Appendix 11

Report on Southern North Sea longshore sediment transport

Southern North Sea Sediment Transport Study, Phase 2
Sediment Transport Report

Appendix 11 Report on Southern North Sea longshore sediment transport

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June 2002, edited July 2002

Abstract

This report summarises the available knowledge about longshore sediment transport rates between Flamborough Head and the Thames. This involved a substantial data-collection exercise, some new modelling and subjective, expert judgement on the reliability of the data to produce a unified set of results. Comments on local geology and mechanisms for longshore transport are included. The report includes a catalogue of sediment transport rates from a wide variety of sources, including results from numerical modelling and observations. It also contains comments on the difficulties in comparing the results from different periods and methods. The report complements an earlier macro-review of this stretch of the coastline [Motyka, 1986, Motyka and Beven, 1987] which provide drift directions and also describe the geology and coastal defence structures in more detail than here.

1. INTRODUCTION

The evolution of beaches is of great importance to the UK. Beaches dissipate wave energy, protect the land behind from flooding and wave damage and provide a valuable recreational resource. Moreover, development often takes place right up to the top of the beach so any erosion of the beach threatens the development above. Changes in a beach's plan shape are related to the transport of sediment along a coastline, the longshore drift. When the volumetric rate of transport varies along a beach, accretion or erosion will occur and the beach plan shape will alter. Because of the fundamental importance of longshore drift in the evolution of beaches, deliberately modifying the natural drift rate has long been at the centre of beach management methods not only in the UK but also around the world. The most obvious examples of this are the large number of groyne systems along both sand and shingle beaches, designed to retain extra beach sediment, albeit often at the expense of adjacent beaches.

In more recent decades, alternative approaches to beach management have been adopted, namely beach recycling and beach recharge operations. A typical example of a recycling exercise involves collecting sand or shingle from the downdrift end of the beach and transporting it to the updrift end, thus counteracting the effects of the longshore drift. A recharge operation involves importing sand or shingle from a supply (often an offshore bank) to increase the volume present in the beach.

Estimating the mean annual nett longshore drift rate, Q, is complicated by the fact that the longshore drift rates vary considerably from year to year, In reality, Q will be a statistic with a Gaussian probability distribution. Accurately estimating the mean of this distribution requires a stationary wave climate and calculation of the annual drift rates for each year over several decades. These calculations will also provide information on the standard deviation of the Gaussian probability distribution, which is usually a large proportion of the mean value, even on coasts with a large longshore drift rate. However, in practice, most mean annual nett drift rates are calculated from ten to twenty years of wave data and the Q 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.

The variability in drift rates from year to year can have a number of implications for beach management. For example, a contract for recycling 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.

Along most coastlines of the world the longshore drift is mainly caused by waves that break obliquely to the shoreline. In some places, tidal currents also affect the longshore drift and this effect is considered in a number of cases here.

This report draws on a large number of previous calculations of longshore transport rate, largely drawn together by Posford Haskoning. A wide variety of methods were used, including observations of morphology, cliff retreat rates, coastal profile modelling and models that transform wave energy into potential transport rates. The interpretation of this catalogue has involved an element of expert judgement. The main criteria for choosing between estimates of drift rate were:

- Site-specific studies were preferred to the results from the broad-scale modelling of a region
- Results that fit in with the regional picture of sediment transport and the understanding of the driving processes were favoured over results that did not fit this pattern, although allowances had to be made for local effects that can reverse the regional transport pattern.
- Studies that were calibrated were preferred to modelling that used default values. Calibration could involve as little as obtaining local sand size distributions or could involve modelling the change in beach plan shape between surveys.
- Studies that used more sophisticated modelling techniques were preferred to more simple methods.

Much of the study area was modelled in the pioneering studies by the University of East Anglia in the late 1970s and early 1980s (Vincent, 1979, Clayton et al., 1983, Onyett and Simonds, 1983). They 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, following the requirement for Shoreline Management Plans, many areas have been modelled in more detail, using more up-to-date techniques and site-specific model settings. Therefore it proved to be an opportune moment to extend and update the work of UEA and to apply it to a greater area

2. LITTORAL PROCESSES AND SHORELINE EVOLUTION

The cliffs, beaches and seabed interact with the environmental loadings to produce a dynamic, continually changing coastline. The principal aim of the study of these “littoral processes” is to explain and then later quantify the potential changes to the beach in response to natural forces and to possible changes in the coastal defences. Figure 1 shows a simplified flowchart setting out the main littoral processes and their interrelationship.

Much of the coastline from Flamborough Head to the Thames has been subject to erosion and retreat since the end of the last Ice Age when the North Sea basin filled (again) with water. The main processes causing the coastal changes can be summarised as follows:

- Variations along the coast in the rate of beach sediment transport (longshore drift);
- Variations in time of the supply of river sediments to the beach
- Erosion of the nearshore seabed, which is normally of similar rock to any cliffs;

- Landwards migration of the beach profile in response to sea level rise;
- Loss of sand from the beaches to the nearshore seabed;
- Wave attack on the cliff or back shore at and above the high water mark;
- Cliff weathering and erosion, e.g. by winds, rainfall, freeze-thaw etc; and
- Land-sliding of the cliff faces caused by saturation by groundwater flows.

Following the construction of coastal defences, especially seawalls, these natural processes were altered, leading to reduction in natural beach or cliff recession rates in some areas (typically where there was greatest human development) but at the expense of increased recession on undefended sections. This effect of increased recession occurred on the down-drift side of any coastal defences (i.e. on the side the sediment was being transported to). The reasons for this are as follows. First, the coastal defences reduced the erosion of the beach behind them, thus reducing the supply of sediment to the beaches locally. Second, and more important, the defences, particularly the groynes, tended to trap beach sand travelling along the coast. Both these effects reduced the amount of sand arriving on the beaches immediately down-drift of the defences, a phenomenon known as “drift starvation”. Because the drift rate on the unprotected coast was now not supplied by (enough) sand arriving from the defended frontage, the beaches, and shortly afterwards any cliffs, eroded to make up the deficit in the sediment budget. Such problems often resulted in the construction of further coastal defences, typically groynes and sometimes seawalls or revetments, further down the coast which reduced the direct wave attack on the cliff faces and reduced the changes in the plan shape of beaches caused by variations in the longshore drift.

There was, however, a tendency for a positive effect on beaches updrift of defended frontages, i.e. on the side of the groyne that the sediment was arriving. Here beach material tended to accumulate since it could only travel past the groynes and seawalls more slowly. Even this effect, however, can have disadvantages since it may reduce cliff erosion and hence the supply of extra beach material. Other littoral processes, however, have continued including the erosion of the nearshore seabed and the increase in mean sea level.

2.1 Methods of modelling the longshore drift rate

Along most coastlines of the world, longshore sediment transport, often called longshore drift, is predominantly caused by waves that break obliquely to the shoreline. This is also the situation along the east coast of England between Flamborough Head and the Thames. Unusually, tidal currents also affect the longshore drift on parts of this coastline, where currents are strong close inshore. Further discussion of the modifying effects of tides on the longshore drift is presented later in this report.

Some early estimates of the net annual longshore drift rate along the coastline of Norfolk were made by research workers at the University of East Anglia in the 1970s (Vincent 1979, Clayton et al, 1983). The basic methodology had three main steps:

1. Modelling a time series of wave heights, periods and directions close to the coast
2. Calculating a longshore transport rate for each wave condition
3. Averaging the drift rates to produce a mean annual nett drift rate.

As normal in such studies, the longshore drift rate was calculated by a simple formula that estimates the instantaneous rate of sediment transport caused by any wave condition. By repeated use of this formula for the whole wave climate, as predicted for a chosen location at the coast, the total volume of longshore drift at that location is estimated. Most of the studies that calculated drift rates in this way used a variation of a formula developed by Komar and Inman (1970) and widely known as the CERC formula because of its use in the Shore Protection Manual (1984).

This approach is still widely used, albeit with refinements in the modelling. However, it is important to realise that the longshore drift rates calculated by this numerical method are subject to a considerable degree of uncertainty unless a site-specific validation can be carried out. In addition, estimates made using information on waves over one period can vary dramatically from subsequent estimates made using wave information for a different period. Moreover, despite the fact that there have been many studies estimating longshore drift rates, there is no way of physically measuring the rates of sand transport along the coastline. The drift rates quoted must therefore be treated as estimates rather than absolute values.

2.2 Methods of assessing beach volume changes

The Environment Agency has conducted 6-monthly beach profile surveys along nearly 420 defined beach profiles between the Humber and the Thames since summer 1991. These are commonly used in strategy studies to assess beach variability and trends in volume along short stretches of coastline. The whole dataset has also been analysed twice, by Leggett et al (1998) and Schans et al (2001) to provide a regional picture of the behaviour of beach volumes. Leggett et al (1998) used the data from 1991–1996 to calculate the average percentage change in beach volume over set lengths of coast they called ‘beach units’. Schans et al. used the data from 1991–1999 and looked at average and standard deviation of the percentage change in beach volume. They also used a split moving window method to provide a statistical measure of the differences in the mean (and standard deviation) of the beach volume changes on either side of a point. This technique was used to identify boundaries between regions of different beach behaviour at a range of lengthscales.

3. HOLDERNESS

3.1 Description of the coastline

The indented coastline of Flamborough Head is replaced to the south by the smooth curving coastline of Holderness. A lot of work has been done on describing and quantifying the development of this coastline, while relatively little has been done on determining drift rates. The Holderness coastline from Bridlington to Kilnsea has very high rates of erosion, due to the boulder clay outcropping at sea level. Cliff recession is known to have continued over hundreds of years and shows no signs of abating. Approximately 1,000 hectares have been lost in the last 900 years. Both cliffs and shore-face are eroding, while the shore-face has thin layer of sediment overlying till (that erodes by abrasion). This till is often exposed.

The Holderness beach profile can be classified as an example of Sunamura’s (1992) Type-A, where the rock resisting force is less than the assailing force and the shore platform extends below low water without a break. Wingfield and Evans (1998) point out that Holderness is different from a typical type-A:

The coast is cut into soft rock, so the erosion rates are very high
Cliff erosion takes place by destabilization.
The shoreface only acquires a sparse and varying supply of sediment to form a beach (except for the extensive South Smithic Bank). Wingfield and Evans (1998) attribute this to the following three reasons. Flamborough Head acts as a barrier to sediment transport from the north. The northern third of the coastline (around Bridlington) has only 70% of the retreat rates shown further south. The sediment supply produced by erosion is transported rapidly south.
The youth of the eroded rock means it is unlikely that the surfaces are antecedent from older cycles of sea-level changes.

Wingfield and Evans (1998) also give figures for the average gradients for the shoreface ramp and the seabed seaward of the shoreface ramp along four profiles. The shoreface ramp extends out to between about 11m and 14m below MHWS and the seabed seaward of the shoreface ramp out to 10km offshore was included, where the depth was between 24m and 28m. These gradients are given in Table 3.1.

Table 3.1 Gradients of the shoreface ramp and seabed seaward of it for Holderness

	Barmston	Hornsea	Tunstall	Dimlington
Gradient of shoreface ramp	1:133	1:118	1:179	1:78
Gradient of seaward seabed	1:708	1:833	1:476	1:708

Estimates of erosion from several studies are given in Balson, Tragheim and Newsham (1998). They conclude that about 1/3 was from cliffs and about 2/3 was from the shore-face. The average rate of erosion from a number of studies yield 3.2×10^{6}m^{3}/year. Wingfield and Evans (1998) estimate average erosion rates of 18m^{3}/m/year for the cliff, 26m^{3}/m/year from the shoreface ramp and provide estimates of rates for deeper water than that as well. One of the most comprehensive studies of the rate of recession of the Holderness cliffs was made by Valentin (1954, 1971) using Ordnance Survey maps. Valentin suggested that the average recession rate was 1.2m per year but that the rate increases southwards in response to energy input from wave action from the north, as shown by the following averaged rates:

- Sewerby (Bridlington) to Earle's Dyke: 0.29m/year
- Earl's Dyke to Hornsea 1.10m/year
- Hornsea to Withernsea 1.12m/year
- Withernsea to Kilnsea Warren 1.75m/yr

The behaviour, transport pathways and sinks depend on particle size and composition. However, the composition varies along coast, as well as the cliff height and recession rates. Balson et al. (1998) reported that the average composition is 74% to 84% silt/clay, 10% to 15% very fine sand, 5% to 10% coarse sand and 1% boulders. Wingfield and Evans (1998) note that about 80% of the sediment released is mud (silt and clay) transported in suspension and distributed throughout the North Sea (with some entering estuarial budgets). Approximately 1% is large gravel and cobbles that help form the ribs or ords along the Holderness coastline. Therefore approximately 6.4×10^{5}m^{3}/year of fine sand or courser is released between cliff top and base of wave action (about 15m depth). The sand is transported by waves and tides to form mobile beaches or sand banks (notably South Smithic) or is transported south towards Spurn Point.

Maddrell, Home, Thurston and Rennie (1999) have analysed bathymetry at Holderness. The offshore part of their analysis (about 20m contour) always showed erosion. They suggest that recession rates may be governed by on/off-shore sediment transport as much as longshore transport at the beach.

The lithology of the cliffs makes them highly susceptible to erosion. The weakly consolidated boulder clay consists of a clay matrix containing a mixture of coarse sediments and pebbles. Erosion takes place intermittently and at variable rates by mass movement as a result of sub-aerial weathering processes. Alternative wetting and drying of the clay leads to cracking, rotational slips and slides. Surface cracking and potential slips are seen at the cliff top. Dislodged material is quickly removed from the base of the cliff by wave attack, so steepening and destabilising the cliff face. The result is that the cliff top recedes intermittently and irregularly as a series of bights.

Most of the cliff line is unprotected by coastal defences. Where these have been built (e.g. at Withernsea and Hornsea) rates of erosion are locally reduced and groyne systems have been successful in capturing sand and maintaining beach levels. This is also clearly visible in Valentin's recession rates (as shown by Balson et al 1998). However, as a direct result, erosion is severe immediately to the south or 'downdrift' of these frontages.

The rate of cliff erosion not only relates to the wave exposure. The configuration of the beach also plays an important role. Erosion is accelerated with the passage of pronounced runnels (locally known as ords) parallel to the cliff base. These features are a marked characteristic of the sandy beaches along the east coast of Holderness and Lincolnshire. Between Barmston and Spurn Head as many as ten ords may exist. Once developed, they migrate southwards as a continuous system under north and north-easterly wave conditions. The fact that ords are not found north of Barmston may be due to the sheltering effect of Flamborough Head. The precise mechanism for the development of ords is not known. Studies have shown that the 'normal' beach profile is modified by the presence of an ord. The lower beach widens and, as a ridge of sand gradually moves landwards, it encloses a water-filled runnel at the foot of the cliff, often exposing the boulder clay platform to erosion.

The beaches fringing the Holderness coastline are narrow and consist of a thin veneer of material only 1-2m thick over the shore platform. If longshore transport models do not take into account the limited volume of sediment that is available to be transported, they can overestimate the longshore transport rates by modelling the longshore transport of sand where there is actually solid shore platform. Such transport rates are referred to as potential sand transport rates.

Exchange between the beach and nearshore zones takes place as a result of beach drawdown under storm wave conditions and onshore movement in calmer conditions. Such exchanges may be important in the development of ords but there appears to be no long-term source of beach material from offshore, rather the opposite may occur. The beaches between Barmston and Hornsea are relatively low and narrow with the clay substratum being frequently exposed. The open exposure of this stretch of coast means that there is high potential for alongshore movement of sediment both northwards and southwards. The net effect of wave action is a southward transport of sand along the whole of the Holderness coast.

The rapidly eroding boulder clay cliffs of the Holderness coast terminate near Kilnsea. At Kilnsea Warren the boulder clay surface drops below sea level and is overlain by wind blown sand. The sand deposits extend southwards as a result of the pronounced southward net littoral transport. They terminate at the distal end of the spit feature of Spurn Head. The spit extends well into the Humber Estuary. The route for sediment transfer to the opposite side of the estuary is also being investigated in the Southern North Sea Sediment Transport Study, Phase 2.

The continued existence of the Spurn peninsula depends heavily on the supply of material from the erosion of the Holderness cliffs. Much of the cliff material is clay; the sand content and hence the southward sand transport is limited in volume. The neck of the spit is quite narrow and the dunes are only a few metres high. There was a severe breach of the dunes (but not the underlying clay till) in 1996 that was quickly filled with concrete rubble. Other wash-over events have taken place recently in this area which can disrupt the road, despite the reinforcement of the backshore with imported “earth”. IECS (1992) reports that Spurn is eroding at the root and has rotated by 17° between 1824 and 1990. Further south the spit widens to form a spatulate shape and there the sand dunes are healthier and considerably higher. Breaches of the underlying clay till to form channels are very rare with the last significant breach of this type occurring half way down the length of Spurn in 1849 (de Boer, 1964). A description of the development of Spurn Point over the Holocene is provided in Binnie, Black and Veatch (2000).

3.2 Estimates of longshore drift rates

No study has systematically modelled the variation in wave conditions or drift rates from Flamborough Head to Spurn Point. However, a number of studies have estimated drift rates at particular stretches of the coastline. The studies are listed below and are described in the following sections. The estimates of drift rate are given in Table 3.2.

