Cell 1 Sediment Transport Study

Phase 2: Main Report

Scarborough Borough Council

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Enhancing Society Together

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SUMMARY

Royal HaskoningDHV was appointed by Scarborough Borough Council to undertake the **Cell 1 Sediment Transport Study** on behalf of all public authorities and other organisations with coastal interests within Coastal Cell 1. This frontage covers the coastline between St. Abb's Head in Scotland and Flamborough Head in the East Riding of Yorkshire.

Management of any coastline is complex due to the dynamic nature of the processes which prevail and the range of interests that exist. In order to provide the best possible management, it is necessary to have a good understanding of the sediment transport processes, so that actions in one area of coast do not unduly affect other areas. To this end, the objective of the Cell 1 Sediment Transport Study is to improve understanding of governing sediment transport mechanisms and pathways across Coastal Cell 1 to help improve future coastal management decision-making.

The **first phase** (the previous scoping phase) of the study was reported in December 2013 and the scoping report was accompanied by a number of supporting atlases. The scoping phase involved the development of a broad-level conceptual understanding of the governing sediment transport processes and sediment-related issues. This was based upon review of existing information, consultation with relevant authorities and organisations, and characterisation of the nearshore marine environment to determine the key sediment transport processes along the Cell 1 coast.

The **second phase** (the present phase) of the study has involved use of a range of analytical and modelling techniques to provide additional levels of detail at a selected number of key locations within Coastal Cell 1:

- Historical Trends Analysis (HTA) has investigated the historical legacy of colliery spoil tipping on the foreshore at Lynemouth Bay and Cambois Bay in Northumberland and at several beaches in County Durham. It is estimated that around 30m tonnes of colliery waste from Lynemouth and Ellington Collieries was tipped at foreshore disposal sites in Lynemouth Bay between 1934 and 2005, with at its peak over 1.5m tonnes tipped in one year (1968). An unknown quantity of excavated clay (and other waste) was tipped over the cliff edge at Cambois Bay until closure of Cambois Colliery in 1968. Over 100m tonnes of colliery waste was tipped along the County Durham coastline, either at offshore disposal sites or at foreshore disposal sites. In all cases, the tipping of waste resulted in significant progradation (seaward movement) of the shoreline and at Lynemouth and in County Durham infilling of the bays to form wide spoil beaches as a 'terrace' on the upper beach. Since cessation of tipping, the shoreline in all former tipping areas has been eroding.

- Numerical modelling using the MIKE LITPACK software suite has investigated the *relative* alongshore (LITDRIFT) and cross-shore (LITPROF) sediment transport potential at a series of sixteen transects throughout the Cell 1 frontage. Longshore sediment transport is only low to moderate in magnitude and is strongly influenced by changes in orientation of the shore profile within bays and the angle of the shore relative to the approach directions that characterise the nearshore wave climate. Cross-shore sediment transport potential exists at all modelled transects under a 1 month timeseries of 'winter' wave data. Combining the outputs from both modelling approaches, it can be confirmed that during storms sediment is removed from the beaches as a cross-shore process and then transported alongshore (with a net direction to the south) in the shallow nearshore zone. After the stormier wave climate has passed, sediment then progressively returns to the beaches as a cross-shore process (either within the same bay or further south along the coast after bypassing a headland) during calmer wave conditions.

The Cell 1 Sediment Transport Study has identified that the shoreline and nearshore sea bed is predominantly controlled by its underlying solid geological structure. Through differential erosion of the different rock types a number of ‘headland and bay’ features of varying spatial extents have been formed. Littoral sediment transport is, generally, relatively well confined to within individual bays.

Whilst littoral sediment transport is predominantly to the south, the rates of drift are relatively low and temporary drift reversals can occur along frontages under short-duration storm events from different directions. The presence of numerous natural headlands, estuaries and associated control structures, such as harbour piers, can cause locally complex physical processes due to wave sheltering, tidal gyres and localised sediment accumulations or drift reversals.

Of great importance is that many beaches experience significant onshore-offshore transport during storm events, with material being drawn down the beach to the lower foreshore and nearshore zone, whereupon it can become entrained by tidal currents and advected along the coast, generally in a southerly direction. In general, beach sediment slowly and progressively returns to the upper foreshore as conditions become calmer, leading to beach recovery.

Following production of this main study report, a subsequent phase of activity will be undertaken in autumn/winter 2014, involving a field experiment using sand tracers in Scarborough South Bay. The purpose of this sand tracer experiment is twofold: (1) to confirm sand transport pathways in Scarborough South Bay; and (2) to test in a field environment the efficacy of the existing sand tracer technique, which may have wider applicability for subsequent use across other frontages within Cell and more widely across other sand-dominated coastal frontages elsewhere.

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UNITS

cm	centimetres
g	grams
kg	kilograms
km	kilometres
m	metres
m^2	square metres
m^3	cubic metres
ml	millilitres
mm	millimetres
s	seconds
µm	micrometres (more commonly known as microns)
yr	year

NOMENCLATURE

α_0	Profile orientation (in °N)
Θ_1	Principal direction of wave approach (in °N)
d_{50}	Mean sediment grain diameter (in mm)
H_s	Significant wave height (in m)
Q_s	Sediment transport potential (in m^3/yr)

ACRONYMS AND ABBREVIATIONS

a.k.a.	also known as
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CETaSS	Cell Eleven Tide and Sediment Study
DAS	Disposal at Sea
DRCM	Direct Reading Current Meter
EGA	Expert Geomorphological Assessment
FEPA	Food and Environmental Protection Act
HR Wallingford	Hydraulics Research Wallingford
HTA	Historic Trends Analysis
MAFF	Ministry of Agriculture, Fisheries and Food
MHWN	Mean High Water Neaps
MHWS	Mean High Water Springs
MLWN	Mean Low Water Neaps
MLWS	Mean Low Water Springs
MRCM	Moored Reading Current Meter
MSL	Mean Sea Level
OD	Ordnance Datum
OS	Ordnance Survey
RHDHV	Royal Haskoning DHV
SCOPAC	Standing Conference on Problems Associated with the Coastline
UK	United Kingdom

GLOSSARY

Term	Definition
Aeolian sediment transport	The transport of sand particles by wind action.
Alongshore sediment transport	The transport of sediments along the shore by the action of waves and/or currents.
Beach recharge or beach replenishment	Artificial process of replenishing a beach with material from another source.
Beach management plan	A document which defines the management approaches for a beach, usually involving some form of sediment replenishment, sediment recycling, sediment bypassing or sediment retention using control structures such as groynes or breakwaters.
Cell 1	The coastal sediment cell which extends between St. Abb's Head in Scotland and Flamborough Head in the East Riding of Yorkshire.
Closure depth	The depth in the sub-tidal zone beyond which negligible wave-induced sediment transport occurs.
Coastal cell	A division of coast within which the transport of coarse-grained sediments (sands and gravels) is theoretically self-contained.
Coastal defence	A composite term involving the management of coastlines by means of coast protection against erosion or sea defence against flooding.
Coastal protection	Management of the coast to reduce risks from coastal erosion.
Coastal sub-cell	A sub-division of coast (within a larger coastal cell) within which the transport of coarse-grained sediments (sands and gravels) is *relatively* self-contained.
Cross-shore sediment transport	The transport of sediments across the shore into the nearshore zone by the action of waves and/or currents.
Downdrift	Direction of alongshore movement of beach materials.
Dune	An accumulation of sand at the interface between the land and sea.
Expert geomorphological assessment	A technique for the synthesis and interpretation of information from various sources to develop a conceptual understanding of the physical processes, sediment characteristics and morphological features of a coastal frontage.
Geomorphology	The branch of physical geography/geology which deals with the form of the Earth, the general configuration of its surface, and the distribution of the land, water, etc.
Hard engineering	Traditional coastal engineering works which attempt to maintain a fixed line of defence against the sea. Examples include sea walls, revetments and embankments.
Historic trends analysis	A technique for analysing timeseries of data at a coastal frontage, usually involving identifying changes over time from maps and surveys.
Inter-tidal zone	The area of foreshore between the limits of high and low water.
Littoral sediment transport	The transport of sediments along the shore by the action of waves and/or currents.
Littoral zone	The portions of inter-tidal and sub-tidal zone within which sediment transport processes are active. It is normally defined by some offshore closure depth.

Term	Definition
Longshore sediment transport	The transport of sediments along the shore by the action of waves and/or currents.
Nearshore zone	The shallow sub-tidal zone.
Offshore zone	The deep sub-tidal zone.
Regression	The seaward movement of the shoreline in response to a fall in relative sea level.
Sand recycling	The extraction of sand from areas of unwanted accretion and re-use in areas where sediment has been depleted over time.
Sea defence	Management of the coast to reduce risks from sea flooding.
Shoreline management plan	A document which sets out management policies for long lengths of coast over the next century to manage risks from coastal erosion and sea flooding.
Soft engineering	Coastal management approaches which attempt to modify or work with natural processes, rather than work against them. Examples include beach replenishment and dune stabilisation.
Sub-tidal zone	The area of the sea bed below low water.
Shoreline Management Plan (SMP)	A document that provides a large-scale assessment of the risks associated with coastal processes and presents a policy framework to reduce these risks to people and the developed, historic and natural environment in a sustainable manner.
Topography	Configuration of a surface including its relief and the position of its natural and man-made features.
Transgression	The landward movement of the shoreline in response to a rise in relative sea level.
Updrift	Direction opposite to the predominant movement of longshore transport.
Wave direction	Direction from which a wave approaches.
Wave diffraction	Process by which the direction of approach and height of a wave changes as it moves around headlands or structures.
Wave refraction	Process by which the direction of approach and height of a wave changes as it moves into shallow water.

SEDIMENT TYPES

Term	Definition
Boulder	A non-cohesive sediment particle in the size range > 256mm
Cobble	A non-cohesive sediment particle in the size range 64mm – 256mm
Gravel	A non-cohesive sediment particle in the size range 2mm – 64mm
Sand	A non-cohesive sediment particle in the size range 62.5µm – 2mm
Silt	A cohesive sediment particle in the size range 3.9µm – 62.5µm
Clay	A cohesive sediment particle in the size range < 3.9µm

1 INTRODUCTION

1.1 Background

Royal HaskoningDHV was appointed by Scarborough Borough Council to undertake the **Cell 1 Sediment Transport Study** on behalf of all public authorities and other organisations with coastal interests within Coastal Cell 1. This frontage covers the coastline between St. Abb's Head in Scotland and Flamborough Head in the East Riding of Yorkshire (Figure 1).

Within this frontage there are ten local authorities with coast protection responsibilities (one in Scotland and nine in England) and the Environment Agency with responsibilities for both sea defence and coastal erosion. Management of the coastline also involves a number of other organisations, such as marine regulators, nature conservation bodies, port and harbour authorities, fisheries committees, utilities providers and other interested parties.

Management of any coastline is complex due to the dynamic nature of the processes which prevail and the range of interests that exist. In order to provide the best possible management, it is necessary to have a good understanding of the sediment transport processes, so that actions in one area of coast do not unduly affect other areas.

To this end, a number of sediment transport studies have been undertaken around the UK on a regional basis in the past years and decades. These have included:

- SCOPAC (South Coast) Sediment Transport Study
- Cell Eleven (North West Coast) Tide and Sediment Study (CETaSS)
- Southern North Sea (East Anglia Coast) Sediment Transport Study

The north east coast is slightly different from many other areas of the English coastline in that whilst sediment transport is important, the shoreline is heavily influenced by the controls exerted by its underlying geology. This tends to create a series of typically sandy bays between harder rock headlands. Often, sediment transport remains relatively contained within these bays, moving in the prevailing direction of the residual tidal currents or predominant waves. However, during storm events, material is often drawn down the beaches to the nearshore zone, where it becomes entrained in the North Sea tidal currents and transported along the nearshore zone (sometimes along nearshore bars), before returning to the beaches when sea states become calmer.

The first and second generation Shoreline Management Plans within Coastal Cell 1 recommended monitoring studies to improve understanding of coastal behaviour in response to typical seasonal and storm events, and to longer term coastal change, such as sea level rise. As a direct result, the Cell 1 Regional Coastal Monitoring Programme was established (run in its present form since 2008) and is collecting much useful data on the changes in the beaches, cliffs, dunes and nearshore zone. Analysis of data from this programme has revealed that in some particular parts of the Cell 1 frontage there remain uncertainties regarding sediment transport processes. The purpose of the Cell 1 Sediment Transport Study is therefore to improve understanding of governing sediment transport mechanisms and pathways across Coastal Cell 1. The project involved consultation with practitioners across Coastal Cell 1 during the Scoping Phase to ensure that it has focus on pertinent management issues relating to sediment transport.

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Figure 1 – Location Plan

1.2 Method

The objectives of the Cell 1 Sediment Transport Study have been delivered by means of a two-phase project.

The **first (scoping) phase** involved the development of a broad-level conceptual understanding of the governing sediment transport processes and sediment-related issues. This was based upon review of existing information, consultation with relevant authorities and organisations to define their needs from the study and ensure that it has focus on pertinent management issues relating to sediment transport, characterisation of the nearshore marine environment to determine the key sediment transport processes along the Cell 1 coast, and preparation of a Scoping Report (Royal HaskoningDHV, 2013) describing the key findings and recommendations for more detailed studies at selected sites during the second phase.

The Scoping Report concluded that the Cell 1 shoreline and nearshore sea bed is predominantly controlled by its underlying solid geological structure. Through differential erosion of the different rock types a number of ‘headland and bay’ features of varying spatial extents have been formed. Littoral sediment transport is, generally, relatively well confined to within individual bays.

Whilst littoral sediment transport is predominantly to the south, the rates of drift are relatively low and temporary drift reversals can occur along frontages under short-duration storm events from different directions. The presence of numerous natural headlands, estuaries and associated control structures, such as harbour piers, can cause locally complex physical processes due to wave sheltering, tidal gyres and localised sediment accumulations or drift reversals.

Of great importance is that many beaches experience significant onshore-offshore transport during storm events, with material being drawn down the beach to the lower foreshore and nearshore zone, whereupon it can become entrained by tidal currents and advected along the coast, generally in a southerly direction. In general, beach sediment slowly and progressively returns to the upper foreshore as conditions become calmer, leading to beach recovery.

Given these findings, the present **second (main) phase** has used a suitable range of modelling and analytical techniques to provide additional levels of detail at a selected number of key locations within Coastal Cell 1. This phase has included a combination of approaches, including:

- Historic Trends Analysis (HTA) of changes at locations that have historically been particularly affected by a long legacy of colliery spoil tipping;
- Numerical modelling of cross-shore response during storms and sediment transport potential across the littoral zone at a series of transects throughout the Cell 1 frontage; and
- Expert Geomorphological Assessment to synthesise all findings into this Main Report.

1.3 Structure of Report

This Phase 2 Main Report presents a summary of the findings from the Historical Trends Analysis (HTA) at Lynemouth Bay, Cambois Bay and along the County Durham coastline (Chapter 2) and the numerical modelling of sediment transport at selected transects across the Cell 1 frontage (Chapter 3). Further details of these activities are presented in the appendices.

The conclusions from these studies are synthesised with the findings from the Scoping Report and other recent studies in Chapter 4. The references cited throughout the report are listed in Chapter 5.

Collectively, the **Phase 1 Scoping Report** (Royal HaskoningDHV, 2013) and this **Phase 2 Main Report** provide an improved understanding of sediment transport within Cell 1 and will aid in future coastal management decisions. (1,2)

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[1] Following production of this Phase 2 Main Report, a subsequent phase of activity will be undertaken in autumn/winter 2014, involving a field experiment using sand tracers in Scarborough South Bay. The purpose of this sand tracer experiment is twofold: (1) to confirm sand transport pathways in Scarborough South Bay; and (2) to test in a field environment the efficacy of the existing sand tracer technique. The methods and results of the sand tracer experiment will be reported separately in due course.

[2] At the time of writing this Phase 2 Main Report, the findings of the *Cell 1 Inter-tidal Habitat Study* were not available for review. However, during development of the *Cell 1 Sediment Transport Study*, there was correspondence with the authors of that study to share ideas about governing physical processes, sediment sources and morphological changes across Cell 1 and there was good consensus regarding these matters. When the *Cell 1 Inter-tidal Habitat Study* becomes available, it is recommended that its content is reviewed in detail for any further insights beyond those contained within this report.

2 HISTORICAL TRENDS ANALYSIS

2.1 Background

The Phase 1 Scoping Report (Royal HaskoningDHV, 2013) collated historic shoreline maps and sea bed charts covering the entirety of Cell 1 and compared these with contemporary Ordnance Survey maps and Admiralty charts.

At the Cell-wide, macro-scale of assessment, little significant change in the position or geomorphology of the shoreline or nearshore sea bed was identified over the timeframe of available datasets across much of the frontage. This is largely due to the controls exerted by the underling geology in terms of its general resistance to erosion.

There were, however, some local changes noted, most evident in association with the:

- historic legacy of colliery spoil tipping in Northumberland and County Durham;

- construction of coastal defences, for example at Newbiggin Bay, Littlehaven, Trow Quarry, Redcar, Skinningrove, Staithes, Whitby West Cliff, Whitby Haggerlythe; and

- alignment of the channels of some estuaries and smaller becks.

The Scoping Report recommended that the Main Report should incorporate an Historical Trends Analysis (HTA) focusing on the coastlines where greatest change has occurred over recent historic time, i.e. those frontages that historically have been subject to practices of colliery spoil tipping, namely Lynemouth Bay, Cambois Bay and the County Durham coastline.

