shipyard, the area between the Western Quay and Fish Quay at North Shields, and along both sides of the navigation channel at the mouth of the river (Fish Quay is located at the north bank close to Line Section 1 shown in Figure 1).

Secondly, bed level changes after six spring tides were computed using a uniform sediment size of $D_{50}=25\mu\text{m}$ (Figure 12). The results show accretion in the pocket area near Howdon, the Swinging Area, along both banks in front of the former North Shields Shipyard and along the Western Quay. Accretion in these areas agrees with Port of Tyne Authority records which shows that these areas are subject to dredging. The computed results, however, do not match the same degree of dredging activity along the Hebburn Quay. In addition, the location of sedimentation at the river mouth does not match with the dredging records.

Less deposition in the upstream area may be explained by relatively coarse bed material. This may indicate that uniform bed material for the whole area may not represent the reality.

The mouth of the river including the SSSI site is currently subject to sedimentation due to sand being transported from the sea into the lower estuarial waters. The morphological change in the mouth area may be subject to the forces of both currents and waves. The model does not cover the coastal area, therefore, it can not simulate the sediment transport from the sea.

Generally, the simulated sedimentation in the river channel particularly in the area close to the proposed tunnel site compares reasonably well with the dredging records. In fact, the uncertainty owing to spatial variation of sediment size along the river will not affect the confidence in the results of scenario tests described later (see discussions on the accuracy and limitation of the model in Section 7.3).

Table 2: Critical Shear Stress

D ₅₀ (mm)	Critical Shear Stress (N/m ²)	D ₅₀ (mm)	Critical Shear Stress (N/m ²)	D ₅₀ (mm)	Critical Shear Stress (N/m ²)
0.01	0.039	0.51	0.266	1.01	0.496
0.02	0.065	0.52	0.269	1.02	0.502
0.03	0.083	0.53	0.273	1.03	0.508
0.04	0.097	0.54	0.276	1.04	0.513
0.05	0.108	0.55	0.280	1.05	0.519
0.06	0.117	0.56	0.284	1.06	0.525
0.07	0.124	0.57	0.287	1.07	0.531
0.08	0.131	0.58	0.291	1.08	0.537
0.09	0.136	0.59	0.295	1.09	0.542
0.10	0.141	0.60	0.299	1.10	0.548
0.11	0.145	0.61	0.303	1.11	0.554
0.12	0.149	0.62	0.307	1.12	0.560
0.13	0.153	0.63	0.311	1.13	0.566
0.14	0.156	0.64	0.315	1.14	0.572
0.15	0.160	0.65	0.319	1.15	0.579
0.16	0.163	0.66	0.323	1.16	0.585
0.17	0.166	0.67	0.328	1.17	0.591
0.18	0.169	0.68	0.332	1.18	0.597
0.19	0.172	0.69	0.336	1.19	0.603
0.20	0.174	0.70	0.341	1.20	0.610
0.21	0.177	0.71	0.345	1.21	0.616
0.22	0.180	0.72	0.349	1.22	0.622
0.23	0.182	0.73	0.354	1.23	0.629
0.24	0.185	0.74	0.358	1.24	0.635
0.25	0.188	0.75	0.363	1.25	0.642
0.26	0.190	0.76	0.368	1.26	0.648
0.27	0.193	0.77	0.372	1.27	0.655
0.28	0.196	0.78	0.377	1.28	0.661
0.29	0.198	0.79	0.382	1.29	0.668
0.30	0.201	0.80	0.386	1.30	0.674
0.31	0.204	0.81	0.391	1.31	0.681
0.32	0.206	0.82	0.396	1.32	0.688
0.33	0.209	0.83	0.401	1.33	0.694
0.34	0.212	0.84	0.406	1.34	0.701
0.35	0.215	0.85	0.411	1.35	0.708
0.36	0.218	0.86	0.416	1.36	0.715
0.37	0.221	0.87	0.421	1.37	0.721
0.38	0.224	0.88	0.426	1.38	0.728
0.39	0.226	0.89	0.431	1.39	0.735
0.40	0.230	0.90	0.437	1.40	0.742
0.41	0.233	0.91	0.442	1.41	0.749
0.42	0.236	0.92	0.447	1.42	0.756
0.43	0.239	0.93	0.452	1.43	0.763
0.44	0.242	0.94	0.458	1.44	0.770
0.45	0.245	0.95	0.463	1.45	0.777
0.46	0.249	0.96	0.468	1.46	0.784
0.47	0.252	0.97	0.474	1.47	0.791
0.48	0.255	0.98	0.479	1.48	0.798
0.49	0.259	0.99	0.485	1.49	0.805
0.50	0.262	1.00	0.491	1.50	0.813

5. River Flows and the Effect of the Temporary Structure

5.1 Tidal and Fluvial Flows

The results of the hydrodynamic model demonstrate the domination of tidal force in the hydrodynamics and sediment transport in the modelled reach of the River Tyne under the normal fluvial condition. A typical spring tide generated an average tidal flow of 1000 m³/s with ebb flow slightly larger than flood flow (Table 3). The peak instantaneous ebb flow reached 2000 m³/s at the tunnel site at mean spring tide. The peak depth-averaged velocity at the tunnel site was 1.24 m/s in mean spring tide. A typical neap tide generated an average tidal flow of 460 m³/s with peak instantaneous ebb flow at 850 m³/s. The peak depth-average velocity at neap tide at the tunnel site was 0.56 m/s, which was less than half of the peak velocity at the spring tide.