- Mason, S.J. and Hansom, J.B. 1988. Cliff erosion and its contribution to a sediment budget for part of the Holderness coast, England. Shore and Beach, 56, 30-38.
- Halcrow, 1988. Holderness Joint Advisory Committee for Coastal Protection. Nearshore Environmental Studies Phase 2. Field Surveys 1987/1988.
- IECS 1991. Filey Bay environmental Statement. The University of Hull, Institute of Estuarine and Coastal Studies.
- IECS, 1994. Holderness Coastal Defence. The University of Hull, Institute of Estuarine and Coastal Studies.
- Posford Duvivier, 1992. Easington
- Posford Duvivier, 2000. The Yorkshire Marina, Bridlington: Environmental Statement.
- Posford Duvivier, 2001. Withersea Coastal Defence Strategy Study. Report for the East Riding of Yorkshire.
- HR Wallingford, 2002a. Annex A to this appendix. Work performed for the Southern North Sea Sediment Transport Study.

3.2.1 Mason and Hansom, 1988

Mason and Hansom (1988) calculated sediment supply to the beach from recession rates along seven sections of the coast between Skipsea and Hornsea. They also calculated longshore transport rates at the boundaries of the sections using the wave refraction programme WAVENRG. Wave energy data was input from a 1-year continuous wave record obtained from a sea bed pressure transducer 1km offshore. Beach profile data was also input and transport rates calculated. The overall nett movement in the field site was given as 2,800m^3/year. However, this was not the average of the quoted longshore supply or removal rates, so is not equivalent to a potential longshore transport rate. The average of the longshore supply rates was 10,600m^3/year.

3.2.2 Halcrow, 1988

Halcrow (1988) ran a tidal model of the Holderness area and produced estimates of the direction of transport due to tides alone at Barmston, Hornsea, Tunstall and Dimlington. Their results are summarised below:

- The shoreface sands at Barmston are mainly fine sands (about 170µm). Sands of this size are set in motion by a U100[1] value of around 30cm/s. At Barmston U100 only exceeds 30cm/s for about 2% of the time. Tidal sand transport will be minimal and confined to slow bedload creep at times of peak spring flows. Based on a comparison of the duration of the flood and ebb near-bed tidal velocities, the direction of transport is northwards.
- The shoreface sands at Hornsea are mainly fine sands (about 170µm). Sands of this size are set in motion by a U100 value of around 30 cm/s. At Barmston U100 only exceeds 30 cm/s for about 5% of the time. Tidal sand transport will be minimal and confined to slow bedload creep at times of peak spring flows. Based on a comparison of the duration of the flood and ebb near-bed tidal velocities, the direction of transport is northwards.
- The shoreface sands at Tunstall are mainly fine sands (about 170µm). Sands of this size are set in motion by a U100 value of around 30 cm/s. At Tunstall U100 is greater than 30 cm/s for 20% of the time and reaches a peak value of 45 cm/s. Over spring tides tidal transport of shoreface toe sands can be expected. Based on a comparison of the duration of the flood and ebb near-bed tidal velocities, the direction of transport is southwards.
- The shoreface sands at Dimlington are mainly fine sands (about 170µm). Sands of this size are set in motion by a U100 value of around 30 cm/s. At Dimlington U100 is greater than 30 cm/s for 40% of the time and reaches peak values of 65 cm/s. Based on a comparison of the duration of the flood and ebb near-bed tidal velocities, the direction of transport is southwards.

3.2.3 Institute of Estuarine and Coastal Studies (IECS) 1991

The University of Hull IECS (1991) calculated that there were 40,000m^3 of wave-dominated sediment transport per year moving south around Flamborough Head. This was calculated in their 'Filey Bay Environmental Statement' using computer modelling techniques for the wave return periods of 1, 10, 25 and 50 year northerly and north-easterly waves. The total volume of sediment transport in 50 years was predicted to be 1,900,000m^3 or approximately 40,000m^3 per year. IECS also stated that sediment is believed to be carried north around Flamborough Head by a tidal current. Tidal current modelling predicted that around 45,000m^3 per year moves north around Flamborough Head.

3.2.4 Posford Duvivier, 1992

Posford Duvivier used the coastal profile model UNIBEST LT to model the wave-driven longshore drift at Easington. They predicted 157,000 to 310,000m^3 of sand transport per year moving south. The offshore wave climate between 1978 and 1987 was input into the model. The estimates assume a uniform sand size of 0.23mm. The estimates are for areas within 200m (157,000 m^3) and 650m (310,000m^3) of the cliff.

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[1] U100 current velocity at 1 metre above the bed

3.2.5 Posford Duvivier, 2000

Longshore transport rates due to waves and tides were calculated separately by the coastal profile model, UNIBEST LT. The longshore transport due to waves was estimated as 83,000-134,000m^3/year moving south at Bridlington. The model was input with a range of wave and water level conditions, equating to 1 year of typical wave climate at each of four beach profile locations. The sediment movement was solely wave-driven and occurred 400-900m offshore. The 50,000m^3 of tide-dominated sediment transport per year moving north at Bridlington were also calculated using the UNIBEST LT model. The model was input with current and water level conditions only to derive an estimate of the tidal-driven transport.

3.2.6 Institute of Estuarine and Coastal Studies (IECS) 1994

IECS produced a report on 'Holderness Coastal Defence' that included estimated sediment transport in the region from Barmston to Cowden. They estimated that the supply of sand from cliff erosion between Barmston and Hornsea was 30,000m^3/year and that this moves south past Hornsea. They also used the coastal profile model LITPACK to estimated potential longshore drift between Hornsea and Mappleton. The model used wave and tidal inputs and nearshore topography to calculate the rate of sediment movement for each wave height and wave approach direction. These were summed to provide the net annual sediment transport. The model calculated the complete sediment transport for a range of wave parameters in a 1-year series from a specific direction. They calculated 360,000m^3 net sediment transport per year as the maximum moving south between Hornsea and Mappleton. IECS also predicted that there was 32,000m^3 of sand per year moving south at Cowden. This was derived from the southerly migration of an intertidal shore attached sand bar. The end of the bar was observed to move 163m in a southerly direction over a 6-month period. The total width of the bar was 108m, and assuming a mean sand depth of 1m, this would mean that approximately 16,000m^3 of sand was moving south during the 6 month period, or 32,000m^3 per year.

3.2.7 Posford Duvivier, 2001

The coastal profile model UNIBEST LT was used to predict 25000 to 35000m^3 of sediment per year moving south at Withernsea. Wave climate data from 1986 to 1996 was used to compute an annual wave climate at each of four beach profile locations and the four results were averaged.

3.2.8 HR Wallingford, 2002

The coastal profile model COSMOS (Nairn and Southgate, 1993, Southgate and Nairn, 1993) was used to calculate the cross-shore distribution of longshore sediment transport just north of Hornsea. Further details of this modelling are provided in Annex A. All calculations were driven by the same wave and tide conditions. Results were produced for sediment transport within 150m of the beach, 1500m of the beach and down to the 15m contour (approximately the base of wave action).

Table 3.2 Longshore drift rates at Holderness.

mE	mN	Name	Dir	Q [m^3/yr]	Type	Reference
527000	471000	Flamborough	0	45000	Tidal	IECS (1991)
527000	470000	Flamborough	180	40000	Wave	IECS (1991)
519300	466300	Bridlington	208	108500	Wave	Posford Duvivier (2000)
519800	466000	Bridlington	28	50000	Tidal^{++}	Posford Duvivier (2000)
518500	459700	Barmston	351	NS	Tidal	Halcrow (1988)
519100	452900	Ulrome-Hornsea	161	2800	Wave	Mason and Hansom (1988)
520150	449830	Hornsea	168	26500	W+T, Sand	Annex A
520150	449830	Hornsea	168	57600	W+T, Sand	Annex A
520150	449830	Hornsea	168	260000	W+T, Sand	Annex A
522200	448600	Hornsea	338	NS	Tidal	Halcrow (1988)
521000	448000	Hornsea	158	30000	Morphology	IECS (1994)
522000	445600	Hornsea-Mappleton	151	360000	Wave	IECS (1994)
523600	442800	Cowden	147	32000	Morphology	IECS (1994)
532600	432700	Tunstall	144	NS	Tidal	Halcrow (1988)
534300	428200	Withernsea	142	30000	Wave^{++}	Posford Duvivier (2001)
541000	421600	Dimlington	148	NS	Tidal	Halcrow (1988)
540400	419800	Easington	153	234000	Wave^{+}	Posford Duvivier (1992)

NS = transport rate not specified – only average direction due to tides specified.
$^{+}$ = average of two numbers
$^{++}$ = average of four numbers

3.2.9 Discussion of longshore drift

The models with sediment transport driven by waves only all show drift rates to the south, although there are no estimates of wave-driven transport between Bridlington and Flamborough Head. The HECAG SMP (Posford Duvivier, 1998) states that the sheltering effect of Flamborough Head allows a longshore drift from south to north, causing changes in the beach level and shape to the north of Fraisthorpe (between Barmston and Bridlington). Posford Duvivier's (2000) modelling at Bridlington gave a strong north to south drift at the town, so northwards drift towards Flamborough Head is likely to be limited to the section between Bridlington and Flamborough Head. Northwards drift that gets close to Flamborough Head may be transported offshore into Smithic Bank by the tidal re-circulation to the south of the headland.

The sediment transport studies that used tides and no waves indicate that the nett tidal residual transport is to the north between Bridlington and Hornsea, but to the south from Tunstall southwards. These studies did not claim that this was the nett direction of motion – rather they provided an estimate of the tidal influence in a region dominated by wave-driven transport. The reason for this change in direction is the influence of Flamborough Head, which creates a circulation pattern behind it during the southwards flowing tide. This result was also obtained during the PISCES coastal area modelling for the Southern North Sea Sediment Transport Study (HR Wallingford, 2002a).

There are two estimates of sediment transport rates from observations of morphology. These are considered to provide unreliable magnitudes of sediment transport, but their directions are considered reasonable, as they are consistent with other transport directions.

HR Wallingford has produced three results for the longshore transport rate of sand for the same cross-shore profile at Hornsea. The three estimates (from lowest to highest) are given for sediment transport out to 150m from the top of the beach, down to the 10m contour and down to the 15m contour (approximately the base of wave action). They differ by an order of magnitude and illustrate the difficulty in determining a longshore transport rate. In this case, BGS facies data indicates that there is no sand further than about 1500m from the coastline. This corresponds to approximately the middle option (58,000m^3/year).

3.3 Conceptual sediment transport map

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 (HR Wallingford, 2002a) 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 point).

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, Land and Wolf (2001) modelled SPM along the Holderness coastline and showed that, for sediment with $d \approx 50\mu$, the observed erosion rate 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 by Mason and Hansom (1988) and by the BGS facies data (reproduced in HR Wallingford, 2002a). 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 on moving south. This is not immediately apparent from the modelled longshore drift rates. This partly reflects to 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 modelling at Hornsea. 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.

The estimated drift rate into Spurn Point is around 125,000m^3/year (Valentin 1954) 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. A sediment trend analysis by Halcrow/Geosea (1990) also indicated that sand moves offshore from Holderness, possibly around Easington. The authors consider 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 (HR Wallingford, 2002a) showed that, during a storm surge, there is a high sediment transport rate across the Humber from Spurn and the Binks towards Donna Nook. This reduces the volume of sediment in the Binks and Spurn Point.

4. LINCOLNSHIRE

4.1 Description of the coastline

4.1.1 Cleethorpes to Mablethorpe

From the Humber to the Wash the land is very low lying and fringed by either saltmarsh or sand dunes. There is also a frontage of low cliffs to the south of the Humber at Cleethorpes. These are protected from wave action by coastal defences.

To the south of Cleethorpes the backshore is only partly developed and the coastal defences are fragmentary. Between Cleethorpes and Humberstone Fitties there is an area of sand dunes, which is prone to damage by public overuse (because of a large number of caravan sites and holiday parks in the area). This frontage has a history of flooding and is protected by flood banks and revetments. An increase in wave activity in this area could have a serious impact on the flood defences, which are not particularly robust.

Further southwards there is a large accumulation of sands and silts in the vicinity of Donna Nook. The gradually sloping foreshore and offshore shoals have enabled saltmarsh development, which extends southwards to Saltfleet. Between Saltfleet and Theddlethorpe the foreshore is wide and sandy and backed by dunes. For most part the dunes are stable and well vegetated and form an effective natural defence against flooding. They also provide a reservoir of sand, which may be returned to the beach under offshore wind conditions or during periods of foreshore erosion. This area has not experienced significant erosion in the recent past. However, as the dunes are composed of fine sand they are sensitive to erosive processes.

Leggett et al. (1998) noted a 2% average increase in beach volume between 1991 and 1996, while Schans et al. (2001) noted that the changes in beach profile had small averages and low standard deviations. Schans et al. also noted a boundary in the beach behaviour around Mablethorpe that was evident over a wide range of scales (in the longshore direction).

4.1.2 Mablethorpe to Skegness

The Lincolnshire coastline from Mablethorpe southwards to Ingoldmells is exposed to strong wave action and the beaches are eroding, partly at least due to the reduction in foreshore width over the last century or so. The foreshore gradually reduces in width in a southerly direction, until the northern outskirts of Skegness are reached.

Between Mablethorpe and Ingoldmells the sand cover on the beach became very thin in the recent past and during storms the underlying boulder clay became exposed and underwent "irreversible" erosion. Most of this frontage is protected by seawalls, the low lying hinterland being very low and having been prone, in the recent past, to disastrous flooding. This was particularly severe during the 1953 surge when the flood defences were overwhelmed, leading to the construction of larger revetments and seawalls over much of this frontage. This course of action may be one of the contributory factors that accelerated the so-called coastal squeeze (or coastal steepening) leading to further deterioration of foreshore conditions. With the continuing deterioration of foreshore levels, the sea defences became under increasing threat of overtopping as well as suffering foundation problems. The groyne systems also became increasingly ineffective. The area has now undergone the largest beach recharge in the U.K. with the recharge material having been won from a dredging area off the north Norfolk coast. The possibility of disastrous flooding has now been greatly diminished. However any changes in the wave climate in this sensitive area would be of considerable concern, for example reducing the expected life span of the recharged beach.

4.1.3 Skegness to The Wash

South of Skegness, in the approaches to The Wash, there is a sediment sink. Sheltered conditions in this area 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. Leggett et al. (1996) noted that there was a consistent gain in volume in the beach profiles between Mablethorpe and Gibraltar Point and Schans et al. (1998) also noted positive averages and large standard deviation in the beach volume changes. Both results reflect the presence of the large beach recharge scheme between Mablethorpe and Skegness that took place during the survey period.

4.2 Estimates of longshore drift rates

The direction of longshore sediment transport has been estimated by a number of observers, but only three studies have calculated longshore drift rates. All of these studies were along the centre of the frontage between Mablethorpe and Skegness.

4.2.1 HR Wallingford, 1991

The calculations were made using HR Wallingford's Nearshore Profile Model – NEARSHORE (the fore-runner of COSMOS). NEARSHORE was a 2D wave propagation, current and sediment transport model. The model incorporates tidal and wave induced currents. Previously calculated inshore wave data was used. This data was based on offshore hindcast data and had been transformed inshore using a refraction model. Tidal current data from Admiralty tables and charts was used. Sediment transport calculations were made at 50m intervals along shore-normal profiles extending seaward from the seawall for Spring and Neap tides. The calculations are for potential rates of sediment transport and therefore do not account for limitations in supply. The rates have also not been calibrated against site data and are therefore of benefit when looking at relative rates but absolute values should be treated with caution. The calculated transport rates are summarised on the GIS layer as a yearly average value for each of the three Lincolnshire sites. However, the actual 50m interval grid point calculations are shown in Tables 4.1, 4.2 and 4.3.

Table 4.1 Longshore transport rates at Sutton Pullover

Distance from wall [m]	Spring tide cumulative longshore transport rate ($10^6 m^3/yr$) (-ve Southwards)	Neap tide cumulative longshore transport rate ($10^6 m^3/yr$) (-ve Southwards)
0	-0.01	0.00
50	-0.97	-0.07
100	-1.22	-0.29
150	-1.45	-0.61
200	-1.79	-1.23
250	-2.15	-1.96
300	-2.48	-2.57
350	-2.84	-3.17
400	-3.56	-4.24
450	-5.86	-6.32

Table 4.2 Longshore transport rates at Anderby Creek

Distance from wall [m]	Spring tide cumulative longshore transport rate ($10^6 m^3/yr$) (-ve Southwards)	Neap tide cumulative longshore transport rate ($10^6 m^3/yr$) (-ve Southwards)
0	0.00	0.00
50	-0.07	0.00
100	-0.10	-0.23
150	-0.22	-0.41
200	-0.28	-0.56
250	-0.35	-0.76
300	-0.46	-0.98
350	-0.55	-1.13
400	-0.62	-1.24
450	-0.98	-1.48

Table 4.3 Longshore transport rates at Vickers Point

Distance from wall [m]	Spring tide cumulative longshore transport rate ($10^6 m^3/yr$) (-ve Southwards)	Neap tide cumulative longshore transport rate ($10^6 m^3/yr$) (-ve Southwards)
0	0.00	0.00
50	-0.19	-0.01
100	-0.24	-0.06
150	-0.26	-0.11
200	-0.29	-0.18
250	-0.44	-0.38

4.2.2 Delft Hydraulics, 1992 and Posford Duvivier, 1998

The cross-shore profile model UNIBEST-LT was used in both studies to calculate the longshore transport rate due to waves at a number of points along the defended frontage from Mablethorpe to Skegness. The estimated mean annual nett longshore drift rates, differ by factors of two to ten, as shown in Table 4.4. The drift calculations for the Posford Duvivier work in 1998 focussed on the upper beach area, examining movement of actual recharged material. Previous work by Delft Hydraulics considered the broader coastal processes over a 1km cross-shore profile. Some correlation was established between trends in the 1998 work and surveyed beach slope. The Posford Duvivier study is the most up-to-date and used the most recent survey information, so was taken as the most reliable representation of drift rates along the frontage for the upper beach. The directions are all southerly along the shoreline.

