Penwith District Council

Hayle Harbour
Hydrodynamic Modelling Report

Final Report – Revision R02

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Executive Summary

This report describes studies undertaken by Babtie Group Ltd on behalf of Penwith District Council to assess estuarine and coastal processes at Hayle Harbour. A need was identified at an early stage for mathematical modelling to investigate the impact of tides, currents and waves on sediment transport mechanisms within the estuary extending into St.Ives Bay.

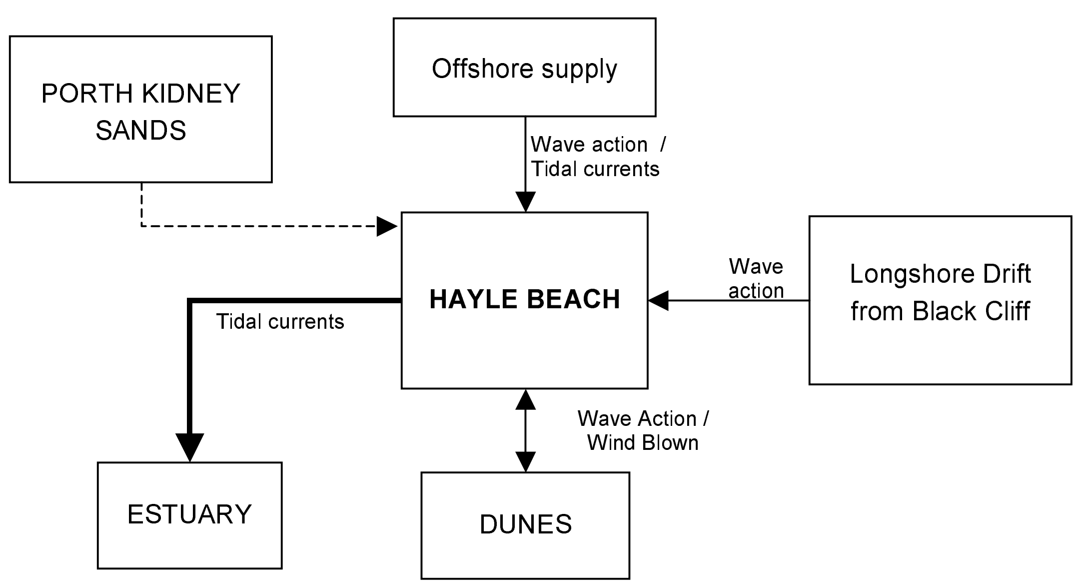
The modelling study was targeted to investigate:

- Rapid accretion of sediment in Hayle Harbour.
- Effect of dredging on sediment transport processes.
- Erosion and retreat of the Hayle Towan dune system.
- Reduction in level of Hayle Beach.
- Interaction between retreating dunes, lowered foreshore and current dredging activities.

Two mathematical models have been constructed to predict the behaviour of waves and tidal currents on sediment transport mechanisms within St. Ives Bay and Hayle estuary including the harbour. At the entrance to the estuary the combined effect of waves and tidal currents has also be investigated.

Our findings are summarised as follows:

- Hayle beach is considered as a sub cell within the St Ives Bay coastal cell (Shoreline Management Plan). The Hayle Beach sediment budget is dependent upon source material feeding into Hayle Beach and natural processes transporting material from Hayle Beach. The following schematic simply demonstrates the various natural processes occurring and the potential movement of beach sand.



- Waves play a significant role in the transport and redistribution of sediment in the intertidal zone. Waves are the principal transport mechanism initiating and maintaining transport of material at Hayle Beach. During storm events it is possible for large quantities of material to be transported seawards to an area of ebb dominated flow.

- The dominance of the flood tide over Hayle Beach results in the transport of material towards the mouth of the estuary during a spring tide, effectively squeezing the present deep-water navigation channel. The predominate wave approaches the coastline at Hayle Beach obliquely, facilitating the littoral drift of beach material towards the west and the estuary mouth.

- Possible sources of sand to Hayle Beach include offshore sources and longshore drift from Porth Kidney Sands and Beach to the east of Black Cliff. The model predicts that very little transport of material feeds Hayle Beach from offshore and littoral transport processes. Sand is being lost from the dune system local to Hayle Beach, as evidenced by the receding dune crest. In addition, lowering of the foreshore results in the beach being submerged more often, and allows wave action to penetrate further up the beach. The beach material is therefore exposed less often, and more cohesive during periods of low water, and this inhibits the growth of the dunes system by wind blown sand.

- Over recent years a reduction of beach level has been observed at Hayle Beach, while during the same period sand has been accumulating within Hayle Estuary. A review of the sediment transport mechanisms in conjunction with the model output indicates that the majority of sand presently within (and continuing to be transported into) Hayle Estuary is sourced from Hayle Beach. It also indicates that the sum of sand being transported into Hayle Beach is less than the amount of sand being transported from Hayle Beach, hence supporting observations of a reduction of beach levels.

- Two possible scenarios may be considered in relation to the future evolution of the Hayle Beach and Estuary system:

  1. Without further intervention, beach levels may eventually stabilise. Thereafter, if the current natural processes continue, then sand offered to Hayle Beach from the dunes, offshore and adjacent beaches could continue to be transported into Hayle Estuary until an equilibrium is reached.

  2. The process of sedimentation presently occuring within Hayle Estuary, and supply of material to Hayle Beach from the dune system may be part of a natural cycle, where estuaries undergo long periods of accretion followed by long periods of erosion.

- It is unlikely that past and present dredging operations at Hayle are the sole cause of the present coastal processes occurring at Hayle Beach, and the subsequent accretion of sand within Hayle Estuary.

- The volume of material being dredged each year (up to 30,000 tonnes) can be approximated to a volume of 15,000m^3. This is equivalent to a depth of around 5mm over the entire area of the St Ives Bay coastal cell, or 110mm over the area of the Hayle Beach sub-cell. If no material was supplied to Hayle Beach from the dunes or from other longshore / offshore sources, and all the material dredged from the estuary was sourced from Hayle Beach, it might be expected that a reduction of beach level of 1m could occur over about a 10 year period.

- While dredging sand from the estuary is probably sustaining the natural processes by the permanent removal of sand from the sub-cell, the cessation of dredging will not in itself arrest the erosion of Hayle Beach or dunes. Removal of material by dredging does however mean that the estuary is unable to reach a 'natural equilibrium' under the prevailing hydrodynamic regime. In addition, if a change occurred in the hydrodynamic regime (eg increased ebb flows within the estuary), this material would no longer be available to replenish Hayle Beach.

The modelling work undertaken to date has been calibrated to HR Wallingford's physical model, and therefore represents the conditions in the estuary approximately 20 years ago. This model has identified credible mechanisms that support the observed evolution of the estuary during the intervening period.

We would recommend that a simple monitoring scheme be implemented to record the position of the dune crest and toe at 3 month intervals, to assist in determining the rate of dune recession and sediment released into the sediment transport sub-cell from this source.

1.0 Introduction

During June 2002 Babtie Group was commissioned by Penwith District Council to undertake an assessment of estuarine processes at Hayle Harbour. A need was identified at an early stage for mathematical modelling to investigate the impact of tides, currents and waves on sediment transport mechanisms within the estuary extending into St.Ives Bay.

This report outlines the results of the modelling study undertaken to investigate the estuarine processes in Hayle Harbour and St Ives Bay in the context of dredging operations.

This study follows on from extensive work undertaken by a number of organisations since the 1980's, most of this work relating to previous proposal for development of the harbour. Physical modelling data produced by HR Wallingford during 1989 forms the basis of the current mathematical modelling. Previous investigations carried out include:

1. Hayle Harbour – Hydraulic and siltation studies, HR Wallingford 1989.
2. Water Level Control in Hayle Harbour, Sir Alexander Gibb & Partners 1989
3. An Investigation of Sediment Dynamics in the Hayle Estuary Cornwall, Sea Sediments 1983.
4. Cornwall & Isles of Scilly Coastal Group, Lands End to Hartland Point Shoreline Management Plan, Halcrow Group 1999.

This study utilises data collected, collated and analysed during these studies.

The issues investigated during the modelling study were:

- Rapid accretion of sediment in Hayle Harbour.
- Effect of dredging on sediment transport processes.
- Erosion and retreat of the Hayle Towan dune system.
- Reduction in level of Hayle Beach.
- Interaction between retreating dunes, lowered foreshore and current dredging activities.

2.0 Background

Hayle Estuary is located on the north coast of Cornwall within the coastal cell of St Ives Bay (Figure 1), which extends from Clodgy Point to Godrevy Point. These headlands are approximately 8km apart and the bay is approximately 3.5km in width. At the centre of the bay is Hayle Estuary, which lies at the mouth of the Rivers Hayle and Angarrack.

The name 'Hayle' derives from the Cornish word 'hayl' or 'heyl', meaning 'tidal flats' or 'estuary'. Until the 16th Century, quite large ships were able to sail for over a mile up the Hayle Estuary, when the River Hayle was navigable. In later years, the river became choked with silt washed down from the mine workings in the surrounding countryside.

The history of modern Hayle began in the early 18th Century when local businessmen began to exploit the commercial potential of the Hayle Estuary in connection with Cornwall's developing copper and tin mining industry. Smelting of copper ore established Hayle as an industrial centre during the 18th Century and there were numerous furnaces at work in the eastern area of the town, long since known as Copperhouse. Figure 2 illustrates the layout of Hayle Estuary circa 1789.

By the end of the 18th Century, Hayle's industrial enterprises were sufficiently great that the town prospered both as a port and as a major centre of Cornish mine engineering, industry and shipbuilding and as one of the main engineering centres of Southern England. Most of the currently existing harbour quays and buildings were constructed during the 18th and 19th Centuries.

Despite the closure of the metal foundries in 1903, Hayle continued to be a thriving port until the Second World War, when it served as a base for ship building, armament production and chemical industries. During the post war years the town experienced industrial decline and although the harbour remained active until the 1960's, commercial shipping ceased during 1970's. Nowadays the harbour supports a small fishing fleet.

Extensive dune systems occur on both sides of the estuary mouth. These dunes and associated beaches form an important feature of Hayle's tourism economy, attracting large numbers of visitors every year.

Over the past 20 years extensive redevelopment plans for the harbour and surrounding area have been proposed. The latest proposals include a tidal barrage at the entrance to the harbour and the subsequent development of a marina. Although investigation of a barrage and associated impacts on estuarine processes is not considered in this report, it is useful to place this study in the context of the overall development proposals for the harbour.

There has been a long history of sand extraction from the estuary, primarily to maintain a navigable channel for shipping. Since 1973, annual tonnage of dredged material has been estimated to be approximately 25,000 to 30,000 tonnes. More recently (Oct 2001 to Feb 2002) dredging of the harbour removed approximately 18,000 tonnes[1]. Historically, dredging has been concentrated within the inner harbour area and the channel extending from the mouth of the estuary to the outer bar. The most recent dredging operation has been concentrated at the entrance to the inner harbour.

Natural processes and human intervention have, over time, influenced the Hayle Towans to the east of the estuary mouth. Tipping of man made material during the late 1940’s and early 1950’s, together with windblown beach sand has probably assisted in the development of the dunes. In more recent years, it has been noted that the dune system has retreated exposing previously tipped material. Although this is perceived to be a ‘recent’ occurrence, observations made by Sea Sediments in 1983 also identified the exposure of man made debris together with the accumulation of windblown material further east towards Black Cliff, an area that is presently continuing to accumulate sand.

With the loss of sand from Hayle beach and retreating dune system, dredging of the harbour has recently become a concern. The local community are concerned that the loss of beach sand and retreating dune system might be a direct result of the current dredging operation.

Previous physical modelling of the estuary by HR Wallingford demonstrated that during a spring tide there is a net accretion of sediment within the estuary. This finding is not surprising given that dredging operations within the estuary have been necessary since the harbour was built to maintain a navigable channel. Since the cessation of dredging operations earlier this year, sediment has continued to accrete within the estuary, impeding the safe navigation of fishing vessels. It is thought, by local residents and fishermen, that the rate of sand accretion has accelerated and during September 2002 dredging recommenced in order to maintain a safe navigable channel.

The Hayle Estuary is the most westerly estuary in England and the Lelant Water is probably the largest muddy feeding ground for birds in the southwest Cornwall. This area has been designated a Site of Special Scientific Interest (SSSI) i.e. an area of recognised scientific value in terms of its flora and fauna. The inter-tidal mud flats found in the Lelant Water are important feeding grounds to migrating and resident birds. HR Wallingford, 1989, observed that some of the mudflats had been covered with sand accretion. This process appears to be continuing to the present day with the loss of valuable wildlife feeding grounds.

Following the reported increased rates of accretion of sand within Hayle Harbour and the wider estuary, Penwith District Council commissioned Babtie Group to investigate current estuarine processes including hydrodynamics, wave climate and sedimentation.

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[1] Statement from D.G.Williams of DGW Sand (Dredging contractor working for Hayle Harbour Company 15/07/02.

3.0 Coastal Processes Overview

The morphological development of estuaries is extremely dynamic and is often unpredictable both at local scale (eg meandering drainage channels) and at the wider scale, where whole estuaries may undergo long periods of accretion followed by long periods of erosion.

It has been reported that Hayle Harbour has been experiencing an increased rate of sediment accretion over the last year. This section gives a general overview of the principal natural processes and how these typically affect sediment transport in the coastal/estuarine environment.

3.1 Tides

Coastal water levels fluctuate in a regular and predictable fashion in response to the gravitational effects of the moon, sun and planets upon the oceans of the earth. The tidal range varies from tide cycle to tide cycle in response to the ever-changing relative positions of these bodies. However, the tidal range undergoes a regular fortnightly cycle, increasing to a maximum over a week (Spring Tides) and then decreasing to a minimum over the following week (Neap Tides), because of the monthly orbit of the moon around the earth.

Currents within the estuary are influenced by freshwater and tidal flows, where tidal flow is normally the predominate force in estuarine sediment transport. Freshwater effects are generally small (but often of significance with respect to water quality) except during times of fluvial flood. In addition to tidal flows the salinity behaviour within the estuary may generate small secondary currents, which may have a significance effect with respect to mixing and sediment transport.

The vertical rise and fall of the tide produces horizontal flows in the form of tidal currents. The magnitude of these currents is dependent upon a number of physical factors including entrance characteristics and the tidal prism. The incoming tide is referred to as the ‘flood tide’ and the outgoing tide the ‘ebb tide’. The magnitude of the ebb and flood tide velocities continually vary with Spring / Neap tidal cycles.

Tidal distortions in shallow estuaries usually result in flood tides having a shorter duration than the ebb. If the tidal range is of a comparable magnitude to the depth of the estuary, the propagation of the tide at high tide is significantly faster than at low tide and hence the rise of the tide is measurably faster than its fall. Consequently, the peak flood tide velocities tend to be greater than peak ebb tide velocities and this has considerable importance when considering sediment transport.

3.2 Waves

Waves are predominately generated by the effect of winds and more intense waves are generated by faster wind speeds, deep water and long distances to land i.e. fetch length.

Wave heights, and the forces they generate, are smaller within estuaries and coastal inlets when compared to the open sea. This is the result of shallower water and shelter provided by surrounding land and hence historically these areas have tended to accumulate sediment

Waves have a significant impact on the coastline at the mouth of the estuary, where the predominant mechanism of erosion is wave action. There are two types of wave conditions that should be considered; swell waves and storm waves. These two wave types result in two different responses from the beach. Low swell waves conditions prevail the majority of the time, and usually wave energy is dissipated easily by the beach's natural defence mechanisms. However, during storm periods wave energy is increased and if the beach is unable to respond by dissipating wave energy, large sections of the beach can be eroded away.

During low swell wave conditions, a wave moving towards the shoreline confronts a sloping bed and as the water depth decreases the wave height increases until the wave is not sustainable, at which point it breaks. Breaking waves result in the dissipation of wave energy, the generation of turbulence causing sediment to be lifted off the bed and swirled around by the turbulent waters. The beach profile is able to adjust itself to respond to small changes in incoming wave energy by a seaward transport of beach material to an area where the bottom water velocities are sufficiently reduced to cause sediment deposition. This deposition of material forms an offshore bar which in turn causes the waves to break further offshore, widening the surf zone over which the wave energy is dissipated.

During storms, strong winds generate high waves with a steepened profile. The wind also often creates a storm surge which raises the mean water level covering parts of the beach which would not normally be in contact with the sea. This increase in water level allows the storm waves to travel over the majority of the surf zone without breaking. Eventually the storm waves break, however, the remaining width of the surf zone is unable to dissipate the wave energy sufficiently and the excess wave energy erodes the beach and possibly the dune system located at the beach head. The eroded sediment is transported to the offshore bar where it is deposited in large quantities. This bar causes storm waves to break further offshore thus reducing the amount of energy spent on the beach. This process is illustrated in figure 3.

Dunes play a significant role in the beach’s natural protection against wave attack and hence they are extremely valuable. The beach and dune systems are interrelated with material being naturally exchanged between the two systems. When sand dries on the foreshore, the particles are no longer cohesive and may be transported to the dunes by the wind. Conversely, the dune system acts as a sand reservoir with sand released from the dunes eroded by wave action during storm events, replaced that lost from the foreshore and helps to raise and flatten the beach profile. This natural process aids in dissipating wave energy within the inter-tidal zone and prevents the further erosion of the dune system.

3.3 Littoral Sediment Transport

Three modes of transport can be identified supplying sediment into Hayle harbour and Lelant channel: wind, fluvial and tide.

The Shoreline Management Plan (SMP) reports that dune and beach material in this area has a high carbonate content and concluded that the main source of sediment is derived from offshore sources. It also reports that it is difficult to speculate as to whether supplies of material from this source will continue into the future.

Other sources of material include those derived from fluvial sources such as the Rivers Hayle and Angarrack, however it is again uncertain whether this material is eventually transported into St Ives Bay as the flushing characteristics of the estuary are considered to be low.

The third transport mechanism, wind, can have a significant impact on the accumulation of material at the head of the beach profile and the subsequent formation of dunes. It is noticeable that wind blown sand is accumulating in the area immediately to the east (towards *Black Cliff*) of those dunes that are currently suffering from wave erosion (Plates 1 & 2). Wind may also be attributing to the local redistribution of tidally transported material within the harbour during low tide.

In the coastal environment the main mechanism for initiating and maintaining movement of sediment is oscillatory wave action as described above. This can result in large quantities of material being removed from the beach profile and similarly result in the accumulation of material. Wave action together with tidal currents also results in the littoral drift of sediment and this process is prevalent within St. Ives Bay.

The net movement of sediment within St Ives Bay by littoral drift mechanism is predominately from west to east. Evidence of this transport pattern is given by the formation of the spit extending from Porth Kidney Sands to the east across the estuary mouth.

Littoral transport is caused by breaking waves stirring up sediment, which is then transported up-beach by the up-rush of water. If the incoming wave is at an angle to the shoreline then the initial direction of the sediment movement is directly related to the angle of the incident wave. The backwash, however, is perpendicular to the beach contours, so the sediment follows a path similar to a 'zig-zag' as illustrated in Figure 4.

The rate of longshore transport is dependent upon the angle of the wave approach, duration, and wave energy. Thus large waves will generally move more material than low waves.

The mathematical model that has been constructed of St Ives Bay and Hayle Harbour has been used to investigate the interaction of the above processes.

4.0 Hydrodynamic Model

The Mike21 suite of software was used to model the hydrodynamics within St.Ives Bay and the Hayle Estuary.

4.1 Model Set-Up

The hydrodynamic model consists of two grids:

i) Grid A covering St.Ives Bay and the Hayle Estuary, which has a grid spacing of 30m, and
ii) Grid B covering the Hayle Estuary and the dunes at the mouth of the Estuary, which has a grid spacing of 10m.

The extent of both grids is shown in Figure 5, which illustrates Grid B lying within Grid A. This modelling technique, known as 'nesting', allows examination of an area of concern (Grid B) in relatively fine detail, whilst accommodating the interaction of processes on a wider scale and being economical in the amount of computation time and memory.

The bathymetric data for the model was collated from a number of sources, including:

- Admiralty Chart No. 1168 - Harbours on the North Coast of Cornwall
- Bathymetric Survey from Sea Sediments Study, 1983
- Nationwide Surveys topographic survey 2000.

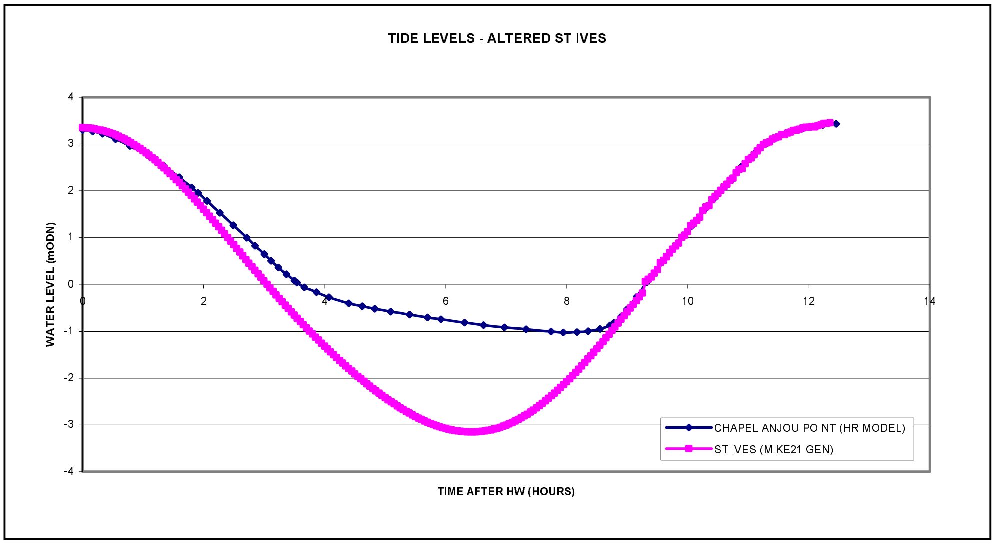
The data on the charts were digitised in-house and converted to a uniform datum and co-ordinate system. This information was then imported into the Bathymetry Editor facility in Mike21 and the two grids were interpolated from the collated data ready for use in the hydrodynamic module of Mike21.

Figures 6 and 7 illustrate the bathymetry for each of the model grids.

4.2 Model Calibration

Once the grids were set up, the Mike21 model was calibrated using data from HR Wallingford's physical model.

HR Wallingford's model covered the estuary only and the boundary condition for their model was a tidal curve based on measurements taken at Chapel Anjou Point on the 10th January 1989. As the Mike21 model extent is larger than the physical model, the boundaries are not coincident and a different tidal curve had to be prepared for use as a boundary condition. Using the Tidal Prediction Tool in the Mike21 software, the tidal conditions for St Ives were produced for the same period as the HR Model (see below). This was then used as the input to the model along the northern boundary of Grid A.



The Environment Agency (EA) provided flow measurements for the River Hayle from the St Erth gauge for January 1989. The flow for the 10th January 1989 was extracted and the mean flow for that period calculated. No information was available for the Angarrack Creek from the EA so the flow information provided in the Sea Sediments Study was adopted.

Source	**Flow (m^3s^{-1})**
River Hayle	1.139
Angarrack Creek	0.150

Calibration points were selected to correspond to those for which water level and velocity information were available from the HR Wallingford report. The locations of these calibration points were determined from a figure contained within the HR Report, which does not display a co-ordinate system. The locations were therefore determined by measuring the distance and orientation from a common point (the end of Middle Weir) and then converted to a grid reference within the Mike21 Grid. We have adopted HR Wallingford's naming system for the calibration points as listed in Table 1. The locations of the points are shown in Figure 8.

4.2.1 Calibration of Water Levels

Water levels at the six calibration points were extracted from the Mike21 model results and compared against the results from the HR Wallingford physical model.

Graphs showing the water levels predicted by both models are provided in Figure 9 (a)-(f). These curves were analysed based on two indicators: shape and magnitude.

	Water Level - Evaluation of Goodness of Fit	
Point ID	Shape	Magnitude
A	Good shape correlation.	Low water level lower than in HR Model.
B	Good shape correlation. Minor temporal shift in ebb and flood.	Low and high water levels compare well.
C	Good shape correlation. Minor temporal shift in ebb and flood.	Low and high water levels compare well.
D	Good shape correlation. Minor temporal shift in ebb and flood.	Low and high water levels compare well.
E	*See discussion in text.*	
F		

(All six of the water level locations in the HR model coincided with the locations of the tide gauges deployed during the physical survey in 1989.)

The water levels compare well in four of the six locations. Points E and F proved difficult to calibrate, as they are located within the two pools that are partially impounded. By limiting the width of the orifice and adjusting the level of the bed at that point, it is possible to represent the weir within the model. However, whilst the width of the weir could be ascertained from the survey carried out by Babtie Group, no information was available on the level of the weir. Hence, an approximation was used based on observations made during the site visit.

At present, water flow in and out of the Carnsew Reservoir is controlled by a series of four gates and a weir at the entrance to the pool. The gates are permanently fixed with two being closed, one being open and the remaining gate being half open. This is also difficult to represent in the model. There is a trapezoidal weir inside the pool, which has a varying crest level. This structure ensures that a certain level of water is retained in the Reservoir at low tide.

In addition to the complications encountered as a result of the control structures, it also became evident that the 'first guess' of initial water level within the two pools had a significant influence on both the predicted water levels and the timing of the water level peaks in the pools in relation to the tide conditions at the boundary. In comparison to the HR Wallingford model, where the effects of a new sluicing regime were an integral part of the proposed harbour development and hence the physical model, our study concentrates on the regime at the mouth of the estuary. Although both pools contribute to the tidal prism, it was decided that the achieved degree of correlation with the available calibration data was sufficient for the purposes of this study.

4.2.2 Calibration of Flow Velocities

The predicted velocities were compared at 12 locations within the Estuary and the results are presented in Figure 10 (a)-(l). On the whole, the flow velocities in the Mike21 model compared relatively well with the physical model.

	Evaluation of Goodness of Fit	
Point ID	Shape	Magnitude
1	Moderate shape correlation	Good correlation of peak ebb velocities. Slightly under predicted flood velocities.
2	Shape comparable	Good correlation of peak ebb velocities. Flood velocities over predicted slightly.
3	Moderate shape correlation	Good correlation on peak ebb velocity. Peak flood velocities slightly high.
4	Moderate shape correlation	Peak ebb velocity low. Peak flood velocity low.
5	Moderate shape correlation	Peak ebb velocity good match. Peak flood velocity slightly high.
6	Poor shape correlation *Point 6 is located adjacent to Lelant Quay. It is likely that there was a local phenomenon present in the physical model that the Mike21 model was unable to replicate, despite various amendments to the bathymetry.*	Poor match on velocities.
7	Moderate shape correlation	Peak ebb and flood velocities slightly low
8	Good shape correlation	Peak ebb and flood velocities slightly low
9	Good shape correlation	Good correlation on both ebb and flood velocities
10	Point too close to nesting boundary to be reliable but shape and magnitude moderate.	
11	Moderate shape correlation	Peak ebb and flood velocities slightly low
12	Moderate shape correlation	Peak ebb and flood velocities slightly low

(Points 1 to 3 in the HR Wallingford model coincided with the location of current meters in the physical survey.)

An additional analysis of the peak ebb and flood velocities was carried out to provide a tangible indication of the correlation between models. This analysis is shown in Table 2. A range of velocities based on ±20% of the peak ebb and flood velocities was established for the HR model results and the results of the Mike21 model compared against these. The ebb velocities compare better than the flood velocities, whilst overall the average percentage differences for peak and ebb is 39% and 40% respectively.