Table 3: The Simulated Flow and Depth-averaged Velocities at the Tunnel Site

	Spring Tide		Neap Tide	
	Flow (m ³ /s)	Velocity (m/s)	Flow (m ³ /s)	Velocity (m/s)
Mean Ebb	1190	0.49	530	0.22
Mean Flood	823	0.40	370	0.19
Peak Ebb	2000	1.24	850	0.56
Peak Flood	1700	0.90	750	0.43
Mean	1000	0.45	460	0.21

The recorded fluvial flow on 8th April 2000 was 40 m³/s, which was close to the mean daily flow of 48 m³/s based on the 15-year gauging station data provided by Environment Agency. It is noted that the average tidal flow of 1000 m³/s is equivalent to 1 in 10 year fluvial flow of 1060 m³/s. Under such fluvial flow condition, there was little upstream particle excursion in the River Tyne.

5.2 Effects of Temporary Structures

The hydrodynamic model has been operated to study the effect of the proposed temporary works (Building Dock coffer-dam and south side training walls) and two tunnel units temporarily stored alongside Howdon Yard when the other two units are under construction in the Building Dock (Figure 13).

The results show that peak velocity was increased by 20% by the temporary structures (Figure 14). Its impact is more obviously illustrated in bed shear stress contours (Figures 10d-11). However, the influence of the proposed temporary structures was greatly limited to the area close to the tunnel.

The hydrodynamic model has also been operated to study the backwater effects caused by the temporary structures. It was calculated that the water level would be increased by 23mm upstream of the tunnel site, under the peak ebb flow. Since the peak flow occurs at a time close to mean tide, it can be concluded that the backwater by the proposed temporary structures has almost no impact on the flood defence standard along the River Tyne.

The results demonstrate that the temporary structures have limited impact on the tidal flow and sediment transport regime.

6. Modelling of Dredging and Backfilling Operations

6.1 Introduction

There are three main areas where dredging operations may affect the water quality of the river:

- Suspended sediment causing an increase in turbidity.
- Re-suspension of contaminants into the water column.
- Increase in oxygen demands on the dissolved oxygen content in the water column.

These water quality issues may have an adverse environmental effect due to:

- Smothering benthic ecology.
- Altering sediment composition of designated inter-tidal habitats.
- Hindering fish migration.

The hydraulic modelling was therefore arranged to simulate:

1. The concentration levels of suspended sediment which are likely to result from dredging operations and the extent that suspended sediment is likely to be transported.
2. The areas and amount of deposition of sediment arising from dredging operations.

Dredging may be divided into three separate areas:

- Dredging within the tunnel element building dock.
- Dredging between the training walls on the south side of the river.
- Dredging the immersion trench between the building dock and the south side training walls.

It is anticipated that dredging within the tunnel element building dock on the north side of the river and between the training walls on the south side of the river will effectively be carried out within "silt screens". Hence the hydraulic modelling has been limited to dredging of the immersion trench between the tunnel element building dock and the training walls on the south side of the river ("the immersion trench").

Within the immersion trench, the estimated volumes of material to be dredged are shown in Table 4.

Table 4: Estimated Volumes of Material to be Dredged

Material Type	Dredged Volume (m ³)
Made Ground and Alluvial Clay/Silt	63,600
Sands and Gravels	147,800
Glacial Clays	8,500
Bedrock	6,800

The made ground and alluvial clays are, to some extent, contaminated by pollutants and contain organic matter which might affect oxygen demand in the dissolved oxygen content in the water. For these reasons the dredging of these materials is considered to have the most significant environmental impact.

To minimise the amount and rate of loss of fine material into the water column during dredging, the made ground and alluvial clay/silt dredging with an enclosed grab dredger has been assessed to be most appropriate.

Specialist advice was sought from Dredging Research Ltd (Appendix D) on the appropriate sediment release rate to assume for this operation and the recommended figure of 1kg/s has been adopted.

For the dredging of the sands and gravels, glacial clays and bedrock, either a backhoe or possibly a cutter suction dredger would appear to be appropriate. The sands and gravels are generally coarser materials than the made ground and alluvial clay/silt. The loss of coarse material during the dredging process is normally less than the loss of fine material.

For the modelling of dredging the sands and gravels, a release rate of 1kg/s was also adopted to give conservative results.

Dredging of the glacial clays and bedrock using a backhoe is likely to be achieved in blocks limiting sediment release into the water column. However sediment will be released into the water column due to disturbance of the clays and bedrock. Release rates for dredging in the glacial clays and bedrock are estimated to be typically 0.75 to 1 kg/s.

Based upon data derived from the river boreholes sunk in Summer 2000, three sizes of bed material were used in the modelling scenarios:

- Fine Silt $D_{50} = 10 \mu\text{m}$
- Coarse Silt $D_{50} = 30 \mu\text{m}$
- Medium Sand $D_{50} = 300 \mu\text{m}$

The estimated period of dredging for the different materials is shown in Table 5. The period of dredging has been estimated based upon dredging for 105 hours per week i.e. 15 hours per day for 7 days per week. The assumed dredging production rates allow for maintenance and breakdowns.