Table 4.4 Longshore transport rates for Lincolnshire

mE	mN	Location	Dir	Q	Reference
550293	386332	Maplethorpe-Skegness	N to S	130000	P Haskoning 1998
550600	385850	Maplethorpe-Skegness	N to S	119000	Delft 1992
550850	385225	Maplethorpe-Skegness	N to S	96000	Delft 1992
551381	384249	Maplethorpe-Skegness	N to S	13851	P Haskoning 1998
551325	384225	Maplethorpe-Skegness	N to S	107000	Delft 1992
551825	383325	Maplethorpe-Skegness	N to S	85000	Delft 1992
552153	382346	Maplethorpe-Skegness	N to S	89000	Delft 1992
552800	381350	Maplethorpe-Skegness	N to S	120000	Delft 1992
552733	380970	Maplethorpe-Skegness	N to S	32830	P Haskoning 1998
553025	380480	Maplethorpe-Skegness	N to S	128000	Delft 1992
553580	379750	Maplethorpe-Skegness	N to S	130000	Delft 1992
554183	378578	Maplethorpe-Skegness	N to S	141000	Delft 1992
554750	377620	Maplethorpe-Skegness	N to S	135000	Delft 1992
555000	376800	Maplethorpe-Skegness	N to S	125000	Delft 1992
555400	375700	Maplethorpe-Skegness	N to S	129000	Delft 1992
555800	374580	Maplethorpe-Skegness	N to S	135000	Delft 1992
556024	373995	Maplethorpe-Skegness	N to S	12726	P Haskoning 1998
556097	373747	Maplethorpe-Skegness	N to S	135000	Delft 1992
556225	372700	Maplethorpe-Skegness	N to S	139000	Delft 1992
556500	371500	Maplethorpe-Skegness	N to S	142000	Delft 1992
556750	369825	Maplethorpe-Skegness	N to S	135000	Delft 1992
557059	369793	Maplethorpe-Skegness	N to S	52921	P Haskoning 1998
557150	369725	Maplethorpe-Skegness	N to S	134000	Delft 1992
557359	368834	Maplethorpe-Skegness	N to S	137000	Delft 1992
557480	368150	Maplethorpe-Skegness	N to S	135000	Delft 1992
557380	366900	Maplethorpe-Skegness	N to S	118000	Delft 1992

Table 4.4 Longshore transport rates for Lincolnshire (continued)

mE	mN	Location	Dir	Q	Reference
557310	365825	Maplethorpe-Skegness	N to S	116000	Delft 1992
557169	364901	Maplethorpe-Skegness	N to S	131000	Delft 1992
557188	364901	Maplethorpe-Skegness	N to S	26693	P Haskoning 1998
557250	364125	Maplethorpe-Skegness	N to S	121000	Delft 1992
557350	363010	Maplethorpe-Skegness	N to S	123000	Delft 1992

4.2.3 Discussion of longshore drift

The HR Wallingford results are considered to be too high (the report warns that the absolute values are to be treated with caution) so will not be considered in further analysis. Delft's results are fairly uniform along the coast, but are rather larger than Posford's. This is not unreasonable as Posford's results only considered the upper part of the beach (the area that was to be recharged). Both Delft's and Posford's results may be regarded as reasonable estimates of the longshore transport rates in the respective areas considered.

4.3 Conceptual sediment transport map

The frontage may reasonably be split into three sections:

- An accretionary area around Donna Nook and Saltfleet
- An erosionary 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 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 outfalls. 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 (2000) showed 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 by HR Wallingford (2002a, Figure 71 and Appendix 12). 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. 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.

Donna Nook is a sediment sink. Research by Robinson (1964, 1968) using seabed drifters as indicators of water/sediment movement, suggests that much of this accumulation originates from release of fine sediments caused by the erosion of the Holderness cliffs. This view is supported by the coastal area modelling performed for this project (HR Wallingford, 2002a) which also strongly supports the view that the sediment pathway is directly across 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. Drift rates may be taken from Posford Duvivier (1998) or Delft Hydraulics (1992) depending on the width of the beach that needs 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 offshore 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 (at least temporary) sink at Gibraltar point, while some of the fines may be transported offshore and then enter the Wash, driven by tidal currents.

5. THE WASH

5.1 Coastline description of the Wash

The Wash is being filled with fine marine sediments and estuarine and alluvial silts. It now forms the estuary of several rivers, including the Ouse, The Nene and The Welland, and continues to act as a "sink" for marine sediments carried southwards down the Lincolnshire coast. Siltation is aided by the accumulation of alluvial and estuarine deposits discharged by the rivers. There are, as a result, large shoaling areas, which effectively dissipate wave energy, allowing the salt marshes around most of the shoreline to continue their development. These internal shores are rarely hit by excessive wave activity, and the cohesive nature of the sediment makes longshore transport calculations surplus to requirements. Much of the south-western shore of the Wash is muddy - extensive mud flats abound, with a man-made (largely by convicts) embankment protecting the low lying hinterland (mainly arable) from salt water ingress. There is a drainage channel landward of the earth embankment from which any salt water transgressing the embankment is pumped back to the sea. There are few coastal defence structures between Gibraltar Point and Snettisham.

The low-lying east shore of The Wash is partly protected from wave action by the wide inter-tidal foreshore and the near-shore sandbanks. The waves generated locally within The Wash (as oppose to those that propagate in from the North Sea) make a significant contribution to the longshore drift along the Snettisham Scalp to Hunstanton shore. The beaches here are popular. There are sailing schools, caravan sites, and extensive public amenities. The beaches themselves vary along the coast, but they are generally of mixed sediment. This can cause localised problems of, for instance, beach cliffing, making public access difficult and dangerous. Should the beach crest breach, there is low-lying land (generally caravan parks) that would be flooded. The flood embankment between Heacham and Hunstanton has been at risk of flooding for many decades. At Hunstanton itself there is a concrete stepped wall, which provides protection against wave overtopping. The beach here has been recharged and regular re-cycling operations are undertaken to counteract the southerly longshore drift. To the north of the Hunstanton seawall there is a short stretch of cliffs formed from consolidated Cretaceous strata. Bridges (1989) notes that a 'sand and shingle beach has grown northwards from Old Hunstanton to the small embayment south of Gore Point'. This almost certainly indicates some form of northwards drift in this area. At Gore Point the coastline takes on a west to east alignment and is low-lying.

5.2 Estimates of longshore drift rates

Estimates of sediment transport have been provided by the following studies:

- Ke, X., Evans, G. and Collins, M.B., 1996. Hydrodynamics and sediment dynamics of the Wash embayment, eastern England. Sedimentology, 43: 157 – 174.
- HR Wallingford, 1998b. Hunstanton/Heacham Sea Defences: Specialist studies for beach nourishment at Heacham and Snettisham. HR Wallingford Report EX 3842.

Brief descriptions of the studies are provided in sections 5.2.1 and 5.2.2 and the results are summarised in Table 5.1.

5.2.1 Ke, Evans and Collins, 1996

Current measurements were taken at 8 stations across the mouth of the Wash (collected by Hydraulics Research Station, 1974) and used to quantify the net direction of bed-load transport across the entrance to the embayment. 'Potential' rates of bed-load movement were calculated at each of the stations using the Steinberg Method. This is based on the relationship between the mean grain diameter of the sea bed sediment and the current speed at 1m above the bed (U100). U100 was derived using a logarithmic distribution of velocity profile and roughness lengths of 0.08 and 0.16cm for the accelerating and decelerating phases of the tide respectively. The derived bed-load transport rates have been multiplied by the percentage of sand present in the sediments, to provide meaningful results. There is a net transport of bed-load sediment into the Wash. However the net direction of movement varies across the mouth. Net inward movement occurs at the Lynn and Boston Deeps, with two narrow sections of seaward movement between the Boston and Lynn Deeps and adjacent to the North Norfolk coastline. This analysis is broadly supported by the tidal sediment transport modelling by HR Wallingford (2002).

5.2.2 HR Wallingford, 1998

The sediment transport along the mixed beaches between Snettisham and Hunstanton were modelled using a coastal profile model. Cross-shore distributions of longshore transport were established along cross-shore profiles from eight nearshore wave prediction points. These were at the 0mCD contour, up to 4km offshore due to inter-tidal flats. Tides and waves (both locally generated and those entering from the North Sea) drove the transport. The transport rates due to shingle and sand were modelled separately. There is a clear longshore variation in the fraction of sand present, so different sediment characteristics were used for each profile. The combined results from the sand and shingle runs were weighted by the sand content. The results are shown in Table 5.1.

Table 5.1 Transport rates into The Wash and between Hunstanton and Snettisham. W+T = sediment transport driven by waves and tides. Sa + Sh = sand and shingle included as beach material

mE	mN	Location	Dir	Q	Type	Reference
566400	352000	Wash Entrance	220	14000	Tidal	Ke et al. (1996)
566750	339910	Hunstanton (NOA8)	195	12440	W+T, Sa + Sh	HR Wallingford (1998b)
566560	338780	Hunstanton (NOA7)	182	450	W+T, Sa + Sh	HR Wallingford (1998b)
566350	337780	Heacham (NOA6)	10	110	W+T, Sa + Sh	HR Wallingford (1998b)
566120	336890	Heacham (NOA5)	202	8670	W+T, Sa + Sh	HR Wallingford (1998b)
565700	335600	S of Heacham (NOA4)	207	1940	W+T, Sa + Sh	HR Wallingford (1998b)
565150	334610	S of Heacham (NOA3)	192	3960	W+T, Sa + Sh	HR Wallingford (1998b)
564730	333510	Snettisham Scalp (NOA2)	195	2730	W+T, Sa + Sh	HR Wallingford (1998b)
564780	332400	Snettisham Scalp (NOB2)	358	500	W+T, Sa + Sh	HR Wallingford (1998b)

5.3 Conceptual sediment transport map of The Wash

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 is no real need for longshore transport rates 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. This is far too low to account for the historical rate of infilling, but most of the material carried into the wash has been carried in suspension (and Ke at al., 1996 did not model the littoral drift entering the Wash at Gibraltar Point). HR Wallingford (1998) modelled the sediment transport along the mixed beaches between Snettisham and Hunstanton, using a coastal profile model. The drift rates are to the south, except for a exceedingly small value at Heacham and a northerly drift rate on the south of Snettisham Scalp. The larger southerly drift rate on the north of Snettisham Scalp and the small northerly drift on the southern side could be responsible for the formation and migration of Snettisham Scalp, which has migrated southwards by about 0.5km in the past 45 years. There is a thinning of the beach immediately south of Snettisham Scalp as a result of the longshore loss of material. The beaches between Heacham and Scolt Head Island are relatively stable, as shown by the analysis of beach profiles (Leggett et al., 1998, Schans et al., 2001).

6. NORTH NORFOLK (GORE POINT TO WINTERTON NESS)

North Norfolk is taken as extending from Gore point (at the north-east corner of The Wash) to the north side of Winterton Ness, near Horsey (south of the Sea Palling area but north of Winterton Ness, Great Yarmouth and Scroby Sand).

6.1 Description of the North Norfolk coastline

The coast on the north-west corner of Norfolk is several kilometres seawards of an old cliffline. There are offshore sand and shingle spits, a wide inter-tidal sandy foreshore and extensive areas of salt marsh between the coast and the cliffline. There is some discussion as to how this should be interpreted. The most common viewpoint is that the cliffline was formed by marine action during a previous high sea level, there has been long-term accretion in front of the cliffline and the shore continues to accrete. The features are a variety of recent shoreline deposits, in this view. However, Andrews et al (2000) suggest that the cliffline was the southern margin of an eastward trending ice front channel. They also suggest that the front of features such as Scolt Head Island and Blakeney point have been rolled back (towards the cliffline) at a rate of about 1m per year and are also moving west at a rate of around 3m per year.

The hinterland between Hunstanton and Weybourne is at risk of flooding, and relies on the marshes and offshore features for defence against the sea. Embankments, that were constructed in this area in various phases of "land reclamation", are generally insufficient to withstand direct wave attack. Leggett et al (1998) noted an average reduction in beach volumes of 7% in 5 years between Heacham and Cromer, with the erosion increasing from Heacham to Cromer. They also calculated a reduction in beach volumes of 12% in 5 years between Cromer and Great Yarmouth. This was ascribed to the continuing re-orientation of the coast since the last Ice Age. Schans et al. (2001) also calculated low average and standard deviations in the beach volume change, indicating stable beaches between Heacham and Scolt Head Island. Schans et al also noted an increasing variability in beach volume changes between Scolt Head Island and (roughly) Mundesley.

6.1.1 Gore point to Brancaster Bay

Ordnance Survey first editions show that Gore Point was formerly a more pronounced headland. Some small offshore shingle and sand bars have been formed by wave action, such as offshore of Thornham (at 572500mE, 345100mN). Another good example occurs further east at Bob Hall's Sand. Bridges (1989) states that these bars can act as the initial stages in the formation of offshore barrier islands, such as Scolt Head Island.

Between Hunstanton and Wells Harbour the larger sand and shingle ridges often cause down-drift erosion problems at the hinterland, which commonly occur at their westward ends. Because these are mobile features the erosion problems are difficult to control. One such problem area is the shoreline at the Royal West Norfolk Golf Club at Brancaster, where the sheltering effect of Scolt Head Island has caused a local drift division, resulting in beach draw-down and erosion.

6.1.2 Scolt Head Island

Scolt Head Island is a 7km long barrier island consisting of a sand and shingle beach backed by dunes, with recurved spits enclosing saltmarshes to the south. The island has been extensively studied, as reported by Birbeck College and Babtie (2000) and Andrews et al. (2000). The island accreted rapidly during the 19th century, but is accreting less rapidly now. Maps and aerial photography have shown that the island has continued to extend westwards through the growing of new recurved spits onto the island's western end. In a typical event, a shoreface-attached spit extends from the beach and is then recurved towards the mainland by wave action. New spits may merge with old ones when recurved by wave action, or may extend beyond the old profile and thus extend the island to the west. Steers (1960) measured the onshore movement of marked pebbles dumped 500m offshore.

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 the shingle needed to extend the western end of the island may well be coming from the erosion of the northern and eastern coastlines, resulting in a re-alignment of the island.

6.1.3 Cley and Wells Next The Sea

Wells-next-the-Sea to the east is connected to the sea by an artificially maintained channel. It relies on the near-shore sand and shingle banks for protection against wave action. It is not safe against flooding, however, and it has been known for vessels to be lifted onto the quay walls during exceptionally severe surge conditions.

Salt marshes and shingle ridges extend eastwards to Cley-Next-The-Sea. The shoreline from is protected by a shingle spit, Blakeney Point. Cley ridge (part of Blakeney Point) is now in a very poor condition and could be breached during severe storms. This could result in the village of Cley being flooded and the coast road being affected.

6.1.4 Blakeney Point

Blakeney Point is a spit, which starts at the cliffs near Weybourne. The spit is 15.5km long from Weybourne to Far Point and is described in Bridges (1989). It is typically 200m wide and almost 10m in height and is estimated to contain some 2.3×10^6m^3 of shingle (Hardy, 1964). It has occasionally formed recurved spits during its growth. About 12 are apparent in the present spit.

Hardy (1964) estimated that the ridge of shingle is moving landwards at a rate of about 1m per year. Steers (1927) estimated that Blakeney point extended by an average of 86.3m per year (between 1886 and 1904) and an average of 46m per year (between 1904 and 1925). The shingle is made up of rounded flint pebbles and is coarser at the eastern end (average 4cm) than at the western (average 1.5cm) (Bridges 1989). The ridge is believed to be a relict feature, but is fed by erosion of the cliffs near Weybourne. However the supply of shingle from these cliffs is insufficient to make up the demand for material, needed to make up losses due to the net westward transport of shingle.

The foreshore along Blakeney Point slopes steeply so little sand is exposed at low tide (so there is no source of sand to build dunes). These is sand exposed at low tide to the west and south of Far Point, and this feeds the dunes, such as Beacon Hill, on the western end of Blakeney Point (Bridges (1989). Schans et al (2001) detected boundaries in beach behaviour on either side of Blakeney Point.