4.3 Conclusions of Calibration Exercise

The degree of correspondence achieved during this calibration exercise was considered sufficient to give confidence that the model is capable of reproducing the important aspects of the tidal flows within the estuary with adequate precision.

It should be noted that model verification was not undertaken at this stage. This would require an up-to-date set of measurements from the estuary against which the calibrated model would be tested.

5.0 Wave Model

Wave modelling was not included within the original brief as the primary area of concern is the estuary, in which there is little wave action due to the nearshore bathymetry and the width of the estuary mouth. During the site visit, the degree of sediment entrainment with only moderate wave action along the dunes to the east of the estuary mouth was notable. It was then proposed that an investigation of the wave induced sediment transport be included in the study and this was agreed with Penwith District Council.

5.1 Model Set-Up

Halcrow undertook wave modelling as part of the production of the SMP for the area. This previous wave modelling, using a refraction model, produced inshore wave climate information for three points local to Hayle: St Ives, Carbis Bay and Gwithian. No inshore wave climate data was provided for the area adjacent to the mouth of the estuary.

The inshore climate information for the three locations was presented as a wave height, wave period and direction table for a range of return periods. No discussion was provided on the combination of wind, wave and water level conditions used to determine the extreme wave conditions.

In order to derive the wave conditions at the mouth of Hayle Estaury, the SWAN (Sea WAves Nearshore) software package was used to model the nearshore wave climate in St Ives Bay. Two model grids were constructed – a 100m spaced grid covering from deep water to the coast and a smaller 30m grid which covers St Ives Bay only. The grids are shown in Figures 11 and 12.

The Shoreline Management Plan (SMP) reports that the offshore wave climate is dominated by waves from the south west, with wave direction being in the 240º and 270º sectors for over 60% of the time. In contrast, the direction of the most extreme offshore storm waves is 300ºN.

The prevailing wind direction, 240ºN, is a longshore wind at Hayle, and is therefore not significant with regard to onshore wave activity. The most active sector producing onshore winds at Hayle is northwest to north.

Taking account of the wind and wave information available, and the orientation of St Ives Bay, it was considered appropriate to evaluate the effect of waves from 300ºN. It is, of course recognised that the Hayle Beach coastal sub-cell is exposed to wave action from sectors from 300ºN to 30ºN, but it is not expected that wave action from this range of directions would significantly alter the findings in this report.

Using the offshore wave data, wind data and extreme water level analysis provided in the SMP, the offshore waves from 300ºN were transformed inshore using the 100m grid. The distribution of waves along the line coincident with the boundary of the smaller 30m grid were extracted and used as boundary input for the 30m grid runs. Wave conditions at Carbis Bay and Gwithian were compared to the results of the Halcrow model (Table 3). The wave conditions at Gwithian were seen to compare well for various combinations of offshore wave condition, wind speeds and water levels, although there is a general under-prediction of significant wave height with respect to the SMP. It is considered that this discrepancy is due to the more sophisticated model used in the current study. The modelling undertaken for the SMP used a first generation wave ray tracking procedure, which would not include many relevant processes such as wave-wave interaction, bed friction and depth induced breaking, which are included in SWAN. Predicted wave conditions at Carbis Bay were significantly lower than that recorded in the SMP and in fact the significant wave height is limited to approximately 2.5m. This limited wave height is probably a result of the shelter afforded by the headland at St.Ives Head and the effects of refraction.

Figure 13 illustrates the predicted effect of wave refraction on a 5 year return period wave height within St.Ives Bay. Due to Carbis Bay and Porth Kidney Sands being sheltered from the predominant wave (300º North) the predicted inshore significant wave heights are small (approximately 1.0m). Further to the east at Hayle Beach and Black Cliff the coastline is prone to direct wave attack from the predominant wave and consequently the predicted significant wave is larger, approximately 2.4m.

A comparison of Figures 13 and 14 illustrates the sheltering effect of St Ives Head. It can be seen that for the 20 year conditions, there is little change in the wave climate within Carbis Bay for the 5 and 20 year return period waves, but increased wave heights at the more exposed site at Gwithian.

Long period swell wave action was also modelled, as shown in Figure 15. The grids presented in Figures 13 to 15 were used in the sediment transport modelling. Predicted wave heights at two sediment transport analysis positions are listed in Table 4.

6.0 Model Runs

The hydrodynamic model was used to assess the sediment transport for the following conditions:

1. Spring tide, no waves
2. Spring tide with a 1:5 year wave condition
3. Spring tide with a swell wave condition

Simulations were carried out using the ‘existing’ bathymetry and also for simulations where there had been a lowering of the foreshore at the east of the mouth of the estuary. The ‘existing’ and amended bathymetry is shown in Figure 16.

An average spring tide for St Ives was generated using the TIDECALC software developed by the UK Hydrographic Office and used as the boundary condition along the northern edge of Grid A. It is considered that the average spring tide, that reoccurs in nature every fortnight and last for approximately 4 days, is representative of the prevailing condition that is disturbing and transporting sediment within the estuary.

The sediment grading curve developed by HR was adopted for this study, as significant alterations in the composition of the sediment within Hayle Estuary were considered unlikely. The sediment is characterised by its median grain size and its grading:

median grain size: d_{50} = 0.35mm

grading: $\sigma_g = 1.386$

The mathematical model provides a number of sediment transport equations for current only sediment transport. Initial runs were carried out using two total load formulations: Engelund & Hansen and Ackers & White. The application of these methods can result in very differing estimates of the volumetric transport rate. The difference between results from the two methods increase with increasing velocity. For example, it is understood that both methods show very small transport rates for velocities less than 0.5m/s, whereas currents in excess of 0.5m/s result in a rapid increase in sediment transport. At current velocities greater that 1.5m/s, the Ackers & White method may predict approximately four times the values given by Engelund & Hansen.

A comparison of the methods of Engelund and Hansen and Ackers and White is shown in Table 5. The comparison shows that there is little difference between the two methods probably a result of predicted current velocities in Hayle Estuary seldom being greater than 1.5m/s. The Engelund & Hansen equations were selected as appropriate for modelling sediment transport within the estuary.

13 point locations (i to xiii – see Figure 17), and 6 cross sections (A to E – see Figure 18) were selected for sediment transport analysis. In addition, a cross section at Black Cliff was analysis to confirm that the model correctly reflected the SMP sub-cell boundary, and the cross section through the mouth of the estuary (Section B) was analysed in detail to evaluate the variation in the sediment transport potential across the cross section.

The model was run for a simulation period of seven days and the results for the last tide cycle were extracted. These are presented in Figure 19 to 38, which show the results for different simulations on the same graphs for ease of comparison between simulations.

For the individual points, results are presented as potential sediment transport rates per linear metre over time ($m^3/s/m$). For the 6 cross sections, the results are presented as potential sediment discharge across the cross section over time (m^3/s).

In the case of sediment transport due to combined waves and current, the Bijker formulation was used to calculate the transport.

Using the transport curves and the sediment characteristics, the weight of sand potentially transported can be calculated for the ebb and flood tides. Adding these together allows us to determine the load over the full tidal cycle.

The reader should also be aware of the definition of 'Potential Sediment Transport Rate', which is referred to in the analysis. The important word here is 'potential'. The model will predict estuarine hydrodynamics and sediment transport patterns for a given condition. The sediment transport rate gives an indication of the amount of sediment that could be transported if material was available to be moved. Similarly, the calculation of the potential weight of sand transported is the weight of sand that would be transported if that quantity of material were available for transportation.

7.0 Modelling Results and Analysis

Two mathematical models (SWAN and MIKE 21) have been constructed to predict the behaviour of waves and tidal currents on sediment transport mechanisms within St.Ives Bay and Hayle estuary including the harbour. At the entrance to the estuary the combined effect of waves and tidal currents has also be investigated.

This chapter presents our findings of the modelling exercise and offers discussion and analysis of the results with respect to the present sedimentation process that is occurring within Hayle Harbour.

7.1 St. Ives Bay

Modelling of St. Ives Bay has assessed the combined effects of waves and tidal flows on sediment transport processes that are attributing to the general reduction of Hayle beach foreshore levels and the erosion of Hayle Towans dunes located at the head of the beach.

Water movement and consequently sediment transport in the inter-tidal zone extending from the estuary mouth are influenced by tidal flows and oscillatory waves. The combined effect of these two natural processes has a significant role in shaping the coastline through transportation and redistribution of sediment.

The combined effect of waves and tidal flows has been investigated at 7 points within St.Ives Bay at Carbis Bay, Porth Kidney Sands, Hayle Beach and Black Cliff (refer to Figure 17). At each point the potential sediment transport rate has been compared for a spring tide with no wave condition, spring tide with a 5 year return period wave and a spring tide with a moderate swell wave from the predominate wave direction (300º North). The results are presented in Figures 19 to 25.

At all locations the effect of wave action upon potential sediment transport is dramatic. For example, Table 6 and Figure 22 show the impact of a 1:5 year wave during a spring tide at Point iv. Sediment transport induced by tidal flow alone results in a net movement landward of 0.018t/m. However, this can be considered insubstantial when compared to the wave-induced transport at the same point of a magnitude of 0.67 t/m.

The results confirm that waves play a significant role in the transport and redistribution of sediment within the inter-tidal zone. It is also interesting to note that the potential net weight of sediment transported in a spring tide increases with location to the east. This is a result of calmer wave conditions at Carbis Bay and Porth Kidney Sands due to wave refraction and the shelter provided by the St Ives headland from waves originating from the 270º to 300º sectors.

7.2 Hayle Beach

Hayle Beach has, over recent years, experienced a reduction in beach levels and it has been suggested that beach levels have fallen by approximately 1m. Plate 9 shows the extent of Hayle beach on the 3rd September 2002 and the exposure of course gravels and rock that have previously been covered with sand. Some of this material is manmade debris, exposed from the eroding dune face.

A reduction in beach levels is directly related to the sand budget. The available sand budget is affected by the quantity of sand supplying an area and the quantity of sand being removed. Obviously, a reduction in beach levels (and consequently a reduction in the sand budget) highlights that the net movement of sediment is away from Hayle Beach. The Mike 21 model has been used to investigate the transport mechanisms causing the net effect of removing sand from Hayle Beach.

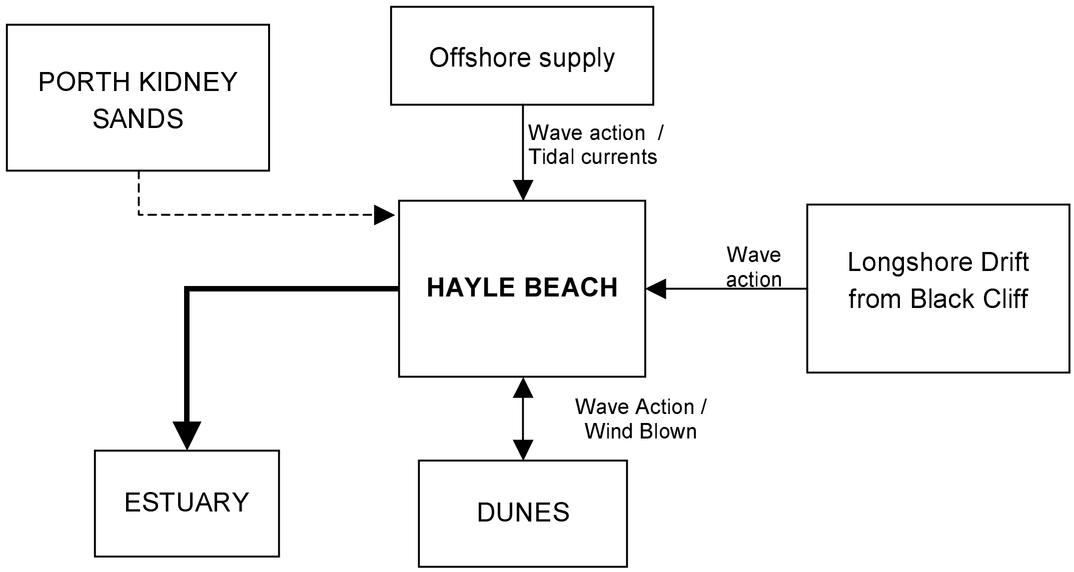
Analysis Points vi and vii are local to Hayle Beach. Point vi is located in the deep-water navigation channel seaward of Hayle Beach and point vii is located within Hayle Beach's inter-tidal zone. (Refer to Figure 17). Sediment transport at both locations is greatly influenced by wave action when present.

The predicted high quantities of sediment that can potentially be transported at Point vi from a combination of a spring tide and moderate wave action is a result of increased local wave condition and tidal flow in this area. Tidal flow at Point vi is significant, accounting for approximately 25% of the net potential transport rate seawards, whereas at points i to v and vii the tidal flow accounts for only 2%. The strong ebb flows are due to the restricted size of the channel and a large proportion of the ebb tide passing through it as water levels falls with the tidal cycle.

This area of strong ebb tidal currents bounds the seaward edge of Hayle beach such that any beach material that is transported seaward by wave action is likely to be removed further seawards by these strong ebb flows. For this potential seaward transport of sediment within the navigation channel to be realised, a sediment budget has to be available for transportation. Hayle Beach and the Hayle Towans provide a massive budget of sand that may become highly mobile under certain wave and tidal conditions.

The main transport mechanism that will potentially transport large quantities sand seawards is wave action. The process of wave action and beach response has been previously discussed in Section 3.2. During storm events it is possible that large quantities of sediment may be transported seawards towards the area of ebb dominated flow. Any beach material that is fed into this area is likely to be transported seawards by strong ebb flows and lost from the Hayle Beach sand budget. The present model is not sophisticated enough to represent this dynamic process in detail, but it does give an indication of the potential amount of sediment that is disturbed by wave forces.

Although the mechanism outlined above may be a contributory factor resulting in the reduction of Hayle Beach levels, it is also important to consider the coastal processes that may feed sediment into Hayle Beach. It is considered that there are three sources that could feed material to Hayle Beach and these are from offshore, the estuary and from adjacent coastlines:



The model indicated that very little sediment is derived directly from offshore sources, as a seaward movement of sediment dominates the lower reaches of Hayle Beach. The offshore spit would also provide a natural barrier for the transportation of sediment directly on Hayle Beach.

Similarly, it is unlikely that sediment from the estuary is feeding Hayle beach as the estuary is presently accreting sand, suggesting that the natural flushing regime is unable to remove sediment seawards.

The Shoreline Management Plan (SMP) indicates that the net littoral drift due to tidal current and wave action within St. Ives Bay as a whole is from west to east; however, the SMP does not offer any indication of the direction at Hayle Beach.

An indication of sediment transport patterns on Hayle Beach is however given by analysing the results from Point vii. Here the tidal influence is low and once again the local wave climate has a significant role in the movement of sediment. The model predicts that at this point the net transport of sediment (0.816t/m) is landward towards Hayle Beach during a combined spring tide and 1 in 5 year return period wave (see Table 6). The magnitude of flood flow velocities increase towards the mouth of the estuary and this is illustrated in Figure 40 which shows the magnitude and direction of the flood flow during mid flood.

It is interesting to note the direction of the tidal currents in the area to the east of Hayle Beach. The model predicts that tidal currents here are predominately towards the east (Black Cliff) and not towards Hayle Beach and Estuary. This will affect the quantity of sediment that is fed into Hayle Beach.

Figure 26 shows the net movement of sediment by tide and wave action through a section taken at right angles to the coastline at Black Cliff. The results indicate that there is little transport of beach material from east to west at Black Cliff. This confirms the findings reported in the Shoreline Management Plan.

Although the ebb flow dominates at the mouth of the estuary, the relationship between water surface elevation and flow velocities is important.

Maximum velocities and sediment transport rates occur at approximately mid tide. However, as the water level reduces, Hayle Beach is exposed and is therefore not affected by ebb tidal flows. Point vii is located within the inter-tidal zone of Hayle Beach where flood flows are the dominant force with respect to sediment transport. At Point vii the beach is dry at +0.25mOD and the maximum ebb flows occurring within the navigation channel and do not affect Hayle Beach.

The dominance of the flood tide over the inter-tidal zone of Hayle Beach is resulting in the transport of mobile beach sediment towards the mouth of the estuary, effectively squeezing the present navigation channel. This has the net result of confining the ebb flow within a restricted channel thus increasing the ebb velocities. An increase in velocities has been observed by local fishermen who have commented on the difficulties of returning to the harbour during the ebb tide.

As already highlighted, wave action plays a significant role in the movement and re-distribution of sediment within the inter-tidal zone and the impact of waves should also be considered.

The wave modelling undertaken as part of this study for the 1 in 5 year condition predicted an inshore wave direction of 323º N at the toe of Hayle Beach. The offshore wave direction is 300º N, indicating that the waves are refracted as they approach Hayle Beach.

The coastline at Hayle Beach is orientated such that it faces 285° N. Waves approaching the coastline obliquely at 323°N will result in a drift of sand towards the mouth of the estuary. This process was observed during the site visit and is recorded in Plate 10, in which it is possible to identify the wave crests approaching the shoreline obliquely.

Plate 10 also illustrates how the beach head at this section of coastline is prone to direct wave attack. Waves can be seen breaking on the extensive beach profiles at Porth Kidney Sands to the west and beach to the east of Black Cliff, but not in the area between. A reduction in beach levels results in deeper water and therefore larger waves are sustainable. These waves are also able to penetrate further up the beach profile. It is evident that the high water mark is currently very close to the toe of the dune system. Wave conditions were considered to be calm on the day of the site visit; however, during storm events with increased water levels and wave height the problems associated with dune erosion can be expected.

Wave modelling has also been performed with a lowered Hayle beach profile to assess the differing wave climate (see Figure 41 for 1 in 5 year condition). When compared with the predicted wave heights for the 'existing' bathymetry (Figure 13). The lowered bathymetry results in larger inshore waves penetrating further up the beach profile.

There are various sediment transport theories that have attempted to predict littoral drift. Most theories relate the volume of littoral drift to angle of attack and wave power, where wave power is directly proportional to the wave height squared. Hence the predicted increase in wave height at Hayle Beach, due to the lowered profile is likely to result in an increased volume of beach material being transported by littoral drift mechanisms.

As previously discussed the dunes play a significant role in the beach's natural protection against wave attack by providing a reservoir of sand to broaden the surf zone and to protect the remaining dune. At Hayle Beach the coastal processes have, over time, transported sediment towards the mouth of the estuary (and also seawards during storm events) thus resulting in the loss of foreshore sand and consequent reduced beach levels.

The reduction of beach levels has possibly exacerbated the erosion problems at Hayle Beach and Towans, in that larger waves are now able to penetrate further up the beach profile and increase the frequency of dune attack. To assess the rate of erosion, we would recommend that a simple monitoring scheme be adopted that recorded the position of the dune crest every 3 months.

7.3 Hayle Estuary

Tidal flows are normally the predominate force in estuarine sediment transport processes. The influences of waves and fluvial discharges are generally small within estuaries and therefore have not been considered with respect to sediment transport in Hayle estuary. The mathematical modelling has concentrated on assessing the impact of tides on sediment motion.

The tidal currents within Hayle Estuary have been investigated using two simulations; the first with the existing bathymetry, and the second with a lowered foreshore on Hayle Beach. The first provides a baseline against which to assess the impact of a lowered Hayle Beach upon the hydrodynamics within the estuary.

Eight points were identified within Hayle Estuary for analysis. In addition to these individual points a comparison has been undertaken to assess the potential net volume of sand passing through six cross sections during a spring tide. The location of the individual points and cross sections are shown in Figure 17 & 18.

Point	Location	Section	Location
vi	Hayle Beach	A	Hayle Beach
vii	Hayle Beach	B	Estuary mouth
viii	Estuary mouth	C_1	Harbour approach channel
ix	Estuary mouth	C_2	Lelant channel
x	Lelant channel	D	Hayle Harbour

xi	Lelant water	E	Lelant water
xii	Harbour approach channel		
xiii	Hayle Harbour		

Table 7 presents the potential rates of sediment transport (tonnes per linear metre width) during a spring tide at the above listed locations within the estuary for both the existing bathymetry and lowered Hayle Beach. Table 8 presents the predicted net quantity of sand passing through six cross sections, again during a spring tide. The results of the detailed analysis of sediment transport potential through Section B are presented in Table 9 and Figure 39.

7.3.1 'Existing' Bathymetry

The results predict that at the mouth of Hayle estuary the potential net movement of sand is seawards. At Lelant Channel (Section C1) a small net landward movement of sand is predicted, the flood flow being equally matched by a strong ebb flow, probably a result of the deeply scoured channel adjacent Lelant Quay. The predicted net transport at the entrance to Lelant Water (Section E) is smaller but also landward. Across the Harbour approach channel (Section C2) there is a strong net movement of sediment landward; however, within the harbour (Section D) there is a smaller net movement of sediment seaward, probably due to the effects of flushing from both Copperhouse Pool and Carnsew Reservoir.

These predictions are also confirmed by assessing the sediment transport rates at the individual points within the harbour, with the exception of two (Points xi and ix) which do not follow the trends suggested by the cross sections:

- Predictions for point xi in Lelant Water suggest a small net seaward movement of sediment, whereas the predicted net flux of sediment into Lelant Water is landward. This anomaly is due to a natural anti-clockwise circular motion of currents within Lelant Water. This analysis also suggests that any sediment transported by fluvial and windblown mechanisms into Lelant Water has little opportunity to be transported seawards.

- At Point ix the predicted net movement of sediment is landward; however, at Point viii and Section B the model predicts a net movement in a seaward direction. This is due to the relative locations of the points across the channel cross section, and is discussed in more detail in Section 7.3.3.

7.3.2 Lowered Beach Effects

The model demonstrates that reducing the level of Hayle Beach by approximately 1m affects the tidal currents within Hayle estuary and the potential sediment transport rates.

At the entrance to Hayle Estuary, the ebb currents are increased compared to the 'existing' case with a marginal decrease in flood currents resulting in a 45% increase in potential sediment transport seaward. Across the entrance to Lelant Water and the harbour approach channel a strong flood current is retained, although a marginal decrease in the net landward movement of sand is predicted. Within Hayle Harbour the potential rate of transport landward has doubled and the potential for sediment to pass into Lelant Water is predicted to increase by a factor of eight.

7.3.3 Discussion

A marked increase in the rate of sediment accretion within Hayle Harbour has been reported over the last year. The mass movement of sediment requires two factors: a source of sand and a transport mechanism. The source of the sand that is presently accreting within the Hayle Estuary and notably within the harbour approach channel and harbour is likely to be derived from Hayle Beach and Hayle Towans. The modelling of the coastal processes occurring within St.Ives Bay and at the mouth of the estuary indicates that sand is likely to be transported to the mouth of the estuary under tidal and wave action from Hayle Beach.

It is notable that the model appears to predict a net seaward movement of sediment at the mouth of the estuary, when in fact large quantities of sand are known to be accreting in and migrating further into the estuary. The process at this location were therefore investigated in more detail.

The model predicts that during a spring tide, the estuary mouth flow is ebb dominated; however, the harbour approach channel and Lelant Channel are flood dominated. Hence between sections B and C the flow characteristics change from being ebb to flood dominated. This would also suggest that the area between cross sections B and C is prone to erosion as no sediment would be entering this area. However, it should be appreciated that tidal flow will also vary along each cross section. What may on first inspection appear to be an ebb dominated flow, such as Section B, with the greater potential for seaward movement of sediment, may in fact be flood dominated in the areas where material is available for transportation landward. Analysis of two points (viii & ix) located between Sections B and C at the estuary mouth, and a more detailed analysis of the transport through Section B was undertaken. Table 8 gives the potential sediment transport rates at points viii and ix for the original and lowered Hayle Beach bathymetry. Table 9 and Figure 39 illustrate the results of the detailed analysis carried out on Section B, where the section was divided into equal lengths of 30 metres and the distribution of sediment transport quantified.

The results show that the tidal flows in the navigation channel at the centre of the section is ebb dominated, whilst to the east and west of the deepwater channel a flood dominated flow regime is predicted. It is this area, mainly to the east, that is accumulating sand, transported by tidal and waves action from Hayle Beach and Hayle Towans.

Point viii is located in the deeper water of the dredged navigation channel and Point ix is located to the east, where sand transported by tidal and wave action from Hayle Beach and Hayle Towans is accumulating. The results from these locations also demonstrate that whilst the deep water navigation channel has an ebb dominated tide, the dominant force on the eastern side of the estuary mouth is the flood tide.

Between the estuary mouth and the entrance to Lelant Water and Hayle Harbour, the flows are dominated by the flood tide, the approach channel to Hayle Harbour being the more strong influenced of the two. The movement of material predicted to negotiate the estuary mouth is rapidly transported landward into Hayle Harbour. Again the potential sediment transport rates are realised by the available sand budget accumulating at the estuary mouth.

For the high potential ebb sediment transport rates to be realised, a source budget of sediment is required. However, for similar reasons to those explaining the dominance of flood flows at Hayle Beach, maximum ebb velocities at the mouth of the estuary occur when a significant proportion of the cross section is dry, and so the source is not available for mobilisation. Strong ebb flows are also predominately contained within drainage channels and hence sand accumulated on existing sand banks within the estuary are not affected by the strong ebb currents. In addition, it is likely that sand transported into the estuary during the flood tide is retained in the estuary, as falling water levels during the ebb tide leave newly formed sand banks exposed. This process results in the gradual accumulation and distribution of sediment within the estuary.

The accumulation of sediment within the estuary is likely to result in a reduction of the tidal prism, potentially giving lower tidal flows on the foreshore and at the estuary mouth, exacerbating the processes outlined above.

A further significant finding is that a reduction in the level of Hayle Beach results in a slight decrease the ebb velocities at Point viii and an increase of flood velocities. Consequently there is a potential landward movement of sand at Point ix. These changes are a direct consequence of bathymetric changes at Hayle Beach, as all other parameters are unaltered. The loss of sand from Hayle Beach results in the early inundation of the foreshore during the tidal cycle prolonging the effects of the flood tide and increasing the net volume of sediment movement. Therefore, the net predicted result of continued loss of sand from Hayle Beach is a progressive increase of the flood tide influence at the estuary mouth.

7.3.4 Effect of Dredging

Dredging operations have existed at Hayle harbour since the construction of the harbour to primarily maintain the navigation channel. Since 1973, the annual tonnage of dredged material has been estimated to be 25,000 to 30,000 tonnes and during the five month period between October ‘01 to February ‘02, 18,000 tonnes of material was removed.

If this rate of removal is projected over a 12 month period, it would suggest that the annual tonnage of material is increasing. However, this latest accounting period is over the winter months where increased storm activity would generally increase the potential for sediment to be moved. Alternatively, during the summer months calmer seas typically prevails and hence less movement of material would be expected, with possibly reduced volumes of dredging. A detailed investigation of the monthly dredging records would be recommended to determine whether the removal of 18,000 tonnes between October and February is abnormal.

During 2002 (March to September) there has been a cessation of the dredging operation. During this period the coastal processes predicted by the model have continued and it has been reported that the rate at which material is accreting within Hayle Harbour is accelerating.

It is without doubt that the removal of seabed material in shallow waters has an effect in the hydraulic processes both locally and on a wider scale. The abstraction of material can result in the loss of sediment that contributes to the natural development of the beach profile. These effects are greatest when dredging in areas of shallow water, where sediment is regularly mobilised by tidal currents and wave action.

At Hayle the natural coastal processes discussed in this report play a significant role in the natural redistribution and movement of sand from Hayle Beach towards the estuary, where again natural processes are redistributing material within the estuary. . The predicted annual weight of sediment transported into the estuary through section B is comparable with the historically dredged quantities stated above.

