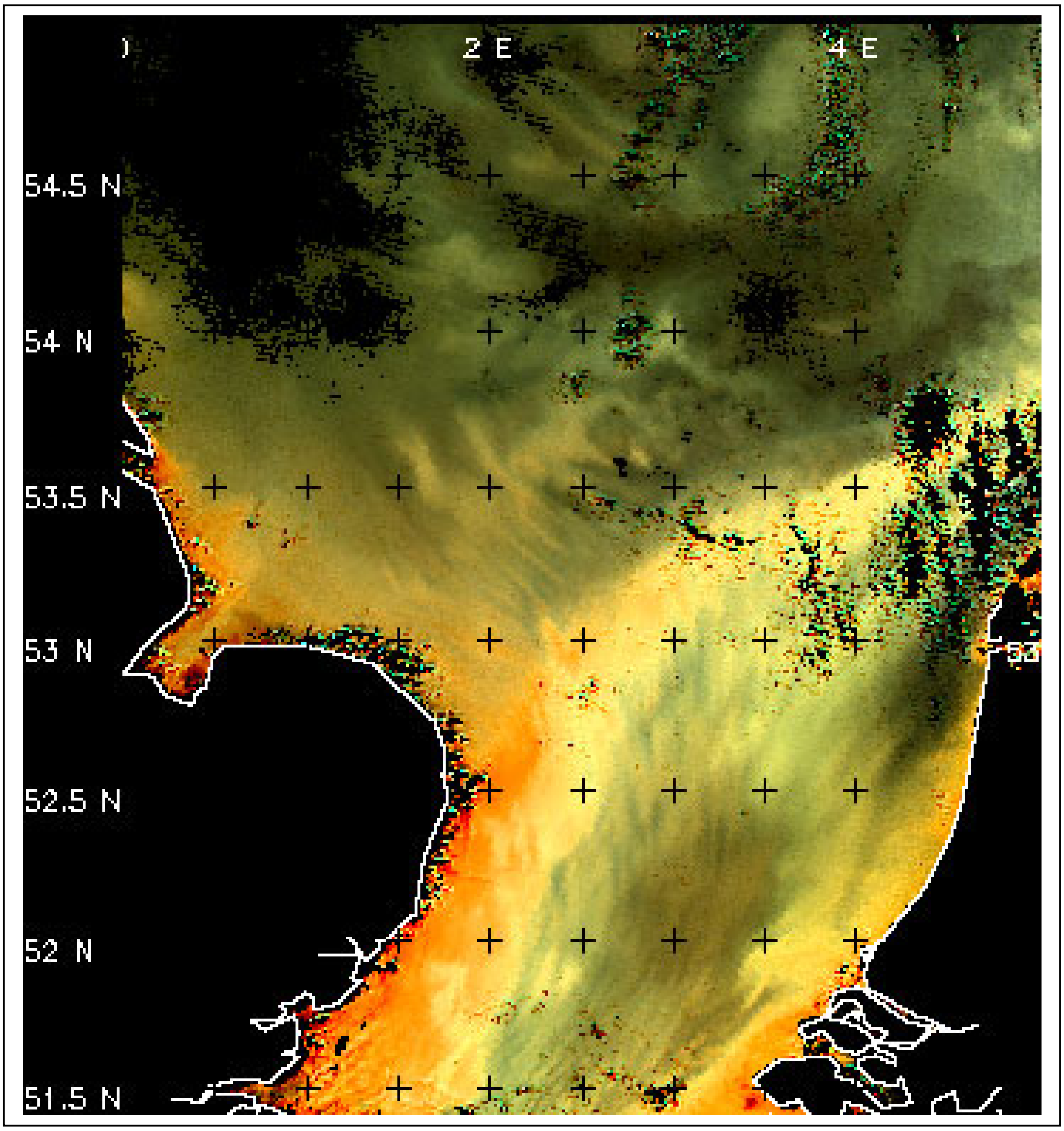
Southern North Sea Sediment Transport Study, Phase 2



Sediment Transport Report
Report EX 4526
August 2002

Southern North Sea Sediment Transport Study, Phase 2

Sediment Transport Report

Report produced for Great Yarmouth Borough Council by HR Wallingford, CEFAS/UEA, Posford Haskoning and Dr Brian D'Olier

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Front cover picture: SeaWifs satellite image of pattern of near surface Suspended Particulate Material in Southern North Sea. Highest concentrations are coloured red. Date of image 19th October 2000. Image courtesy of Plymouth Marine Laboratory.

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Southend Borough Council

BMAPA

British Marine Aggregate Producers Association

ENGLISH NATURE

Contract - Consultancy

This report describes work carried out as part of the Southern North Sea Sediment Transport Study, Phase 2. The contract was with Great Yarmouth Borough Council (the Client) and the HR job number was CPR2926. The Project Manager representing the Client Study Partnership was Mr Julian Walker of Waveney District Council and the HR Wallingford Project Manager was Dr Richard Whitehouse.

The work in this report was carried out by a study team comprising staff from HR Wallingford, CEFAS (The Centre for Environment, Fisheries and Aquaculture Science), Posford Haskoning, University of East Anglia and Dr Brian D'Olier.

The views expressed in this report are those of the study team.

Prepared by ....
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Approved by ....
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Authorised by ....
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(Title)

Date ....

Executive Summary

Southern North Sea Sediment Transport Study Phase 2

Sediment Transport Report

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1. Study Context

Sediment movements in the southern North Sea influence the eastern English coastline through supplying or removing beach material. It is important to understand these movements thoroughly so as to improve the data on which Shoreline Management Plans (SMPs) and the assessment of dredging licence applications are based. A fuller understanding of sediment movements will facilitate a greater awareness of issues affecting management of beaches and coastal defences, the coastline and sediment resources offshore.

The Southern North Sea Sediment Transport Study Phase 2 was designed to provide the broad appreciation and detailed understanding of sediment transport along the eastern coastline of England between Flamborough Head in Yorkshire and North Foreland in Kent, on the south side of the Thames Estuary (Figure 1). The study was undertaken between 2000 and 2002 by a consortium comprising of HR Wallingford, CEFAS Lowestoft Laboratory and UEA Norwich, Posford Haskoning and independent consultant Dr Brian D'Olier.

The study was commissioned by a group of nine local authorities, together with the Environment Agency and English Nature and the dredging industry. It built on the earlier Phase 1 study completed in 1996 (ABP Research & Consultancy, 1996a, 1996b and 2000). The present study was part funded by the Department for Environment, Food & Rural Affairs (DEFRA). The client project manager was Julian Walker of Waveney District Council on behalf of Great Yarmouth Borough Council, the client group leader. The consultant team was led by Richard Whitehouse of HR Wallingford.

The study is described below and where appropriate links to the report Appendices and Sections are indicated to enable the reader to follow up specific information.

2. Summary of outputs

The outcomes of the study have been presented in the Sediment Transport Report (HR Wallingford, 2002) which is supported by 15 Appendices containing detailed information on various facets of the study. A database, field data and various map data is available for use within a Geographical Information System.

It is expected that the report will be of use to engineers and scientists with roles in managing, regulating or working within the coastal and seabed areas encompassed by the study area (Figure 1). At a generic level it will be relevant to those undertaking research into coastal and seabed processes.

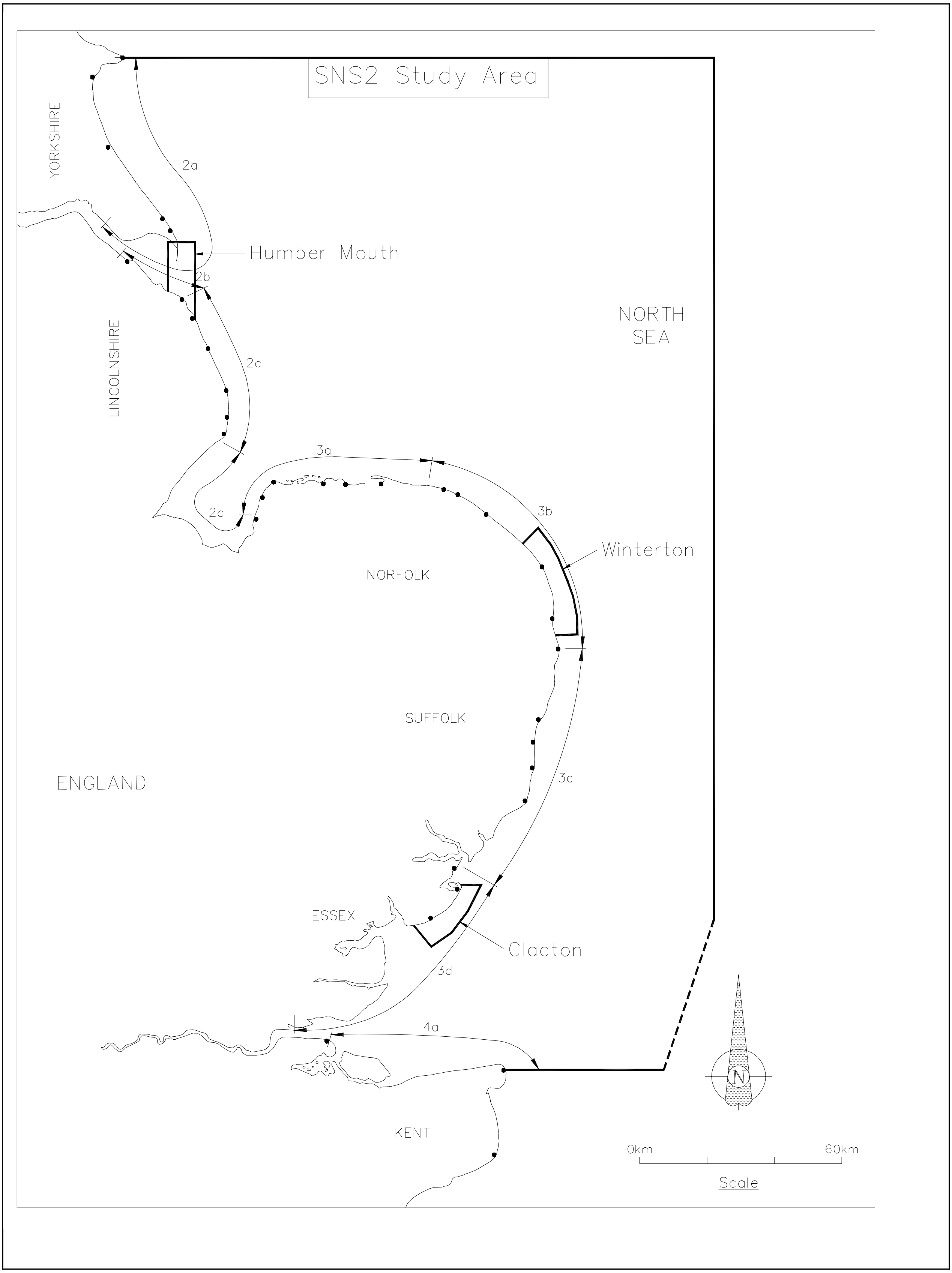

Figure 1 **Location map showing the study area, the extent of the coastal subcells used for coastal management (numbered 2a to 4a), and the location of the sites for new data collection (Humber mouth, Winterton, Clacton)**

3. Objective

The study addressed the broad objective detailed in Box 1.

Box 1

To obtain an improved understanding of the Southern North Sea sediment transport system, and its links with the eastern England coastline between Flamborough Head and the River Thames.

To include:

- Identification of sediment sources, transport pathways, volumes of sediment transport and areas of deposition, across the complete range of particle sizes and temporal scales
- Identification of the location, size, variability and evidence of offshore features, and their influence on and interaction with waves and tidal current climates
- Provision of the information that is required for the updating of SMPs, and which enables a more informed assessment to be made of the influence of offshore dredging on the eastern coast of England

4. Methodology

To deliver the objectives and address the issues the study team planned and executed a series of interdisciplinary activities: identification of key strategic issues; data/knowledge review, collation and capture; computational modelling of sediment transport in coastal and seabed areas; new field data collection of hydrodynamics and sediment transport; mapping of information including seabed sediment transport indicators, and expert analysis and interpretation. A flow chart of these activities is presented in Figure 2. The activities under each of the headings will be described briefly.

4.1 Identification of key strategic issues with respect to sediment transport

An important part of the study was to determine the strategic issues with respect to sediment transport along the study coastline. A key step in identifying these issues was a focussed consultation process with maritime local authorities from the whole of the study region, the Environment Agency and English Nature, as well as representatives of the dredging industry (Appendix 4). In parallel the eight existing Shoreline Management Plans for the study coastline were reviewed for sediment transport related issues (Appendix 3). The combined outcome of this process was the identification and reporting of key strategic issues, strategy level issues and local issues in an Inception Report (HR Wallingford, 2001). The study then focussed on tackling the strategic issues where it was felt the most significant gains could be made and an improved coherence in the sediment transport understanding could be delivered.

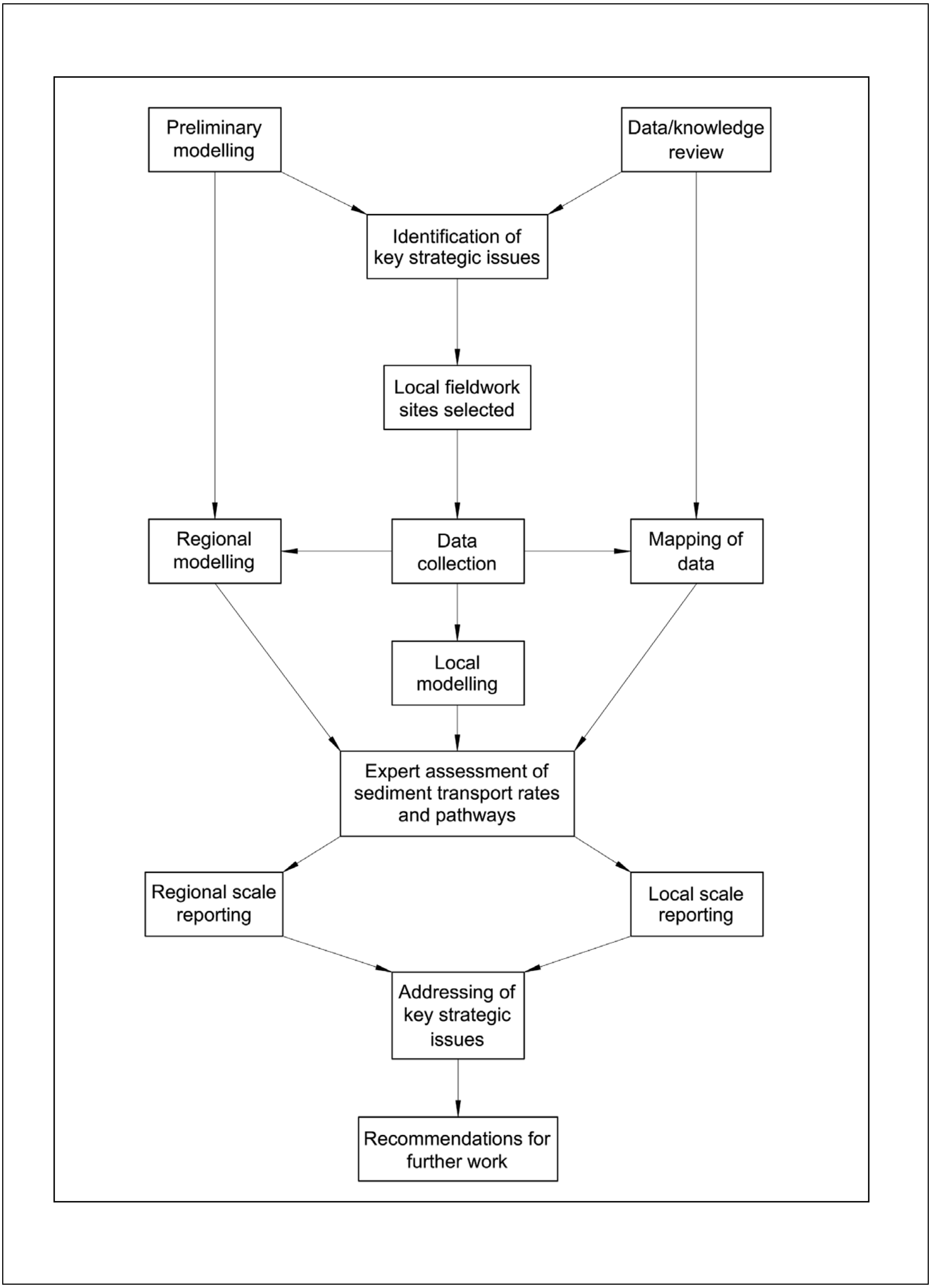

Figure 2 Project methodology

The strategic issues were encompassed in the following headings:

- Issue A – Northern Boundary
- Issue B – Role of Holderness
- Issue C – The role of the Wash
- Issue D – Nearshore banks
- Issue E – North Norfolk drift divide
- Issue F – Sediment circulation Cromer to Benacre Ness
- Issue G – The role of the Sizewell-Dunwich Banks
- Issue H – Suffolk Coastline
- Issue I – Clacton
- Issue J – North Kent coast and nearshore
- Issue K – Thames Estuary

4.2 Data/knowledge review, collation and capture

The knowledge capture and collation (summarised in Appendix 8) involved building on the earlier Phase 1 studies completed in 1996 by identifying and consulting the results of relevant studies and published material in the fields of maritime civil engineering and hydraulics, oceanography, physical geography/geomorphology, and geology. New information was listed in a web browser based sediment transport database which has been distributed to the client group and funders (Appendix 5); this was consistent with and included all the information from the Phase 1 database. New knowledge brought to the study was input and correlated through expert assessment at study workshops designed to address the key strategic issues. The new knowledge included a summary of sediment processes (Appendix 2), results from sediment transport modelling studies carried out as part of coastal strategy or scheme studies, field measurement and modelling of flows and sediment transport in the study area, mapping of seabed features (primarily the larger sedimentary features called sandwaves and megaripples), and a synthesis of the geological context including sediment sources, pathways and sinks (Appendix 10, 14). The latter was supported for the Holderness coast, Humber and north Lincolnshire by an appraisal of previously collected mineralogical data (Appendix 9). The development of aggregate dredging and disposal activities at a practical and policy level was also reviewed (Appendix 1).

An extensive amount of modelling of longshore sediment transport (littoral drift) has been completed since the 1970s. This has been undertaken by different organisations at various times with different objectives. The volume of available information has been brought together for the first time to form a catalogue of predicted longshore sediment transport rates (Appendix 11). Where possible the rates and direction of sediment transport have been specified, at other locations it has only been possible to determine the net direction (e.g. from observed coastal features).

4.3 Computational modelling of sediment transport

A key aspect of the study was the computational modelling of sediment transport by waves, tides and an extreme water level event (North Sea surge) (Appendix 12). This provided consistent information over the entire study area using a calibrated depth-averaged tidal flow model (TELEMAC) and a calibrated and validated total load (bedload and suspended load, SANDFLOW) sediment transport module. The model validation showed that a high degree of confidence could be placed in the results. The results were plotted both at the scale of the whole study area and for 11 local areas:

- Flamborough Head to the Humber
- Humber Entrance and Lincolnshire
- Lincolnshire and the Wash
- North Norfolk
- East Norfolk
- North Suffolk
- Suffolk and Essex
- South Essex
- Outer Thames
- North Kent
- East Kent

The computational modelling could not represent and explain all the complexities of the actual sediment transport processes in the Southern North Sea. This was because within the limitations of the study it was not possible to consider all possible tidal ranges, all possible surges/wind/wave conditions and the fine detail of seabed sediments over such a large area. Rather the approach was to carry out a modest number of hypothetical situations that could provide potential answers to specific results for fine sand (0.1 mm size), medium sand (0.4 mm size) and fine gravel (2 mm size) under neap and spring tides, spring tides with increasing levels of wave activity (1 to 5 m significant wave height), and an extreme North Sea surge event (20 year return period). The reader has been provided with guidance as to the relevance of each of the scenarios that have been run (Appendix 13). The role of surge events in modifying flow and sediment transport patterns was identified (Appendix 7), and the dominating effect of an extreme surge on the coastal currents and sediment transport was confirmed by the model results.

Refined tidal modelling of sediment transport was undertaken at Clacton and detailed modelling of wave and current sediment transport was completed at Winterton Ness. This was undertaken in parallel with the field data collection activity at these sites (see 4.4 below).

The large number of modelling results were collated into a report (Appendix 12) describing predicted sediment transport rates which forms an “atlas of synthetic data” showing the way in which sediment transport rates and patterns are altered by different levels of tidal and wave forcing. These results have been used as one of the inputs to the expert analysis by which the strategic issues have been answered. They also form a source of information that can be turned to when future specific questions are asked (e.g. what will happen to fine sand dumped from dredging operations at a specific location in a particular area of seabed?).

In addition, the local longshore sediment transport by waves and tidal currents was modelled to fill a data gap on the Holderness coastline and the results were input into the longshore sediment transport catalogue (Annex to Appendix 11).

4.4 New field data collection

To support the strategic objectives new field data was collected at three key locations in the study area (Figure 1 of this summary and Appendix 6). The sites were chosen in conjunction with the client group to fill data gaps (HR Wallingford, 2001):

- Between Happisburgh and Winterton Ness on the Norfolk coast (April 2001): Calibrated measurements of waves, currents, water depths and sediment concentrations (fines and sands) were made over a 14 day period with a number of seabed mounted instrument packages. In addition nearshore transects were completed to map out the vertical structure and tidal time variation of the coastal tidal current. Off Winterton Ness and south through the bank complex off Great Yarmouth the seabed features were mapped to determine sediment transport pathways. A sand sediment tracer study was completed at Winterton Ness itself and surface water samples were taken over a large area to characterise the background sediment concentration of fine material.

- Clacton in Essex and the adjacent Gunfleet Bank (September 2001): Calibrated measurements of waves, currents, water depths and sediment concentrations (fines and sands) were completed over a 14 day period with a number of seabed mounted instrument packages. A transect was run between the shore and the Gunfleet Bank to map out the vertical structure and tidal time variation of the coastal tidal current. The seabed features were mapped to determine sediment transport pathways. Surface water samples were taken over the nearshore area to characterise the background sediment concentration of fine material.

- The mouth of the Humber Estuary (December 2001): The seabed features were mapped to determine sediment transport pathways. Surface water samples were taken over the nearshore area to characterise the background sediment concentration of fine material and water salinity.

The process measurement results have been used to validate the computational model with which the sediment transport predictions have been made. The seabed features have been interpreted and mapped as part of the analysis of seabed sediment transport. The data collected within the study is available for use in support of subsequent studies in conjunction with the field data report (Appendix 6).

4.5 Mapping of seabed sediment transport indicators

Sediment transport features such as sandwaves and megaripples have been observed on seabed surveys made using acoustic sidescan sonar equipment since the 1960s. Once the observations are interpreted they provide good indications as to the presence (or not) and dimensions of seabed features at the time of the survey (or the last sediment transporting event). Sandwaves and megaripples are the primary features indicating sediment transport activity as they travel predominantly in the direction of the prevailing tidal flows, i.e their crests lie perpendicular to the tidal flow axis. The asymmetry in cross-section of these features can be used to provide a clear indication as to the net direction of sediment transport at the time the image was captured. Both published information from the literature and unpublished information provided through contacts with the dredging industry have been combined with the new interpreted data collected in this study to produce a comprehensive and detailed map of sediment transport indicators for the entire study area. The concentration of information is mainly within 20 km of the coastline, except off North East Norfolk in the sandbank complex and offshore of the Outer Thames Estuary. The data has been mapped with two levels of indication (Appendix 15): firstly, a net transport direction was determined for those locations where the asymmetry of seabed features could be determined with certainty; and secondly, no-net direction where the axis of transport could be determined with certainty, but the net direction could not. The latter case arises where bedforms have no clear asymmetry in cross-section but can also be obtained from the orientation of other flow parallel seabed features including sand ribbons and sand streaks, comet marks and wreck marks. The sand ribbons are low amplitude features which are oriented parallel to the predominant tidal currents, they can be seen extending over otherwise essentially immobile seabeds of gravel and clays. Sand streaks are seen at the outer extents of sand patches and indicate transport into or out of the sand patch. Comet marks and wreck marks are the pattern of erosion and deposition seen around seafloor obstacles and wrecks, once again these are oriented parallel to the main flow direction.

5. Expert assessment of sediment transport rates and pathways - addressing key strategic issues

The sediment transport knowledge, modelling, field data and interpreted seabed sediment transport indicators have all been brought together in an expert analysis of sediment transport pathways in the study area. The expert analysis has generated improved understanding and certainty to be able to address the key strategic issues A to I listed above (Section 5 and 6 of main report), and the sediment transport context of the licensed aggregate dredging areas. To convey the information to the reader the understanding has been portrayed schematically on a series of maps covering the whole of the study coastline (contained in Section 6 of the main report), e.g. as shown for the Wash on Figure 3. These maps show the "every-day" transport situation and for comparison the interpreted sediment transport situation for the extreme water level (storm surge) condition that was modelled. The causes of variability in sediment transport and timescales for sediment transport have also been discussed (Section 7 of main report).

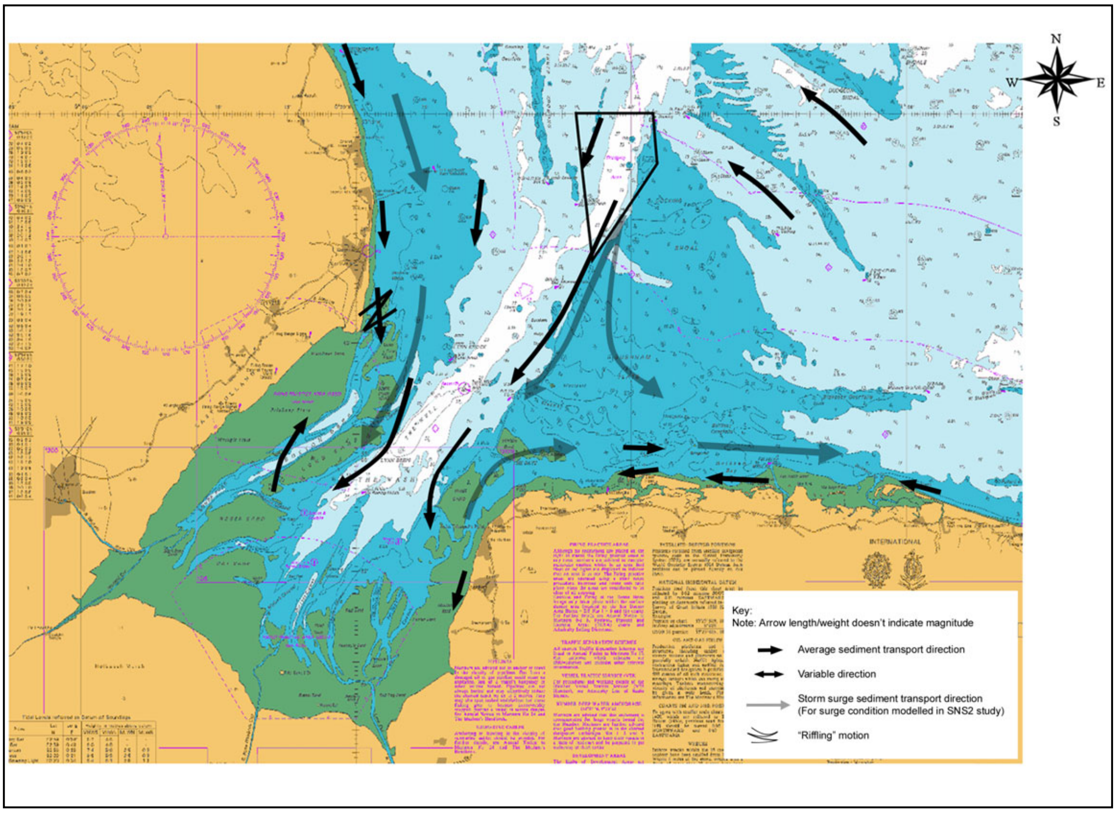

Figure 3 **Schematic sediment transport pathways for average conditions and interpreted for the extreme water level (surge), wind and wave event modelled in this study (overlain on Admiralty Chart 1408)**

6. Report Usage and Study Outcome

Section 8 of the report contains a description of how the report can be used to assess sediment transport in the study area. It also describes how the project objectives have been met, the limitations on the material presented and the links with other ongoing projects which has provided added value towards the design/sustainability of coastal/sea defence works, seabed works and the assessment of dredging activities.

7. Recommendations for further work

Finally, the findings of the study have been used in a consideration of the boundaries for SMPs and to derive recommendations for further studies and research (Section 9 of the main report) which are required to fill gaps in knowledge or data

8. References

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For **further information** about the study contact either Richard Whitehouse at HR Wallingford (Telephone: 01491 835381, Email: rjsw@hrwallingford.co.uk) or Julian Walker at Waveney District Council (Telephone: 01502 562111, Email: julian.walker@waveney.gov.uk). The field data is hosted by the Environment Agency, Anglian Region, contact Jane Rawson (Telephone: 01733 371811, Email: jane.rawson@environment-agency.gov.uk).