6.1.5 Sheringham

From Weybourne eastwards high sandy cliffs (up to 75m) back the shingle beaches over a platform of more resistant chalk, which outcrops towards the water line. Chalk forms the base of the cliffs from Weybourne to Sheringham but further east the chalk surface falls below sea level. The cliffs are weakly consolidated and consist of glacial drift, sands, clays and gravels, and yield readily to wave induced erosion. Between Weyborne and Sheringham there is a steep shingle beach.

At Sheringham the sea frontage was developed over a century ago, and since then considerable shoreline recession has taken place. In the centre of the town the seawalls now project well to the seaward of the natural shoreline; to the east and west the cliffs continue to erode. The town's sea defences have been recently upgraded, including the protection of the toe of the walls with armour stone. Since the stone was put into place there has been a small build up of sand, which is welcome. This veneer of sand is highly mobile and would be put into suspension during periods of severe wave action, thus adding little to the protection of this frontage.

6.1.6 Cromer

Between Sheringham and Cromer the chalk forms a wide wave cut platform as the less resistant glacial overburden has been eroded away. This coastline has been undergoing long term erosion in post-glacial times. The cliffs comprise soft weakly consolidated layers of glacial drift, sands, clays and outwash gravels that yield readily to wave action. The layers are very much contorted, folded and overthrust by ice pressure. Large chalk erratics are exposed in the cliff face between Mundesley and Sheringham such as at East Runton Gap where there is a chalk remnant some 300m wide. Some themselves show signs of folding under the immense pressure of the ice movement. The erosion of the chalk erratics produces chalk rubble on the beach but this is quickly broken down and removed by waves.

The unconsolidated nature of the cliff material makes them vulnerable to mass movement and erosion by sub-aerial processes. The principal mechanism of cliff top retreat along the North Norfolk coast is by landslide. The type of slide is controlled by the lithology, hydrogeology and height of the cliffs. Under natural conditions the base of the cliffs are reached by high tides along much of their length, so the slip lobes are quickly eroded by wave action and the material removed thus maintaining a steep and stable cliff face. The actual rate of recession varies considerably in the short term, with events being episodic. Landslides occur intermittently but higher rates of erosion will tend to coincide with storms and higher tidal levels such as surges. During the 1953 surge some unprotected stretches of the cliff-line were cut back by 30m. Since this time protective works at the toe of the cliff have been constructed over increasing stretches of this coastline in an effort to curb erosion. However, this defence system affects the supply of beach material to the beaches further south. In fact, a recent failure of these defences (at Happisburgh) has led to very rapid erosion of the cliffs and a 'knock on' type effect of defence failure.

Shingle forms a sparse covering on the upper beach (apart from between Weybourne and Sheringham) and the beaches are mainly of sand, which generally becomes coarser downdrift. This trend is seen both to the east and the west of Cromer (McCave, 1978) and is therefore consistent with the idea of drift parting in this area. Moreover, this suggests that finer sand is winnowed away and lost offshore as sediment moves down the transport path. McCave (1978) also calculated the mean annual travel distance for sand and found it to be of the order of 1-1.5km/year. There is therefore a long time-lag between changes in cliff and shoreface retreat and changes in downdrift beaches.

Schans et al (2001) identified a boundary between regions of different beach behaviour at Cromer over a wide range of (longshore) lengthscales. Leggett et al (1998) also identified Cromer as an important point as the rate of beach erosion increased from Heacham to Cromer but decreased from Cromer to Great Yarmouth.

6.1.7 Overstrand, Mundesley, Happisburgh and Eccles on Sea

This stretch of coastline has been subject to erosion and retreat since the end of the last Ice Age when the North Sea basin filled (again) with water (Motyka, 1986, HR Wallingford, 2001b). The main processes causing the coastal changes have been summarised in Section 2.

Prior to the construction of coastal defences in the Happisburgh area, the rates of cliff recession appears to have been at a rate of approximately 0.5m/ year, although there were variations in this rate along the coast and in response to varying weather conditions. Following the construction of coastal defences, these natural processes were altered, leading to reduction in natural cliff recession rates in some areas (typically where there was greatest human development of the cliff-top land) but at the expense of increased recession on undefended sections. This effect of increased recession occurred on the eastern or southern side of any coastal defences. The reasons for this are as follows. First, the coastal defences reduced the erosion of the cliffs behind them, thus reducing the supply of sediment to the beaches locally. Second, and more important, the defences, particularly the groynes, tended to trap beach sand travelling along the coast from the west and north to the east and south. Both these effects reduced the amount of sand arriving on the beaches in front of the cliffs immediately east and south of the defences, a phenomenon known as “drift starvation”. Because the drift rate on the unprotected coast was now not supplied by (enough) sand arriving from the defended frontage, the beaches, and shortly afterwards the cliffs, eroded to make up the deficit in the sediment budget. This phenomenon is clearly shown by the cliff erosion rates at Overstrand and Mundesley (HR Wallingford, 2002b).

There was, however, an opposite effect on beaches to the west and north of defended frontages, where beach material tended to accumulate since it could only travel past the groynes and seawalls more slowly. For this reason, it seems unlikely that the present problems of rapid erosion south of Happisburgh are being made worse by the offshore breakwaters installed by the Environment Agency near Sea Palling, further south. If anything, these defences should have a slightly beneficial effect on the problems of cliff recession further north.

The problems of increased erosion to the east and south of defences has led, over the years, to the construction of further defences until large sections of the coastline, for example from Walcott to Eccles-on-Sea, was protected. These defences comprised of groynes and a variety of seawall or revetment structures which, in particular, reduced the direct wave attack on the cliff faces and reduced the changes in the plan shape of beaches caused by variations in the longshore drift. Other littoral processes, however, have continued including the erosion of the nearshore seabed and the increase in mean sea level. Previous studies have commented on the significant quantities of beach sediment that are lost offshore from this part of the North Norfolk coastline, although without explaining the mechanisms involved in detail. McCave

(1978) suggests that there is a gradual winnowing of the sand as it moves along its longshore pathway. The consequence is that the finer fractions get transported away by tidal action and the beach sediment gets courser, further from its source. Another possible mechanism for diverting longshore drift offshore is the presence of low inter-tidal and subtidal ridges that run diagonally across the beach.

Other causes of beach loss have also been mentioned in connection with the recent increased rate of recession near Happisburgh. Of these the most frequent concern is the effect of offshore dredging for aggregates. The nearest area of seabed where any such dredging has taken place in recent years is offshore from Caister, about 40km distant to the ESE. This dredging is too far away and in water too deep to affect waves, tidal currents or sediment transport processes in the Happisburgh area.

Visual inspections of the cliffs between Walcott and Cart Gap, on numerous occasions, has revealed that where the cliffs are well protected by coastal defences, for example at Coastline Village, they stand nearly vertical. There seems little evidence of substantial land-sliding activity even where water discharges through and over the their faces from the cliff-top fields.

In this respect the cliffs near Happisburgh village seem to be of a different character to cliffs further north, for example at Overstrand, where major rotational failures caused by groundwater processes cause sudden and dramatic (up to 30m in one event) recession of the cliff top edge. High Point Rendel (1995) also made this point, drawing a distinction between different types of cliff erosion. For the study frontage, their description of the cliffs was: “Low (>20m) sub-vertical cliff developed in sandy glacial drift that are retreating mainly in response to marine undercutting.” Schans et al. (2001) identified a boundary between regions of different beach behaviour close to Happisburgh and another boundary (at smaller scales) close to Sea Palling, which may reflect the influence of recent sea defences in this area.

Considerable erosion has occurred at Horsey. Clayton (1977) reported losses of 250,000m^3/year from 1974-1976.

6.2 Estimates of longshore drift rates

Longshore transport rates around East Anglia were modelled in the pioneering studies by the University of East Anglia in the late 1970s and early 1980s (Vincent, 1979, Clayton et al., 1983, Onyett and Simonds, 1983). They 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, following the requirement for Shoreline management plans, many areas have been modelled in more detail, using more up-to-date techniques and site-specific model settings. Therefore it proved to be an opportune moment to extend and update the work of UEA and to apply it to a greater area

Predictions of longshore transport rates were made in the following reports:

- Vincent, C.E., 1979. Longshore sand transport rates – a simple model for the East Anglian coastline. Coastal Engineering 3: 113–136
- Onyett, D. and Simmonds, A., 1983. East Anglian Coastal Research Programme Final Report 8: beach transport and longshore transport.
- Clayton, KM, McCave, IN, and CE Vincent, 1983. The establishment of a sand budget for the East Anglian coast and its implications for coastal stability. In Shoreline Protection, proceedings of a conference organised by the ICE. Thomas Telford, London. pp 91–96.
- HR Wallingford, 1994. Sheringham Coast Protection Scheme 902. HR Wallingford Report EX 2888.
- Halcrow, 1995. Happisburgh to Winterton Sea Defences.
- HR Wallingford, 2001a. Cromer Coastal Strategy Study. HR Wallingford Report EX 4363.
- HR Wallingford, 2001b. Ostend to Cart Gap Coastal Strategy Study. HR Wallingford Report EX 4342.
- Halcrow, 2001a. Happisburgh to Winterton Sea Defences. Stage three strategy review. Project Appraisal Report.
- HR Wallingford, 2002b. Overstrand to Mundesley Strategy Study.

These transport rate predictions are described below and the results are shown in Table 6.1

6.2.1 Vincent, 1977 and 1979

The longshore sand transport rate was calculated using daily vector-averaged wind data from a single site, input into empirical equations to calculate the offshore wave heights. Wave refraction diagrams with the offshore topography provided the angle of incidence of waves on the beach and the ratio of the incident wave's energy per unit crest length to the offshore wave energy per unit crest length. Six-second period waves were considered, with the cosine-squared directional spread of energy about the average wind direction. Wind data for 1964-1976 inclusive was input into the model. The longshore transport rate was calculated using the CERC formula. Results were averaged over not less then 5 km of coast.

6.2.2 Onyett and Simmonds, 1983

The longshore sand transport rate was calculated using daily vector-averaged wind data from a single site input into empirical equations to calculate the offshore wave heights. Wave refraction diagrams with the offshore topography provided the angle of incidence of waves on the beach and the ratio of the incident wave's energy per unit crest length to the offshore wave energy per unit crest length. The longshore transport rate was calculated for the 20 years between 1961 and 1980 inclusive. Note that Onyett and Simmonds provided the results used by Clayton McCave and Vincent (1983) and that these results came from the same UEA project as Vincent's.

6.2.3 HR Wallingford, 1994

HR Wallingford (1994) modelled the longshore drift of shingle above the 0mCD contour at Sheringham. The values for potential longshore transport of shingle are given in Table 6.1. There was a nett transport potential towards the east that increases on going east. The nett drift direction was confirmed by observations of the Sheringham frontage. Analysis of differential cliff change also showed that cliff and beach recession was nearly four times higher on the east side of Sheringham as compared to the west indicating downdrift scour to the east. Moreover, the amount of shingle on the frontage reduced towards the east. This was explained in terms of the increasing transport potential towards the east. The results suggested that the drift null point was to the west of Sheringham. However, the location of the drift divide may be different for shingle and sand and will vary in time as the wave climate exhibits inter-annual variability. Indeed Vincent [private communication] has shown that decadal averages of nett longshore transport rates at Cromer have different directions. Comparisons are only strictly valid if generated in similar manners using the same wind data.

The potential sediment transport was influenced by a number of factors.

i. The supply of sediment was restricted
ii. Beach control structures and discontinuities modify the drift
iii. Tidal current will favour shingle transport to the east.

Shingle supply is almost all from the west. The shingle beaches to the west of Sheringham were healthy (in 1994) while discontinuities in the plan beach shape to the east of Sheringham means that there was very little possibility of shingle being transported from east of the frontage to the west. At high tide recorded peak tidal flows are 0.44m/s to the east. There was little reverse transport at low water as the shingle beach was dry. The fact that a higher rate of potential transport existed to the east of the frontage but there was much less shingle there, may imply that the actual transport rate was limited by supply from the west.

6.2.4 Halcrow, 1995

Halcrow carried out drift calculations using predictions of wave conditions between 1979 and 1986 and predicted a mean nett annual drift rate of 400,000m^3/year at Happisburgh. This was a substantial increase on their previous estimate of 200,000m^3/year made by Sir William Halcrow and Partners (1990).

6.2.5 HR Wallingford 2001a (Cromer)

HR Wallingford (2001a) also calculated net longshore drift rates at Cromer along the "natural" coastline (i.e. ignoring the presence of groynes). The longshore transport rate at Comer was therefore calculated using 22 years of wave data covering the period between 1979 and 2000. These calculations were made for two locations along the seafront, west and east of Cromer Pier. These estimates of drift rates were made using the standard CERC formula, as used by previous researchers. This allowed a straightforward comparison with the results of the earlier studies mentioned above.

The seawalls along the seafront at Cromer now effectively prevent any additional sediment being added to the beaches to compensate for losses. Sand and shingle beaches were modelled separately and the results were combined, giving values of 24,500m^3/year west of the pier, and 53,900 m^3/year east of the pier, in both cases from west to east. Between 1979 and 1987, the annual drift direction was eastward in some years, westwards in others. From 1988 onwards, however, the drift was predominantly eastwards. Comparing the mean annual drift for the period 1979 – 1987 with that for the period 1988 – 2000, it was found that the drift rate has approximately doubled in the latter period.

6.2.6 HR Wallingford (Happisburgh) 2001b

HR Wallingford (2001b) made further predictions of longshore drift rate between 1975 and 1994. The average drift rate between 1979 and 1986 was calculated as 429,000m^3/year, which is very close to the Halcrow (1995) value. However, the average drift rate between 1975 and 1994 was found to be 505,000m^3/year, considerably larger than the rate from 1979-1986. This illustrates the difficulty in comparing results from different periods and, indeed, from slightly different positions along the coast. Moreover, in three of the years, the nett annual drift direction was from east to west – reversing the usual strong trend and illustrating the huge variability in annual nett drift rates.

6.2.7 Halcrow, 2001

Halcrow's Beach Plan Shape Model (BPSM) was used to calculate the net longshore sediment transport rate at Eccles on Sea, Sea Palling and Horsey. BPSM is an evolutionary one-line beach model that updates the beach plan position after calculating the longshore transport rate for every wave record at each model drift node.

6.2.8 HR Wallingford, 2002b

HR Wallingford developed a conceptual sediment budget for Cromer to Overstrand to Trimingham to Mundesley to Paston. The sediment budget was developed from a range of data, including the input of beach material from retreating cliffs, changes in beach volume and modelled potential net longshore drift rates. It was assumed that there was no net loss or gain of sediment from offshore.

Table 6.1 Longshore transport rates in North Norfolk

mE	mN	Location	Dir	Q [m^3/yr]	Type	Source
577050	345150	Royal West Nflk GC	270	0	Observation	HR Wallingford
584500	346700	Scolt Head Island	270	190000	Wave	Vincent (1977)
597000	346400	Stiffkey	270	290000	Wave	Vincent (1979)
600000	347000	Blakeney	270	350000	Wave	Onyett & Simmonds (1983)
602500	346300	Blakeney	288	600000	Wave	Vincent (1979)
609500	344200	Weybourne	283	160000	Wave	Vincent (1979)
611300	343800	Weybourne	274	200000	Wave	Onyett & Simmonds (1983)
615000	343550	Sheringham (west)	87	6900	Wv, Sh	HR Wallingford (1994)
616000	343500	Sheringham (centre)	94	18800	Wv, Sh	HR Wallingford (1994)
617000	343400	Sheringham (east)	100	28100	Wv, Sh	HR Wallingford (1994)
617750	343400	Sheringham	278	87000	Wave	Vincent (1979)

Table 6.1 Longshore transport rates in North Norfolk (continued)

mE	mN	Location	Dir	Q [m^3/yr]	Type	Source
620000	343100	Sheringham	284	160000	Wave	Onyett & Simmonds (1983)
621600	342425	Cromer (West)	102	24500	Wave, Sa + Sh	HR Wallingford (2001a)
621900	342500	Cromer	111	400000	Wave	Onyett & Simmonds (1983)
622450	342200	Cromer (East)	108	53900	Wave, Sa + Sh	HR Wallingford (2001a)
625000	341000	Overstrand	130	73000	Sed budget	HR Wallingford (2002b)
627000	339800	Overstrand	122	42000	Wave	Vincent (1979)
628000	339000	Trimingham	121	188000	Sed budget	HR Wallingford (2002b)
631750	336600	Mundesley	130	10000	Wave	Onyett & Simmonds (1983)
631500	336800	Mundesley	134	311000	Sed budget	HR Wallingford (2002b)
633300	335000	Paston	130	346000	Sed budget	HR Wallingford (2002b)
638000	331550	Happisburgh	130	230000	Wave	Onyett & Simmonds (1983)
638000	331550	Happisburgh	130	400000	1979–1986	Halcrow (1995)
638450	331200	Happisburgh	130	429000	1979–1986	HR Wallingford (2001b)
638450	331200	Happisburgh	130	505000	1975–1994	HR Wallingford (2001b)
639000	330700	Happisburgh (Walcott)	128	148000	Wave	Vincent (1979)
640600	329600	Eccles On Sea	125	55000	Wave	Halcrow (2001a)
643000	327700	Sea Palling	128	15000	Wave	Halcrow (2001a)
646300	324600	Horsey	135	150000	Wave	Halcrow (2001a)

6.3 Discussion of longshore drift rates for North Norfolk

Some early estimates of the net annual longshore drift rate along the coastline of Norfolk were made by research workers at the University of East Anglia (UEA) in the 1970s (Vincent 1979, Clayton et al, 1983). The basic methodology had three main steps:

1. A time series of wave heights, periods and directions close to the coast was modelled
2. Longshore transport rate was calculated for each wave condition
3. The drift rates were averaged to produce a mean annual nett drift rate.