The dredging operation has in the past removed sand from the estuary. It is very unlikely that past and present dredging in the inner channel at Hayle is the cause of the loss of beach material or dune erosion at Hayle Beach and Towans. However, by permanently removing this sand from the sediment transport sub-cell, dredging is sustaining the overall process of sediment transport from Hayle Beach and Towans into the estuary, and is therefore considered to be a contributory factor in increasing the rate at which sand can be transported into the harbour.

The dredging operation is a human response to a natural process, in order to maintain a working harbour. The natural processes and more importantly the magnitude of these processes are affected by subtle changes in cyclic effects of the tides, and annual and seasonal weather patterns. This study has demonstrated that estuary and surrounding coastlines are strongly influenced by tidal currents and also wind and waves. Slight variations in estuarine geometry, as demonstrated here by lowering Hayle Beach, can have significant (and usually unforeseen) effects on estuarine flow characteristics and the movement of sediment.

8.0 Coastal Protection Measures

The stretch of dunes currently being eroded is very local (approximately 100m) and it lies directly to the east of the estuary mouth. The main mechanism of erosion of the dunes here is head erosion, where erosion occurs at the seaward edge of the dune system during high water and wave events. The waves erode the base of the dune and the unsupported upper part collapses, leaving a steep unvegetated face that is vulnerable to wind erosion and further wave attack (Plate 3).

The dunes further to the east of this area of are not prone to direct wave attack, mainly due to a noticeably elevated beach level. There is evidence of further dune development in this area, where wind blown sand from the beach has accumulated, forming a berm in front of the established dunes (Plates 1 & 2).

Coastal management schemes are usually considered under two headings *Sea Defence* and *Coastal Protection* and in some cases it is appropriate to combine the two. In this instance, the main consideration is the protection and preservation of the foreshore and dune system for environmental, ecological and recreational reasons. Although the ground level behind the Hayle Towans is elevated and risk of flooding is not considered to be an issue, a small number of domestic dwellings are located behind the second dune ridge and subsequently it is desirable to prevent further erosion of the dune system here. Indeed it is noted that over the last 30 years, several chalets have already been lost as the seaward edge of the dune system was progressively eroded.

As discussed earlier the erosion mechanism of the Hayle Towans appears to be a general reduction in beach elevation. This has two effects:

- large waves are able to penetrate further up the beach and, when combined with a high tide, they are able to attach and erode the base of the dunes.

- Less beach material is available for transport to the dunes by the wind during low tide, hence the dune is unable to recover following storm events.

Engineering options that have in the past been used to stabilise dunes systems are groynes, beach replenishment, rock revetment and sand filled container systems. These options are discussed in outline below. It should be noted, however that the Shoreline Management Plan recommends management of the dunes system to maintain and stabilise the current position. It also recommends that there should be no hard defence intervention.

8.1 Groynes

Groynes are used to stabilise an eroding beach and are generally positioned at right angles to the shoreline. The principal purpose of a groyne is to intercept and hence accumulate beach material, reducing the littoral drift along the beach.

Typically groynes are constructed of wooden piles driven into the beach, with wooden planks attached between the piles. Alternatively, they can be constructed with precast concrete units or rock. The layout of the groyne system is described by their length, spacing, height and orientation to the beachline and these characteristics are controlled by the volume of sediment to be trapped, the size of the beach material and the angle of the wave attack.

The effectiveness of a groyne system in reducing littoral drift is debatable. The purpose of the groyne is to intercept littoral drift, and as this material is accumulated against the groyne, the beach downdrift may suffer erosion, due to the non-replacement of sediment from the updrift source. Only when the accretion of material has reached the seaward end of the groyne will material be transported downdrift.

The mathematical model suggests that littoral drift of sediment on the beach to the east of the estuary mouth is from east to west, the opposite direction to the net movement of transport within the St.Ives Bay i.e. west to east. This is a result of the predominant wave approaching the coastline obliquely. Therefore a single groyne of either rock or timber located at the interface between the dune and estuary mouth may be valuable in dealing with the management of these dunes. It would act to control the tidal currents and resulting littoral transport toward the mouth of the estuary and the subsequent redistribution of sediment within the estuary. Such a groyne may also encourage beach accretion in this area maintaining a higher, wider beach potentially leading to a healthier dune system. Any groyne positioned on the foreshore would require further investigation to assess its impact on the tidal regime given its close proximity to the navigation channel.

General advantages of implementing rock groynes are that they are long life structures and require minimal maintenance. Timber groynes on the other hand are far less long standing than rock and typically require a considerable amount of maintenance. Timber is also (subjectively) less aesthetic than rock groynes and does not have the same ability as rock to resist wave attack. There are also other issues related to the use of timber and its sourcing from environmentally sustainable sources.

8.2 Beach Replenishment

Beach replenishment may be used as an alternative to, or in conjunction with, a groyne system. The purpose is to re-nourish the beach thus increasing the natural defence afforded to the hinterland.

Generally the rate of replenishment should be designed so that littoral drift losses are balanced. There are several alternative methods adopted to replenish beaches: feeding material at the up-drift end, uniformly along the coastline and finally at specific locations. The area of Hayle beach that requires management is relatively small and hence feeding material uniformly over the beach profile would probably be most appropriate. It is not usually necessary to sort the beach fill material, or to place it in to a particular gradient because wave action will sort and distribute the material along the beach.

The economics of replenishment schemes depend on the rate of beach depletion and the source and cost (including transport) of the supply material. Sand currently being dredged from the harbour is being stockpiled, although in the past this dredged material was removed altogether. In order to prevent further loss of beach material and retreat of the dune system, consideration should be given to re-using the dredged material from the harbour to replenish Hayle beach. However, environmental concerns regarding the potential for contamination, and licensing requirements would have to be investigated and addressed. In addition, it would be necessary to devise an appropriate method of retaining the material on Hayle Beach, to avoid an ongoing requirement for a continuous dredge / replenish operation.

8.3 Rock Armouring

Placing rock armour at the toe of the dune may offer short term temporary protection, preventing the undermining of the dune face by wave action. In the long term, the effectiveness may reduce if beach levels continue to fall. Eventually the rock structure itself may be undermined and ultimately fail. A rock revetment will also interfere with the free interchange of sand between the beach and dune. As a consequence the beach will be unable to draw upon a reservoir of extra sand during severe storm events, potentially leading to a further reduction in beach levels. Similarly, there will be less sand available from the beach, which can be transported by wind to the dunes for dune development.

8.4 Sand Filled Container Systems

The use of large, sand filled geotextile containers for coastal protection has been used in Holland, Belgium, Germany and the United States, however their use within the UK has been limited. They have been previously used for various coastal structures, including sea walls, groynes and breakwaters with varying degrees of success. They can be positioned within the beach profile and usually used in conjunction with beach recharge in the area landward of the structure (see Figure 41). Inherently they can suffer from the same problems as rock revetment in that they inhibit the natural interchange of material from the beach and dune. However, if they are placed some distance in front of the dune system they may provide dune toe scour protection and encourage deposition of sediment in their lee by causing waves to break as they pass over

Due to the limited vertical height it is possible that sand filled container systems are prone to being undercut and dislodged if the beach, seaward of the structure, is eroded. Also their effectiveness is severely limited when storm surge level is higher than the structure itself such that storm waves are unaffected as they pass overhead.

8.5 Dune Management Techniques

Dunes are a valuable coastal habitat. When managing designing or modifying beaches the various environmental requirements of the dune system should be considered.

Trampling by pedestrians and vehicle movement associated with the recreational use of a beach will lead to the progressive degradation of the dune system and should be avoided through careful visitor management. This can be achieved by providing fencing to encourage visitors to use certain areas of the dune, which are least sensitive to disturbance, the use of boardwalks to prevent trampling of vegetation etc.

Vegetation also plays a significant role in preventing the erosion of sand from dunes due to wind. Planting of marran grass and similar natural dune vegetation can be successful when combined with other management techniques in preventing dune losses and encouraging future sand accretion.

8.6 Summary

The above section gives a brief overview of possible mitigation measures to protect Hayle beach and Towans from further erosion. It should be noted that any option to manage this issue should address the integrated management of the beach and the dunes.

Methods that are adopted to maintain and strengthen dune systems are likely to fail if the beach in front of the dunes continues to erode. Therefore it is usually the case that good beach management is inherently linked with good dune management.

The recharge of Hayle Beach with dredged material would address this matter by increasing the width and height of the beach in front of the dunes. This would not only protect the toe of the dunes from further erosion due to direct wave action, but would also create conditions in which the dune system is more likely to prosper. However, beach replenishment must be properly considered (including the environmental impacts) and maintained if it is to be successful over a long period of time.

9.0 Summary and Conclusions

9.1 Summary

The following points can be summarised from the study.

- Two mathematical models have been constructed to predict the behaviour of waves and tidal currents on sediment transport mechanisms within St. Ives Bay and Hayle estuary including the harbour. At the entrance to the estuary the combined effect of waves and tidal currents was investigated, while within the estuary the only tidal currents were modelled.

- The Mike 21 suite of software was used to model the hydrodynamics within St.Ives Bay and Hayle Estuary. Water levels and flow velocities were compared on the basis of curve shape and magnitude. A further analysis of the peak ebb and flood velocities was carried out to provide a tangible indication of the correlation between models. The model has been calibrated to HR Wallingford's physical model. It has not however been verified, as this would require up-to-date hydrodynamic and topographic data from the estuary against which the calibrated model would be tested. Verification of the model should be undertaken prior to further use of the model for to support engineering design work.

- The degree of calibration achieved is sufficient to give confidence that the model is capable of reproducing the important aspects of the tidal flows within the estuary with adequate precision.

- Wave modelling of the predominant wave condition was undertaken using SWAN (Sea Waves Nearshore) to model the inshore wave climate at the mouth of the estuary. The inshore wave condition modelled at Carbis Bay and Gwithian were compared with the conditions presented in the Shoreline Management Plan and a good comparison was reached.

- The hydrodynamic model was used to assess sediment transport for a spring tide and no waves, a spring tide with 1:5 year wave and spring tide with a swell wave. Simulations were carried out using the existing bathymetry and also for simulations where Hayle Beach had been lowered by 1m.

- Waves play a significant role in the transport and redistribution of sediment in the intertidal zone. Waves are the principal transport mechanism initiating and maintaining transport of material at Hayle Beach. During storm events it is possible for large quantities of material to be transported seawards to an area of ebb dominated flow.

- The dominance of the flood tide over Hayle Beach results in the transport of material towards the mouth of the estuary during a spring tide, effectively squeezing the present deep-water navigation channel. Extreme waves approach the coastline at Hayle Beach obliquely, facilitating the littoral drift of beach material to the west and the estuary mouth.

- Very little littoral transport of material is predicted to feed Hayle beach from the vast sources of beach material to the east of Black Cliff.

- A reduction in the level of Hayle Beach results in changes to the flood and ebb velocities at the mouth of the estuary, and a consequent potential landward movement of sand. These changes are a direct consequence of bathymetric changes at Hayle Beach, as all other parameters are unaltered. The loss of sand from Hayle Beach results in the early inundation of the foreshore during the tidal cycle prolonging the effects of the flood tide and increasing the net volume of sediment movement. Therefore, the net predicted result of continued loss of sand from Hayle Beach is a progressive increase of the flood tide influence at the estuary mouth.

- In addition, the reduction of beach levels has possibly exacerbated the erosion problems at Hayle Beach and Towans, as larger magnitude waves are able to penetrate further up the beach profile and increase the frequency of dune attack. To assess the rate of erosion, we would recommend that a simple monitoring scheme is adopted to record the position of the dune crest every 3 months.

- The hydrodynamic model with the ‘existing’ bathymetry predicts that, due to tidal influences, there is a net movement of sand seawards at the mouth of the estuary, a net movement of sand landwards at the entrance to Lelant channel, harbour approach channel and a smaller movement landwards at the entrance to the Lelant Water.

- For the lowered Hayle Beach profile, assumed 1m below the ‘existing’ bathymetry, the hydrodynamic model predicts an increase in the ebb currents at the mouth of the estuary. Little change is predicted at the Lelant channel and harbour approach channel. Within Hayle harbour sediment transport rates are predicted to double and sediment transport into Lelant Water is predicted to increase by eight times. At the mouth of the estuary strong ebb flows are confined to the deep-water navigation channel whilst to the east a flood dominated flow is predicted. The coastal processes transporting material towards the mouth of the estuary provides the source sediment that is subsequently transported into the estuary, where it is rapidly drawn into Hayle Harbour.

- A detailed analysis of the potential movement of sediment at the mouth of the estuary demonstrated that the tidal flows in the navigation channel at the centre of the section are ebb dominated, whilst to the east and west of the deepwater channel a flood dominated flow regime is predicted. It is this area, mainly to the east, that is accumulating sand, transported by tidal and waves action from Hayle Beach and Hayle Towans.

- As maximum ebb velocities though the mouth of the estuary (Section B) occur at mid ebb tide, at a lower water level than mid flood tide, the sand that has accumulated at the east of the estuary mouth during the flood tide is likely to be dry, and cannot therefore be re-mobilised by these strong ebb currents. This scenario results in a flood dominated sediment transport regime through the section and the transport of material into the estuary.

- The predicted annual weight of sediment transported into the estuary through Section B is comparable with the historic harbour dredging quantities.

9.2 Concluding Comments

Estuaries are extremely dynamic and often unpredictable, and whole estuaries may naturally undergo long periods of accretion followed by long periods of erosion. It is unlikely that past and present dredging in the channel at Hayle Harbour is the sole cause of the accretion and erosion problems that are being experienced today. However, by permanently removing sand, dredging is sustaining the overall process of sediment transport from Hayle Beach and Towans into the estuary. It is therefore contributing to the increasing rate at which sand can be transported into the harbour.

Engineering methods to maintain and strengthen dune systems are likely to fail if the beach in front of the dunes continues to erode. Therefore it is recommended that an integrated beach and dune management scheme is adopted. The recharge of Hayle Beach with dredged material would address this matter by increasing the width and height of the beach in front of the dunes. This would not only protect the toe of the dunes from further erosion due to direct wave action, but would also create conditions in which the dune system is more likely to prosper. However, beach replenishment must be properly considered (including the environmental impacts) and maintained if it is to be successful over a long period of time.

REFERENCES

1. Hayle Harbour Hydraulic and Siltation Studies, HR Wallingford, 1989.

2. Land's End to Hartland Point, Shoreline Management Plan, Halcrow Maritime, 1999.

3. An Investigation of Sediment Dynamics in the Hayle Estuary, Cornwall, Sea Sediments, 1983.

4. Shore Protection Manual, US Army Corp, 1984.

5. Beach Management Manual, AH Brampton et al., CIRIA Report 156, 1986.

TABLES

Table 1 – Model Calibration Points

Point ID	**Calibration Type**
A	Water level
B	Water level
C	Water level
D	Water level
E	Water level
F	Water level
1	Current velocity
2	Current velocity
3	Current velocity
4	Current velocity
5	Current velocity
6	Current velocity
7	Current velocity
8	Current velocity
9	Current velocity
10	Current velocity
11	Current velocity
12	Current velocity

Table 2 – Analysis of Peak Velocities

Ebb Velocities

Point ID	HR Model	Lower Limit	Upper Limit	Mike21	±%
1	1.58	1.26	2.84	1.68	+6
2	0.99	0.79	1.78	0.76	-23
3	0.81	0.65	1.46	1.11	+37
4	1.85	1.48	3.33	1.38	-25
5	1.77	1.42	3.19	1.64	-7
6	2.36	1.89	4.25	0.50	-79
7	1.18	1.94	2.12	1.66	-44
8	0.93	1.74	1.67	1.76	-18
9	0.40	1.32	0.72	1.00	+150
10	0.85	0.68	1.53	0.65	-24
11	1.31	1.05	2.36	1.10	-16
12	1.43	1.14	2.57	0.80	-44
				Average	40

Flood Velocities

Point ID	HR Model	Lower Limit	Upper Limit	Mike21	±%
1	1.33	1.06	1.60	1.80	+35
2	0.94	0.75	1.13	1.21	+29
3	0.72	0.58	0.86	1.20	+67
4	2.12	1.70	2.54	1.70	-20
5	1.13	0.90	1.36	1.50	+33
6	1.92	1.54	2.30	1.11	-42
7	1.40	1.12	1.68	0.87	-38
8	0.71	0.57	0.85	0.38	-46
9	0.93	0.74	1.12	0.65	-30
10	0.83	0.66	1.00	0.50	-40
11	1.23	0.98	1.48	0.64	-48
12	1.43	1.14	1.72	0.80	-44
				Average	39

Table 3 – Comparison of Nearshore Wave Modelling Results

Return Period (years)	Carbis Bay				Gwithian			
	SMP		SWAN		SMP		SWAN	
	H_s (m)	T_m (s)	H_s (m)	T_m (s)	H_s (m)	T_m (s)	H_s (m)	T_m (s)
1:5	4.3	9.3	2.4	9.0	5.7	9.0	4.8	9.0
1:10	4.9	9.8	2.5	9.4	6.4	9.4	5.0	9.4
1:20	5.5	10.1	2.5	9.7	7.1	9.7	5.1	9.6
1:50	6.2	10.6	2.5	9.6	7.3	9.8	5.3	9.7
1:100	6.6	10.7	2.5	9.8	7.7	10.0	5.4	9.9
1:200	7.3	11.2	2.4	10.4	8.5	10.3	5.4	10.4

Table 4 – Predicted Nearshore Wave Condition at Hayle Beach

Return Period (years)	Hayle Beach Point vi		Hayle Beach Point vii	
	H_s (m)	T_m (s)	H_s (m)	T_m (s)
1:5	1.09	10.5	3.66	10.3
1:10	1.45	10.9	3.96	10.7
1:20	1.45	11.2	4.00	11.0
1:50	1.44	11.0	4.03	11.1
1:100	1.44	11.2	4.05	11.3
1:200	1.47	11.9	4.07	11.9

Notation
H_s = Significant Wave Height
T_m = Mean Wave Period

Table 5 – Comparison of Potential Sediment Transport Rates

Point	Predicted Sediment Movement during a Spring Tide (tonnes/metre)					
	Engelund and Hansen			Ackers and White		
	Ebb	Flood	Net	Ebb	Flood	Net
vi	0.480	-0.018	0.460	0.094	-0.000	0.094
vii	-0.007	-0.016	-0.022	0.000	-0.000	-0.000
viii	1.980	-0.900	1.080	1.924	-1.000	0.925
ix	0.139	-0.372	-0.234	0.043	-0.705	-0.661
x	0.188	-0.690	-0.500	0.136	-0.368	-0.231
xi	0.002	-0.001	0.003	0.000	-0.000	0.000
xii	0.076	-0.270	-0.190	0.023	-0.241	-0.218
xiii	0.010	-0.007	0.002	0.000	-0.002	-0.002

Table 6 – Potential Wave and Tide Induced Sediment Transport

Point	Predicted Sediment Movement (tonnes/metre)								
	Spring tide			Spring tide & swell wave			Spring tide & 1:5 wave		
	Ebb	Flood	Net	Ebb	Flood	Net	Ebb	Flood	Net
i	-4×10^{-6}	19×10^{-6}	15×10^{-6}	0.006	-0.058	-0.052	0.030	-0.220	-0.190
ii	-2×10^{-6}	-30×10^{-6}	-32×10^{-6}	0.000	-0.090	-0.090	-0.030	-0.240	-0.270
iii	0.004	-0.0170	-0.013	0.081	-0.234	-0.153	0.180	-0.610	-0.430
iv	-0.001	-0.017	-0.018	-0.131	-0.445	-0.576	-0.150	-0.520	-0.670
v	0.021	-0.027	-0.006	0.922	-1.236	-0.314	1.070	-1.600	-0.530
vi	0.405	-0.034	0.372	1.730	-0.308	1.422	1.948	-0.367	1.580
vii	-0.004	-0.012	-0.016	-0.142	-0.547	-0.688	-0.177	-0.638	-0.816

- Negative   Net transport is in landward direction
+ Positive   Net transport is in seaward direction

Table 7 – Potential Sediment Transport Rates

Point	Predicted Sediment Movement during a Spring Tide (tonnes/metre)					
	Original			Lowered		
	Ebb	Flood	Net	Ebb	Flood	Net
vi	0.480	-0.018	0.460	0.1587	-0.0058	0.1529
vii	-0.007	-0.016	-0.022	0.0002	-0.0054	-0.0052
viii	1.980	-0.900	1.080	1.89	-0.99	0.89
ix	0.139	-0.372	-0.234	0.07	-0.695	-0.62
x	0.188	-0.690	-0.500	0.19	-0.49	-0.3017
xi	0.002	-0.001	0.003	0.0005	-0.0048	0.0043
xii	0.076	-0.270	-0.190	0.0337	-0.23	-0.2
xiii	0.010	-0.007	0.002	0.0029	-0.014	-0.0112

Table 8 – Potential Sediment Transport through Cross Sections during a Spring Tide

Cross Section	Predicted Weight of Sand Movement (tonnes)					
	'Existing'			Lowered		
	Ebb	Flood	Net	Ebb	Flood	Net
A	61.9	-6.9	55.0	52.1	-5.1	47.0
B	45.9	-27.3	18.6	52.5	-25.4	27.1
C1	141.9	-179.9	-38	118.4	-148.6	-30.0
C2	47.3	-278.8	-231.6	61.34	-206.4	-145.1
D	25.7	-60.8	-35.2	21.2	-99.1	-77.9
E	4.3	-5.3	-1.0	2.9	-10.4	-8.3

- Negative Net transport is in landward direction
+ Positive Net transport is in seaward direction

xx.x For breakdown see Table 9

Table 9 – Distribution of Predicted Sediment Transport across Section B ('Existing')

	Chainage	Predicted Weight of Sand Movement (tonnes)		
		Ebb	Flood	Net
West	**0 – 30**	0.00	0.00	0.00
	30 – 60	-0.01	0.00	0.00
	60 – 90	0.04	-1.04	-1.00
	90 – 120	4.44	-7.35	-2.90
	110 – 150	30.29	-10.32	19.96
	140 – 180	11.23	-4.85	6.38
	170 – 210	0.50	-3.14	-2.64
	200 – 240	-0.56	-0.65	-1.20
	230 – 270	0.0003	0.0005	0.0003
East	**260 – 300**	0	0	0

- Negative Net transport is in landward direction

+ Positive Net transport is in seaward direction

FIGURES

Figure 1 – Location Plan

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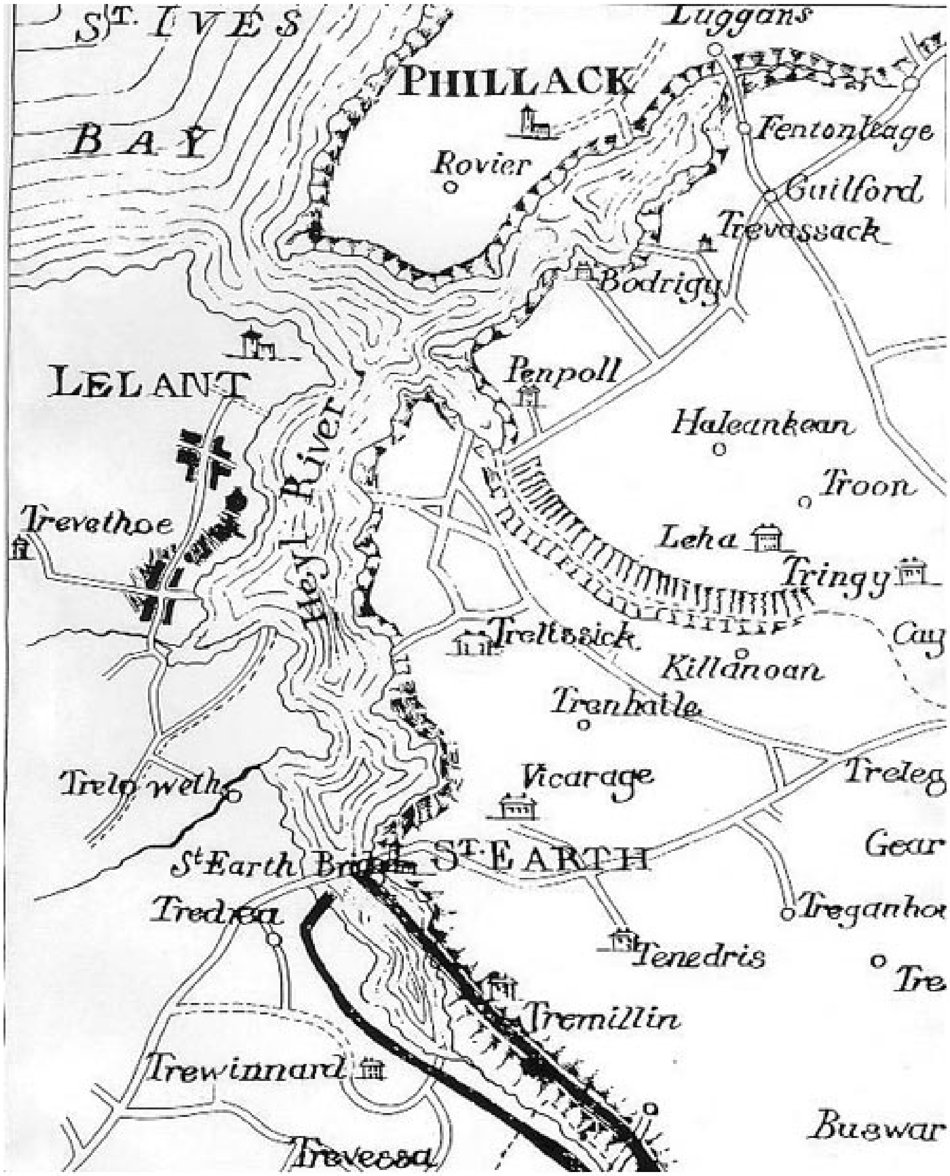