Table 5: Estimated Period of Dredging for the Different Materials

Material Type	Volume (m ³)	Dredging Periods (Days)
Made Ground and Alluvial Clay/Silt	63,600	33
Sands and Gravels	147,800	32
Glacial Clays	8,500	5
Bedrock	6,800	10
	TOTAL	80

6.2 Dredging Activities Modelled

Ten different dredging activities were modelled, namely:

1. Dredging at the centre of the navigation channel in the alluvial clay/silt assuming release of fine silt into the water column at spring tide together with a normal fluvial flow.
2. Dredging at the centre of the navigation channel in the alluvial clay/silt assuming release of fine silt into the water column at spring tide together with a 1 in 10 year fluvial flow.
3. Dredging at the northern edge of the navigation channel in the alluvial clay/silt assuming release of fine silt into the water column at spring tide together with a normal year fluvial flow.
4. Dredging at the southern edge of the navigation channel in the alluvial clay/silt assuming release of fine silt into the water column at spring tide together with a normal year fluvial flow.
5. Dredging at the centre of the navigation channel in the alluvial materials assuming release of coarse silt into the water column at spring tide together with a normal year fluvial flow.
6. Dredging at the northern edge of the navigation channel in the alluvial materials assuming release of coarse silt into the water column at spring tide together with a normal fluvial flow.
7. Dredging at the southern edge of the navigation channel in the alluvial materials assuming release of coarse silt into the water column at spring tide together with a normal year fluvial flow.
8. Dredging at the centre of the navigation channel in the alluvial sands and gravels assuming release of medium sand into the water column at spring tide together with a normal year fluvial flow.
9. Dredging at the centre of the navigation channel in the alluvial clay/silt assuming release of fine silt into the water column at neap tide together with a normal fluvial flow.

10. Dredging at the centre of the navigation channel in the alluvial clay/silt assuming release of fine silt into the water column at spring tide together with a normal fluvial flow. Assuming all of the sediments that cross the upstream boundary return on the next tidal cycle.

6.3 Period of Modelling of Dredging and Tidal Conditions

In general the nine (Runs 1-9) dredging activities were modelled over a period of six tidal cycles at spring tides to determine the overall trend of sediment transport and the peak levels of turbidity (sediment concentrations) resulting from the dredging process. In these nine scenario runs, it was assumed that no sediment which was moved out of the computational domain would return, i.e. always clean water entered the domain from both upstream and downstream boundaries.

From our discussions with the EA we understand that sediment deposition upstream of Walker tends to occur on the river banks between Redheugh Bridge and Newburn Haugh where the river widens and tidal velocities are reduced. Hence it may be unrealistic to assume that 100% of sediment which crosses the upstream boundary on spring tides will return on subsequent tides as it is likely that a proportion of sediment will be deposited at slack water.

Modelling over a period of six tidal cycles does not illustrate to what degree the ongoing dredging operation will progressively increase the sediment concentration in the water column. Therefore the dredging of fine silt in the made ground and alluvial clay/silt was modelled assuming a continuous 24 hour dredging operation for a period of 42 tidal cycles (spring tides) i.e. approximately 23 days* (Run 10). For this simulation the dredger was assumed to be working in the centre of the navigation channel. The simulation also assumed that sediment which moved out of the upstream boundary would return to the domain fully. Under this assumption, the computed accumulated suspended sediment concentrations may be conservative since it is unlikely that 100 percent of moved-out sediment would return to the domain.

Modelling at spring tides was carried out to ascertain the largest movement in sediment away from the dredging location. It was recognised that sediment transport would be less for neap tides resulting in greater sediment concentration and deposition of sediments around the dredging location. Hence one of the simulated activities was repeated at neap tides to allow direct comparison of results.

As the dredging operations will take place over a period of several weeks, in reality the tidal conditions will vary during dredging throughout a series of complete tidal cycles. In consequence the actual sediment concentration and transport levels may be expected to be somewhere between the "extreme" spring tide and neap tide levels indicated by the modelling.

The suspended sediment plumes and overall dispersal of suspended sediment has been simulated without any wind or ship movement effects. It may be expected that suspended sediment will in reality disperse to a greater extent affecting a greater width of the river at a reduced concentration as dispersal results in dilution.

The modelling of dredging operations assumes a continuous dredging process. Whilst the Contractor may wish to dredge continuously it is likely that dredging may not be allowed at night-time due to noise and the proximity of housing. A cessation of dredging operations for several hours during the 24 hour period will allow sediment to disperse and to settle out reducing the sediment concentration in the water column. The modelling results do not reflect this and hence the illustrated sediment concentrations in the river due to dredging operations may be regarded as conservative.

**23 days represents the approximate period required for dredging made ground and alluvial silt/clay with an enclosed grab assuming continuous 24 hr dredging. The period extends to 33 days if 15 hour dredging per day is assumed (See Table 5).*

6.4 Suspended Sediment Concentrations Caused by Dredging

6.4.1 General

The output of the hydraulic modelling is illustrated as:

- Contours of suspended sediment concentration.
- Contours of sediment depositions.

The illustrations of suspended sediment concentration do not include for suspended sediment concentrations which exist naturally in the river or due to other activities in the river which would add to the concentration.

The illustrations of sediment deposition do not include for sediment deposition which occurs in the river due to natural events or due to other activities.

The modelling of different dredging activities and locations have certain common features, namely:

- Initially as dredging commences there is a build up of sediment concentration local to the dredger.
- On the ebb tide, suspended sediment is transported downstream as a plume before the plume breaks off and disperses.
- As the tide turns the flow in the river becomes small and the suspended sediment concentration increases locally around the dredger and there is no sediment plume.
- On the flood tide suspended sediment arising from the dredger is transported upstream as a plume before the plume breaks off and disperses.
- On both the ebb and flood tides some of the sediment which was transported along the river on the previous tide (which has not settled out), returns with the tide.