As normal in such studies, the longshore drift rate was calculated by a simple formula that estimates the instantaneous rate of sediment transport caused by any wave condition. By repeated use of this formula for the whole wave climate, as predicted for a chosen location at the coast, the total volume of longshore drift at that location was estimated.

This approach is still widely used, but it is important to realise that the longshore drift rates calculated by this numerical method are subject to a considerable degree of uncertainty unless a site-specific validation can be carried out. In addition, estimates made using information on waves over one period can vary dramatically from subsequent estimates made using wave information for a different period (as shown for Happisburgh). Moreover, although many studies estimating drift rates along the North Norfolk coast have been carried out, 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.

The early work by the University of East Anglia, however, developed the following picture:

- Estimated longshore drift rates along some parts of the Norfolk coast are very large (indeed as high or higher than anywhere else in the UK)
- There are large potential drift rates towards the west between Cromer and Blakeney Point
- There is an increase in the longshore drift rate on going along the coastline from the Cromer area, where the rate is very low, to an area near Happisburgh where it has a maximum value. From that area southward, there a decrease in the rate until it is nearly zero again south of Great Yarmouth.

Subsequent studies have modified the picture presented by the UEA results somewhat (as discussed below) but refining the modelling does not diminish the pioneering nature of the studies. In all cases, the potential sediment transport rate for sand was calculated and if the beach had less than that potential volume of sand available for transport, then the calculated transport rate could not have occurred. Moreover, the transport rate will have been incorrect if the sediment present was not medium sand. Typically, the transport rate for sand is of the order of 15 to 20 times greater than the transport rate for shingle. Vincent (1979, Figure 5) showed the fraction of shingle and sand present at each site. In some cases (such as Blakeney Point and Orford Ness) the beach sediment was essentially shingle and the calculated rates must be considered to be significantly greater than the actual transport rate of shingle. Therefore the rates quoted in Vincent (1979) should be interpreted with caution (as the author himself has stated).

6.3.1 Gore Point to Blakeney Village

Clayton et al. (1983) reviewed the work of Vincent and suggested that there was very little longshore drift between Gore Point and Blakeney village (inshore of Blakeney Point). There must, however, be some longshore littoral drift from east to west in this area as the western end of Scolt Head Island continues to accrete. Vincent's potential sand transport rate of 190,000m^3/year on Scolt Head Island is rather high for a beach that contains pebbles and gravel as well as sand. The actual transport rate would depend on the beach size distribution. For example, if the beach were half sand and half shingle, the potential transport rate would drop to around 100,000m^3/year (assuming that the transport rate for shingle is about 1/15 of that for sand). However, if the beach was only 25% sand the total potential transport rate might drop below 60,000m^3/year.

BGS survey of seabed sediments and facies shows that the transport direction for sand offshore of Scolt Head Island is from west to east, at least below the 7m contour. This agrees with the other facies data (shown in HR Wallingford, 2002a) that shows west to east transport further offshore. The 7m contour is not far offshore of Scolt Head Island, and the littoral drift is east to west. This suggests that sand and shingle is being transported to the west on the beach face, but that sand is transported to the east if it is carried offshore of the steep beach face onto Burnham Flats, perhaps during a storm.

6.3.2 Blakeney Point to Weybourne

At Blakeney Point, Vincent (1979) calculated potential sand transport rate of 600,000m^3/year westwards towards the spit. This was a lot greater than his calculated sediment yield from cliff erosion to the east of 150,000±50,000m^3/year. Moreover, the cliff erosion included silts, sands and gravel, while Blakeney Point contains mainly gravel. As a rough estimate, the 600,000m^3/year of potential sand transport reduce to 60,000m^3/year of sand combined with 36,000m^3/year of shingle transport (using the 15:1 transport ratio and assuming 90% shingle). Note that when there is a clear break between the single and sand parts of a beach (such as at Blakeney point) it would be better to calculate separate cross-shore distributions of sand and shingle potential transport. These could be combined by taking shingle on the upper beach and sand on the lower beach, using the measured change in sediment in the modelling.

The sorts of reduced rates determined above could be achieved in approximate balance with the sediment yields from the cliffs. Onyett and Simmonds (1983) suggest a lower figure of 350,000m^3/year of longshore transport along Blakeney Point, while Vincent (1979) calculated a drift rate of 160,000m^3/year just west of Weybourne, in the region that supplies Blakeney Point with its new material. Vincent's value is again for sand in a region that is approximately 90% shingle. Vincent states that the increase in drift rates from Weybourne towards Blakeney (from 160,000m^3/year to 600,000m^3/year) is due to the decreasing fetches for westerly winds. He therefore suggests that the actual drift rate along the frontage is limited by the drift rate at Weybourne. The increase in potential drift along Blakeney Point may serve to push the Point back towards the south (and west) as suggested by Andrews et al. (2000). The increase in potential drift rates along Blakeney Point may be unreliable due to the difficulties in applying the type of wave model used over the wide shallow area of Burnham Flats (as the wave model ignores bottom friction).

There is no obvious pathway for shingle to move west from Blakeney Point. There are small shingle ridges to the west, but they may have been formed by local supplies of shingle being pushed onshore by wave action, not fed by Blakeney Point. The sand that is released to the beach by erosion around Weybourne is likely to travel west towards and along 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 (HR Wallingford, 2002a).

The lower estimates of longshore drift (produced by estimating the combined sand and shingle transport rate from the potential sand transport) lead to correspondingly lower combined sand and shingle drift rates. The net transport direction along Blakeney Point is clearly from east to west. Clayton et al. (1983) also suggested a revised value of around 60,000m^3/year from east to west for the sediment transport between approximately Cromer and Blakeney. The location of this estimate is unclear, although it appears reasonable if it applies between Weybourne and Blakeney.

6.3.3 Weybourne to Cromer

The net longshore drift rate in the vicinity of Sheringham and Cromer has been estimated several times in the past, with a wide range of predictions. These have been made assuming that the coastline was still in a natural state, i.e. with no groynes or other coastal defences that affect the transport of beach sediment. One of the earliest estimates, of about 97,000 m^3/year *from east to west* between Sheringham and Cromer was made by the University of East Anglia (Vincent, 1979). However, HR Wallingford (1994, 2001) visited Sheringham and Cromer and noted very clear indications of a *nett west to east* drift at both (although the observations at Sheringham were for shingle, not sand). Clayton et al. (1983) also noted evidence of drift from west to east at Cromer. Onyett and Simmonds calculated drift rates of 160,000m^3/year to the west between Sheringham and Cromer, but a nett drift rate of 400,000m^3/year to the east at Cromer.

In interpreting the results of their studies of the drift regime for the whole of the coastline of East Anglia, the UEA team indicated that there was a "drift divide" at Cromer, with the longshore drift moving westwards to the west of the town, and eastwards from the eastern end of its seafront. Beaches in the vicinity of a drift divide can be expected to rapidly erode, especially in a location where there is no supply of fresh sediment, e.g. from eroding cliffs. However, Clayton (1977) estimated that the North Norfolk cliffs are eroding at a rate of about 400,000m^3/year of sand, so there is a supply of sediment to the beaches.

Recent studies and site visits have provided evidence that the present-day drift divide lies to the west of Sheringham, and that between Sheringham and Cromer the drift appears to be from west to east. Note also that the "drift divide" or null point in the mean nett annual sediment transport rate is purely a statistical phenomenon. Sediment travels in both directions past this null point and in some years the nett annual drift direction will be to the east and in other years it will be to the west. However, on average, the nett transport rate is about zero at the null point. The position of the null point will vary in time, on a yearly and a decadal scale. It may be different for shingle and sand.

HR Wallingford (1994) modelled the longshore drift of shingle above the 0mCD contour at Sheringham. The values for potential longshore transport of shingle are given in Table 6.1. There was a nett transport potential towards the east that increases on going east. The nett drift direction was confirmed by observations of the Sheringham frontage. Analysis of differential cliff change also showed that cliff and beach recession was nearly four times higher on the eastern side of Sheringham as compared to the west indicating downdrift scour to the east. Moreover, the amount of shingle on the frontage reduced towards the east. This was explained in terms of the increasing transport potential towards the east. The results suggested that the drift null point was to the west of Sheringham. However, the location of the drift divide may be different for shingle and sand and will vary in time as the wave climate exhibits inter-annual variability. Indeed Vincent [private communication] has shown that decadal averages of nett longshore transport rates at Cromer have different directions. Comparisons are only strictly valid if generated in similar manners using the same wind data.

The potential sediment transport at Sheringham was influenced by a number of factors.

i. The supply of sediment was restricted
ii. Beach control structures and discontinuities modify the drift
iii. Tidal current will favour shingle transport to the east.

Shingle supply is almost all from the west. The shingle beaches to the west of Sheringham were healthy (in 1994) while discontinuities in the plan beach shape to the east of Sheringham means that there was very little possibility of shingle being transported from east of the frontage to the west. At high tide recorded peak tidal flows are 0.44m/s to the east. There was little reverse transport at low water as the shingle beach was dry. The fact that a higher rate of potential transport existed to the east of the frontage but there was much less shingle there, may imply that the actual transport rate was limited by supply from the west.

HR Wallingford (2001a) also calculated net longshore drift rates at Cromer along the “natural” coastline (i.e. ignoring the presence of groynes). The longshore transport rate at Comer was therefore calculated using 22 years of wave data covering the period between 1979 and 2000. These calculations were made for two locations along the seafront, west and east of Cromer Pier. These estimates of drift rates were made using the standard CERC formula, as used by previous researchers. This allowed a straightforward comparison with the results of the earlier studies mentioned above.

The seawalls along the seafront at Cromer now effectively prevent any additional sediment being added to the beaches to compensate for losses. Sand and shingle beaches were modelled separately and the results were combined, giving values of 24,500m^3/year west of the pier, and 53,900 m^3/year east of the pier, in both cases from west to east (HR Wallingford, 2001a). Between 1979 and 1987, the annual drift direction was eastward in some years, westwards in others. From 1988 onwards, however, the drift was predominantly eastwards. Comparing the mean annual drift for the period 1979 – 1987 with that for the period 1988 – 2000, it was found that the drift rate has approximately doubled in the latter period. Onyett and Simmonds (1983) calculated a drift rate of 400,000m^3/year to the east at Cromer.

The differences in the results deserve some comment. The results from Vincent (1979) Onyett and Simmonds (1983) and Clayton, McCave and Vincent (1983) were all from the same study. The differences between their results come from using different and developing the methodologies through the programme and from re-interpreting and re-analysing different effects. Vincent (1979) published two sets of figures from the same data. He had calculated longshore drift rates at a large number of points then averaged over a length of coastline. His specific rates were averaged over stretches of, typically, 5km, while his average rates were calculated by averaging over around 25km of coastline. The average rates give a broad overview of sediment transport around East Anglia, but were not included in Table 6.1 because of a desire to produce a more detailed picture. Averaging over such a long length of coast can also be slightly misleading, particularly in areas of rapid variation, such as around the drift null point near Weybourne and Cromer. Figure 1 of Clayton, McCave and Vincent (1983) produced two illustrations of transport rates and sources. The first is based on Vincent’s average rates, while the second is their estimate of the most probable drift rates, taking supply and other factors into account. It is an improvement on Vincent’s (1979) average results, but is also at a broad regional scale and also calculates the potential sand transport rate at all locations, irrespective of sand content.

The specific rates in Vincent (1979) and Onyett and Simmonds (1983) were calculated using similar techniques and so are broadly compatible, generally within 50% of each other when calculations were made relatively close together. Onyett and Simmonds used a longer timeseries of wind vectors to derive their waves and transport rates than Vincent. This can have an important effect on the magnitudes of transport calculated, so may be the main difference between the two sets of data. The main difference between their results and later results around Cromer and Sheringham are that Vincent and Clayton et al. calculated potential sand transport rates, while HR Wallingford (1994, 2001a) estimated a transport rate for shingle or a combination of sand and shingle. There are problems in determining the position of the drift divide, which was originally estimated to be near Cromer, but is probably closer to Weybourne. However, this may be due to the length of coastline averaged over, changes in modelling techniques and changes in wave conditions over time.

As mentioned previously, there are substantial uncertainties in these theoretical calculations. One of the most important of these potential sources of error is whether there is sufficient sediment to “satisfy” this calculated drift rate. The source of sand on the beaches of this coastline is largely from the eroding cliffs of North Norfolk, while the shingle is probably largely derived from the chalk exposed on the nearshore seabed. Further inaccuracies will result from the numerical modelling of the waves and the neglect of tidal currents. However, at present based on the evidence from site appraisals and the drift calculations, the net longshore drift rate around Cromer is eastwards.

The increase in drift rates on moving east from Sheringham is fundamentally important to understanding the evolution of the coastline in the Cromer area. It implies the drift rate out of the eastern end of the frontage (towards Overstrand) is likely to be higher than the rate of sediment arriving at the western end (i.e. from Runton). This difference in volume leads to beach erosion, and then cliff recession. This is therefore a purely natural phenomenon, caused by the gradual changes in orientation of the Norfolk coastline and the character of the waves generated in the North Sea. The rather sharp change in beach orientation in the vicinity of Cromer Pier can be expected to locally emphasise the increase in drift rates from west to east along this part of the coast.

6.3.4 Overstrand to Mundesley

The early work of Vincent (1979) and Clayton et al. (1983) showed that there was a low longshore drift rate around the Sheringham/Cromer area and a high longshore drift rate near Happisburgh. From that area southward, there a decrease in the rate until it is nearly zero again south of Great Yarmouth. This implies that the volume of sand travelling into this frontage from the north is much less that the volume travelling out of the area to the south. This difference in volume leads to beach erosion, and then cliff recession. This is a purely natural phenomenon, caused by the gradual changes in orientation of the Norfolk coastline and the character of the waves generated in the North Sea. The cliff recession between Cromer and Happisburgh produced sediment for the beaches, which has (partly) compensated for the deficit between the different drift rates at either end of this frontage.

However, such a simple analysis ignores the role that Haisborough Sand plays in modifying the wave climate between Cromer and Happisburgh. Vincent (1979) and Onyett and Simmonds (1983) included the effect of Happisburgh Sand in reducing wave heights in a simple manner. Vincent (1979) predicted a mean annual transport rate of 42,000m^3/year at Overstrand, while Onyett and Simmonds (1983) calculated a mean annual transport rate of only 10,000m^3/year at Mundesley. Both of these results are considerably lower than Onyett and Simmonds (1983) transport rates at Cromer and Happisburgh and this reduction is believed to be due to Haisborough Sand. However, However, the cliffs between Cromer and east of Mundesley are still eroding and supplying sediment to the beach. The volumetric rates of sediment supply to the beach are greater than the calculated potential drift rates at Mundesley. It is likely that the simple methods of estimating wave height and direction used did not adequately model the effects of the bank on the waves near the shore.

This confusion over the modelled potential longshore transport rates led HR Wallingford (2002b) to produce a conceptual sediment budget for Overstrand to Mundesley. The net longshore drift was calculated as the residual from adding the sources and sinks of sediment. This produced a smoothly increasing longshore drift rate from Cromer to Happisburgh, with rates of 73,000m^3/year at Overstrand, 188,000m^3/year at Trimingham, 341,000m^3/year at Mundesley and 356,000m^3/year at Paston.

6.3.5 Happisburgh

The net longshore drift rate in the vicinity of Happisburgh village has been estimated several times in the past, with a wide range of predictions. These have been made assuming that the coastline was still in a natural state, i.e. with no groynes or other coastal defences that affect the transport of beach sediment. One of the earliest estimates, of 148,000m^3/year, was made by the University of East Anglia (Vincent, 1979) but subsequent studies have suggested higher rates. Clayton, McCave and Vincent (1983) revised the calculations to a regional (average) rate of 260,000m^3/year and a study by Sir William Halcrow & Partners (1990), dealing with sea defences between Happisburgh and Winterton estimated a rate of 200,00m^3/year. Halcrow (1995) again carried out calculations of drift rates and by predicting wave conditions between 1979 and 1986 revised their earlier results to 400,000m^3/year. HR Wallingford (2001b) then made further predictions between 1975 and 1994. The average drift rate between 1979 and 1986 was calculated as 429,000m^3/year, which is very close to the Halcrow (1995) value. However, the average drift rate between 1975 and 1994 was found to be 505,000m^3/year, considerably larger than the rate from 1979-1986. This illustrates the difficulty in comparing results from different periods and, indeed, from slightly different positions along the coast. Moreover, in three of the years, the nett annual drift direction was from east to west – reversing the usual strong trend and illustrating the huge variability in annual nett drift rates.