Figure 2 – Hayle Estuary circa 1789

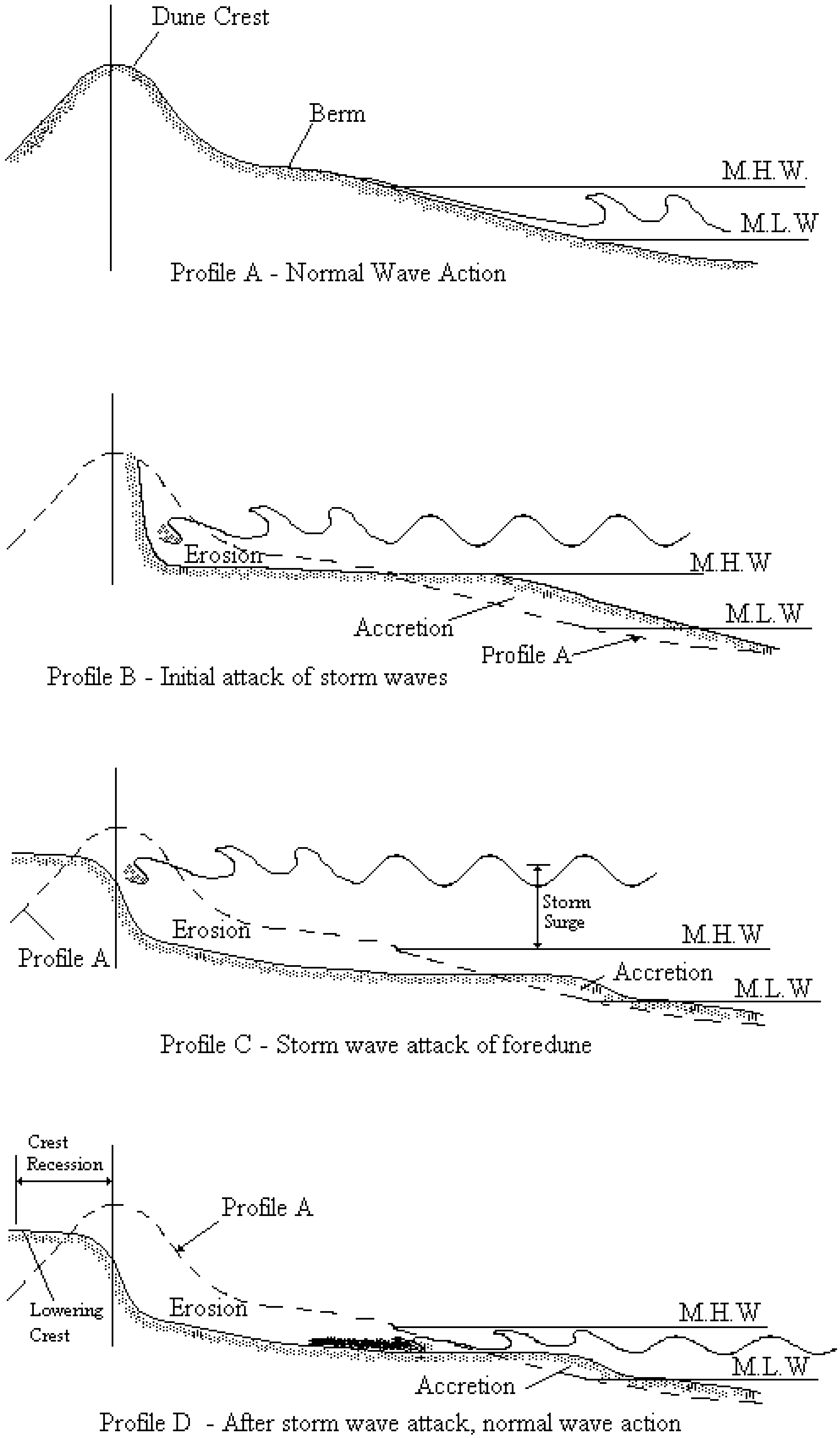

Figure 3 – Typical Beach Profiles

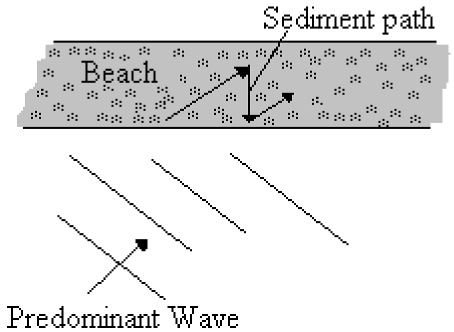

Figure 4 – Longshore Transport

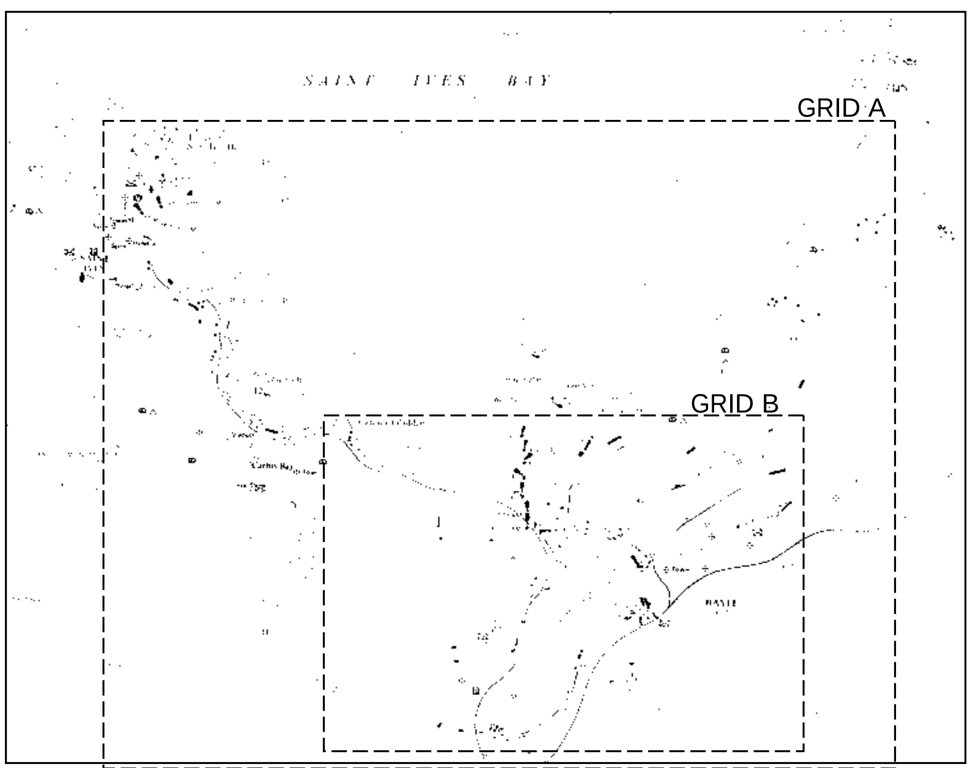

Figure 5 – Extent of Hydrodynamic Model Grids

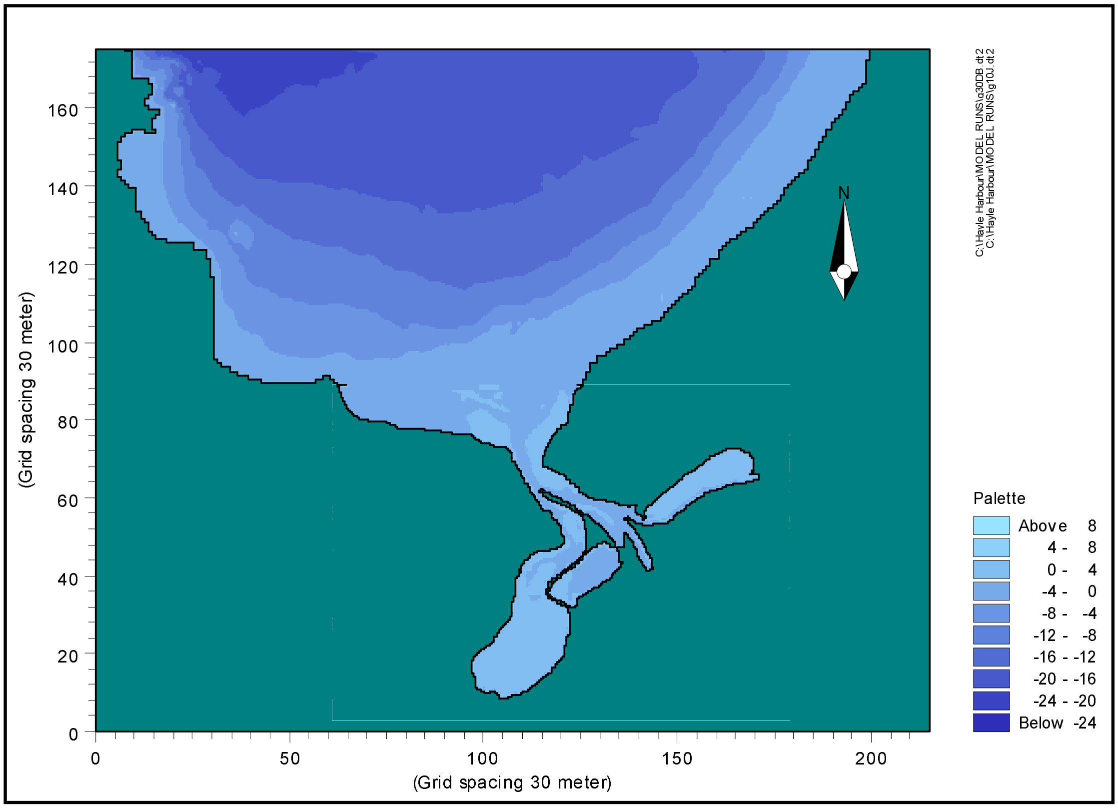

Figure 6 – Grid A: Mike21 (100m Grid)

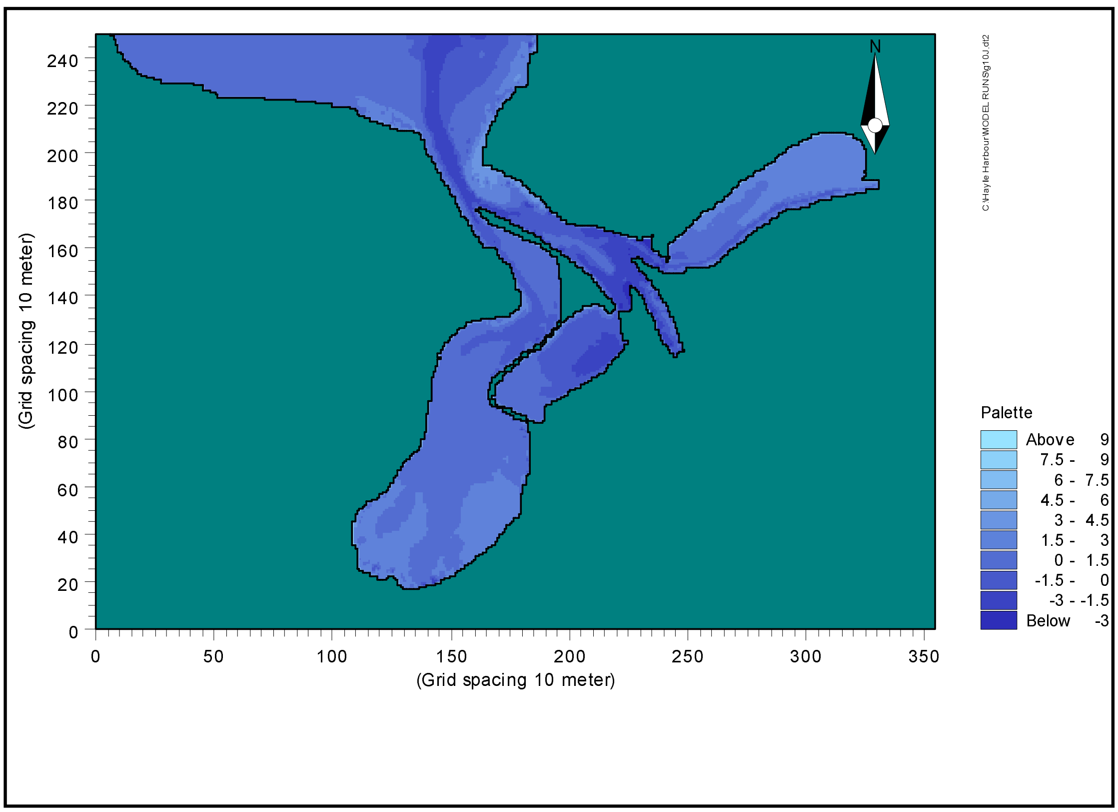

Figure 7 – Grid B: Mike21 (30m Grid)