- After several tidal cycles there is a volume of sediment in suspension which moves up and down the river on each tidal cycle independently of further ongoing dredging. This sediment either slowly settles out and is deposited or is transported beyond the boundaries of the model.

Each of the ten modelled dredging activities are illustrated as a series of figures to show the suspended sediment concentration in parts per million at various stages of the tidal cycle (Appendix E). The suspended sediment concentrations are colour coded between zero ppm (blue) and 50 ppm (red).

Animations of the modelled dredging scenarios are available on CD if required.

6.4.2 Run 1 : Dredging Fine Silt in The Middle of The Navigation Channel

The dredging of fine silt in the middle of the navigation channel during a spring tide, is shown by the eight illustration phases in Figures E.1a and E.1b in Appendix E.

Phase 1: Shows the flood tide shortly before the tide turns. The flow up river is weak as it approaches slack water and therefore a concentrated cloud of suspended sediment forms around the dredger. The cloud has a peak value of approximately 50 ppm and extends approximately 100m along the river and 40m transversely. Sediment concentrations are less than 10 ppm within 300m of the dredger and there is clear water between the dredger and riverbank on both sides.

Phase 2: Shows the ebb tide shortly after the tide has turned. A plume is beginning to form downstream of the dredger as the concentrated cloud of sediment formed in slack water starts to move down stream, becoming diluted. The dilution of suspended sediment in the cloud results in a sediment concentration of approximately 15 ppm over a length of some 500m and a width of 150m. Clear water still exists between the dredger and the riverbank on both sides.

Phase 3: Shows the ebb tide shortly before the diluted sediment cloud breaks away from the plume. The cloud now extends to the north bank with maximum concentration levels of less than 10 ppm except very locally to the dredger. Clear water still exists between the dredger and the south bank.

Phase 4: Shows the ebb tide after the cloud has broken away. The cloud continues to move down stream and is now very diluted. The ebb tidal currents have reached their peak, and sediments are diluted immediately on release from the dredger.

Phase 5: Shows the ebb tide shortly before the tide turns. The flow down river is again weak as it approaches slack water, causing a second cloud of concentrated suspended sediment to form in the location of the dredger, with a peak value of approximately 50 ppm. There is clear water between the dredger and riverbank on both sides.

Phase 6: Shows the flood tide shortly after the tide has turned. The new cloud is beginning to dilute and spread upstream of the dredger and there is a residual low concentration cloud downstream of the dredger. The sediment concentration in the upstream cloud is typically in the range 20 to 40 ppm over an area of approximately

200m long × 100m wide. Clear water still remains between the cloud and riverbank on both sides.

Phase 7: Shows the flood tide shortly before the cloud breaks away from the sediment plume. The cloud remains generally in mid river. Dispersal has caused the sediment concentration to reduce, typically in the range 10 to 15 ppm. Clear water still remains between the cloud and riverbank on both sides.

Phase 8: Shows completion of the tidal cycle on the flood tide after the cloud has broken away and continues to be diluted as it moves further upstream. Similarly to phase 4, the flood tidal currents have reached their peak, and sediments are diluted immediately on release from the dredger.

6.4.3 Run 2 : Dredging Fine Silt in The North of The Navigation Channel with 1 in 10 Year fluvial scenario

The dredging of fine silt in the middle of the navigation channel during a spring tide with 1 in 10 year fluvial flow, is shown by the eight illustration phases in Figures E.2a and E.2b in Appendix E.

In principal, Run 2 behaves in a very similar way to Run 1, with a concentrated cloud of suspended sediment forming during slack water. This cloud then breaks off from the main plume as the ebb current increases while the rest of the released sediment is dispersed immediately on release. This phenomena occurs much more quickly for Run 2 than for Run 1 since the ebb flows are greatly increased and last for a much longer period of time. On the flood tide, the cloud of concentrated sediment is formed as usual. However, since the duration of flood current is greatly reduced from Run 1, the cloud of concentrated sediment is not able to detach from the main plume, and gets transported down stream again, as the tide changes back from flood to ebb.

6.4.4 Run 3 : Dredging Fine Silt in The North of The Navigation Channel

The dredging of fine silt in the north of the navigation channel during a spring tide, is shown by the eight illustration phases in Figures E.3a and E.3b in Appendix E.

For Run 3, the fundamental changes over time, in both cloud of concentrated sediments and the overall sediment plume, remain the same as Run 1. However, the currents in the northern part of the channel are stronger than the southern and middle region, hence with respect to Run 1, the cloud is dispersed much further along the river in the same time period. The dilution of the cloud, as a result, is increased, although the overall width of the cloud is much narrower than the cloud in Run 1, as it remains contained in the faster, but narrow, northern currents.

6.4.5 Run 4 : Dredging Fine Silt in The South of The Navigation Channel

The dredging of fine silt in the south of the navigation channel during a spring tide, is shown by the eight illustration phases in Figures E.4a and E.4b in Appendix E.

In Run 4 the sediment is released in the south side of the channel. In this section currents are very similar to the currents in the middle of the channel, and so there is very little difference between the concentrated sediment cloud in Run 1 and Run 4 except the cloud extends to the south bank instead of the north bank and some suspended sediment is trapped in the sheltered area near the Tyne Car Terminal during ebb tide.

6.4.6 Run 5-6-7 : Dredging Coarse Silt in The Navigation Channel

The dredging of coarse silt in the middle of the navigation channel during a spring tide is shown by the eight illustration phases in Figures E.5a and E.5b in Appendix E.