This Executive Summary is available from the project web site: www.sns2.org

Glossary of Sediment Transport

ACRONYMS USED IN REPORT AND APPENDICES

ACM	Acoustic Current Meter
ABS	Acoustic Backscatter Sensor – used to measure sand concentrations
ADCP	Acoustic Doppler Current Profiler
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CTD	Conductivity, Temperature and Depth (sensor for measurement of either moored or towed behind vessel, sometimes undulating through the water depth)
FSI	Falmouth Scientific Instruments
FEPA	Food and Environment Protection Act II
FTU	Formazin Turbidity Unit
GIS	Geographical Information System –e.g. MapInfo™ and ArcView™
GPS	Global Positioning System
HRW	HR Wallingford
OBS	Optical Backscatter Sensor – used to measure silts in suspension
PVD	Progressive vector diagrams
PSU	Practical Salinity Units
QTC	Questor Tangent Corporation – a seabed discrimination system produced by that company
SMP	Shoreline Management Plan
SPM	Suspended Particulate Matter
UEA	University of East Anglia

GLOSSARY

Abrasion	Friction erosion by material carried by wind and waves
Accretion	The accumulation of sedimentary material deposited by natural fluid flow processes

Glossary of Sediment Transport continued

ADCP	Acoustic Doppler Current Profiler. An oceanographic instrument for measuring the variation of current speed with time at a number of heights above the seabed. Either deployed, looking downwards, from a vessel to monitor transects across an area of interest or mounted on the seafloor (upwards looking). Can be also used to determine water column sediment concentration at the same time (through backscattered signal) given suitable analysis software and *in situ* calibration samples
Alongshore	See longshore
Alluvial deposits	Detrital material which is transported by a river and deposited. Commonly composed of sands and gravels
Amplitude	Half the peak to trough range of a wave (water wave or sedimentary wave)
Astronomical tide	The tide levels and character which would result from the gravitational effects of the earth sun and moon without any atmospheric influences
Attenuation	The loss or dissipation of wave energy, resulting in a reduction of wave height
Bathymetry	The measurement of depths of water in oceans, seas; also the information derived from such measurements
Bed	The bottom of any body of water, e.g. seabed
Bedforms	Features on the seabed (eg sand waves, ripples) resulting from the movement of sediment over it
Bedload	Sediment particles that travel near or on the bed
Bed shear stress	The way in which waves and currents transfer energy to the seabed
Boulder	A rounded rock that is greater than 256mm in diameter, larger than a cobble
Boundary conditions	Environmental conditions eg waves, currents, drifts etc used as boundary input to numerical models

Glossary of Sediment Transport continued

Clastic rocks	Rocks built up of fragments that have been produced by the processes of weathering and erosion.
Clay	A fine grained sediment with a typical grainsize of less than 0.004mm. Possesses electromagnetic properties which bind the grains together to give a bulk strength or cohesion
Cliff	A high steep face of rock
Climate change	Refers to any long-term trend in mean sea level, wave height, wind speed etc
Coast	A strip of land of indefinite length and width that extends from the seashore inland to the first major change in terrain features
Coastal currents	Those currents that flow roughly parallel to the shore and constitute a relatively uniform drift in the deeper water adjacent to the surf zone. These currents may be tidal, transient, wind driven or associated with the distribution of mass in local waters
Coastal Cell	Coastline unit within which sediment movement is self contained
Coastal forcing	The natural processes that drive coastal hydro- and morphodynamics (winds, waves, tides etc)
Coastal processes	Collective term covering the action of natural forces on the shoreline and the nearshore seabed
Coastal zone	The land-sea-air interface zone extending from the landward edge of the shoreline to the outer extent of the continental shelf
Coastline	The line that forms the boundary between the coast and the shore
Cobble	Rounded rocks, ranging in diameter from ~64-256mm
Colloid	Sediment particles that are smaller than 0.00024mm diameter
Cohesive sediment	Sediment containing a significant proportion of clays, the electromagnetic properties of which cause the particles to bind together

Glossary of Sediment Transport continued

Comet marks	Seabed features that form in the lee of structures such as wrecks. May result from sediment scour or accumulation
Contour line	A line connecting on the land or under the sea which have equal elevation. See also isobath
Coriolis	Force due to the Earth's rotation, capable of generating currents
Crest	Highest point on a beach face or bedform
Cross-shore	Perpendicular to the shoreline
Current	Flow of water generated by a variety of forcing mechanisms (eg waves, tides, wind etc)
Current meter	An instrument for measuring the velocity of a current. See also ADCP
Datum	Any position or element in relation to which, others are determined
Deep water	Water too deep for waves to be affected by the seabed (typically taken as half the wavelength)
Depth limited	Situation in which wave generation is limited by water depth
Depth	Vertical distance from still water level or other specified datum to the seabed
Detritus	Small fragments of rock that have been worn or broken away by wave or tidal current action
Direction of current	Direction toward which current is flowing
Direction of waves	Direction from which waves are coming
Direction of wind	Direction from which wind is blowing
Dispersion	The separation of waves by virtue of their differing rates of movement
Diurnal	Having a period of a tidal day 24.84 hours
Downdrift	The direction of predominant movement of littoral sediments

Glossary of Sediment Transport continued

Dredging	Excavation of the seabed, usually by mechanical methods. Most dredging is undertaken in order to obtain aggregates for the construction industry
Drift divide	location on a coastline where there is no net drift in either direction along that coastline. In some cases the gross annual drift of sediment past this position in either direction can be quite large whilst the net drift is small
Dunes	A type of bedform indicating significant sediment transport over a sandy bed
Ebb tide	Period of time during which the tidal level is falling
Erosion	Wearing away of the land or seabed by natural forces (wind, waves, currents, chemical weathering)
Event	An occurrence meeting specified conditions, e.g. damage, a threshold wave height or water level
Extreme	The value expected to be exceeded in a given (long) period of time
Facies	The sum total of features such as sedimentary rock type, mineral content, sedimentary structures, bedding characteristics, fossil content etc which characterise sediment as having been deposited in a given environment
Fathom	A measure of depth equal to 6ft (1.83m)
Fetch	Distance over which the wind acts to produce waves
Flocculation	The change which takes place when the dispersed phase of a colloid (e.g. clay particles in suspension) forms a series of discrete particles which are capable of settling out from the dispersion medium
Flood tide	The period of time when tide levels are rising
Friction factor	Factor used to represent the roughness of the seabed

Glossary of Sediment Transport continued

GIS	Geographical Information System – A system of spatially referencing information, including computer programs that acquire, store, manipulate, analyse and display spatial data
Geomorphology	The investigation of the history of geologic changes through the interpretation of topographic forms
GPS	Global Positioning System – A navigational and positioning system by which the location of a position on or above the earth can be determined by a special receiver at the point interpreting signals received simultaneously from a constellation of satellites
Graded bedding	An arrangement of particles within a single bed
Gravel	Loose, rounded fragments of rock larger than sand but smaller than cobbles. Material larger than 2 mm (Wentworth scale used in sedimentology) or 5 mm (used in dredging industry)
Headland	Hard feature, natural or artificial forming the local limit of the longshore extent of a beach
High water	Maximum level reached by the rising tide
Hydrodynamics	Deals with the motion of fluids
Incident wave	Wave moving in a landwards direction
Inshore current	Any current inside the surf zone
Inshore	Areas where waves are transformed by interactions with the seabed
Isobath	Lines connecting points of equal water depth. Seabed contours
Isopachyte	Lines connecting points on the seabed with equal depth of sediment
Joint probability	The probability of two or more things occurring together
Laminar flow	Characteristic of low fluid flow velocities and particles of sediment in the flow zones are moved by rolling or saltation

Glossary of Sediment Transport continued

Littoral	Of or pertaining to the shore
Littoral drift/littoral transport	The movement of beach material in the littoral zone by waves and currents. Includes movement parallel (along-shore) and perpendicular (cross-shore) to the shoreline
Longshore	Parallel and close to the shoreline
Longshore current	A current located in the surf zone, moving generally parallel to the shoreline that is generated by waves breaking at an angle with the shoreline
Longshore drift	The movement of sediment approximately parallel to the shoreline
Longshore transport rate	Rate of transport of sedimentary material parallel to the shore. Usually expressed in cubic metres per year
Low tide	See low water
Low water	The minimum height reached by the falling tide
Mean sea level	The average level of the sea over a period of approximately 12 months, taking account of all tidal effects but excluding surge events
Mean water level	The average level of the water over the time period for which the level is determined
Megaripples	Bedforms of wavelength = 0.6 – 10m and height = 0.1 – 1m. These features are smaller than sandwaves but larger than ripples
Metadata	Text that describes the key points relating to e.g. a particular field dataset, paper or report
Mineral	A naturally occurring inorganic crystalline solid that has a definite chemical composition and possesses characteristic physical properties
Morphodynamics	The mutual interaction and adjustment of the seafloor topography and fluid dynamics involving the motion of sediment
Mudflat	A muddy, low lying strip of ground by the shore, usually submerged by the rising tide

Glossary of Sediment Transport *continued*

Nearshore	The zone which extends from the swash zone to the position marking the start of the offshore zone (~20m)
Ness	Roughly triangular promontory of land jutting into the sea, often consisting of mobile material
Numerical modelling	Refers to the analysis of coastal processes using computational models
Offshore	The zone beyond the nearshore zone where wave induced sediment motion effectively ceases and where the influence of the seabed on wave action has become small in comparison with the effects of wind
Onshore	A direction landward from the sea
Onshore current	Any current flowing towards the shore
Onshore wind	A wind blowing landwards from the sea
Outcrop	A surface exposure of bare rock, not covered by sediment or vegetation
Particle size	In dealing with sediments and sedimentary rocks, it is necessary that precise dimensions should be applied to such terms as clay, sand etc. Numerous scales have been developed and the Wentworth scale is widely accepted as an international standard
Peak period	The wave period determined by the inverse frequency at which the wave energy spectrum reaches its maximum
Pebbles	Sedimentary material that is usually well rounded and between 4-64mm diameter
Permanent current	A current that runs continuously and is independent of the tides or other forcing mechanisms. Permanent currents include large scale ocean circulatory flows and the freshwater discharge from rivers
Permeability	The property of bulk material (sand, gravel etc) that permits movement of water through the pore spacing

Glossary of Sediment Transport *continued*

Pleistocene	An epoch of the Quaternary Period characterised by several glacial ages
Promontary	See headland
Quaternary	The youngest geological period that includes the present time
Radioactive tracers	The use of radioactive elements to track sediment movements
Recession	A continuing landward movement of the shoreline
Reflector	A surface (usually rock or a sediment layer) that strongly reflects seismic waves
Residual water level	The components of water level not attibutable to astronomical effects
Ripple	Undulation produced by fluid movement over sediments. Oscillatory currents produce symmetric ripples whereas a well defined current direction produces asymmetric ripples. The crest line of a ripple may be straight or sinuous. The characteristic features of these bedforms depend upon current velocity, particle size and the persistence of current direction. Ripples usually have low amplitudes (~ <0.1m)
Rocks	An aggregate of one or more minerals that falls into one of three categories: Igneous rock that is formed from molten material, sedimentary rock that results from the consolidation of loose sediment that has accumulated in layers and metamorphic rock that has formed from pre-existing rock as a result of heat or pressure
Saltation	A term used to describe the movement of a particle being transported that is too heavy to remain in suspension. The particle is rolled forward by the current, generates lift and rises, loses the forward momentum and settles to the bed. The process is then repeated
Sand	Sediment particles, mainly of quartz with a diameter of between 0.062mm and 2mm (Wentworth scale), or less than 5mm (dredging industry). Sand is generally classified as fine, medium or coarse

Glossary of Sediment Transport continued

Sandwaves	Large scale asymmetric bedforms with heights of up to 1/3 water depth. Sandwaves may be used to give an indication of the predominant direction of sediment transport. These features are sometimes known to migrate at speeds of several km/year
Sea-level rise	The long term trend in mean sea level
Sediment	Particulate matter derived from rock, minerals or bioclastic matter
Sediment cell	In the context of a strategic approach to coastal management, a length of coastline in which interuptions to the movement of sand or shingle along the beaches or nearshore seabed do not significantly affect beaches in the adjacent lengths of coastline
Sediment flux	The flow of sediment across the seabed
Sediment sink	A point or area at which sediment is irretrievably lost from a coastal cell or transport pathway, such as an estuary or a deep channel in the seabed
Sediment source	A point or area from which sediment arises such as an eroding cliff or river mouth
Sediment transport	the movement of a mass of sedimentary material by the forces of currents and waves. The sediment in motion can comprise fine material (silts and muds), sands and gravels. **Potential** sediment transport is the full amount of sediment that could be expected to move under a given combination of waves and currents, i.e. not supply limited
Sediment transport pathway	The routes along which net sediment movements occur
Semidiurnal	Having a period of approximately one half of a tidal day (12.4 hours). The predominating type of tide throughout the world is semidiurnal with 2 high waters and 2 low waters each day
Sheet flow	Sediment grains under high shear stress moving as a layer that extends from the bed surface to some distance below (of the order of a few cm). Grains are transported in the direction of the flow

Glossary of Sediment Transport continued

Shingle	A loose term for the coarsest beach material, a mixture of gravel, pebbles and larger material. Often well rounded and of hard rock such as chert or flint
Sidescan sonar	Survey technique which identifies seabed features based upon acoustic reflections
Significant wave height	The average height of the highest one third of the waves for a given period of time
Silt	Sediment particles with a grain size between 0.004mm and 0.062mm, i.e. coarser than clay but finer than sand
Sink	a depositional area (estuarine, coastal or offshore) into which sediment moves and finally settles out
Slack water	The state of the tidal current when its velocity is virtually zero, particularly when the reversing current changes direction
Sorting	Process of selection and separation of sediment grains according to their grain size (or grain shape, or specific gravity)
Source	an erosional area (cliffs, intertidal or subtidal) from which sediment is released for sediment transport
Spring tide	A tide that occurs at or near the time of the full or new moon and which displays the greatest positive and negative deviation from mean sea level
Stillwater level	The surface of the water if all wave and wind action were to cease
Storm surge	A rise or piling up of water against the shore, produced by strong winds blowing onshore and large atmospheric pressure gradients. For coastal flooding storm surge level is most severe when it occurs in conjunction with a high spring tide
Subsidence	Sinking or downwarping of part of the earth's surface
Surf zone	The nearshore zone along which waves become breakers as they approach the shore

Glossary of Sediment Transport continued

Surge	Changes in water level as a result of meteorological forcing (wind, high or low barometric pressure) causing a difference between the recorded water level and that predicted by harmonic analysis. The surge may be positive or negative
Suspended load	The finest sediment particles that are light enough in weight to remain lifted indefinitely above the bottom by turbulent flows
Terrigenous sediments	Land formed sediment that has been deposited on the sea floor
Threshold velocity	The minimum velocity at which the sediment on the bed becomes mobile
Tidal current	The alternating horizontal movement of water associated with the rise and fall of the tide
Tide	The periodic rise and fall of the water that results from the gravitational attraction of the moon and sun acting upon the rotating earth
Topography	The form of the features of the actual surface of the earth in a particular region considered collectively
Tracer	sedimentary material tagged in some way or coated with coloured or fluorescent paint/dye; at one time particles were tagged with radioactive material. The tagged or marked material is placed at the location of interest on the beach or seabed and the bed sediment is sampled over a suitable period of time in a systematic fashion to recover seabed samples. The samples are analysed to determine the presence/absence of tagged material, and number of grains if present. Methods exist to estimate the sediment transport rate based on the dispersion pattern and rate of dispersion of the tracer
Transgression	The invasion of a large area of land by the sea in a relatively short space of time. The reverse of regression
Trough	A long and broad submarine depression with gently sloping sides, or trough of a wave or sedimentary feature

Glossary of Sediment Transport *continued*

Unconsolidated	Sediment grains packed in a loose arrangement
Updrift	The direction opposite to that of the predominant longshore movement of nearshore sediments
Water level	The elevation of a particular point of a body of water above a specific point or surface, averaged over a given period of time
Wave climate	Average condition of the waves at a given place over a period of years, as shown by height, period, direction etc
Wave direction	The direction from which the waves are propagating
Wave height	The vertical distance between the crest and the trough
Wavelength	The horizontal distance between consecutive wave crests
Wave period	The time it takes for two successive crests (or troughs) to pass a given point
Wind current	A current created by the action of the wind on the water surface
Wind set-up	Elevation of the water level over an area caused by wind stress on the sea surface

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Appendices (included in full binder)

1. ORIGINS AND PURPOSE OF THE STUDY

Sediment movements in the southern North Sea influence the eastern English coastline by supplying or removing beach material. It is important to understand these movements thoroughly so as to improve the data on which Shoreline Management Plans (SMPs) and the assessment of dredging licence applications are based. The first step in such a process is to identify sediment sources and volumes, transport pathways and areas of deposition. Data can then be used to update current SMPs, as well as allowing a more informed assessment to be made of the influence of offshore dredging around the eastern coast of England. With a fuller understanding of sediment movements and processes it should become easier to manage beaches and coastal defences, the coastline, and sediment resources offshore in an informed fashion.

This report arises from studies carried out within Phase 2 of the Southern North Sea Sediment Transport Study (SNS2) between September 2000 and April 2002 following the programme of desk assessment, computational modelling and fieldwork outlined by the Study Team (HR Wallingford, 2001).

For the production of second generation Shoreline Management Plans along the east coast of England it was necessary to provide an improved and more detailed understanding of the large scale sediment transport patterns, and the mechanisms which govern them, as well as the details of interactions with the coastline. There was also a similar requirement with respect to assessments of licence applications for aggregate dredging.

With this in mind, a group of UK coastal local authorities and the Environment Agency joined with representatives from the dredging industry, Crown Estate and English Nature, to initiate a study of sediment movement between Flamborough Head (Yorkshire) and North Foreland (Thames Estuary). The work built on the recommendations for modelling and field data collection made in the Phase 1 report (ABP, 1996a). The Southern North Sea Sediment Transport Study was part-funded by MAFF (now DEFRA), the consultancy team was led by Dr Richard Whitehouse of HR Wallingford (HRW) and the lead authority was Great Yarmouth Borough Council.

The area of study is defined in Figure 1, lying between Flamborough Head and North Foreland with its offshore boundary situated at the median line of the North Sea which is located at the 2° 30′E longitude about 50 km east of Lowestoft. The study covered the whole stretch of coastline and seabed within these boundaries but most emphasis was placed on the 450 km stretch of coastline between Flamborough Head and Southend in Essex on the north side of the Thames Estuary.

Within the large-scale picture, the study area has many local sources and sinks of sediments, for example the North Norfolk cliffs are sources of sediment and the marshes are sinks for fine sediment. The aim of the Phase 2 study was to identify and quantify local sources and sinks of sedimentary materials as well as the sediment transport pathways between them.

The report contains:

- An appreciation of the key objectives and strategic issues associated with obtaining a better understanding of sediment transport in the area of study. The main processes transporting sediment are discussed in Appendix 2
- Information on the main work packages completed in the study
- Descriptions of the collection, analysis and interpretation of sediment transport information

- A description of the updated information database

- Information on the way in which the new data has been interpreted and integrated with existing data to improve the existing conceptual sediment transport model for the Study Area

- Appropriate maps and figures which illustrate graphically the important aspects of the study. These are presented for the whole study area and at a sufficiently detailed level to resolve the sediment transport within coastal sub-cells (see Figure 2 for current definitions).

- Results which facilitate an initial assessment of the potential influence of existing and future dredging licences (see Figure 2 for current licensed areas off the east coast of England)

The main report is supported by 15 Appendices which contain detailed information produced during the study.

Appendix 1	Review of aggregate dredging and disposal activities in the study area
Appendix 2	Summary of sediment transport processes including definition and plotting of transport rate
Appendix 3	Review of Shoreline Management Plans
Appendix 4	Summary of findings from end user consultations
Appendix 5	End user database
Appendix 6	Report on field data collected in 2001around Winterton, Clacton and the Humber
Appendix 7	Assessment of the influence of storm surges on sediment transport
Appendix 8	Summary of inputs
Appendix 9	Report on mineralogical tracers
Appendix 10	A geological background to sediment sources, pathways and sinks
Appendix 11	Report on Southern North Sea longshore sediment transport
Appendix 12	Computational modelling of sediment transport in the Southern North Sea by tide, wave and surge
Appendix 13	How do the modelling scenarios relate to reality?
Appendix 14	Summary of sediment sources and sinks
Appendix 15	Map of seabed sediment transport indicators

1.1 Objectives

The objectives of the study are outlined below in Box 1 taken from the Study Brief issued in January 2000 (GYBC, 2000).

Box 1

1. To obtain an improved understanding of the Southern North Sea sediment transport system, and its links with the eastern England coastline between Flamborough Head and the River Thames.

   To include:
   - Identification of sediment sources, transport pathways, volumes of sediment transport and areas of deposition, across the complete range of particle sizes and temporal scales
   - Identification of the location, size, variability and evidence of offshore features, and their influence on and interaction with waves and tidal current climates.
   - Provision of the information that is required for the updating of SMPs, and which enable a more informed assessment to be made of the influence of offshore dredging on the eastern coast of England.

The specific objectives, as set out in the study brief, are as follows:

2. To identify the nature and distribution of mobile and non-mobile sediments under present conditions in the Study Area.

3. To identify and quantify sediment sources, sediment transport mechanisms and pathways, and areas of sediment deposition in the offshore areas of the Study Area, for all sediment types. Particular attention is to be paid to the specific geographical areas identified in the conclusions of the Phase 1 study documents, as well as areas where information is non-existent, scant or of poor quality.

4. To identify and quantify sediment transport pathways along which sediments are exchanged between offshore areas and the western boundary of the Study Area, which comprises the coastline of eastern England, between Flamborough Head and North Foreland.

5. To examine the coast in the Study Area, to identify and quantify sediment sources, (particularly erosional sources), transport mechanisms and pathways, and location and volumes of deposition.

6. To examine the offshore boundaries of the Study Area, in order to determine possible deposition areas for sediments transported beyond the Study Area boundaries.

7. To examine the offshore boundaries of the Study Area, in order to determine possible sediment transport pathways and volumes of sediment transport across the boundaries into the Study Area.

8. To assess the need for regular reviewing and updating of the Study Area results, and suggest methodologies with budget costs were appropriate.

9. To produce a Sediment Transport Report, incorporating the outcome of all the objectives.

10. To update the Phase 1 information database, to the end of the contract, using both published and unpublished sources of information related to sediment transport in the Study Area following the Format of Data Collection and Presentation in the Study Brief.

11. To develop a bedload/suspended load transport model that provides information on both offshore and onshore sediment transport within the study area so that the effects of dredging applications on coastal processes can be adequately evaluated by those with responsibility for the coastline.

12. To assess the nature and stability of seabed features over which waves travel on their way to the coast so that changes to wave climate caused by dredging operations can be evaluated objectively.

13. To comment on the temporal scales associated with circulation of sediment within identified sediment transport routes.

1.2 Appreciation of issues

Improved knowledge of the seabed sediment transport will lead to a greater understanding of the factors controlling evolution of the coastline. The deposits of gravel, sand, and mud on and under the present-day seabed, and the movements of this sediment over it and in the waters of the North Sea, all provide an insight into the long-term evolution of the sedimentary coastlines along its boundaries.

Large areas of sediment on the floor of the North Sea, originally laid down in the Pleistocene glacial period (2 million years Before Present (BP) to 10,000 years BP), are being reworked by present day tidal and wave forcing to produce the sediment distribution that we see today (Figure 3). The regional sediment distributions broadly reflect the strength of the transport mechanisms. Generally speaking fine grade sands and muds are found in the deeper waters where tidal velocities are less strong and medium to coarse grade sands and gravels, and mixtures in varying proportions, are found in the mobile nearshore zones. However, in some offshore areas, e.g. on the Broken Bank 60 km NE of East Anglia within the North Norfolk Banks, velocities are still high enough for sediment to be mobile for 77% of the time during a spring tidal cycle.

A large volume of work has been undertaken over the last 50 years on water movements in the North Sea, sediment characteristics and behaviour, seabed morphology, and coastal and seabed evolution. However much of this work was undertaken in isolation using a range of different methods. The review work undertaken in Phase 1 of the study (ABP, 1996a) brought together much of the relevant information and catalogued it in a database. A conceptual model for bedload and suspended sediment transport was derived for the Southern North Sea based on this information (Figure 4).

Processes in the sea also dominate the evolution of the coastline. The hydrodynamics of the coastal zone are controlled by the hydrodynamics of the sea, and when these are evaluated, it is almost always assumed that the seabed is “fixed”. This assumption is normally reasonable, leading to accurate predictions of waves and tides. As a consequence, coastal managers tend not to spend much time considering the changes in the seabed or the movement of sediment over it.

However, changes in the position and shape of sandbanks have the potential to affect coastlines and hence their management. While some of these changes are beyond human control, others such as dredging and disposal of dredged material, can be planned. A greater understanding of the movements of sediment over the seabed will allow better decisions to be made about such proposed activities.

Management of the coastline, particularly beaches, requires knowledge of the losses and gains of sediment, i.e. mud, sand and gravel. Often, these losses and gains have been ascribed to interchanges of sediment between the coastline and the seabed, although the evidence for this is often poor. Understanding and if possible quantifying these exchanges is potentially important when making decisions about managing the coast and its defences. For example, reducing the losses of sediment to the seabed and avoiding disruption of an onshore supply of sediment are both helpful in maintaining beach volumes.

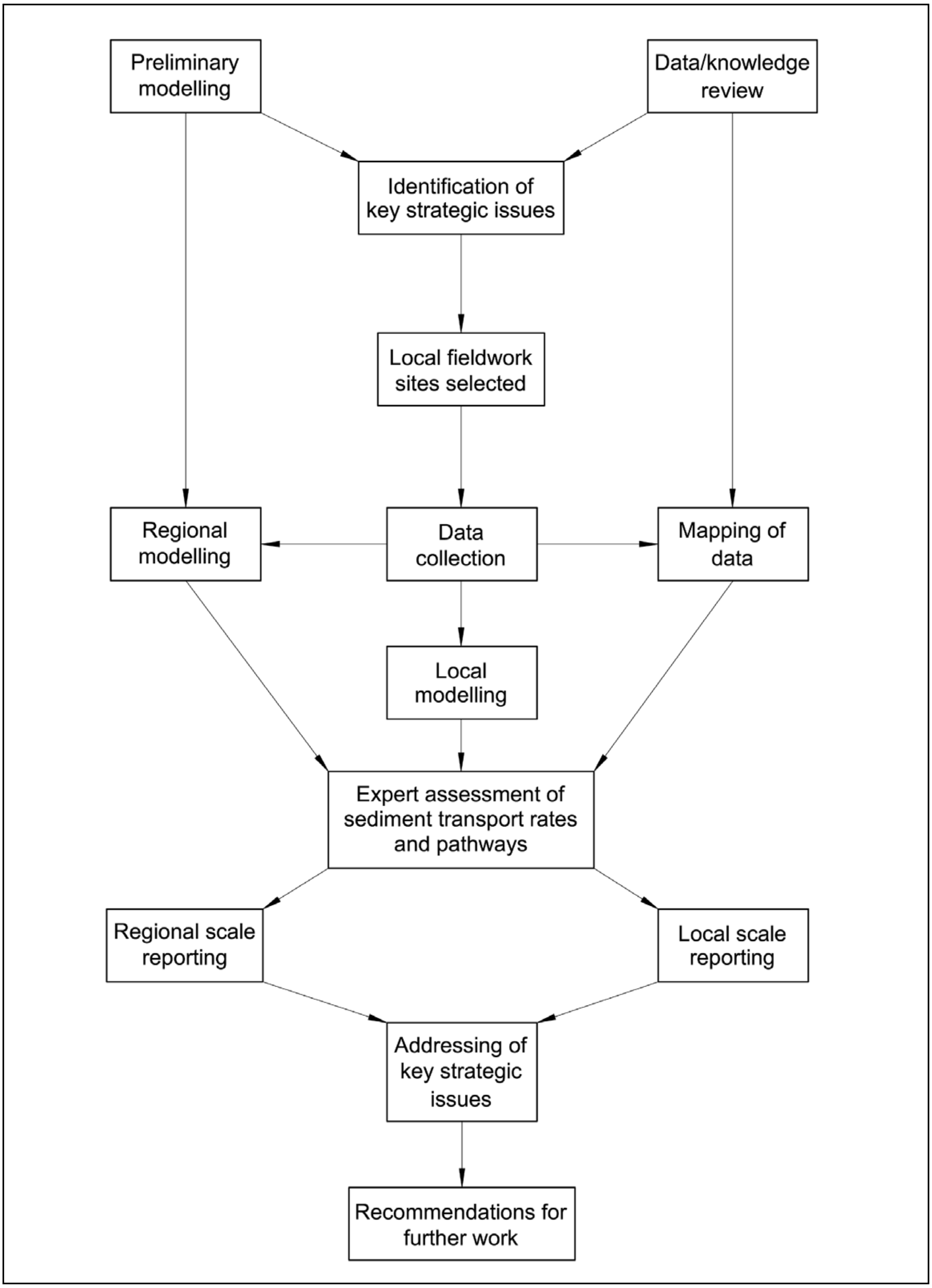
Estuarine systems and their associated saltmarshes and flats are dependent upon the supply of fine sediment transported in suspension. Removal of fine material from an estuarine system through maintenance dredging is now perceived to be a negative influence and retention of sediment within the system may be preferred. Hence the transport and fate of muds is considered in addition to the transport of non-cohesive sands and gravels.

It is also important to recognise that sediment transport on beaches and the seabed can be dominated by infrequent but extreme events. Previous research has shown that in many areas of the Southern North Sea the major contribution to annual sediment budgets arises from events with a frequency of occurrence of less than 10 times per year. Thus any appraisal of sediment fluxes must consider not only averaged conditions but also extreme storm and surge events. In addition there is increasingly strong evidence that global climates are changing. This may lead to increased sea levels, more frequent and possibly more persistent storms, and subtle changes in annually averaged wind, and hence wave directions. All of these changes could be reflected in the sediment transport regime, influencing both the frequency of transport and the residual transport direction. If management of the coast is to be sustainable it will be necessary to evaluate the sensitivity of the existing sediment transport regime to these natural changes.

This report goes on to tackle these sediment transport issues both with respect to sediment transport within the study area and also across boundaries.

1.3 Methodology

To deliver the objectives the study team planned and executed a series of interdisciplinary activities: identification of key strategic issues, knowledge capture and synthesis, computational modelling of coastal and seabed hydrodynamics and sediment transport, field data collection of hydrodynamics and sediment transport, information mapping and expert analysis and interpretation. A flow chart of these activities is presented in the Figure below.



1.4 Report structure

The structure of the report is as follows:

Section 2 summarises the process by which the strategic issues were identified and summarises them. Section 3 presents the technical methodology and summarises the key points arising from the various activities undertaken during the study. Section 4 describes the sediment transport regime at the scale of the whole study area using the results from the study supported with published information. Section 5 describes the approach used to address the strategic issues. Section 6 presents a discussion of the detailed results from the study at the local level and through this the key strategic issues are addressed. Section 7 covers matters relating to variability and timescales for sediment transport. Section 8 provides guidance on how to use the report and assesses how well the study has met the objectives (Section 1). Section 9 provides information on recommendations and research needs, and Section 10 lists the acknowledgements.

2. IDENTIFICATION OF ISSUES

A review and consultation process was undertaken to identify the main issues of concern with respect to sediment transport along the study coastline. The information obtained from consultations with coastal managers, and other interested parties, was collated to determine the locations along the study coastline at which key issues needed to be addressed. This need was balanced with the information contained in the eight existing Shoreline Management Plans for this stretch of coastline. The outcome was the identification of key strategic issues with specific questions regarding sediment transport that needed to be addressed to form a coherent picture of sediment transport along the study coastline. Other associated issues were also identified at the strategy and local level, as well as matters of public perception. All these issues provided additional focus with respect to delivering the objectives of the study.

2.1 Matching the research to address the key strategic issues

The eight existing SMPs (Shoreline Management Plans) for the study coastline were reviewed and consultation was undertaken with coastal managers from local authorities from along the whole study coastline, the Environment Agency and English Nature. The background to dredging for aggregates, maintenance and capital dredging, and dumping operations was also reviewed. All this information was synthesised in the Inception Report (HR Wallingford, 2001) but is presented in this report in a revised form.

The following SMPs were reviewed (see Figure 2 for sub-cell extents) with the date of publication being given in brackets.

Sub-cell	Area
2a/2b	Humber Estuaries Coastal Authorities Group SMP: Subcell 2a/2b Flamborough Head to Donna Nook (April 1998)
2c	Lincolnshire SMP: Donna Nook to Gibraltar Point (December 1996)
2d	The Wash SMP: Gibraltar Point to Snettisham (December 1998)
3a	North Norfolk SMP: Sheringham to Snettisham Scalp (July 1996)
3b	Sheringham to Lowestoft SMP, cell 3b (May 1996)
3c	Lowestoft to Harwich SMP, cell 3c (May 1998)
3d	Essex SMP Harwich to Mardyke (April 1998)
4a/4b	North Kent Coast, Isle of Grain to Dover Harbour (August 1996)

This part of the study enabled:

- Identification of how the understanding and interpretation of sediment movement and coastal processes had been developed, and established the degree of confidence that can be placed on information such as sediment drift rates or data on sediment sources.

- Identification of where further information relating to the broader sediment regime of the Southern North Sea can best assist in future development of shoreline management.

The review, unlike other reviews of SMPs, was strictly focussed on the interpretation of sediment movement. It did not attempt to make any assessment of the shoreline management policy nor did it consider environmental or use aspects.

The review has been summarised in the sheets contained in Appendix 3. In these sheets the results were set out in the following manner:

Section 1: Base Data and Analysis
This section provides a précis of key information and sources from which the SMP was developed. In particular, consideration is given (where appropriate) to wave, tide and tidal flow data; sediment transport analysis, erosion and accretion rates; and finally geomorphology. The basis for the SMP analysis is considered and the assumptions made identified.

Section 2: Coherence
This section in part provides a critique of the SMP but, as important, also considers the coherence of the data sets and of the overall pattern of sediment movement. This section considers the consistency of results between SMPs and between their interpretation and that provided by Phase 1 of SNSSTS and identifies upon what issues the coherence of the SMP interpretation relies.

Section 3: Critical points
This final section discusses specific issues or assumptions that are critical to the development and usefulness of the SMP.