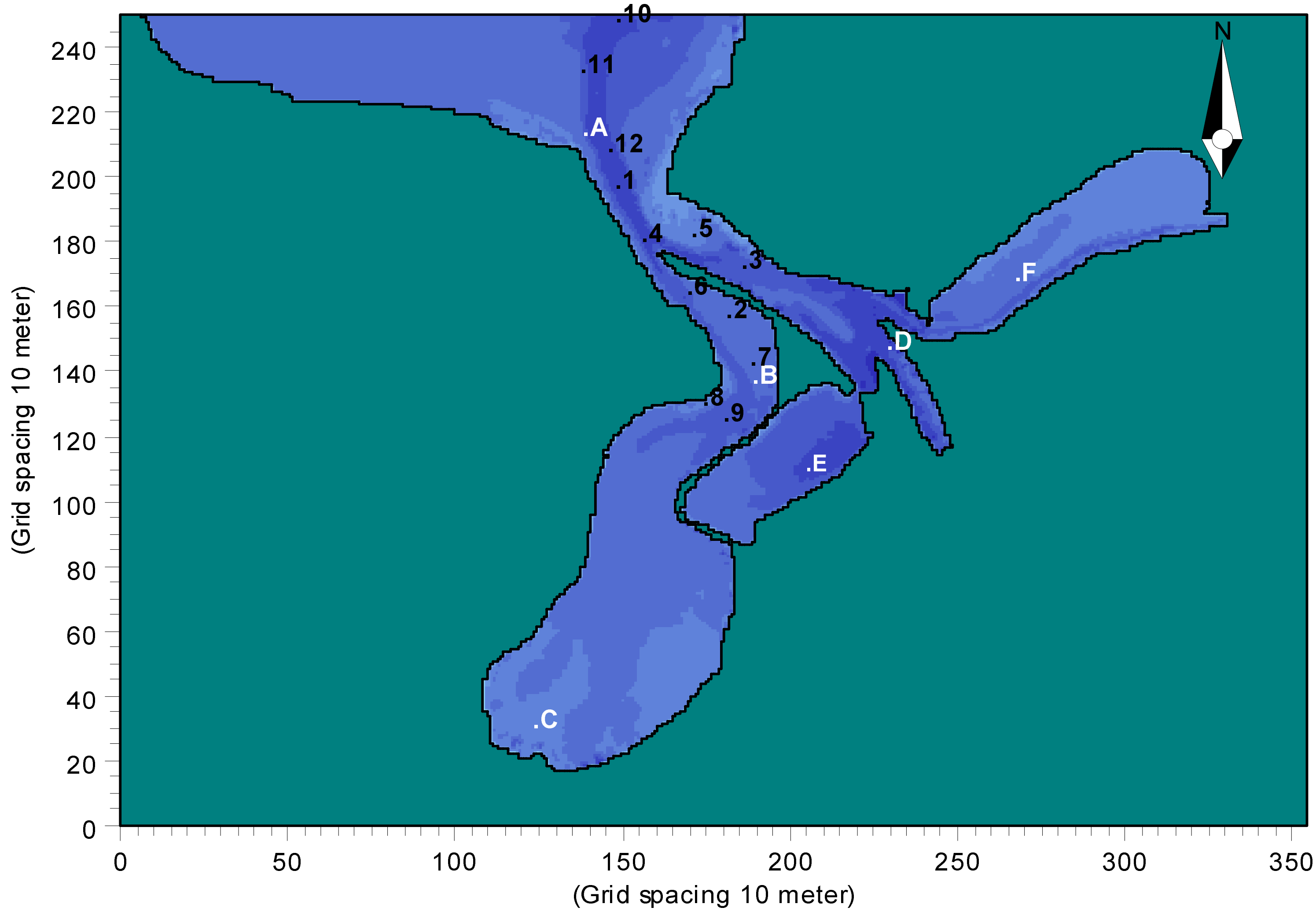

Figure 8 – Location of Calibration Points

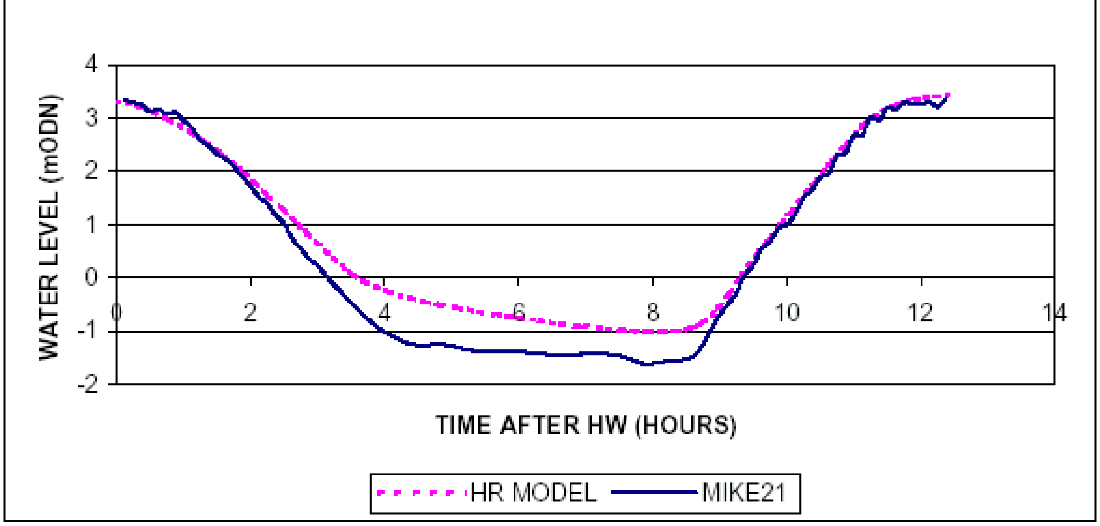

Figure 9(a) – Comparison of Water Levels at Point A

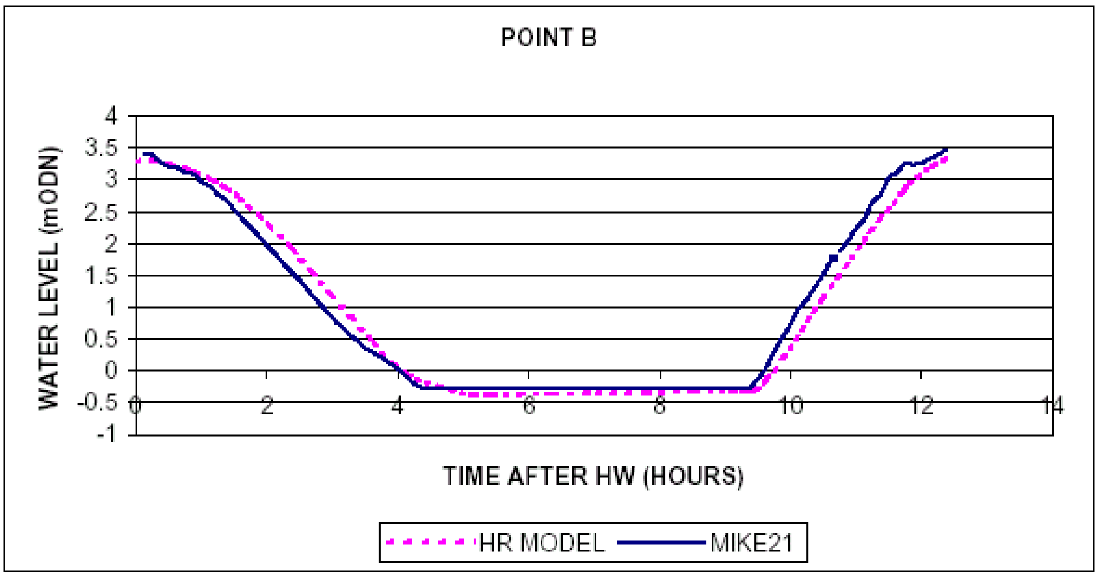

Figure 9(b) – Comparison of Water Levels at Point B

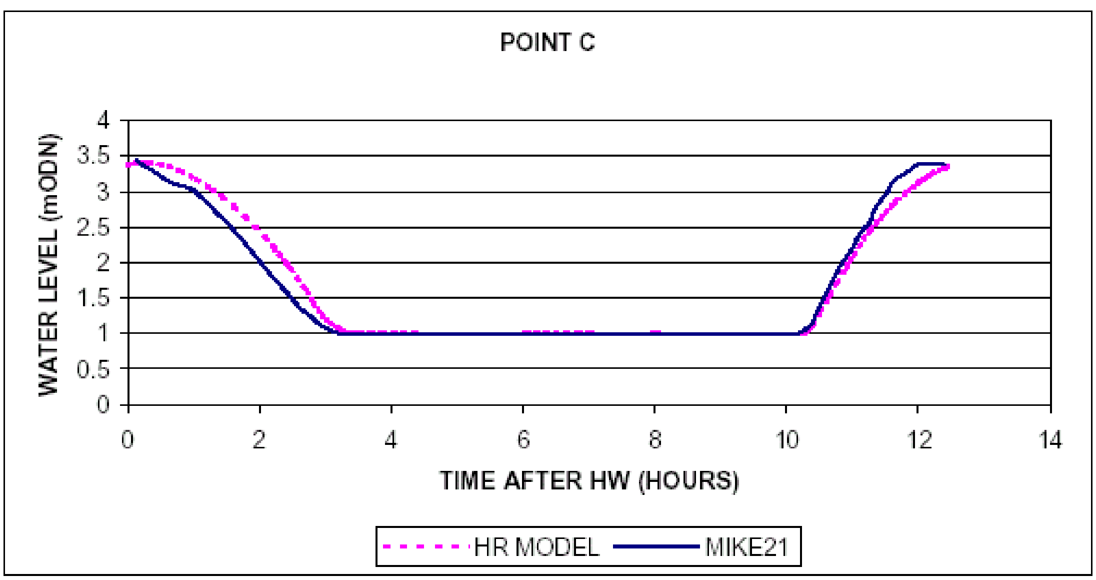

Figure 9(c) – Comparison of Water Levels at Point C

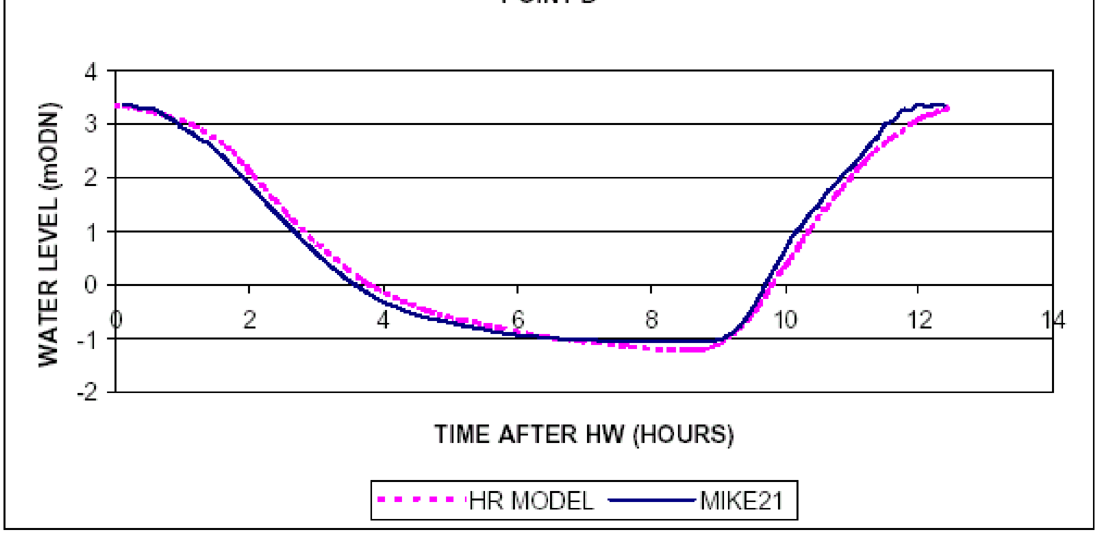

Figure 9(d) – Comparison of Water Levels at Point D

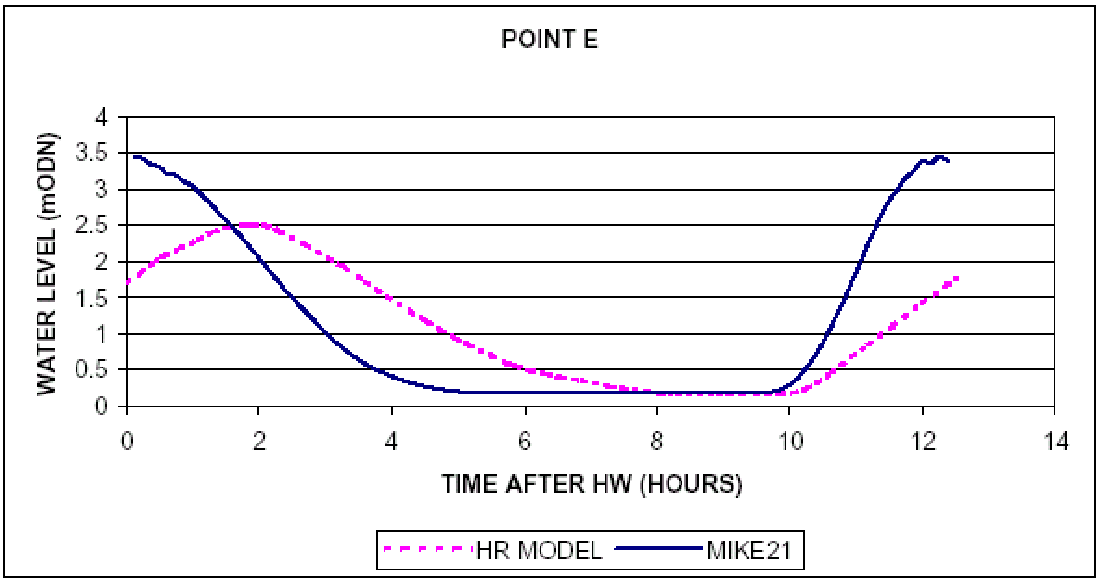

Figure 9(e) – Comparison of Water Levels at Point E

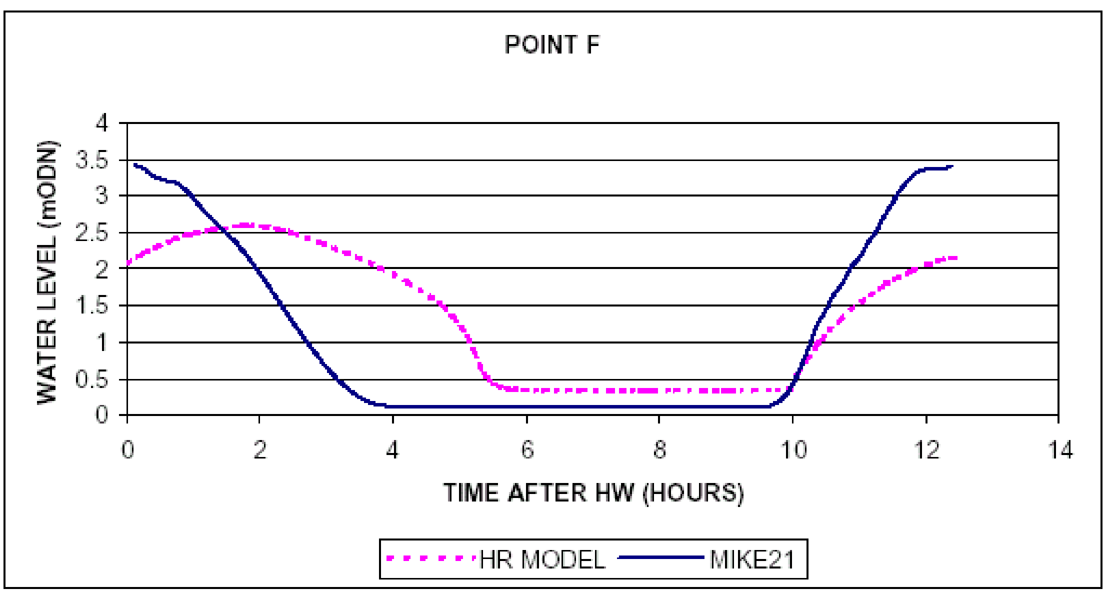

Figure 9(f) – Comparison of Water Levels at Point F

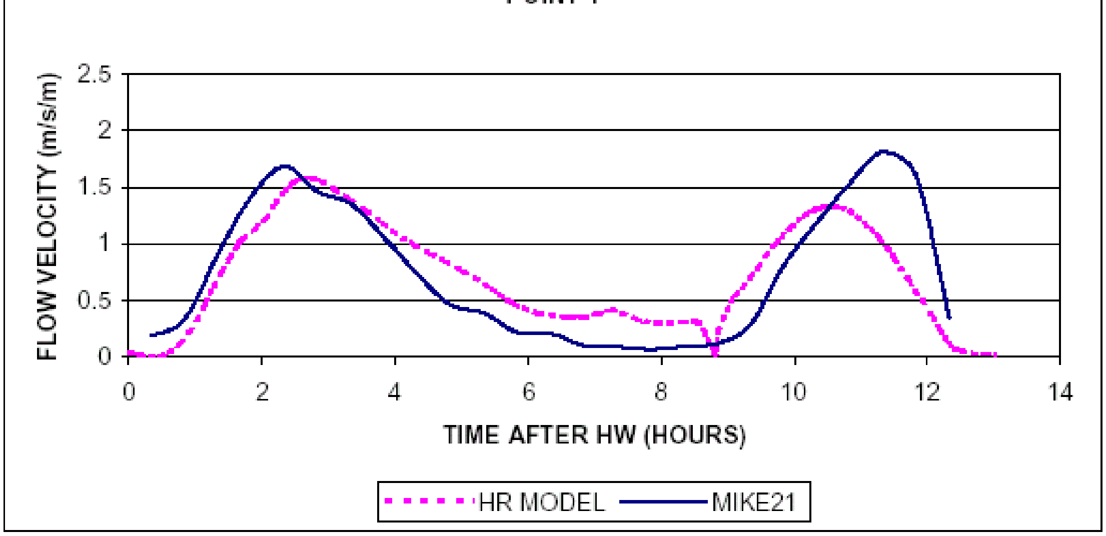

Figure 10(a) – Comparison of Current Flow Velocity at Point 1

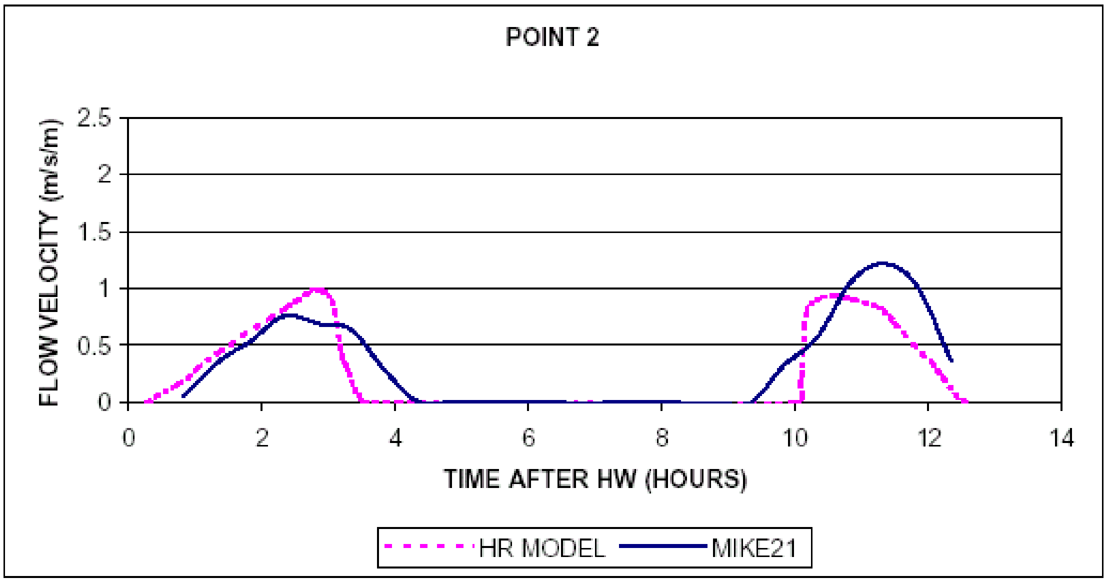

Figure 10(a) – Comparison of Current Flow Velocity at Point 2

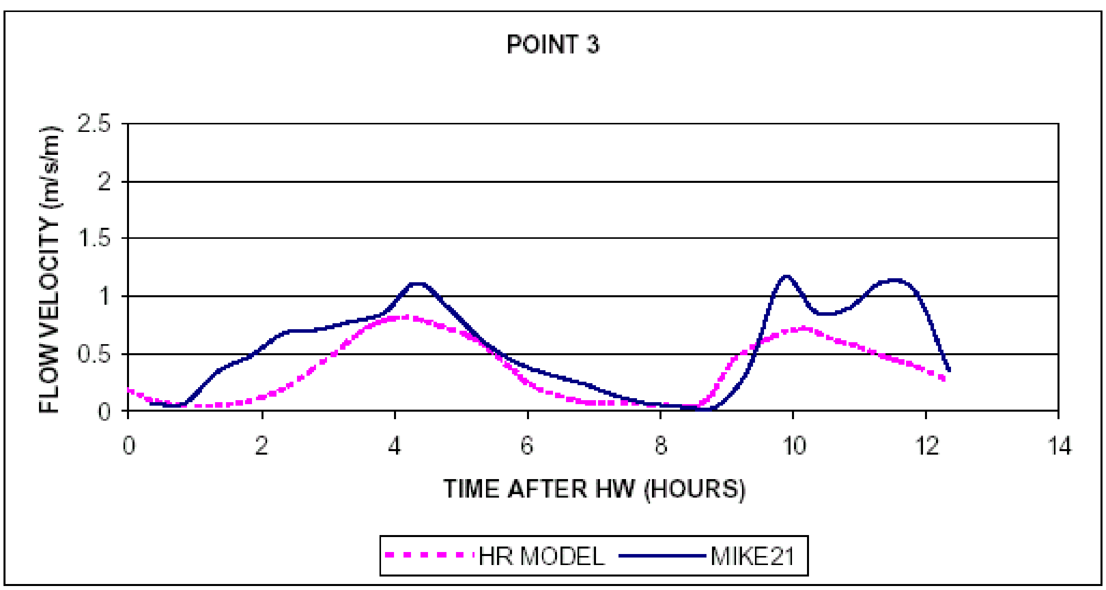

Figure 10(a) – Comparison of Current Flow Velocity at Point 3

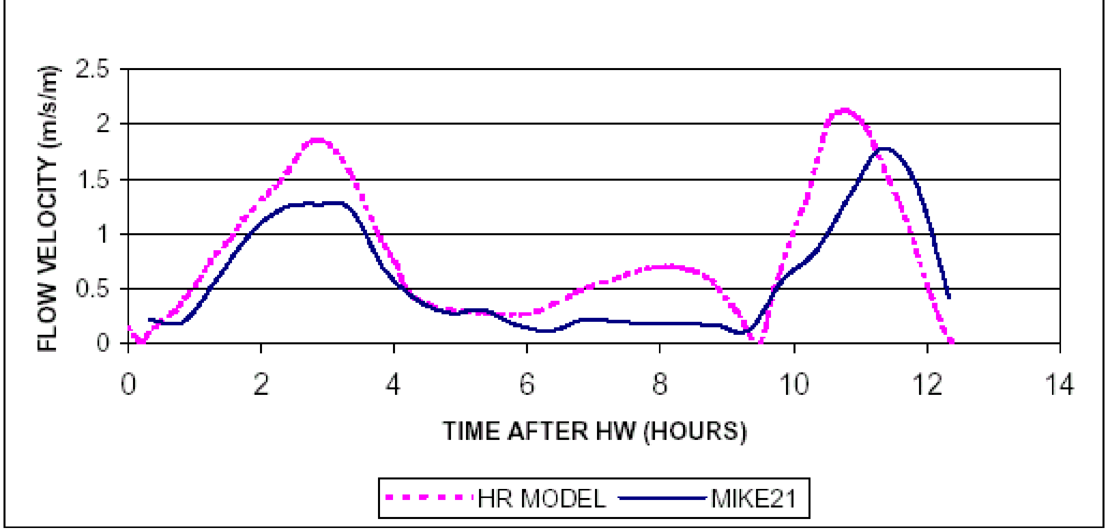

Figure 10(d) – Comparison of Current Flow Velocity at Point 4

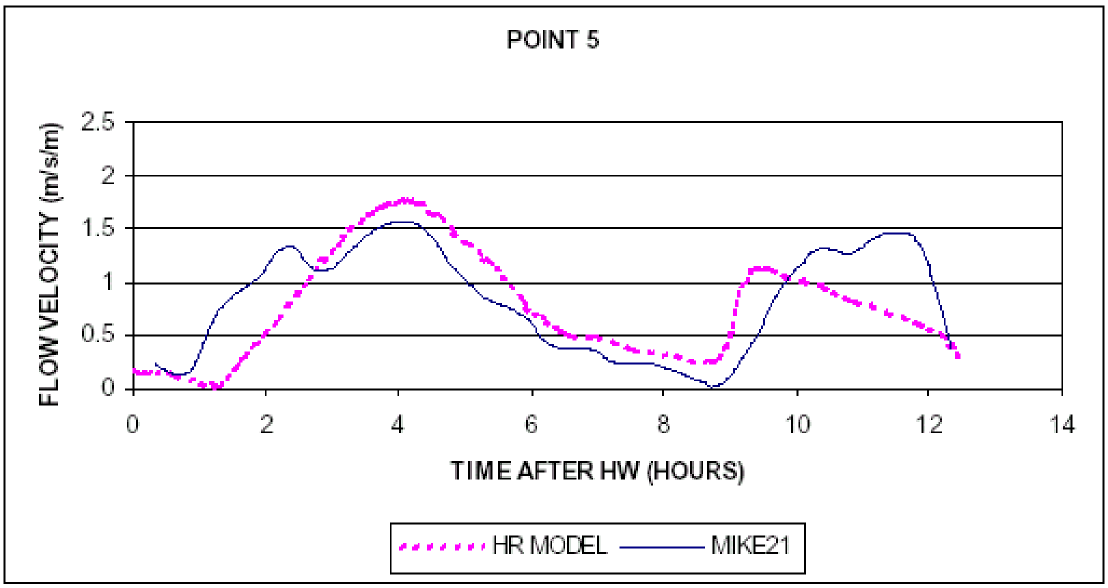

Figure 10(e) – Comparison of Current Flow Velocity at Point 5

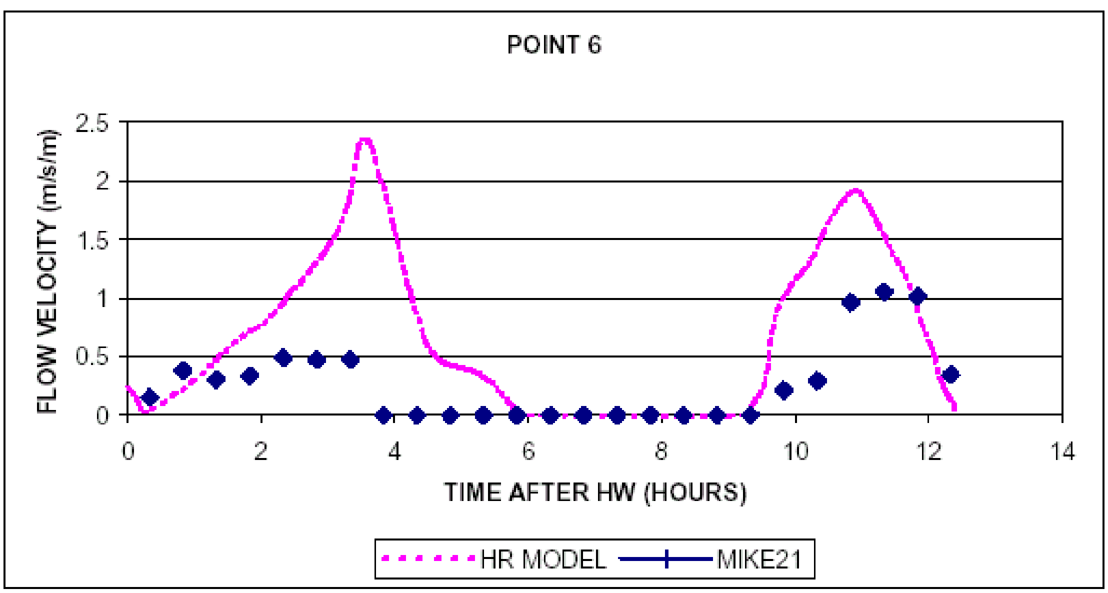

Figure 10(f) – Comparison of Current Flow Velocity at Point 6