The changes and differences in the sediment plume and cloud of sediment concentration over both time and location for Runs 5, 6 and 7, are similar to those in Runs 1, 3 and 4. However since the sediment size of Runs 5, 6 and 7, is significantly larger than that in Runs 1, 2 and 3, the quantity of sediment in suspension is much less. The plume and cloud are diluted more efficiently, and therefore the cloud is broken away from the plume earlier. The released sediment travels less distance along the river due to the increased dispersion and sediment settling.

6.4.7 Run 8: Dredging Medium Sand in The Navigation Channel

The dredging of medium sand in the middle of the navigation channel during a spring tide, is shown by the eight illustration phases in Figures E.6a and E.6b in Appendix E.

For Run 8, the sediment size is greatly increased to coarse sediments, and so virtually all sediments are deposited in a distance less than 100m longitudinally to the dredger location in a narrow belt.

6.4.8 Run 9 : Dredging Fine Silt in The Middle of The Navigation Channel over a Neap Tide

The dredging of fine silt in the middle of the navigation channel during a neap tide is shown by the eight illustration phases in Figures E.7a and E.7b in Appendix E.

Phase 1: Shows the flood tide shortly before the tide turns. Like Run 1 the flow up river is weak as it approaches slack water, and therefore a concentrated cloud of suspended sediment forms around the dredger. The cloud peak concentration value is much greater than Run 1, at approximately 150 ppm, though this higher concentration only occurs in the dredger region (extending about 30m along the river and 10m transversely). Sediment concentrations are less than 10 ppm within 300m of the dredger, and concentration is approximately between 2 ppm to 3 ppm between the dredger and riverbank on both sides. A large residue of sediment still remains in the water column from the previous flood tide although the concentration of this region is generally less than 5ppm.

Phase 2: Shows the ebb tide shortly after the tide has turned. Like Run 1 the plume is beginning to form downstream of the dredger as the concentrated cloud of sediment formed in slack water starts to move down stream and becomes diluted. The dilution

of suspended sediment in the cloud results in a sediment concentration of approximately 40 ppm over a shorter length of 350m and a width of 100m. Clear water can now be found between the dredger and the riverbank on both sides.

Phase 3: Shows the ebb tide shortly before the diluted sediment cloud breaks away from the plume. The cloud now extends to the north bank with maximum concentration levels of approximately 20 ppm. Clear water still exists between the dredger and the south bank.

Phase 4: Shows the ebb tide shortly after the main cloud has broken away. However a strong residue of suspended sediment can still be observed both upstream of the dredger, (remaining from the previous flood tide), and downstream of the dredger as the sediment cloud continues to move seawards. The cloud remains at higher concentration to the cloud in Run 1, and travels a much shorter distance. Although the ebb tidal currents have reached their peak, sediments are still not totally diluted on release and the plume can still be seen stretching downstream from the dredger, with a concentration approximately 15 ppm.

Phase 5: Shows the ebb tide shortly before the tide turns. By now upstream from the dredger, the residue sediment left from the previous flood tide has now totally dispersed. The flow down river is again weak as it approaches slack water, causing a second cloud of concentrated suspended sediment to form in the location of the dredger, with a peak value of approximately 200ppm. This high concentration, however, only occurs at the location right by the dredger, and only lasts for fifteen minutes. Downstream from the dredger residual sediment still remains.

Phase 6: Shows the flood tide shortly after the tide has turned. The new cloud is beginning to dilute and spread upstream of the dredger and there is a residual low concentration cloud downstream of the dredger (about 5ppm). The sediment concentration in the upstream cloud is typically in the range 20 to 40 ppm over an area of approximately 200m long x 100m wide. Clear water still remains between the cloud and riverbank on both sides.

Phase 7: Shows the flood tide shortly before the cloud breaks away from the sediment plume. The cloud has spread out to the middle and northern region of the channel. Dispersal has caused the sediment concentration to reduce, typically in the range 10 to 15 ppm. Small quantities (1ppm) of suspended sediment can be found on the south side of the river.

Phase 8: Shows completion of the tidal cycle on the flood tide after the cloud has broken away and continues to be diluted as it moves further upstream. Similarly to phase 4, although the flood tidal currents have reached their peak, residue sediments remain as the cloud travels upstream. The plume can still be viewed occurring from the dredger.

6.4.9 Run 10 : Dredging Fine Silt in The Middle of The Navigation Channel over a Spring Tide (assuming all of the sediments which cross the upstream boundary return on the next tidal cycle).

The dredging of fine silt in the middle of the navigation channel during a spring tide (assuming all of the sediments that cross the upstream boundary return on the next tidal cycle), is shown by the eight illustration phases in Figures E.8a and E.8b in Appendix E. The suspended sediment concentration in the river rose significantly in the first 10 tidal cycle due to returning sediment from the upstream boundary. The figures illustrated are based on the simulation at the 42nd tidal cycle when the concentration has reached equilibrium status (see Section 6.6 for more detail).

The changes and differences in the sediment plume and cloud of sediment concentration over time is very similar to Run 1. However, because of the returning sediment in the upstream boundary, other important features are observed.

The returning sediment causes, over time, a large low concentration sediment cloud to move up and downstream with the tide. As the length of dredging time increases, the concentration and size of the cloud increases until equilibrium is established. As seen in phase 1 (slack water), the tail of the large low concentration sediment can be observed, as a smaller more concentrated sediment plume forms at the dredger location. As seen in phase 2 the cloud of sediment that is formed at slack water is slightly larger than the cloud of Run 1 because of the remains of the larger sediment cloud increasing the sediment concentration.