The 505,000m^3/year were taken as the best average nett transport rate as the modelling covered the longest period and the beach planshape model was calibrated by modelling the development of the shoreline. It is certain from these various estimates that the longshore drift rate along this coastline is very large. As a consequence, the installation of coastal defences such as groynes, even if they are only partly effective at altering the "natural" drift rates, will provoke rapid changes in the beach plan shape. More relevantly from the viewpoint of recent erosion of the coast south of Happisburgh, any change in such defences along this coastline will similarly provoke rapid changes in the beaches and hence the cliffs behind them.

HR Wallingford (2001b) also modelled the effect of tidal currents on the sediment transport, using a representative wave condition. The tidal current had had two effects. Firstly, on the lower part of the beach profile, the predicted sediment transport for this wave condition was reduced or reversed, i.e. with a net transport to the west/north. This was the effect of the ebb tidal flow around the time of low water. At this time, waves agitated the sand and although they also tried to produce an east/south flowing current it was shown that this was countered by the stronger tidal flows.

The second effect is that the peak east/southward drift on the upper part of the beach profile was increased by the effects of the flood tide near the time of high water. This effect was of the order of 7.5% for the example situation considered. An inaccuracy in the longshore drift calculations of this magnitude, through the neglecting of tidal currents, could be considered acceptable in the light of the general accuracy of sediment transport calculations. One implication of this, however, is that the downdrift effects of for instance, a groyne system may be greater than anticipated at design stage.

6.3.6 Eccles on Sea, Sea Palling and Horsey

The early work of Vincent (1979) and Clayton et al. (1983) also suggests that along the coastline between Happisburgh and Great Yarmouth the beaches would be gradually gaining sand, since at each point there is more sediment arriving from the north than leaving to the south. This only seems to be the case, however, for a short stretch of coast immediately north of Great Yarmouth. The long-term erosion of the shoreline between Happisburgh and Winterton Ness belies this simple explanation of littoral processes and shoreline evolution, and because of this it has long been argued that there is a net loss of sediment offshore from the coastline of Norfolk.

Halcrow (2001a) used their Beach Plan Shape Model (BPSM) was used to calculate the net longshore sediment transport rate. BPSM is an evolutionary one line beach model that updates the beach plan position after calculating the longshore transport rate for every wave record at each model drift node. Halcrow were responsible for the installation of offshore detached breakwaters at Sea Palling and have modelled this area. The drift rates are very much lower than those calculated for a natural (groyne and breakwater free) beach at Happisburgh, to the north-west. The offshore breakwaters were intended to reduce the local rate of longshore transport. The southernmost prediction, at Horsey, is about 4km south-east of the reefs and shows transport rates building up again, as the influence of the reefs diminishes.

Table 6.2 Selected Longshore drift rates along the North Norfolk Coastline

mE	mN	Location	Dir	Q [10^3m^3]	Type	Reference
577050	345150	Royal West Nflk GC	270	0	Observation	HR Wallingford
584500	346700	Scolt Head Island	270	60	Wave	Interpretation of Vincent
602500	346300	Blakeney	288	60	Wave	Interpretation of Vincent
609500	344200	Weybourne	283	160	Wave	Vincent (1979)
611300	343800	Weybourne	274	200	Wave	Onyett and Simmonds (1983)
615000	343550	Sheringham (west)	87	7	Wave, Shingle	HRW EX2888 (1994)
616000	343500	Sheringham (centre)	94	19	Wave, Shingle	HRW EX2888 (1994)
617000	343400	Sheringham (east)	100	28	Wave, Shingle	HRW EX2888 (1994)
621600	342425	Cromer (West)	102	24	Wave, Sa + Sh	HRW EX 4363 (2001)
622450	342200	Cromer (East)	108	54	Wave, Sa + Sh	HRW EX 4363 (2001)
625000	341000	Overstrand	130	73	Wave	Vincent (1979)
628000	339000	Trimingham	121	188	Sed budget	HR Wallingford (2002a)
631500	336800	Mundesley	134	311	Sed budget	HR Wallingford (2002a)
633300	335000	Paston	130	346	Sed budget	HR Wallingford (2002a)
638000	331550	Happisburgh	130	400	Wave	Halcrow (1995)
638450	331200	Happisburgh	130	429	Wave	HRW EX 4342 (2001)
638450	331200	Happisburgh	130	505	Wave	HRW EX 4342 (2001)
639000	330700	Happisburgh	128	148	Wave	Vincent (1979)
640600	329600	Eccles On Sea	125	55	Wave	Halcrow (2001a)
643000	327700	Sea Palling	128	15	Wave	Halcrow (2001a)
646300	324600	Horsey	135	150	Wave	Halcrow (2001a)

6.4 Conceptual sediment transport map for North Norfolk

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.

6.4.1 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). The beach volumes are largely stable. 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, as much of the accretion on its western end is fed by erosion of the seaward face of the island. The coastline at the eastern end in moving south more rapidly than at the west and this re-orientation of the seaward coastline suggests that there is no great supply of sediment. Seabed facies data and coastal area modelling 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 a storm.

Sand and shingle is transported west from around Weybourne along Blakeney Point. The volumes transported are a lot lower than would appear from a superficial reading of the early paper of Vincent (1979) as the transport rates quoted are ‘potential sand-equivalent’ transport rates (Vincent’s own words). When the proportion of sand and gravel is taken into account, the 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 potential 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 increasing potential drift rate on going out along Blakeney Point and the limited supply of shingle from erosion around Weybourne may be causing the end of Blakeney Point to move westwards and possible southwards. Schans et al. (2001) identified boundaries between regions of different beach behaviour on either side of Blakeney Point, emphasising its existence as a single unit, different from the beaches on either side.

There is no obvious pathway for shingle to move west from Blakeney Point. There are small shingle ridges to the west, but they may have been formed by local supplies of shingle being pushed onshore by wave action, not fed by Blakeney Point. The sand that is released to the beach by erosion around Weybourne is likely to travel west towards and along 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 (HR Wallingford, 2002a).

Somewhere in the vicinity of Weybourne (probably west of Sheringham) there is a null point in the longshore transport. This is a statistical phenomenon whereby, on average, the mean nett annual longshore drift rate (over a period of years) is around zero. 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 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. Vincent (1979) suggests a value of 150,000±50,000m^3/year, however it is not clear what percentage is feeding west, and what percentage is feeding to the east.

6.4.2 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. Leggett et al. (1998) suggest that the rate of beach volume loss increases between Heacham and Cromer, but decreases between Cromer and Great Yarmouth. The spatial filtering technique of Schans et al (2001) also strongly identified the region around Cromer as a divide between regions of different beach behaviour. Both analyses (and the identification of a drift divide close to Cromer) emphasise the importance of the area around Cromer in the long-term evolution of the East Anglian Coastline.

The potential sediment transport rate is much larger at Happisburgh than at Cromer. 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 right the way from Sheringham through to and beyond Happisburgh (probably right up to Horsey). 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. The reduction in the estimated potential transport rate between Cromer and Mundesley can be combined with the cliff erosion rates to argue that a lot of sand must be transported offshore along this stretch of coastline. It is important to realise that this predicted offshore movement is really the remainder term in a sediment budget and so includes all the errors in modelling the other terms. Note also that the sheltering effect of Haisborough Sand is included rather simplistically in most of the modelling studies. Therefore, although the local sediment budgets imply offshore sand loss and some mechanisms for such losses have been suggested , much of the predicted sediment loss reflects uncertainty in the calculation of other processes.

This confusion over the modelled potential longshore transport rates led HR Wallingford (2002b) to produce a conceptual sediment budget for Overstrand to Mundesley. The net longshore drift was calculated 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 (HR Wallingford 2001a). 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 (typically 6m to 8m below mean sea level).

Offshore cross-shore transport was calculated during storms, but it was assumed that this was balanced by onshore transport during periods of low wave conditions. This approach minimised the reliance on wave modelling but required the assumption of no nett cross-shore transport. Schans et al. (2001) identified boundaries between regions of different beach behaviour close to Happisburgh and Sea Palling using data from 1991-1999. The latter may reflect the presence of recent sea defences in this area.

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, while the sands and gravel are transported along the shore. 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.

7. EAST ANGLIA (WINTERTON NESS TO SOUTHWOLD)

7.1 Coastline Description from Winterton Ness to Southwold

7.1.1 Winterton Ness, Great Yarmouth and Corton

Winterton Ness, 8km north of Caister, is the most northerly of five coastal projections or ness features on the coast of Norfolk and Suffolk. The accretion of sand at Winterton has taken the form of dune ridges that have grown out some distance from the former cliffline, which runs southwards to Scratby and Caister. The Ness marks a change in orientation of the coastline to a more north-south alignment. The Ness has migrated to the south since the beginning of the last century with a recent northward movement related to a change in the configuration of the offshore bank and associated flood channel.

At Caister and immediately to the north, erosion of the soft boulder clay and gravel cliffs is taking place, at a rate such that where sea walls exist these now project seawards of the natural beach position.

At the north end of Great Yarmouth sand has accreted to form a ness feature at North Denes (otherwise known as Caister Ness) in the shelter of Middle Scroby Sand. The Ness has been prograding since the 1930's, since when it has built out over 300m. Clayton (1977) reported a volume increase of more than 50,000m^3/year over a 4km length of beach (as reported by Vincent, 1979). From here south the coast is north-south aligned. At Great Yarmouth the River Yare has been deflected 4km to the south by a sandy spit. At one time in the 14th Century the spit was much longer, reaching as far south as Corton, but artificial cuts made to maintain the harbour facility have eventually cut off the sediment supply from the north. This has in turn re-exposed the coastline south of the entrance to the River Yare, from Gorleston to Corton, to direct wave action and considerable downdrift erosion.

Photographic evidence suggests that Gorleston beach was in poor condition during the 1880's, as it was also in the latter part of the 20th Century. The deterioration of beach levels in these years coincides with the completion of extended impermeable pier structures at the harbour entrance. However, the direct interruption of longshore drift may only be one of the several mechanisms responsible for the erosion at Gorleston beach. For instance, the wave climate appears to be more severe in the immediate vicinity due to reduction of protection afforded by the nearshore banks on this area. This situation is exacerbated by wave reflection from the South Pier.

Leggett et al. (1998) calculated an average reduction in beach volumes of 10% in 5 years between Great Yarmouth and Southwold, with the rate of beach loss reducing to the south.

7.1.2 Lowestoft

The Ness feature at Lowestoft is the most easterly point of the British Isles. It may formed where alongshore drift of material from north Norfolk converged with a small amount travelling north from the cliffs on the Suffolk coast (although present-day estimates of transport rates are to the south on both the northern and southern side of the Ness). It is approximately 4km long and 300m wide at the apex. It is no longer a natural accretionary feature and has suffered progressive erosion over almost 100 years or so. The present position of the ness is now maintained by seawalls and groynes to protect industrial development. Beach levels along the wide foreshore fronting Lowestoft are generally low and sandy. However, at Pakefield (the southernmost part of Lowestoft) McCave (1977) reported that the beach was 98% shingle. The swift tidal currents around the ness at Lowestoft, together with the sand bank orientation suggest that material is being moved offshore at this point (McCave, 1977).

7.1.3 Benacre Ness

Benacre Ness is a cuspate foreland (a low almost triangular promontory) of sand and shingle at Kessingland, south of Lowestoft. Historic maps indicate that the Ness has been moving north, against the regional longshore drift direction, at a rate of about 20m/year (Birbeck College and Babtie, 2000). It has accreted on the updrift side and migrated along the coast in the updrift direction. Birbeck College and Babtie (2000) state that this occurred because the longshore transport is less than the sediment supply. Russell’s alternative model suggests that the northwards migration against the direction of longshore transport is due to differential accretion on the up-drift side and erosion at the down-drift side.

Birbeck College and Babtie (2000) also performed an analysis of bathymetric charts that supports the theory that the ness is a site where sediment is lost from the beach and transferred offshore. Repeat surveys showed that the Ness was accreting at a rate of around 66,000m^3/year (between 1995 and 1997). Birbeck College and Babtie (2000) also concluded that sediment is being transferred offshore and is accumulating below the 12m contour. This conclusion agrees with McCave (1978).

7.1.4 Covehithe to Southwold

There is an undulating cliff line to the north of Southwold. It is intersected by a number of stretches of low-lying land backed by saltmarsh (Easton Broad and Easton Marshes for example). Cliff recession here is very rapid, providing a supply of sand to the beaches at Southwold. However, there has been a variation in the source material from gravel to sand with time as the gravel in the cliffs exists in localised banks. Moreover, continued coastal retreat threatens the stability of the shingle ridges, which protect the low lying marshland from inundation by the sea. McCave (1978) reported that from Kessingland and Covehithe the shingle percentage increases from 60% up to 100% at Orford.

7.2 Estimates of longshore transport rates

7.2.1 Vincent (1979) and Onyett and Simmonds (1983)

The Vincent (1979) and Onyett and Simmonds (1983) methodologies used along this stretch of coast were the same as before. Descriptions can be found in Sections 6.2.1 and 6.2.2. The results are summarised in Table 7.1.

Table 7.1 Vincent (1979) Onyett and Simmonds (1983) transport rates from Winterton to Southwold

mE	mN	Location	Dir	Q [m^3/yr]	Type	Source
650250	319650	Winterton-on-Sea	151	290000	Wave	Onyett and Simmonds (1983)
652400	313500	Caister	161	258000	Wave	Vincent (1979)
653300	311000	Caister	164	270000	Wave	Onyett and Simmonds (1983)
653350	307900	Great Yarmouth	181	100000	Wave	Onyett and Simmonds (1983)
653200	303000	Gorleston	172	4000	Wave	Onyett and Simmonds (1983)

Table 7.1 Vincent (1979) Onyett and Simmonds (1983) transport rates from Winterton to Southwold (continued)

mE	mN	Location	Dir	Q [m^3/yr]	Type	Source
653200	302000	Gorleston	172	18000	Wave	Vincent (1979)
654500	297500	Corton	161	60000	Wave	Onyett and Simmonds (1983)
655200	295500	Lowestoft North	162	20000	Wave	Vincent (1979)
655500	294500	Lowestoft North	166	40000	Wave	Onyett and Simmonds (1983)
655700	293700	Lowestoft	180	500000	Wave	Onyett and Simmonds (1983)
654000	289000	Lowestoft South	5	41000	Wave	Vincent (1979)
653750	287700	Lowestoft South	2	13000	Wave	Onyett and Simmonds (1983)
653500	283350	Benacre South	200	105000	Wave	Onyett and Simmonds (1983)

7.2.2 HR Wallingford, 1998

The longshore transport rates around Great Yarmouth (from Caister to Corton) were the subject of an extensive recent study by HR Wallingford (1998). Nearshore wave climates were derived at five locations near Great Yarmouth, which involved propagation of 3216 discrete wave conditions over the offshore sandbank system using the coastal area wave model FDWAVE. Coastal area wave models, such as FDWAVE, represent more of the processes involved in inshore wave transformation than do ray models. They give a more stable response to the presence of offshore sandbanks, so their use is to be encouraged in cases where there is a complex bathymetry, such as inshore of a sandbank. They are, however two to three orders of magnitude slower than a ray model, so have rarely been used for such studies.

Five nearshore wave climates were derived at five locations: Caister, Yarmouth (North Denes), Yarmouth (South Denes), Gorleston and Corton. Three of the nearshore climates were generated by propagating an average annual offshore wave climate over different bank configurations. The other two climates used alternative offshore wave climates over the 1996 bathymetry.

Wave-induced littoral drift was modelled using the coastal profile model COSMOS at the five locations for each of the nearshore wave climates. This produced a prediction of the baseline drift and the sensitivity of this drift to natural changes in the offshore wave climate and bank configuration. It also aided in the selection of six representative wave climates for input into the coastal area model PISCES. This was shown to reproduce the net drift throughout the model area. Only the COSMOS results have been included here.

Table 7.2 shows wave-induced longshore transport at each of five locations, for five scenarios. Two profiles were used at Caister. Positive drift rates indicate northerly transport. Mean climate 1996 bathy means that the average annual wave climate was used with the 1996 offshore sandbank bathymetry in the calculation of longshore drift rates. The net annual drift with the 1996 sandbank bathymetry is strong (>$10^5 m^3$/yr) and southerly at Caister and Corton, moderate and southerly at Gorleston and weak and variable at Yarmouth (North Denes and South Denes). The 1986 sandbank configuration gives similar transport rates at Caister, a significant increase in northerly transport at Gorleston, Corton and South Denes, but a reduction in northerly transport at North Denes. The 1970 bathymetry gives greatly reduced southerly transport rates at Caister and increased northerly transport at North Denes (this is the only bank configuration that gives northerly transport at North Denes). It also shows large increases in northerly and southerly transport rates at South Denes, Gorleston and Corton, but with northerly increasing more at South Denes and Gorleston and southerly increasing more at Corton. The 1970 bank configuration clearly allowed much greater wave penetration into the nearshore area from North Denes to Corton.

The net longshore transport rate is southerly at Caister and Corton but northerly at South Denes for all three bank configurations. However, using the UKMO average wave climate with the 1996 bathymetry gives a southerly transport rate for South Denes. The results from 1993 give a single year from the average annual climate and indicate how much variability there can be between individual years and the average.