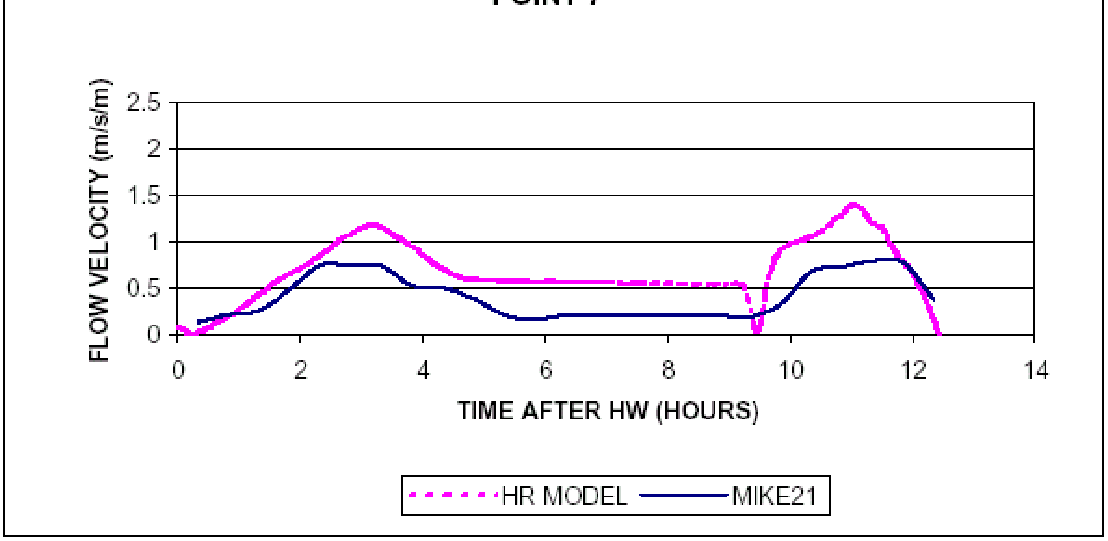

Figure 10(g) – Comparison of Current Flow Velocity at Point 7

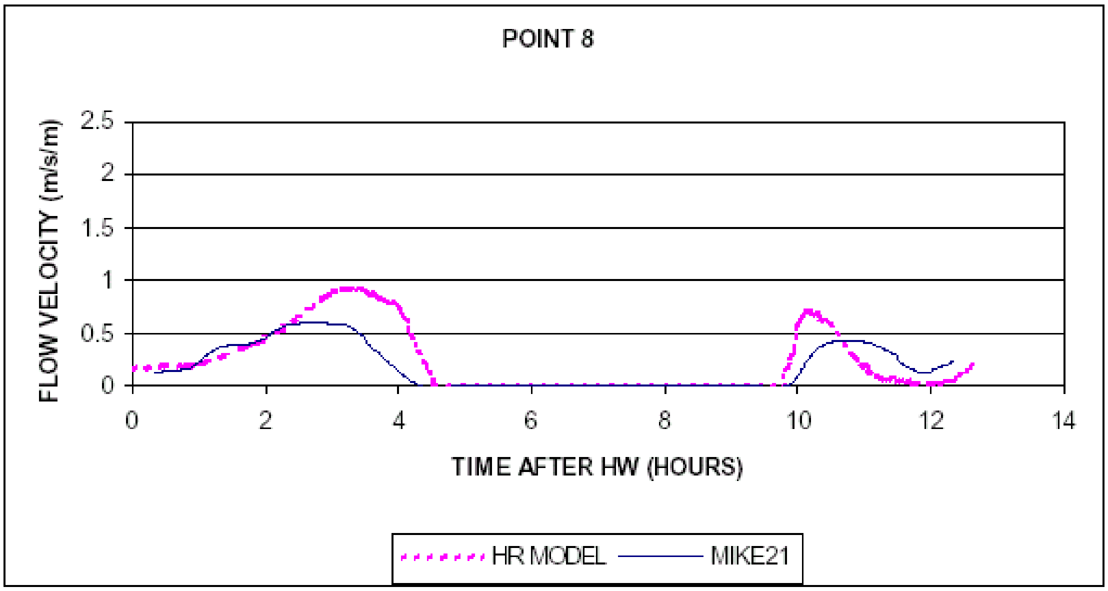

Figure 10(h) – Comparison of Current Flow Velocity at Point 8

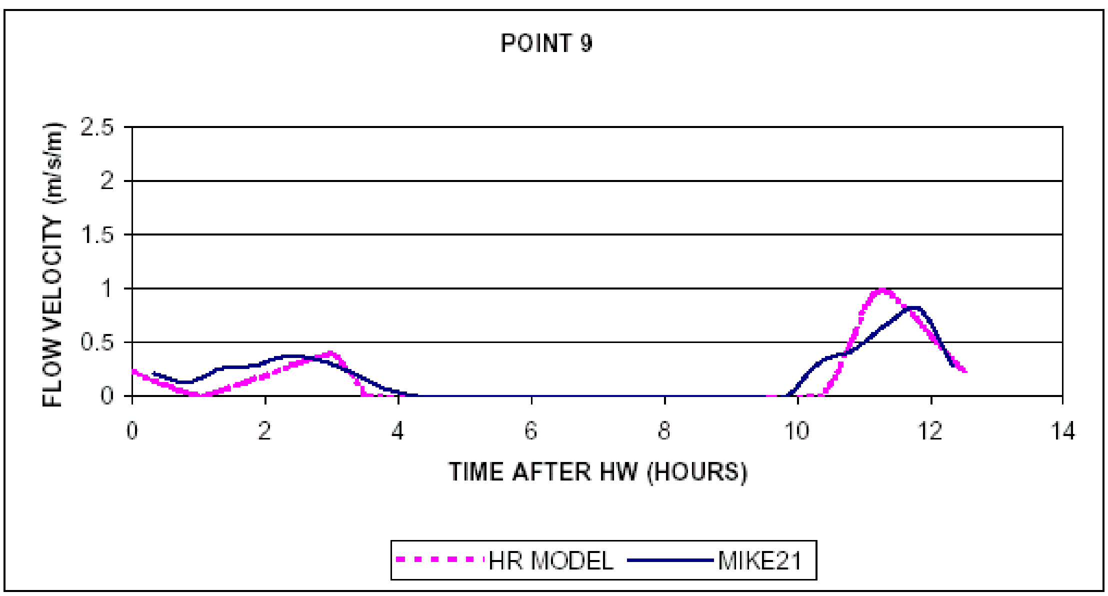

Figure 10(i) – Comparison of Current Flow Velocity at Point 9

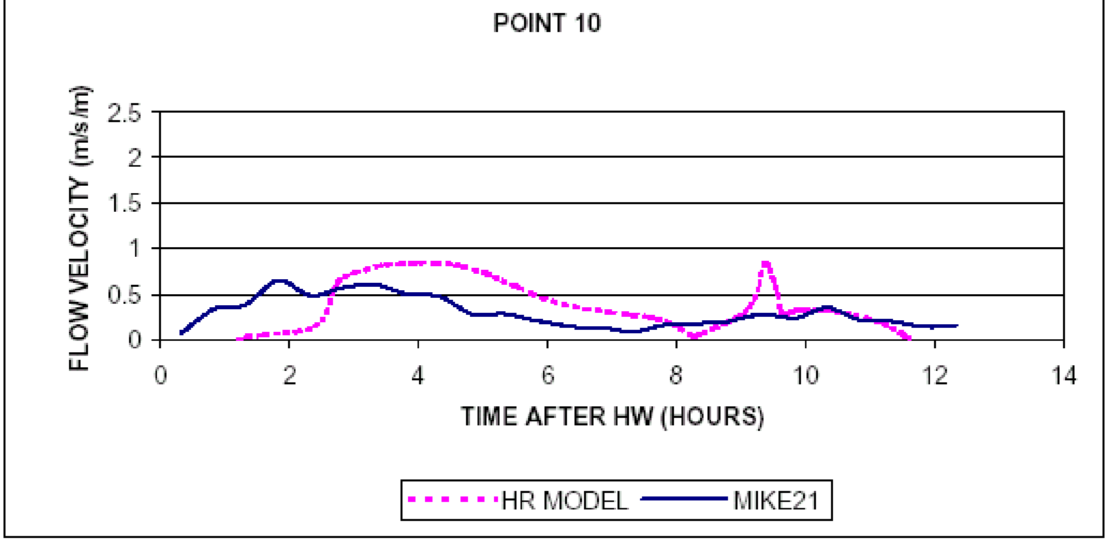

Figure 10(j) – Comparison of Current Flow Velocity at Point 10

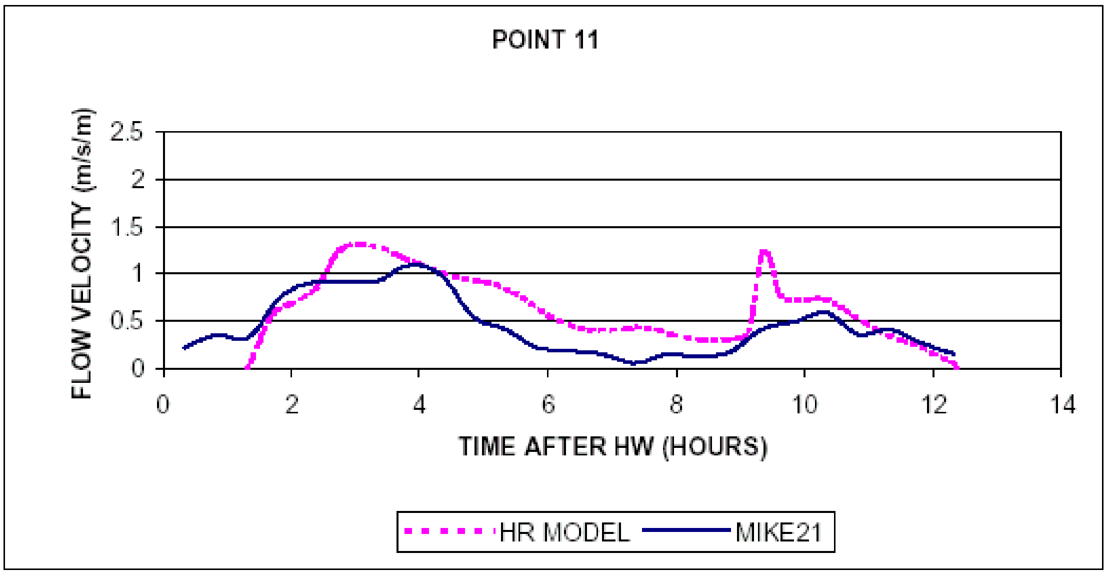

Figure 10(k) – Comparison of Current Flow Velocity at Point 11

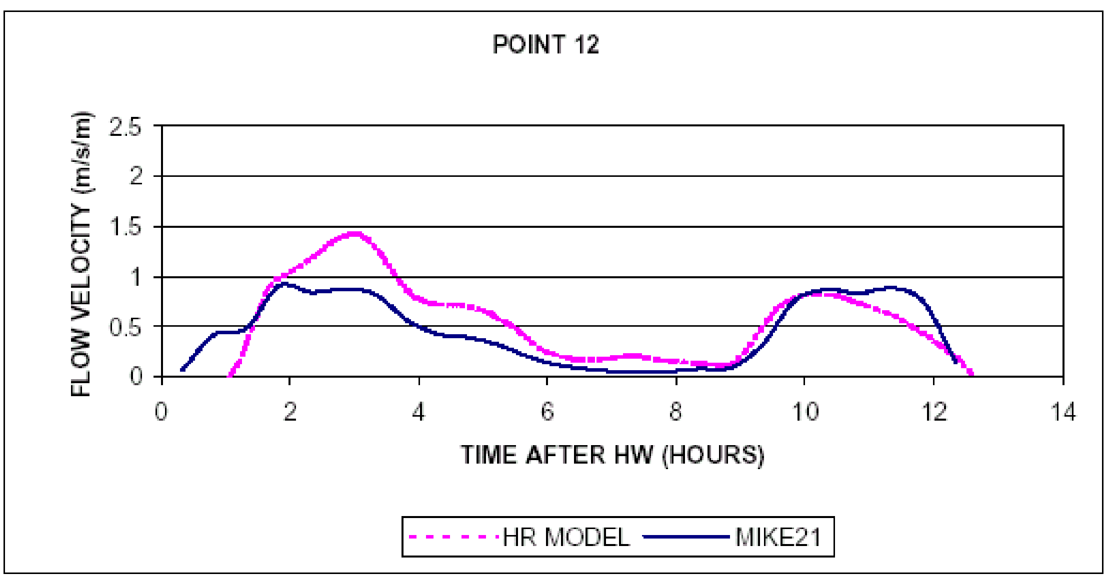

Figure 10(l) – Comparison of Current Flow Velocity at Point 12

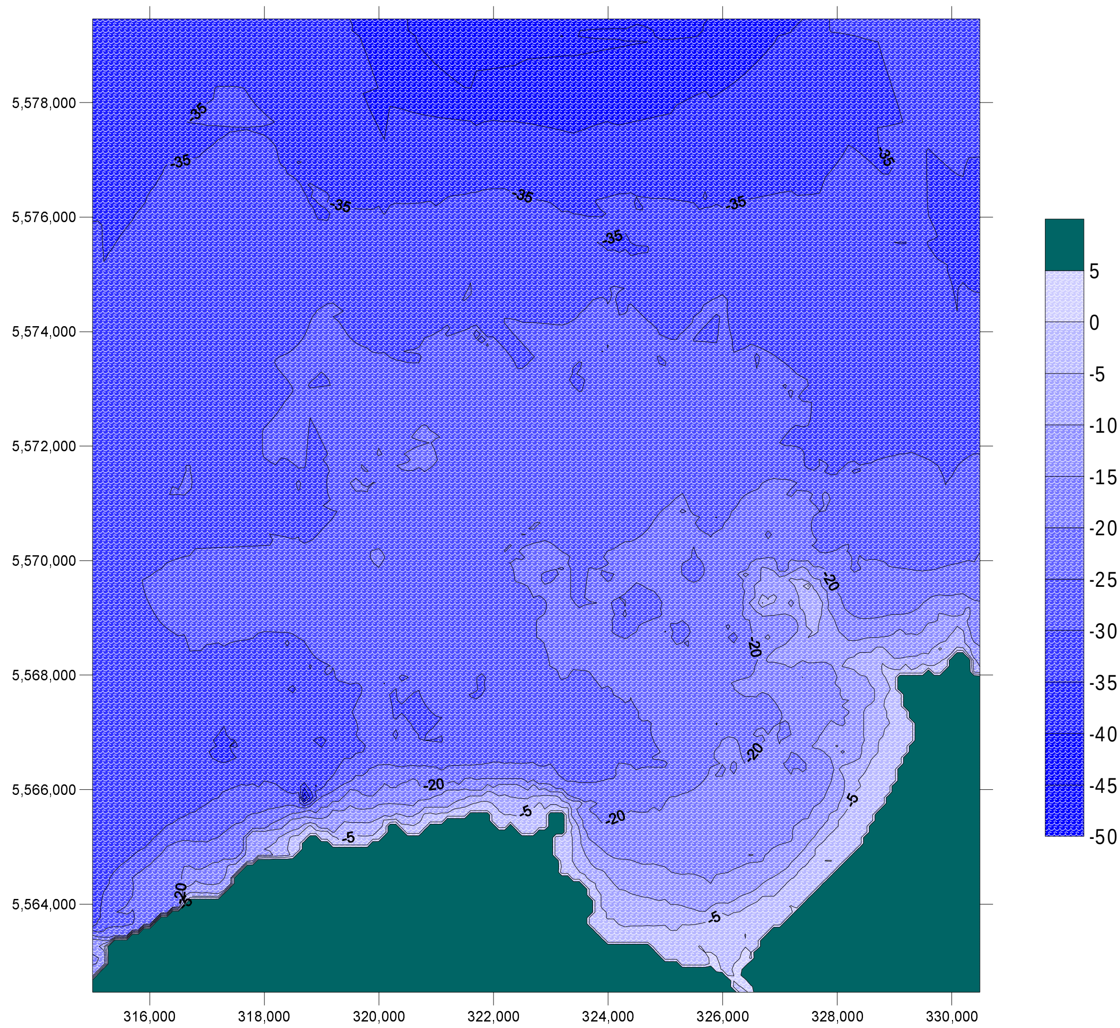

Figure 11 – 100m Model Grid for SWAN

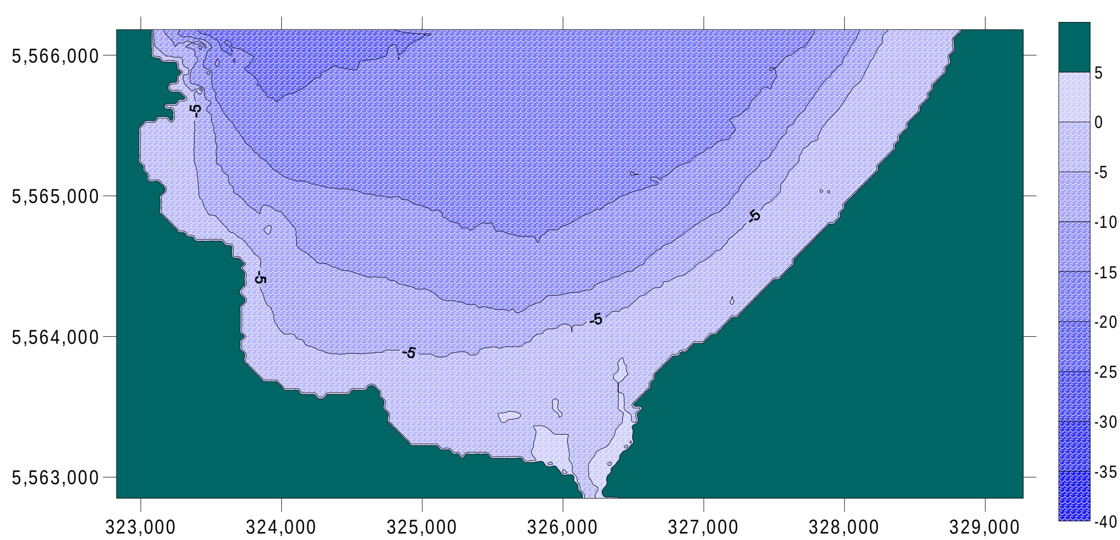

Figure 12 – 30m Model Grid for SWAN

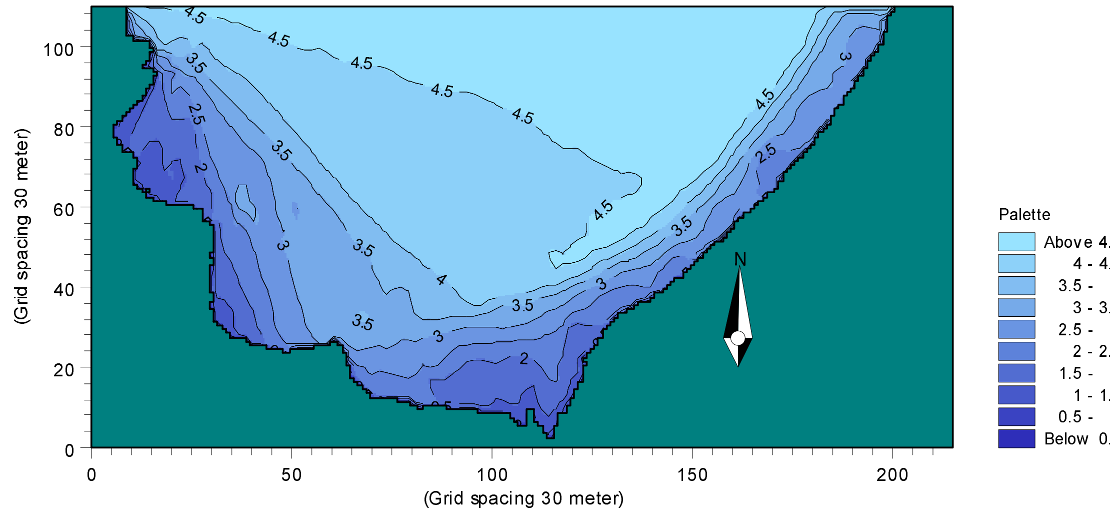

Figure 13 – SWAN Wave Grid for 1:5 Year Condition, MHWS

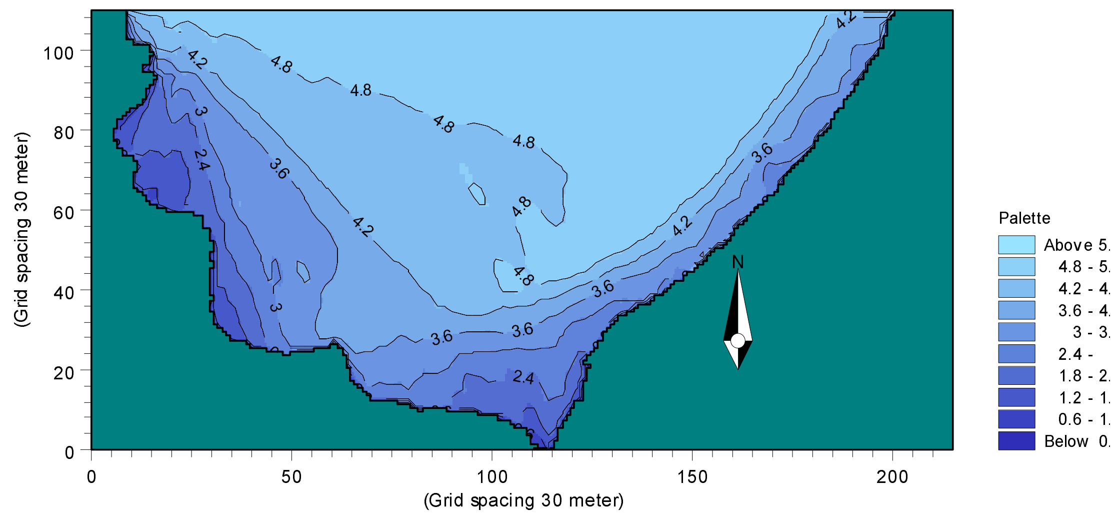

Figure 14 – SWAN Wave Grid for 20 Year Condition, MHWS + Surge

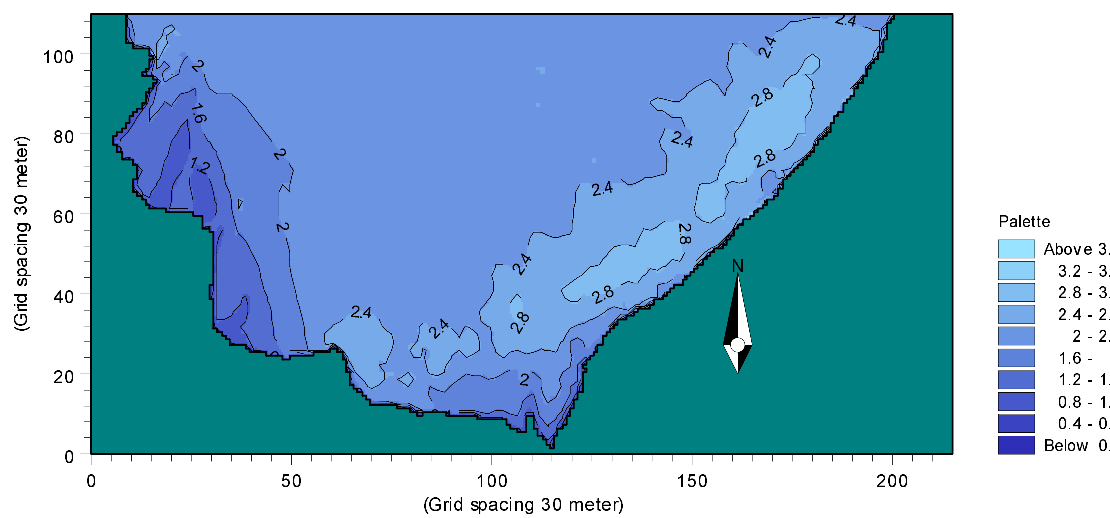

Figure 15 – SWAN Wave Grid for Swell Wave Condition, MHWS

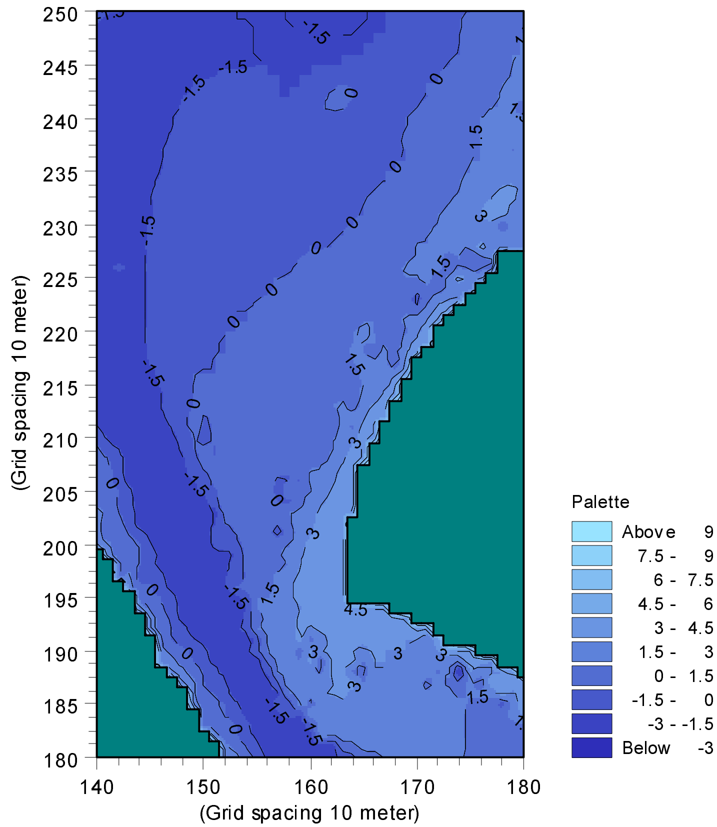

Figure 16(a) – Original Bathymetry at Hayle Beach

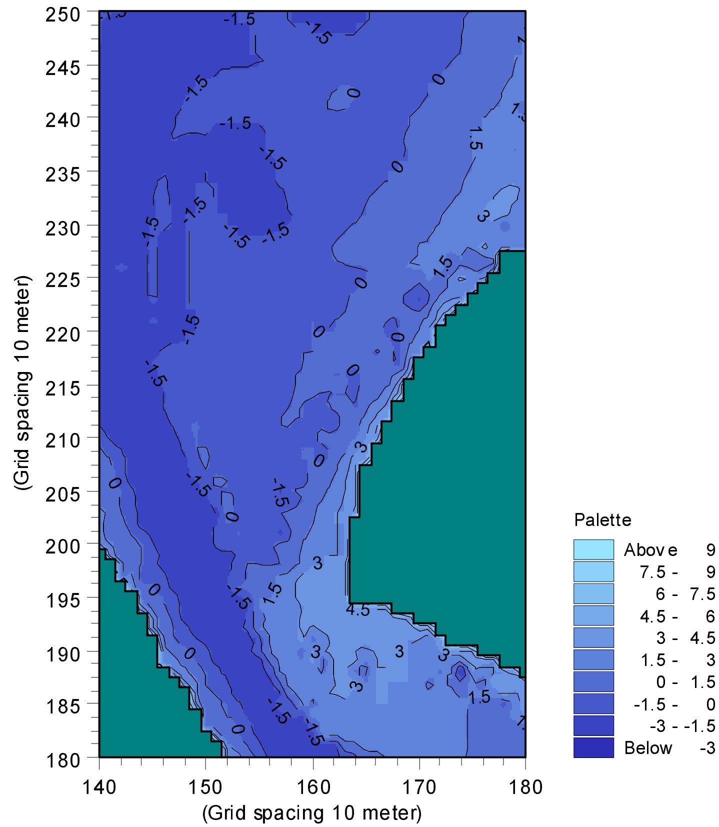