As seen in phase 4, after the smaller concentrated cloud breaks away from the plume and starts to become diluted, the larger low concentration sediment cloud returns from the upstream boundary and enters the region of dredging. At slack water therefore, in phase 5, the sedimentation in the water column is again both a combination of a new concentrated sediment cloud forming at the dredger location and the previous larger and less concentrated sediment cloud moving downstream. Between phase 7 and phase 8, as the new smaller cloud breaks away, the larger diluted cloud can be seen returning back into the dredging region as it continues to move upstream.

6.5 Backfilling

The backfilling material will be non-contaminated sand and gravel obtained from the dredging operation. It is proposed that the backfilling material will be placed into position, rather than dropped from water surface, so that the amount of sediment released into the water column will be smaller than the amount by the dredging process. Assuming the same release rate for the dredging process is applied to the backfilling process, which leads to conservative results, the suspended sediment concentration caused by backfilling coarse material is low (the highest suspended sediment concentration is less than 80 ppm) and the size of the plume is small (an area enclosed by 80ppm contour is less than 20m×20m) (see Figures E6a-E6b in Appendix E).

6.6 Sediment Transport and Description

Deposition of the released sediment by 9 dredging scenario (Run 1 and Runs 3-10 described in Section 6.2) is shown in Figures F.1 and F.17 in Appendix F.

The results show that for medium sand, the majority of the released material deposits in a short distance of 800 metres both sides of the dredging location (Figures F.8 and F.17-18). The majority of the released coarse silt deposits within the modelled area (Figures F.5-7 and F.14-16). However, a large portion of the released fine silt is transported out of the modelled area (Figures F.1-3 and F.10-12).

Transport and deposition of fine silt largely depend on the magnitude of river flow. Fine material is transported over much longer distance during a spring tide than a neap tide (Figures F.1 and F.4).

It should be noted that Run1 and Runs 3-9 assume no sediment returning to the modelled area once it moves out of the boundary. Assuming 100% sediment returns to the modelled area from the upstream boundary and no sediment returns from the downstream boundary, deposition of the released fine silt after 23 day continuous dredging operation is illustrated in Figure F.9 (Run 10). The figure shows that the deposition of fine silts spreads across the modelled area though the deposition layer close to the dredging area is relatively much thicker. The deposition depth over 0.1mm is within approximately 800m both sides of the dredging location. Sediment deposition in the SSSI area (see Figure 1) is minimal.

The simulated transport and deposition of the released sediment for 9 dredging scenarios are summarised in Table 6.

Compared to medium sand, fine silts will stay in suspension for a much longer time after entering the water column. Consequently they will move over a great distance in a spring tide. When the dredging location was in the middle of the navigation channel, only approximately 11% released silts were deposited within the modelled area. Nearly half released silts moved out of the domain. Approximately 38% released sediment moved out of the upstream boundary and 9% moved out of the downstream boundary. The rest of the released silts were still in suspension (Figure 15).

For fine silts, a large percentage (38%) of released sediment is transported out of the upstream boundary. It was not clear what distance the suspended sediment could go and the percentage of those suspended sediment that would return to the domain. To obtain the worst scenario, the model was operated with an assumption that 100% of the moved-out sediment returned to the computation domain during ebb tides. The model was operated continuously for 42 tidal cycles (approximately 23 days). The results are presented in Table 7 and illustrated in Figures 16, 17 and 18. The results show that, under this worst case scenario, eventually, approximately two thirds of the released sediment would be deposited within the modelled area and one third would move out to the open sea.

In the first 10 tidal cycles, the suspended sediment concentration in the river rose significantly due to returning sediment from the upstream boundary. After 42 tidal cycles, the concentration has reached to the equilibrium status.

It was found that the transport and deposition of the released silt was sensitive to the dredging location cross-sectionally. However, the significance of the dredging location may be greatly reduced considering the impact of cross-sectional flow and turbulence generated by passing ships and wind.

The mobility of suspended sediment is significantly lower during a neap tide as opposed to a spring tide. The limit of the upstream excursion of the suspended sediment during a neap tide is estimated between Lower Walker and Bill Point. The escape rate at the upstream boundary reduces to 16% from the spring tide value of 38%.

If a 1 in 10 year fluvial flow were to occur during construction, there would be almost no upstream sediment excursion even at a spring tide.

Again, Table 7 shows that the deposition of sediment in the SSSI area is marginal, accounting for only 0.04% of the total released sediment. The mean accumulated deposition depth is 0.001mm after 23 days dredging in the SSSI area.

Using a typical release rate of 1.0 kg/s for made ground, alluvial clay/silt, sand and gravel, and 0.75kg/s for glacial clay and bedrock (see Section 6.1), the total amount of sediments which cross the upstream boundary is estimated to be 540 tonnes. The figure takes account of the variation of sediment transport capacity between spring and neap tides.