HTA is a method for interrogating series of data to identify trends and rates of change over time (Pye and van der Wal, 2000). Often it is associated with analysis of historic maps, charts, aerial photographs, beach profiles or bathymetric surveys.

HTA at the locations of historic colliery spoil tipping was intended to help identify the past and ongoing changes associated with the erosion and transport of colliery spoil as a basis for future projections of likely re-activation of (presently dormant) backing sea cliff or coastal slope recession processes.

HTA was therefore recommended to take the form of targeted historic map analysis and beach profile analysis at all three sites, namely Lynemouth Bay, Cambois Bay and the County Durham coastline.

2.2 Main Findings

Appendix A presents the detailed findings from the Historic Trends Analysis, with a summary presented in this section.

2.2.1 Lynemouth Bay

- Lynemouth Bay was affected by colliery waste tipping from both Lynemouth Colliery and Ellington Colliery.

- Tipping commenced in 1934 at two tipping sites, one to the north of the River Lyne and one to the south along Lyne Sands.

- Tipping continued until closure of Ellington Colliery in 1994, but then recommenced (at the northern site only) when the colliery was re-opened in 1995 until its final closure in 2005.

- Tipping resulted in significant seaward movement of the beach front and infilling of Lyne Sands and the wider Lynemouth Bay (Figure 2).

- At the peak of the recorded tipping (1968) over 1.5m tonnes was deposited onto the foreshore and in each year from 1965 to 1983 around 1m tonnes was tipped. Volumes then fell substantially during the 1984 Miners' Strike. In total, it is likely that over 30m tonnes of colliery waste was tipped at Lynemouth Bay over seven decades, with the greatest volumes occurring in the late 1950s, throughout the 1960s and 1970s and into the early 1980s.

- The progradation of the shoreline that occurred when tipping was intense facilitated the subsequent development of a coal-fired power station on the reclaimed land.

- Since cessation of tipping, the shoreline has been retreating in parts of Lynemouth Bay, most notably in the vicinity of the power station and Lyne Sands to the south. This necessitated construction of coastal defences to protect the power station in 1995 and their extension to protect a coal-stocking yard in 2005-06 (Figure 3).

- Previous monitoring and research identified that temporal changes in wave height, period and direction were the major factors influencing sediment transport of the tipped spoil, with such changes primarily affecting onshore-offshore sediment movement rather than longshore drift.

- Of the estimated 70 – 90% of spoil transported onshore-offshore, most sediment would be confined to within the 10m sea bed contour of the nearshore zone. It was considered that it would only be the very finest fractions of spoil (<180µm) that would be carried further out to sea. The net transport of any material deposited in the nearshore zone would then be governed by the residual drift of tidal currents, imposing a net southward movement in the nearshore zone.

Figure 2 – Colliery Spoil Beach at Lynemouth Bay

Figure 3 – Coastal Defences at Lynemouth Power Station

2.2.2 Cambois Bay

- Cambois Bay experienced colliery waste tipping from Cambois Colliery, which opened in 1862 and exploited under-sea reserves before closing in April 1968.

- Tipping of excavated clay (and other material, including from the nearby brickworks) occurred from the cliff top, effectively defining an artificial cliff face in a more seaward position.

- Cessation of colliery spoil tipping, combined with mining-induced subsidence of the shore and nearshore sea bed, has led to an increase in erosion in recent decades within some parts of the bay.

- A rock armour revetment was constructed around the late 1970s to prevent erosion of the Vald Birn foundry.

- Between 1966 and the present day, the high water mark has eroded by around 110m in the vicinity of Cambois House and by around 90m in the vicinity of Cambois Farm.

- There is little net sediment transport along the frontage, but gross transport during storms from different directions can occur.

- The main movement of sediment within Cambois Bay tends to be in an onshore-offshore direction.

Figure 4 - Spoil Cliffs at Cambois Bay

2.2.3 County Durham Coastline

- The collieries of the east County Durham coastline were opened only in the 1900s, but during the decades that followed, the beaches and sea became significantly affected by waste dumped from Dawdon, Easington, Horden and Blackhall Collieries.

- The volumes tipped on the foreshore in the recorded database (i.e. since 1976) peaked at 2.5m tonnes in one year (1983) but literature cites at least 100m tonnes of colliery waste having been dumped into the sea off County Durham, at both foreshore tipping grounds and in offshore dump sites.

- The tipping resulted in significant infilling of bays between (and in some cases beyond) headlands at Dawdon Bankside, Dawdon Blast Beach, Easington, Horden and Blackhall Colliery. Although tipping did not take place directly at Hawthorne Hive or Shippersea Bay, these bays also filled with waste, generally transported southwards from Dawdon Blast Beach by longshore drift. The backing cliffs became relict features protected by a significant width of spoil beach.

- Tipping ceased in 1993 with closure of Easington as the last of the collieries and natural processes of erosion started to migrate the shoreline landwards; a process that continues to the present day (and beyond) and will ultimately result in re-activation of erosion in the backing cliffs in future decades.

- The *Turning the Tide* project played a significant role in cleaning up the beaches and improving the amenity and natural environment of the area between 1997 and 2002, and this work continues today under the direction of the Durham Heritage Coast.

- Previous research has identified that waves are the dominant process in influencing sediment transport and whilst the overall (bay to bay) longshore drift is intermittent and low (being controlled by the presence of the headlands), the underlying trend is for sediment to migrate (slowly) towards Crimdon.

It was also estimated that between 70% and 90% of the spoil which was dumped on the beaches was lost offshore, rather than alongshore. This was supported by the fact that coal is found in varying concentrations over large areas of the sea bed. The waste transported to the nearshore sea bed is broken down into smaller particles and then advection by tidal currents and storm wave action in a general southerly direction.

Figure 5 – Colliery Spoil Beach at Dawdon Blast Beach

Figure 6 – Colliery Spoil Beach at Horden

2.2.4 Overview

The Historical Trends Analysis reported in detail in Appendix A has investigated the historical legacy of colliery spoil tipping at Lynemouth Bay and Cambois Bay in Northumberland and at Dawdon Bankside, Dawdon Blast Beach, Easington, Horden and Blackhall Colliery in County Durham.

Particular focus has been placed on understanding the artificial supply of sediment to the foreshores caused by spoil tipping, the associated historical effects on shoreline behaviour and the effects of subsequent cessation of that sediment supply on present day responses.

The HTA has identified that large quantities of solid wastes, from a number of sources, were dumped for many years either directly onto the shore or some miles off parts of the north-east coast of England. Wastes from some coastal collieries in Northumberland and Durham were tipped directly onto foreshore tipping sites where they have been dispersed by wave action. Wastes from other collieries, fly ash from coal-fired power stations and harbour dredgings were dumped at offshore disposal sites.

In most cases, dumping started well before statutory controls entered into force in the UK in 1974. Since that date, disposal of these wastes became regulated under license. It is estimated that:

- around 30m tonnes of colliery waste (minestone) from Lynemouth and Ellington Collieries was tipped at foreshore disposal sites in Lynemouth Bay between 1934 and 2005, with at its peak over 1.5m tonnes tipped in one year (1968);
- an unknown quantity of excavated clay (and other waste) was tipped over the cliff edge at Cambois Bay until closure of Cambois Colliery in 1968; and
- over 100m tonnes of colliery waste (minestone) was tipped along the County Durham coastline, either at offshore disposal sites or at foreshore disposal sites. The foreshore tipping of waste from Dawdon, Easington, Horden and Blackhall Collieries occurred from the early 20th Century to 1993 when the last colliery (Easington) closed, with, at its peak, over 2.5m tonnes tipped in one year (1983).

In all cases, the tipping of waste resulted in significant progradation (seaward movement) of the shoreline and infilling of the bays to form wide spoil beaches as a 'terrace' on the upper beach. In Lynemouth Bay this occurred to such an extent that reclaimed land was developed with construction of the Lynemouth power station and along the County Durham coastline the spoil beaches became so wide that the backing cliffs became divorced from marine action and are currently relict features.

Due to geochemical processes that occurred after extraction of the spoil and its placement on the foreshore, its composition altered from a granular state to a more consolidated clayey condition that is somewhat more resistant to erosion than the constituent sediment grains would otherwise be.

The majority of the colliery waste that was tipped became eroded and transported seawards to the nearshore zone (within the 10m sea bed contour). This ‘loss’ from the shoreline was more than compensated for many decades by the ongoing tipping. Material moved to the shallow nearshore zone would then become further broken up into smaller particles by marine action and, when sufficiently small in grain size, transported by tidal currents in the direction of the net southerly current residuals. Larger grain sizes would tend to remain on the beach as lag boulder, cobble or gravel deposits.

Some longshore transport of material also occurred, particularly when the spoil beaches had increased in width so much that the high water mark extended beyond the rock headlands that intersect adjacent bays. This was most notable along the County Durham frontage where both Hawthorne Hive and Shippersea Bay (both located to the south of Dawdon Blast Beach) became infilled with colliery spoil, despite not directly being tipping sites. Concerns were also raised about despoilment of the beaches at Crimdon, south of Blackball Colliery. However, the general net southerly drift was relatively small and intermittent, predominantly being storm-driven.

Since cessation of tipping, the shoreline in all former tipping areas has been retreating. This has caused retreat of the high water line to a position landward of the headlands. This means that potential for ‘bay to bay’ transport of remaining spoil beaches due to longshore drift has further reduced.

The ongoing retreat of the shoreline since cessation of spoil tipping on the foreshores has caused particular problems in Lynemouth Bay, where a rock revetment was constructed in 1995 in front of the power station and then was extended in 2005 around the adjacent coal-stocking yard, and in Cambois Bay where a rock revetment was constructed in the late 1970s in front of the (former) Vald Birn foundry. There are also ongoing concerns in Cambois Bay about continued cliff slumping affecting the property of Cambois House.

In County Durham it has been recorded by beach profile surveys that rapid rates (20m/year) of retreat of the colliery spoil beaches occurred initially (2 – 5 years) after cessation of tipping, but the rate then reduced significantly (to around 0.5 - 2.0m/year) as the erosion encroached into the older, consolidated spoil. Ongoing beach surveys and walk-over visual inspections that form part of the Cell 1 Regional Coastal Monitoring Programme are monitoring the ongoing retreat of the spoil beaches, which is clearly measureable.

It is envisaged that the cliffs that are currently protected by spoil could retreat at rates up to 0.3m/year when the spoil beaches have become eroded and marine processes are re-activated at the toe of the cliffs. Initially, the rate could be higher as accelerated erosion is likely to occur in the exposed rock face which, though isolated from the sea for many years, has weakened through weathering processes. Along Dawdon Bankside, the residual colliery spoil beach is now so narrow that parts of the backing cliffs have started to experience slumping in recent years.

3 SEDIMENT TRANSPORT MODELLING

3.1 Background

The Phase 1 Scoping Report (Royal HaskoningDHV, 2013) revealed that throughout much of the Cell 1 frontage, onshore-offshore sediment transport and subsequent advection of sediments by tidal currents and, potentially, wave action within the nearshore zone are considerably more important to overall understanding of the interactions between sections of the coast than the alongshore transport of beach sediments within the inter-tidal zone.

Due to this, the Scoping Report recommended that these processes are investigated further by the selection of a number of appropriately located cross-shore transects, each extending from the upper beach across the inter-tidal zone and nearshore sea bed to the 20m sea bed contour.

At each transect location, the longshore transport potential across the profile could be determined using the LITDRIFT model and the cross-shore response to wave action could be determined using the LITPROF model.

It was recommended in the Scoping Report that the modelling in Phase 2 be undertaken in a staged manner, with an initial pilot study involving modelling at transects at Newbiggin, Whitby and Scarborough North Bay and Scarborough South Bay to investigate the value of the outputs before embarking on modelling at other transects.

Subsequently, it was decided to remove the Newbiggin Bay transect and replace it with the Cambois Bay transect for the pilot study because the sediment transport processes at Newbiggin are so interrupted by the presence of the offshore breakwater in the centre of Newbiggin Bay and do not represent a natural condition.

The reason for selecting these four locations for the pilot modelling study is because suitable timeseries of nearshore wave data are directly available at, or very close to, these sites from the wave buoys deployed as part of the Cell 1 Regional Coastal Monitoring Programme at Newbiggin, Whitby and Scarborough.

3.2 Pilot Modelling Study

The pilot modelling study is described in full in Appendix B, including a short description of the LITDRIFT and LITPROF numerical models, the beach and bathymetric data and wave data sets used as input to the models, the set-up of the models, and the modelling results.

The longshore sediment transport modelling using LITDRIFT showed that, generally, longshore sediment transport potential at the four transects is relatively low in magnitude. In terms of relative ‘ranking’ of the locations, longshore transport potential is least (negligible) at Cambois Bay, increases (but remains very low) at Whitby West Beach, increases further (but remains *relatively* low) at Scarborough North Bay and is greatest (but remaining only modest in magnitude) at Scarborough South Bay. This is fully commensurate with the findings of the Scoping Report prepared during the first phase of the present study.

The LITDRIFT modelling has further identified that the longshore sediment transport rates are highly dependent upon the angle of shoreline orientation relative to the defined wave climate. This means that rather than replicating a large number of locations within only a single transect each (as originally recommended by the Scoping Report), it would be better to consider extending the modelling to a smaller number of locations, but exploring sensitivity to shoreline orientation more fully at each location considered, within the context of the natural alignments present.

The pilot modelling study also identified that the LITDRIFT modelling approach works best in areas where the coastal orientation is relatively uniform (e.g. Whitby West Beach) rather than in more deeply indented bays (e.g. Scarborough North Bay and South Bay). Whilst possessing subtle changes in shoreline orientation, large shallow bays (e.g. Cambois Bay) appear reasonably well suited to the approaches (including sensitivity tests relating to angle of orientation). Where bays are strongly influenced by major headlands (Scarborough North Bay and South Bay) there are limitations of the LITDRIFT approach, since its one-dimensional nature does not allow wave diffraction effects around the headland or interaction with complex residual current systems (induced by headland features) to be incorporated. Consequently, the pilot modelling study recommended that any transects that could be affected by headland-related effects (wave diffraction, tidal gyres) be omitted from future stages. Such effects can also be induced by the presence of breakwaters and harbour piers.

Whilst the influence of tidal currents was identified (through a sensitivity test at Cambois Bay) to enhance gross and net drift (in the direction of the residual current), the changes were so small as to be negligible compared to the modelling of drift with waves alone and therefore further sensitivity tests with currents were not deemed entirely necessary.

It was recommended by the pilot modelling study that LITDRIFT modelling should take the above considerations into account and omit any locations originally proposed in the Scoping Report where strong headland effects or structural effects influence local sediment transport pathways. This means that the main modelling study should focus on the following transects (locations shown in Figure 7):

Undertaken within pilot modelling study (and repeated within the main modelling study):

- Cambois Bay
- Whitby West Beach
- Scarborough North Bay *
- Scarborough South Bay *

Suitable for main modelling study:

- Bamburgh
- Druridge Bay
- Lynemouth Bay
- Blyth South Beach
- Whitley Bay
- Tynemouth Longsands
- Salterfen Rocks
- Blast Beach
- Hartlepool North Sands
- Saltburn-by-the-Sea
- Skinningrove
- Sandsend

* Note that longshore drift rates will be affected at these sites by headland-related effects (such as wave diffraction, tidal gyres) which are not incorporated in the one-dimensional LITDRIFT model.

No	Model Location
1	Bamburgh
2	Druridge Bay
3	Lynemouth Bay
4	Cambois Bay
5	Blyth South Beach
6	Whitley Bay
7	Tynemouth Longsands
8	Salterfen Rocks
9	Blast Beach
10	Hartlepool North
11	Saltburn
12	Skinningrove
13	Sandsend
14	Whitby West Beach
15	Scarborough North
16	Scarborough South

National Geographic, Esri, DeLorme, NAVTEQ, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, iPC

Figure 7 - Location of Transects used in Numerical Modelling

The cross-shore sediment transport modelling using LITPROF in the pilot study showed that, generally, a rapid succession of several reasonably sized storm events causes the 'classic' winter beach profile response of upper beach erosion and lower beach and nearshore deposition, resulting in a temporary 'flattening' of the profile. This is deemed perhaps more important than a single short duration storm event of greater magnitude (until significant 'extreme' events are reached when more direct damage would be expected).

There clearly is connectivity in the cross-shore transport processes between the inter-tidal zone and the shallow nearshore zone, as inferred within the Scoping Report (and based on ongoing beach profile monitoring as part of the Cell 1 Regional Coastal Monitoring Programme) but never previously demonstrably proven.

In going forward with further modelling, the pilot modelling study recommended that LITPROF is used at a selected number of locations where monitoring has identified that cross-shore storm and seasonal behaviour is apparent, i.e. the same transects that will be used for the LITDRIFT modelling. The approach of 'forcing' the beach response with the 1-month timeseries of 'stormy' wave data will be used in preference to a single 12 hour storm event.

3.3 Main Modelling Study

The purpose of the main modelling study is to test *relative* behaviours (rates and directions of sediment movement) between transect locations within the Cell 1 frontage and explore sensitivities in the mechanisms that drive sediment transport in the inter-tidal and nearshore zones within the context of a Cell-wide study. It is not intended to precisely quantify sediment transport rates in detail at each of the transect locations considered (as may be undertaken for a site-specific study, for example).