Figure 16(b) – Amended bathymetry at Hayle Beach

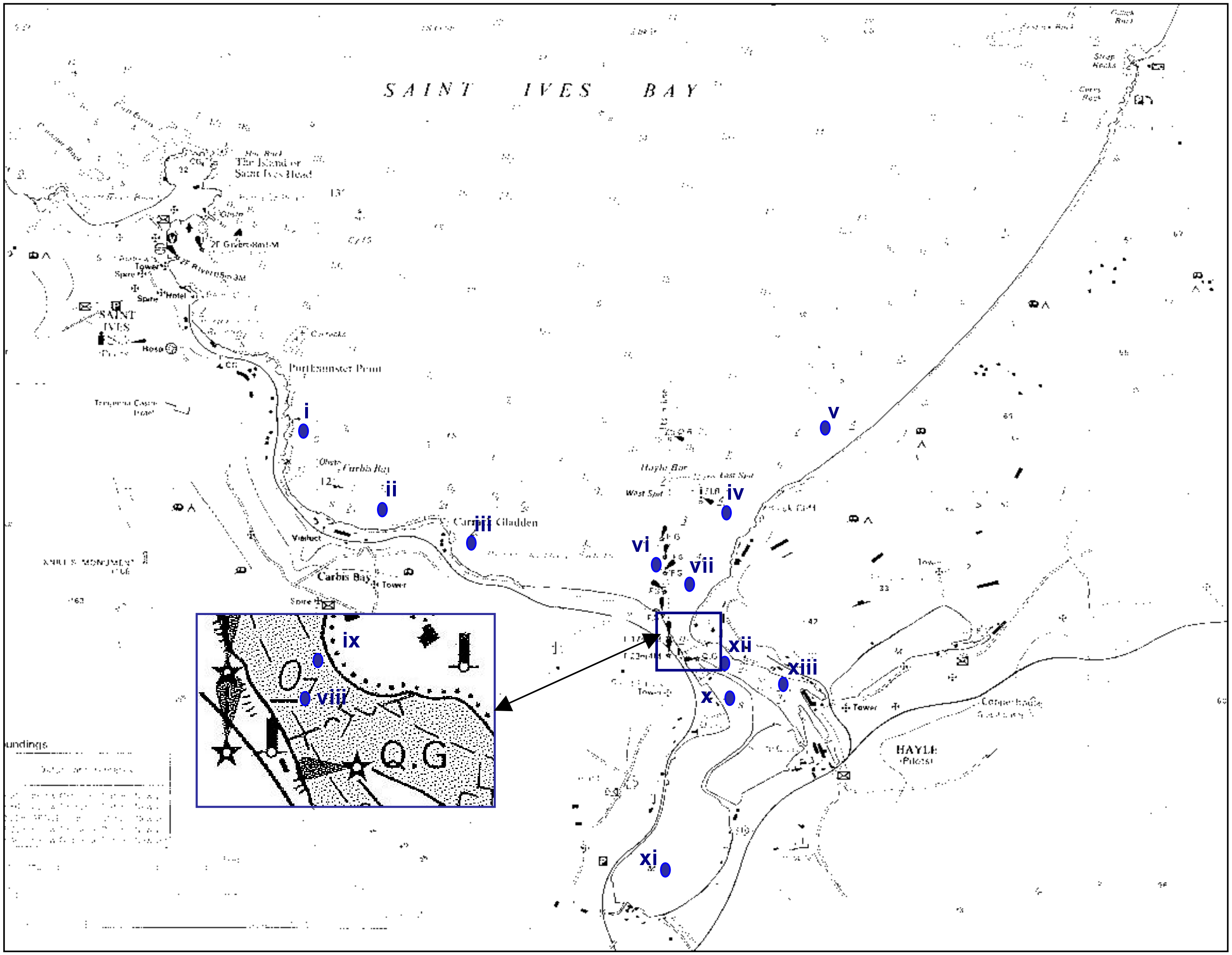

Figure 17 – Location of Analysis Points i - xiii

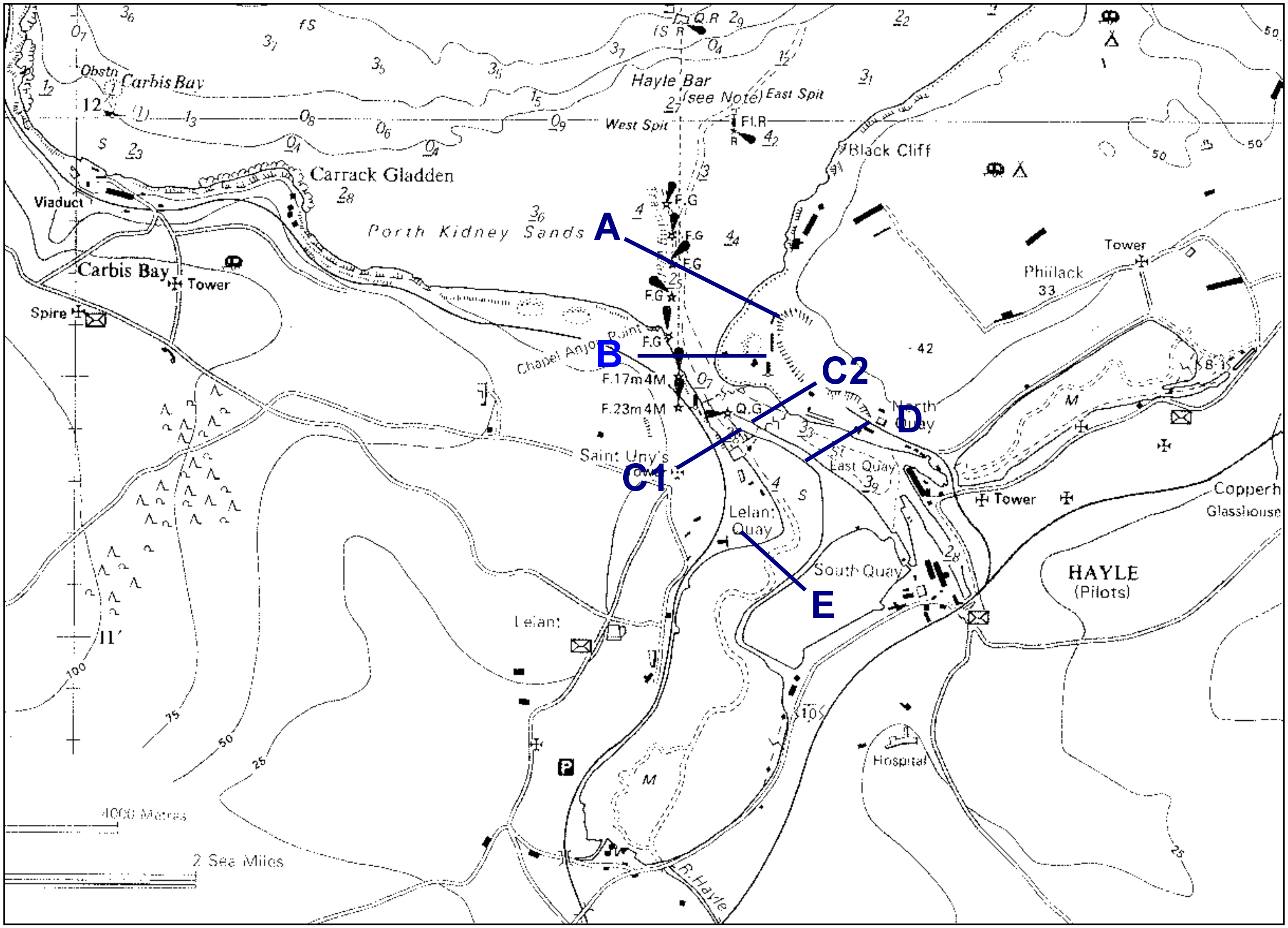

Figure 18 – Location of Cross-Sections A - E

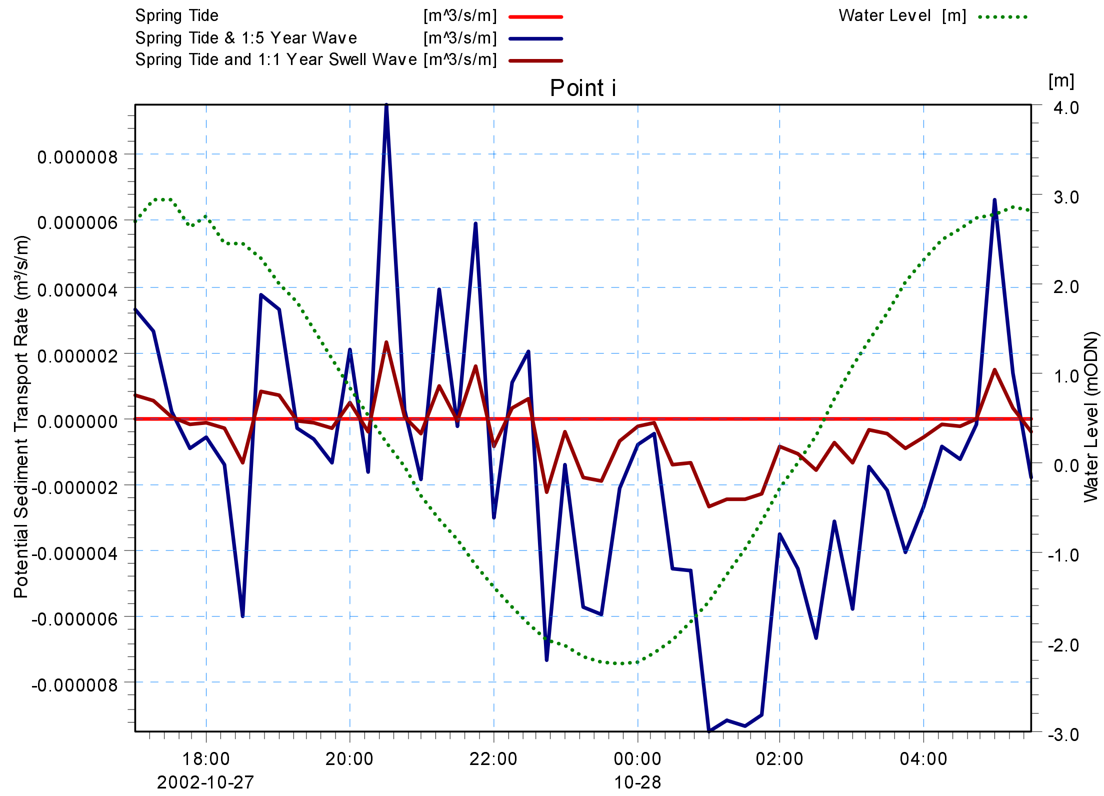

Figure 19 – Point i Sediment Transport Rates

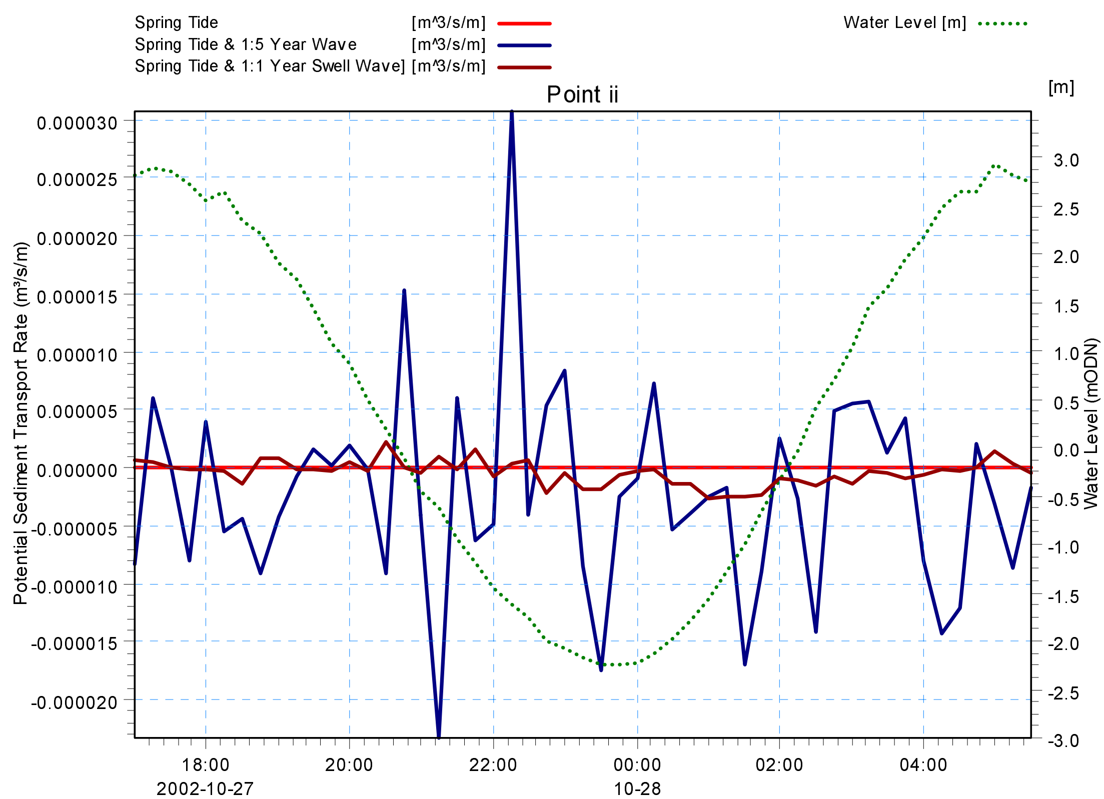

Figure 20 – Point ii Sediment Transport Rates

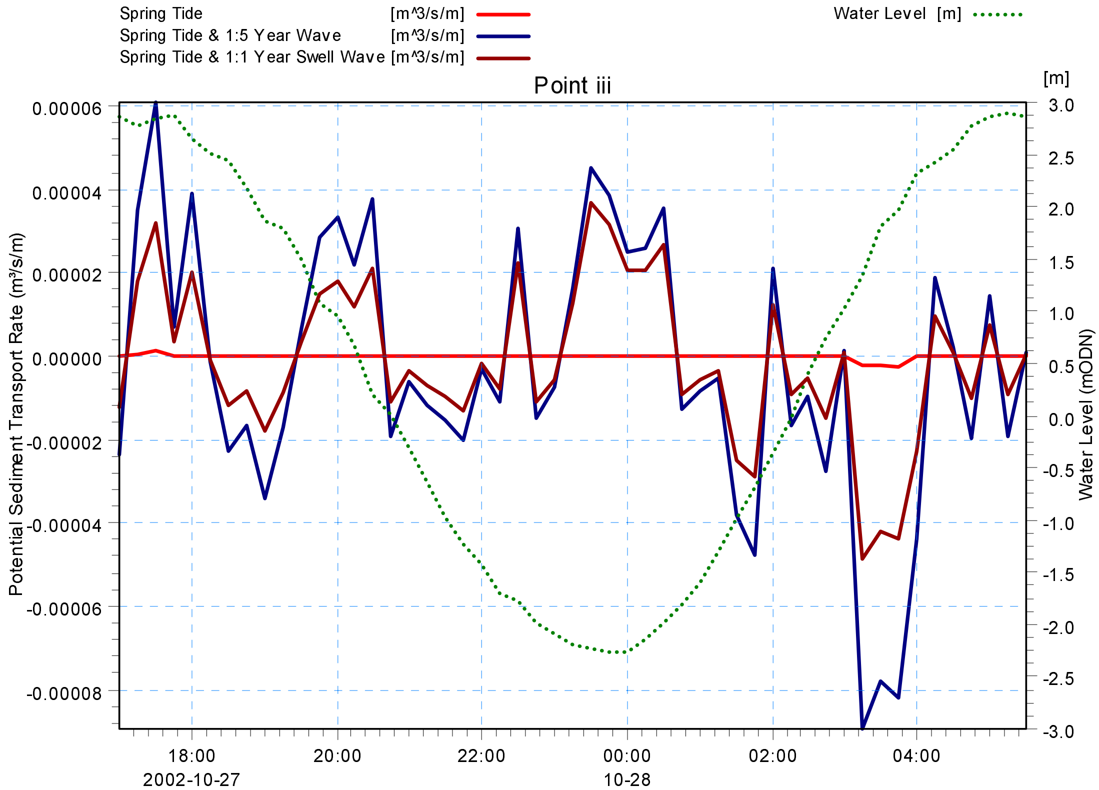

Figure 21 – Point iii Sediment Transport Rates

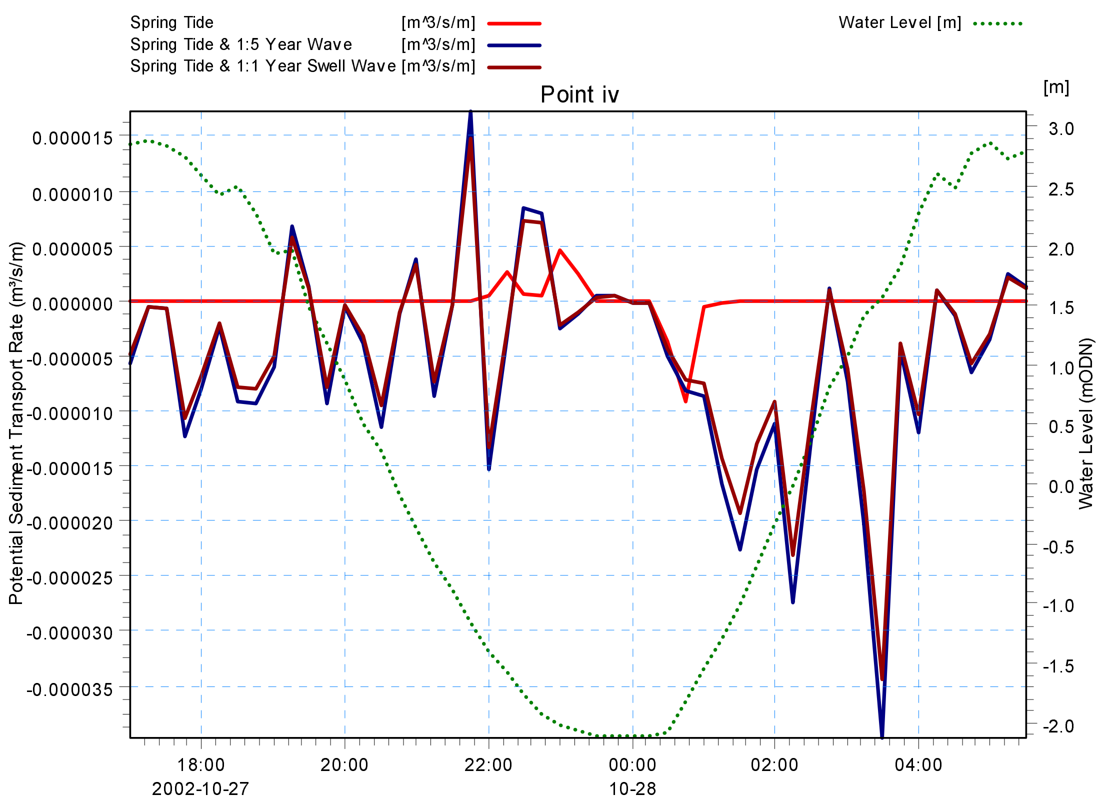

Figure 22 – Point iv Sediment Transport Rates

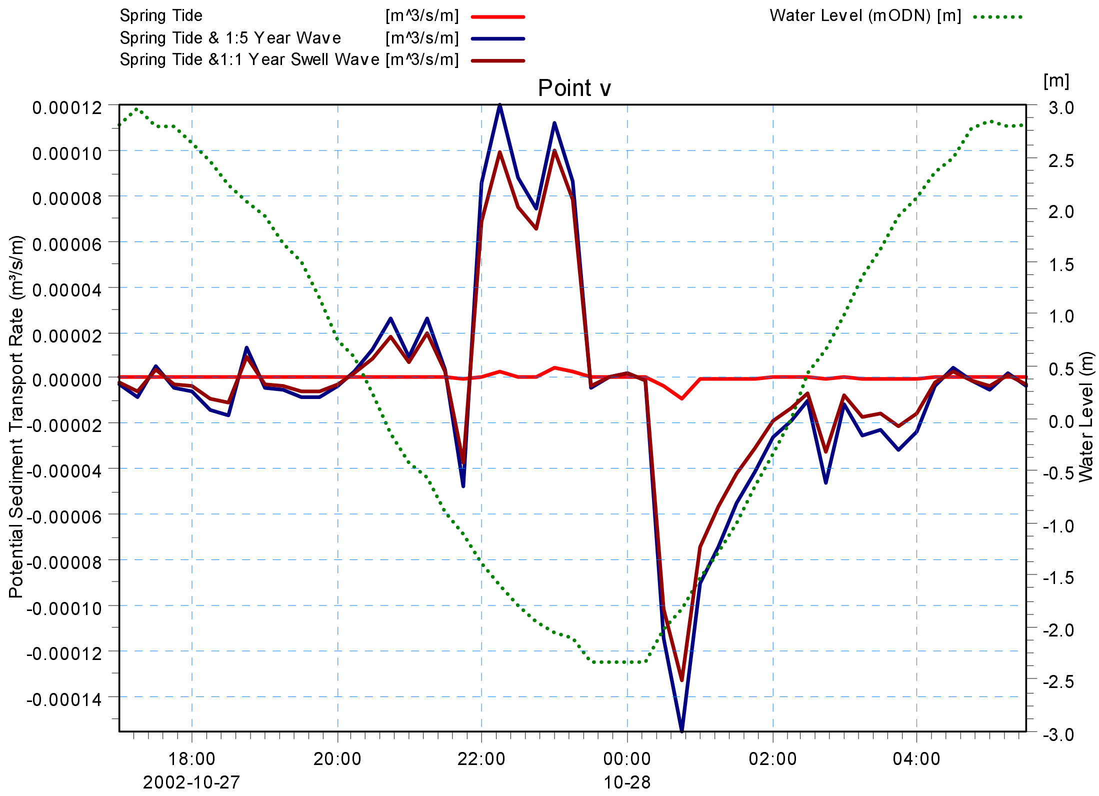

Figure 23 – Point v Sediment Transport Rates

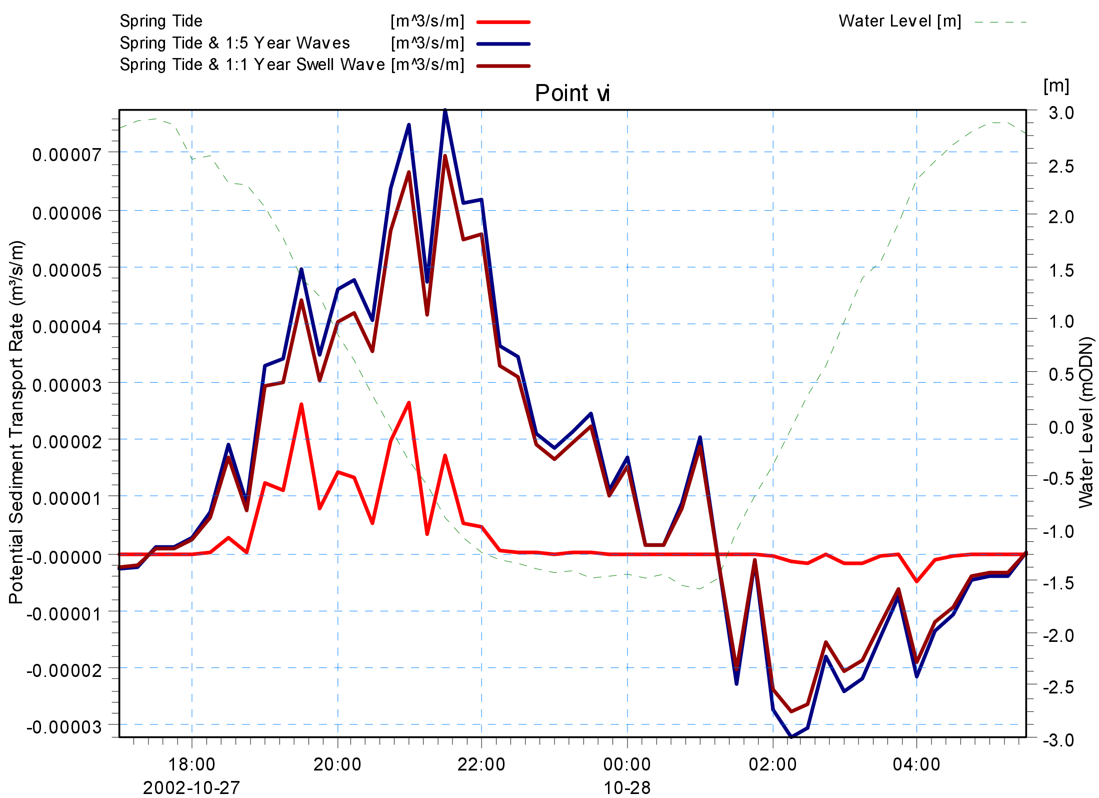

Figure 24 – Point vi Sediment Transport Rates

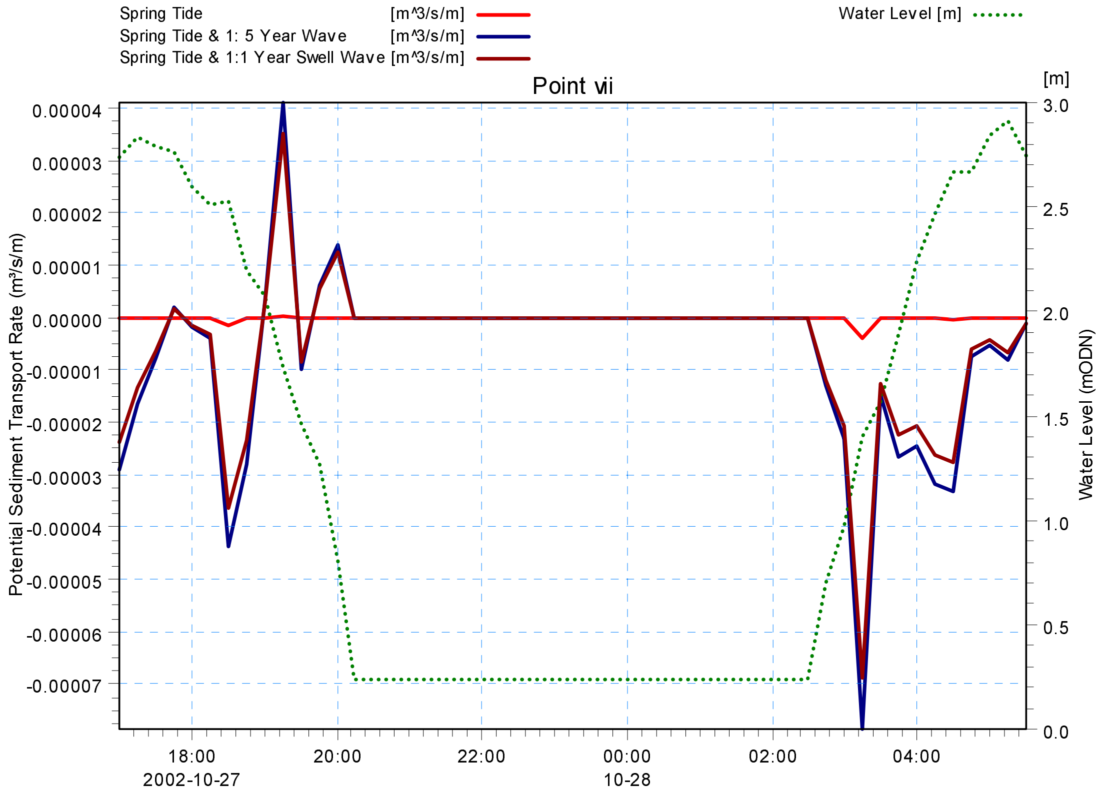

Figure 25 – Point vii Sediment Transport Rates

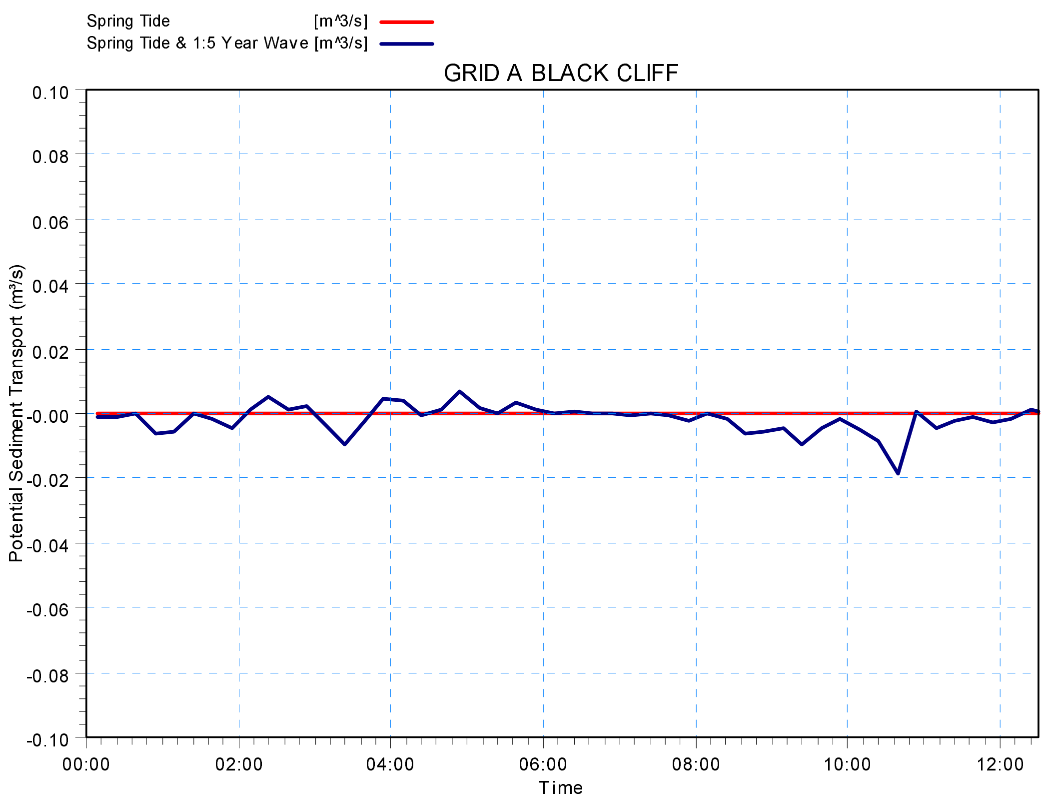

Figure 26 – Potential Sediment Transport at Black Cliff

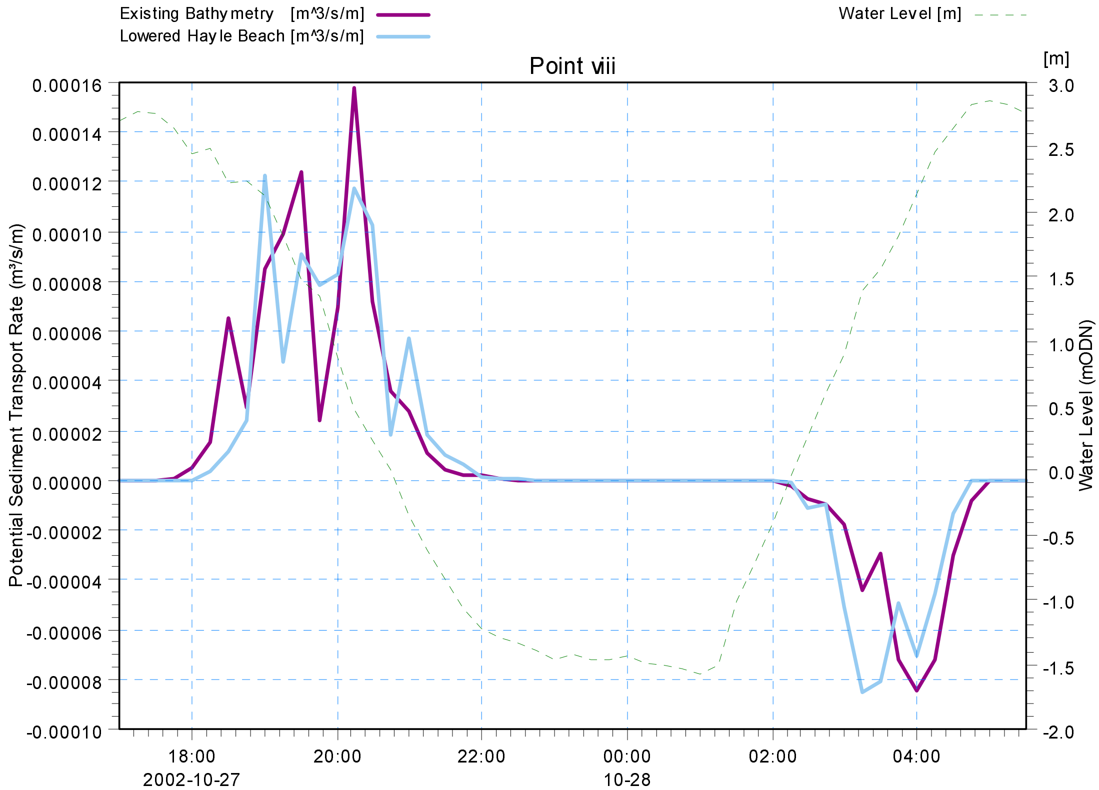

Figure 27 – Point viii Sediment Transport Rates

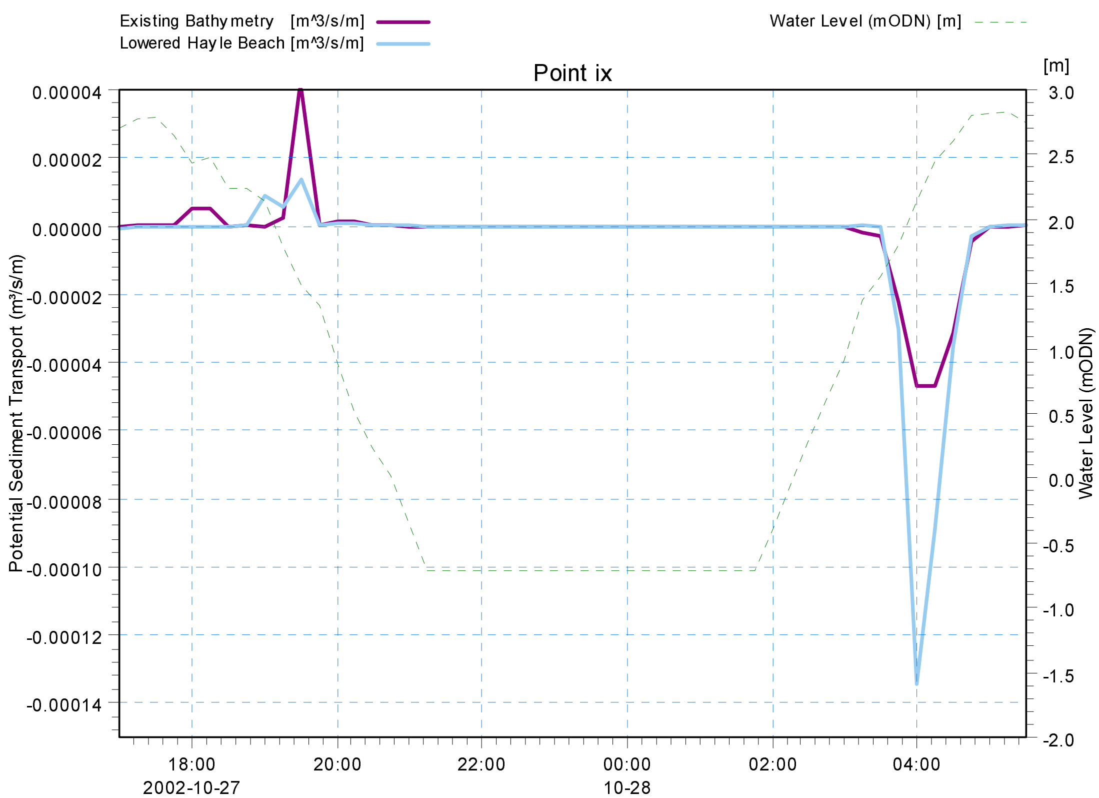

Figure 28 – Point ix Sediment Transport Rates

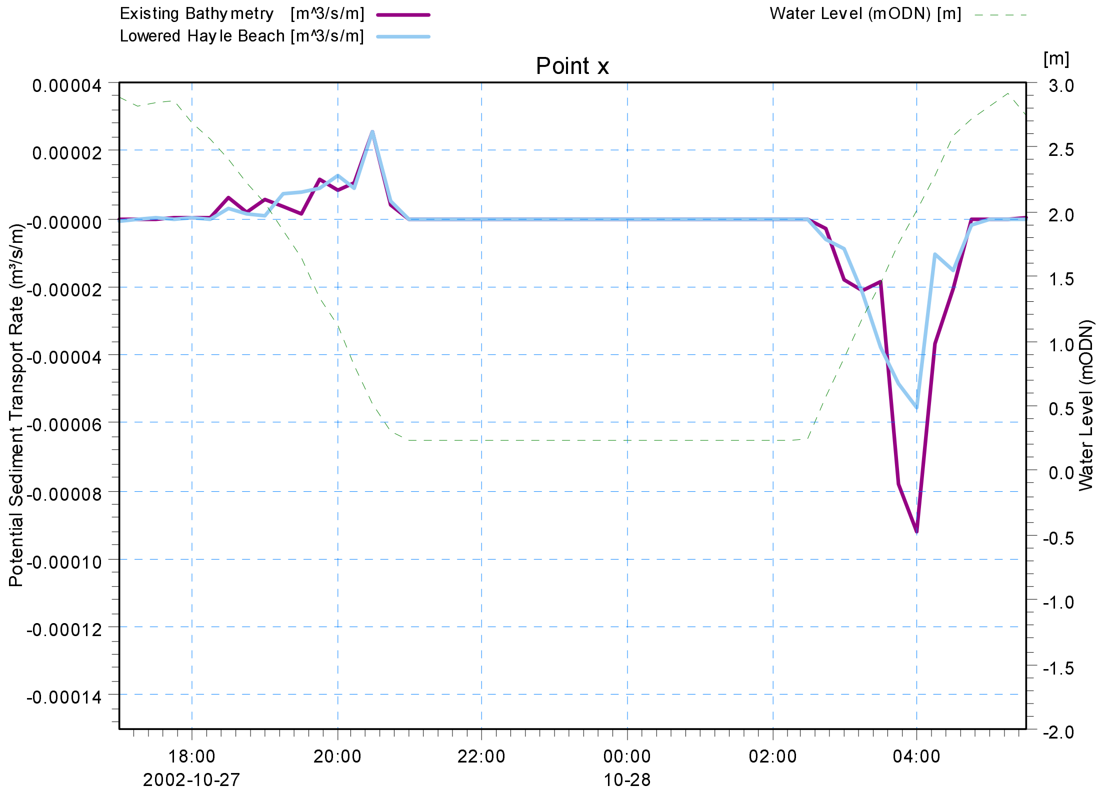

Figure 29 – Point x Sediment Transport Rates

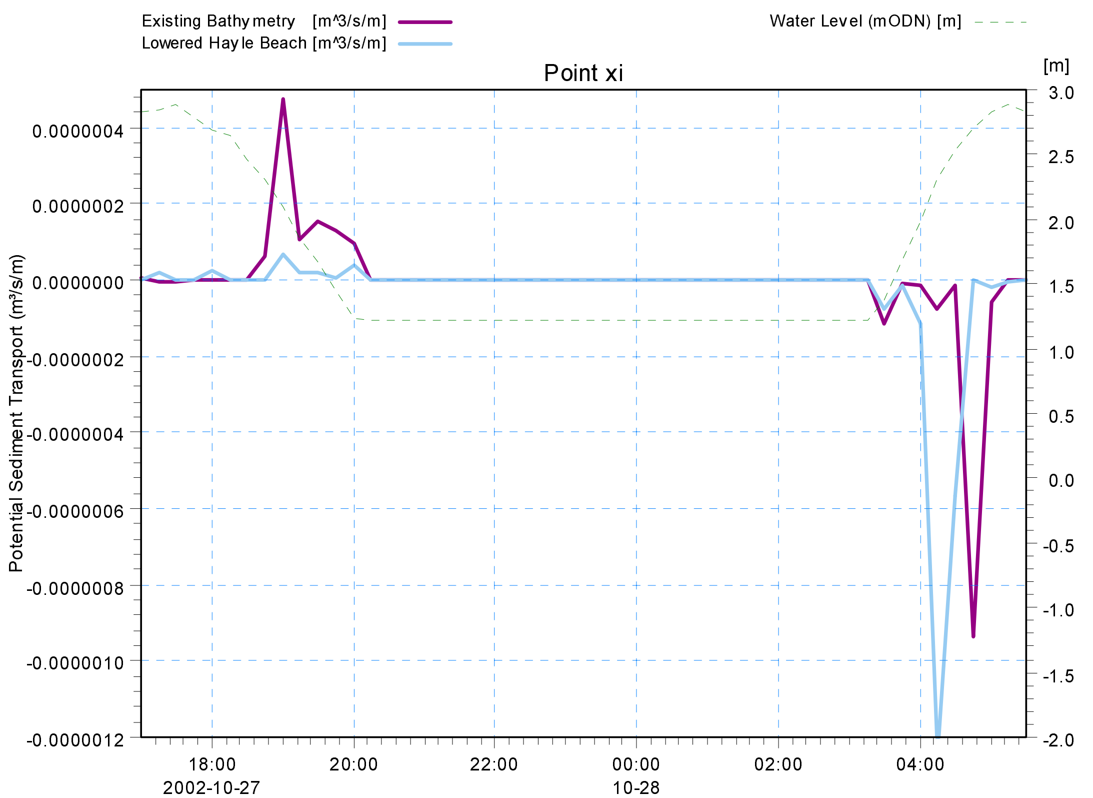