Table 6: Simulation of Dredging/Backfilling for Six Tidal Cycles

Dredging Material	Dredging Locations	Flow Conditions	Deposition Rate	Leave u/s Boundary	Leave d/s Boundary	Remain in Water
Fine Silt ($d_{50}=10\mu\text{m}$)	North	Spring	7.4%	20.5%	0.5%	71.6%
	Middle	Spring	10.6%	38.5%	8.2%	42.7%
	South	Spring	15.0%	46.3%	18.1%	20.6%
	Middle	Neap	39.8%	15.7%	0.1%	44.4%
	Middle	Spring+1:10 Year Fluvial	9.4%	0.0%	23.1%	67.5%
Coarse Silt ($d_{50}=30\mu\text{m}$)	North	Spring	37.3%	7.2%	0.0%	55.5%
	Middle	Spring	46.4%	17.9%	0.2%	35.5%
	South	Spring	51.8%	18.4%	1.3%	28.5%
Sand ($d_{50}=300\mu\text{m}$)	Middle	Spring	92.6%	0.0%	0.0%	7.4%

Notes:

- 1) total released sediment after six tidal cycles is 278.6 tonnes based upon a release rate of 1kg/s.
- 2) the above simulation assumes that no sediment which is moved out of the computational domain will return.
- 3) "North" or "South" mean dredging at the north or south edge of the navigation channel. "Middle" means the dredging in the middle of the navigation channel.
- 4) "Spring" or "Neap" mean normal fluvial flow with a spring or a neap tide.

Table 7: Simulation of Dredging/Backfilling for 42 Tidal Cycles

Tidal Cycles	Deposition Rates (%)		Mean Deposition Depths (mm)	Mean S.S (ppm)	Leaving Rate (%)	Remaining Rate (%)
	Whole Domain	SSSI Area				
2	9.6	0.00	0.0000	0.343	1.6	88.8
4	15.9	0.00	0.0000	0.474	6.3	77.9
6	20.6	0.00	0.0000	0.565	9.4	70.0
8	24.4	0.00	0.0000	0.632	11.8	63.7
10	27.5	0.01	0.0000	0.681	13.9	58.6
12	30.0	0.01	0.0001	0.728	15.5	54.5
14	32.2	0.02	0.0001	0.782	17.0	50.8
16	34.0	0.02	0.0002	0.807	18.5	47.5
18	35.6	0.02	0.0003	0.821	19.7	44.7
20	36.9	0.03	0.0003	0.829	20.8	42.3
22	38.1	0.03	0.0004	0.838	21.6	40.3
24	39.1	0.03	0.0005	0.842	22.4	38.5
26	39.9	0.03	0.0006	0.844	23.1	37.0
28	40.7	0.04	0.0006	0.846	23.6	35.7
30	41.3	0.04	0.0007	0.847	24.1	34.5
32	41.9	0.04	0.0008	0.848	24.6	33.5
34	42.4	0.04	0.0009	0.849	25.0	32.6
36	42.9	0.03	0.0008	0.849	25.3	31.8
38	43.2	0.04	0.0008	0.849	25.6	31.2
40	43.6	0.04	0.0009	0.850	25.9	30.4
42	43.9	0.04	0.0010	0.850	26.2	29.9
Final	62.6	0.04	-	-	37.4	0.0

Notes:

- 1) *the above simulation assumes that sediment which moves out of the upstream boundary will return to the domain fully, and no sediment returns from the downstream boundary.*
- 2) *total released sediment for six tidal cycles assumed to be 2,000 tonnes.*
- 3) *Leaving rate means the accumulated percentage of the released sediment moving out of the downstream boundary.*

7. Model Limitations and Accuracy

There are two main assumptions within C-DIVAST and STM, which might affect the accuracy of the modelling results. They are the hydrostatic assumption and the dispersion and diffusion process caused by turbulence.

7.1 Hydrostatic Assumption

The hydrodynamic model C-DIVAST is a depth-integrated model. It assumes a fixed parabolic profile of vertical velocity distribution. The vertical velocity profile is represented by a depth-averaged velocity. In well-mixed estuaries, considering a depth averaged water column does not pose a problem. However, if estuaries are stratified, with the surface current flowing in an opposite direction to the bed current, then a depth averaged current will not be appropriate, and considering the model as such will produce incorrect results.

Therefore, it is vital to ascertain whether or not the estuary to be modelled by C-DIVAST is stratified or well mixed. In order to achieve this, the survey data provided by EMU Environment Ltd.^[1] was examined. The survey data consisted of salinity, temperature, and current readings taken at a spring tide using an ADCP at three transects along the River Tyne.

The results from the survey indicate the presence of a salt wedge around slack water between ebb and flood flows. The salt wedge can be detected by observing the direction change in the three recorded layers: 20%, 60% and 80% of water depth below the water surface. Around slack water, from ebb to flood, the bottom (80%) current can be seen to change direction. This is caused by the flooding salt water starting to move upstream. However, the middle and upper parts of the water column remain in the same direction, hence a salt wedge is created. This situation generally lasts for less than one hour, and since the situation occurs during slack water, the current magnitudes are quite weak. Therefore the effect of the minor stratification occurring for a small time period, will not affect the overall running of the model, since the majority of the time, the water column is well mixed.

The measured water velocities were low when stratification was found to occur during spring tidal conditions. Measurements were not taken under neap tidal conditions and hence it is not clear how stratification occurs over a neap tide. According to the information provided by Environment Agency, it is believed that the salt wedge may last much longer over a neap tide with well developed flow stratification.

When the surface current flows in an opposite direction to the bed current, the model will underestimate the transport capacity of the flow. This is because vertically opposite velocities cancel each other out in a depth-averaged velocity. As a result of stratified flow, the predicted sediment travel distance during a neap tide is likely to be underestimated and the suspended sediment concentration close to the dredging area is likely to be overestimated.

Obviously, a fully three-dimensional hydrodynamic model is ideal for this study. However, the practical solution to the problem is either a depth-integrated or width-integrated two-dimensional model.