With this in mind, the only difference between the pilot modelling study and the main modelling study is in the wave data used as input to the LITDRIFT and LITPROF models. For the pilot modelling study, timeseries of wave data recorded as part of the Cell 1 Regional Monitoring Programme from buoys deployed at Newbiggin, Whitby and Scarborough were used as input. These buoys are located in suitable water depths at the seaward limit of the extent of the beach and bathymetric survey used to define each transect.

When extending from the pilot modelling study across the wider Cell 1 frontage, there are no similar measured timeseries wave data available at other transect locations. Instead, hindcast timeseries wave data were obtained from CEFAS for the period 1980 to 2012 at six locations (in a suitable water depth) across the Cell 1 frontage (Figure 8). These hindcast data were produced by The Met Office using the WAVEWATCH III wave model (Li, 2011).

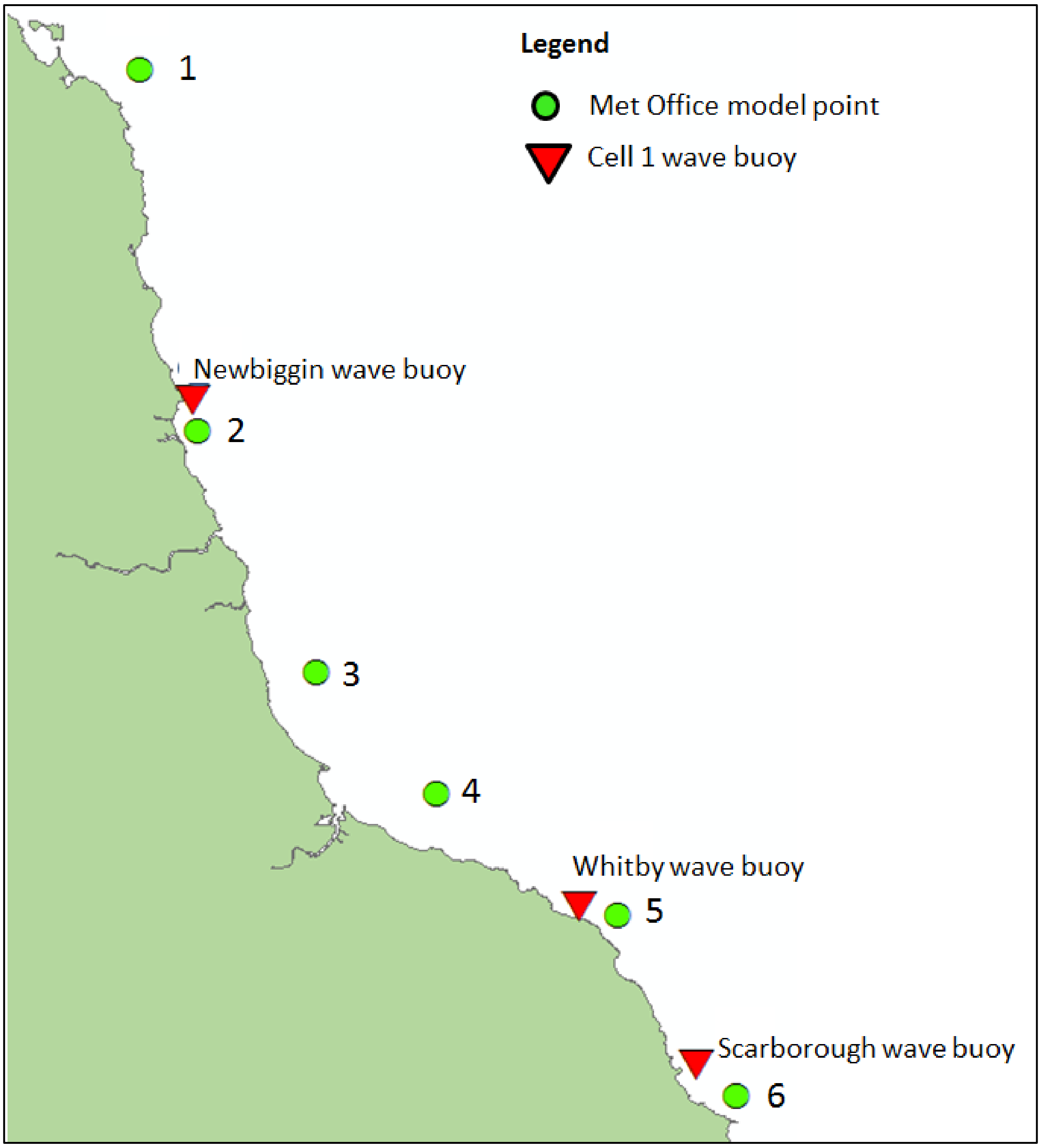


Figure 8 – Locations of Met Office (hindcast) timeseries wave data (1980 - 2012)

Three of the six locations (points 2, 5 and 6) were chosen close the wave buoy locations (Newbiggin, Whitby and Scarborough) so that cross-comparison of the datasets could be undertaken.

The hindcast wave data from each of the six Met Office model points have been used to create a wave rose at each location. Each hindcast dataset has been considered as being representative across a wider zone of coast, as shown in Figure 9 and Table 1. The table also shows which hindcast modelled datasets have been applied to each transect in the main modelling study.

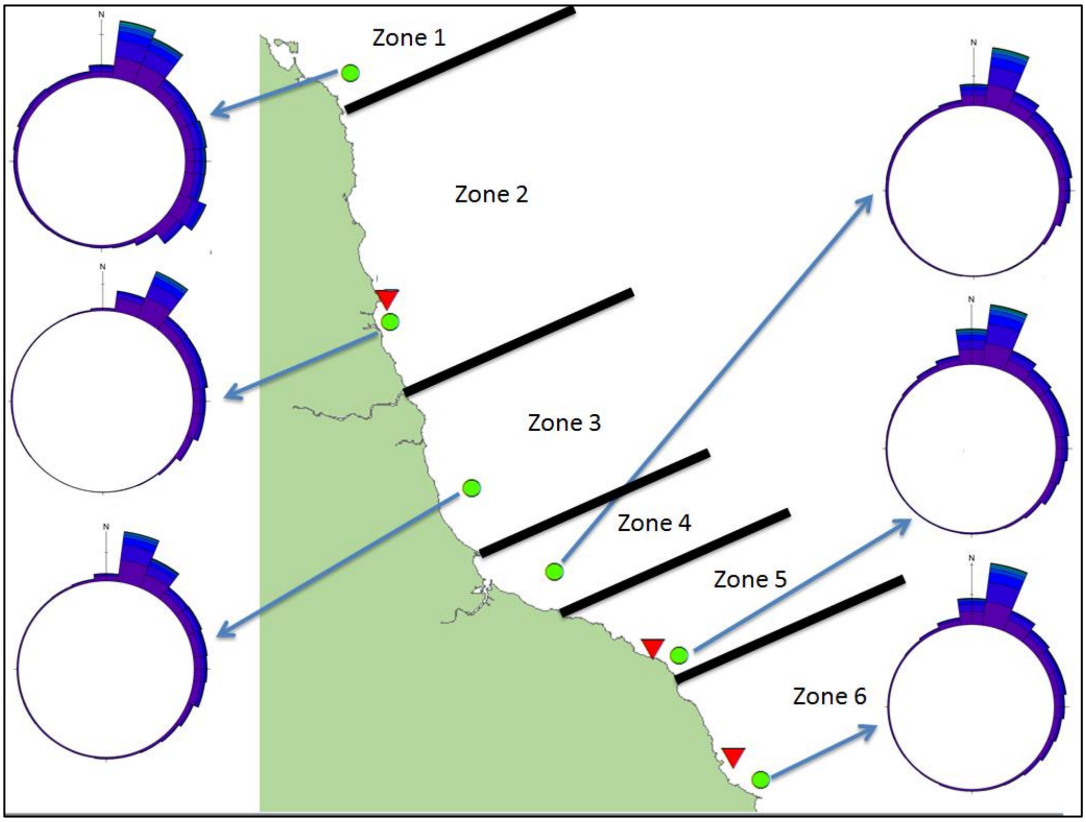


Figure 9 – Hindcast wave roses across the Cell 1 frontage

Table 1 – Zonal application of hindcast wave datasets to transects in main modelling study

Hindcast Model Point	Zone	Transect Location	Transect Orientation(s)
1	1	Bamburgh	30° (38° & 73° sensitivity)
2	2	Druridge Bay Lynemouth Bay Cambois Bay Blyth South Beach Whitley Bay Tynemouth Longsands	110°(N), 80°(C), 68°(S) 65° 73° 72°(C), 55°(S) 70°(C), 58°(S) 65°
3	3	Salterfen Rocks Blast Beach Hartlepool North	75° 65° 45°
4	4	Saltburn	25°
5	5	Skinningrove Sandsend Whitby	45° 30° 30°
6	6	Scarborough North Bay Scarborough South Bay	57° 83°

Where: (N) = north of bay, (C) = centre of bay, (S) = south of bay

Figures 10, 11 and 12 show a wave rose produced using the measured wave buoy data for each of Newbiggin, Whitby and Scarborough and the modelled hindcast data from the nearest adjacent point. These figures show good general overall similarity between the datasets but some slight differences are observed when examined in detail. These differences are to be expected since: (i) the locations, whilst similar, are not co-existent; and (ii) the measured data cover a relatively short time period (~1 year) whilst the hindcast data show a much longer period (32 years) and therefore may be more representative of the longer term 'average' wave climate.

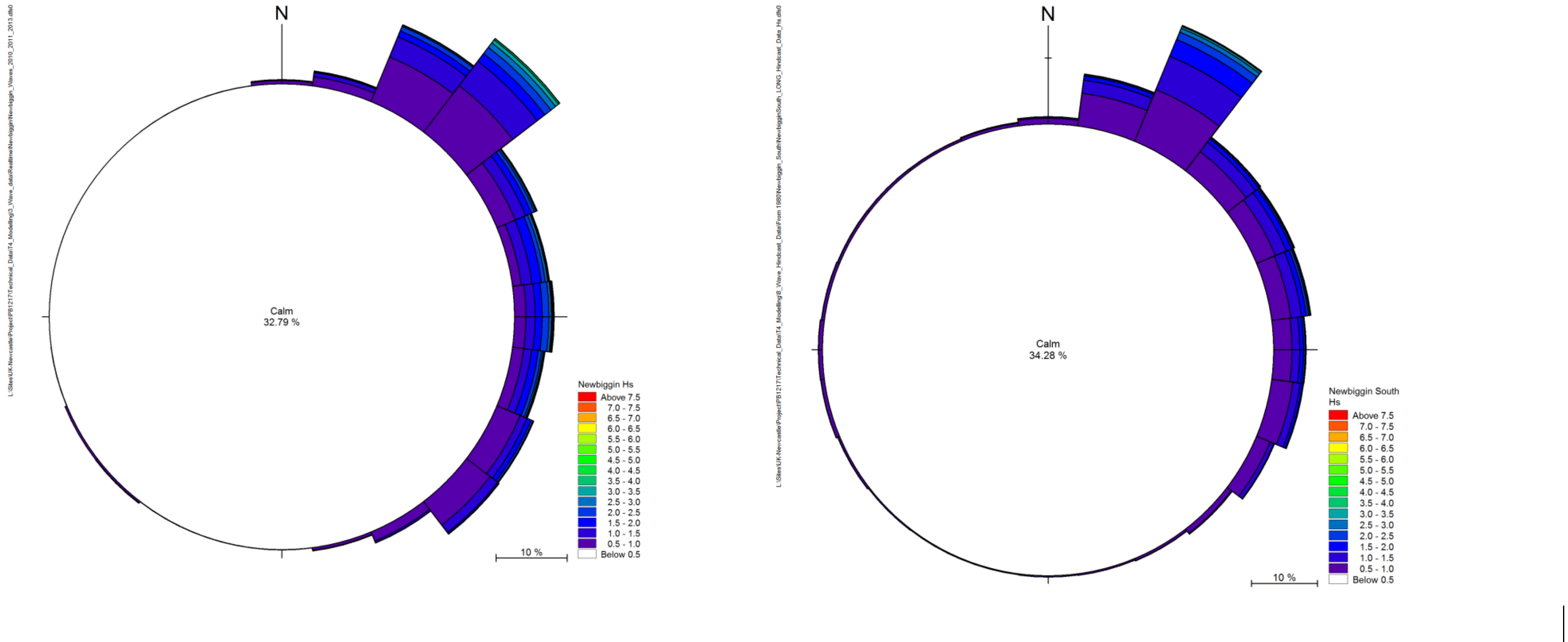
The implications of the subtle differences in the annual wave climate between the datasets were examined by re-running some of the pilot model study transects with the appropriate hindcast wave datasets to determine the extent of influence on sediment transport results previously calculated at those locations.

At Cambois, the wave climate input data shows a slight shift from a predominant north-east wave direction in the measured data (at Newbiggin wave buoy) to a predominant nor-north-east wave direction in the hindcast data (at point 2). There is also a slight reduction in waves from the south-east within the hindcast data when compared against the measured data. These factors combined would be expected to lead to a slight increase in the gross southerly drift, a slight decrease in the gross northerly drift and, as a consequence, a net southerly drift overall when the hindcast data are used as model input instead of the measured data that were used in the pilot study. Figures 13 and 14 confirm this finding for sediment transport at MHWS and MLWS respectively.

At Whitby, the wave climate input data shows more waves from due north in the hindcast data (at point 5) than in the measured data (at Whitby wave buoy). There is also a slight reduction in waves from the east within the hindcast data when compared against the measured data, but a component of wave activity becomes incorporated from the south-east within the hindcast data. Figures 15 and 16 show that these factors combined lead to a narrower zone within which sediment transport occurs at MHWS and at MLWS respectively. At MHWS there is a slightly lower gross drift to the east and a slightly higher gross drift to the west and whilst the overall net drift remains to the east, it is lower in magnitude than was observed from the model runs in the pilot model study using the measured wave data.

At Scarborough, the wave climate input data shows more waves from due north in the hindcast data (at point 6) than in the measured data (at Scarborough wave buoy). There is also a slight reduction in waves from both the east and the south-east within the hindcast data when compared against the measured data, and a general reduction in overall 'storminess' of the wave climate, with calm conditions occurring for 27.4% of the time instead of 23.5% of the time in the measured data. Figures 17 to 20 show that these factors combined lead to sediment transport of a lower magnitude at MHWS and MLWS at both Scarborough North Bay and Scarborough South Bay.

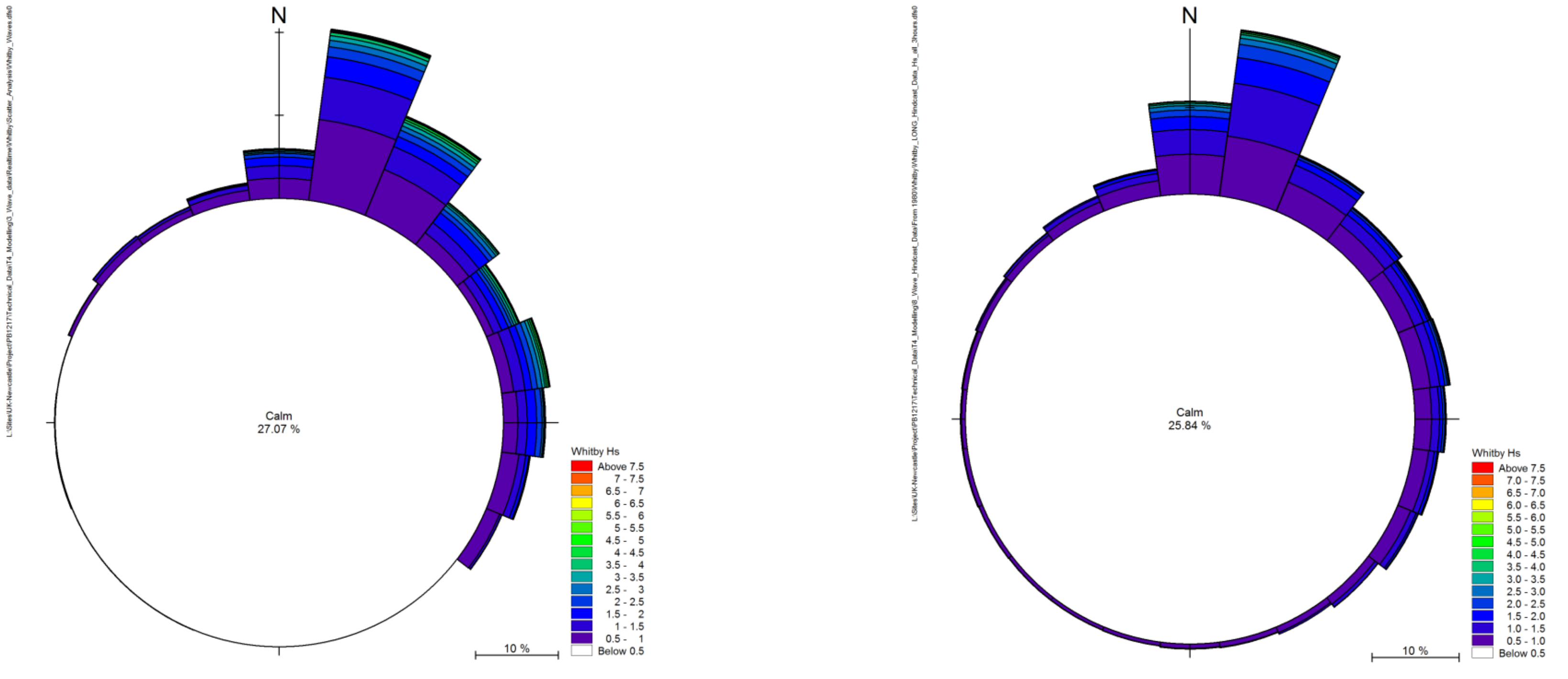
The model runs performed to investigate the effect of using the hindcast wave data on sediment transport reveal that the general patterns of behaviour observed during the pilot study using the measured wave data are reproduced, but the magnitudes of change are slightly different. For purposes of ensuring consistency of comparison throughout Cell 1 and, most likely, providing a better representation of a longer term 'average' annual wave climate, the hindcast data were therefore used throughout the main modelling study.