Figure 30 – Point xi Sediment Transport Rates

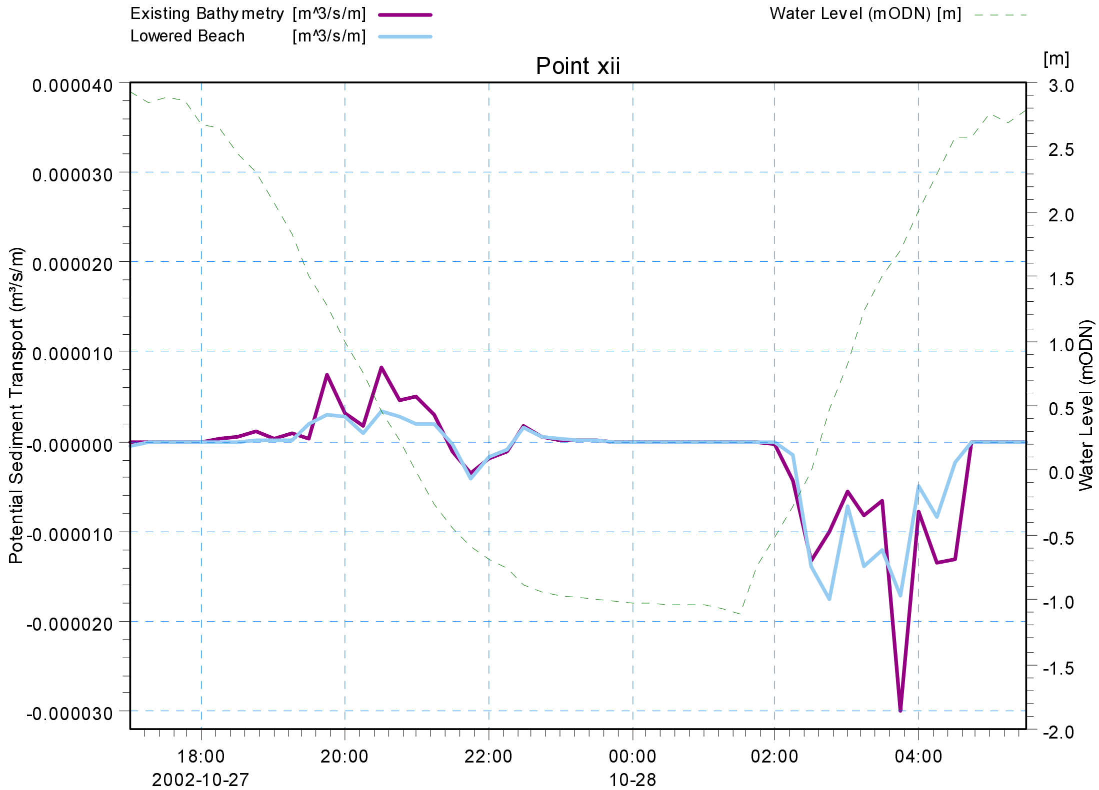

Figure 31 – Point xii Sediment Transport Rates

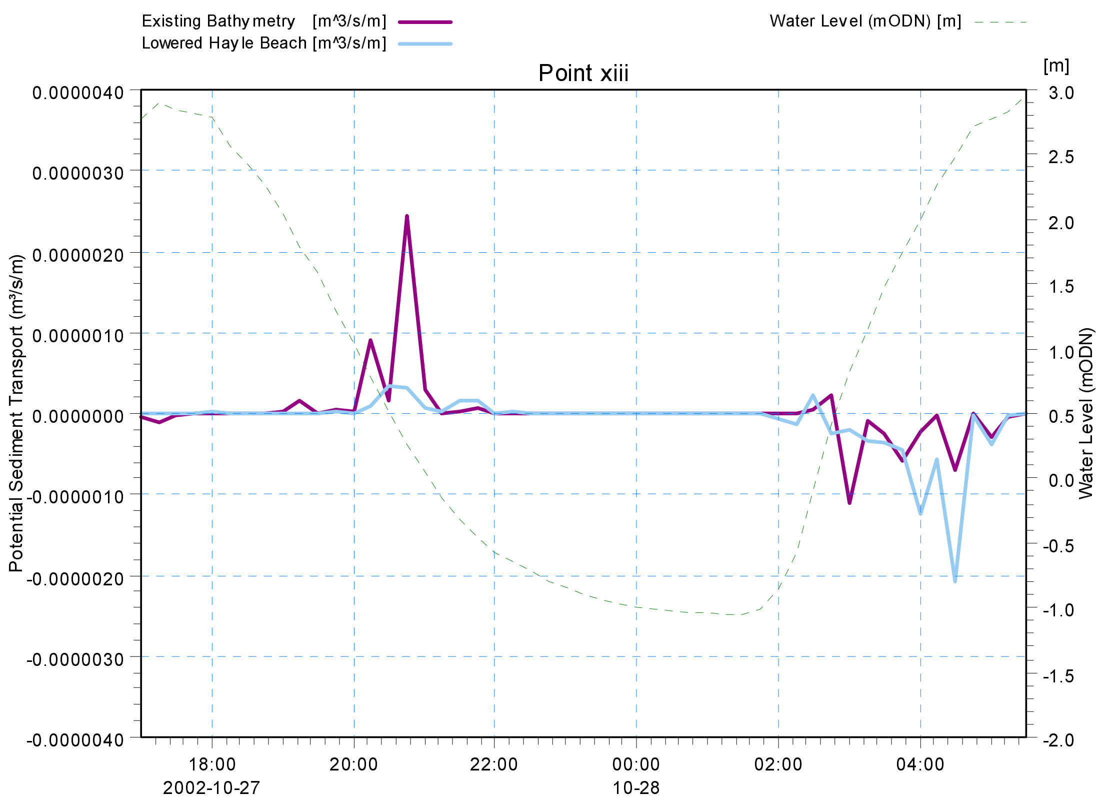

Figure 32 – Point xiii Sediment Transport Rates

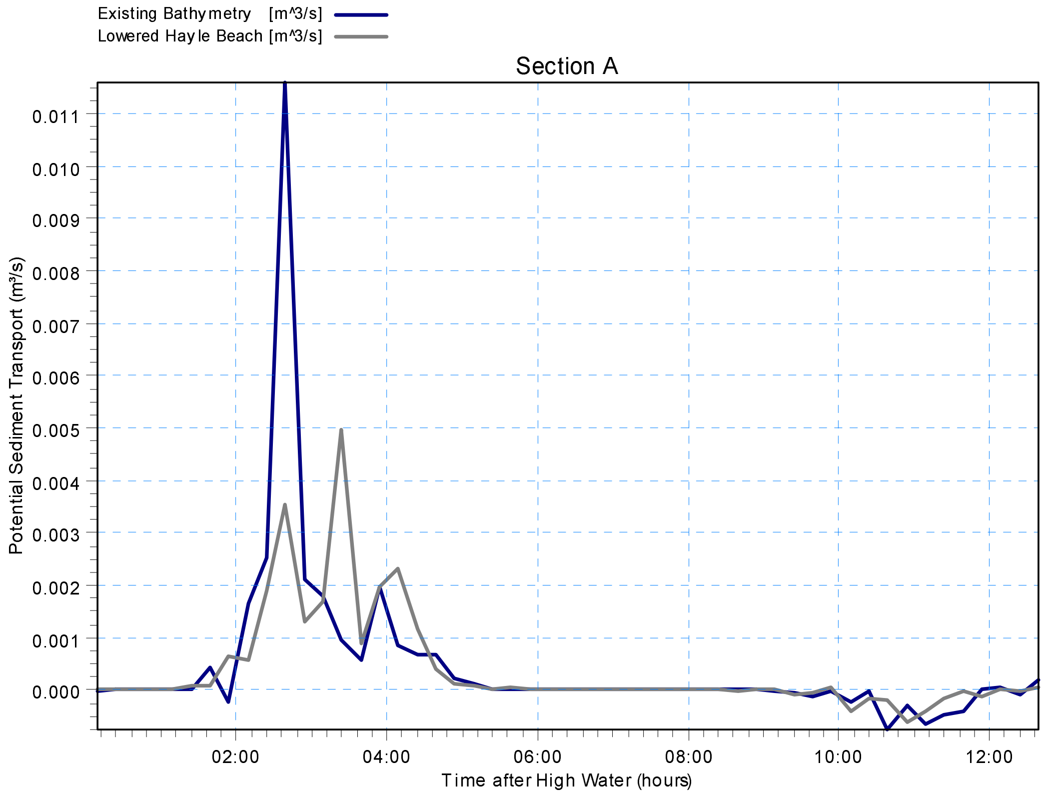

Figure 33 – Section A Potential Sediment Transport Rate

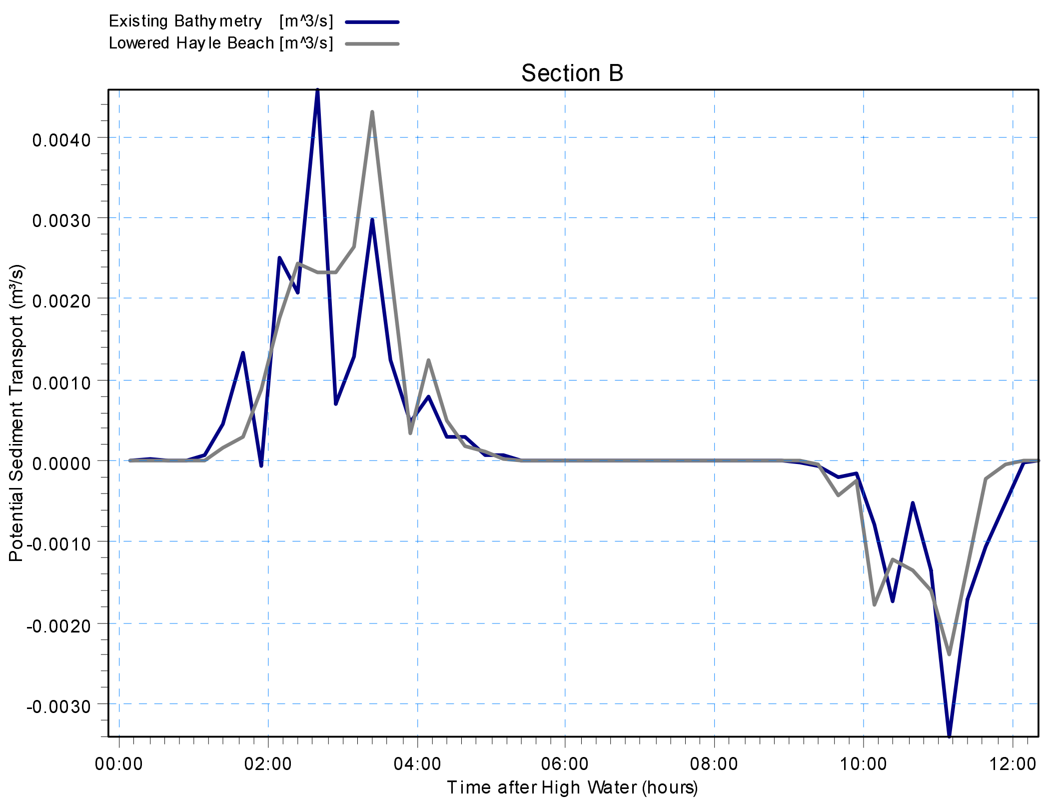

Figure 34 – Section B Potential Sediment Transport Rate

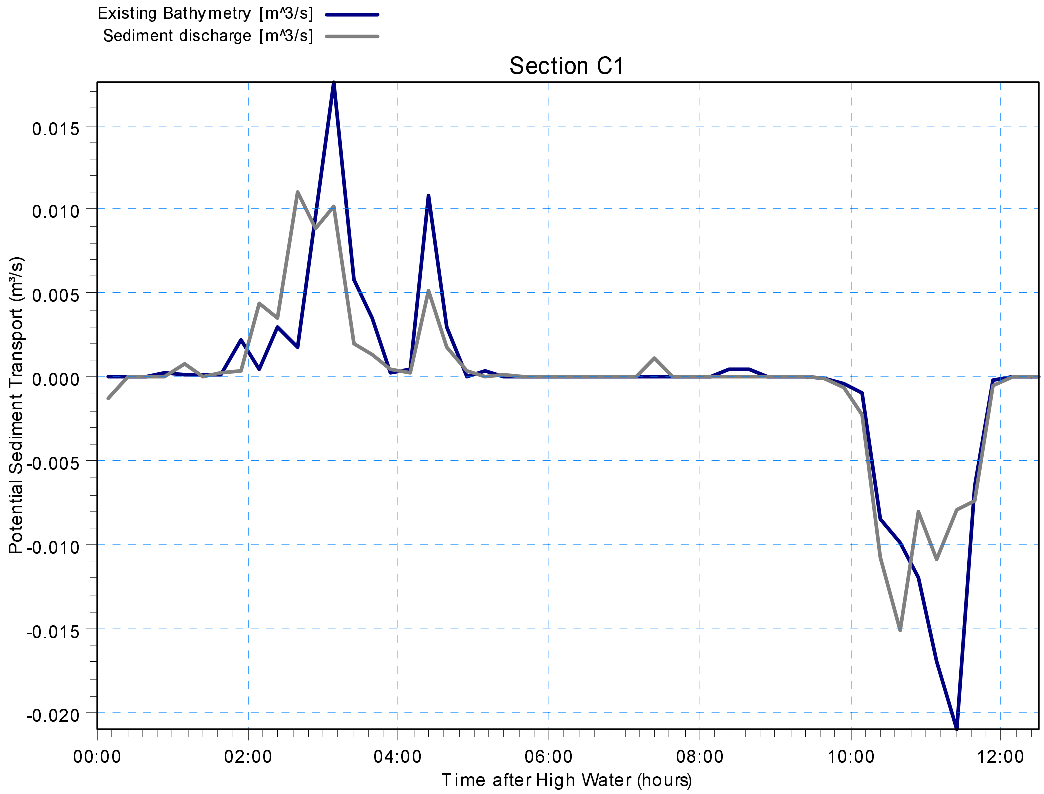

Figure 35 – Section C1 Potential Sediment Transport Rate

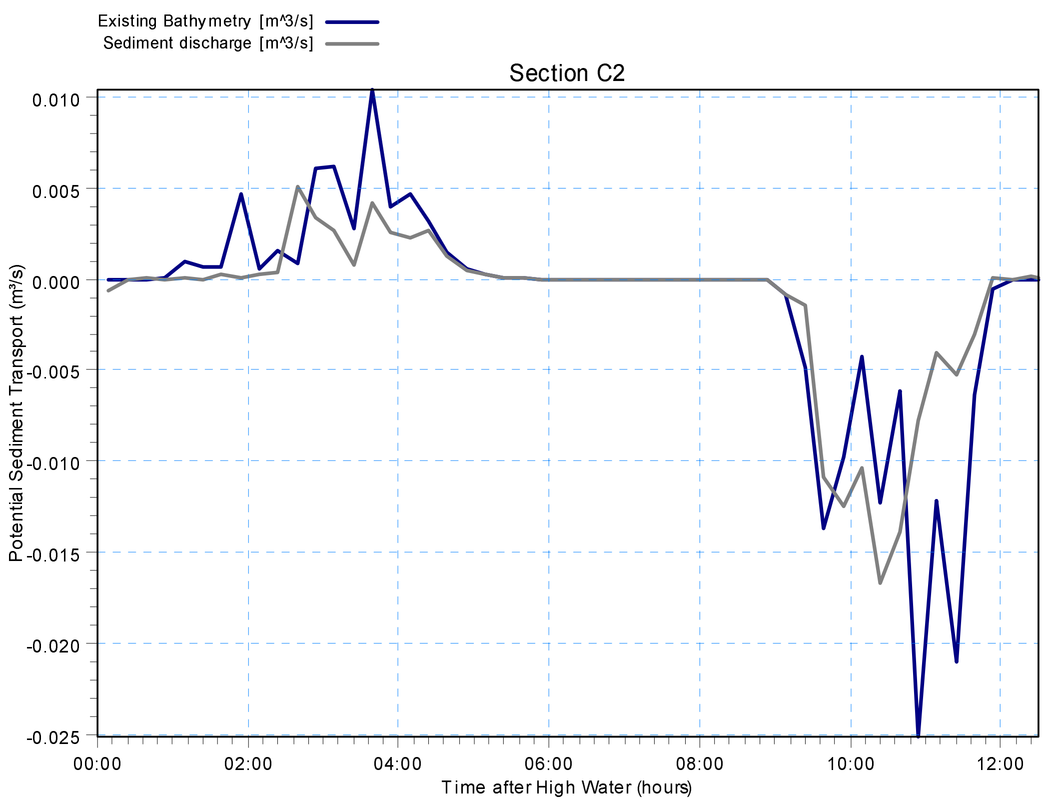

Figure 36 – Section C2 Potential Sediment Transport Rate

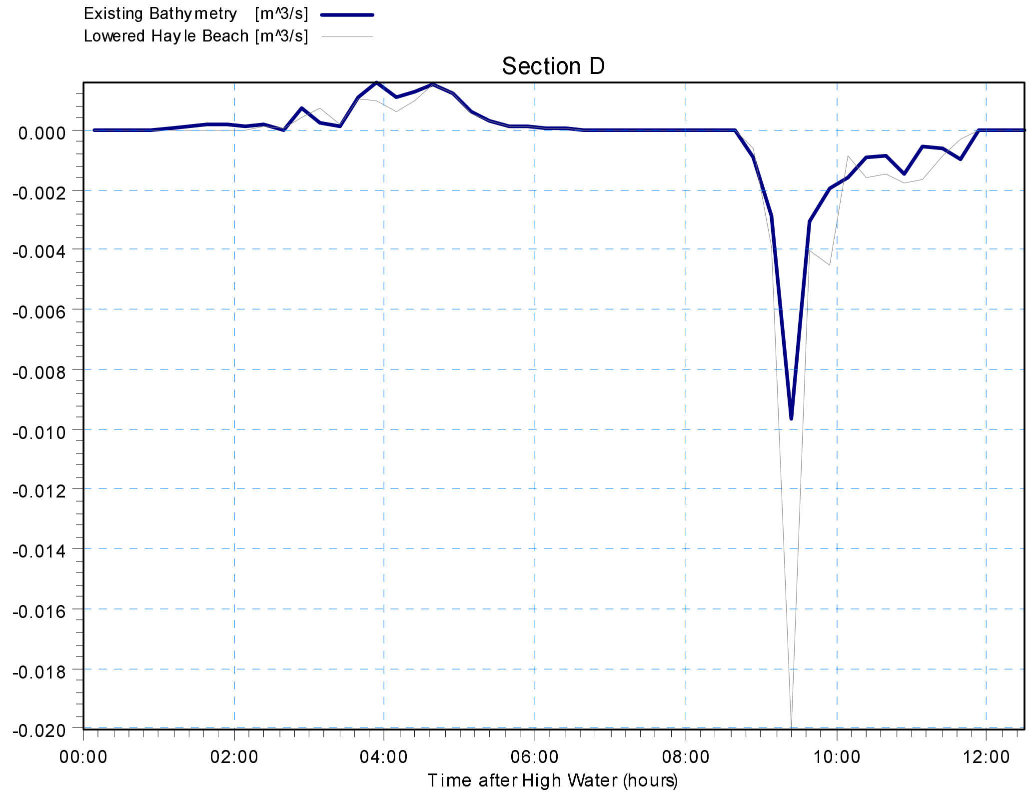

Figure 37 – Section D Potential Sediment Transport Rate

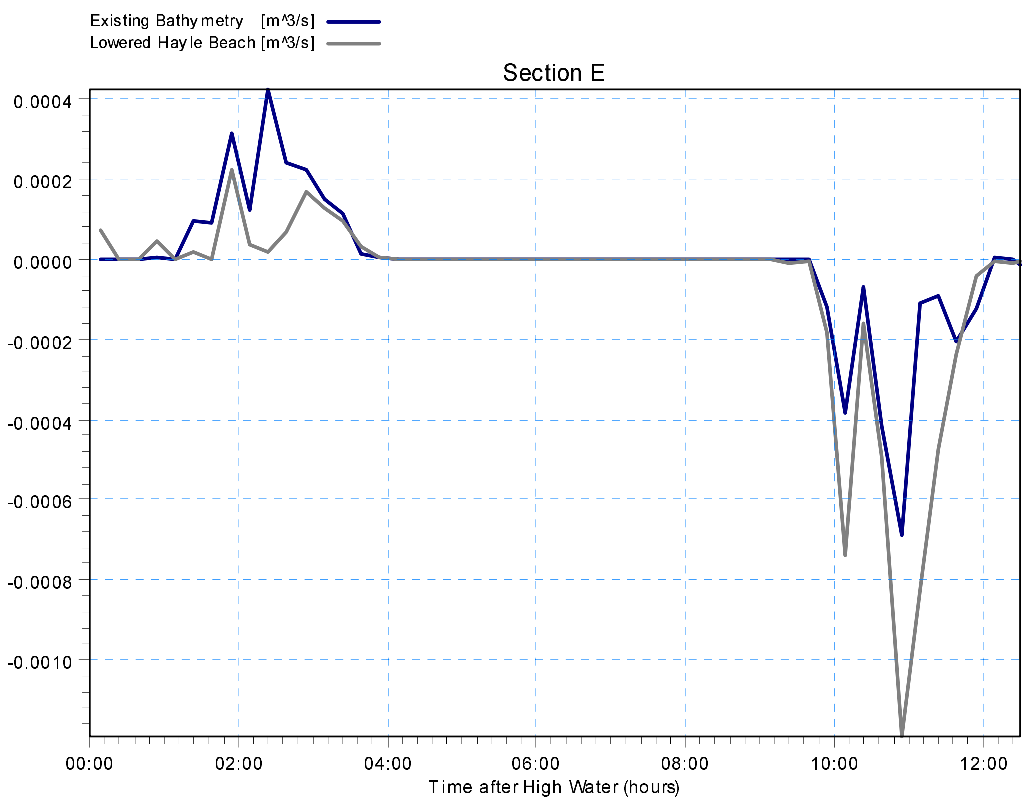

Figure 38 – Section E Potential Sediment Transport Rate

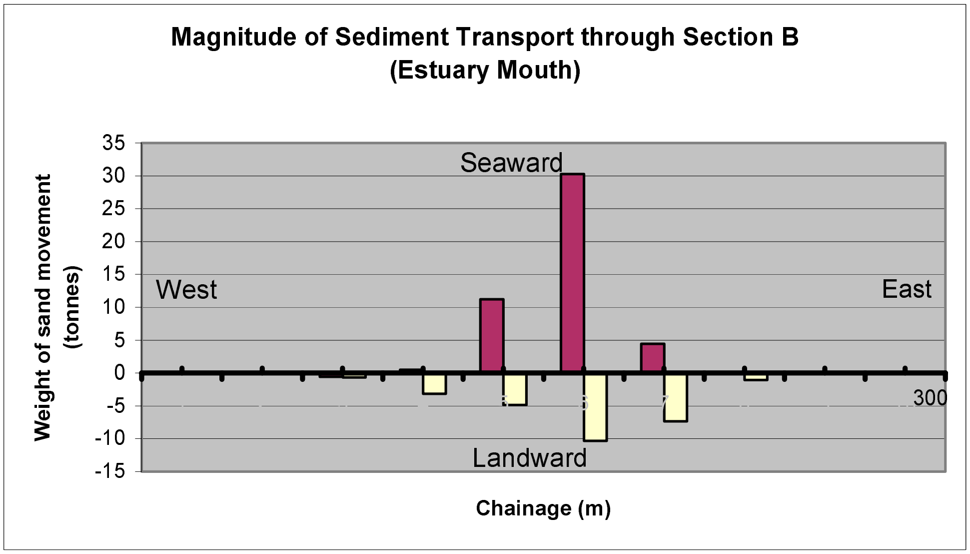

Figure 39 – Magnitude of Sediment Transport through Section B (Estuary Mouth)

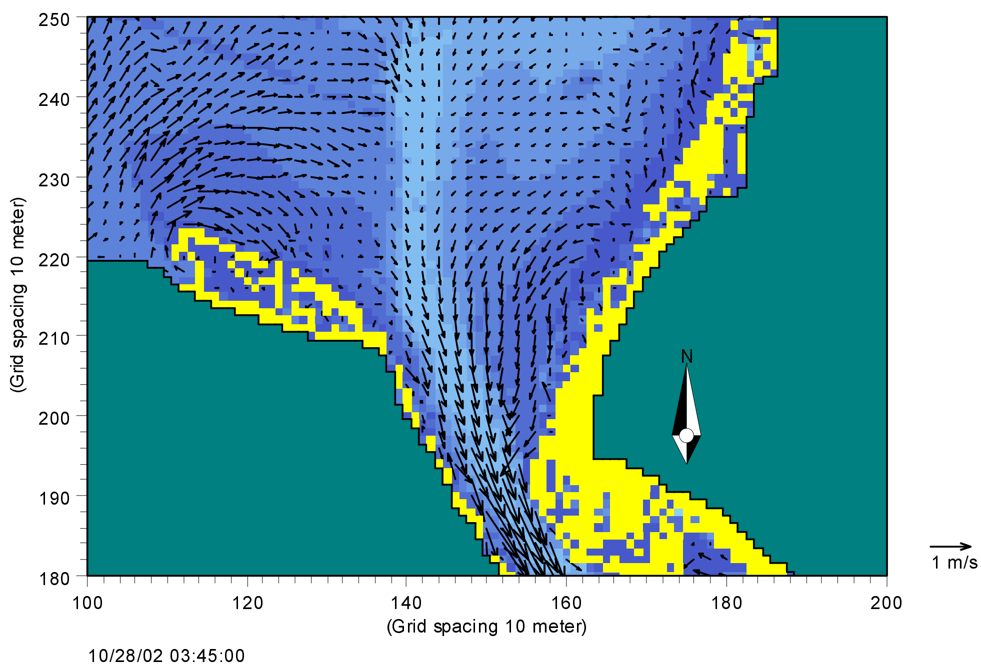

Figure 40 – Magnitude and Direction of Tidal Flows During Mid Flood

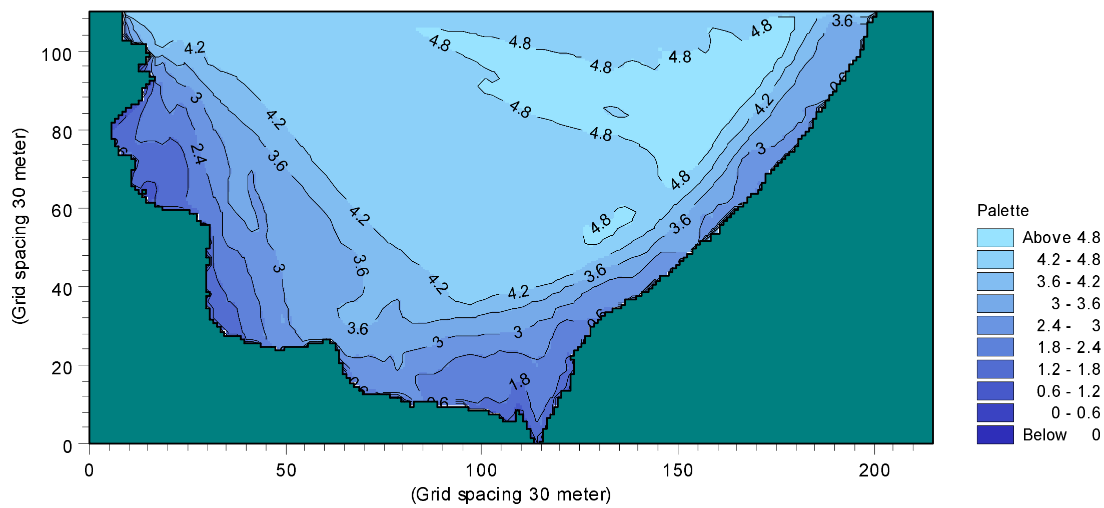

Figure 41 – 1 in 5 Year Wave SWAN Output with Amended Bathymetry

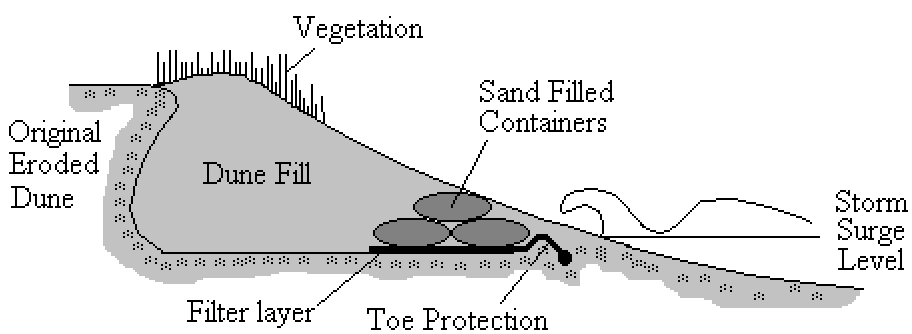

Figure 42 – Sand Filled Container Dune Protection System