Table 7.2 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. The results generated for the mean wave climate, using the 1996 bathymetry are taken as the most representative of the drift rate calculations for the present day.

Table 7.2 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

7.2.3 Halcrow, 1998, 1999, 2001b

Halcrow calculated the longshore transport rate at Caister in 1998, between Great Yarmouth and Lowestoft in 1999 and between Lowestoft South and Thorpeness in 2001. In all three studies, Halcrow used their Beach Plan Shape Model. This is an evolutionary beach plan shape model that updates the beach plan position after calculating the longshore transport rate for every wave record at each model drift node. The results from the extensive 2001 study are included as far south as Southwold only in this section. The estimated drift rates from the three studies are shown in Table 7.3.

Halcrow (1999) calculated the longshore transport rate at seven management units between Gorleston and Lowestoft (although only three full years of wind data was available). Longshore drift was, on average, to the south in all cases and the average annual rate for the 1998 bathymetry varied between 17,000m^3/year and 60,000m^3/year, with an average value of 30,000m^3/year.

Table 7.3 Longshore transport rates by Halcrow from Caister to Southwold

mE	mN	Location	Dir	Q [m^3/yr]	Type	Reference
652800	312500	Caister	161	100,000	Wave	Halcrow (1998)
654150	298550	Corton	159	30,000	Wave	Halcrow (1999)
654000	290300	Lowestoft South	199	1,050	Wave	Halcrow (2001b)
653700	286700	Kessingland	2	28,150	Wave	Halcrow (2001b)
653800	284300	Benacre Ness South	200	2,500	Wave	Halcrow (2001b)
652800	281500	Covehithe	200	18,250	Wave	Halcrow (2001b)
651400	277300	Southwold	190	3,100	Wave	Halcrow (2001b)

7.2.4 Discussion of longshore transport rates

The transport rates of Vincent (1979) and Onyett and Simmonds (1983) at Winterton and Caister are similar, but both studies give larger results than the HR Wallingford (1998) or Halcrow (1998) studies. The HR Wallingford (1998) study of drift rates between Caister and Corton is believed to be the most thorough and extensive study of this complex area. The study used a coastal area wave model that included bottom friction and wave breaking, rather than a ray model, to generate the inshore wave climates from the offshore wave climates. This process modelled the effects of the sandbanks in a more thorough and robust way than, for example, previous studies that included the effect of Haisborough Sand. The results in Table 7.2 clearly illustrate both the influence of the bathymetry of the offshore sandbanks and the wave climate used to drive the transport rates. There is a huge variability in the mean annual drift rates, depending on the bathymetry used and this can change the direction of the mean annual drift rate. The results from the mean wave climate using the 1996 bathymetry are taken as the best representation of recent longshore drift rates in the area from Caister to Corton.

Halcrow (1999) also predicted the drift rate at between South Denes and Lowestoft using a bathymetry from 1998, but only three complete years of wave data. They predicted longshore drift rates of 25,000m^3/year at South Denes, 30,000m^3/year at Gorleston, 25,000m^3/year either side of Hopton, 15,000m^3/year at Hopton, 30,000m^3/year at Corton, 60,000m^3/year between Corton and Lowestoft and 30,000m^3/year at the North of Lowestoft. These results were averaged to give a rate of 30,000m^3/year at Corton. This is considerably less than the HR Wallingford value for the mean climate and the 1996 sandbank bathymetry, but is compatible with the HR result from the 1986 bathymetry. The differences may be due to the change in location as well. The Halcrow drift rate quoted is the average of seven results from their study and as such is broadly compatible with the 1998 study.
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The calculated transport rates between Corton and Lowestoft Ness are in the range 20,000m^3/year to 60,000m^3/year of sand. The Onyett and Simmonds value of 500,000m^3/year at Lowestoft appears to be unreasonably large. It is much higher than the transport rates from other studies, or indeed, from other points on their own study. All transport rates are to the south here, though. The Halcrow (2001b) sediment transport at South Lowestoft was very small but still southerly, whereas Vincent's (1979) transport rate was to the north. Onyett and Simmonds (1983) and Halcrow (2001b) also predict northerly transport between Lowestoft and Kessingland. This is consistent with observations of erosion of the beach between Kessingland and Pakefield.

The longshore transport returns to a southerly direction, probably on the northern side of Benacre Ness (although it is moving north towards the null point). The exact point at which the drift direction changes to the south is not known (and will vary with wave conditions and the bathymetry). Birbeck College and Babtie (2000) concluded that historically Benacre Ness has moved north at a rate of about 20m/year. They calculated that the Ness is accreting (at around 60,000m^3/year between 1995 and 1997) but that sediment was also lost offshore at the Ness. Their proposed mechanism for the northward migration was that the sediment supply exceeded sediment lost. For this to happen, with the Ness accreting and losing sediment offshore would have required a substantial sediment transport rate from the north or south to Benacre Ness. It is unlikely that such a supply could have come from littoral drift, given the proximity of the area of northerly drift near Kessingland and the southerly drift rates calculated from Benacre south. The sediment balance for Benacre Ness is therefore in some doubt. However, there does seem to be a link between Benacre Ness and the sandbanks to the north-east (HR Wallingford, 2002a).

The overall interpretation of the sediment budget for Benacre Ness is that it is fed from the north by littoral drift but loses sand to the south by littoral drift and 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.

The Halcrow (2001b) longshore drift rates continue to the south as far as Thorpeness (the southern extent of the study). The transport rates are all low (less than 20,000m^3/year, south of Benacre Ness). The rates calculated in previous studies by Vincent (1979) and Onyett and Simmonds (1983) and shown in Table 7.1 were all much higher, being in the range 100,000 – 200,000m^3/year. However, these rates were all for sand transport and the beach material in this region increases from about 60% shingle to almost 100% shingle on moving south. Therefore (as Vincent pointed out) the transport rates from these studies are difficult to interpret in terms of changes to shingle beaches. As noted before, shingle is transported at a rate of the order of 1/15 that of sand. The Vincent (1979) and Onyett and Simmonds (1983) results are therefore broadly compatible with, although perhaps slightly larger than, the Halcrow (2001b) study when this is taken this into account. The Halcrow (2001b) results are therefore taken as the best estimates of mean longshore drift in this region.

McCave (1978) provides evidence that the cliffs at Covehithe and Easton erode by about 30,000m^3/year. He also used grain size analysis to suggest that material moves north and south from there, with the minority of this sand moving north towards Lowestoft. The longshore transport calculations suggest that there is no path north from the Covehithe and Easton cliffs to Lowestoft along the beach. This does not exclude the possibility of there being an offshore path.

7.3 Conceptual sediment transport map

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. 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 sediment transport is to the south between Great Yarmouth and Lowestoft. Some sediment is lost to offshore at the Ness. There is a drift null point around Kessingland, with localised drift to the north (towards Lowestoft). The beach is eroding around the site of the drift null point. 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. There does appear to be a sediment pathway between Benacre Ness and the offshore sandbanks to the north-east. There does not appear to be a sediment pathway north along the coast from the cliffs of Covehithe and Dunwich to Benacre Ness.

Recently (1991-1996) there has been a reduction in the beach volume of around 2% per year between Great Yarmouth and Southwold, with the erosion decreasing to the south.

8. SOUTHWOLD TO LANDGUARD POINT

8.1 Coastline Description

8.1.1 Southwold

The town of Southwold is situated on high ground and is fronted by a relatively narrow, heavily groyned sand and shingle beach. South of the town a wide shingle beach has built up against the north pier of Southwold Harbour. It is likely that sand is transported in suspension across the harbour entrance, since Walberswick Beach, south of the harbour is relatively stable. The entrance was entrained in the 16th century. Since then there has been a regression of 120m in the high water mark on the southern (downdrift) side (Taylor and Marsden, 1983).

Potential problems from, for instance, increased storminess, include overtopping of the shingle ridge at Easton Broad and south of Walberswick, acceleration of cliff erosion at Easton Bavents, reduced beach levels as a result of drawdown along the town frontage and changes in the patterns of sedimentation around Southwold Harbour.

The Dunwich cliffs are eroding, providing a source of sediment to the beach, estimated at 40,000m^3/year by Clayton et al. (1983).

8.1.2 Aldeburgh and Orford Ness to Shingle Street

The town of Aldeburgh is situated south of the promontory of Thorpeness, which tends to trap much of the southward net littoral drift. Seawalls protect the town itself and the foreshore is heavily groyned. At present the northern part of the frontage is relatively secure, while the southern end, which traditionally has been starved of sediment supply is protected by recently constructed defences. South of the Martello Tower, beyond the southern end of the town, is the beginning of Orford beach. This is a massive shingle bank that extends south as far as Orford Haven to form Orford Ness. This deflects the mouth of the River Alde from an approximately west to east alignment to a roughly north to south alignment. The change in alignment occurs at Slaghden, south of the town centre and at the north of Orford Ness.

Breaching of the defences at Slaughden could open up a new route for the flow of the River Alde into the sea. Changes in the rate of littoral drift or changes in the severity of wave action could affect the stability of Orford Ness, from the Martello Tower to Orford Haven. Fortunately, the shingle ridge along most of this frontage is wide. Any breach, however, could result in the innundation of large tracts of low-lying partly reclaimed marshland immediately landward of the ridge. Reversals of sediment movement on the northern part of the Ness between Slaghden and Aldeburgh have been noted (pers. comm.) when waves are from the southeast. Under these conditions, sediment moves north towards Aldeburgh.

Orford Ness is a shingle cuspate foreland that shows changes in elevation attributed to changes in sea-level rise during its formation. Birbeck College and Babtie (2000, henceforth BC&B) report that it appears to have formed since the rate of sea level rise slowed around 6000 years ago and was probably formed from a spit. It has been supplied with sediment by longshore transport from the north. The growth of the ness is shown by ancient shorelines, preserved as shingle ridges. Orford Ness has gone through cyclic variations in plan shape and will continue to be extremely sensitive to wave climate. BC&B used an analysis of beach profile data from 1991 to 1997 to conclude that there is erosion on the northern side of the ness and accretion along the southern side. Erosion appeared to be greater than accretion at the apex, indicating a longer term erosion (or southwards translation) of the ness.

The shingle ridges continue south to Orford Haven, at which point shingle accumulates in a series of nearshore shingle banks. These form the route by which shingle is transported downdrift to the west of Shingle Street. Changes in the distribution of shingle banks off Orford Haven could also have a wide impact, by interrupting the supply of shingle to the downdrift coast.

8.1.3 River Deben

At Bawdsey the land rises and the cliffs extend southwards to Bawdsey Manor, on the north side of the mouth of the River Deben. This frontage relies on the shingle beach as the primary defence against the sea, hence significant changes in beach width would accelerate the erosion of the cliffs. The cliff is erosive, but well protected by the shingle banks. The cliff is made of the same material as the few sandwaves that form Cutler Bank. The most sensitive area extends from the seawall opposite East Lane, Bawdsey, southwards to the Martello Tower. Damage to the seawall could cause a breach and this would result in extensive flooding of low lying land, while erosion of the cliffs might put cliff top properties to the south of the wall at risk.

There are extensive shingle banks (The Knolls) at Woodbridge Haven which provide a considerable amount of shelter from wave activity to the low-lying shoreline at Felixstowe Ferry on the south shore of the Haven. The Knolls are fed by southerly transport and act as a temporary sediment store, extending southwards as their volume increases. Some sediment can move across the estuary to the southern side, and occasionally the channel breaks through the banks and takes a more northerly alignment (Pettitt et al, 2001). The volume of sediment to the south of the new channel then moves onshore. It then moves into the Deben and up towards Felixstowe Ferry, or southwards towards Felixstowe.

8.1.4 Felixstowe to Landguard Point

The beach in front of Felixstowe is groyned along its entire length and negligible shoreline movement has occurred since the groynes were installed. Some of the groynes are now in a poor condition, however and short-term fluctuations in beach level threaten to undermine the seawalls or create an overtopping problem (Halcrow, 2001c). The beaches towards Landguard Point have a significantly greater shingle portion than along the rest of the Felixstowe frontage. As shingle requires a more severe wave condition to move it and most of the storms come from the northeast, this suggests a net southerly movement of shingle to the Point. Shingle used to be extracted from the beach at Landguard Point during the mid-1980s. Since then no extraction has taken place and Halcrow (2001c) noted that no significant accumulation of beach material had been witnessed. However, Halcrow (2001c) also report that from 1996-2000 shingle accumulations formed on the southern side of Languard Jetty and migrated northwards toward the Port of Felixstowe.

Leggett et al. (1998) calculated that beach volumes did not change, on average, during the period 1991–1996 between Southwold and Felixstowe. Schans et al. (2001) noted that there were low average changes in the beach volumes and decreasing standard deviations between the river Deben and the Naze.

8.2 Estimates of longshore drift rates between Southwold and Felixstowe

8.2.1 Halcrow (2001b)

The southern part of the Halcrow (2001b) study ran from Southwold to Thorpeness. The modelling was performed using the Beach Plan Shape Model. All their transport rates were low (less than or equal to 11,000m^3/year) and all were to the south. The results are summarised in Table 8.1.

Table 8.1 Longshore transport rates from Southwold to Thorpeness (Halcrow, 2001b)

mE	mN	Location	Dir	Q [m^3/yr]	Type	Reference
651400	277300	Southwold	190	3,100	Wave	Halcrow (2001b)
648400	271900	Reedland Marshes	198	11,000	Wave	Halcrow (2001b)
647800	264800	Sizewell	182	3,450	Wave	Halcrow (2001b)
647800	260600	Thorpeness	178	300	Wave	Halcrow (2001b)

8.2.2 Vincent (1979) and Onyett and Simmonds (1983)

The transport rates from Vincent (1979) and Onyett and Simmonds (1983) studies in this region are summarised in Table 8.2. The methodologies were described in Sections 6.2.1 and 6.2.2.

Table 8.2 Longshore transport rates by Vincent and Oynett and Simmonds from Southwold to Felixstowe

mE	mN	Location	Dir	Q [m^3/yr]	Type	Source
651300	276500	Southwold	196	200,000	Wave	Onyett and Simmonds (1983)
650000	274250	Walberswick	224	210,000	Wave	Onyett and Simmonds (1983)
649200	273200	Walberswick	213	148,000	Wave	Vincent (1979)
648100	270550	Dunwich	190	130,000	Wave	Onyett and Simmonds (1983)
648000	267700	Dunwich	0	101,000	Wave	Vincent (1979)
647800	263200	Sizewell	180	85,000	Wave	Vincent (1979)
647800	261300	Thorpeness North	178	200,000	Wave	Onyett and Simmonds (1983)
647500	259500	Thorpeness South	202	55,000	Wave	Onyett and Simmonds (1983)
646000	251500	Aldeburgh	185	80,000	Wave	Vincent (1979)
641300	246600	Orford	242	195,000	Wave	Vincent (1979)
636500	242000	Shingle Street	207	83,000	Wave	Onyett and Simmonds (1983)
636300	241300	Shingle Street	198	64,000	Wave	Vincent (1979)
633150	237450	Bawdsey	230	210,000	Wave	Onyett & Simmonds (1983)
630800	234400	Felixstowe	245	400,000	Wave	Onyett & Simmonds (1983)

8.2.3 Posford Duvivier (2000b)

Posford Duvivier (2000b) used the coastal profile model UNIBEST-LT to analyse longshore transport rates between Orford Ness and Felixstowe. UNIBEST-LT models tide and wave induced longshore currents, wave set up and set down and longshore sediment transport distribution across the beach profile. The model contains various formulae for calculating the transport rate of sand or shingle due to predefined wave climate and tidal regime. Wave data were input to the model from the Southern Met Office offshore wave station. The calculated potential transport rates are shown in Table 8.3.

Table 8.3 Mean potential longshore transport rates from Posford Duvivier (2000b)

mE	mN	Location	Dir	Q [m^3/yr]	Type	Source
644200	248150	Orford Ness	242	132,700	Wave	Posford Duvivier (2000b)
638750	245150	North Weir Point	231	67,200	Wave	Posford Duvivier (2000b)
636900	242650	Shingle Street	31	83,300	Wave	Posford Duvivier (2000b)
633150	237450	Bawdsey	227	141000	Wave	Posford Duvivier (2000b)
631750	235000	Felixstowe	210	62700	Wave	Posford Duvivier (2000b)

8.2.4 HR Wallingford (1997)

HR Wallingford (1997) used the DRCALC model to calculate the long-term average potential nett drift on the upper shingle beach, above the 0m contour as a layer of shingle covers the upper beach from Deben Estuary to Landguard Point. Similar calculations were made for sand at points on the southern side of the Harwich Channel, as reported in Section 9. DRCALC calculated the total longshore drift produced by the wave climate using the CERC formula. No data was available for the size distribution of the shingle so the model was run using an assumed size of shingle. The magnitudes of the transport rates are therefore uncertain, but the relative size and direction should be consistent. The wave model was run at mean high water level as the upper beach transport was affected more by waves arriving at higher water levels. A bathymetry from 1992 was used. The transport rates from 1973-1990 are given in table 8.4. The results were very sensitive to beach direction. The nett drift results from a balance between largest waves, which approach the beach from the east and larger numbers of smaller waves from the south-east and south. The results from the part of the study north of the Harwich Channel are shown in Table 8.4. HR Wallingford's 1997 results were based on an earlier, 1993, set of model results.