Measured data (Newbiggin)

Hindcast data (Point 2)

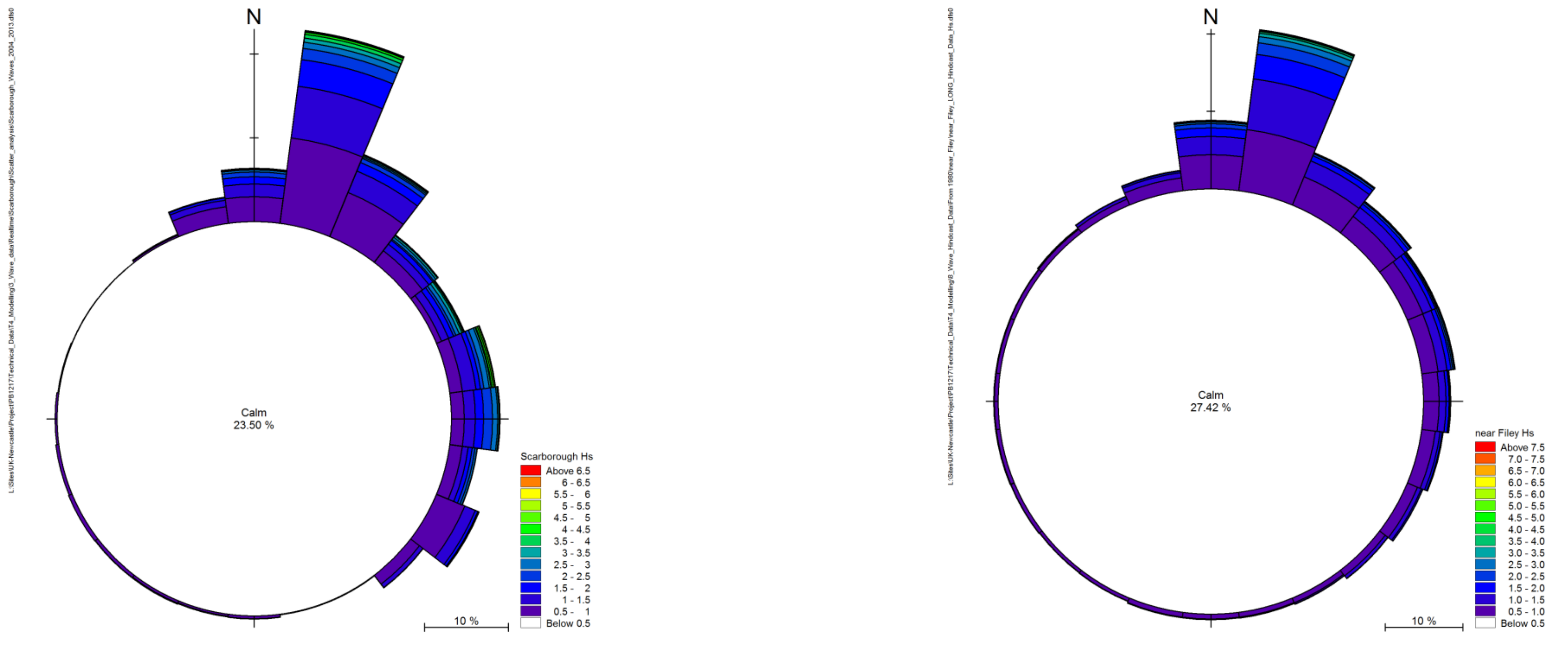
Figure 10 – Comparison of measured wave data at Newbiggin and hindcast wave data south of Newbiggin



Measured data (Whitby)

Hindcast data (Point 5)

Figure 11 – Comparison of measured wave data at Whitby and hindcast wave data near Whitby



Measured data (Scarborough)

Hindcast data (Point 6)

Figure 12 – Comparison of measured wave data at Scarborough and hindcast wave data south of Scarborough

Figure 13	Cambois Bay (MHWS) Longshore sediment transport under measured (top plot) and hindcast (bottom plot) annual wave climate data	Net Drift: m^3/year

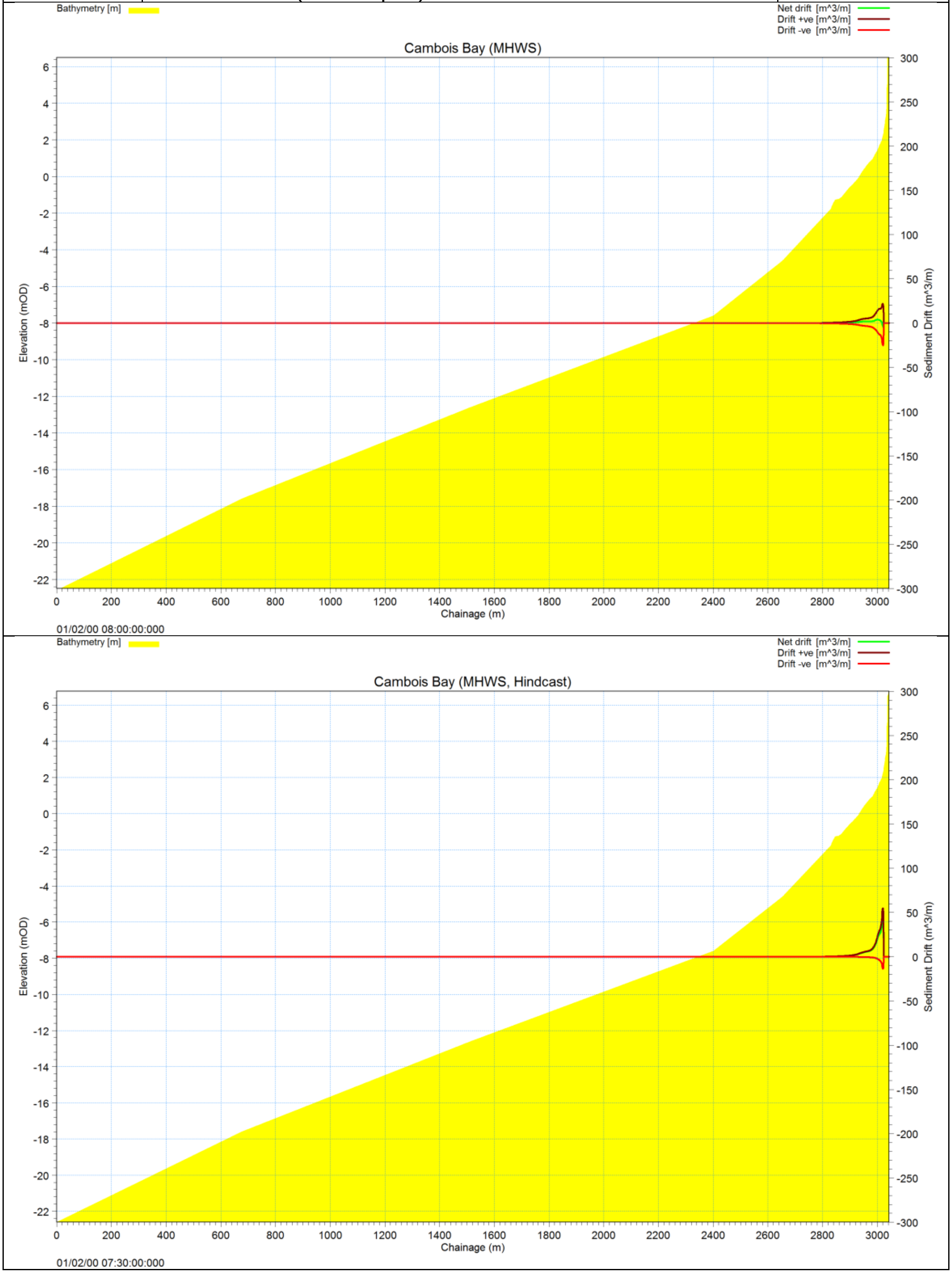


Figure 14	Cambois Bay (MLWS) Longshore sediment transport under measured (top plot) and hindcast (bottom plot) annual wave climate data	Net Drift: m^3/year

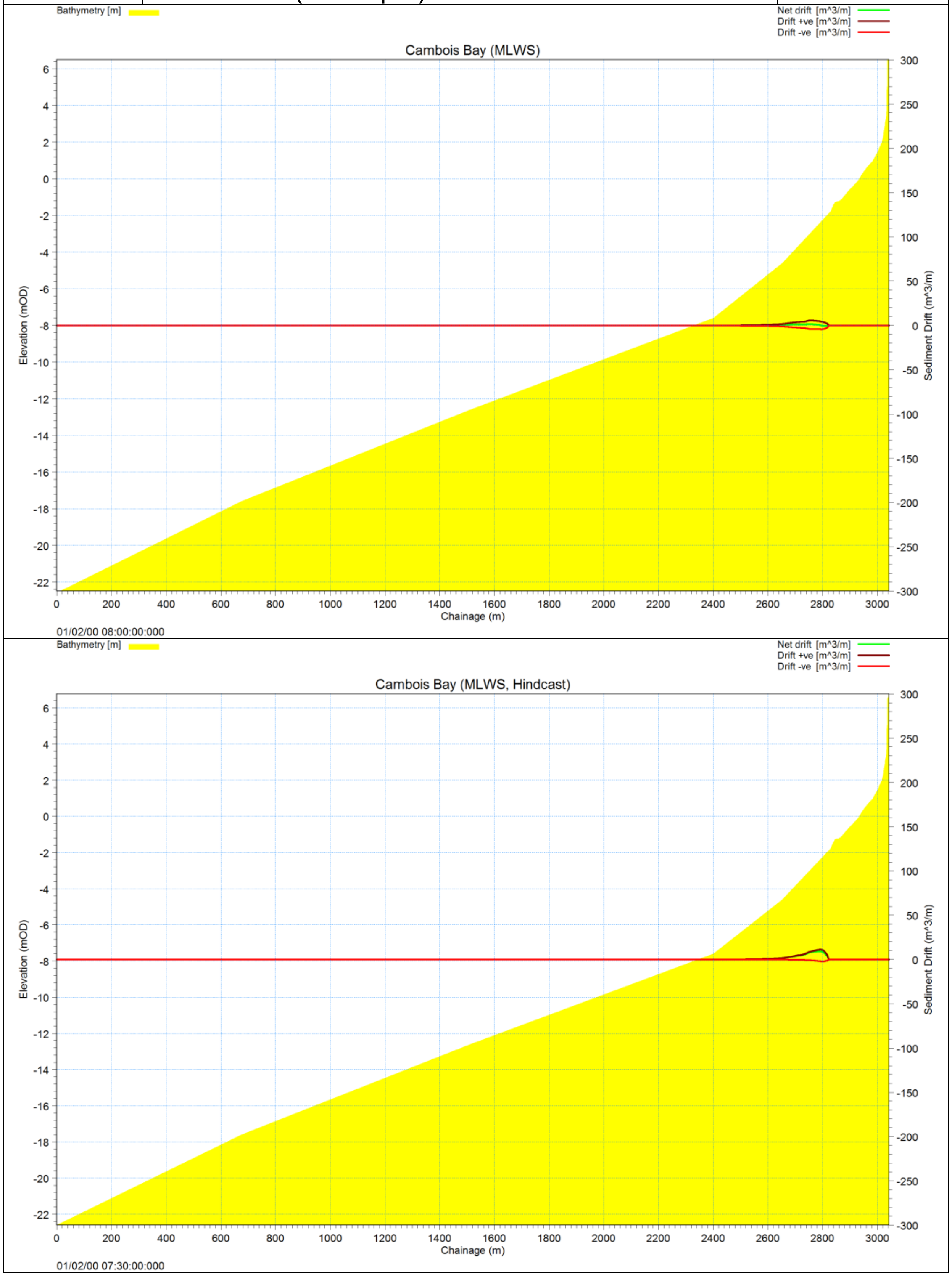
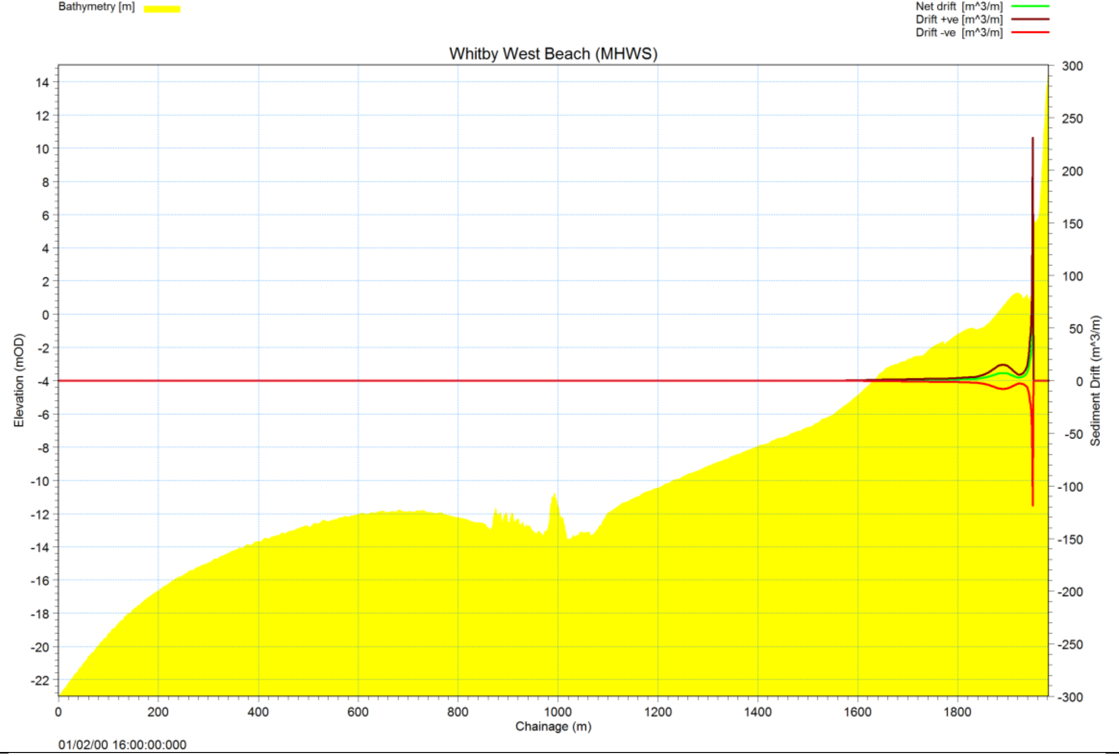


Figure 15	Whitby (MHWS) Longshore sediment transport under measured (top plot) and hindcast (bottom plot) annual wave climate data	Net Drift: m^3/year