2.1.1 Overview of SMPs

It was found that the quality of information varied from SMP to SMP, as did the focus given to different aspects considered in the SMPs.

At the northern extent of the study area (Holderness) the main focus was addressing the drift along the shore, coupled with producing a good understanding of the shoreline processes. The links into the broader offshore pattern of sediment movement were stated to occur primarily at the north and south boundaries of the area; i.e. the feed into the Southern North Sea at Flamborough and the links between the southern limits of Holderness and the shores to the south of the Humber.

A similar approach had been developed for the Lincolnshire shoreline but in this case critical factors were the supply of material from the north (the link with the northern SMP) and the feed of material to the south into the Wash.

In the Wash SMP, a considerable feed of sediment into the Wash embayment was identified. While this provides a consistency to the processes at work within the Wash, there was clearly a need to define the potential source of the sediment input.

Along the North Norfolk shore, the SMP had been developed primarily on the basis of geomorphological assessment of discrete sections of the shore. This was done to provide, in effect, an inferred regime along the whole frontage. While it was felt that SNS2 may not be able to provide more detailed assessment of the foreshore process, it was considered feasible to provide a better overall context, within which the existing information in the SMP could be assessed.

Further south the Norfolk SMP and the Suffolk SMP both developed an understanding of the shore from a greater consideration of the linkage to the nearshore bank systems. A plausible argument was, therefore, put forward for explaining the apparent inconsistency in the quantified linear sediment budgets, through the loss or gain to or from the nearshore bank system. Quantification of the nearshore processes was limited and as such, this limited the confidence in the shoreline rates of drift. These SMPs, in acknowledging the link with the nearshore regime, could not with confidence define fully the zones of influence along the shore. The SNS2 study is in a position to provide this better understanding of the inter-connection between various bank systems.

There was considerable uncertainty associated with the interactions between the southern end of the Suffolk SMP and the Essex SMP. Both SMPs recognised the link and had adopted a fuzzy boundary. However, the linkages were inconsistent between SMPs.

The Essex SMP, and to a degree the Kent SMP, focussed far more on the broader offshore processes out of necessity, in that they are, in effect, working within the silt laden estuary system of the Thames. Comparisons between SMPs, and with the findings of Phase 1 of the Southern North Sea Sediment Transport Study (SNSSTS; ABP, 1996a) highlighted a significant difference in the baseline assessment of residual tidal flows and as a consequence in the assessment of suspended sediment movement. This was therefore a key aspect for further assessment in the present study.

The review sheets presented in Appendix 3 to this report contain more details.

2.2 End-User consultation

Contact was made with all Local Authority Coastal Managers, representatives of the Environment Agency and English Nature, with responsibility for the coastline between Flamborough Head and North Foreland. Consultation was focussed on those directly responsible for management of the coast and, as such, those most able to identify the issues that would need to be addressed by the project.

It was agreed that, given the possible range and variation in interests and concerns, meetings with consultees would be preferred to obtaining views through a more generic questionnaire. This, it was felt, complied best with the intent of the exercise.

Table 1 provides a list of consultees and identifies those with whom meetings were held. Certain Local Authorities were confident that discussions with the Environment Agency would cover their issues of concern.

In addition to those responsible for the management of interests along the east coast of the Southern North Sea, the importance of involving those on the North Kent Shoreline was identified. Although only Canterbury City Council were, in the end, interviewed, this was supplemented by a meeting with Brian D'Olier, as a recognised expert for this area and as advisor to many of the Kent authorities.

The aim of these meetings was, primarily, to identify from the coastal managers where they felt uncomfortable with the present understanding of the Southern North Sea sediment pathways, or where they felt that answers to specific strategic questions held back their efforts to correctly manage their responsibilities. Accordingly, the meetings were conducted in a loosely structured manner, with discussion very largely being driven by the consultee.

The interviews tended to be wide-ranging covering issues from a local to strategic level. The benefits of the meetings exceeded expectations and have provided:

- Identification of strategic concerns.
- An excellent background understanding at the local level.
- Identification of other available information and detailed studies.
- A better mutual understanding of the intent of the study.

The consultees are thanked for their time in contributing to improving the focus of the study.

2.2.1 Intent of the study

Underlying all consultation responses was the concern of those involved that the study should produce answers that helped them. There was a general concern that the study should not get "bogged down" at too detailed a level as this, it was felt, would miss the opportunity to provide the overview of how the shoreline interrelates with the offshore. In addition, there was a recognised need to develop a coherent pattern of the sediment pathways across the offshore area.

Having identified this broad intent, it was also generally remarked that the overall picture of sediment transport generated through the study must be consistent with the local understanding of the shoreline behaviour. This overall picture should provide the context for understanding sediment transport behaviour at the local level.

In addition, some consultees hoped that the study, while not specifically setting out to do so, would help define or confirm generic process understanding through some of the detailed measurement and modelling work that was being undertaken.

It was also seen as important that the study should address issues and perceptions. As much as anything, several end users hoped the study would enable them to give more definitive answers on questions regarding issues such as: the significance of dredging or the importance of their coast in relation to other frontages.

It was generally agreed that, while improving the quantification of transport rates was considered important, the essential result was the definition of the basic sediment pathways. Furthermore, from this, it was seen as important that the significance, in terms of the relative magnitude of inputs, of movement along and outputs from these pathways, was defined with respect to the residual volumes of material. This came across in terms of a need to look at cumulative effects as well as the relative importance of shore-linked sediment tributaries.

2.2.2 Classification of issues

As identified above there was an acceptance, indeed a requirement, that the study should not set out to specifically address local issues. The primary benefit of the study was perceived to be provision of the broader picture, the context for more detailed examination or understanding of the coast. In considering the responses and in sifting through the wealth of knowledge presented during the consultation, it was important to make clear at what level various concerns or issues were felt to reside.

In doing this, three basic classifications were developed. As far as is appropriate these have been related to coastal process subcells, coastal process unit and coastal management units although this should not be taken as the fundamental criterion.

The three classifications chosen were:

Strategic issue:
This is at the scale of, or crosses, the boundary of a coastal process cell or sub-cell. It describes a concern relating to a fundamental uncertainty in the transfer between inshore and offshore: the likely feed to or from a larger pattern of sediment movement offshore (this would generally be outside the typical linear focus of an SMP). The uncertainty may result in a precautionary objection to activities beyond an administrative boundary. Such issues should receive full consideration within the present study.

Strategy level issue:
This is typically such that the effect or influence is contained within a coastal process unit, influencing local decision making but still generally outside the typical linear focus of an SMP. It may be fundamentally important to the development of a coastal strategy but is not significant at an SMP level. The present study should assist in defining the boundaries for such issues but may not go into the detailed processes.

Local issue:
This relates to a single issue or concern, important at a management unit level, and is likely to be dealt with within the linear focus of the SMP. The present study must recognise the existence of such issues and produce outputs, which are compatible with the local processes and provide a context within which the local issue is examined.

It is, however, recognised that until an issue is examined in detail it may remain uncertain as to what degree the local issue impacts at the strategic level. However, in providing a coherent framework of sediment transport knowledge the study may allow clarification of such uncertainties.

Information and comment from the consultees were classified under two other headings where they did not fall comfortably within the three significance levels described above.

Public perception:
This identifies issues not directly relating to the movement of sediment but rather to a broader understanding or lack of understanding. Where possible these issues need to be addressed by the findings of the study. Issues associated with the influence of dredging typically fall within this category.

Further Information:
Information on sources of data, previous or on-going strategy studies or research.

The reports of the consultee meetings are presented in Appendix 4, with issues classified under the above headings. **A summary of the strategic issues** is provided later in Section 6 of this report where answers to each issue are provided. The reader may move straight to Section 6 where the issues are discussed in a stand-alone fashion.

More details of the work successfully completed in the study are given in the Section 3 of the report. Section 4 provides an overview of sediment transport in the southern North Sea, and Section 6 presents information at the level of the coastal process cells and sub-cells.

2.3 Listing of strategic issues

The strategic issues were encompassed in the following headings:

- Issue A – Northern Boundary
- Issue B – Role of Holderness
- Issue C – The role of the Wash
- Issue D – Nearshore banks
- Issue E – North Norfolk drift divide
- Issue F – Sediment circulation Cromer to Benacre Ness
- Issue G – The role of the Sizewell-Dunwich Banks
- Issue H – Suffolk Coastline
- Issue I – Clacton
- Issue J – North Kent coast and nearshore
- Issue K – Thames Estuary

These are addressed later in the report.

2.3.1 Licensed dredging of aggregate from the seabed

A similar approach was taken to seabed disposal sites and licensed aggregate dredging considerations as they potentially affect the East Coast of England. An analysis of reports produced for individual licence applications, of existing data regarding the seabed and its changes, and the possible effects that might result from the dredging of the offshore licensed areas has been undertaken.

The accumulative and related effects of this sediment loss and consequent release of screened out material to redeposit on the seabed within the nearshore sediment budget have been considered (see Appendix 1). The work involved:

- Direct consultation with the dredging companies and harbour authorities as appropriate
- Examining the CESTATS data on the internet (Crown Estate web site http://www.crownestate.co.uk/estates/marine/)
- Preparing a statement on the varying factors that affect sediment extraction from the Southern North Sea considering the inter-relationship between seabed resource areas, adjacent areas of seabed and the coastline relating to physical connections and sediment pathways

Dredging of the seabed takes place usually for one of two reasons, firstly, for the production of sand and gravel for use by the building industry and secondly for the creation or maintenance of shipping channels and other marine construction works. Commercial dredging for sand and gravel off the eastern coast of England between Flamborough Head and North Kent is concentrated in currently licensed areas shown in Figure 2. Dredging in the licensed areas off Great Yarmouth (mainly lying seawards of the coastline between Caister Ness and Lowestoft) during 1999 resulted in the extraction of over 9 million tonnes of sand and gravel. This region therefore contributed almost 50% of the total tonnage dredged from around the UK coastline in 1999 (about 20 million tonnes in total).

Dredging activity is closely and accurately monitored by the Crown Estate. Until about 1930, aggregate extraction was largely confined to the sheltered waters of estuaries, and typically carried out using cranes mounted on pontoons. More recently, dredgers have been equipped with centrifugal pumps. From about 1960 onwards, dredgers that worked “at anchor” excavating a relatively deep but localised depression in the seafloor have by and large been replaced by “trailer suction” dredgers that excavate long, narrow and shallow “furrows” in a single pass over the seabed. This latter type of vessel was developed for navigational dredging, e.g. removing sand that accumulates within an approach channel to a harbour, and is used throughout the world for this purpose. Every vessel with a Crown Estate licence is fitted with an Electronic Monitoring System, which automatically records the date, time and position of all dredging activity.

A full review of the study of dredging and the assessment of cumulative effects was included in the Inception Report (HR Wallingford, 2001). This has been updated and the updated version is included in Appendix 1 of this report. It also includes a review of the potential effects on the seabed and coastline of licensed aggregate dredging. The various possible effects are all considered in a modern-day environmental assessment of any proposed marine aggregate dredging (see CIRIA, 1998).

The position of licensed aggregate dredging areas relative to existing sediment transport pathways has been assessed under the heading of the Strategic Issues within each of the local areas discussed in Section 6.

3. TECHNICAL METHODOLOGY

This section of the report summarises the various activities completed during the study. A large amount of existing field data and sediment transport knowledge was reviewed and synthesised. The source data of this information was added to the Southern North Sea Sediment Transport Study end-user database, of which an extended version based on web browser technology has been delivered as part of the study. A computational model was calibrated and validated and then used to make predictions of sand and gravel transport in the study area under tidal conditions, with waves and wind, and an extreme storm surge condition. These results have been presented at a detailed level for local areas of coastline throughout the study area. Refined modelling was undertaken at Winterton Ness and the nearshore area off Clacton. The "atlas" of predicted model results for different grades of sand and forcing conditions forms a useful reference set of synthetic data. The available information on predicted net annual longshore sediment transport rates was catalogued and mapped. New field data for flows, waves and sediment transport has been collected at Happisburgh and Winterton Ness, Clacton and in the mouth of the Humber Estuary. All the data has been synthesised and mapped for expert assessment of sediment transport pathways.

3.1 Introduction

The project methodology was summarised in Section 1.3 and here more details are given of the technical activities completed during the study.

3.2 Using existing data

A large volume of relevant knowledge and archived data was brought to the study which has proven valuable in delivering the objectives. The information from the Phase 1 study (ABP, 1996a – see Figure 4) and other relevant studies such as the MAFF funded "Sandbanks" and "Spits and Nesses" projects were considered.

The Holocene (last 10,000 years) evolution of the Southern North Sea sedimentary basin and coastline of the East Coast of England was assessed. This is important because it provides the legacy for the present-day sedimentary regimes of the Southern North Sea and the shoreline. The analysis of existing and pertinent data for the relationships between Pleistocene geology/Holocene sediments and geomorphological units was undertaken (see Appendix 10). The genesis and relationship with existing shoreline sediments was established. The presence of relatively unconsolidated "bedrock" at sea bed and its contribution to sediment flux has been recognised.

The range of sediment sources, both offshore and onshore has been identified, along with sediment sinks within the study area, and the sediment pathways between them evaluated. Where appropriate these results were assessed in light of the available remote sensing/satellite imaging data and published results of the NERC funded North Sea Programme.

The situation at the southern boundary of the study area (North Foreland) had been identified as an area of uncertainty. It was examined by making a digest of existing data on the pathways between the Thames Estuary and The Goodwin Sands/ Brake Sands/ South Falls.

The large volume of archived field data which was not available to the Phase 1 study was used both directly and in combination with the preliminary computational modelling referred to below (Section 3.4.1):

- The wide distribution of current meter locations within the central southern North Sea allowed comparison of measured residual currents with predicted currents from numerical models.

- Patterns of surface and near-bed suspended loads were established.

- Time-series of near-bed suspended sediment concentrations were compared with those predicted for key sites.

The Environment Agency (Anglian Region) undertakes a bi-annual survey of beach profiles on a one-kilometre spacing. These data were made available to the project. In addition aerial photographs such as those provided by Waveney District Council, the Environment Agency and other members of ACAG and HECAG were useful in examining the present-day situation at the shoreline.

The seabed facies data between Flamborough Head and the Deben estuary in Suffolk were made available to the study by the British Geological Survey (see Figures 5a and 5b). These provide important information on the presence of sedimentary bedforms which can be analysed to indicate the mobility of seabed sediments (mainly sands). Examples of the types of features seen on sidescan records collected during the present study are shown in Figure 6. The sandwaves and megaripples are usually indicative of bedload transport of material over the seabed with the predominant transport usually taking place perpendicular to the crest lines of the features. Bedforms with an asymmetry of cross-section can be used to infer a net transport direction and the time of the survey. This is because material transported along the seabed moves up the less steep flank of the bedform and passes over the crest to partially avalanche down the steeper downstream facing slope. Bedforms without an asymmetry can be used to infer an axis of transport but not a net direction. The linear erosion patterns formed by tidal scour marks and erosion-deposition pattern around wrecks (wreck marks), as well as patterns around any other seabed obstacle (comet marks), can be used to infer an axis of transport. All these features tell the observer about the transport axis and/or direction but not about the transport rate of sediment.

This bed data was supplemented by unpublished material available to the study team, previously published material – including the survey corridors completed as part of the Anglian Sea Defence Management Study – and the results from aggregate prospecting surveys. The data from these surveys were made available to the study by members of BMAPA (British Marine Aggregate Producers Association). With all this data available it was possible to construct a comprehensive map of sediment transport indicators for the whole nearshore zone between Flamborough Head and the Thames Estuary (Figure 7).

It should be noted here that the dredging companies provided access to their prospecting surveys and hence some of the licensed areas (Figure 8) may appear to have more sediment transport indicators than the surrounding area. This does not necessarily imply the adjacent areas of seabed behave in different ways. The indicators and the model results described later in this report provide a good baseline assessment of the sediment mobility in these areas but does not preclude the need for detailed studies as are currently undertaken.

3.3 Information collation and the sediment transport database

The study team converted the existing database to a recognised metadata format for data storage and modified it for use within a web browser (Internet Explorer 5.5). A front end display is accessed through the web browser for data querying as this represented the most robust and versatile way forward for the database. Access to the database therefore only requires a suitable web-browser rather than having to install a database application.

The study team has produced a working database using this methodology (Appendix 5) and additional entries have been made as listed in Appendix 5. The database has been circulated on CD-ROM to the Client Study Partners and is used as follows:

3.3.1 Using the Database

Getting Started

To search the database it is intended to operate from the version installed on CD ROM by taking the following steps:

- To access the files from CD, from the top **File** menu of your web browser (Internet Explorer 5.5[1]) go to '**Open…**' and on the Open dialogue box click **'Browse…'**. You can then easily navigate to your CD drive.
- Opening the folder should reveal the file ***SNS-DATABASEV1.5.HTML***.
- Click the ***Open*** button and then ***OK***. The database will then load in your browser. You can save this address as a 'favourite' like any usual web page for future opening.

Making a Search

The following steps are taken to define and operate the searching of the database:

- To search for a particular record you need to first enter the text string in the "Enter Text" box. Wild cards are implicit in the search, so searching for 'white' will return records containing *Whitehouse, Whitehead, whitecap, grey-white*. If case sensitivity was de-selected only *whitecap* and *grey-white* would be returned.
- Enter the text to search for and click the green 'Find' button to search the database.
- Results will be shown. Entering the text '*BP*' and searching '*Identification only*' will return three records. The search can be modified by the use of boolean operators such as AND and OR, together with their negatives NAND and NOR.
- In addition the searching can be made case sensitive to return proper nouns etc. So it is possible to conduct a search of the type:

Find a record where {Keywords = 'wave'} and {author/title = 'Soulsby'}

Find a record where {Metadata = 'HR Wallingford'} and {Identification = 'currents'}

Viewing, printing and copying/pasting records

From the record summary you can click on the summary to display more details. The details are divided into six areas:

- Identification, Quality, Spatial, Attributes, Distribution and Metadata.

These can be clicked to reveal this information. To return to the search summary hit the 'Find' button again or the link at the bottom of each page.

Selecting {Metadata = 'HR Wallingford'} is a useful way of returning all records input to the database in SNS2. Selecting {Metadata = 'ABP'} will return all records from SNS1.

The records can be printed using the 'Print' command in the IE5 'File' menu like any normal web page.

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[1] Technical specification:
Whatever web browser is used it will need to be capable of understanding the extensible Markup Language (XML) transformation language XSLT, in the current study this was achieved using Internet Explorer 5.5 with the Microsoft MSXML3 parser installed. The latest version of Internet Explorer (Version 6.0) has full support for XSLT. This database is encoded in XML and can be queried via an HTML interface.

The display can also be cut and pasted from the screen into Microsoft Word if desired. To achieve this use the mouse to place the cursor over the text of interest and press the left button to locate the page of information to be copied. Next select 'Select all' from the 'Edit' menu on the toolbar, this should highlight the entire text which can then be copied 'Edit' menu, select 'Copy' and pasted into the Word document using the 'Paste' function under the 'Edit' menu.

3.4 Overview of the modelling studies of sediment transport by tides, waves, wind and surge

3.4.1 Introduction

A computational model for tidal, wave and sediment transport processes was applied during the SNS2 study. The TELEMAC 2DH model, modelling in the two horizontal dimensions, was used. This is based on solving mathematical formulae for the depth-averaged tidal flow, including the influence of wave processes and wind stress on the sea surface. In the offshore areas, the direction of wave propagation is not crucial to the predictions of transport but in shallow areas, e.g. at the coastline, breaking waves which have arrived obliquely at the coastline induce a longshore current. This process can also be reproduced by the TELEMAC model if required.

The TELEMAC finite element model was developed by LNH-EDF of France and has been used at HR Wallingford for a number of years and in many comparable applications. TELEMAC has the significant benefit of allowing fine model resolution in specified areas, which allows a large area to be simulated as well as good representation of the flow field in complex areas. This capability has the added advantage of optimising the computational effort in the areas of interest.

It is therefore appropriate for use over the whole study area which has an irregular coastline and irregular seabed. The model is driven at the boundaries with information on the tidal constituents and the set of equations is solved to determine the way in which the flow speed and direction varies at every mesh point within the model domain.

Sand transport was simulated using the HR Wallingford SANDFLOW model, which is a non-equilibrium finite element sediment transport that simulates the total load (suspended and bedload), with input flows from TELEMAC, and the specified wave conditions. The model uses the Soulsby-Van Rijn equation for predicting the total sediment transport rate in currents and waves (Soulsby, 1997). This equation can predict the sediment transport due to currents and also with the effect of wave stirring of bed sediments, which serves to enhance the tide alone transport rate. It includes a term for the threshold of sediment motion below which sediment is not mobilised. To represent the action of waves a wave height and period can be specified over the model domain. It has been verified against laboratory and field data for sediment transport of sands and gravels. It has also been validated with measurements of storm induced sediment transport in the Southern North Sea by Williams and Rose (2001).

For the coarser gravels simulated, SANDFLOW was modified to represent the bedload fraction only. Although SANDFLOW has the capability of masking discrete areas of the seabed with deposits of the grain size for simulation (with other areas bare of sediment) all model simulations were performed assuming an abundant supply of material over the entire domain.

Output from SANDFLOW gives the sediment flux patterns throughout the period simulated (typically an individual tidal cycle), and the net residual transport over this period. This net residual is the field that has been analysed in detail in this report, in order to focus on the longer-term transport pathways rather than intra-tidal detail.

A number of existing 2DH depth averaged, computational models of the Southern North Sea were re-run for tidal conditions and preliminary results for flows and sediment transport obtained (HR Wallingford, 2001). These previous models had in the main been used to focus on a particular area rather than the whole sea. The model predictions of flows were checked against current meter data from the CEFAS archive (HR Wallingford, 2001). Results from the 2D and 3D (Odd and Cooper, 1992) models were compared and found to be similar in the study area.

Taken as a whole the models were able to reproduce most of the features of the flow in the southern North Sea. To improve the model the following steps were identified:

- The model mesh should be modified to resolve the offshore banks
- The model mesh should be fine enough to resolve deep channels such as in the Wash

The preliminary model results presented in HR Wallingford (2001) were used to support the assessment of fieldwork sites.

3.4.2 Modelling scenarios

The computational model studies were designed to provide complementary information to the project over the whole study area including the key sites at which fieldwork was completed. The strength of using a computational model is that it allows the various key processes producing sediment transport to be represented across the whole study area, a range of scenarios to be implemented, and the sensitivity of the sediment transport patterns to be determined. In this way the modelling studies were an intrinsic part of the overall study.

Therefore the computational modelling was undertaken at both the regional scale and also at a local scale for the selected areas of Winterton Ness and Clacton/Gunfleet. For the purposes of this report, the results from the regional modelling only are presented both for the whole study area and for sub-areas so that the more detailed distribution of sediment transport can be seen. The detail of the local area modelling around Winterton Ness and Clacton/Gunfleet Sand is reported separately (see Appendix 12).

The modelling utilised the HR Wallingford Southern North Sea model which extended from north of Flamborough Head in the North Sea to Plymouth in the English Channel (see inset in Figure 9). Siting the southern boundary this far away from the study area enabled good resolution of the tidal propagation through the Straits of Dover, and also simplified the boundary specifications for driving the model. The model grid was resolved locally to provide greater resolution at the coastline and over deeps and banks. The model bathymetry is shown in Figure 9 and it can be seen that a good representation of the study area is obtained including the banks and deeps.

The regional flow model was run by supplying a time history of water levels along the two open boundaries and imposing a surface wind stress when required. The water levels were determined either from a harmonic analysis using published information on harmonic constituents, or in the case of the surge tide simulation, from a synthesised time history of water levels at strategic points along each boundary. The flow model was calibrated against synthesised tide curves based on published tidal harmonics for stations down the coast, and against current measurements and information presented on tidal charts (tidal diamonds). This calibration exercise has been presented in a separate modelling report (Appendix 12).

The model performance was validated against the field data collected in the study.

In order to assess the influence of waves on the magnitude and patterns of sediment transport, a wave height and period was specified over the model domain (with depth-limiting of the wave height if necessary). From this the main wave contribution of the stirring effect due to the wave orbital velocity at the seabed was calculated. The effects of wave breaking were not represented in the regional modelling, but were included in the modelling at Winterton Ness referred to above.

Sediment transport was simulated for a variety of conditions summarised in the table below.

Sediment grain size (mm)	Hydrodynamic condition						
	Neaps	Springs					Surge
	calm	calm	1m, 5s waves	3m, 6s waves	3m, 10s waves	5m, 10s waves	5m, 10s waves
0.1	✓	✓	✓	✓	✓	✓	✓
0.4		✓					
2.0		✓					✓

3.4.3 How do the modelling scenarios relate to reality?

This section is reproduced in full from Appendix 13.

Sediment transport in coastal waters depends primarily on the strength of the currents and the oscillatory velocities at the seabed produced by waves. The waves stir up the sediment (aided by the current), which is then transported by the current. The pattern of currents is produced by a combination of forcing by tides, winds and waves. In the Southern North Sea the tides are the dominant factor in generating currents, but wind and wave forcing cannot be ignored. This is especially true when considering the long-term net sediment transport, since in many areas the tidal currents are approximately symmetrical. Exactly symmetrical flood and ebb half-cycles would yield zero net sediment transport, so it is the departures from symmetry of the tidal currents, and the bias in wind- and wave-driven currents, that are important in determining the long-term sediment transport paths.

Taken over time-scales of decades, the sediment transport paths are the resultant of a large number of combinations of tide, wind and waves. Thus a representative selection of scenarios has been modelled in this study. The mean transport could be determined by taking a weighted mean of the individual scenarios, in which the weighting factor is the proportion of total time occupied by each scenario. An approximate indication of the time occupied by each scenario is given below.

Mean Spring Tide:
Spring tides occur every 14.8 days on average. The pattern of peak sediment transport rates depends on the degree of tidal asymmetry, with their directions and magnitudes determined by the strongest current (flood or ebb).

On the coastline of the study area, the Mean Spring tidal range varies from 5.7 m at Spurn Head, through 1.9 m at Lowestoft, to 3.8 m at Walton-on-the-Naze. However, individual spring ranges vary considerably about these values. Taking all the 24 spring tides in the year 2000 (for example), at Spurn Head three spring tides had a range as small as 5.0 m, and two as large as 6.9 m, compared with the mean of 5.7 m.

It is implicit in the scenario "(Calm) Mean Spring Tide" that wave effects are negligible. If we take this to mean that the significant wave height H_s is less than 0.5 m, then long-term wave records at the Dowsing Light Vessel (Draper, 1991) (towards the centre of the study coastline), show that $H_s < 0.5$ m for 13% of the time.

Mean Neap Tide:
Neap tides also occur every 14.8 days on average. The Mean Neap Tide range in elevation varies along the study coastline from 2.8m at Spurn Head, through 1.1 m at Lowestoft, to 2.3 m at Walton-on-the-Naze.

The Mean Neap range is thus between about 50% and 60% of the Mean Spring range on this coastline. The peak current speeds on Mean Neap tides are also much smaller than on Mean Spring tides (typically between 50% and 60%). The sediment transport rate varies strongly with current, typically proportional to $U(U-U_{cr})^{2.4}$ (Soulsby, 1997), where U is the current speed, and U_{cr} is the threshold current speed below which sediment does not move. This means that for many locations the sediment transported on neap tides is considerably less than that which occurs on spring tides.

Mean Spring Tide plus Wave Stirring:
The addition of waves to a current greatly enhances the sediment transport rate, provided that the water is sufficiently shallow that the wave-induced oscillatory velocities penetrate to the seabed. The effect of the waves increases with wave height and wave period, and decreases with water depth. Waves can cause sediment to be transported by a current whose speed is less than the threshold value U_{cr}, due to their stirring effect. At current speeds slightly above threshold the waves can enhance the sediment transport rate by as much as 100 times. For larger current speeds the wave enhancement factor reduces, but can still be a factor of 10 for $U_{cr} = 1.0\ ms^{-1}$.

The modelling study took wave inputs of significant heights (H_s) and mean periods (T_m) of: 5 m and 10 s; 3 m and 10 s; 3 m and 6 s; 1 m and 5 s. The proportions of the time corresponding to these cases can be obtained from the long series of wave records at Dowsing Light Vessel (Draper, 1991). Dividing the waves into classes yields:

Class	**Wave height H_s (m)**	**Wave period T_m (s)**	**Occurrence (% of time)**
1	$0 < H_s < 0.5$ m	All periods	13%
2	$0.5\text{ m} < H_s < 2$ m	All periods	70%
3	$2\text{ m} < H_s < 4$ m	$T_m < 8$ s	15%
4	$2\text{ m} < H_s < 4$ m	$T_m > 8$ s	0.8%
5	$H_s > 4$ m	all periods	1.2%

Thus:

- Class 2, represented by $H_s = 1$ m and $T_m = 5$ s occurs for much the largest proportion of the time, but has relatively little effect on the sediment transport.
- Class 3, represented by $H_s = 3$ m and $T_m = 6$ s, occurs for a significant fraction of the time and also has a significant enhancement effect on the sediment transport.
- Classes 4 and 5 both have a large effect on the sediment transport, but occur very rarely.

Class 4, represented by $H_s = 3$ m and $T_m = 10$ s can be considered representative of swell waves. These long-period waves, generated by Atlantic storms, penetrate readily to the seabed and stir up the sediments. Swell waves measured off Mablethorpe had periods of 8 to 14 s and heights up to 3.5 m (Hawkes et al, 1997). Within the study area, the largest swell occurs off south Norfolk/north Suffolk (Hawkes et al, 1997).

Mean Spring Tide plus Winter Wind:
Wind generates a drag on the sea surface so that water moves with the wind. This can produce a bias in the currents, which modifies the patterns of residual currents and net sediment fluxes produced by the tides alone. The effect on the current is proportional to the wind speed. It has a much stronger effect on the sediment transport, because of the strong dependence on current speed described earlier. Thus the sediment transport patterns in winter, when winds tend to be strongest, may be different to those in summer.

Mean Spring Tide plus (February 1993) Surge:
On rare occasions the track of North Atlantic depressions can be such as to stimulate, through the action of wind and atmospheric pressure, a surge of elevated water that runs at the same speed as the tidal wave southwards down the east coasts of Scotland and England. These are most damaging when they coincide with the movement of High Water of Spring Tides. They influence the sediment transport through various mechanisms:

- larger than normal currents
- higher than normal elevations reaching normally dry areas of beach or soft cliff

- ➢ high waves generated by the winds producing enhanced stirring
- ➢ bias of the tidal currents by the winds.

The February 1993 surge was chosen because it had a large effect on water levels in the Lowestoft area. In terms of surge elevation, this surge had a 20-year return period.

However, individual surges can vary considerably in all the effects listed above, depending on the exact meteorological conditions, so this example should not be treated as representative of all surges, but provides a clear indication as to the magnitude of effect of a large surge event. The influence of storm surge events is discussed more generally in Appendix 7.

3.5 Longshore sediment transport

The available knowledge about longshore sediment transport rates between Flamborough Head and Jaywick in Essex has been summarised and interpreted in a separate longshore drift report (Appendix 11).

Much of the study area was modelled in the pioneering studies by the University of East Anglia in the late 1970s and early 1980s. UEA developed a model for longshore transport that was applied to the whole of East Anglia and some of Essex. Many of the regions were not modelled again for several years. However, within a number of Shoreline Management Plans, scheme and strategy studies many areas have been modelled in more detail, using more up-to-date techniques and site-specific model settings.

For the first time an in-depth collation exercise of drift results has been undertaken, supplemented with some new modelling (COSMOS 2D) at Hornsea (Holderness coast), to produce a large catalogue of sediment transport rates and, where possible, directions. The large catalogue of sediment transport rates on which the report is based came from a wide variety of sources, including results from numerical modelling and observations. These are difficult to compare as the wave climate is highly variable from year to year and so predictions made from different periods may vary by a large amount, without necessarily being incompatible.