The width-integrated two-dimensional (vertical) is capable of simulating the sediment re-suspension from the riverbed more accurately since it considers the effects of stagnated zone close to the riverbed due to relatively higher density of salt wedge. However, it can not accurately model the geometric change of river banks on horizontal velocities. It may under-estimate the sediment travelling distance since in reality the velocity in the middle of the channel is faster than the width-average velocity.

In contrast to the width-integrated model, the depth-integrated model considers the effects of asymmetry of the river banks, and can produce realistic two-dimensional horizontal velocities. It is capable of modelling horizontal plume of suspended sediment caused by the proposed dredger, and it can be used to assess the impact of different dredging locations cross-sectionally.

The model was used to simulate the transport and settling process of released sediment not the re-suspension process. Therefore, it was believed that the depth-integrated two-dimensional hydrodynamic model is more appropriate than the width-integrated model.

7.2 Effects of Turbulence

The sediment transport model considers the dispersion and diffusion process caused by flow turbulence. The turbulence is modelled by a so-called "zero-equation" model based on "mixing length" theory using a constant turbulence viscosity. This may not provide an accurate estimation of flow turbulence. The latest "two equation" models are now capable of modelling turbulence more accurately. However, the required computer power for "two equation" turbulence modelling is intensive and such efforts might be meaningless when considering flow turbulence generated by ships and winds.

The flow turbulence caused by ships and winds were not considered in this modelling study. Such turbulence could introduce significant cross-sectional suspended sediment transport. At present, the results show that the trajectory of suspended sediment is stretched longitudinally with little cross-sectional movement, and significance of the dredging location.

7.3 Uncertainty of Sediment Sizes

The sediment transport model uses a uniform sediment size (D_{50}). When this assumption was applied to the modelling of the bed level change under existing conditions, the sediment transport model did not predict correctly in the upstream part of the modelled area (see Section 4.3). However, the sediment transport model was used to simulate the movement and settling of suspended sediment for a particular size of sediment. The spatial variation of the property of bed material was not relevant in this study.

The key factors for this sediment transport modelling are the estimation of sediment falling velocity, and dispersion and diffusion process. In this study, a standard formulation for solitary sediment falling velocity was used^[4]. It might introduce errors for non-standard sediment such as cohesive and flake-shape sediment.

Generally, the two-dimensional depth integrated hydrodynamic model, coupled with a quasi three-dimensional sediment transport model are suitable for this study. For a spring tide, the inaccuracy of the modelling are believed to be small (within 20-30%). The errors of modelling a neap tide might be further increased due to lack of survey data. However, the errors might only lead to more conservative values, i.e. shorter travel distance and higher suspended sediment concentration.

8. Conclusions

1. The two-dimensional (plan) hydrodynamic model C-DIVAST and quasi three-dimensional sediment transport STM have been successfully set up and calibrated. The predicted velocities, suspended sediment concentration and bed level changes compared reasonably well with the measured data and the dredging records.
2. The results show the domination of tidal force in the hydrodynamics and sediment transport in the modelled reach of the River Tyne under the normal fluvial condition. A spring tide generated flow is equivalent to 1:10 year fluvial flows. The tidal flow generated by a neap tide is approximately half of those by a spring tide.
3. The depth averaged velocity at the tunnel site will be increased by 20% by the proposed temporary structures and the storage of two tunnel units along Howdon Yard. The backwater effects by the temporary structures and storage was 23mm at peak ebb flow, which will have little impact on the flood defence standard.
4. The depth-averaged velocity at the tunnel site will be increased by 50% during 1:10 year fluvial event coinciding with a spring tide compared to the existing conditions.
5. For coarse sediments, the suspended sediment concentration did not travel far up or downstream, with most of the deposition occurring around the dredging region.
6. For dredging in fine silts, some of the suspended sediment is transported past both the upstream (Low Water) and downstream (river mouth) model boundaries.
7. Only a minimal amount of sediment arising from the dredging operation is deposited in the SSSI area downstream of North Shields Fish Quay.
8. Spring tides caused the largest movement in sediment away from the dredging location, whereas neap tides showed the largest concentration and deposition of sediments around the dredging location.
9. The magnitudes of suspended sediment concentration and sediment transport continually changes throughout the tidal cycle. Peak suspended sediment concentrations of up to 200 ppm occur around the dredger at slack water. However, these peaks are localised around the dredger and remain for only a short duration. Generally suspended concentration levels are lower than 20 ppm which compares with the "background" turbidity levels of 15 - 45 ppm recorded during the hydrographic survey.

10. Whilst peak suspended sediment concentrations occur around the dredger the majority of the water column across the width of the river at the dredging location is largely unaffected regardless of the position of the dredger.
11. Assuming 100% sediment returned from the upstream boundary to the computation domain, then the amount of sediment deposited in the domain was approximately 63%, and the rest of the released sediment was transported out of the downstream boundary after 23 day continuous dredging operation and a settling period of 2 - 3 days.
12. The total amount of sediments which cross the upstream boundary of the model during the proposed 80 day dredging operation is estimated to be 540 tonnes.

REFERENCES

- [1] EMU Environmental Ltd., River Tyne Transect Survey, Report No. 00/J/1/02/0183, May 2000.
- [2] Allied Exploration & Geotechnics Ltd., New Tyne Crossing - Preliminary Ground Investigation, June 2000.
- [3] Department of Civil Engineering, University of Durham, Hydraulic and Sediment Survey of the Estuary of the River Tyne, July.
- [4] van Rijn, L.C. (1984), Sediment Transport, Part II: Suspended Load Transport.