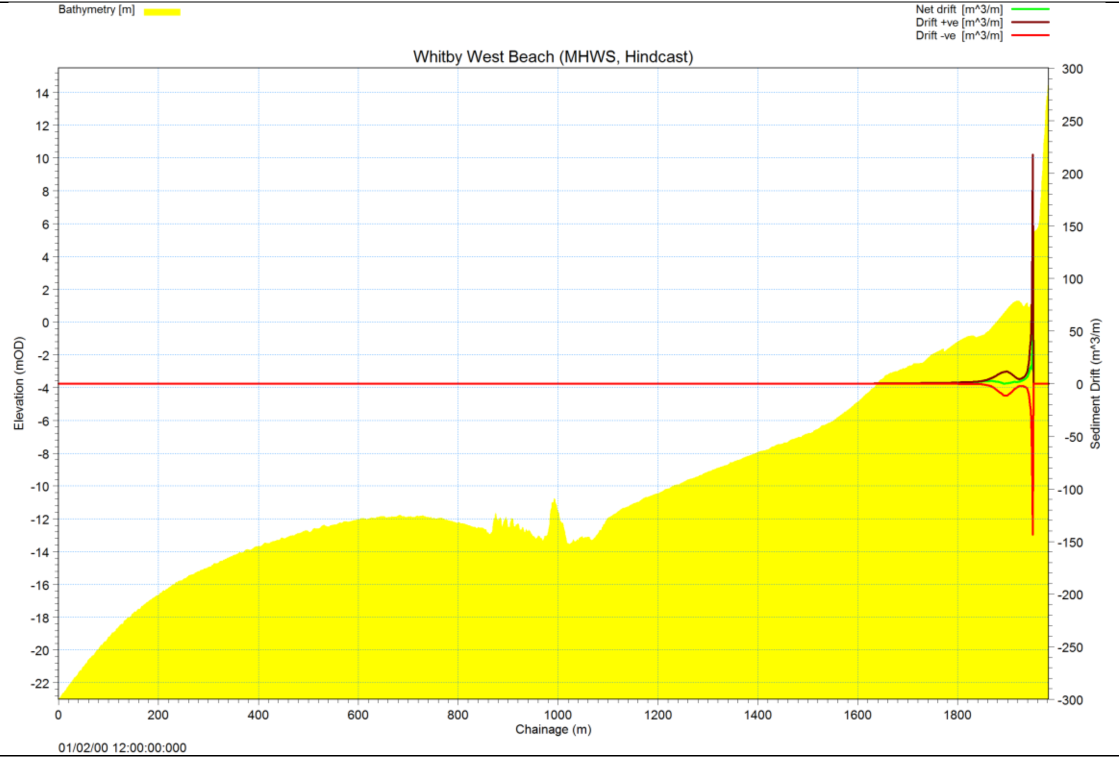
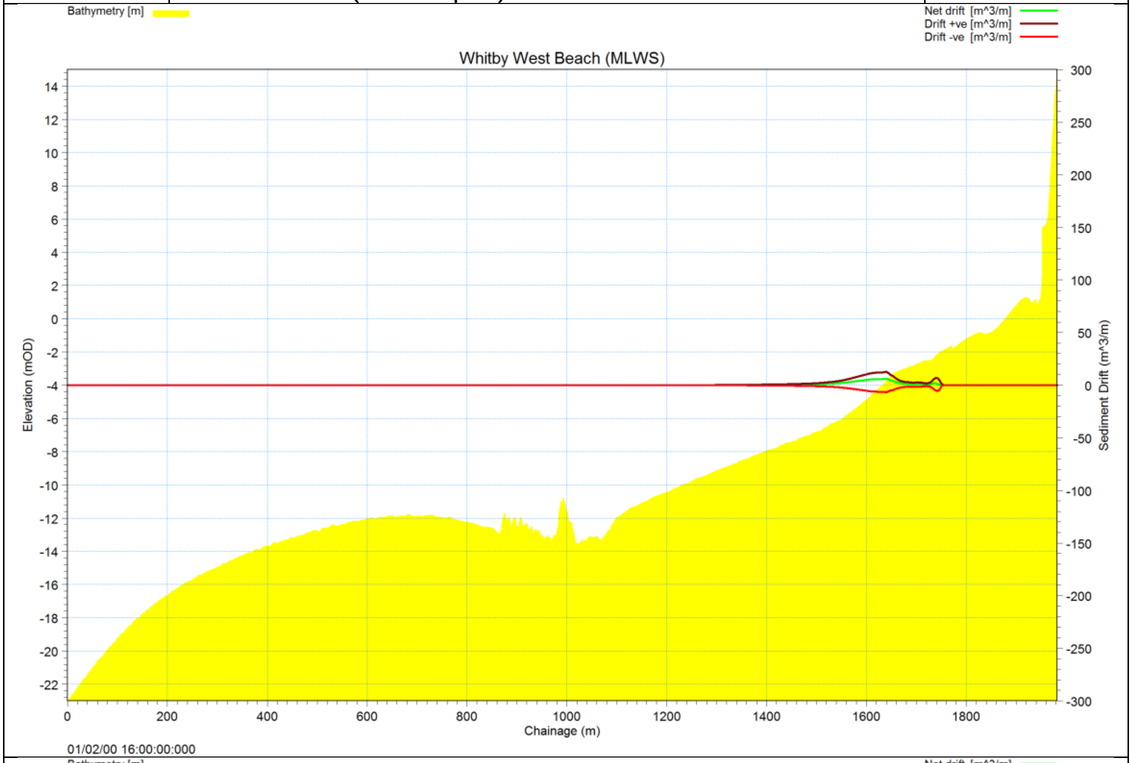


Figure 16	Whitby (MLWS) Longshore sediment transport under measured (top plot) and hindcast (bottom plot) annual wave climate data	Net Drift: m^3/year



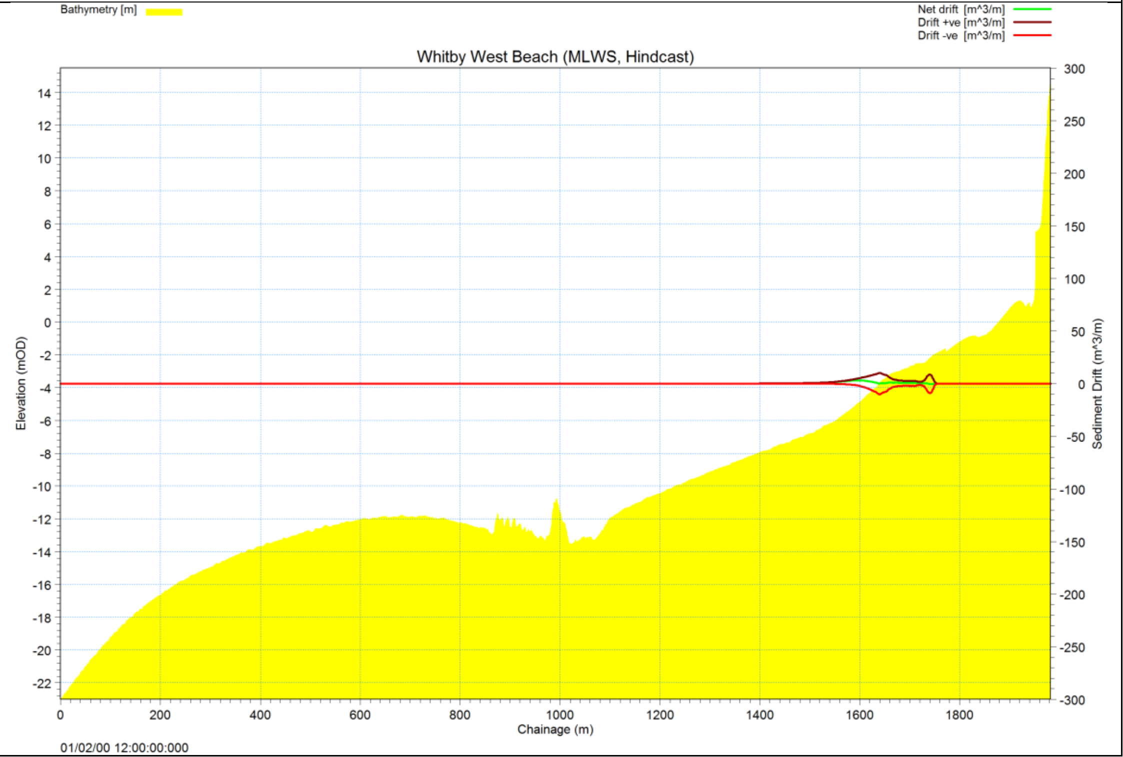
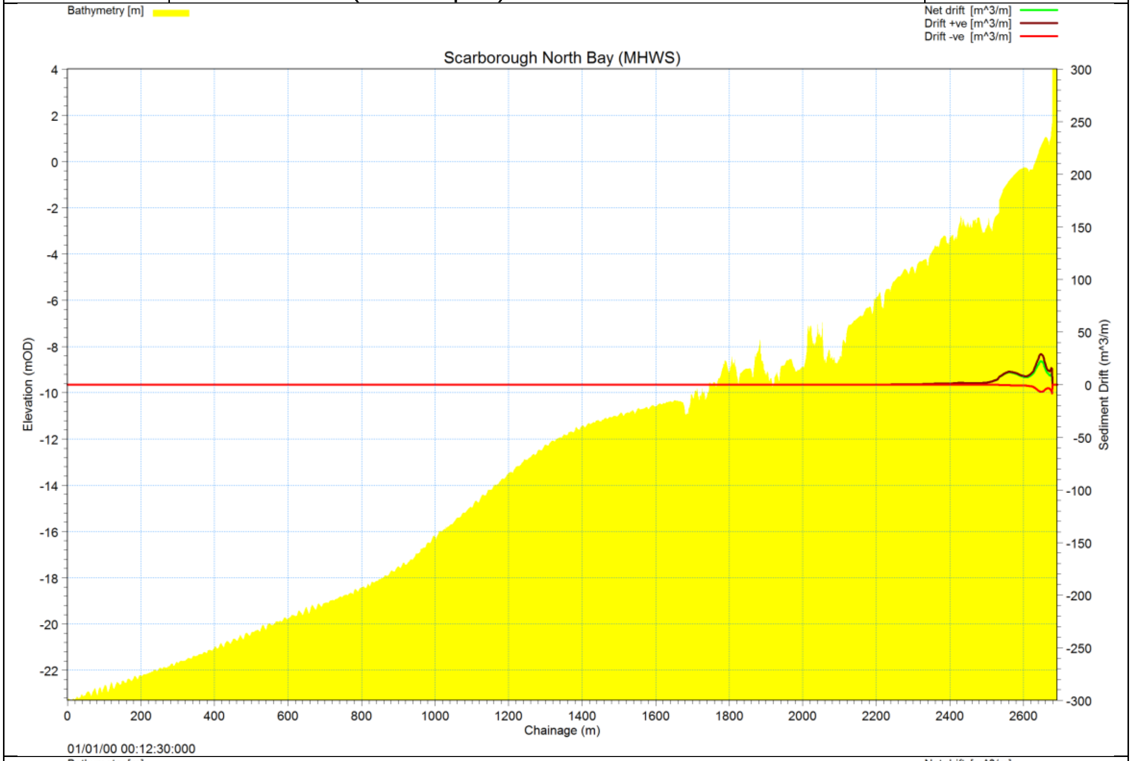


Figure 17	Scarborough North Bay (MHWS) Longshore sediment transport under measured (top plot) and hindcast (bottom plot) annual wave climate data	Net Drift: m^3/year



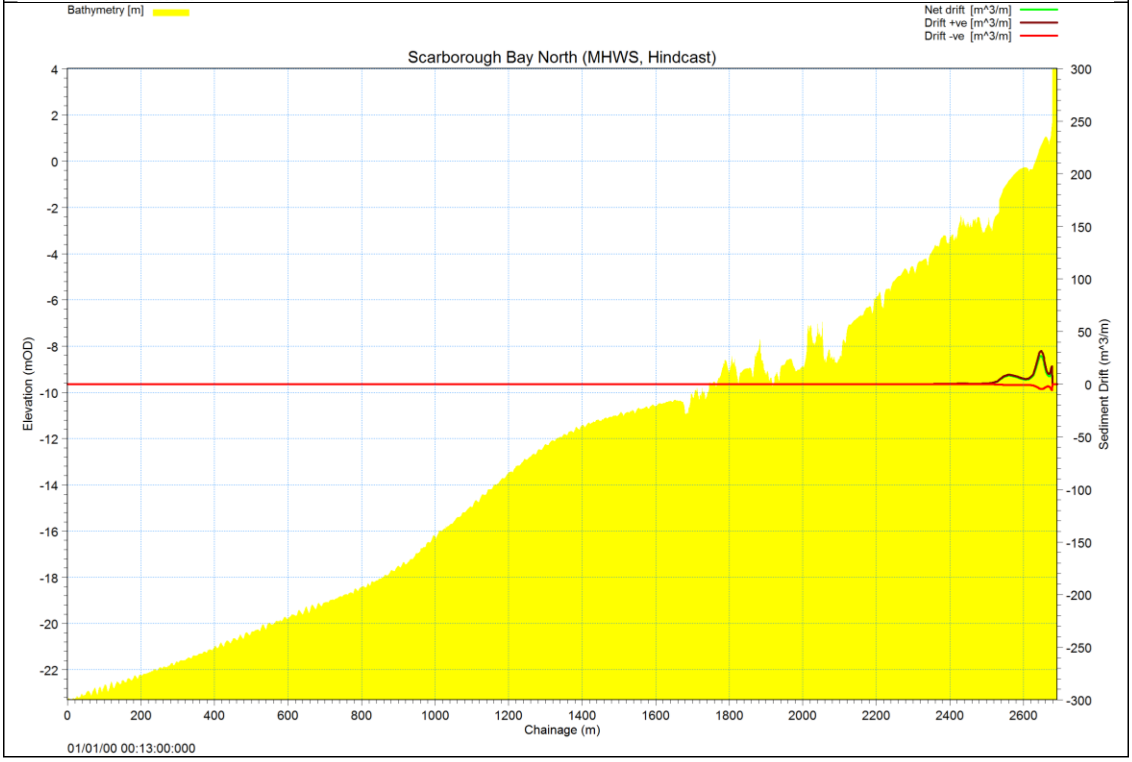


Figure 18	Scarborough North Bay (MLWS) Longshore sediment transport under measured (top plot) and hindcast (bottom plot) annual wave climate data	Net Drift: m^3/year

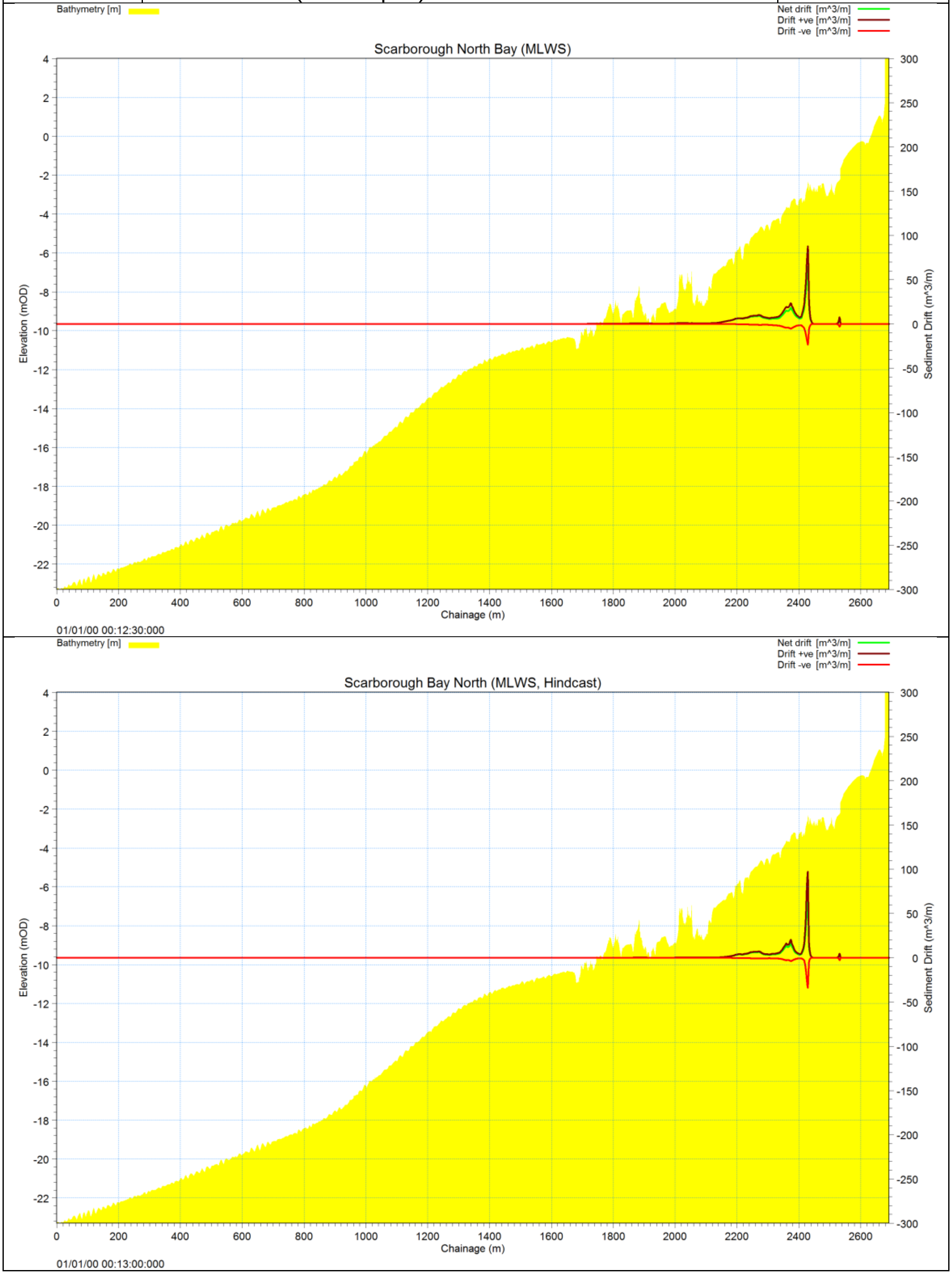


Figure 19	Scarborough South Bay (MHWS) Longshore sediment transport under measured (top plot) and hindcast (bottom plot) annual wave climate data	Net Drift: m^3/year