These values should be interpreted with caution for a number of reasons, including:

- Potential transport rates were calculated: assuming that at all times there was a sufficient volume of material to be transported. In some locations this is not the case
- Many of the transport rates are for medium sand – even when the beaches were of mixed sand and shingle, or even of pure shingle. The potential sand transport rate will be far higher than the transport rate for shingle at the same site
- The standard deviation in the mean annual nett longshore drift rate is commonly a substantial proportion of the mean rate. Indeed it is not uncommon for the nett transport rate direction to reverse in some years in a sequence – even when the mean rate has quite a high value
- The majority of model results are driven by waves only and the effect of the tide is generally ignored. In areas of the coastline with strong tidal currents nearshore the transport will also be influenced by the tidal currents.
- There is no way of physically measuring the rates of sand transport along the coastline. Any drift rates quoted must therefore be treated as estimates rather than absolute values
- All calibrations of sediment transport formulae using point measurements exhibit a large degree of scatter

The report contains a unified set of results through an interpretation using subjective, expert judgement on the reliability of the data. The results from a number of recent studies have proved particularly beneficial in confirming likely values for the mean annual nett longshore drift rate. The final set of information for the mean annual nett longshore drift rates are broadly consistent between studies and with knowledge gained by observations along the coastline. These results are plotted in Figure 10 for the whole study coastline, although it was noted that there was a lack of predicted data on the north coast of the Thames and north Kent coast.

3.6 Field data collection at key sites

The Inception Report (HR Wallingford, 2001) re-assessed the range of sites for fieldwork identified in the Phase 1 study by ABP (ABP, 1996a, 1996b, 2000). The sites chosen for fieldwork in the present study were:

- Winterton Ness/Overfalls
- Clacton/Gunfleet Sand
- Humber mouth including work on cliff/beach/bank mineralogy

The aims of the field data collection campaign were twofold, firstly to build up an understanding of the physical characteristics of the seabed, flows and sediment transport processes at specific sites, and secondly to provide data for calibration and validation of the computational model.

A combination of survey techniques was used with post survey analysis and interpretation delivering one layer of input to the sediment transport maps. The fieldwork programme made use of a range of both conventional equipment (e.g. current meter moorings, sidescan sonar) and novel instrumentation (e.g. nearbed acoustic backscatter device for sediment concentrations) that had been developed by CEFAS and UEA. The instrumentation was calibrated using appropriate standards and methods. The data collection took place between April and December 2001.

The fieldwork programme is shown schematically in Figure 11 and an overview of it is presented below.

3.6.1 Winterton Ness/Overfalls

The work at Winterton Ness was highlighted as being of strategic importance. The seabed in this area is largely sandy, and the high tidal currents and shallow water provides a mobile seabed environment adjacent to the coastal area around the ness and a zone for possible sediment transport links to the nearshore banks. Because of the complexity of the seabed-shoreline configuration at this point it was appropriate to conduct measurements to determine the hydrodynamics and sediment transport. Measurements were also made to the northwest between Happisburgh village and Haisborough Sand.

Survey layout:
The planned survey layout is shown in Figure 12. The main components were:

a) 5 seabed moorings containing a mid-depth current meter and sensors to measure water depth, waves and suspended sediment concentrations near the bed. These were positioned on a shore normal array between Happisburgh and Haisborough Sand sandbank, and on a shore parallel array in the nearshore banks off Winterton Ness

b) 1 Minipod mooring with more sophisticated instrumentation for measuring suspended sediment concentrations and waves and currents, placed at the inshore end of the Happisburgh transect

c) 3 full tide ADCP surveys in support of the current meter moorings and also off the coast across the banks off Great Yarmouth. Simultaneous use of the ‘Batfish’ towed array giving profiles of suspended particulate matter, and water temperature and salinity

d) An array of near surface samples of water and suspended particulate material

e) Extensive coverage of the seabed with high resolution digital sidescan sonar and QTC (Quester Tangent Corporation) seabed discrimination system

f) Fluorescent tracer release (medium grade sand) on the –5 m isobath at Winterton Ness with subsequent seabed grab sampling and beach sampling to determine dispersion. The grab samples provided some ground truthing for the sidescan data

Outcome:
The April 2001 survey was largely successful although constraints on ship operations due to the weather meant that only the ADCP survey directly off the ness was carried out and the Batfish and QTC surveys were not carried out. Also one of the current meter moorings in a) was lost and attempts to recover the seabed frame were unsuccessful. Otherwise all the objectives were met to provide an improved understanding of sediment transport in this area.

A comprehensive digital sidescan sonar survey was carried out to map a 300 m wide swath of the seabed from which the nature of the seabed and associated sedimentary bedforms could be analysed. The survey route is shown in Figure 13. The bedforms identified on this survey have been added to the database. Examples of the process measurements off Happisburgh are presented in Figure 14 and Figure 15. These show the significant wave height and current speeds measured on the 10 m isobath. The survey period experienced a high amount of wave activity as shown on Figure 14, reaching as high as 2.3 m on the 20th and 21st April. The horizontal current speeds, important for transporting sediment, were also high reaching 1 ms^{-1} on the spring tides during the first five days of the survey (Figure 15). Time series of suspended sediment concentration showed resuspension of sediments at tidal frequencies but the effect of the storm around the 20th to 21st of April producing noticeable increases in the concentration of resuspended sediment.

The water samples were fed into the synoptic chart of North Sea suspended sediment concentrations (see Figure 29 later).

More details of the field data collected at this site are given in Appendix 6.

3.6.2 Clacton/Gunfleet Sand

The work at Clacton was highlighted as being of strategic importance. The characteristics of this area of coastline and seabed are in marked contrast to Winterton in that there are a number of estuaries in the area and a background load of fine suspended sediment. The nearshore bank, Gunfleet Sand, is comprised of medium sand but is largely dissimilar material to the adjacent coastline and intervening seabed. The aim of the survey work was to identify both the long-shore and offshore transport of sediment relevant to the coastal area around the Gunfleet Sand. At the outset of the study there was conflicting evidence about the existence of a direct link for sediment transport between the Gunfleet Sand and the frontage at Clacton (see Appendix 3, Essex SMP). Because of the complexity of the seabed-shoreline configuration at this point it was appropriate to conduct measurements to determine the hydrodynamics and sediment transport.

Survey layout:
The planned survey layout is shown in Figure 16. The main components were:

a) 3 seabed moorings containing a mid-depth current meter and sensors to measure water depth, waves and suspended sediment concentrations near the bed. These were positioned on the shorewards flank of the Gunfleet Bank, north east of the head of the bank and about halfway down the bank. A nearshore mooring off the Clacton frontage was also laid

b) 1 Minipod mooring with more sophisticated instrumentation for measuring suspended sediment concentrations and waves and currents, placed on the 5 m isobath east of the Naze

c) 1 full tide ADCP survey in support of the current meter mooring

d) An array of near surface samples of water and suspended particulate material

e) Extensive coverage of the seabed with high resolution digital sidescan sonar

Outcome:
The September 2001 survey was successful and all the objectives were achieved. All the process measurement moorings were successfully retrieved and in conjunction with the sidescan sonar data an improved understanding of sediment transport in this area was achieved. Currents in the shallow area off the Naze exceeded 1 ms^{-1} on spring tides and were less strong on neap tides and also reduced with distance further away from the shore along the inshore flank of the Gunfleet. Fine sediments and sands were resuspended at tidal frequencies by the currents and the concentrations were higher on spring tides than neap tides. Even at spring tides the sand settled out of suspension at slack water. The largest wave heights measured in the shallow water off the Naze were around 1 m (significant wave height). The measurements showed modulation in wave height due to the combined effect of sheltering by the nearshore sandbanks at low tide and interaction with tidal currents.

The data were combined to calculate the time series of sediment flux (in the lowest 0.8 m of the water column). The total net flux of fine and coarse sand due to tide and wave effects during the 14 day spring neap cycle measured at this location was around 5.2 tonnes (dry mass) per metre width of seabed in an approximately northerly direction.

A comprehensive digital sidescan sonar survey was carried out to map a 300 m wide swath of the seabed from which the nature of the seabed and associated sedimentary bedforms could be analysed. The survey route is shown in Figure 17. The bedforms identified from this survey have been added to the database.

The water samples were fed into the synoptic chart of North Sea suspended sediment concentrations (see Figure 29 later).

More details of the field data collected at this site are given in Appendix 6.

3.6.3 Humber mouth including work on cliff/beach/bank mineralogy

There were two issues of strategic importance associated with the mouth of the Humber:

1. Interchange of sediment between the estuary and the open sea through seabed sediment pathways
2. Transport across the estuary mouth and fate of material eroded from the Holderness coast

It was recommended that this was tackled in two ways, firstly using sidescan sonar to identify seabed pathways for sediment and secondly to collect further seabed sediment samples for analysis. The report by Cox (2001) (see Appendix 9) had identified a gap in the mineral analysis off the Humber mouth and hence a programme of bottom sampling of sediments was devised to fill this gap.

Survey layout:
The planned survey layout is given in Figure 18. The main components were:

a) Extensive coverage of the seabed with high resolution digital sidescan sonar

b) Grab samples of seabed sediments for ground truthing the sidescan data and for subsequent laboratory analysis for mineral types

Outcome:
The survey was completed in December 2001 and the track lines are shown in Figure 19. During the planning stage it was recognised there were constraints on times when the vessel could enter the firing range extending seawards from RAF Donna Nook. There were also tidal constraints on when the survey vessel could gain access to the shallow areas on both the south side and north side of the estuary. Despite contingency time being added into the programme, the influence of bad weather reduced the density of completed east-west survey lines actually completed and prevented the grab sampling programme from being completed. During the September 2001, as part of the Humber Estuary Shoreline Management Plan Phase 2 studies (HESMP2), British Geological Survey (BGS) had obtained some sidescan and shallow

seismic data (along the tracks also shown on Figure 19). However they experienced poor weather which prevented them from obtaining data on the south side of the estuary.

The quality of the data collected in SNS2 was high and the final assessment of the data analysis was made in close consultation with BGS to bring on board information from the HESMP2 survey and their previous experience as necessary. However, constraints of time in the present study prevented a complete merging and analysis of the two datasets*.

The water samples were fed into the synoptic chart of North Sea suspended sediment concentrations (see Figure 30 later).

The data collected during this part of the study is described in more detail in Appendix 6.

3.7 Mapping the sediment transport data

The data obtained from the various sources has been mapped using the Geographical Information Systems ArcView™ and MapInfo™. This allowed for accurate geo-referenced plotting to take place in National Grid coordinates. These data have been overlain on Admiralty Charts from the electronic ARCS™ system (Admiralty Raster Chart Service) which improves the quality of presentation as the co-location of features with the coastline and seabed topography is immediately apparent.

The drift rate predictions have also been mapped onto the coastline using the GIS.

The results from the computational model were plotted in National Grid coordinates using the standard post-processing package from the TELEMAC software.

The most appropriate way to reduce uncertainty is to combine and contrast the various sources of information for the sediment transport rates and pathways. This was achieved by plotting all the available datasets in a geo-referenced manner and comparing and contrasting the information through a process of expert assessment to yield the conceptual model for sediment transport.

3.8 Determining sediment transport rates and pathways

The expert assessment of results relies on results from seabed mapping, fieldwork, computational model results, and information on sources and sinks, which can be combined to produce an interpretation of sediment transport in the study area.

Sediment transport rates can be determined using a variety of methods. These include direct methods using calibrated field data collection instrumentation, the production of "synthetic" data using a calibrated and validated computational model, or indirect methods such as measurements of erosion or accretion which can be used to determine a rate of sediment transport for a unit area (e.g. 1 square metre) on the seabed. Computational model results provide a useful function in being able to interpolate in a physically meaningful way between discrete measurement locations.

The field data collection methods utilise equipment to measure the volume concentration of sediment in the water column at a particular height above the bed. By taking simultaneous measurements of the time averaged current speed, the flux (product of concentration and velocity) can be determined. By making multiple measurements at a number of discrete heights above the seabed a profile for the flux can be determined. The integrated profile through the water column yields the sediment transport rate which is usually specified as a dry mass of sediment moving over a unit width of seabed in a unit time (typically kg/m/s). If continuous measurements are taken throughout a tidal cycle then the gross and net sediment transport rate and direction can be determined from these measurements. Recent developments in acoustic devices facilitate high resolution measurements of the sediment flux. The Acoustic Doppler Current Profiler (ADCP) technology can be deployed from a vessel and used to produce profiles over the entire water depth, the Acoustic Backscatter Sensor (ABS) technology allows high resolution measurements in

* The merged datasets will be used in the ongoing Humber Estuary Shoreline Management Project, Phase 2.

the bottom boundary layer of the flow (where most of the sand will be transported). Both methods need good in situ calibration of sediment concentrations to add confidence to the results.

Quantifying the movement of sediment along the seabed as bedload is much more difficult to achieve. Traps have been deployed to catch sediment but these can suffer from unknown sampling efficiency, tagged particles have been used (tracers), and a frequently used proxy is to measure the migration of seabed bedforms (sandwaves and megaripples). Analysis of the internal structure of sedimentary features can be utilised to yield migration rates. The rates of sediment erosion have to be determined from repeat surveys of the seabed or coastline, but these usually only yield reliable results over long periods of time (no less than several years). Rates of sediment deposition are once again determined from long term measurements of seabed levels, or can be determined directly using sediment traps placed in frames on the seabed, or from maintenance dredging records in port approach channels.

Computer models can be used to determine sediment transport rates. Different models are utilised to determine different processes at a variety of temporal and spatial scales as discussed in the DEFRA funded manual on coastal morphology model selection (Southgate and Brampton, 2001). These utilise semi-theoretical predictors of the sediment transport rate driven by the predicted field of waves and currents.

Pathways of sediment transport are more difficult to determine as they rely on the tracking of parcels of sediment over the seabed. On the way the characteristics of the sediment parcel may change (becoming coarser or finer due to hydraulic processes or the mixing in of other particles from different sources). One approach to determining pathways has been proposed by McLaren which utilises properties of the grain sorting in discrete seabed samples to determine the pathways of sediment from statistical techniques. Another approach is to use tracers in the sediments, either naturally occurring mineral tracers or added tracer material (tagged particles). It is then possible to examine the characteristics of the material deposited at a particular location and to correlate that with the various source materials that are available. For many years plume dispersion models have been utilised to predict the movement of fine particles (lost from dredging operations for example) as they move within the water column. Only very recently (2001) have particle tracking models for coarse bedload material become available and hence these are not routinely applied in studies.

Seabed drifters have been used to determine the movement of seabed currents, these are thought to more closely relate to the movement of coarser sediments along the bed. The distribution of returns from a drifter study (either by stranding on the shoreline or returned by trawlers or dredging activity) yield information about the ultimate destination of nearbed material but do not provide information on the intervening pathway.

The tools (models and measurement equipment) available in support of coastal management have been assessed by members of the COAST3D project team, including the Environment Agency and Netherlands Rijkswaterstaat. More details can be found in the report by Mulder et al (2001).

4. REGIONAL SCALE ASSESSMENT OF SEDIMENT TRANSPORT

Sediment transport in the Southern North Sea relates to the movement of a pattern of sediment deposits inherited from millennia of erosion, transport and deposition of the deposits left after the last glaciation. The present day distribution of sediment deposits comprising muds, sands and gravels is well known and arises from the continuous action of tidal currents with periodic storm wave and surge activity that have shaped the seabed over the last few thousand years. This present day distribution and the seabed morphology (shape) combine with the forcing by waves and currents to dictate the present day pattern of sediment transport. This pattern of sediment transport has been assessed at the regional scale (whole study area) using published information and the results from the computational modelling of sediment transport completed in the present study.

4.1 Introduction

In this section of the report the sediment regime of the Southern North Sea is assessed using published information and the results from the computational modelling of flows and sediment transport in the study area.

4.2 The sediment regime of the Southern North Sea

Sediments on the floor of the southern North Sea, originally laid down in the Pleistocene glacial period, are being modified by present-day tidal currents, with wave stirring and wind-induced and surge currents playing a significant role. Appendix 2 contains a discussion of sediment transport processes.

The distribution of maximum depth-averaged tidal currents in the study area is shown in Figures 20, 21 and 22. The flow model covers the whole of the Southern North Sea and the eastern half of the English Channel, but in order to increase the scale at which the results can be shown only the predictions within the study area have been plotted. Peak tidal currents are around 1 ms^{-1}. On spring and neap tides (Figures 20 and 21) in the northern part of the study area near the coastline the peak currents are directed southward along the Holderness and Lincolnshire coasts, both into the Wash and veering to a easterly direction past North Norfolk. In the southern part of the study area flows are northwards converging with the eastward flow past North Norfolk and passing northeast offshore over the Norfolk Offshore banks. In the southernmost portion the flow is directed in a southerly direction. On the storm surge tide (Figure 22) the flow pattern at the northern boundary changes to a northerly flow but is still southerly off the southern part of the Holderness coastline and past the Lincolnshire coast. There are some further noticeable differences, the convergence in flow over the North Norfolk banks is no longer present and flow is in a southerly direction over most of the southernmost portion of the study area.

The sediments comprise sand and gravelly sand offshore and up to at least 50 km from the coast off Holderness, Lincolnshire and North Norfolk. Similar grades of sedimentary material are found off the coasts of Suffolk, Essex and Kent (see Figure 3). The regional sediment distributions generally reflect the level of hydrodynamic forcing (including waves) with fine sands and muds in the deeper waters where tidal velocities and wave stirring are reduced, and coarse and medium sands in the highly mobile nearshore zones. Muddy sediments are also found locally in estuaries and embayments, as well as offshore of some rivers/estuaries.

A more detailed sediment type distribution for the coastal strip has been plotted in Figure 23 based on a finer interpolation of the sediment data which formed the basis of Figure 3.

Over most of the seabed the surficial sediments are only of order decimetres or metres in thickness, and geological investigations have shown that in some places (e.g. off North Norfolk) the sediment is only present in a thin veneer. The results from the analysis by British Geological Survey of seabed grab and core samples have been mapped on a 1 km grid showing the variation in mean grain size of the sand fraction of the bed material (Figure 24). From the results plotted in Figure 24 it can be concluded that at the kilometre scale there appears to be at least a thin veneer of fine to medium grade sandy sediment over much of the study area.

Many of the nearshore areas have locally thicker accumulations of sandy and gravelly material, often in the form of banks. Changes in the position and shape of these banks through sediment transport have the potential to affect the exposure of coastlines to waves and hence are considered important to their management (Whitehouse (ed.), 2001).

Estuarine systems and their associated saltmarshes and flats are dependent upon the supply of fine sediment transported in suspension. Removal of fine material from an estuarine system through maintenance dredging is now perceived to be have a negative effect and retention of sediment within the system is a preferred approach. Hence the transport and fate of muds needs to be considered in addition to the transport of non-cohesive sands and gravels.

It is important to recognise that sediment transport rates and directions both on beaches and over the seabed can be highly variable and may be dominated by infrequent but extreme events. Thus any appraisal of sediment fluxes must consider not only averaged conditions but also extreme storm and surge events. In addition there is increasingly strong evidence that global climates are changing. This may lead to increased sea levels, more frequent and possibly more persistent storms, and subtle changes in annually averaged wind, and hence wave directions. All of these changes could be reflected in the sediment transport regime, influencing both the frequency of transport and the residual direction. If management of the coast is to be sustainable it will be necessary to be able to evaluate the sensitivity of the existing sediment transport regime to these natural changes.

Management of the coastline, particularly beaches, requires knowledge of the losses and gains of sediment, i.e. mud, sand and gravel. Often, these losses and gains have been ascribed to interchanges of sediment between the coastline and the seabed, although the evidence for this is often poor. Understanding and if possible quantifying these exchanges is potentially important when making decisions about managing the coast and its defences. For example, reducing the losses of sediment to the seabed and avoiding disruption of an onshore supply of sediment are both helpful in maintaining beach volumes.

Within this broad scale picture, the study area has many local sources (e.g. cliffs, seabed rock/clay outcrops and rivers) and sinks (e.g. sand dunes, deeper or distant areas of the North Sea, estuaries and embayments) of sediments of different grades, these will be elucidated in the project. The project aimed to identify and quantify local sources and sinks of sedimentary materials as well as the sediment transport pathways that serve them.

Knowledge of the seabed, particularly its morphological evolution and the transport of its sediments, leads to a greater understanding of the evolution of the coastline. The deposits of gravel, sand, and mud on and under the present-day seabed, and the movements of this sediment over it and in the waters of the North Sea, all provide an insight into the long-term evolution of the sedimentary coastlines along its boundaries.

4.3 Large scale coastal evolution

Recently the large volume of data collected between 1991 and 1996 by the Anglian Region of the Environment Agency has been analysed to provide a “strategic insight into how the coast is evolving at an integrated scale”(Leggett et al, 1998). This is important data because it provides direct information about how the beach and nearshore sediment volumes are changing with time (see Figure 25).

The data shows how whole stretches of coastline are increasing or losing sediment volume over this 5 year timescale. The Lincolnshire coast has increased its sediment volume, particularly south of Mablethorpe – not least in part due to the beach nourishment in this area. North and Northeast Norfolk and the Suffolk coast to Southwold have lost volume. Southwold to Harwich has neither lost nor gained volume and other than for the area of Mersea Island the Essex coastline has gained volume.

The data from Anglian Region does not cover the Holderness coast north of the Humber and hence a comparable analysis is not available at present. However, it is known that this is an eroding area of coastline. The North Kent coastline is largely protected by defences other than the eroding cliffs of the Isle of Sheppey.

4.4 Overview of published information on sediment transport pathways

The pioneering work undertaken by the Institute of Oceanographic Sciences in the 1960's and 1970's contributed a considerable advance in knowledge about the presence of sandwaves and sandbanks on the floor of the North Sea as well as around the whole of the UK Continental Shelf. The distribution of sandwaves in the southern North Sea is depicted in Figure 26 from Stride (1982). Analysis of this data led to the first schematic maps of sediment transport on the UKCS based on seabed observations (Figure 27). A more detailed assessment was made for the seabed off the Outer Thames and the inferred sediment pathways are plotted in Figure 28 (Kenyon et al, 1981).

4.5 Overview of longshore sediment transport

The presently available predictions of longshore sediment transport rates along the study coastline have been assessed in Appendix 11 and are catalogued within the GIS database. The interpreted results have been plotted for the entire study coastline in Figure 10. Each of the arrows on Figure 10 has been colour coded to show the net annual longshore drift of sediment (sand or gravel) in cubic metres per year, the direction of the arrow shows the drift direction. Detailed information on the sediment transport for smaller lengths of coastline are presented in the figures associated with Section 6 of this report.

4.6 Southern North Sea scale suspended sediments

The summer and winter distributions of suspended fine sediments obtained by sampling the surface waters are shown in Figures 29 and 30 respectively. The database of SPM values held by CEFAS (data-holding as at April 2002 and including the data collected in this project) was classified into values taken in summer and winter, the point values were plotted – the stars in Figures 29 and 30 – and these point values were contoured.

Values of suspended sediment in summer (Figure 29) are generally low in offshore areas – typically 0 to 4 mg/l. The estuaries are generally areas with higher SPM e.g. in the Wash and Thames with especially high concentrations in the Humber (300 mg/l +). There are three areas of high concentration close to the coast, on the Lincolnshire coast, Great Yarmouth/Lowestoft coast and Orford Ness. The former is most probably an extension of the Humber plume south and only appears as an isolated high value due to a data gap to the north of Cleethorpes. High spring tidal currents cause the Great Yarmouth/Lowestoft high concentration. The Orford Ness high is defined well to the north and southeast but not inshore to the west and further to the southwest. It is not associated with any spring tidal current maximum. Possible sources are from the Orford area or from wave resuspension in one particular survey but the latter is thought unlikely in summer in the location. Another alternative is that there may be biological influences prevalent. This data set is insufficiently detailed to identify these influences or the detail of sources.

The winter suspended sediment distribution (Figure 30) shows a similar pattern in the coastal areas but the concentrations are higher. Generally the summer maxima are strengthened in the winter with a doubling of the suspended sediment concentrations. The main feature of the sediment concentration distribution picked out by the winter data is the plume-like feature in the suspended sediment field extending from north-east Norfolk out in a northeastern direction across the North Sea towards the island of Texel in the Netherlands. This "plume" has also been reported by Dyer and Moffat (1998) and modelled with a 3D computational hydrodynamic model by HR Wallingford (1992).

The most likely source of this material is local resuspension by wave activity but other theories include transport of material down from the Humber along the Norfolk coast and then offshore. The available data suggest a low value just off Cromer perhaps breaking the chain. However, it is noted that the data density in this region is very low, leading to a large uncertainty in the patterns off the North Norfolk coast by direct measurement.

The implication of the "hook" of suspended sediment present off the Suffolk coast at Orford Ness, which is also shown in corresponding satellite imagery, warrants further consideration.

4.7 Results from the computational model

Sediment transport patterns were simulated using a variety of techniques. The movement of very fine sediment carried in suspension was assessed by calculating over the entire model domain the net residual tidal velocity for spring and neap tides (Figures 31 and 32), and including the surface stress from the wind (Figure 33) and storm surge effects (Figure 34). For the purposes of presentation all results in vector form are represented on a regular mesh that is coarser than the mesh used to define the currents, and the easternmost extent of the figures is plotted to coincide with the offshore boundary of the study area. The entire model domain is much larger and is shown by the inset in Figure 9. The axes on these figures are Eastings and Northings (in metres). Clearly, there will be some areas not resolved by this model including the smaller estuaries.

It is assumed that the fine material carried in suspension remains in the water column and does not exchange with the seabed over the short term, the residual drift currents may serve to identify the transport pathways and sinks of this grade of sedimentary material. However, it became apparent that the 2D depth-averaged model does not adequately capture the surface drift current generated under wind action and hence a 2D depth averaged model is not capable of fully resolving the plume of suspended material seen in field data discussed in the previous section (Figure 30). This result is discussed further in the next section.

Residual flow patterns

Figures 31 and 32 show the tidal residual currents for spring and neap tides. The inset on the figures indicates the length of vector used to show a magnitude of 0.1 ms^{-1}, with the length of the vector stem being proportionately longer or shorter for flows which are larger or smaller. The most striking feature of these plots (most notably for spring tides) is the indication of a net drift that flows north along the study boundary. In the north east part of the study area there is an element of flow to the northeast as well. This latter feature is not present on neap tides where there is a general northerly drift over most of the southern part of the Southern North Sea. On spring tides there is a pattern of drift to the east from the region of the Holderness and Humber and also along the North Norfolk coast to the east, which is weaker and switches direction on neap tides. There are also a number of areas of circulation in the flow patterns.

Spring tide patterns show a significant net drift south through the Straits of Dover, that does not feature on the neap tides. The area of the outer Thames is generally not well organised, probably as a consequence of the banks in this area, whereas further north around the Suffolk and Norfolk coast the net drift is weak on springs but shows a northerly drift on neaps. The pattern in the Wash is consistent for both tides. The Holderness and Lincolnshire coasts both exhibit southerly drift which is quite strong across the Humber, with the above mentioned easterly flow further offshore (especially on spring tides). Net flows off Flamborough Head are northeastwards.

A winter wind condition was simulated by applying a 10 ms^{-1} wind from the west over the entire domain for spring tide conditions, and the results are presented in Figure 33. The effect of this wind is to drive flows through the Straits of Dover and generally northwards along the eastern boundary of the study area. Conversely, Figure 33 shows the net tidal current residual for the case of a specific surge event, and the tidal residual is dominated by a general southerly drift in the southern half of the North Sea, which is very high through the Straits of Dover. In the northern part of the study area the residual flows are towards the west.

This drift does not correspond very well with the well-known drift across the North Sea identified from a number of sources (including satellite imagery on front cover and Figure 30) and referred to as the "English River". However, there is some agreement with the sub-surface currents predicted with a fully

3D model of the North Sea (which also included temperature and salinity fields) (Odd and Cooper (1992)). This 3D model was able to reproduce the “English River”, which is most apparent in the surface layers, and in particular when a winter wind field is applied. Accordingly, reproduction of the detail of this flow structure with a depth-averaged model should not be anticipated. The correspondence of the results from the 2D model with the sub-surface flow patterns is, however, encouraging and demonstrates that the model is capable of reproducing the general flow patterns.

Net sand and gravel transport
The SANDFLOW model was used to simulate the transport of sand and gravel over the model domain.

Figure 35 shows the potential for seabed mobility under spring tide conditions, in terms of the maximum grain size that is capable of being mobilised by the tidal current. This figure indicates that the greatest potential mobility (2 to 4 mm size material) occurs off the coasts of East Kent, Orford Ness, northeast Norfolk, the central channel of the Wash and offshore extension of that channel, offshore of the Humber entrance, and around Flamborough Head. Over the rest of the domain the maximum grain size that can be moved on a spring tide is typically coarse sand of diameter 0.5 to 2 mm. In the Outer Thames the currents in some areas are weaker and only medium sand is moved, whereas off the coast of Kent the energy is sufficient to move even pebbles. Figure 3 shows the general distribution of surface sediment characteristics and it can be seen that gravelly areas are generally seen to coincide with the highest mobility areas. Generally, the surficial sediment size (Figure 24) is smaller than the sediment size that can be mobilised (very fine sand corresponds to sediment sizes 0.063 mm to 0.125 mm, fine sand 0.125 mm to 0.250 mm, medium sand 0.250 mm to 0.500 mm, coarse sand 0.500 mm to 1.0 mm, and very coarse sand 1.0 mm to 2.0 mm.

Sediment transport was simulated for a variety of conditions summarised in the table below. Figure numbers indicate the plots for net tidal flux contained in this report. The inset on the figures indicates the length of vector used to show a magnitude of 10,000 kg per metre width of seabed per tide within the band 1,000 to 10,000 kg per metre width of seabed per tide, with the length of the vector stem being proportionately longer or shorter for fluxes which are larger or smaller.

Sediment grain size (mm)	**Hydrodynamic condition**						
	Neaps	**Springs**					**Surge**
	Calm	**calm**	**1m, 5s waves**	**3m, 6s waves**	**3m, 10s waves**	**5m, 10s waves**	**5m, 10s waves**
0.1	Fig 41	Fig 36	Fig 42	Fig 43	Fig 44	Fig 45	Fig 46
0.4		Fig 37					
2.0		Fig 38					Fig 47

The net tidal sediment transport patterns are shown in the remaining figures of this chapter using a format shown in Figure 36. The magnitude of sediment transport is extremely non-linear, with areas of high current transporting material at a rate of orders of magnitude higher than the calmer areas. Accordingly, a non-linear vector scale is used on these plots with colour coding. The magnitude of the transport rate (denoted as sediment flux in these figures) is colour coded and in addition the larger transport vectors have a vector “tail” where the length of the tail is linearly proportional to the sediment flux. The sediment flux is predicted as the total transport rate from the product of the sediment concentration and flow velocity throughout the water depth which is calibrated in the SANDFLOW model. The sediment transport predictions have been made assuming that the specified sediment grain size in the above table is available everywhere in the model domain.

Figure 36 shows the net spring tidal residual sediment flux for 0.1mm sand, and Figure 37 shows the same information for 0.4mm sand. There is a strong southerly flux of sand past Flamborough Head and along the Holderness coast, and the transport across the Humber is relatively strong and southerly. This trend continues down the Lincolnshire coast and there is a significant influx into the Wash through the main deep water channel. Transport along the north Norfolk coast is eastwards round as far as Great Yarmouth. From Great Yarmouth to the Outer Thames there is a general northerly flux within the main coastal strip (i.e. 20km from the shore). The Outer Thames region is relatively disorganised, with complex flux patterns around the linear banks. The drift on the North Kent coast is relatively weak and off the East Kent coast there is a net northerly flux.