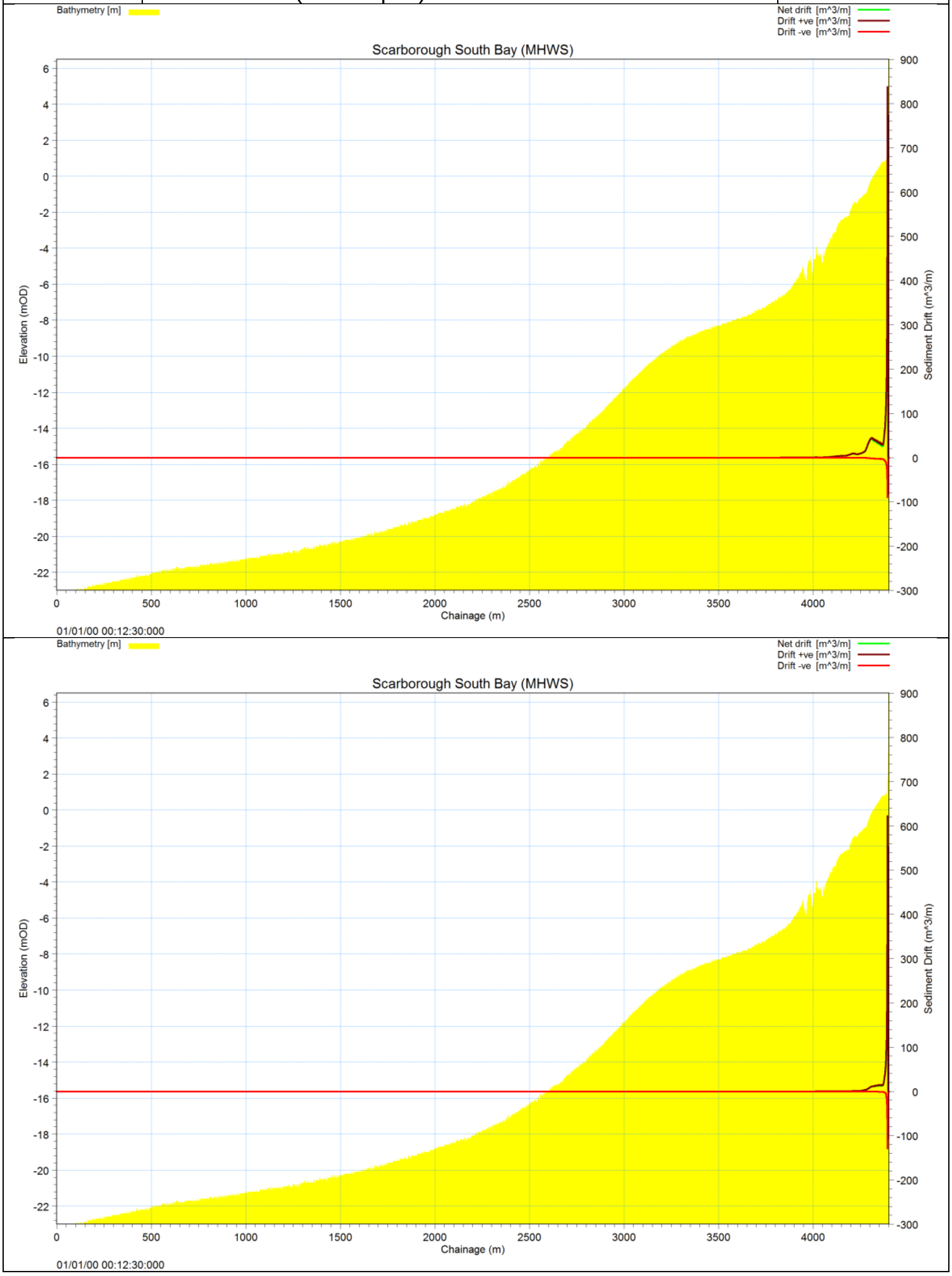
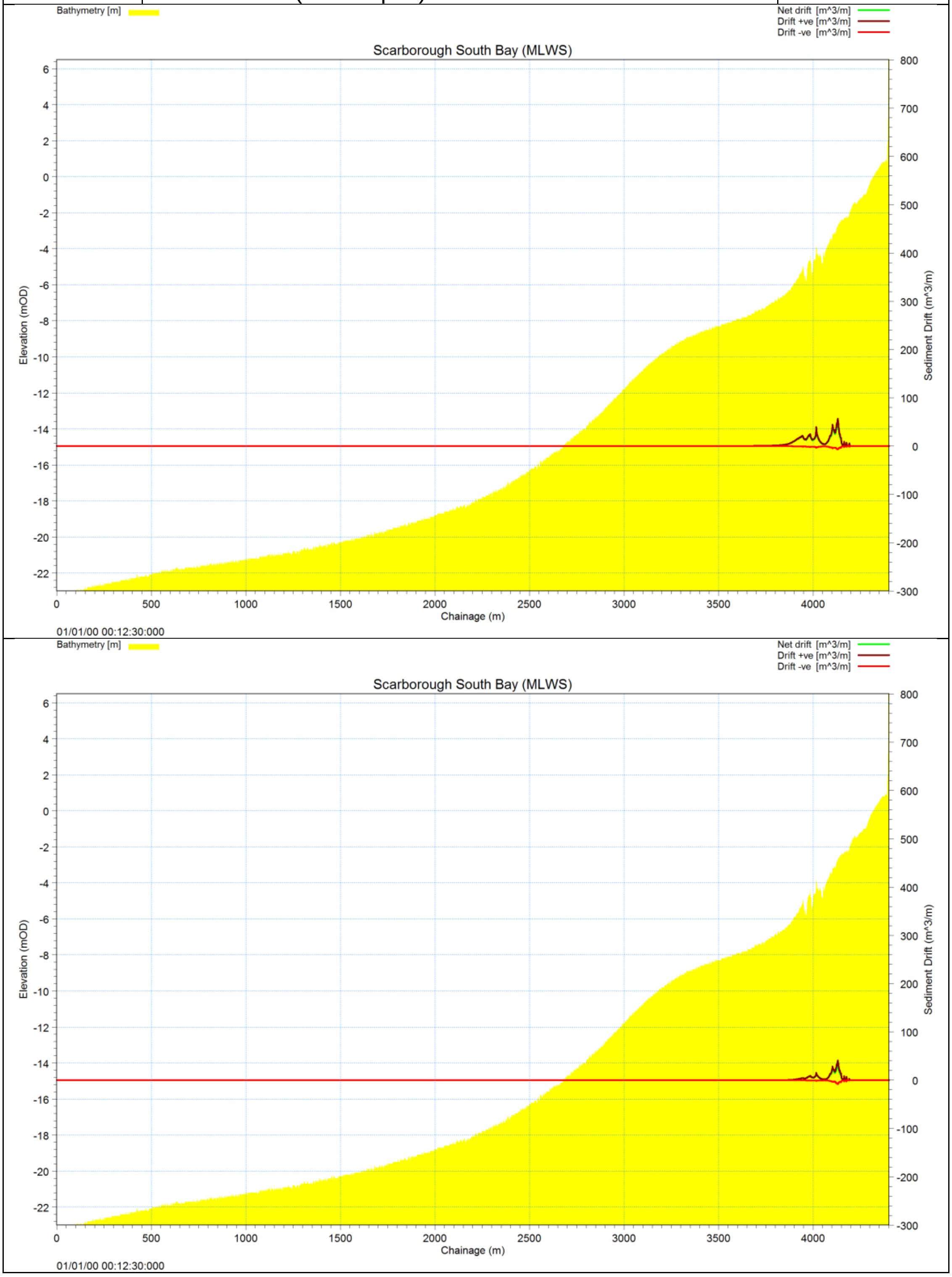


Figure 20	Scarborough South Bay (MLWS) Longshore sediment transport under measured (top plot) and hindcast (bottom plot) annual wave climate data	Net Drift: m^3/year



3.4 Main Findings

3.4.1 LITDRIFT Modelling Results

Appendix C presents a series of plots from the LITDRIFT modelling, showing the gross and net longshore sediment transport potential at each transect under MHWS and MLWS water levels.

On each plot:

- the yellow area shows the original shore profile and nearshore bathymetry
- the brown line shows the gross positive (southerly) sediment transport potential across the shore profile and nearshore bathymetry
- the red line shows the gross negative (northerly) sediment transport potential across the shore profile and nearshore bathymetry
- the green line shows the net sediment transport potential across the shore profile and nearshore bathymetry

Note: The topographic/bathymetric levels (in metres OD) are shown on the primary y-axis, the sediment drift (m^3 per metre run) is shown on the secondary y-axis and the transect chainage (in metres) is shown on the x-axis.

The gross and net longshore sediment transport potential at each transect under MHWS and MLWS water levels are shown in Table 2. In all cases, the gross and net drift is relatively low in magnitude and in all but one case (Bamburgh) the net drift is directed towards the south.

Table 2 - Gross and net longshore sediment transport potential at various locations within Cell 1

	Drift Potential (m^3/yr) at MHWS			Drift Potential (m^3/yr) at MLWS		
Profile	Gross S Drift (+ve)	Gross N Drift (-ve)	Net Drift	Gross S Drift (+ve)	Gross N Drift (-ve)	Net Drift
Bamburgh	1,356	-2,189	-833	888	-1,047	-159
Druridge Bay - North	1,857	-39	1,818	1,523	-33	1,490
Druridge Bay - Centre	2,150	-256	1,894	1,730	-214	1,516
Druridge Bay - South	1,843	-437	1,406	1,475	-375	1,100
Lynemouth Bay	3,604	-1,057	2,547	3,028	-932	2,096
Cambois Bay	1,492	-195	1,297	1,179	-147	1,032
Blyth South Beach - Centre	2,030	-346	1,684	1,245	-251	994
Blyth South Beach - South	1,370	-770	600	867	-499	368
Whitley Bay - Centre	2,264	-440	1,824	1,230	-280	950
Whitley Bay - South	1,691	-784	907	981	-461	520

	Drift Potential (m^3/yr) at MHWS			Drift Potential (m^3/yr) at MLWS		
Profile	Gross S Drift (+ve)	Gross N Drift (-ve)	Net Drift	Gross S Drift (+ve)	Gross N Drift (-ve)	Net Drift
Tynemouth Longsands	1,709	-508	1,201	2,877	-652	2,225
Salterfen Rocks	1,534	-240	1,294	2,234	-453	1,781
Blast Beach	515	-91	424	582	-107	475
Hartlepool North	1,153	-547	606	890	-410	480
Saltburn	1,001	-912	89	880	-718	162
Skinningrove	5,213	-1,260	3,953	3,853	-786	3,067
Sandsend	1,079	-608	471	1,230	-610	620
Whitby	1,510	-952	558	1,079	-712	367
Scarborough North Bay	1,779	-245	1,534	2,629	-541	2,088
Scarborough South Bay	4,483	-566	3,917	2,458	-326	2,132

Figure 21 shows that the gross southerly drift is primarily governed by transport within the inter-tidal zone (e.g. at times of high water) but that there are also important sediment transport processes in the shallow nearshore zone (e.g. at times of low water). It is noticeable that at Tynemouth, Salterfen Rocks, Blast Beach, Sandsend and Scarborough North Bay, the nearshore transport is greater than the inter-tidal transport, indicating the importance of nearshore bars or nearshore currents in these locations in transporting sediment parallel to the shore.

Figure 21 – Gross Positive Drift at Transects within Cell 1

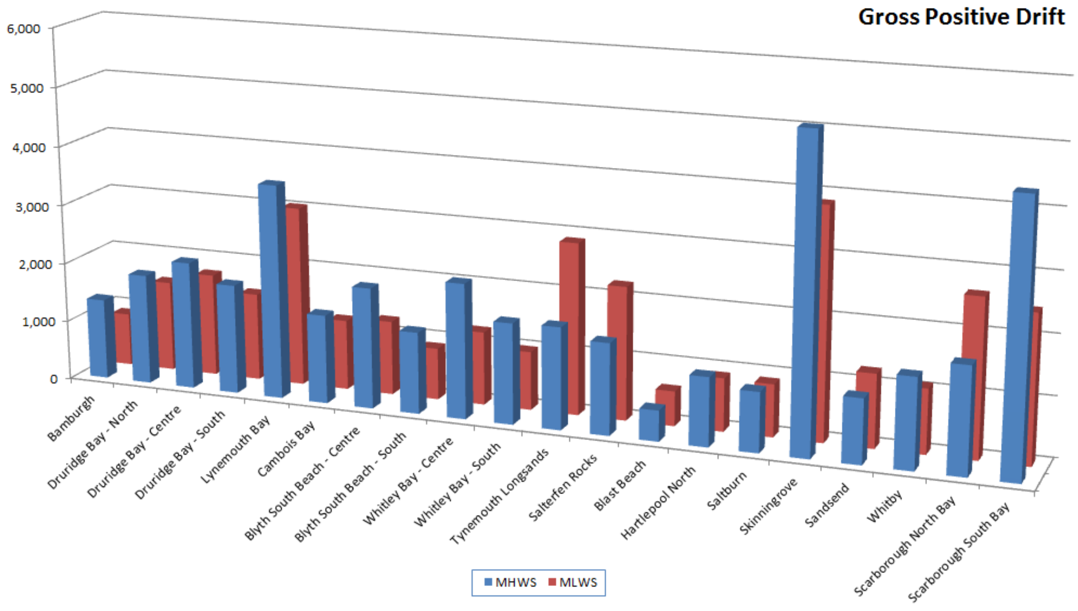
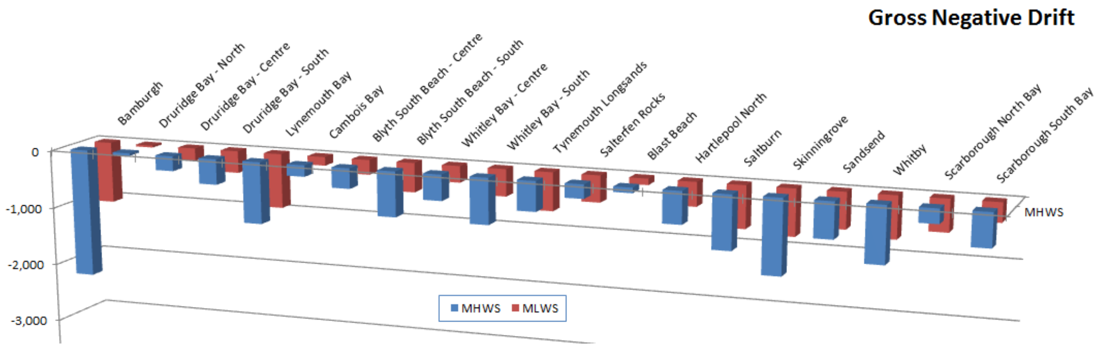


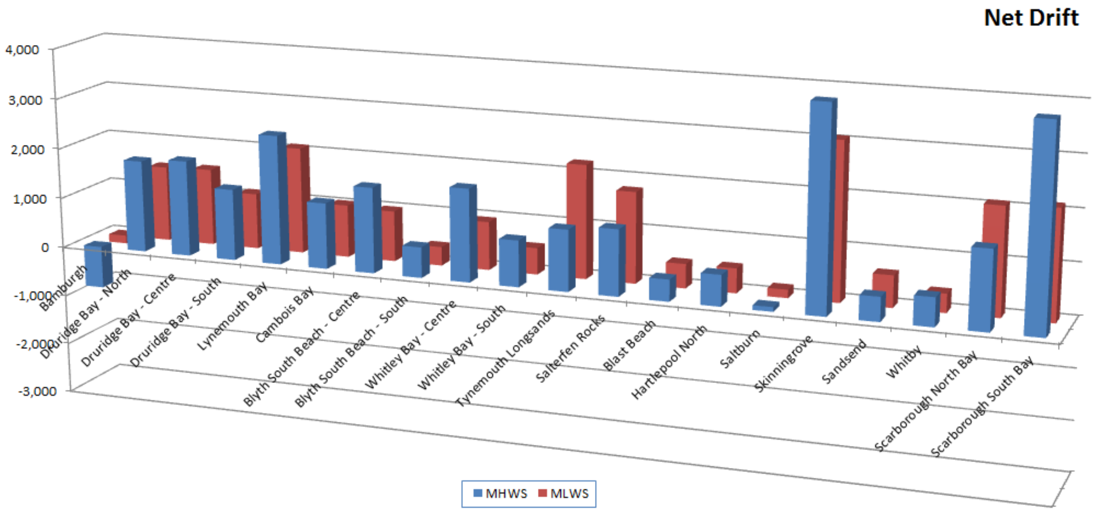
Figure 22 shows that the gross northerly drift is in all but one case less than the gross southerly drift, again with transport possible in the inter-tidal and nearshore zones.

Figure 22 – Gross Negative Drift at Transects within Cell 1



The net effect is a general southerly net drift (Figure 23), with one exception which is discussed later. It is noticeable that the transects exhibiting the least net drift are the ones aligned normal to the predominant incoming wave direction, namely Saltburn, Sandsend, Whitby, Bamburgh, Hartlepool. Where sensitivity of shore alignment within bays was investigated, net drift rates were least at the south of bays. The greatest drift rates were noted along Skinningrove and Scarborough South Bay.

Figure 23 – Net Drift at Transects within Cell 1



A single exception to the net southerly drift exists at Bamburgh where (low magnitude) net drift is directed to the north along the transect that was used in the modelling. This is largely a function of the orientation of the shore with respect to the predominant wave approach direction. Shore profiles with an orientation of 20°N to 30°N along the Bamburgh frontage (Figure 24) are aligned largely normal to the predominant direction of incoming waves, which results in little net longshore drift from these sectors. However, the hindcast wave data for point 1 does have a component of wave activity from the south-east and this will tend to drive sediment to the north-west, i.e. parallel to the shore alignment.

It is noticeable, through a sensitivity test, that net drift potential reduces, but remains northerly, as the aspect changes from 30°N (the modelled transect, with results reproduced in Figure 25) to 38°N (results shown in Figure 26), which is more characteristic of the shoreline further east, around the rock outcrop of Islestone. As the aspect of the shore becomes more easterly facing (typically 73°N) with progression to the south of Islestone, so the net drift becomes southerly (results shown in Figure 27).

Figure 24 – Changes in shore alignment at Bamburgh

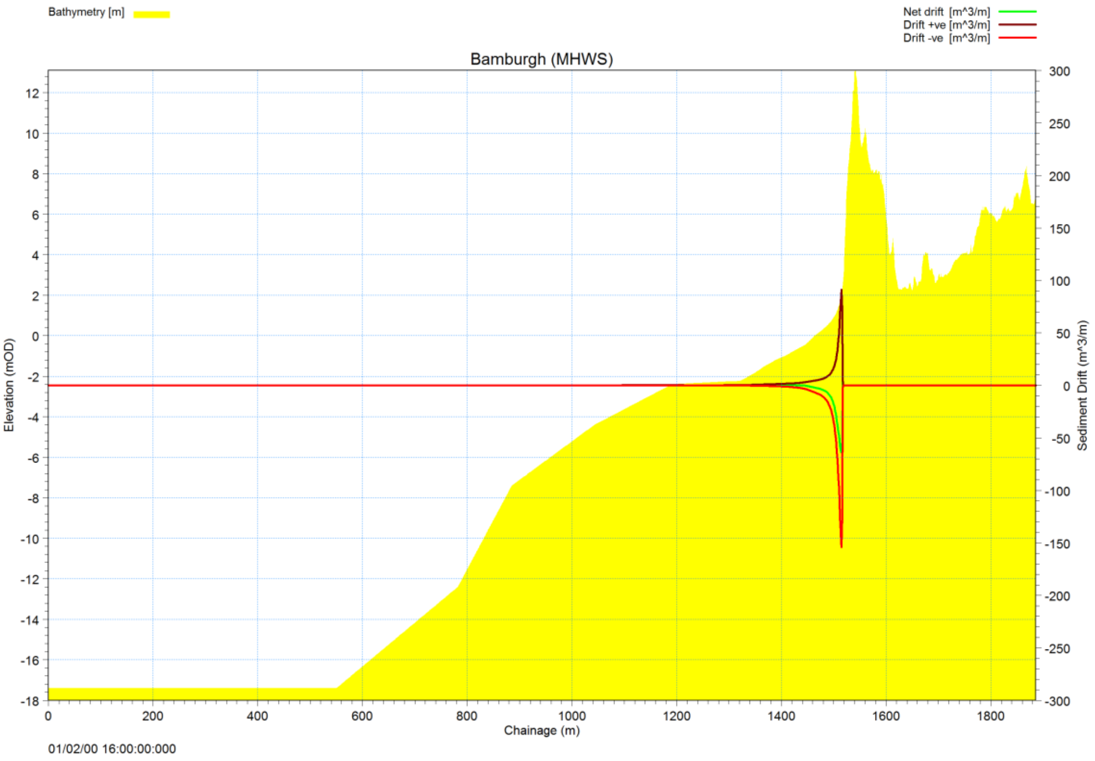


Figure 25 – Longshore sediment transport potential at Bamburgh (30°N profile orientation)

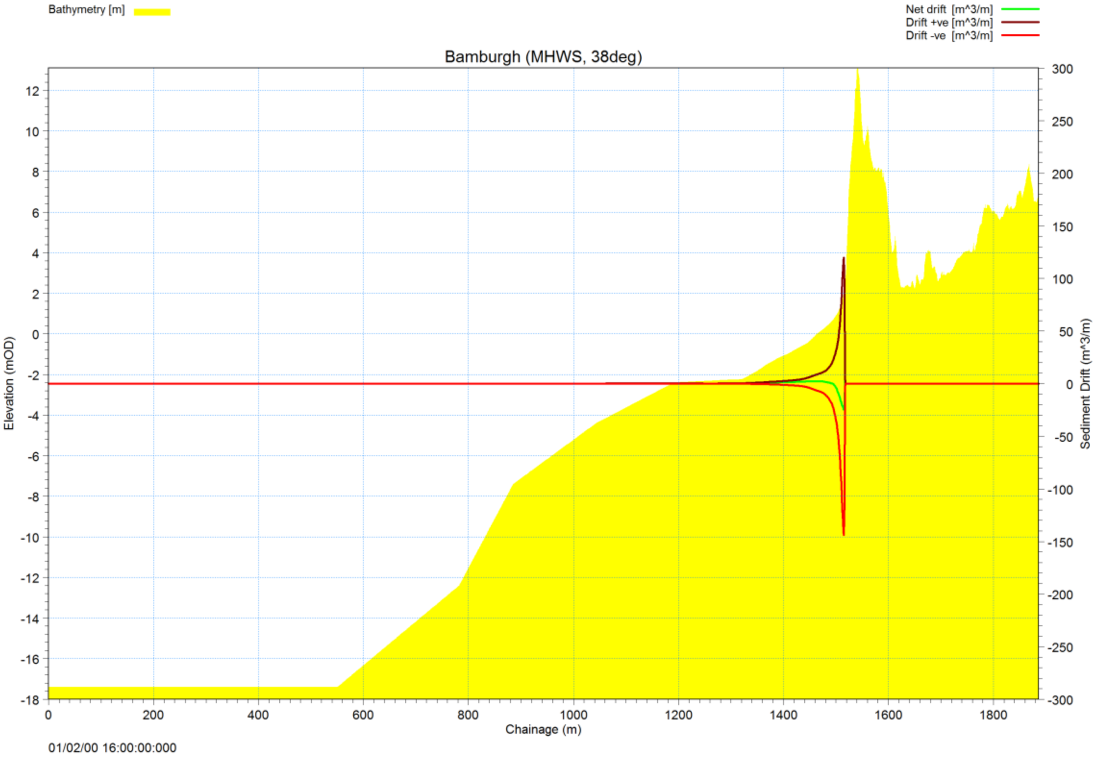


Figure 26 – Longshore sediment transport potential at Bamburgh (38°N profile orientation)

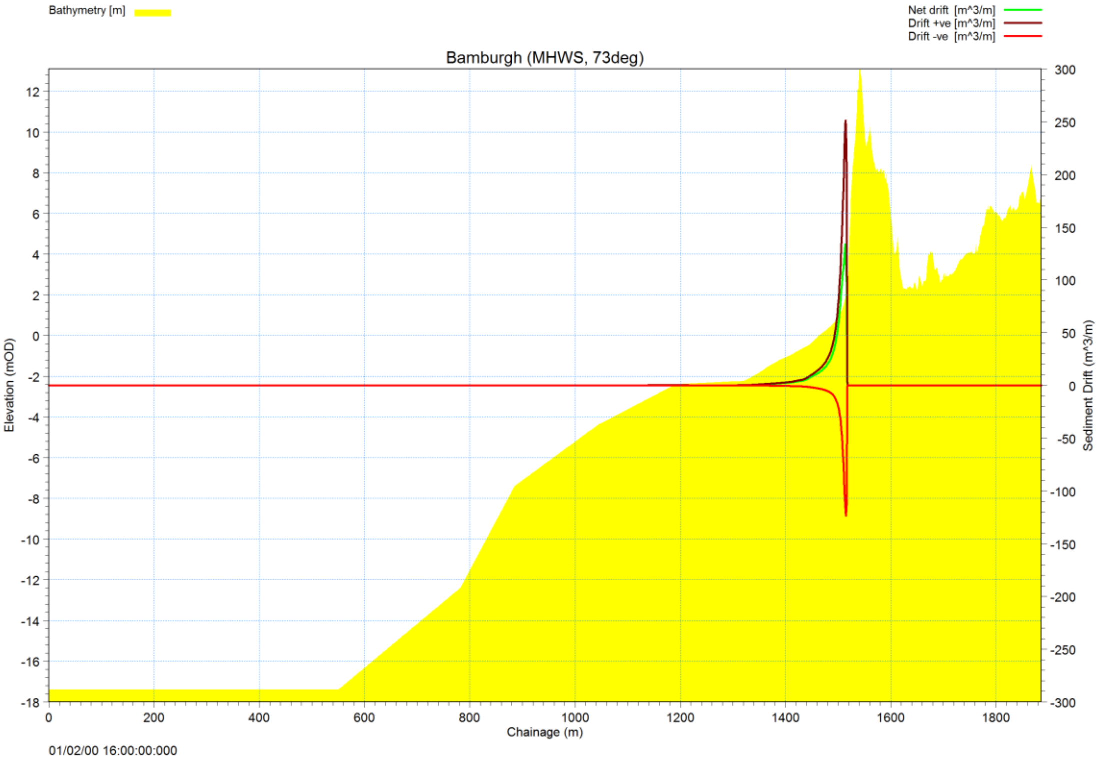


Figure 27 – Longshore sediment transport potential at Bamburgh (73°N profile orientation)

3.4.2 LITPROF Modelling Results

Appendix D presents a series of plots from the LITPROF modelling, showing the beach and bathymetric changes following application of a 1 month storm wave climate derived from the hindcast wave data at the appropriate point for each transect location.

On each plot:

- the yellow area shows the original shore profile and nearshore bathymetry
- the green dashed line shows the shore profile and nearshore bathymetry at the end of the 1 month simulation period

Note: The topographic/bathymetric levels (in metres OD) are shown on the y-axis and the transect chainage (in metres) is shown on the x-axis.

As the changes in morphology due to the 1 month wave climate are generally small in magnitude in relation to the scale of the entire plotted transect, insets diagrams have been added to many of the figures to zoom in on areas of most notable change.

Results from all transects show a ‘text book’ response of the shore profile to winter storm events, with erosion of beach sediments at the toe of the coastal defences, sand dunes, coastal slope or sea cliffs and associated deposition of these sediments further down the foreshore or in the shallow nearshore zone, resulting in a general flattening of the shore profile.

At both Bamburgh and Druridge Bay, only a small amount of sand was eroded from the dune toe, and deposited on the lower foreshore. This is in keeping with the general stability shown in the beach profiles at these locations from the Cell 1 Regional Coastal Monitoring Programme.

Changes were greater at Lynemouth Bay, where erosion occurred at two locations across the transect; one at the toe of the coastal slope comprised of colliery spoil and one at the seaward scarp of the colliery spoil beach across the foreshore. In both cases, the landward retreat was measureable (tens of metres). This is in keeping with the persistently high rates of retreat of the colliery spoil shown in the beach profiles at this location from the Cell 1 Regional Coastal Monitoring Programme.

At both Cambois Bay and Blyth South Beach, erosion at the dune toe was observed, with material being deposited on the foreshore around the mark of mean low water and within the shallow nearshore zone.

This process was repeated at both Whitley Bay and Tynemouth Longsands. However, the erosion tended to affect the upper beach above MSL. Deposition tended to occur on the lower beach and, to a lesser extent, in the shallow nearshore zone. This process formed a small bar at Whitley Bay and a more pronounced bar in the shallow nearshore zone at Tynemouth Longsands.

Changes at Salterfen Rocks were minor and confined to the upper foreshore because elsewhere the cross-shore profile is dominated by hard rock and boulders.

The shore profile at Blast Beach, like the one at Lynemouth, exhibited notable (>20m) cut back in the position of the scarp of the colliery spoil beach in front of the backing cliffs. The rest of the profile exhibited little change.

At Hartlepool North there was a small amount of erosion at the toe of the dunes, but a more notable flattening of a berm present at around MSL, with deposition of the material lower down the shore profile.

At Saltburn, there was erosion (small in magnitude) across the whole upper beach, with associated deposition across the lower beach. A small berm present in the original profile just below MLWS became flattened by the 1 month wave climate, with material being spread across the sea bed within the shallow nearshore zone to a depth of around 5m below OD.

At Skinningrove, the response was generally for erosion across the foreshore, with the creation of a series of ridges and runnels in the shallow nearshore zone. Existing ridge and runnel features remained largely intact across the nearshore zone, including down to around 24m below OD.

At both Sandsend and Whitby there was a classic winter beach response to the 1 month wave climate, with material removed from the upper beach and deposited on the lower inter-tidal foreshore and within the shallow nearshore zone.

This process was repeated at both Scarborough North Bay and Scarborough South Bay, with notable ridge and runnel features present in the shallow nearshore zone along both transects.

3.4.3 Overview

The numerical modelling approach has investigated the *relative* alongshore and cross-shore sediment transport potential at a series of sixteen transects throughout the Cell 1 frontage.

Modelling results presented in Appendix C show that longshore sediment transport is only modest in magnitude throughout Cell 1 and is strongly influenced by changes in orientation of the shore profile within bays and the angle of the shore relative to the approach directions that characterise the nearshore wave climate.

In this regard, there are complex physical process effects in the lee of major headlands (e.g. Hartlepool Headland, Scarborough Castle Headland) and significant shore-perpendicular structures (e.g. North and South Gare Breakwaters, Whitby Harbour Piers) which have localised effects on sediment transport directions and rates.

Results suggest that along most transects, there is strongest sediment transport potential (although only low to moderate in magnitude) along the upper inter-tidal zone, but some potential also exists in the nearshore zone. This is particularly notable at Tynemouth Longsands, Sandsend and, to a lesser extent, at Whitby. Generally, it is wave-generated forces that dominate longshore transport, with tidal currents making little effect in the mobilisation of sediments.

Modelling results presented in Appendix D show that cross-shore sediment transport potential exists at all modelled transects under a 1 month timeseries of ‘winter’ wave data. Material is typically eroded from the upper beach and deposited on the lower beach or within the nearshore zone. A rapid succession of several reasonably sized storm events causes this ‘classic’ winter beach profile response of upper beach erosion and lower beach and nearshore deposition, resulting in a temporary ‘flattening’ of the profile. Generally, sediment volumes involved in such short-term cross-shore transport can be greater – in many cases orders of magnitude greater – than the net alongshore sediment transport potential.

Since most transects show some longshore transport potential in the nearshore zone, it is likely that during storms sediment is removed from the beaches as a cross-shore process and then transported alongshore (predominantly to the south) in the shallow nearshore zone. After the stormier wave climate has passed, the sediment then progressively returns to the beaches as a cross-shore process (either within the same bay or further south along the coast after bypassing a headland) during calmer wave conditions.

4 SYNTHESIS AND CONCLUSIONS

4.1 Datasets and Literature Sources

In preparing the Scoping Report for the Cell 1 Sediment Transport Study, a large number of published and grey literature sources, maps, charts, photographs, datasets and numerical modelling outputs were collated and reviewed to provide a synthesis of present understanding of the key sediment transport understanding issues and uncertainties within Cell 1 (Royal HaskoningDHV, 2013). Since that time, a number of additional datasets and other literature sources have been newly acquired which are of relevance to sediment transport within Cell 1. These include survey data from the Cell 1 Regional Monitoring Programme and the East Riding of Yorkshire Coastal Monitoring Programme, and reporting from the Cell 1 Inter-tidal Habitat Study.

4.1.1 East Riding of Yorkshire Bathymetry Survey

A bathymetric survey was undertaken around Flamborough Head by NetSurvey Ltd. in 2011 as part of the East Riding of Yorkshire Coastal Monitoring Programme (Figure 28). The survey actually extended along the whole East Riding of Yorkshire frontage, between Speeton and Spurn Point, but just the data from around Flamborough Head are considered here. Multi-beam echo sounder technology was used between the offshore extent of the survey and the 2m sea bed contour, with single-beam echo sounder completing the survey to at least MLWS.

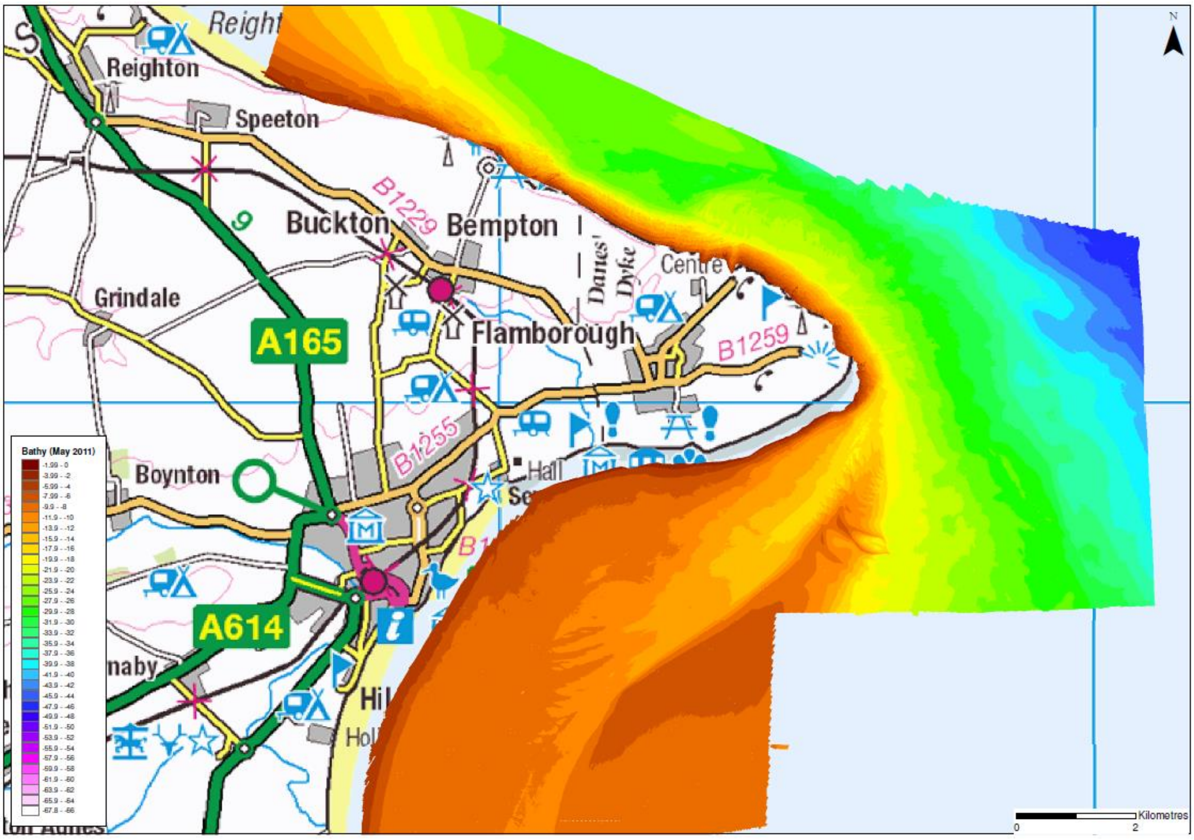


Figure 28 – Bathymetric survey (2011) around Flamborough Head

NetSurvey Ltd. (2011) report that on the northern side of Flamborough Head, between Speeton and Bempton Cliffs, the area surveyed extended to sea bed depths in excess of 20m. Examination of the bathymetry and derived contours shows that close to shore the bathymetry is characterised by rock ledges and boulders, which are evident down to 10m. The sea bed from 10m down is mostly a gently deepening sea bed with few features.