By comparison of the depth-averaged residual tidal flow velocities in Figure 31 and tidal residual sediment flux of fine sand in Figure 36, it can be seen that the residual velocities are not necessarily a good indicator of residual sediment transport rate or direction for fine sand let alone coarser sediment sizes.

The potential transport of gravel is limited to the higher energy areas of the model domain (Figure 38) which corresponds well with the areas of larger material mobility already shown in Figure 35. There is the potential for southerly transport both off the Humber entrance and also outside the Wash. Off northeast Norfolk the transport is generally north-northwesterly. In the south there is some northwards transport off Orford Ness and the transport is generally southwards through the Straits of Dover.

Having established these baseline patterns for sand and gravel transport, various sensitivity testing and further analysis of the results was carried out as a means of identifying specific characteristics of the flux field.

A sensitivity test was carried out to assess the effect of imposing a variable roughness in the flow model based on the known seabed characteristics. Further details of this test are presented in Appendix 12, and the resulting sediment flux for 0.1mm sand was presented in Figure 39. Comparison with Figure 36 indicates a number of important features of this test. Although the flux in the deeper areas of the eastern part of the study area is not significantly modified, the transport around the English coast shows particular differences to that predicted with a constant roughness. The sediment flux in the Holderness to Wash region is not substantially modified (other than the transport rate), whereas the drift past the East Norfolk coast is reversed to a NW direction. Off the Suffolk reach the drift is northerly, and whilst the Outer Thames region is not substantially modified there is a divide with strong southerly drift past Kent into the English Channel. This sensitivity test highlights those areas where the drift direction as well as magnitude may be variable. In summary:

- The area between Flamborough Head and the Wash was largely insensitive to the choice of seabed roughness
- The area from the North Norfolk Banks south and including the Dover Straits was sensitive to the choice of seabed roughness

Figure 40 shows the peak sediment transport rate through a tidal cycle. This field was calculated on the basis that the orientation of bed features being undertaken as part of this study may be better correlated with the peak transport rate (rather than the tidal average). In this figure the most important feature is the direction of the transport. It is interesting to note that the pattern in the directions of peak flux is comparable with the directions of net transport (Figure 36), and that the pattern of flux around the North Norfolk banks is complex. This ties in with the information resulting from the seabed features analysis (summarised on Figure 7).

Figure 41 shows the sediment flux patterns for 0.1mm sand under neap tides. The most striking feature is the lower transport rates over most of the study area, but that the direction of transport is generally similar to that under springs. The most noticeable differences are off Great Yarmouth where the spring tide flux is variable in direction whereas the neap tide flux is generally northerly. Also the flux pattern changes in the offshore area bordered by the North Norfolk coastline and the coastline between Flamborough and the Wash, with a pronounced northwesterly drift on the neap tide.

Figures 42 to 45 present the simulation of 0.1mm sand transport under spring tides but with wave enhancement. The general effect of the wave enhancement is to increase the magnitude of the transport rate, although the net direction can also be modified (by changing the proportions of the gross transport in each direction). The figures show that the transport rate increases with wave height and also with wave period, which is to be expected. Under the 5m storm wave conditions the transport rate is increased over much of the study area by an order of magnitude or more.

A test was made as to the sensitivity of the transport rate due to storm surge conditions, with both 0.1mm sand and gravel simulations, and the resulting patterns of transport are presented in Figures 46 and 47. Full details of the surge condition simulated were discussed in Section 3.4 (also see Appendix 12). For these tests SANDFLOW was run using tidal currents which included the wind stress during the time of the surge, and 5m 10s waves were assumed to occur over the study area. In both cases the sediment transport under this surge condition was dominated by southerly drift. The flux magnitude of the 0.1mm sand fraction is an order or magnitude higher than on the spring tide, and greatest over the Northeast Norfolk and southern part of the Southern North Sea through to the English Channel. The transport of gravel is also significantly enhanced, where the conditions mobilise the gravel over a much larger area.

For each of the simulations undertaken, the regional model results were replotted to provide the details of the sediment transport patterns over smaller areas. These areas of detail are shown in Figure 47 and these will be used to illustrate the discussions in the next section of the report. To provide a clear comparison between the sand transport vectors for 0.1mm sand under spring tide conditions, and for the surge case these results have been plotted in Figures 72 to 81 and 82 to 91 respectively. Results for all the tests are replotted for these detailed areas in the modelling report (Appendix 12) in order to provide an Atlas of modelling results from this study.

4.8 Sources and sinks

Information on sources and sinks has been summarised in Table 2 and Appendix 14 contains a detailed summary for each sub-cell of the quantified sources and sinks.

A detailed assessment of the geological background to the current day sediment transport pattern observed along the study coastline and in the associated offshore areas is presented in Appendix 10. This provides information on the sources, pathways and sinks of material. It is recommended that the reader studies this Appendix to provide the background to the particular area of interest.

4.8.1 Sediment fluxes across study boundaries determined from model results

The fluxes through the northern, eastern and southern boundaries are not known as an annual average, although Appendix 12 summarises the results of specific model computations. The integrated fluxes of sediment (sand and gravel) across the northern, southern and eastern boundaries of the study area were determined for all the scenarios that were run. Results have also been determined for the Humber, Wash and Thames and are tabulated in the modelling report (Appendix 12). These results provide estimates of the magnitude and direction of net sediment fluxes and show how increasing levels of wave activity can alter the flux magnitude and direction in some cases.

The transects were of varying lengths:

North	185.2km
South	68.7km
East	304.6km
Thames	21.9km
Humber	20.0km
Wash	32.1km

The results of these integrations indicate the level of variability that might be expected in the sediment flux across a particular transect. For the North boundary sediment flux is always to the south, including the predictions from spatially varying bed roughness, but the magnitude varies. For the South boundary the flux is to the north for all sediment grades modelled, switching to the south under increasing wave height and with the surge condition; it also switches to the south for the variable bed roughness case under tidal conditions alone. The East boundary has a net easterly movement of sediment except for the case with the variable bed roughness and the simulated surge. The Thames and Humber are both net exporters of sediment, except under surge conditions. The detailed estuary processes are not reproduced in this model and hence the results may not be reliable as it is considered likely that both estuaries are accreting material even if not at a very fast rate. What is significant however is the influence of the surge storm tide in reversing the flux so that it is directed into these estuaries. The results for the Wash are always for a flux into the embayment which is in general accord with recent historic experience of sediment accretion.

The model results integrated in this way should be primarily viewed in terms of the trends and variability that they show between different scenarios rather than the absolute values.

5. APPROACH FOR ADDRESSING THE KEY STRATEGIC ISSUES

This section of the report discusses how the study results were brought together through expert assessment to address the key strategic issues involving sediment transport along the coastline between Flamborough Head and North Foreland. The information was brought together in a series of Collation Points which are then referenced in Section 6 of the report when addressing the key strategic issues. The generic issue relating to the role of nearshore banks is discussed.

5.1 The Approach

Throughout SNS2 there has been emphasis on providing practical advice to those managing the coast through building from a broad background of information. This information can be used when updating the SMPs and assessing the boundaries of SMPs. The information provides a context within which to understand uncertainty with respect to sediment movement and to assess the likelihood of significant effects with respect to offshore activities such as aggregate dredging.

The key issues were summarised in Appendix 4. Discussion of these issues not only forms a key output of the study but has, importantly, formed the anchor point for the study team when pulling together the myriad of mixed information into a coherent and consistent interpretation of sediment movement. They are based on an, approximately, north to south collation of all the information obtained during the consultations. They set the context for the presentation of interpreted information from the study.

The strategic issues were encompassed under the following headings:

- Issue A – Northern Boundary
- Issue B – Role of Holderness
- Issue C – The role of the Wash
- Issue D – Nearshore banks
- Issue E – North Norfolk drift divide
- Issue F – Sediment circulation Cromer to Benacre Ness
- Issue G – The role of the Sizewell-Dunwich Banks
- Issue H – Suffolk Coastline
- Issue I – Clacton
- Issue J – North Kent coast and nearshore
- Issue K – Thames Estuary

It was recognised that, although these issues were of most apparent significance at the time of the present study[2], other issues may come to light in the future. The information contained within this report and the database provides the baseline for addressing these future issues. This section of the report adopts, therefore, a similar approach to that taken during the development of the study. It is the intent within this section not merely to address and discuss each issue but also use this to demonstrate how to navigate the various collations of data, analysis and interpretations.

The location of the primary strategic issues have been mapped on Figure 49 with each issue referenced by a letter (i.e A, B...) and the potential implication referenced by A^1, A^2…etc. The key points highlighted within each issue and specific implications are summarised in box format.

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[2] March 2001

To facilitate ongoing use of the results from the study it was considered most useful to draw together areas of work and investigation into a series of collation points and by expert assessment examine and resolve issues by reference to these collations. The interpretation process[3] then correctly derives from the issue, ensuring a proper focus on specific detail without losing sight of the broader picture.

In collating this information these documents refer to source data derived during the SNS2 study, allowing further in depth investigation to be followed through, relevant to any issue. Figure 50, outlines the typical approach adopted for each issue, but fundamentally this can only be a guide and the sequence and outcome is ultimately driven by the issue.

In providing the analysis of issues these collation points (CP) are detailed as follows:

CP1 Geological context (Appendix 10 on sources, sinks and pathways) and bathymetric charts (Figures 51 to 58) and sediments (Figures 3, 5, 23, 24)

CP2 Overview of sediment pathways (Section 4)

CP3 Review of SMPs (Appendix 3)

CP4 Synthesis and chart of seabed sediment transport indicators (Figure 7 summary and Appendix 15)

CP5 Report on computational model predictions and "atlas" of results (Section 4.7 and figures and Appendix 12 for full set)

CP6 Review and catalogue of longshore transport rates (Figure 10 summary and Appendix 11)

CP7 Field measurement study report (Appendix 6 summarised in Section 3.6)

CP8 Discussion of the influence of surges on sediment transport (Appendix 7)

CP9 Report on mineralogical tracers (Appendix 9)

CP10 Locations of licensed aggregate dredging areas and review of dredging (see Figure 2 summary and Appendix 1)

All the issues apart from Issue D (Nearshore Banks) were site specific and are dealt with by geographic region in the next Section of the report. Issue D is generic and is dealt with below.

5.1.1 (Generic) Issue D – Nearshore banks

The main items in this issue can be broadly summarised as follows.

Summary of Issue D – Nearshore Banks

This issue was raised by all the East Coast Authorities and is fundamental to the study; the better definition of the movement of material along the outer face of the various sand bank systems between North Norfolk and Essex. There was a perception that there may be a greater extent of transfer of material along the outer banks than is evident from the more apparently localised transfer of material within the bank system. Given the bed load parting trend identified in Phase 1 of SNSSTS this was felt to be possibly a mechanism for loss of material from the nearshore region.

Implications: This issue is clearly one of the principal drivers for SNS2. It defines the overall linkage of the Southern North Sea system and provides the context and coherence for more local analysis.

Information: Various reports identified in Phase 1 SNSSTS and ongoing strategy studies (e.g. Lowestoft to Thorpeness).

[3] Undertaken in March 2002

And the interpretation of the SNS2 results has generated the following assessment of this issue:

Assessment of Issue D Nearshore Banks

Key points

- *Movement along the outer banks and interaction between banks*
- *Possible loss from the nearshore regime through the bank systems*

Context

The principal banks and bank systems are discussed in the geological review. There is also a substantial amount of information based on the sea bed indicators both for the banks and for the interstices between banks. At times these indicators are seen to be reinforced by specific tide condition flux residuals. At other times the indicated patterns are clearly overruled under surge condition. ***CP1***

In general many of the banks outside the Thames Estuary are seen as either existing banner banks fed and shaped from the shoreline headlands or as self sustaining banner banks formed in the lee of a former, more advanced, headland now disassociated from the coast as the coast has retreated. A significant difference in behaviour is noted between perched banks such as the Smithic, the Dunwich or the Bawdsey or Shipwash down near Harwich and the more mobile banks, deep-seated on available sediment within the old channel of the Yare between Great Yarmouth and Lowestoft. ***CP1***

Discussion

Discussion of this issue has been more appropriately addressed area by area in association with other issues for each area. See issues referenced here:

- *A, C, E, F, G, H, I, J and K*

Conclusions

The corridors between banks and the shoreline (nesses) are key areas for sediment exchange as discussed at the local level in Issues C (Gibraltar Point) and F (between and including Winterton Ness and Benacre Ness).

Recommendation

- Further research into these links is recommended (see Section 9)

6. LOCAL SCALE ASSESSMENT OF SEDIMENT TRANSPORT AND ADDRESSING THE KEY STRATEGIC ISSUES

This section of the report presents the detailed sediment transport information produced during this study for each sub-section of the coastline. This includes knowledge on sediment type, sources and sinks, drift rates, computational modelling results, field data, and seabed sediment transport indicators. The information has been assessed to provide a coherent basis for the assessment of strategic issues with respect to sediment transport identified earlier in the report. These issues are focussed on specific parts of the study area and are discussed under the relevant geographical region in which they occur. The discussion for each section of the coastline is accompanied by a description of a conceptual longshore drift model and a schematic sediment transport map showing everyday and extreme (storm surge) sediment transport pathways.

In this section of the report the sediment transport along the study coastline is presented in detail for the following regions with the relevant issues for that stretch of coastline also being dealt with:

- Flamborough/Holderness/Humber with Issue A – Northern Boundary and Issue B – Role of Holderness
- Lincolnshire
- The Wash with Issue C – The Role of the Wash
- North Norfolk with Issue E – North Norfolk drift divide
- East Norfolk/Suffolk with Issue F – Sediment circulation Cromer to Benacre Ness, Issue G – The role of the Sizewell-Dunwich Banks, Issue H – Suffolk coastline
- Essex with Issue I – Clacton
- Thames/North Kent with Issue J – North Kent coast and nearshore and Issue K – Thames Estuary

The actual movement of sediment along any particular route depends:

- On there being sediment to move (the source or transient supply)
- On all or part of the available sediment becoming mobilised
- On the specific nature of the hydrodynamic energy event; be it spring tides with or without wave stirring, external or internal North Sea surge events, and at the coast the vagaries, duration and sequence of wave direction. The predictions of sediment transport made in the studies associated with this report relate to potential sediment transport, i.e. it is assumed there is sufficient sediment of a particular grade for transport to occur

In any event, sediment may, therefore, be moved through a path solely because that specific set of circumstances has made sediment available to be moved and at the same time provides the mechanism to take sediment through that pathway. Under different conditions, there may be a mechanism for movement, but no mechanism for delivering sediment onto the pathway. The late arrival of a connecting train is an imperfect but useful analogy. It is against this complexity of processes and their inherent variability (Section 7) that sediment related issues have been examined.

6.1 Flamborough/Holderness/Humber

Chart – Figure 51, 52 (Humber)
Seabed facies(sediment type, features) – Figure 59, 60
Sediment drift rates – Figure 65
Net transport of fine sand on spring tide – Figure 72, 73
Net transport of fine sand under storm surge condition – Figure 82, 83
Seabed sediment transport indicators – Figure 92, 93

Setting (Figures 51, 52, 59, 60)
This stretch of the coastline is characterised by the curve of the coastline southwards from the chalk cliffs at Flamborough Head along the relatively straight section of the central Holderness coastline with its boulder clay till cliffs. Located at the southern end of the Holderness coast is the Spurn Head spit and the wide mouth of the Humber Estuary with its banks and channels.

Conceptual longshore drift model for Holderness (Figure 65) (Appendix 11 provides more details)
The northern boundary of the study area is Flamborough Head, which extends into deep water, thereby limiting the inter-tidal longshore drift to almost zero. There is a modelled sediment transport from the north to south just offshore from Flamborough Head and this feeds Smithic Bank, which may itself feed to the shoreline somewhere between Bridlington and around Tunstall. However, sand transported offshore by storms can enter the tidally dominant region where it will be transported north into Smithic Bank (if transported offshore between Flamborough Head and about Tunstall) or south (if transported offshore between Tunstall and Spurn Head spit).

The area between Bridlington and Flamborough Head is sheltered from the northerly waves and has a limited potential longshore drift towards Flamborough Head. The direction of longshore drift is to the south between Bridlington and Spurn Point. This sediment transport is fed by supply from the cliffs and the shore platform, which are both eroding. Most of the eroded material is mud / clay and is transported in suspension, ultimately away from the Holderness coastline. Prandle, Lane and Wolf (2001) modelled suspended particulate matter along the Holderness coastline and showed that, for sediment with $d \approx 50$ microns, the eroded material could be transported within a few kilometres of the coast solely by tidal forcing. This was little influenced by wave activity.

Along part of the coast, potential sediment transport rates are greater than the rate of supply of sediment into the system and the underlying rock can be exposed as shown in Figure 59. The coarse gravel (from Barmston south) forms into ridges, ribs or ords, that move slowly south (probably mainly during storms).

The sheltering effect of Flamborough Head diminishes on moving south so the potential longshore drift rate to the south increases. This is not immediately apparent from the modelled longshore drift rates. This partly reflects the different periods modelled and partly the different models used. The variation in longshore drift rate with distance from the shore has been demonstrated by the new modelling at Hornsea (see Annex to Appendix 11). The width of sand beach varies and unless the cross-shore distribution of longshore sediment transport can be estimated, and the width is known, it is difficult to estimate the longshore transport. However, the potential longshore transport rate (that would occur if there was a sufficient supply of sand at all points and at all times) is between around 200,000m^3/year and 350,000m^3/year between Hornsea and Easington (southward).

The estimated drift rate into Spurn Point is around 125,000m^3/year and this is less than the potential drift rate. It is likely that small variations in the local bathymetry north of Withernsea deflect some sediment offshore and that storms transport more sediment offshore from the inter-tidal zone. It is considered that this sediment feeds into the Binks, which act as a temporary store for sediment. The numerical modelling of sediment transport around the mouth of the Humber showed that, during a storm surge (Figure 83), there is a high sediment transport rate across the Humber from Spurn and the Binks towards Donna Nook. This redistributes the volume of sediment in the Binks and Spurn Point until it builds up again by tidal action.

In summary, much the greatest source of mud, sand and gravel is the cliffs of the Holderness coast and the adjacent subtidal ramp. Fine sediment can be imported into the Humber on storm tides as shown by measurements of flows and suspended sediment concentrations (Hardisty, 2002). Within the broad scope of the present study it has not been possible to refine further the sediment budget for the Humber produced in the Humber Geo2 studies (Binnie, Black and Veatch, 2000). Sediment sinks for material include the saltmarshes on the north shore of the Humber, sand and fine sediment accretion on the Lincolnshire coast at Donna Nook.

The geological context for sources, pathways and sinks is discussed more fully in Appendices 10 and 14.

Modelling results (Figures 72, 73, 82, 83)
The transport rate of sand and gravel in this region can be assessed at an overview level from the material presented in Section 4.7 of the report. The detailed results for this area have been plotted to show comparison between the two extreme cases of tidal transport of fine sand and storm surge transport of fine sand.

Seabed sediment transport indicators (Figures 92, 93)
The most up to date information on seabed sediment transport indicators has been mapped. These figures show the net direction of sediment transport inferred from seabed bedforms or the axis of transport where no net direction could be determined.

Field data (mouth of Humber estuary)
New field data has been collected for the seabed sediment transport indicators and the pattern of surface suspended particulate material and water salinity (Appendix 6). This has been discussed in Section 3.6.3 and interpreted data added to the seabed sediment transport indicator map (Figure 93). The interpretation was undertaken in collaboration with the British Geological Survey through a meeting at their offices where they were able to consult other information available to them, including preliminary analysis of their own new field data collected within the Humber Estuary Shoreline Management Project Phase 2. The detailed behaviour of sediment in the mouth is expected to be confirmed in the HESMP2 study.

6.1.1 Schematic sediment transport diagram

The interpreted sediment transport for this region has been presented in Figures 100 and 101. The backdrop is taken from the relevant Admiralty Chart showing the land (beige), the intertidal area above 0 m Chart Datum (green), depths above 10 m (mid-blue), and depths above 20 m (pale-blue).

The black arrows indicate average transport that might be happening on a day to day basis due to tidal and wave action, either with a preferred direction (in the direction of the arrows for single headed arrows) or in both directions at different times and under different conditions (double headed arrows). The grey arrows indicate the situation under tidal current action with the effects of an extreme water level (surge) event superimposed, wave stirring and wind drift. The model scenario on which this interpretation was based had a return period of around 1:20 years. The locations of the arrows are intended to aid the reader in interpreting the sediment transport pathways in a particular area and the summary of information addressing the key strategic issues.

6.1.2 Issue A – Northern Boundary

The main items in this issue can be broadly summarised as follows.

Summary of Issue A – Northern Boundary

At the northern boundary of Southern North Sea Sediment Transport Study (SNS2), material is understood to move south along the nearshore area, feeding past Flamborough Head. Under certain circumstances material is believed to move north. The movement of material further offshore is uncertain.

This forms the boundary to the study area and as such it is seen as critical that movement across this boundary is considered. In addition, the supply of sediment from the north along the nearshore area is identified as balancing the sediment budget for Holderness. In terms of coherence, confidence in this boundary process is critical.

Implications: This information is important in providing confidence in the defining sediment pathways within the study area. It is seen as important to the management of the Bridlington frontage and its interaction with the Smithic Bank (*strategy level issue,* A^1) and in understanding the behaviour of Holderness (A^2).

Information: Several studies (Appendix 3, Flamborough Head to Donna Nook) have been carried out in the area. Bedform information may assist in the analysis.

And the interpretation of the SNS2 results has generated the following assessment of this issue:

Assessment of Issue A Northern Boundary

Key points

- *Confirm boundary to SNS2 at Flamborough Head*
- *Feed past Flamborough Head to north of Holderness and relationship with Smithic Bank*

Ref:

Context

Examination of the charts show deep water close to Flamborough Head, compared to the much wider nearshore zone to the south. With the exception of the Smithic, shown as sand, the offshore sea bed is shown as a gravel to medium sand sheet with areas of sand waves and, closer to shore, areas of exposed till. The Smithic bank is seen as the development of a banner bank developed from the headland, with a net clockwise circulation. The SMP review has identified an average annual drift in the order of 40,000 m^3 feeding from the north. Seabed indicators indicate some southerly drift close offshore to the Head and continuing south both in the offshore and along the outer face of Smithic. Further south and well offshore there is a cluster of non-directional megaripple indicators with BGS interpreted features showing both north and south seabed movement. ***CP1*** ***CP3*** ***CP4*** ***Fig.92 to 93***

The general plots of sediment residual for spring tides show a strong net southerly movement close to Flamborough Head, even for 2 mm gravel just to the north of Flamborough. This stream of southerly movement, though weaker, continues south offshore of Holderness. Both the general and more detailed plots show the anticipated circulation pattern around the Smithic Bank. The general pattern of spring tide movement is merely reinforced by wave stirring. Neap tide residuals show a significant, though much weaker, drift reversal over much of the area. The surge plot shows a strong reinforcement of normal spring tide features in the inshore area, to the extent of overriding the circulation pattern around the Smithic, but an apparent northerly pattern of drift in the offshore area. ***Fig.72*** ***Fig 72*** ***Fig 37*** ***Fig.42*** ***CP6***

Under this relatively extreme condition modelled, southerly net seabed drift strengthens towards the shore forming a distinctive corridor of movement.

Longshore drift models show a consistent pattern of southerly drift from the south of Bridlington and a variable drift north of Bridlington possibly indicating a weak northerly movement against the shore in the lee of Flamborough Head. The drift rates calculated at a particular location will be dependent on the width of foreshore considered in the calculations, i.e. how much influence of tidal currents there is in addition to wave driven transport.

Discussion
There is a good consistency in data relating drift from the north of Flamborough feeding, both on a geological and present day timescale, the development of the Smithic Bank. Further offshore net flux decreases. The direction of flux over the inshore area is consistently south and this is supported by bedform indicators. The features offshore show a less clear indication of drift and, even, the possibility of northward movement on occasions. This is consistent with the variation noted due to neap, but more significantly, surge tide conditions.
The impact of surge conditions is such that material is likely to be driven from the nearshore sink of Smithic on to the coast, primarily south of Bridlington, between Bridlington and Hornsea. This feed, drawing on the accumulation under normal conditions within the Smithic Bank area, is significant to the management of the main Holderness coastline; potentially providing material and explaining the high drift rates at the north of the main frontage.
Possible links from the shore to Smithic Bank have been identified in local strategic studies but these are considered to be weak.

Conclusions
- *Boundary,* although there is a drift across the northern boundary of the SNS2 it is felt that this location is still an appropriate choice. North of the boundary sediment patterns and the geological structure are far more complex.
- *Sediment supply,* The main flux feed is close to Flamborough Head, this feeds to the Smithic Bank area and from there, sporadically, to the shore. There is, potentially, a weaker supply into the study area further offshore but its movement south may be relatively limited

6.1.3 Issue B – Role of Holderness

The main items in this issue can be broadly summarised as follows.

Summary of Issue B – Role of Holderness

The SMP has identified, partly by inference from studies of erosion and shoreline transport rates and in part from sediment trend analysis, that there is a division of transport to the southern end of Holderness, in the area of Easington, between that moving longshore and that moving offshore. It is suggested that some 60% of material from the Holderness system moves from the shore at this point. This is put forward as the main transport mechanism for material to the North Lincolnshire shoreline. It is not clear whether the transfer of material is direct or indirect, through the offshore bank system.

Implications: Questions raised by this issue are:
- The independence of Holderness *(B^1)*
- To what degree might changes in the Humber Estuary influence the movement of material across the estuary mouth *(B^2)*
- To what degree is the Cleethorpes (Donna Nook) frontage directly influenced by actions on Holderness and to what degree is the frontage influenced by the behaviour or use of the material in the offshore bank system *(B^3)*
- What is the possible extent of supply from Holderness (e.g South Lincolnshire, the Wash or North Norfolk) *(B^4)*.

Information: Various reports (Appendix 3, Flamborough Head to Donna Nook, Donna Nook to Gibraltar Point) are referenced in the SMP and Phase 1 of SNSSTS. Measurement work has been carried out off the Humber Estuary.

The interpretation of the SNS2 results has generated the following assessment of this issue:

Assessment of Issue B The Role of Holderness	
Key points	
➢ *Understanding of sediment drift along Holderness*	
➢ *Potential divergence of sediment offshore at Easington*	
➢ *Pathway to Lincolnshire*	
➢ *Suspended sediment into the Humber*	
➢ *Impact of dredging sites offshore of the Humber*	Ref
Context	
The eroding Holderness cliff line is identified as a major source providing both suspended and semi-suspended fines (3M m^3/yr) and coarser bed load (0.3M m^3/yr). Only some 100k m^3 is deposited on or moves along Spurn. Donna Nook, to the south of the Humber is seen as a major sediment sink.	***CP1,***
Sea bed indicators suggest significant movement around the Binks, southeast of Spurn, but the pattern closer to the Humber channel is confused with indicators possibly demonstrating a zig-zag progression of material southward.	***CP2 and 4*** ***CP7*** ***Fig 93***
Bedload indicators further east along the edge of the Humber channel suggest a possible northerly movement of material with feed back offshore to a convergence area offshore of Hornsea.	
Longshore drift models indicate drift rates similar to those given above consistently along the frontage. Higher drift rates include up to 1km of the foreshore, with drift rates at the cliff toe being only of the order of 30k m3.	***CP3 and 6*** ***CP8***
The SMP review identified work suggesting that the main drift regime is driven by high energy low frequency events (HELF). Issue A identifies a potential significant feed from the Smithic Bank under HELF events at the northern end of the frontage.	***CP9***
The work on Mineralogical Tracers indicates a narrow (up to 7km wide) but strong pathway between Holderness and Donna Nook. This is constrained further east by an erosional area around the Inner Silver Pit. There is a strong indicator of supply of fine material into the Humber and a link between the Humber and the wider area of the North Sea.	***CP2 and 5*** ***Fig 36,, 73*** ***Fig 40***
The model results for residual flux show a general southerly drift on spring tides over the whole area, increasing towards the Humber but decreasing immediately to the south of the Humber channel. Neap tides show a similar if weaker drift in the inshore region but turning to the north offshore. The pattern of movement along the Humber channel on neap tides becomes confused, with a northerly drift from the Silver Pit area. Increasing wave stirring, increases the southerly inshore flux against the shore. The specific surge event modelled shows a very strong but narrow pathway parallel to, then leaving the shore, in a more direct southerly direction, at Easington. This southerly flow in effect ignores the existence of the Humber.	***Fig 41 to 45***
Dredging areas adjacent to the Humber are to the east of the main sediment pathway.	***CP10 and Fig 52***

Discussion

Put together, there is consistent evidence of bedload material moving across the Humber, linking Holderness to Lincolnshire. This link occurs relatively close inshore and is direct. Under general low to medium energy conditions there is a relatively weak drift along the shore, moving along the shore to Spurn, through the Binks and "riffling" across the Humber channel. Indications are that this movement may be well under 100k m^3/yr, with material being taken out in the accumulation on Spurn, lost potentially to the estuary and recycled from the Binks back north to the shore or offshore.

Under more extreme conditions, material is most probably fed into the Holderness shore from the Smithic (Issue A area), gathering material from the eroding cliffs and deposits of the foreshore along the whole frontage and forcing clear of the shore, at the reorientation at Easington. Material is then driven unimpeded to the Lincolnshire coast. This supply may well be at the upper end of estimates for drift along Holderness (330k m^3/yr) over a series of individual events.

The principal pathway for bedload movement remains near to the shore, this being consistent with the distinct erosional area of the New Sand Hole and Silver Pit. Seabed indicators suggesting northerly movement from the northern side of the Humber channel (North Sand Hole) may be offshore and outwith this intense high energy nearshore stream or may be reflecting, or supporting, the other indicators of limited northerly drift under specific conditions. This potential for northerly drift, on occasion, may be significant in maintaining material further offshore from the Holderness coastline.

Suspended or semi-suspended material from Holderness has been important to the development of the Humber and would potentially be an important source for changes within the estuary. Suspended sediment pathways tend to work across the nearshore bedload stream, with material from Holderness being fed into the North Sea sediment stock and material being carried in and out of the Humber.

Conclusions

- Under general conditions there is a relatively weak drift south over the frontage from south of Bridlington onto Spurn.
- The nature of material will vary as different exposures of the cliff are tapped.
- The main drift system is activated by higher energy, particularly surge driven events. Under such events material is fed to the northern end of the frontage from Smithic, but continues to gather the bulk of material along the whole frontage. The main stream of material leaves the coast at Easington but continues in a narrow path across the Humber, to Donna Nook.
- Dredging activities are well outside this principal sediment stream.
- There may be some sediment drift north in the offshore region, further evidence could be obtained in relation to this extending the mineralogical work and in examining the transient nature of bedform indicators.
- Holderness provides a potentially important sediment supply for the Humber.

6.2 Lincolnshire

Chart – Figure 52, 53
Seabed facies(sediment type, features) – Figure 60, 61
Sediment drift rates – Figure 66
Net transport of fine sand on spring tide – Figure 73, 74
Net transport of fine sand under storm surge condition – Figure 83, 84
Seabed sediment transport indicators – Figure 93, 94

Setting (Figures 52, 53, 60, 61)
This stretch of the coastline is characterised by the embayment of the outer Humber Estuary in the north and the Wash in the south. The coastline is relatively straight with some nearshore and offshore banks in the southern part of the coastline.

Conceptual longshore drift model forLincolnshire (Figure 66) (Appendix 11 provides more details)

The frontage may be split into four sections:

- An accretionary area around Donna Nook and Saltfleet
- A relatively stable area between Saltfleet and Mablethorpe
- An erosional area between Mablethorpe and Skegness
- An accretionary area between Skegness and Gibraltar Point.

In the vicinity of Cleethorpes, Motyka (1986) reported there was a low rate of northward (up estuary) littoral transport, which was captured by the extensive system of groynes. However, south of the town Motyka (1986) reported definite evidence of southerly net drift. Robinson (1970) states that longshore drift is to the north at Grainthorpe and Tetney Haven (on the northern side of Donna Nook) as shown by the diversions of the channels formed by outfalls in this location. However, the Department of the Environment (1980) 'Coast Protection Survey' reported that the general direction of littoral drift just south of Cleethorpes was to the south-east. The more recent Shoreline Management Plan (Posford Duvivier, 1998, volume 1) accepts that longshore drift is from east to west between Donna Nook and Cleethorpes. In particular, the nett longshore drift from Cleethorpes to Grimsby (management unit 17) and Humberston to Donna Nook (management unit 18) was reported to be westerly. However, the SMP (Posford Duvivier, 1998, volume 2) also gives an example of a rock breakwater at Humberston retaining sand on its western side and having very low beaches to the east, implying easterly transport.

This area is at the mouth of the Humber Estuary so sediment transport is strongly influenced by tidal currents, although the estuarine influence decreases towards the east. Modelling by ABP (2000b) shows tidal residual currents near the bed forming eddies in the lee of Spurn Point. It also showed onshore-directed tidal residuals at Donna Nook. The tidal residuals divide, with residuals heading into the estuary and south along the coast. This parting was also modelled in this study (Figure 73). The direction of net sediment transport due to tidal action is from east to west between Donna Nook and Humberston Fitties. However, the sheltering influence of Spurn decreases on moving south-east along the coast so the potential for easterly transport, due to breaking waves on the beach, increases in this direction.

Therefore the balance between the sediment transport due to waves and tides varies in the long-shore and cross-shore directions. The tidal influence decreases both as one moves southeast and as one moves inshore. Conversely, the influence of waves on the sediment transport increases as one moves southeast and as one moves inshore. However, there will be a time variation as situations will arise where wave-driven transport at the top of the beach will be to the southeast while tidal transport even at low water will be to the northwest.

From historical evidence, Donna Nook is a sediment sink. Previous research using seabed drifters as indicators of water/sediment movement, suggests that much of this accumulation originated from the release of fine sediments arising from the erosion of the Holderness cliffs. This view is supported by the coastal area modelling performed for this project (Figure 73) and the seabed indicators (Figure 93) which also strongly supports the view that the sediment pathway to the Lincolnshire coast is in the vicinity of the mouth of the Humber, rather than further offshore. The sediments tend to accumulate in the vicinity of Donna Nook, where the south-moving ebb current from the Humber meets the north moving ebb current off the coast of Lincolnshire, creating the right conditions for a "sediment sink". This convergence of tidal currents is held to be largely responsible for the outgrowth of the lower foreshore, which now extends more than 5km seawards at low tide.

South of Donna Nook the increased exposure to wave action results in redistribution of some of the muds, silts and sands. Finer fractions are transported offshore in suspension, while sands tend to be blown onshore or transported southwards by littoral currents. The southerly diversion of the outfall at Saltfleet Haven (south of Donna Nook) indicates that longshore drift is to the south there.

The Mablethorpe to Skegness frontage has eroded in recent years. Beach levels lowered, leading to the largest beach recharge operation in the UK to date. The rate of littoral transport varies slowly along the frontage and is everywhere, on average, to the south. The quoted modelled longshore drift rate magnitudes depend on the width of the beach that is to be considered.

South of Skegness, in the approaches to The Wash, there is a sediment sink. Sediment moves south from Skegness into an area where sheltered conditions have resulted in the development of a wide sand foreshore and an extensive system of sand dunes and salt marsh, which extend southwards to Gibraltar Point. The longshore movement of sand to the south builds up spit features at Gibraltar Point and deflects the course of the Steeping River. There are a large number of sand banks off Gibraltar Point and the sediment transport in this area is too three-dimensional to be modelled using coastal profile models. However, it is believed that much of the sand enters a (perhaps temporary) sink at Gibraltar Point (Figure 94), while some of the fines may be transported offshore and then enter the Wash, driven by tidal currents (Figure 74).

Local sources of material in this section include some beach and sand dune erosion and erosion of the clay substrate underlying the beaches, particularly in the south Lincolnshire coast. Accretion of material has taken place at Donna Nook and to the south of Skegness. The geological context for sources, pathways and sinks is discussed more fully in Appendices 10 and 14.

Seabed sediment transport indicators (Figures 93, 94)
The most up to date information on seabed sediment transport indicators has been mapped. These figures show the net direction of sediment transport inferred from seabed bedforms or the axis of transport where no net direction could be determined.

Modelling results (Figures 73, 74, 83, 84)
The transport rate of sand and gravel in this region can be assessed at an overview level from the material presented in Section 4 of the report. The detailed results for this area have been plotted to show comparison between the two extreme cases of tidal transport of fine sand and storm surge transport of fine sand.

6.2.1 Schematic sediment transport diagram

The interpreted sediment transport for this region has been presented in Figures 101 and 102. The backdrop is taken from the relevant Admiralty Chart showing the land (beige), the intertidal area above 0 m Chart Datum (green), depths above 10 m (mid-blue), and depths above 20 m (pale-blue).

The black arrows indicate average transport that might be happening on a day to day basis due to tidal and wave action, either with a preferred direction (in the direction of the arrows for single headed arrows) or in both directions at different times and under different conditions (double headed arrows). The grey arrows indicate the situation under tidal current action with the effects of an extreme water level (surge) event superimposed, wave stirring and wind drift. The model scenario on which this interpretation was based had a return period of around 1:20 years. The locations of the arrows are intended to aid the reader in interpreting the sediment transport pathways in a particular area and the summary of information addressing the key strategic issues.

6.3 The Wash

Chart – Figure 53 *Seabed facies(sediment type, features) – Figure 3, 61* *Sediment drift rates – Figure 67* *Net transport of fine sand on spring tide – Figure 74* *Net transport of fine sand under storm surge condition – Figure 84* *Seabed sediment transport indicators – Figure 94*

Setting (Figures 3, 53, 61)
This stretch of the coastline is characterised by the embayment with its fringing banks and flats.

Conceptual longshore drift model for The Wash (Figure 67) (Appendix 11 provides more details)
The Wash is filling with fine marine sediments and estuarine and alluvial silts. There are large shoaling areas, which effectively dissipate wave energy. Therefore there has been no strong call for longshore transport modelling along most of the coastline of the Wash. The shoaling areas also allow salt marshes to continue developing. Ke et al. (1996) used a tidal model to estimate that bedload sediment transport into the Wash amounted to approximately 14,000m^3/year. The historic rate of infilling was faster than it is today, and most of the material carried into the Wash has been carried in suspension (although Ke at al., 1996 did not model the littoral drift entering the Wash at Gibraltar Point). The modelling in this study has shown infilling by tidal action (Figure 74) enhanced on surge tides (Figure 84). Seabed indicators also show transport pathways into The Wash. The modelled sediment transport along the mixed beaches between Snettisham and Hunstanton are to the south and generally small.

The banks in the Wash act as sinks for sand sized material and the foreshore for finer material.
The geological context for sources, pathways and sinks is discussed more fully in Appendices 10 and 14.

Modelling results (Figures 74, 84)
The transport rate of sand and gravel in this region can be assessed at an overview level from the material presented in Section 4 of the report. The detailed results for this area have been plotted to show comparison between the two extreme cases of tidal transport of fine sand and storm surge transport of fine sand.

Seabed sediment transport indicators (Figures 94)
The most up to date information on seabed sediment transport indicators has been mapped. These figures show the net direction of sediment transport inferred from seabed bedforms or the axis of transport where no net direction could be determined.

The area offshore the Wash lies at the junction between two of the BGS seabed sediment facies datasets (Figure 5b) and the key to sediment type is not entirely conformal between the two datasets, hence the difference in colour.

6.3.1 Schematic sediment transport diagram

The interpreted sediment transport for this region has been presented in Figure 102. The black arrows indicate average transport that might be happening on a day to day basis due to tidal and wave action, either with a preferred direction (in the direction of the arrows for single headed arrows) or in both directions at different times and under different conditions (double headed arrows). The grey arrows indicate the situation under tidal current action with the effects of an extreme water level (surge) event superimposed, wave stirring and wind drift. The model scenario on which this interpretation was based had a return period of around 1:20 years. The locations of the arrows are intended to aid the reader in interpreting the sediment transport pathways in a particular area and the summary of information addressing the key strategic issues.

6.3.2 Issue C – The role of the Wash

The main items in this issue can be broadly summarised as follows.

Summary of Issue C – The Role of the Wash

Both the Environment Agency and Kings Lynne and West Norfolk District Councils identified the need to better establish the sediment links between the Wash and the other areas of the North Sea. It is an area perceived by many as being independent from the sediment regime offshore. Within the Wash there is a consistent pattern with respect to finer material suggested in the SMP and the subsequent strategy studies, identifying a trend for material to be moved in through the central channel and then to move out along the edges of the Wash. There is some question as to possible movement of coarser material from the Lincolnshire shoreline and similarly from the western end of the North Norfolk coast. The main issue, raised by consultees, was, however, the identification of the source.

Implications: The main concerns relating to this were:

- The supply of finer material feeding the Wash banks and to what degree this came from other sections of the coast *(C^1)* . (This issue relates to issue B above.)
- To what degree should the management of the Wash be concerned with the re-nourishment of the Lincolnshire shore *(C^2)*.
- To what degree should there be concern about the erosion at Gore Point *(C^3)* on the eastern shore of the Wash.

Information: There have been several reports and seminars relating to the North Norfolk Shoreline development. Strategies have been developed for sections of the Wash shoreline, the Lincolnshire shoreline and the behaviour of the river outfalls.

Less work has been identified in relation to the offshore links and this will need to be a focus for SNS2, particularly in relation to finer suspended materials.

The interpretation of the SNS2 results has generated the following assessment of this issue:

Assessment of Issue C The Role of the Wash

Key points

- *Continuation of sediment path south from Donna Nook*
- *Impact of beach recharge on the sediment input to the Wash*
- *Identification of sources*
- *Linkage with North Norfolk*

Ref

Context

The offshore to nearshore seabed is shown as a continuation of the gravel to medium grained sand sheet of further north. In terms of bathymetry this is cut by the central channel of the Wash, linking through to the Silver Pit off the Humber. Historically, there has been growth of the Donna Nook and Saltfleet sand areas to the north of the Lincolnshire coast, the denuded and denuding beaches of central Lincolnshire and the growth of the shoreline at Gibraltar Point.

CP1, ***CP3***, ***CP1***

To the east of the Wash are the horizontally eroding barrier features of the North Norfolk coast, moving back over, and exposing to erosion, the erstwhile vertically accreting marshes behind. There is a continuous narrow sand strip within the inshore area running from Blakeney Point to Gore Point; there is no such continuity of shingle along the tide line. Between Norfolk and Lincolnshire, is the massive traditional sink of the Wash that has *absorbed a large volume of the available sediment through its central channel.*

CP4, ***Fig 94***

Sea bed indicators suggest a general southerly movement in the nearshore region of the Lincolnshire coast, becoming more confused in the region of the shore parallel banks off Saltfleet. There is a potential northerly movement indicated to the seaward side of these banks at their northern end (the Protector Overfalls), feeding back across the Humber well offshore. Further south (the Inner Dowsing) offshore of the Lincolnshire coast there is a more consistently southerly movement towards the Wash. On the eastern flank of the central channel (the western edge of the Docking Shoal) there are strong indicators of movement south, but further south the movement is east across the Burnham Flats. This easterly movement is again evident, this time from the Wash, feeding into a consistent stream east across North Norfolk.

Fig 93, ***CP4***, ***Fig 94***, ***CP5***, ***Fig 36,, 74, 75***

Offshore along the Race Bank and the Dudgeon Shoal a north west movement is indicated towards the confluence of the central channel and the southern end of the Silver Pit. This band of anticlockwise movement appears to derive from an area of non-directional indicators off Cromer.

Fig 94, 75

Net tidal residuals of sediment flux for spring tides show two dominant corridors of drift; nearshore from Saltfleet working south and along the central channel from the southern end of the Silver Pit. There is some confusion further to the east with relatively low residuals showing little consistent movement away from the central channel across the Burnham Flats. Neap tides show only a strong drift into the Wash local to the entrance to the Wash and a sediment drift towards the northwest offshore from the North Norfolk. Spring residuals for gravel tend to suggest a southerly movement from the Humber area but an anticlockwise movement centred on the Docking Shoal.

Fig 95, ***CP5***, ***Fig 74, 75***, ***Fig 40***, ***CP6***

The modelled surge residuals highlight the nearshore stream across the Humber, decreasing and narrowing south of Donna Nook, before accelerating along the Lincolnshire shoreline, leaving the coast at Skegness to enter through the inner central channel of the Wash. At the same time, although not initially as strong, there is an increasing flux down the central channel bifurcating between the central feed to the Wash, and strengthening, across the Docking and Burnham Flats. This latter flow moves as a stream close to the shore along the North Norfolk coast, towards Cromer.

CP3, ***Fig 46***

Continued

Shoreline drift modelling has shown a consistent, but varying southerly drift along the Lincolnshire shoreline. The variation in drift identified in the modelling report reflects the difference in the width of shore modelled and, in consequence, highlights the significant movement in the nearshore area. Indicators are, from the modelling, that little shoreline drift is active north of Saltfleet, with the possibility of a north net drift into the Donna Nook system. *CP5*

The few estimates of drift along the North Norfolk coastline suggest relatively high east to west movement. However, there is a recognition that modelling techniques may result in very site specific rates. Other suggestions have been for far lower continuous rates over the frontage and for waves of material to be deposited and moved from west to east. *CP6* *CP3*

The peak tidal currents are directed into the Wash at its mouth whilst tidal residuals indicate no consistent net flow of fines into the Wash, although there is a generally high concentration of suspended sediment available. The tide residuals show no clear suspended sediment trail of fine material from Holderness. Rather the indication is of a general availability from the North Sea pool of fine material. *Fig 20 ,21* *Fig 31, 32*

Dredging areas lie between the southern end of the Silver Pit and the Proctor Overfalls and along the outer area of the central channel. Although, in this latter case, material is taken from the western edge of the Docking Shoal. *CP10* *Fig 53*

Discussion

There is a complex and condition driven pattern of pathways over the region between Donna Nook and Cromer, focussed in on the Wash. This may possibly be best described by dividing the area along the central channel of the Wash.

Donna Nook receives sediment from Holderness, principally during more extreme events, as a stream, close inshore across the Humber. The overall movement of material decreases south of Saltfleet with the bulk of material feeding both directly and through working by wave action into the system at Saltfleet. There is, potentially some reworking of material back north further offshore by neap tide action.

Feed moving beyond Saltfleet will tend to move in the main nearshore flow being accelerated past the Lincolnshire coast to feed into the central channel of the Wash through the banks off Gibraltar Point. This increase in movement to the south is also evident under normal spring tide action and along the shore by wave action tending to denude the Lincolnshire nearshore and beach. Material moved off the beaches of Lincolnshire will tend to move into this southerly flow. Overall drift rates alongshore and nearshore are likely to be in the order of that modelled as 100k m^3/yr. This will to a degree be dependent on fresh surge driven material from the north.

A secondary flow of material, potentially weaker but more continuous, moves from the southern area of the Silver Pit along the central channel under both normal and surge conditions.

Within the Wash, there is a re-circulation of material to and then north along the northern bank of the Wash. This feeds back into the clockwise sediment stream.

Considering the eastern flank of the central channel; under normal tide conditions little material escapes from the channel, with a confusion of movement over the Burnham Flats. Some material escapes from the southern side of the Wash to form a weak shoreline stream.

Continued

During surge conditions, and possibly dependent on specific surge conditions, a large proportion of the material brought into the central channel is diverted from its course to the Wash, moving eastward into the area offshore of Cromer. In particular a very strong stream is developed along the North Norfolk coast taking material from the Wash at Gore Point and from within the Sunk Sand and Middle Bank. It is not possible to conclude whether these banks actually suffer net loss under such conditions but any loss could expose the shoreline to increased wave activity.

Further offshore, to the northeast, both spring and neap tides have the potential to bring material from the east into the central channel, supplementing supply to the area robbed during the surge event.

Conflicting evidence as to the drift along the North Norfolk coast, and as a consequence to the Wash, may to a degree be resolved from the study findings. While under normal or moderate wave conditions there may be a west tending drift of sand along a narrow width of frontage, there is a weaker counter-drift within the nearshore area to the east. Under more extreme events both pathways may be active but in terms of sediment movement the eastward movement dominates.

Overall, the area of interaction centred around the Wash extends: north along the coast to Saltfleet, with a moderate supply of material by-passing Donna Nook from Holderness, out to the southern end of the Silver Pit and includes a potential re-circulation of material from the offshore in the region of Cromer. At the same time there is potential leak of sediment along the nearshore to Cromer and beyond (see Issue E) with a small potential movement of sand along the shoreline back from the east.

One of the licensed aggregate dredging area northeast offshore of the Wash is sited between the two main pathways into the Wash area. The central channel is a significant pathway for fine sand sized material feeding the Wash. However, it is important to compare in a relative way the high volumes of natural movement with the quantities and size grading of material being dredged.

Furthermore it is understood that sand sized material from licensed areas off the Wash is also used for beach recharge to Lincolnshire (Lincshore) and may, therefore, merely being moved from one principal pathway to another.

Conclusions

- The pathway from Holderness past Donna Nook is seen as significant and principally active on extreme storm surge events. Under normal tidal action material is taken from the nearshore of the Lincolnshire coastline
- Sand sediment dredged from licensed areas offshore of the Wash and placed in the Lincolnshire re-charge is likely to enter the Wash but through the nearshore banks at Gibraltar Point, rather than through seabed transport further offshore.
- Principal sources for bedload are: Holderness (<100k m^3/yr), Lincolnshire coast and nearshore, southern end of the Silver Pit, offshore from the east and, potentially, from offshore of Cromer.
- Principal source of suspended sediment is less clearly defined, potentially being derived from the full arc of the North Sea defined by the angles of the adjacent coast. The Wash is not shown as a net importer of material, rather as an opportunistic accumulator when conditions within the Estuary are appropriate.
- There is a strong two way link between North Norfolk and the Wash.

6.4 North Norfolk

Chart – Figure 53 *Seabed facies(sediment type, features) – Figure 61, 62* *Sediment drift rates – Figure 67* *Net transport of fine sand on spring tide – Figure 74, 75* *Net transport of fine sand under storm surge condition – Figure 84,85* *Seabed sediment transport indicators – Figure 94, 95*

Setting (Figures 53, 61, 62)
This stretch of the coastline is characterised by cliffed and duned sections as well as barrier beaches. There is a large concentration of nearshore and offshore banks.

Conceptual longshore drift model for North Norfolk (Figure 67) (Appendix 11 provides more details)
The longshore transport regime along the north Norfolk coast can broadly be split into two sections: Gore Point to Weybourne and Weybourne to Winterton Ness.

Gore Point to Weybourne
There is limited longshore drift from east to west between Gore Point and Blakeney village (in the shelter of Blakeney Point) and local reversals in the lee of banks. The most obvious sign of this is in the continued accretion of spits at the western end of Scolt Head Island. This has caused some problems in the sheltered area inshore of the point, where a local drift divide has caused some beach lowering and erosion. However, it is not clear if Scolt Head Island is fed by sediment from a source to the east, or whether the accretion on its western end is fed by erosion of the seaward face of the island. . Andrews et al. (2000) and Bridges (1989) note that the coastline of Scolt Head Island is moving south and extending west. Bridges suggests that the coastline at the eastern end has moved south faster than the western end. Thus much of the shingle needed to extend the western end of the island comes from the erosion of the northern coastline, suggesting that there is no great supply of sediment. BGS data suggests that although sand and shingle is being transported to the west on the beach face, sand is transported to the east if it is carried offshore of the steep beach face onto Burnham Flats, perhaps during storms.

Sand and shingle is transported west from around Weybourne along Blakeney Point. The volumes transported are a lot lower than would appear to be the case from the early paper of Vincent (1979) as the transport rates quoted are 'potential sand-equivalent' transport rates (Vincent, personal communication). When the proportion of sand and gravel is taken into account, the calculated transport rates are of the order of 10,000-15,000m^3/year of sand and the same volume of shingle transported from the west of Weybourne towards the base of Blakeney Point. Along the Point, the transport rates rise to values of the order of 40,000-60,000m^3/year of potential sand transport and 20,000-40,000m^3/year of shingle longshore transport. These figures are re-interpretations of old model predictions, so should be taken as indicative only. The potential drift rate increases on going west along Blakeney Point and the limited supply of shingle from erosion around Weybourne may be the main cause of the westwards and southwards movement of the end of Blakeney Point (Andrews et al., 2000).

There is no obvious pathway for shingle to move west from Blakeney Point. There are small shingle ridges to the west, but they may be relict features, not fed by Blakeney Point. It may be possible for some sand to be transported to the west, from Blakeney, below the level of the shingle beach. However, there are no obvious signs of such a supply arriving further west along the coast and any sand that moves significantly offshore will almost certainly be transported to the east by tidal action (Figures 74 and 75) as shown by the seabed indicators (Figures 94 and 95).

Somewhere in the vicinity of Weybourne (probably west of Cromer and Sheringham) there is a null point in the longshore transport (Figure 67). This is a statistical phenomenon whereby, on average, the mean nett annual longshore drift rate (over a period of years) is around zero – as discussed further in Section 7. It does not represent any form of physical divide. Its position changes in time, as it primarily depends on the wave conditions, which vary in time. Evidence (discussed in Appendix 11) suggests that the drift divide is west of Sheringham (at least for shingle) and east of Blakeney Point. There is some sediment supply into this region from the eroding cliffs around Weybourne.

Weybourne to the north of Winterton Ness

Around Sheringham there are low drift rates from west to east, for shingle. These increase from west to east but the supply decreases, implying that the drift rate on the eastern side of the frontage is limited by sediment supply, rather than potential transport rate. At Cromer, there is a mixed beach and it is important to consider shingle as well as sand in the modelling. The percentage of shingle reduces to the east.

The potential sediment transport rate increases from Sheringham through to Happisburgh, although this is not a monotonic increase due to the sheltering effect of Haisborough Sand. It is important to include the effect of Haisborough Sand in the modelling of longshore drift rates from Sheringham through to and beyond Happisburgh (probably to Hornsey). The effect of the offshore sandbank on wave and drift calculations is important in limiting the wave climate from particular directions. This effects the magnitude and possibly the direction of the mean nett annual drift rate.

An alternative approach has been examined based on calculating the net longshore drift as the residual from adding the sources and sinks of sediment. This produced a smoothly increasing longshore drift rate from Cromer to Happisburgh. This approach assumed that the longshore drift rates at Cromer (the western boundary of the study) was reasonably well established by a previous Strategy Study. It also assumed that there was no nett gain or loss of sand in the cross-shore direction at the base of effective wave action. This approach minimised the reliance on wave modelling but required the assumption of no nett cross-shore transport.

This region is eroding, with the North Norfolk cliffs supplying about 400,000m^3/year of sand into the littoral zone. The cliff erosion also supplies fines and gravel. The fines are transported offshore in suspension (Figure 75), while the sands and gravel are transported along the shore and also in the offshore area (Figures 68 and 75).

Between Mundesley and Happisburgh the transport rate is reasonably constant to the southeast along the coastline.

East of Happisburgh the offshore, detached breakwaters installed at Sea Palling have reduced the local drift rate considerably. The drift rate has recovered somewhat by Horsey, some 4km down-drift from the breakwaters.

The geological context for sources, pathways and sinks is discussed more fully in Appendices 10 and 14.

Modelling results (Figures 74, 75, 84, 85)

The transport rate of sand and gravel in this region can be assessed at an overview level from the material presented in Section 4 of the report. The detailed results for this area have been plotted to show comparison between the two extreme cases of tidal transport of fine sand and storm surge transport of fine sand.

Field data (Happisburgh, Winterton Ness, Yarmouth Banks)

New data has been collected for the currents, waves and sediment processes near the seabed. Data was also obtained on the patterns of surface Suspended Particulate Material and the seabed characteristics and indicators of sediment transport (Appendix 6). A tracer study into the dispersion of sandy material was also carried out. This showed high dispersion and net movement of the centroid of the tracer was to just east of north by around 120 m in one day.

Seabed sediment transport indicators (Figures 94, 95)

The most up to date information on seabed sediment transport indicators has been mapped. These figures show the net direction of sediment transport inferred from seabed bedforms or the axis of transport where no net direction could be determined.

6.4.1 Schematic sediment transport diagram

The interpreted sediment transport for this region has been presented in Figures 102 and 103. The backdrop is taken from the relevant Admiralty Chart showing the land (beige), the intertidal area above 0 m Chart Datum (green), depths above 10 m (mid-blue), and depths above 20 m (pale-blue).

The black arrows indicate average transport that might be happening on a day to day basis due to tidal and wave action, either with a preferred direction (in the direction of the arrows for single headed arrows) or in both directions at different times and under different conditions (double headed arrows). The grey arrows indicate the situation under tidal current action with the effects of an extreme water level (surge) event superimposed, wave stirring and wind drift. The model scenario on which this interpretation was based had a return period of around 1:20 years. The locations of the arrows are intended to aid the reader in interpreting the sediment transport pathways in a particular area and the summary of information addressing the key strategic issues.

6.4.2 Issue E – North Norfolk drift divide

The main items in this issue can be broadly summarised as follows.

Summary of Issue E – North Norfolk drift divide

This issue relates to the concerns over conflicting evidence with respect to the North Norfolk drift divide in the region of Sheringham and Cromer. Although at the shoreline there is a clear distinction between material moving west to Sheringham and south to the main East Anglian shore, there is uncertainty as to the behaviour of material in the nearshore region. Various concepts have been expounded. Coupled with this is the mechanism for feed to the Cromer shore.

Implications: Clearly the issues raised above are quite fundamental in setting out North Norfolk's policy to dredging.

Information: North Norfolk DC has completed a local strategy study for this frontage. Various papers and presentations have been produced on the area.

And the interpretation of the SNS2 results has generated the following assessment of this issue:

Assessment of Issue E North Norfolk Drift Divide

Key points

- *Conflicting evidence as to movement along the North Norfolk Coast , in particular in the area around Sheringham and Cromer*
- *Relationship as to feed onto the Cromer Frontage*

Context

The sea bed facies maps indicate a significant change between the areas to east and west of Cromer. To the west there are the relatively large sand banks of Burnham Flats and the Docking Shoal, to the east, and more immediately offshore of Cromer, are the relatively immobile beds of sandy gravel overlying chalk platform. ***CP1 Fig. 23a, 62***

The geological review, identifies the importance and variability (in terms of material types) of the cliffs west of Cromer as a source to the frontage. Further west the report identifies a complex pattern of historical development of the barrier and temporary sink along North Norfolk. This frontage is seen as having had a history of accretion inshore of the barrier system, with a progressive erosion of the barriers (e.g Scolt Head) and their subsequent elongation, principally westward. This barrier erosion has tended to roll back over the marsh behind, exposing the marsh to erosion at the seaward edge. ***CP1***

The discussion of the drift divide within the longshore drift collation identifies no clear divide along the frontage. Material is capable of being moved in either direction. However, the predicted drift results shown an increasing *statistical* preference for material to drift west as one moves west of Cromer, and a corresponding but more dominant tendency for easterly drift to the east of Sheringham. Although there is a lower foreshore pathway for the transfer of finer sediment along North Norfolk, there is little evidence of a consistent drift pathway for shingle. Blakeney Spit is seen, therefore, as a sink for coarse material. ***CP6*** ***CP1*** ***Fig 68***

Offshore seabed indicators show both nearshore and offshore (over the Burnham Flats and Docking Shoal) movement in an easterly direction. Further offshore there is some indication of movement to the west. Offshore of Cromer the sea bed indicators show shore-parallel movement with no clear evidence of direction. ***Fig 95***

Tidal sediment flux residuals for the spring tide show a weak movement in a nearshore stream from the Wash area towards Cromer, increasing to the east of Cromer. Further offshore the flux direction is more confused. Neap flow residuals show a less persistent nearshore flow than on springs but a more consistent westerly movement offshore. ***Fig 36*** ***CP8 Fig 31, 32***

Wave stirring under the spring tide condition tends to reinforce the spring tide pattern. The more extreme wave conditions tend more towards the surge conditions modelled. The surge plots show a strong west to east sediment flow across the Burnham Flats close along the shore towards and past Cromer. ***Fig 42 Fig 46***

Discussion

The study is showing no single pattern of sediment movement. The main source to the shore is considered to be the cliffs to the west of Cromer and depending on exposures this material may vary, with time, from virtually all sand to the occasional input of shingle or flints. Both sand and shingle will tend to be moved to the west, but on occasions can feed to Cromer itself. Material passing Cromer will continue to move exclusively southeast. Coarse material moving west will tend to travel only as far as Blakeney but is unlikely to be moved back from Blakeney Point. Sands moving west from Cromer can and do move further along the shore towards Scolt Head and may provide a weak feed to this region. Any movement offshore of the beach is likely to progress back to the east in the tidally induced sediment stream.

Under surge conditions, there is a greater supply of sand working along the nearshore stream. There is some indication that this may attach itself to the coast in places, offering a potential supply of finer material to the Cromer frontage.

Generally, however, this stream tends to accelerate to the east with the potential to remove material from the inshore bar system adjacent to Cromer. There appears to be little link between the inshore system and the sediment stream further offshore. Mobile sediment offshore appears as streaks, and may be relatively transient. Well offshore, under normal conditions there may be a weak feed to the northwest and under storm surge conditions a strong shore-parallel feed to the east, possibly feeding the Haisborough Bank.

Based on the results of this study there appears to be a low likelihood of there being any influence from licensed dredging activities on the nearshore sediment transport regime.

Conclusions

- The study has provided a better understanding of the variability and helps to resolve some of the conflicting evidence as to sediment movement.
- Feed to the Cromer frontage comes in part from the cliffs to the west both directly by wave action and indirectly through shoreline drift west and partial return in the inshore sediment stream. This stream in strongly reinforced by extreme events providing material from the Burnham Flats to the Cromer frontage.

6.5 East Norfolk/Suffolk

Chart – Figure 54,55, 56, 57
Seabed facies (sediment type, features) – Figure 62, 63, 64
Sediment drift rates – Figure 68, 69, 70
Net transport of fine sand on spring tide – Figure 76, 77, 78
Net transport of fine sand under storm surge condition – Figure 86, 87, 88
Seabed sediment transport indicators – Figure 95, 96, 97, 98

Setting (Figures 54, 55, 56, 57)
This stretch of the coastline is characterised by the realignment of the coast from an essentially northerly aspect to an easterly aspect. There are a number of nearshore and offshore banks.

Conceptual longshore drift model for Winterton Ness to Southwold (Figure 68, 69, 70) (Appendix 11 provides more details)
Sediment enters this area by longshore transport from the north. Around Great Yarmouth the offshore banks produces a complicated pattern of wave transformation that induces some localised northerly sediment transport around South Denes. This offshore bank configuration is not stable, but varies in time, which alters the longshore transport on the beach significantly. The direction of mean transport at a point can change when the banks move – the implications of this are discussed in Section 7. Tidal processes interact with wave-driven processes to move sediment offshore, in a complicated manner that is not included in present-day longshore drift rate models.

The modelled sediment transport is variable but predominantly to the south between Great Yarmouth and Lowestoft (Figures 76 and 77). Some sediment is lost to offshore at the Ness. The drift direction at Kessingland is variable. The longshore transport returns to the south on the northern side of Benacre Ness and remains southerly right down to Southwold. Benacre Ness is moving northwards towards the drift null point. The mechanism for its migration and its sediment balance are in some doubt (Appendix 11) but it is likely that it moves north by differential accretion and erosion. It also loses sand to offshore, with the likely destination of sand being the sandbanks to the northeast. The volume may undergo increases and decreases as the sediment budget varies in time. There does not appear to be a sediment pathway north along the coast from the cliffs of Covehithe and Dunwich to Benacre Ness.