Between North Cliff on the north side of Flamborough Head and Cattlemere Hole on the south, the survey extends around the eastern extents of the headland with depths observed from the drying line to in excess of 25m. In the vicinity of Cattlemore Hole, the northeastern extents of North Smithic Shoal (sand bank) exhibit sandwave features up to 1.5m high. The area to the south and inside of the headland appears to be more sandy in origin with sandwaves and ripple features evident in the topography.

Further offshore, between North Smithic Shoal and sea bed areas eastwards off Flamborough Head, the survey extends into deeper water, reaching in excess of 40m. Sandwaves are present on the southeastern side of North Smithic Shoal which may indicate some mobility of the sea bed sediments.

On the south side of Flamborough Head, between Cattlemere Hole and Sewerby Rocks, the survey extends to depths in excess of 13m and then onto North Smithic Shoal. The sea bed in the west of North Smithic Shoal is gently sloping down to 6 - 7m, whilst to the east it is characterised by the channel that runs between the headland and North Smithic shoal. There are sandwave features up to 2.5m in height along the flank of North Smithic Shoal.

4.1.2 East Riding of Yorkshire Sediment Transport

Sutherland *et al*. (2002) compiled estimates of longshore sediment transport directions and rates along the East Riding of Yorkshire coastline, between Flamborough Head and Spurn Point. Whilst this frontage is outside of Cell 1, it is interesting to note that the direction of net longshore sediment transport along most of the East Riding of Yorkshire coastline is towards the south, due to the dominance of waves approaching from the northeast, this general pattern is reversed in the very north, because Flamborough Head provides protection from northeasterly waves.

Furthermore, previous studies by the Institute of Estuarine and Coastal Studies (IECS) at the University of Hull suggest that some sediment on the sea bed offshore from south of Flamborough Head is carried north around the headland by the tidal currents (IECS, 1991), as shown in Figure 29.

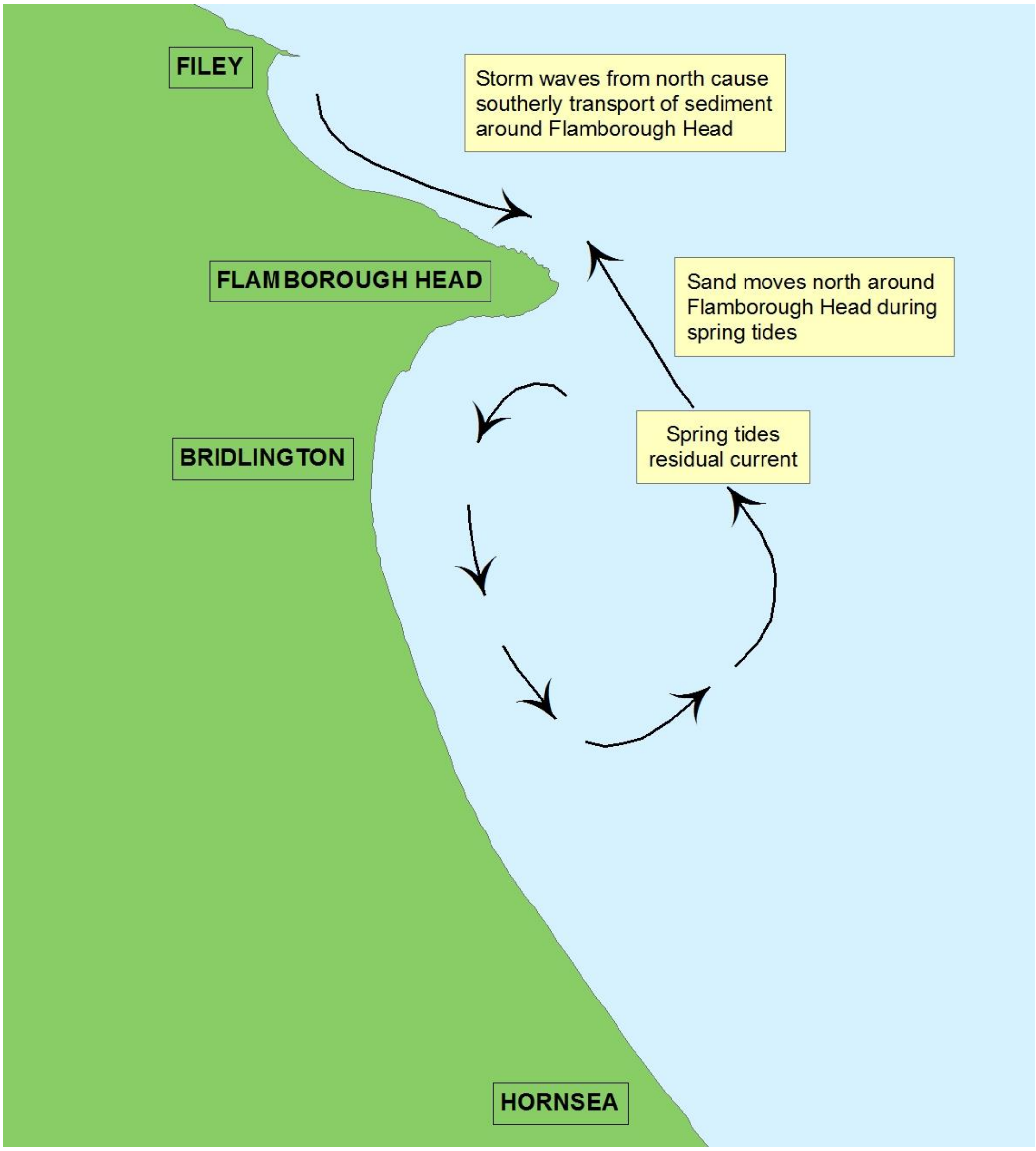


Figure 29 – Northward movement of sand around Flamborough Head (source: IECS, 1991)

4.2 Historical Trends Analysis

The historical legacy of colliery spoil tipping at Lynemouth Bay and Cambois Bay in Northumberland and at Dawdon Bankside, Dawdon Blast Beach, Easington, Horden and Blackhall Colliery in County Durham has been investigated as part of the present study. Large quantities of colliery spoil were tipped directly onto foreshore tipping sites (as well as offshore dump sites) where they have been dispersed by wave action. In most cases, dumping started well before statutory controls entered into force in the UK in 1974. Since that date, disposal of these wastes became regulated under license. It is estimated that around 30m tonnes of colliery waste was tipped at foreshore disposal sites in Lynemouth Bay between 1934 and 2005, with at its peak over 1.5m tonnes tipped in one year (1968) and over 100m tonnes of colliery waste was tipped along the County Durham coastline, either at offshore disposal sites or at foreshore disposal sites.

In all cases, the tipping of waste resulted in significant progradation (seaward movement) of the shoreline and infilling of the bays to form wide spoil beaches as a ‘terrace’ on the upper beach. The majority of the colliery waste that was tipped became eroded and transported seawards to the nearshore zone (within the 10m sea bed contour). This ‘loss’ from the shoreline was more than compensated for many decades by the ongoing tipping. Material moved to the shallow nearshore zone would then become further broken up into smaller particles by marine action and, when sufficiently small in grain size, transported by tidal currents in the direction of the net southerly current residuals. Larger grain sizes would tend to remain on the beach as lag boulder, cobble or gravel deposits.

Some longshore transport of material also occurred, particularly when the spoil beaches had increased in width so much that the high water mark extended beyond the rock headlands that intersect adjacent bays. This was most notable along the County Durham frontage where both Hawthorne Hive and Shippersea Bay (both located to the south of Dawdon Blast Beach) became infilled with colliery spoil, despite not directly being tipping sites, and concerns were also raised about despoilment of the beaches at Crimdon, south of Blackball Colliery. However, the general net southerly drift was relatively small and intermittent, predominantly being storm-driven.

Since cessation of tipping, the shoreline in all former tipping areas has been retreating. This has caused retreat of the high water line to a position landward of the headlands, meaning that potential for ‘bay to bay’ transport of remaining spoil beaches due to longshore drift has further reduced. The ongoing retreat of the shoreline since cessation of spoil tipping on the foreshores has caused particular problems in Lynemouth Bay, where a rock revetment was constructed in 1995 in front of the power station and then was extended in 2005 around the adjacent coal-stocking yard.

4.3 Sediment Transport Modelling

The numerical modelling approach of the present study has investigated the *relative* alongshore and cross-shore sediment transport potential at a series of sixteen transects throughout the Cell 1 frontage.

Longshore sediment transport is only modest in magnitude and is strongly influenced by changes in orientation of the shore profile within bays and the angle of the shore relative to the approach directions that characterise the nearshore wave climate. There are complex physical process effects in the lee of major headlands (e.g. Hartlepool Headland, Scarborough Castle Headland) and significant shore-perpendicular structures (e.g. North and South Gare Breakwaters, Whitby Harbour Piers) which have localised effects on sediment transport directions and rates. Results suggest that along most transects, there is strongest sediment transport potential (although only low to moderate in magnitude) along the upper inter-tidal zone, but some potential also exists in the nearshore zone. Generally, it is wave-generated forces that dominate longshore transport, with tidal currents making little effect in the mobilisation of sediments.

Cross-shore sediment transport potential exists at all modelled transects under a 1 month timeseries of ‘winter’ wave data. Material is typically eroded from the upper beach and deposited on the lower beach or within the nearshore zone. A rapid succession of several reasonably sized storm events causes this ‘classic’ winter beach profile response of upper beach erosion and lower beach and nearshore deposition, resulting in a temporary ‘flattening’ of the profile. Generally, sediment volumes involved in such short-term cross-shore transport can be greater – in many cases orders of magnitude greater – than the net alongshore sediment transport potential. Since most transects show some longshore transport potential in the nearshore zone, it is likely that during storms sediment is removed from the beaches as a cross-shore process and then transported alongshore (predominantly to the south) in the shallow nearshore zone. After the stormier wave climate has passed, the sediment then progressively returns to the beaches as a cross-shore process (either within the same bay or further south along the coast after bypassing a headland) during calmer wave conditions.

4.4 Conclusions and Recommendations

The principal findings of Phases 1 and 2 of the *Cell 1 Sediment Transport Study* are:

- The Cell 1 shoreline and nearshore sea bed is predominantly controlled by its underlying solid geological structure, with the more recent glacial or post-glacial deposits of boulder clay or sand also being of significance in terms of the sea cliffs, coastal slopes and sand dunes that are present.

- Through differential erosion of the different rock types, or exploitation of faults and other structural weaknesses, a number of headland and bay features of varying spatial extents from small indentations (often known locally as 'holes') to expansive sandy bays have been formed.

- Littoral sediment transport is, generally, relatively well confined to movement within individual bays (or a short series of bays separated by less well defined headlands). Whilst littoral sediment transport is predominantly to the south, the rates of drift are relatively low and temporary drift reversal can occur along frontages under short-duration storm events from different directions.

- The presence of numerous natural headlands, estuaries and their associated control structures, such as harbour piers, can cause locally complex physical processes due to wave sheltering, tidal gyres and localised sediment accumulations or drift reversals.

- There are sections of high energy rock platforms backed by hard sections of cliff, where there is high drift potential, but little evidence of sediment moving through that section of the shoreline. This may be due to limited supply and limited actual drift or, in some cases, where sediment is not evidenced due to the rapid transport of sediment through the area.

- Of greater importance than alongshore sediment transport, many beaches experience significant onshore-offshore transport during storm events, particularly during autumn, winter and early spring months. In areas backed by dunes, there tends to be toe erosion of the dunes and reduction in upper beach levels, with material being drawn down the beach to the lower foreshore and nearshore zone. Liberated sediment can then become entrained by tidal currents and advected along the coast, generally in a southerly direction. Where beaches are backed by coastal defences such as sea walls, upper foreshore lowering can be notable during these events. In general, beach sediment slowly and progressively returns to the upper foreshore as conditions become calmer, leading to beach and dune recovery. However, there remains uncertainty about these processes.

- North of the River Tyne estuary, the principal issue is the genesis and evolution of the dune systems in relation to sea level history and projections. Most of the dunes, especially in Northumberland, are associated with regressive (prograding) shorelines consequent upon a fall in relative sea level from its Holocene peak. Relative sea level acted as a macro-scale control through its influence on sediment supply and accommodation space for dune development. Most dune-building occurred during the Little Ice Age. The coastal systems of Northumberland are characterised by a range of responses to the historically low rates of relative sea-level change (generally less than 1mm/yr) coupled with local variations in sediment supply. Particularly with the anticipated increased rate of sea level rise, it is possible that a change in state could occur.

- Between the River Tyne estuary and Hartlepool, the principal controls are exerted by the geology of the cliffs and legacy industrial practices, including the large-scale disposal of colliery spoil along the beaches of County Durham. Historically millions of tonnes of spoil was tipped on the beaches, resulting in the creation of artificial spoil beaches which have prograded the shoreline and stranded the backing sea cliffs. With cessation of tipping, the spoil beaches have been substantially cleared-up as part of the ‘Turning the Tide’ project and remaining spoil is now undergoing active erosion processes. In other areas, such as south of Sunderland, thick mantling of boulder clay over the cliffs has contributed sediment supply, especially pebbles, locally to the foreshore.

- In Tees Bay, the low tidal currents and set-back alignment of the shore combine to encourage the accumulation of marine-derived sediments, most notably sands, resulting in notable infilling of the River Tees estuary which necessitates an active dredging regime to maintain advertised navigation depths. The beaches between the mouth of the River Tees estuary and Saltburn exhibit measurable changes depending on prevailing conditions, but overall have accreted with significant quantities of sand in recent years, despite a recent loss of sediment from Redcar Sands in front of the recently-completed sea defences.

- Between Saltburn and Flamborough Head, the coastline is again dominated by geology, with pronounced headland and bay shorelines prevalent. Boulder clay deposits which overlay the solid geology often are subject to landslip events which can locally, but only episodically, contribute notable sediment yields to the littoral system. Several major headlands, including Castle Headland, Filey Brigg and Flamborough Head, exert significant control on shoreline form and sediment transport processes over notable lengths of frontage.

Given these findings, it is considered that the present scope and frequency of inspection, measurements and surveying that is undertaken as part of the *Cell 1 Regional Coastal Monitoring Programme* is, in the main, suitable for the describing the characteristic changes in morphological behaviour of the frontages within Cell 1, and furthermore is proportionate to the nature of the risks from erosion or sea flooding that are present.

However, whilst the programme routinely captures information on the condition of built defences and natural features (from visual inspections) and also records the morphological changes and principal forcing conditions of waves and tides, the measurements of sediment composition are restricted to 2-yearly characterisation surveys using swathe bathymetry and (limited) grab sampling of the sea bed. These sea bed surveys are currently undertaken only along a series of shore-perpendicular transect lines and do not capture wider sea bed areas. Furthermore, the surveys are only undertaken across the sea bed between the River Tyne and Flamborough Head and not the North Tyneside or Northumberland frontages.

The above issues relating to the sea bed surveys have been reviewed on occasion during the lifespan to date of the programme and it is recommended that further consideration should be given to this topic when the programme extension beyond 2016 is being developed.

The findings from the *Cell 1 Sediment Transport Study* suggest that whilst it would of course be desirable to have further measurements of the sedimentological character of the sea bed and shore and measurements of the sea bed changes across the whole of Cell 1, the limited number of bed forms that exist and the somewhat limited bedload transport potential that occurs means that this is not necessarily deemed essential.

Following production of this main study report, a subsequent phase of activity will be undertaken in autumn/winter 2014, involving a field experiment using sand tracers in Scarborough South Bay. The purpose of this sand tracer experiment is twofold: (1) to confirm sand transport pathways in Scarborough South Bay; and (2) to test in a field environment the efficacy of the existing sand tracer technique, which may have wider applicability for subsequent use across other frontages within Cell and more widely across other sand-dominated coastal frontages elsewhere. The methods and results of the sand tracer experiment will be presented in a separate report in due course.

At the time of writing this report, the findings of the *Cell 1 Inter-tidal Habitat Study* were not available for review. However, during development of the *Cell 1 Sediment Transport Study*, there was correspondence with the authors of that study to share ideas about governing physical processes, sediment sources and morphological changes across Cell 1 and there was good consensus regarding these matters. When the *Cell 1 Inter-tidal Habitat Study* becomes available, it is recommended that its content is reviewed in detail for any further insights beyond those contained within this report.

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