Conceptual longshore drift model for Southwold to Landguard Point (Figure 68, 69, 70) (Appendix 11 provides more details)
Net longshore transport is southwards along most of this coastline. The direction of sediment transport may reverse when waves are from the south-east (such as occurs on the northern part of Orford Ness where shingle can be transported north towards Aldeburgh) but the average drift direction is to the south along most of this coastline. There is a supply of sediment of around 40,000m^3/year from the eroding cliff at Dunwich. The percentage of shingle on the beach increases to virtually 100% at Orfordness. It is believed that sand leaves the coast at Orfordness whereas the shingle continues to move southwards from Orfordness.

The predicted longshore transport rates at Bawdsey Manor, just north of the River Deben were to the south-west (Figure 70), implying that beach material from in front of Bawdsey Cliff may be carried across the River Deben entrance. This ties in with many observations, e.g. of downdrift erosion south of the old military fort at East Lane Bawdsey in 1996.

The broad pattern of longshore transport is from north to south between the Deben and Felixstowe. There may be a small, local region of northerly drift in the north of Cobbolds Point, but the transport rates there are low and the variability large. The most notable exception is that there is southwards drift at Landguard Jetty. Some of the shingle moving south to Landguard Point then gets pushed into Harwich Harbour and north towards the harbour. There is no evidence of accretion at the Pleasure Pier however. Rather there are indications of erosion. Previous modelling suggests that this area received a high concentration of wave energy and was therefore a point where beach material was transported offshore during storms (Halcrow, 2001).

The geological context for sources, pathways and sinks is discussed more fully in Appendices 10 and 14.

Modelling results (Figures 76, 77, 78, 86, 87, 88)
The transport rate of sand and gravel in this region can be assessed at an overview level from the material presented in Section 4 of the report. The detailed results for this area have been plotted to show comparison between the two extreme cases of tidal transport of fine sand and storm surge transport of fine sand.

Seabed sediment transport indicators (Figures 96, 97, 98)
The most up to date information on seabed sediment transport indicators has been mapped. These figures show the net direction of sediment transport inferred from seabed bedforms or the axis of transport where no net direction could be determined.

6.5.1 Schematic sediment transport diagram

The interpreted sediment transport for this region has been presented in Figures 103, 104 and 105. The black arrows indicate average transport that might be happening on a day to day basis due to tidal and wave action, either with a preferred direction (in the direction of the arrows for single headed arrows) or in both directions at different times and under different conditions (double headed arrows). The grey arrows indicate the situation under tidal current action with the effects of an extreme water level (surge) event superimposed, wave stirring and wind drift. The model scenario on which this interpretation was based had a return period of around 1:20 years. The locations of the arrows are intended to aid the reader in interpreting the sediment transport pathways in a particular area and the summary of information addressing the key strategic issues.

6.5.2 Issue F- Sediment circulation Cromer to Benacre Ness

The main items in this issue can be broadly summarised as follows.

Summary of Issue F – Sediment Circulation Cromer to Benacre Ness

As with issue D, this issue relating to the links between or the independence of local sediment circulations along the coast between Cromer and Benacre Ness, is seen as one of the fundamental questions which need to be addressed. Understanding better the various ness mechanisms is seen as important. Local strategies have identified apparent circulations between the shore and the inshore banks. It is important to identify to what degree these are closed systems.

Implications: Behind this issue is the question as to the geographical extent of impacts of major shoreline works and from this to what degree sections of the frontage may be considered independent. Particular sites were identified:

- The Sea Palling Breakwaters (F^1)
- The Caister Breakwaters (F^2)
- Recirculation of material from Great Yarmouth (F^2)
- The proposals for Great Yarmouth Harbour extension (F^3)
- The independence of the Great Yarmouth to Lowestoft frontage (F^4)
- The change in material type and accretion south of Lowestoft (F^5)
- The behaviour of Benacre Ness (F^5)

Information: Various studies including Happisburgh to Winterton strategy, Great Yarmouth Outer Harbour studies, current strategies for Great Yarmouth to Lowestoft and Lowestoft to Thorpeness. Considerable work has been undertaken in examining the historical changes in the Great Yarmouth Lowestoft Banks. Some data may be available from Bacton with respect pipeline landfalls.

Both North Norfolk DC and Great Yarmouth BC felt that understanding better the processes around Winterton Ness would not only help understanding of a specific coastal link, but could also give more information of a more generic nature on the links between local circulations.

And the interpretation of the SNS2 results has generated the following assessment of this issue:

Assessment of Issue F Sediment Circulation Cromer to Benacre Ness

Key points

- *The effect of nearshore control structures on the overall drift pattern.*
- *The re-circulation of material in the Great Yarmouth area.*
- *The continuity of the bank system between Great Yarmouth and Lowestoft*
- *Implications for Great Yarmouth Outer Harbour extension.*
- *The potential links to Benacre Ness and the change in material type south of Lowestoft*

Context

The coast changes in orientation and character over this section. Prominent in this change are the remnant headlands of the Northern Upland (Winterton Ness) and the Southern Upland (Lowestoft and Kessingland) and between them the geomorphological influence of the former Yare Valley. To the south of Kessingland the various headlands exhibit a double banner bank association, while to the north the dominance of nearshore material movement is to the south. The banks off Great Yarmouth are seen in this context of a convergent system with the dominance strongly in favour of the strong southerly drift. ***Fig 54, 55 CP1*** ***CP1***

Within the system the mobility of the banks and channels is influenced by the depth of mobile material within the former Yare Valley and those of its tributaries draining from the upland to either side. ***CP1, CP7, CP6***

The primary source of sediment to this area has been and still is the Norfolk cliffs with additional input from the nearshore streams north of Winterton. ***CP1, CP4***

The bank system forms in effect an umbrella reaching down from Winterton to Benacre (Scroby, Holm and Newcome) within which is a complex circulation and re-circulation of sediment between the shore, the inner banks and the outer banks. Typical movement is clockwise around the banks. Seabed indicators suggest a possible northerly loss to the system through the Cross Sands but more obviously to the south offshore of Lowestoft. Further offshore the pattern of movement indicated is less directional and confused, suggesting banding of sediment paths. ***Fig 36, 76, 77*** ***CP6, CP3*** ***CP1***

Drift is predicted as being predominantly south along the shore but with offshore loss at certain locations. South of Lowestoft longshore drift is shown as to the north with links defined both to the northern end of Newcome Sands and from Newcome to the shore at Benacre. ***Fig 69, 77***

There is a strong suggestion that within the overall system the position of the Holm channel and the Holm Sands results in a variation to drift on the shore and potentially in the links between the northern and southern banks ***Fig 55, 69***

Spring and Neap tide flux residuals indicate a difference in sediment movement. The Springs tend to show a dominance of southerly drift over the general area with intermittent bands of northerly movement. Neap tides show relatively little movement nearshore but increasing northerly movement, away from the banks, further offshore.

Surge sediment flux residuals show a strong nearshore flow of material curving southeast from Cromer, setting slightly against the coast north of Winterton Ness before leaving the coast to the south and increasing again. Through the bank system the flows wax and wane suggesting potential differential movement of material within the banks. The overall trend is strongly south, increasing again at Lowestoft Ness and heading into a more even flow offshore. ***Fig46, 86, 87***

Continued

The seabed indicators at Winterton clearly show a movement of material south into Cockle Shoal. Further south there are other linkages at subtidal spurs between shore and Caister Shoal. ***CP7***

Present licenced aggregate dredging activity is confined within an area offshore of the main bank system and sediment pathways. ***CP10, Fig 55***

Discussion

Overall there is a consistent pattern of development with material moving south along the shore from the north, leaving the shore at Winterton Ness to feed into the Caister and Scroby banks. The coastal cliffs to the northwest do provide an important source. Some minor feed may proceed south along the shore but there is an indication of occasional northerly feed immediately south of Winterton Ness. Both under spring and surge tides the main stream of sediment is quite broad extending some distance offshore. It is known that an inshore bar frequently forms parallel to the beach, and the model results confirm this lies well within the overall zone of sediment movement. The pattern of sediment flow is such that while being relatively shore parallel over much of the coast it tends to set against the coast closer to Winterton Ness.

South of Winterton Ness shoreline drift pathways and movement pathways in the offshore banks are quite distinct. Sediment moving south along the coast is shown in the modelling with an indication from the fieldwork of subtidal spurs providing pathways for sediment to leave the shore. This material then joins a northerly-moving stream along the inner edge of the nearshore bank.

Material is moved clockwise around each bank and may shed material at the northern and southern ends. Whether material then rejoins the shore can depend on the relative position of channels and banks to the south. The nearshore banks can in effect leapfrog material along the coast resulting in a variation in sediment supply to the shoreline.

Material is likely to be delivered to the southern extent of the banks at Benacre Ness. The development and maintenance of this feature is seen, in part, due to this feed and, in part, the differential deposition of material to its northern flank and erosion to its southern flank. The pattern of sediment movement around the banks at the southern end of the system is dependent on the movement of the Newcome Bank in relation to the shore. As this bank moves inshore, tending to close the channel against the shore, so this channel tends towards an ebb (northerly) dominance.

Conclusions

- Although the structures at Sea Palling have a substantial impact on material moving down the shore, this is not believed to have a significant impact at a regional level. The drift stream along the coast is quite broad, beyond the influence of the structures. Material driven offshore by the structures will join this stream and will in part be delivered back to the shore north of Winterton Ness. There will be a local down drift effect due to the structures but this will not extend beyond Winterton Ness.
- Further south a similar movement of material driven away from the shore could be more significant, tending to move material into the north going clockwise movement along the inner face of the banks. Such material may not immediately be returned to the shore.
- To a degree the feed between the Great Yarmouth Banks and the Lowestoft banks depends on the position of the Holm Channel. This may be significant in the development of Great Yarmouth Outer Harbour extension but requires more detailed information than appropriate to the levels of SNS2.

Continued

- Benacre Ness is fed from the offshore banks and is to a degree dependent on the integrity of the linkage along the outer face of the bank system.
- The change in the nature of the beach south of Lowestoft is likely to relate to the narrowing of the channel between the shore and Newcome Sands.
- Variation in the banks is difficult to predict and, within the overall pattern of movement provided by the study, the management of the shore should reflect this need for a responsive approach: based on potential change and vulnerability.
- Currently licensed aggregate dredging takes place in an area which is outside of the main sediment circulation patterns.

6.5.3 Issue G – The role of the Sizewell-Dunwich Banks

The main items in this issue can be broadly summarised as follows.

Summary of Issue G – The Role of the Sizewell-Dunwich Banks

Similar to but quite possibly distinct, in terms of circulation, from Issue F, was the link between the shore and the Dunwich and Sizewell banks. This issue was extended in the concern over the general supply of shingle to the Suffolk Coast.

Implications: The principal local implications relate to the management of the Southwold to Thorpeness frontage (G^1) and the management of the Aldeburgh frontage (G^2). In addition to this, however, is the need to understand better the supply of material to the massive shingle systems of Orford, Shingle Street and the Deben Estuary(G^3) .

Information: There is relatively good quality data available for the shoreline drift system based on the strategy studies, although there is still considerable uncertainty as to specific quantities of material in motion. Little information is identified in terms of the onshore offshore links.

And the interpretation of the SNS2 results has generated the following assessment of this issue:

Assessment of Issue G The role of Sizewell and Dunwich Banks

Key points

- *Links between these banks and the shore*
- *Drift, source and sink to Dunwich frontage*
- *Drift source and sink to Aldeburgh frontage*
- *Links in terms of source to Orford*

Context

There has been rapid erosion of this section of the coast, releasing substantial quantities of material. The dominant drift system has been to the south and, in addition to providing material to the Thames Estuary sink, has provided material to Orford. The retreat of the shore has accentuated the influence of the more resilient geology, creating the existing Ness features at Southwold, Thorpeness and Orford Ness. The offshore banks are consistent with earlier banner banks associated with these ness features, when these features were further to the east. The existing banks of Aldeburgh Ridge, Sizewell and Dunwich are seen as present day banner bank features. There is evidence of growth in the Sizewell and Dunwich banks. The cliffs to the north of Southwold and the Dunwich cliffs are seen as the only significant sediment source for the frontage. ***CP 1***

There are few inshore sea bed sediment transport indicators but from sediment tracer and sea bed current meter moorings a clockwise circulation around the Sizewell and Dunwich Banks has been proposed. Further offshore there is both indeterminate sand streaks and some sea bed features indicating a southerly movement. ***CP1 & 4 Fig 97***

Longshore drift consistently indicates a southerly drift but with more recent studies showing little net movement south of Southwold and virtually no net movement past Thorpeness. There is recognised to be significant gross movement and this movement is very sensitive to wave climate. ***CP6***

Modelled results of sediment flux show, in general, a relatively weak movement to the north over much of the area both on Spring and Neap tides. ***CP2 Fig 36, 41***

Closer examination at the local scale shows considerable variation both inshore and offshore. ***Fig 77***

Storm surge sediment flux patterns shows a typical overriding drift to the south, relatively close to the shore, setting against the coast to the south of Southwold and leaving the coast at Thorpeness and Orford. ***Fig 87, 88***

Dredging areas are well offshore of Southwold and likely to be outside the main sediment circulation patterns of the banks. ***Fig 56***

Discussion

The retreat of the coast within the geologically harder headlands has resulted in a relatively stable shoreline. This reflected in the drift model results. There is also, as a consequence, little feed or supply along the shore. To a large degree the material that is on the beach is likely to form the limit of material available to be worked. There is some supply from the north of Southwold but this will diminish with time.

Some finer material is lost offshore at each headland feeding into the various nearshore banks.

The system of banks appears to closed to the offshore, but with evidence of some re-circulation back to the shore at Thorpeness.

Conclusions

- The Dunwich, Sizewell and Aldeburgh Ridge banks are banner banks being actively fed with finer material from the various headlands. [Based on previous studies there may also be some re-circulation from Sizewell and Dunwich banks back to the Dunwich shoreline.]
- There is some supply from north of Southwold to the Dunwich frontage, this is likely to diminish. This is supplemented by a small supply from the Dunwich cliffs.
- There is little supply to the Aldeburgh frontage from the north and no association with the offshore sediment.
- Historically the supply to Orford Ness came from the eroding coastline to the north. This has largely ceased.
- Thorpeness, while limiting supply to the south plays a major role in holding material to the north.
- The position of and gap between the Sizewell and Dunwich banks dictates the inshore wave climate along the length of shore resulting in differential movement allowing local build up of material.
- There are no established pathways between the dredging areas offshore of Southwold and either the shoreline or the nearshore banks.

6.5.4 Issue H – Suffolk Coastline

The main items in this issue can be broadly summarised as follows.

Summary of Issue H – Suffolk Coastline

It is generally recognised that the drift over the Suffolk coast is towards the south. Concern was expressed that there was a poor understanding of what happens at Harwich. A particular issue is the identification of high shingle drift rates over the Felixstowe frontage and the apparent absence of shingle beyond (south of) Landguard Point. It is believed that sand and muds are moved offshore and merge with the circulation system around Cork Sands. Material is then fed back to Walton, to Hamford Water and Dovercourt. There is no reference to shingle.

Implications: There are three basic concerns associated with this issue:

- The understanding of how material is moved across the Harwich channel and how it feeds the shore to the south (H^1).
- The degree to which the Suffolk shore system is linked through offshore movement of material into the feed mechanism at Clacton (H^2 this also links with issue I discussed below).
- The degree to which management of the Felixstowe frontage (in particular the movement of the backshore shingle) can be treated in isolation to the management of the shores to the south of Harwich.

Information: Extensive studies have been undertaken around the area of Harwich.

And the interpretation of the SNS2 results has generated the following assessment of this issue:

Assessment of Issue H Suffolk Coastline	
Key points	
➢ *Supply of sediment to Suffolk*	
➢ *Links across the channel at Harwich*	
Context	*Ref*
Bedrock is close to the surface over much of this area. Orford Ness is built on a base of harder material than the surrounding bed. The supply to Orford has been in the past from the rapidly eroding shore of Suffolk. Banner banks of the Shipwash, Bawdsey and Whiting are indicative of the recession of a former headland at Orford. Only the Whiting receives sediment from the shore at present.	***CP1***
Movement of material from the Harwich spoil ground suggests movement to the northeast.	***CP1***
Seabed indicators show a sweeping movement of material towards the Thames with local clockwise circulation around the above banks. There is no apparent direct link inshore of the line of the Bawdsey bank to the area off Harwich.	***CP4, Fig97, 98***
Spring tidal flux shows a relatively mixed pattern of movement to the south of Orford. There is some indication of a general northerly movement close inshore but more varied north and south further offshore.	***Fig 36, 78***
The neap tide residuals tend again to show a weak northerly movement but this time extending further offshore. Wave stirring tends to result in a more confused pattern of movement. The surge residuals indicate an acceleration of movement from Orford Ness tending offshore. This movement tends to be pushed further offshore south of Harwich.	***Fig 41*** ***Fig. 42 to 46*** ***Fig 88***
Longshore drift analysis has shown a significant variation in volumes and directions along the shore. Several reports have highlighted the sensitivity of the shore to different wave directions and as a consequence to change in wave climate, yearly or over decades. The predominant drift direction is to the south, increasing south of Orford Ness but weakening further south. Material is held in the temporary sinks of Orford Ness spit and the Knolls at the mouth of the Deben, not only limiting available sediment supply but also influencing the pattern of sediment drift along the shore to the south of each feature. Various reports provide different drift rates and directions for areas south of the Deben.	***CP6***
There is an intermittent feed through to Landguard Point of some 20k m^3 to 30k m^3 / year, which accumulates and is removed by dredging.	***Fig 70***
Licensed dredging areas are offshore to the east and to the south of the Shipwash Bank and hence unlikely to have any influence the nearshore sediment transport on the Suffolk coast.	***CP10 Fig57***
Discussion	
No links have been established between the shore and the banks even under the surge residual flux, apart from a possible feed of fine material from Orford to the Whiting. There is a movement of material around the banks and potentially through the banks, both north and south, within the offshore zone. The nature of a surge event may be quite specific to this area changing in relation to the balance between internal and externally driven North Sea surges.	

Continued

Along the shore, there is a weak net drift into Orford Ness from the north. The main supply for the coast to the south is, however, the Ness and spit itself. There is a continuous but highly intermittent movement of material from Orford through to Felixstowe. What material, however, is on the coast is the limit of availability. In crude terms it is postulated that Orford Ness has some 2000 years worth of supply left.
There is no evidence of material moving from the Felixstowe frontage across the main channel to Harwich. Generally, with the exception of some small potential movement north, the Harwich channel is seen as a naturally occurring drift break point.

Conclusions

- There is no major supply of sediment to the Suffolk coast.
- There is no significant movement of material from Suffolk to Essex in the nearshore regime.
- There is a relatively minor supply of material to Orford Ness from an area immediately to the north. This supply does not balance the movement away from the Ness to the south, and hence under the present drift situation the Ness will continue to diminish.

6.6 Essex

Chart – Figure 57
Seabed facies (sediment type, features) – Figures 3 and 23b
Sediment drift rates – Figure 71
Net transport of fine sand on spring tide – Figure 78, 79, 80
Net transport of fine sand under storm surge condition – Figure 88, 89, 90
Seabed sediment transport indicators – Figure 98

Setting (Figure 57)
This stretch of the coastline is characterised by the embayments around the mouth of the Stour and Orwell and the Crouch and Blackwater estuaries, and to the south the large embayment of the Outer Thames Estuary. This is fringed on its northern side by the extensive sedimentary deposits of the Maplin and Foulness Sands. There is a large concentration of nearshore and offshore banks. Sediment information is shown on Figures 3 and 23b.

Conceptual longshore drift model for Essex (Figure 71) (Appendix 11 provides more details)
The cliffs of the Naze are eroding at a rate of around 10,000m^3/year. Some of the released sediment is transported north, round the tip of the Naze to the west, but some is also transported south to Walton. The longshore transport round the north tip of the Naze transports sand towards the entrance to Hamford Water. There is also a limited longshore drift to the north, along the Dovercourt to Harwich frontage.

The longshore transport along the Walton to Jaywick frontage is variable but essentially towards the south-west (Figure 71). There is a limited volume of sediment available to be transported, as the previous supply from the erosion of the frontage has been cut off by the development of the frontage. The groynes along the frontage were designed to hold some of the remaining sediment in place. Sediment transport continues along to the west of Jaywick to Colne Point, which serves as a sediment sink,

The geological context for sources, pathways and sinks is discussed more fully in Appendices 10 and 14.

Modelling results (Figures 78, 79, 80, 88, 89, 90)
The transport rate of sand and gravel in this region can be assessed at an overview level from the material presented in Section 4 of the report. The detailed results for this area have been plotted to show comparison between the two extreme cases of tidal transport of fine sand and storm surge transport of fine sand.

Seabed sediment transport indicators (Figures 98)
The most up to date information on seabed sediment transport indicators has been mapped. These figures show the net direction of sediment transport inferred from seabed bedforms or the axis of transport where no net direction could be determined. This is based on analysis of material provided by the dredging industry and results obtained by Dr B. D'Olier.

6.6.1 Schematic sediment transport diagram

The interpreted sediment transport for this region has been presented in Figure 106. The backdrop is taken from the relevant Admiralty Chart showing the land (beige), the intertidal area above 0 m Chart Datum (green), depths above 10 m (mid-blue), and depths above 20 m (pale-blue).

The black arrows indicate average transport that might be happening on a day to day basis due to tidal and wave action, either with a preferred direction (in the direction of the arrows for single headed arrows) or in both directions at different times and under different conditions (double headed arrows). The grey arrows indicate the situation under tidal current action with the effects of an extreme water level (surge) event superimposed, wave stirring and wind drift. The model scenario on which this interpretation was based had a return period of around 1:20 years. The locations of the arrows are intended to aid the reader in interpreting the sediment transport pathways in a particular area and the summary of information addressing the key strategic issues.

6.6.2 Issue I – Clacton

The main items in this issue can be broadly summarised as follows.

Summary of Issue I – Clacton

The SMP identifies a feed on to the shore at Clacton. This feed can also be inferred from shoreline sediment drift in that Clacton is at a drift divide. There is potentially another drift divide further north (Walton). Work undertaken for the Essex SMP suggests a significantly different pattern of movement to that put forward in the Phase 1 of SNSSTS. The SMP indicates a greater interaction with material from the Gunfleet and possibly less interaction with the shore to the north.

Implications: The main implications associated with the Clacton sediment supply are:

- The possible interaction with the Suffolk coast and Harwich operations (I^1).
- The potential links with the Gunfleet and from this the broader management issues across the Thames (I^2).
- The interactions with the estuaries at either end of the Tendring Peninsula (I^3).

Information: Some additional work has been carried as part of the Clacton Strategy, but this tends to be limited to foreshore sediment movement.

And the interpretation of the SNS2 results has generated the following assessment of this issue:

Assessment of Issue I Clacton

Key points

- *Links to the coast north of Harwich*
- *Links between the shore and the Gunfleet Sand*
- *The Pattern of drift and sediment supply to the Tendring Peninsula*
- *Interaction with the estuaries to either end of the Peninsula*

Context

The Gunfleet Sand is believed to have developed as a banner bank from when the Naze headland was considerably further to the northeast. The Gunfleet is now considered to be a moribund sediment sink. ***CP1***

The Tendring frontage has a history of erosion associated with accretion at Colne Point and to the north of the Naze. Both Colne Point and Hamford Waters are seen as sediment sinks though there is now concern that both Hamford and Colne Point are now erosional.

There is evidence that material placed to the north of the Naze will move through to the Harwich frontage.

There is considered to be no significant feed across from the Suffolk coast or nearshore area.

All major sources in terms of cliff erosion are now protected with the exception of the Naze. ***CP4 Fig 98***

Sea bed indicators show a general clockwise movement of material around the Gunfleet Sand and a circulation around the Cork Sands. ***CP7***

The field measurement work and analysis of seabed sediment transport indicators provided strong proof of no link between the Gunfleet and the shore and no substantial link between the Cork Sands and the Naze. ***Fig98***

Sediment flux residuals show a relatively confused pattern of movement in the area but with no cross shore movement over the Wallet. Surge tide residuals show the potential for a strong movement of material within the Wallet but with a flow onto the Gunfleet and south towards the Dengie Flats. ***CP8 Fig 88***

Sediment drift analysis shows a broad variation in drift rates and directions. On balance it is believed that this indicates a very variable longshore drift with only weak net movement. Movement along the shore is very sensitive to wave direction. The Naze is seen as a drift divide and there is a stronger net drift to the south along the shore. ***CP6 Fig 71***

There is no licensed aggregate dredging identified in this area. ***CP10***

Discussion

The various elements of work show no significant pathways for sediment between the shore and the nearshore.

The only substantial sediment source for the frontage is from the Naze, and material is carried both north and south from here. The net drift rates along the frontage are weak to the north section of the coast and increase to the south, beyond Clacton. Movement is variable along the frontage. What material exists on the frontage is likely to be the limit of material available for drift.

Conclusions

- There are no links established with the Suffolk coast.
- There is no link between the Gunfleet and the coast.
- There is no significant supply of material to the shoreline.
- Colne Point acts as a minor sink but the volume of material now received may be limited. There is no established link from the shore to the estuaries.
- To the north, material from Tendring has fed Hamford Water, the mechanism is still there but Hamford may now be erosional and the supply of material limited.
- There is no significant tidal residual either into Hamford nor the Blackwater and Colne. It is likely that supply of suspended sediment is merely local ambient material.

6.7 Thames/ North Kent

Chart – Figure 58
Seabed facies(sediment type, features) – Figures 3 and 23b
Sediment drift rates – No drift model data available
Net transport of fine sand on spring tide – Figure 80, 81
Net transport of fine sand under storm surge condition – Figure 90, 91
Seabed sediment transport indicators – Figure 99

Setting (Figure 58)
This stretch of the coastline is characterised to the north by the embayment of the Outer Thames Estuary, to the west by the Isle of Sheppey and to the east by North Foreland, a promontory on the northwest flank of the Dover Straits. The shoreline comprises cliffs fronted by extensive areas of intertidal flats and a number of nearshore banks. The flats on this side of the estuary are less extensive than those on the north side.

Conceptual longshore drift model for Thames/North Kent
The volume of work with predicted sediment drift rates in this region was considerably smaller than further north and hence it was not possible to produce a summary at the same level of detail as for other sections of the coastline. In general on the north side of the estuary the coastline is variable in orientation and indented with estuaries which break up the coastline into small, almost self-contained, frontages (Motyka and Brampton, 1993). On the south side of the estuary littoral drift is generally to the west along the shoreline. Erosion of fine material can take place from exposed seabed outcrops of London Clay and the cliffs of the Isle of Sheppey. Accretion of fine to medium sand takes place on the north side of the estuary in the Maplin Sands and the Dengie Flat, in the banks within the estuary, and on the south side of the estuary in the area northeast of Margate Sands off the Kent coast.

The geological context for sources, pathways and sinks is discussed more fully in Appendices 10 and 14.

Modelling results (Figures 80, 81, 90, 91)
The transport rate of sand and gravel in this region can be assessed at an overview level from the material presented in Section 4 of the report. The detailed results for this area have been plotted to show comparison between the two extreme cases of tidal transport of fine sand and storm surge transport of fine sand.

Seabed sediment transport indicators (Figure 99)
The most up to date information on seabed sediment transport indicators has been mapped. These figures show the net direction of sediment transport inferred from seabed bedforms or the axis of transport where no net direction could be determined. This is based on analysis of material provided by the dredging industry and results obtained by Dr B. D'Olier.

6.7.1 Schematic sediment transport diagram

The interpreted sediment transport for this region has been presented in Figures 106 and 107. The backdrop is taken from the relevant Admiralty Chart showing the land (beige), the intertidal area above 0 m Chart Datum (green), depths above 10 m (mid-blue), and depths above 20 m (pale-blue).

The black arrows indicate average transport that might be happening on a day to day basis due to tidal and wave action, either with a preferred direction (in the direction of the arrows for single headed arrows) or in both directions at different times and under different conditions (double headed arrows). The grey arrows indicate the situation under tidal current action with the effects of an extreme water level (surge) event superimposed, wave stirring and wind drift. The model scenario on which this interpretation was based had a return period of around 1:20 years. The locations of the arrows are intended to aid the reader in interpreting the sediment transport pathways in a particular area and the summary of information addressing the key strategic issues.

6.7.2 Issue J – North Kent coast and nearshore

The main items in this issue can be broadly summarised as follows.

Summary of Issue J – North Kent Coast and Nearshore

The North Kent SMP draws upon a significant amount of information, concluding that the principal onshore-offshore links relate to the Margate Sands area. The main feed to these banks is seen as being from the south and east. This runs counter to the indications from stage 1 of SNSSTS, which suggests a feed from a more northerly source, potentially from the outer banks along the East Anglian coast. The main concern is in the need to confirm or disprove such links.

Implications: The main issue raised clearly comes from the degree to which management or dredging on the East Coast may impact on Kent (J^1).

Information: The Kent SMP identifies several studies carried out within the region. Further geological analysis is possible of the more direct links to the northern shore of the Thames.

And the interpretation of the SNS2 results has generated the following assessment of this issue:

Assessment of Issue J North Kent Coast and Nearshore

Key points

- *The potential links across the Thames or with offshore source material from the north.*

Context

The principal sinks off the North Kent coast are the Margate Sand and the Tongue Sands. Pathways and sources are identified to them from the offshore, south of the Kentish Knock, and from the Goodwin Sands, although this latter pathway may reverse under northerly wave conditions. ***CP 1***

There is a re-circulation suggested between the Margate Sands and the shore. ***CP3***

Seabed indicators show a general clockwise pattern of movement around each bank with an increased cross flow over Long Sand. To the south of Kentish Knock indicators show material brought in towards the centre of the Thames. There are strong indicators (non-directional) of movement offshore of Kentish Knock, with an apparently alternating north and south stream of material cutting across the South Falls bank.

The residual flux patterns for both spring and neap present a confused pattern of both north and south vectors over the outer Thames, the more detailed plot for the spring tide showing a typically westward flow in to the North Kent area. ***Fig 36, 41*** ***Fig 81***

On the surge plots this flow is reversed suggesting a movement eastward along the nearshore of the Kent coast and accelerating past North Foreland. Further offshore there is a strong movement indicated into the Thames with only a weak movement towards the Kent coast to the south of the Long Sand bank. ***Fig 91***

It is noted that the dredging areas situated to the northeast and outside the Thames Estuary lie within the sandy sediment pathways feeding into the banks in the Outer Estuary. However, the licensed dredging in these areas is for gravel, hence the "extra" sand generated as the dredgers "screen" the cargo to obtain the required mix of gravel/sand may be liberated into these sand pathways. These pathways are weak and variable but may be reinforced by storm surge conditions. It is not anticipated based on findings of the present study that there is any direct link with sediment at the coastline. ***Fig 57***

Discussion

There is reasonable confirmation from the SNS2 results of a sediment source from the northeast to the Margate Sand that it feeds through a pathway to the south of Kentish Knock. The results reinforce the likelihood of a sediment link between the Goodwin Sands (off east Kent in the English Channel) and the Margate Sands and the surge model certainly shows the capacity for this link to reverse.

Conclusions

- While material is coming to the Kent coast from the North Sea the material seems likely to derive from outwith the main areas effecting or effected by East Anglia.
- There is no substantive link in terms of sediment supply between the coast to the north and that to the south of the Thames.

6.7.3 Issue K –Thames Estuary

The main items in this issue can be broadly summarised as follows.

Summary of Issue K – Thames Estuary
Considerable work has been carried out on potential sources, and potentially more important, sinks in the Thames area for fine material. It is felt that this should be developed to provide a clearer pattern of fine sediment movement over the area.
Implications: Fine sediment supply is of critical importance to the management and development of the outer Thames estuary creeks and estuaries (K^1).
Information: Considerable information is held by Dr B. D'Olier.

And the interpretation of the SNS2 results has generated the following assessment of this issue:

Assessment of Issue K Thames Estuary

Key points

- *Further information on the suspended sediments within the Thames Estuary*
- *Further definition of the Thames as a sink for bedload sediment*
- *Suspended sediment links between Harwich and the Blackwater*

Context

The Thames must geologically be seen as a sink with the infill of the Old Thames Valley and that of its tributaries. Bed load material is seen as feeding in through the Knock Deep and the Long Sand being moved north to feed Foulness and the Dengie.	***CP1***
Sea bed indicators concentrate on the Knock Deep showing a southerly movement. Indicators for the Long Sand show an increased tendency of sediment to run up and across the bank.	***CP 4*** ***Fig 98, 99***
Spring tide residuals tend to show a clockwise movement into the Thames and in towards the Essex shoreline.	***Fig 36, 78, 81***
Surge tide vectors show a more general movement into the Thames but with a significant leak along the North Kent coastline and south down into the Dover Straits.	***Fig 46, 88, 91***
Surface suspended sediment plots (fine SPM) show significant variation between summer and winter. The "English River" is evident in the winter data, quite distinct from the plume associated with the Wash and Humber, concentrated against the Suffolk shore and releasing to the northeast past Norfolk.	***Fig 29, 30***
The study identifies various sources of material including the Thames as being between 360k tons and 700k tons of primarily suspended load per year.	***CP1***

Discussion

The residual flux plots show no single path for bedload sediment into the Thames despite a strong indication from sea bed indicators as to a southerly transport. More detailed examination of the residuals, however, suggests a series of potential pathways as bands from the near to offshore. This is consistent with the sea bed indicators.

Within or close to the Thames there is stronger evidence for material being brought in to the central channels and then thrown northwest towards Foulness and the Dengie.

During major surge events there is a suggestion that material may also be brought in along a path, associated with the Gunfleet or the Wallet, which then drives more to the southwest on to the Foulness banks.

Suspended sediment supply within the Thames is relatively small with a suggestion, certainly, during winter conditions of a movement away from the Thames. There is no indication from the tidal residuals of a clear feed into the Thames Estuary.

It is noted that the dredging areas situated to the northeast and outside the Thames Estuary lie within the sandy sediment pathways feeding into the banks in the Outer Estuary. However, the licensed dredging in these areas is for gravel, hence the “extra” sand generated as the dredgers “screen” the cargo to obtain the required mix of gravel/sand may be liberated into these sand pathways. These pathways are weak and variable but may be reinforced by storm surge conditions. It is not anticipated based on findings of the present study that there is any direct link with sediment at the coastline. *Fig 57*

Conclusions

- The study has collated a large database of suspended sediment concentration data. There is no obvious residual movement of this into the Thames area.
- The study has drawn together a significant amount of research into the Thames as a sink and provides a coherent pattern of sediment pathways.
- There is no established bed load feed to the Sales Point (North Dengie) and the accumulation of material at this location is characteristic of migratory Chenier (shell deposit) ridges.
- There is no direct link made, in terms of suspended sediment, between Harwich and the Blackwater. Also bed indicators have shown movement of material from the Harwich spoil grounds to trend to the northeast (*Issue H*).

7. SEDIMENT TRANSPORT VARIABILITY AND TIMESCALES

This section of the report discusses the causes of variability in sediment transport arising from currents, waves, sediment supply and the behaviour of banks. It also discusses the timescales associated with sediment transport.

Uncertainty in sediment transport can arise in two ways, firstly, a specific dataset for sediment transport might be collected or a particular scenario of sediment transport applied in a computer model. The uncertainty that arises in this case relates to knowing how applicable the information is to other time periods and locations. An attempt to address this issue has been made in Section 3.4.3. Secondly, spatial gradients in flows, waves and sediment can make it difficult to assess the representativeness of process measurements at a point for another point 500 m away on a different seabed material. In this case the application of a validated computational model for waves, flows and sediment transport can be used to extend the results to other areas.

7.1 The causes of variability

Variability in sediment transport takes place at a variety of temporal and spatial scales. The causes of sediment transport variability are summarised below:

- Tidal currents – these are the primary driver of sediment transport in the southern North Sea. The strength of the currents determines the transport rate and direction. Currents vary on a daily timescale (diurnal inequality), from day to day (spring-neap cycle), half-yearly (equinoctal) and on much longer cyclical timescales (e.g. 18.6 year cycle)

- Wind – this can set up currents in the water column which influence the residual drift of water, in shallow water onshore and offshore winds can induce offshore and onshore drift respectively which can lead to sediment movement off or onshore. The detailed pattern of wind speeds and directions over the study area will vary from day to day, and the same pattern will not be repeated year after year. Average patterns of wind can be determined on a monthly and seasonal basis which capture the main features of the wind field

- Waves – the annual time series of waves (height, period and direction) will not always be exactly the same, as for the wind. However, from year to year the climate of waves is relatively constant (in terms of total wave energy) other than for the postulated effects of climate change. There is presently conflicting evidence as to the exact nature of the change in wave climate over the next 75 years

- Rainfall – the influence of rainfall is felt primarily in the enhanced level of fluvial flow which can transport sediment into the sea and through the influence of rainfall on cliff stability

- Storm events – The periodic influence of wave stirring and surges in the North Sea cause relatively infrequent but significant contributions to the sediment transport

- Sediment supply – seabed and cliff deposits have varying amounts of clay, sand and gravel in them. The erosion of one particular segment with particular characteristics may lead to the exposure of a segment with a different composition. Over the long-term cliff and seabed erosion rates may appear quite stable but there can be significant variations from year to year

- Bedforms – bedforms on the seafloor provide enhanced resistance to tidal and wave flow and can influence the way in which sediment is transported. Storm events can modify these bedforms or even, temporarily destroy them. They are then built up again by the action of tides and waves. The transport of sediment grains within and over bedforms means that the presence of these features is indicative of an actively mobile seabed area

- Channels and banks – channels and banks can change their shape and position over periods of time measured in months and longer. Changes in the location of these features lead to changes in the pattern of waves and currents and, where they are near the coast, to the wave activity at the shoreline which generates longshore sediment transport

- Biological influences – biological influences are felt in the North Sea both in terms of the seasonal growth and decay of algal blooms, the dead bloom settles as a low density deposit on the seafloor sediments, and the influence of bottom dwelling organisms some of which serve to destabilise the seabed sediment and some which can make the bottom sediments more stable. The importance of these influences to the long-term sediment transport patterns are not well understood

For the present study, two aspects of variability which it was felt warranted further discussion were (1) the variability in sediment drift rates at the shoreline due to inherent variability in the wind/wave climate and (2) the influence of changes in nearshore banks on the longshore drift

(1) Annual and longer term variability in drift rates

Estimating the mean annual nett longshore drift rate is complicated by the fact that the longshore drift rates vary considerably from year to year. In reality the mean rate is only a (meaningful) statistic within a distribution of higher and smaller rates. Accurately estimating the mean of this distribution requires the annual wave climate to remain consistent, and the calculation of the annual drift rates for each year over many years. These calculations also provide information on the standard deviation of the distribution of rates, which is usually a large proportion of the mean value, even on coasts with a high longshore drift rate. However, in practice, most mean annual nett drift rates are calculated from ten to twenty years of wave data and the *mean* value obtained varies with both the length of simulation and the period modelled. This complicates the task of comparing model results from different studies, even when similar methodologies were used.

Along most coastlines of the world the longshore drift is mainly caused by waves that break obliquely to the shoreline. In some places where tidal currents are known to be high near the shoreline, or the tidal range is high, this can produce a noticeable effect on the longshore drift and hence this effect needs to be included in modelling studies.

The variability in drift rates from year to year can have a number of implications for beach management. For example, a contract for recharge operations will have to be flexible in terms of arranging for the potentially very different amount of work required to restore the beach from one year to the next. On a beach with groynes, the variations in drift rate can cause short-term variations in beach plan shape that may have significant effects on coastal defences, e.g. because beach levels on the downdrift side of groynes are lower for longer when drift rates are larger. As with the mean annual longshore drift, therefore, the higher the inter-annual variability of drift rates is, the greater the problems for beach management.

The potential variability is illustrated in Figure 108 taken from the paper by Thomalla et al (2001). This shows the potential annual and decadal transport (at Sea Palling) based on 50 years of daily wind data (1931-1980). It is the variability in rates and directions that is significant in this analysis. The dashed line is the 50-year average of 161,000m^3/y compared with the standard deviation which is 455,000m^3/y.

The results from a similar analysis for the Mundesley to Sheringham section of the coastline is shown in Figure 109. Decadal averages are 219,000, 253,000, 123,000, -51,000 , -60,000 m^3/y. This indicates the annual variability in rates and directions and highlights the feature of the drift 'parting' at Cromer-Sheringham which is a **statistical** feature as sand goes in both directions. In this plot positive drift rates are those going in an easterly direction.

(2) Variability in drift rates due to changes in sandbanks

The influence of changes in the highly volatile banks off Great Yarmouth has already been studied and the results have been fed into this project. The influence of banks on wave propagation and drift rate was assessed and shown to be of potential significance in earlier research (Whitehouse, 2001).

The longshore transport rates around Great Yarmouth (from Caister to Corton) were the subject of an extensive study by HR Wallingford (1998). The study produced a prediction of the baseline drift and examined the sensitivity of this drift to natural changes in the offshore wave climate and bank configuration. Table 3 shows wave-induced longshore transport at each of five locations studied, for five scenarios. Positive drift rates indicate northerly transport.

Table 3 clearly indicates that the longshore drift rates around Great Yarmouth, inshore of Scroby Sands, depend highly on the sandbank's bathymetry. As the bathymetry changes in time, the ability to predict future longshore drift rates in this area depends on the ability to predict the long-term morphological development of Scroby Sands. Further summary of this work is included in Appendix 11.

7.2 Timescales for sediment transport

The timescales for sediment transport are of interest because sediment transport is the primary mechanism for natural changes to occur in the seabed and coastal profile. The rate of sediment transport not only controls the movement along sediment pathways but also controls the rate of depletion of a source of material, or rate of accretion of material in a sediment sink.

There are a wide variation in timescales for sediment transport on the seabed and foreshore. These range from the scale of seconds where the flow turbulence or wave motion controls the pick up and advection of sediment, through to the variation in wave activity between low and storm periods or tidal current strength between neap and spring tides over periods of days. At the longer timescale seasonal effects are evident in terms of the height and persistence of storm wave activity. Soulsby (1997) examined the contributions made by waves and currents at a site in the Southern North Sea to the long-term mean sediment transport. He concluded that large contributions were made by currents lying between the peaks of mean neap and mean spring tides, combined with waves in the range 1.5 m $< H_s <$ 3.8 m. He also concluded that the largest contributions were made by currents nid-way between mean neap and mean spring tide, combined with waves of H_s = 2.5 m, corresponding to an exceedance of 9%.

In terms of the impact on morphology change there is almost an instantaneous equilibrium between hydrodynamic processes, sediment transport and morphology change acting on the smallest scale bedforms, i.e. ripples. In general, the larger the morphological feature the larger the volume of sediment that is stored in that feature, and hence the longer the response time due to sediment transport processes. Hence there is often a quasi-equilibrium on the larger scale features – nearshore bars, ridges and banks – because these features are continuously adjusting to the changing hydrodynamic conditions and associated sediment transport (Van Rijn, 1998). Beach volumes change seasonally (e.g. winter-summer profiles) and more frequently depending on the chronology of tides and waves.

The way in which timescales for sediment transport are examined depends on what is required from the analysis; for example, whether information is required on the rate of bedform migration, the rate at which sediment is moved along or across the nearshore profile, or the rate at which a dredged trench may infill.

If it is the movement of individual particles that is required then this is best determined from the dispersion of tracer studies, or from computational models which can track sediment particles (these are only just becoming routinely available). Typical dispersion rates give results of order 100 m per day (from the tracer study off Winterton Ness, Appendix 6).

If it is the movement of parcels of water (and fine sediment as wash load) that is required then this can be determined from seabed drifters, or the analysis of field or model data for the residual drift currents. Drift rates for the upper layers of the water column will be variable but the annual mean surface drift currents in the North Sea are typically of the order of 1.5 nautical miles per day (MAFF, 1981) (2.8 km per day). Seabed drifter results for the Humber, Lincolnshire and Thames areas have given return times to the shoreline of between one and two weeks and a couple of months (and longer) depending on the proximity of the release point to the coastline and the prevailing tidal and weather conditions. In coastal areas it has been shown that the reappearance time of drifters deployed offshore can be shortened by offshore winds which produce a net onshore drift of bottom water.

If it is the rate of development of a seabed feature or beach that is required then this is best assessed from the sediment transport rate field, i.e the spatially varying sediment transport rate and direction at a grid of points over the study area (Soulsby, 1997; Southgate and Brampton, 2001). Continuity of mass is then used to determine the rate at which an area of the seabed erodes or accretes as a function of the gradients in the sediment transport rate.

Analysis of timescales can be carried out at the larger scale:

- From an analysis of flow and sedimentological data from the Haisborough Sand sandbank McCave and Langhorne (1982) deduced that the transport of sand around that bank took 550 years to make a full circuit around the bank. The mobile sediment is only a small proportion of the overall volume of the bank and hence the response time of the bank is slow. Smaller bedforms (such as sandwaves and megaripples) have net migration rates under spring tidal action which are of order 0.1 m per day.

- In the current study the longshore drift along the Suffolk coastline has been examined (Section 6.5.4) and a weak net drift into Orford Ness from the north identified. The main supply of sediment for the coast to the south is, however, the Ness and spit itself, and there is a continuous but highly intermittent movement of material from Orford through to Felixstowe. Therefore it has been hypothesised that the material on the coast in this area forms a finite limit to the limit of availability. In crude terms it was postulated that under the current regime of longshore drift Orford Ness has some 2000 years worth of supply left to feed the downdrift coastline.

8. REPORT USAGE AND STUDY OUTCOMES

8.1 How to use the report for assessing sediment transport

Figure 50 shows how the information in this report can be used to undertake a baseline assessment of sediment transport magnitudes, directions and sensitivities at any specified location in the study area. The information in the report has already been used to address specific issues, as has been documented in Section 6. The report also provides an extensive resource of sediment transport information, which can be accessed as part of studies related to engineering works in the nearshore, or licence applications for offshore dredging of aggregate.

The following steps are recommended:

- The location and proximity to seabed and coastal features can be assessed from charts
- The historic behaviour of seabed and coastal features can be assessed from comparison with historic charts and maps
- The sediment type can be determined from the maps of sediment distribution
- The geological context should be reviewed (sources, sinks and pathways)
- The seabed sediment transport indicators can be assessed to see where the seabed is likely to be mobile, the axis of mobility and an indication of the most likely direction of transport, and sediment transport connectivity between coastal and nearshore features
- The magnitude and direction of sediment transport for various grades under varying levels of wave and current activity can be assessed from the model results
- The sensitivity of the sediment transport predictions to different levels of tidal and wave forcing can be assessed from a comparison of the model results
- The longshore drift of sediment at the coastline can be assessed from the collation of results for longshore drift

8.2 How and how successfully have the project objectives been met?

The key objectives identified in Section 1 have been successfully delivered by the study.

A key issue identified throughout consultation and through the review of studies and first generation SMPs has been the overall coherence of any interpretation of the sediment system for the Southern North Sea. This has, in many significant areas, being lacking. This lack of consistency is often most apparent along the shoreline in observation of areas of accretion with no obvious source or in the apparent evaporation of sediment at points of theoretical convergence. In many areas this coherence gap has, of necessity, been attributed to onshore/ offshore supply, or loss, through the difference between potential, actual theoretical and observed sediment movement and through consideration of differing confidence levels, in particular, of conflicting data sets.

While clearly confidence in data sets, in analysis and interpretation remains an issue, this is not felt, from the findings of SNS2, to be the most significant factor in resolving issues. The results from SNS2 highlight major variations on, along and offshore of the coast in term both of geography, in time and in uncertainty and continuity of events. This is possibly most evident in comparing the results of the tidal modelling when considering the variation of sediment flux residuals for spring tides (Figure 36), for neap tides (Figure 41) and for the single surge event modelled (Figure 46). It also becomes apparent in the comparison of seabed indicators (Figure 7). It is evident from this that there is rarely a single sediment pathway, apart from specific circulations around banks or in terms of the long term underlying trends such as the sediment sink of the Thames or the Wash.

8.3 Comparison with Phase 1 conceptual sediment transport model

The Phase 1 conceptual sediment transport model was presented in Figure 4. The overall comparison between the Phase 1 model and the schematised results obtained in the Phase 2 study are favourable. The Phase 2 work has added extra detailed information on the patterns of sediment transport based on the modelling and fieldwork and synthesis activities undertaken.

8.4 Limitations on the information presented in this report

There will be some limitations on the information presented in the report, for example:

- The bathymetry used in the computational model is considered to be representative of present day conditions but may not be representative of seabed conditions at some future time, especially in areas with complex bathymetry around sandbanks

- The model scenarios run in this study are considered to be representative of the range of conditions that might be experienced in the study area, but in reality the sediment transport regime is controlled by a time varying sequence of wave, currents, water levels and wind. The relevance of the conditions modelled were discussed in Section 3.4.3

- The field data applies to the periods in which it was taken and has been used to validate the computational model. The magnitude of values and characteristics identified within the datasets may not be applicable outside the periods in which it was collected

- Seabed features observed in the sidescan sonar datasets may be transient and change position or characteristics with time. Hence the interpreted sediment transport regime may be at variance with future datasets

The expectations and limitations with coastal sediment transport and its application to coastal morphological modelling have been explored by Southgate and Brampton (2001).

8.5 Added value

The study has provided added value towards the design/sustainability of coastal/sea defence works, seabed works and the assessment of dredging activities by raising the technical understanding of the processes of sediment transport along and offshore of the coastline of eastern England between Flamborough Head and North Foreland. The assessment of sediment issues along a substantial length of the east coast has enabled an overview of the main issues which have been able to be linked at this regional scale, rather than being examined in isolation. The results produced by the study and the new site specific field data collected in the study will be of lasting value for comparison against future studies.

The links forged with other projects have also added value to the study:

- The longshore drift catalogue compiled in this study was made available to the DEFRA funded study of future coastal morphological change (Futurecoast).
- The analysis of the seabed data collected off the Humber in the present study has been verified through a meeting with British Geological Survey. The seabed sediment transport indicator data collected from the Humber estuary has been made available to BGS for integration with their own datasets and for analysis within the Humber Estuary SMP Phase 2 study.
- The results from the present study have been referred to in ChaMPs studies for Suffolk, Essex, Norfolk and North Kent.
- The results from the present study have been made available in support of the Lincshore strategy study.

- The regional computational model can be used to provide boundary conditions for other models (e.g. Clacton-on-Sea study)
- Through these and other links the study results have been made available to consultants and universities to inform other studies

9. RECOMMENDATIONS FOR FUTURE STUDIES AND RESEARCH

This section of the report presents an assessment of SMP boundaries, and additional data, modelling and research initiatives identified as likely to yield additional understanding of sediment transport in the study area.

9.1 Considerations with respect boundaries of SMPs

Humber - Holderness/Lincolnshire

- Consideration should be given to extending the sub-cell boundaries across the Humber in terms of examining strategic impacts or as a minimum providing a higher level review of policy implications across the current boundary

Wash

- Consideration of changing SMP boundaries such that the Wash is included as part of the Lincolnshire coast south of Saltfleet and the North Norfolk Coast as far as Blakeney

North Norfolk Drift Divide

- On balance it is felt that the boundary of the SMP at Sheringham is appropriate but further assessment to the west and south can be made using the understanding of drift patterns from SNS2 and the results from the recently completed Cromer strategy study (which have been included in this report)

Cromer-Benacre

- The SMP boundaries for this area should possibly more sensibly be placed from Benacre north, including Winterton

9.2 Recommendations for future studies

Holderness

- Investigate the significance of the Smithic Bank as a potential sporadic source of sediment to Holderness
- Merge the new SNS2 Humber sidescan dataset with the BGS sidescan dataset for an in-depth analysis of seabed pathways (this will be undertaken in HESMP2 study)
- Consider undertaking mineralogical studies in the area off the mouth of the Humber. This was planned for in SNS2 but unable to be completed owing to constraints of weather on the field programme
- Complete ADCP sections across the mouth of the Humber, from Spurn Head due south, to determine the spatial and temporal variation in flows and sediment flux within a tide. Ideally data would be collected on at least three tide ranges: spring, mid and neap This would confirm the location of the flood/ebb dominated channels and when combined with calibrated backscatter of sediment concentration, the sediment flux. Flux estimates will need to be analysed carefully given the potential errors in determining the gross flood and ebb fluxes over the tidal cycle, which will be large compared with the net flux residual. Calibration data for the sediment concentration will be required across the transect and during the survey an anchor station could be completed at one key point with half hourly suspended sediment profiles to provide additional temporal and vertical calibration data. A downwards looking ADCP could also be mounted on the stationary vessel to obtain velocities
- Simultaneous sidescan sonar records can be obtained to determine bedload sediment pathways. The tides at the mouth of the Humber are extremely strong and capable of moving sand for large parts of the tidal cycle. It is proposed that a small area should be surveyed repeatedly over a full tidal cycle to determine the absence, size, shape and the mobility of bedforms. This may produce further evidence of the transfer of sediment from Spurn Point to Donna Nook and to allow its nature and variability to be characterised

Wash

- Continue to monitor the link between the banks off Gibraltar and the Lincolnshire recharge. Examination of the processes causing sediment transfer
- Examination of the change and link between the nearshore banks associated with Gore Point and extreme conditions
- More detailed examination of surge events, considering potential different behaviour resulting from the balance between internal and external surges

East Norfolk

- The SNS2 process data from the Winterton survey has shown interactions between wave-tide-current. The interaction process and significance for sediment transport in the study area need to be further investigated

Suffolk

- Further examination of the impact of different surge conditions as this has been shown to be an area where the surge tide can alter the net seabed sediment transport directions

Essex/Thames

- Consider the merits of working up BGS seabed facies data for the seabed area south of the Deben and including the Thames Estuary
- The SNS2 process data from the Clacton survey has shown interactions between wave-tide-current. The interaction process and significance for sediment transport in the study area need to be further investigated
- Inner Thames Estuary: To traverse the inner estuary between Southend and the Isle of Grain over a number of spring tidal cycles using an ADCP to measure the structure of currents and use of calibrated acoustic backscatter readings to determine the suspended sediment concentration. This could be undertaken in conjunction with bed frame measurements to provide the longer term monitoring required to fully understand the annual situation, although the importance of spatial variability in sediment flux should be recognised. This work could be backed up with sidescan sonar data interpreted to show seabed pathways for sediment transport

  There are a number of initiatives currently under development by PLA and others relating to sediment transport in the Thames Estuary. Therefore it is recommended to collaborate directly with PLA on measurements and to recognise the role of the Thames Estuary Partnership co-ordinated through the Environment Agency

9.3 Field data for near-surface suspended sediment

- Gaps in surface suspended sediment distribution: Although the distribution of the suspended sediment data is well mapped in both summer and winter, several gaps have been identified (heading south, no priority order):

  1. Humber to Cleethorpes
  2. North Norfolk coast
     The whole inshore area has very few data points.
  3. Norfolk Offshore sandbanks
  4. Essex Marsh approaches
     The whole inshore area from the Orford Ness along the Essex coast has very few data points.

  This need should be reviewed in the context of existing datasets for suspended sediment (e.g. held by the Environment Agency and the British Oceanographic Data Centre) including the analysis of satellite and airborne (CASI) imagery. Satellite data provides a wide-area synoptic view of parameters in the context of traditional in-situ measurements. Processed suspended particulate matter SeaWifs images for the Southern North Sea can be obtained from Plymouth Marine Laboratory (as shown on front cover of this report)

9.4 Seabed datasets

- It is recommended that all sidescan sonar surveys that are collected digitally and funded by DEFRA (and ideally other Government departments) are available at one location. This can be achieved through the formation of a digital sidescan sonar archive for datasets at the Environment Agency, CEFAS and/or other commercial bodies

9.5 Research needs

- Integrated longshore sediment transport modelling further recognising the importance of tidal influences and the decadal variability in drift rates

- Application of recently developed bed particle tracking models for seabed sediment transport within tidal computational models to confirm sediment transport pathways

- Interaction of coastal sandbanks and nesses
  Sandbanks and nesses in many coastal locations appear to be intrinsically linked. It will be beneficial to integrate and build on the earlier MAFF funded Spits and Nesses (Babtie and Birkbeck, 2000) and Sandbanks (Whitehouse, 2001) projects using results from the SNS2 study and new data for both the short term and longer term interaction between these features. Some further process studies at contrasting sites could be undertaken to investigate the nature and variability of these links

- Potential effect of licensed aggregate dredging on the coastline
  The review and analysis of surveys of the seabed that are carried out to fulfil one of the conditions under which a licence is issued may be an interesting area for further (academic) research. This information may shed light into numerous aspects of seabed and coastal sediment processes, and any connections between the two. The research might complement similar research into the effects of dredging on the biological environment of the seabed, for example as undertaken by CEFAS

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HRW – Richard Whitehouse (editor), James Sutherland, Tim Chesher, Alan Brampton, Richard Soulsby, Tim Chesher, Keiran Millard, Alison Houghton, Keith Powell
Posford Haskoning (PH) – Greg Guthrie, David Brew, Alun Williams
CEFAS – Jon Rees
UEA – Chris Vincent
Brian D'Olier

Specific appendices were drafted by the following with final editing by Richard Whitehouse:
Appendix 1 Review of aggregate dredging and disposal activities in the study area
Alan Brampton, Mike Dearnaley (HRW), Nigel Feates (HRW)
Appendix 2 Summary of sediment transport processes including definition and plotting of transport rate
Richard Soulsby, Richard Whitehouse
Appendix 3 Review of Shoreline Management Plans
Alun Williams, Greg Guthrie
Appendix 4 Summary of findings from end user consultations
Alun Williams, Greg Guthrie
Appendix 5 End user database
Keiran Millard, Richard Whitehouse
Appendix 6 Report on field data collected in 2001around Winterton, Clacton and the Humber
Jon Rees, Bill Meadows (CEFAS), Chris Vincent, Adam Leadbetter (UEA), Jon Taylor (Compass Hydrographic Services Ltd)
Appendix 7 Assessment of the influence of storm surges on sediment transport
Alison Houghton
Appendix 8 Summary of inputs
Richard Whitehouse
Appendix 9 Report on mineralogical tracers
Jon Cox (UEA, now at Cambridge University)
Appendix 10 A geological background to sediment sources, pathways and sinks
Brian D'Olier
Appendix 11 Report on Southern North Sea longshore sediment transport
James Sutherland, David Brew, Alun Williams (PH), with contributions from Stuart Stripling (HRW) and Alan Brampton
Appendix 12 Computational modelling of sediment transport in the Southern North Sea by tide, wave and surge
Tim Chesher, with Alan Cooper, John Baugh, Jennifer Semmence, Liam Foley (HRW)
Appendix 13 How do the modelling scenarios relate to reality?
Richard Soulsby
Appendix 14 Summary of sediment sources and sinks
Suzanne Clarke (HRW), Richard Whitehouse
Appendix 15 Map of seabed sediment transport indicators
Richard Whitehouse, Alison Houghton, Brian D'Olier, Jon Rees, Richard Soulsby,

Suppliers: BGS for data on mean seabed sediment size (1 km grid for southern North Sea), 20 km coastal strip seabed sediment type data, 20 km coastal strip seabed facies data between Flamborough Head to the Deben estuary (Suffolk); POL for boundary conditions for surge sediment transport modelling from their

Continental Shelf Model; Intelliscan for electronic raster format Admiralty charts (ARCS™); dredging industry companies for access to their seabed data archives; Harwich Haven Authority for access to their seabed surveys; publishers for permission to use figures reproduced in this report

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Tables

Table 1 Record of consultation

A: LOCAL AUTHORITIES

Organisation	Personnel
East Riding of Yorkshire Council	Patrick Ferguson / Adrian Dawson / Neil McLauchlan
North East Lincolnshire Council	Adrian Coy
Suffolk Coastal D.C.	Barry Sanders / Roy Stoddard
Tendring D.C.	John Ryan
Waveney D.C.	Julian Walker / Paul Patterson / Ivan Baldwin
North Norfolk D.C.	Peter Frew
Kings Lynn and West Norfolk D.C.	Tony Porter
Great Yarmouth B.C.	Ian Boon
Southend-on-Sea B.C.	Richard Atkins
Canterbury City Council	Peter Brookes
Maldon D.C.	Nicky Spur / Nigel Harmer

B: ENVIRONMENT AGENCY

Area Covered by Representative	Personnel
Anglian Region	Clive Flanders / Jane Rawson
Anglian Region	Dave Denness
Norfolk / Suffolk and Essex	Karen Thomas
Norfolk / Suffolk and Essex	Mark Dixon
Lincolnshire	John Ulyat
Norfolk / Suffolk	Stan Jeavons
Essex	Tom Miller

C: ENGLISH NATURE

Area Covered by Representative	Personnel
Entire Study Area (national)	Chris Pater
Yorkshire	Denice Coverdale
Lincolnshire	Ian Patterson / Rebecca Tibbetts
Suffolk	Duncan Smith
Essex	Robin Hamilton

D: DREDGING INDUSTRY

Area Covered by Representative	Personnel
Seabed facies and sediment transport indicators in licensed dredging areas	BMAPA company representatives

Table 2 Sources and sinks of sediment in the Southern North Sea, information tabulated from ABP (1996a) showing sand and fine material with limits on estimates

Southern North Sea Sediment Transport Study
Data on Sources and Sinks from R546 ABP Research Report on SNSSTS Phase I

Sediments Budget	**Assumed density of material 2.6 tonnes/m^3**					
Sources	**sand | limits 10^3 tonnes/y**			**fines/mud| limits 10^3 tonnes/y**		
Holderness	1430	182		4160	520	
Holderness (Cox, 1999)			*9100*			*Total volume eroded, including subtidal ramp*
Lincolnshire	57	13		0		
Norfolk-Suffolk	575	156		442	130	
Essex	156	78		156	78	
Thames	0			29	10	
Sinks	**sand 10^3 tonnes/y**			**fines/mud 10^3 tonnes/y**		
Lincolnshire mudflats & Saltmarshes				63		
Wash						800-8000 *Ke et al (1996) 5%-70% sand in suspension*
Norfolk saltmarshes				100		
Suffolk rivers						100 - total undefined sand silt/mud
Essex & Thames				17		

More information on sources and sinks is tabulated in Appendix 14

Table 3 Wave-induced longshore transport near Great Yarmouth. Positive drift rates indicate northerly transport

Location	EA Profile	Angle	Mean climate 1996 bathy [m^3/yr]	Mean climate 1986 bathy [m^3/yr]	Mean climate 1970 bathy [m^3/yr]	UKMO climate 1996 bathy [m^3/yr]	1993 climate 1996 bathy [m^3/yr]
Caister (N)	N4B1	67°	-186,728	-171,207	-40,819	-215,594	-346,029
Caister (S)	N4B1	78°	-159,746	-147,657	-1,125	-180,441	-318,185
North Denes	N4A2	96°	-6,839	-14,905	93,680	-9,342	-18,387
South Denes	N4A6	88°	4,029	30,673	112,602	-1,987	-21,594
Gorleston	SWG2	91°	-36,059	9,721	14,254	-43,435	-93,943
Corton	SWF2	72°	-100,787	-31,570	-129,571	-118,9061	-205,806

Figures

Appendices