8.2.5 Halcrow (2001c), plus Dobbie and Partners (1990), IECS (1993) and SMP (1995)

Most of the modelling results for Cobbolds Point to Landguard Point were reviewed in Halcrow (2001c). They included the longshore transport results of Dobbie and Partners (1990), IECS (1993), HR Wallingford (1997) and Shoreline Management Partnership (SMP, 1995). They did not include the work of Onyett and Simmonds (1983) or the Posford Duvivier (2000b) predictions from the southern end of their Hollesley to Bawdsey study (as used in section 8.2.3). They concluded that each successive modelling effort had improved on the previous ones. They then went on to model the area from Cobbold's Point to Landguard Point. The Halcrow (2001c) results are the most site-specific and calibrated results to date for that frontage. Indeed Halcrow (2001c) states that the rates that they calculated were not potential transport rates, but were 'actual theoretical' transport rates.

Table 8.4 Predicted longshore transport rates from Bawdsey to Landguard Point

mE	mN	Location	Dir	Q	Type	Source
632440	235350	Cobbolds Point	210	36000	Wave	Dobbie and Partners (1990)
631055	234264	Landguard to Cobbolds	247	90200	Wave	Dobbie and Partners (1990)
629949	233377	Landguard to Cobbolds	210	33000	Wave	Dobbie and Partners (1990)
628982	231940	Landguard Point	213	40000	Wave	Dobbie and Partners (1990)
628750	232000	Landguard Point	205	60000	Wave	IECS (1993)

Table 8.4 Predicted longshore transport rates from Bawdsey to Landguard Point (continued)

634121	237377	Bawdesey	234	8500	Wave, Sh	HR Wallingford (1997)
632440	235350	Cobbolds Point	30	3200	Wave, Sh	HR Wallingford (1997)
631055	234264	Landguard to Cobbolds	247	13600	Wave, Sh	HR Wallingford (1997)
629949	233377	Landguard to Cobbolds	30	3900	Wave, Sh	HR Wallingford (1997)
628982	231940	Landguard Point	213	3700	Wave, Sh	HR Wallingford (1997)
631600	234900	Cobbolds Point		3100		SMP (1995)
630600	234450	Felixstowe Spa Gardens		13600		SMP (1995)
630100	234200	Felixstowe Pleasure Pier		9500		SMP (1995)
630640	234935	North of Cobbolds Point	37	500	Wave, Sh	Halcrow (2001c)
631470	234830	South of Cobbolds Point	248	1250	Wave, Sh	Halcrow (2001c)
630670	234440	Felixstowe Spa Gardens	240	2700	Wave, Sh	Halcrow (2001c)
630130	234180	North of Pleasure Pier	235	2450	Wave, Sh	Halcrow (2001c)
629780	233800	South of Pleasure Pier	33	1500	Wave, Sh	Halcrow (2001c)
629280	232890	Felixstowe Manor End	27	5900	Wave, Sh	Halcrow (2001c)
628830	232130	Landguard Common	33	11650	Wave, Sh	Halcrow (2001c)
628380	231360	North of Landguard Point	34	6050	Wave, Sh	Halcrow (2001c)

8.2.6 Discussion of longshore drift rates from Southwold to Aldeburgh

One result that is notable is the Vincent (1979) transport rate at Dunwich, which is to the north. The cause of this northward transport is the shelter provided by Dunwich Bank, which prevents waves from the north-east driving as much sediment south as they would have done, had the bank not been there. No other study has modelled this particular stretch of the coast, so there are no nearby results to compare to. However, Vincent (1979) argued that the convergence of large quantities of sediment suggested by his results was unsupported by evidence from the site. The authors conclude that there is unlikely to be a significant drift reversal at this location and that Vincent's result may have been due to difficulties in modelling the wave conditions inshore of Dunwich bank.

8.2.7 Discussion of longshore drift rates from Aldeburgh to Shingle Street

Sediment transport along this stretch of coastline has been studied by Posford Duvivier (2000b) Vincent (1979) and Onyett and Simmonds (1983). The results from these studies are shown in Tables 8.2 and 8.3. The transport rates are broadly in agreement from Aldeburgh past Orford Ness. The rates are similar along Shingle Street, but the Posford Duvivier direction is opposite to that predicted by Vincent and Onyett and Simmonds. The reason offered for this change in direction was that the local beach angle restricted the supply of sediment from the north. However, it may be possible that the offshore wave point used in the study was too far south to adequately represent the waves at that point.

The Vincent and Onyett and Simmonds results were calculated for sand, in an area where the beaches are almost entirely of gravel. The high transport rates and low amount of sand present implies that any sand entering this stretch of coastline is rapidly transported through the area without settling to form sand beaches. The shingle moves more slowly and lower volumes are transported for a particular sand transport potential. In 1966/7 a beach recharge scheme moved 350,000m^3 of shingle northwards from Orford Ness to Aldeburgh replenish the eroding shingle ridge. Taylor and Marsden (1983) reported that after 15 years most of it had disappeared, implying a transport rate of the order of 20,000m^3/year of shingle.

8.2.8 Discussion of longshore drift rates from River Deben to Landguard Point

North of the River Deben (at Bawdsey) (1983) Posford Duvivier (2000b) and HR Wallingford (1997) agree that net drift is to the south, but the predicted volumes are significantly different. All HR Wallingford's modelling is of shingle above the 0mCD contour, while Onyett and Simmonds and Posford's modelling was for the entire beach width. Onyett and Simmonds, of course, modelled sand. The total longshore transport rate is a combination of the whole-beach sand modelling and the shingle modelling from the top of the beach.

Longshore transport rates between Bawdsey and Landguard Point were calculated by Onyett and Simmonds (1983), Dobbie and Partners (1990), IECS (1993), HR Wallingford (1997), Shoreline Management Partnership (SMP, 1995), Posford Duvivier (2000b) and Halcrow (2001c). The Halcrow (2001c) results were produced following a review of previous studies. They are broadly in agreement with the HR Wallingford (1997) results.

HR Wallingford (1997) and Halcrow (2001c) both predict very low northerly transport rates between Cobold's Point and Bawdsey. Halcrow (2001c) state that north-easterly storms are refracted so that they are almost normal to the coast there, thereby inducing little littoral drift. They also stated that the more common but lower waves from the southeast will approach the shore at a more acute angle and cause the dominant drift. However, it is clear that the longshore transport direction along most of the coastline is from north to south and there is certainly southerly transport at the river Deben. Therefore any modelled northerly drift there must be a local phenomenon, caused by the change in beach orientation. Moreover, the modelled drift to the south of Cobbold's Point is southerly. Cobbolds Point therefore appears to be a point of drift divergence but there would also have to be a point of drift convergence (or offshore transport) between Cobbold's Point and the River Deben if this were so. This may be an unnecessarily complicated view of the situation as low net transport rates are rather unreliable as they tend to be the difference between two much larger terms. It is simpler to regard the broad pattern of longshore transport to be 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 so this cannot be regarded as a major drift feature.

8.3 Conceptual sediment transport map

Longshore transport is southwards 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. There is southwards net movement of shingle along Orfordness, although the direction of transport can reverse under appropriate wave conditions. Schans et al. (2001) identified a boundary between regions of different beach behaviour near the southern tip of Orford Ness.

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

The interpretation of longshore drift around Felixstowe is based on Halcrow (2001c). 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 so this cannot be regarded as a major drift feature

The Pleasure Pier to the south-west of Cobbolds Point would appear to be a point of drift convergence as the net drift is northwards between the Landguard Point and the Pleasure Pier, except for small reversals. 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. Modelling by Halcrow (2001c) suggest that this area received a high concentration of wave energy and was therefore a point where beach material was transported offshore during storms.

9. ESSEX

9.1 Coastline Description

9.1.1 The Naze

The large tidal inlet between Harwich and the Naze has historically been an area of sedimentation. However, the salt marshes fringing the tidal creeks are in a state of decline. The tidal embankment at Foulton Hall has needed reinforcement in recent years due to deterioration taking place as a result of falling beach levels and increased wave action. The northern tip of Horsea Island has also suffered erosion and is now protected by a series of offshore breakwaters.

The Naze promontory south of Hamford Water consists of highly unstable soft cliffs that are eroding rapidly and there is considerable local concern about the amount of cliff top land being lost. However, Clayton et al. (1983) reported erosion of no more than 10,000m^3/year. The cliffs themselves provide little beach material and there are frequent periods throughout the year when there is no beach at all fronting the cliffs, with the clay shore platform being exposed and abraided by sediment moving under wave action. The beach at the northern tip of the Naze has been recharged by with material from Harwich maintenance dredging, as recommended by Clayton et al. (1983). The dredging has not prevented beach material from reaching the Naze as there is no known pathway across the Harwich channel.

9.1.2 Walton to Jaywick

South of the cliffs at the Naze, the beach is narrow, backed by seawall and held in place by an extensive groyne field. Clayton et al. (1983) reported beach volume losses on the Walton to Jaywick frontage of 3,000m^3/km/year from 1975-1982. This amounts to about 60,000m^3/year of losses along the 20km frontage. The beaches used to be fed by erosion of this frontage but since the construction of the seawalls there has been no sediment entering the system and the beaches have reduced in volume instead.

The urban frontage of Clacton-on-Sea is situated on high ground which extends south westwards to Jaywick. The Clacton frontage is extensively developed and the groynes along this frontage hold up the southerly transport of beach material. At Jaywick, a massive seawall protects low-lying land against flooding. The coastal strip has extensive holiday developments, behind which there is a network of channels and ditches that drain St. Osyth Marsh. The seawall extends to Seawick, to the west of which the shoreline is largely unprotected. Colne point is a nature reserve and consists of saltings and a series of shingle ridges that extend eastwards, then northwards into the Blackwater Estuary.

Coastal defences at Jaywick have been extensively redeveloped and the first line of defence is now the artificially replenished beach, which is held in place by a series of large rock breakwaters. Without this beach the seawall would now provide inadequate protection against flooding. The area is relatively sheltered, and inshore wave conditions are moderate. However, as the interior is very low lying, any breaching or overtopping of the defences would cause extensive flooding of the hinterland.

Leggett et al (1998) note that there was an average 3% increase in the beach volumes between the Naze and Colne Point between 1991 and 1996. There was stability in the northern part of the region, accretion along the front at Clacton, due to the use of beach control structures, but erosion downdrift of the defences. The downdrift beaches have been starved of sediment by the effectiveness of the beach control structures.

9.1.3 Maplin Sands

From the estuary of the Blackwater south and westwards into the Thames estuary, the coastline is much indented by tidal estuaries formed as a result of subsidence of a low coast. The coast is made up of recent sediments overlying the London Clay. The gradual shallowing of the North Sea basin to the south and the reduction of fetch lengths from all directions excepting the north-east, leads to a reduction in wave activity in the area. It therefore acts as a sink for large quantities of sediment originally derived from the East

Anglian coast together with river sediments from the Thames. The question of how much (if any) of this material escapes further south via the Dover Straits is a key issue in the Southern North Sea Sediment Transport Study, Phase 2. Sand is deposited on the shoals and offshore banks that trend north-east to south-west, more or less parallel to the coast. Many of these banks dry at low tide and are undoubtedly shaped by the tidal currents. Finer muds and silts derived from the erosion of glacial drift are deposited at the coastal margin.

The coast mainly consists of saltings. The Dengie and Bradwell marshes north of the River Crouch are much dissected by small creeks but form a single compact area since reclamation. To the south of the Crouch, tidal channels separate a close knit group of islands all below high water and protected by embankments e.g. Foulness, Potton, Havengore, Wallasea and Rushley. Reclamation of these areas for agriculture has gone on for centuries and further natural saltings have developed seawards of the embankments. The salt marshes have provided a natural defence against the sea where the tidal range is large and the actual length of the coastline is very long. Because of the shelter of the offshore banks, wave action is generally slight except in severe storms at high tidal levels when flooding may be serious, as it was in 1953.

Although concern has been expressed about the recession of the salt marshes along the coast and within the estuaries of the Crouch and Blackwater, Leggett et al. (1998) noted a small average increase in the beach volumes between the Dengie and Shoburyness, caused by salt marsh accretion.. The salt marsh often appears to end abruptly as a cliff about 1m high at the edge of the mudflats.

9.2 Estimates of longshore drift rates

9.2.1 Vincent (1977) and Onyett and Simmonds (1983)

Essex is the southernmost limit of the studies of Vincent (1977) and Onyett and Simmonds (1983). The methodologies used have been described in Sections 6.2.1 and 6.2.2. The predicted net longshore transport rates from the studies are given in Table 9.1.

Table 9.1 Longshore transport rates in Essex from Vincent (1977) and Onyett and Simmonds (1983)

mE	mN	Location	Dir	Q [m3/yr]	Type	Source
626800	224200	The Naze	0	75000	Wave	Onyett and Simmonds (1983)
624800	220600	Frinton-On-Sea	215	21000	Wave	Onyett and Simmonds (1983)
621500	216700	Clacton	233	105000	Wave	Vincent (1977)
620000	215850	Holland-On-Sea	240	80000	Wave	Onyett and Simmonds (1983)
618650	215050	Clacton-On-Sea	231	50000	Wave	Onyett and Simmonds (1983)
612500	212400	Jaywick	262	70000	Wave	Onyett and Simmonds (1983)

9.2.2 HR Wallingford (1997) and Posford Duvivier (2001a)

Longshore transport rates were calculated by HR Wallingford (1997) between Dovercourt and Walton and by Posford Duvivier (2001a) between Frinton-on-Sea and Jaywick. The HR Wallingford (1997) results came from the southern part of their Harwich channel study (as reported in Section 8.2.4) but were for sand, rather than shingle. The Posford Duvivier study used the coastal profile model UNIBEST-LT, which models tide and wave induced longshore currents, wave set up and set down and longshore sediment transport distribution across the beach profile. The model contains various formulae for calculating the transport rate of sand or shingle due to predefined wave climate and tidal regime. Summer and Winter 2000 beach profiles were used for the analysis. A D50 value of 0.4 mm and a D90 of 1.0 mm were used as input to UNIBEST-LT. Gross transport volumes in opposing directions were calculated from which the net value was determined. The predicted net longshore transport rates from the two studies are given in Table 9.2.

Table 9.2 Transport rates in Essex by HR Wallingford (1997) and Posford Duvivier (2001a)

mE	mN	Location	Dir	Q [m^3/yr]	Type	Source
625989	230875	Dovercourt	35	49,600	Wave, Sand	HR Wallingford (1997)
624984	228974	Foulton Hall	22	3,400	Wave, Sand	HR Wallingford (1997)
625990	225770	Naze (North)	310	254,900	Wave, Sand	HR Wallingford (1997)
627397	223884	Naze (South)	9	26,600	Wave, Sand	HR Wallingford (1997)
626334	221979	Walton	215	45,100	Wave, Sand	HR Wallingford (1997)
624240	219820	Frinton-On-Sea	216	16,350	Wave	Posford Duvivier (2001a)
623420	218600	Holland Gap	219	5,450	Wave	Posford Duvivier (2001a)
622040	217260	Holland-On-Sea	228	1,950	Wave	Posford Duvivier (2001a)
620800	216380	Holland-On-Sea	238	2,725	Wave	Posford Duvivier (2000a)
617770	214480	Clacton	55	4,675	Wave	Posford Duvivier (2000a)
615520	213030	Jaywick	244	7,875	Wave	Posford Duvivier (2000a)

9.2.3 Discussion of longshore drift rates in Essex

The transport rates calculated by Vincent (1977) and Onyett and Simmonds (1983) are much larger than the more recent estimates, which were more detailed local studies and probably reflect the present situation more accurately. However, the sediment size in the HR Wallingford study was estimated so these magnitudes should be taken as indicative only. Therefore the Vincent (1977) and Onyett and Simmonds (1983) results have not been considered in the conceptual sediment transport map.

9.3 Conceptual sediment transport map for Essex

The conceptual sediment transport map for Essex is based the transport rates in Table 9.2. 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 essentially towards the south-west. 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. This caused the measured beach volume reductions. There are now a lot of groynes along the frontage designed to hold some of the remaining frontage in place. Sediment transport continues along to the west of Jaywick to Colne Point, which serves as a sediment sink.

10. SUMMARY

This report presents an assessment of longshore drift around the coast from Flamborough head to Jaywick. It has been based mainly on existing predictions of longshore drift from a variety of sources. 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. The work complements and adds to a previous macro-review of the same stretch of coastline (Motyka, 1986, Motyka and Beven, 1987). This report adds estimates of longshore transport rates along the coastline. 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 majority of model results are driven by waves only – the effect of the tide is generally ignored. In many cases this approach is fine. In some cases it has been shown to make a difference of a few percent.
- 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.

Nevertheless, the results from a number of different recent studies have proved particularly beneficial in adding likely values for the mean annual nett longshore drift rate. 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. Nevertheless, the distributions of mean annual nett longshore drift rates are broadly consistent between studies and with knowledge gained by observations along the coastline.

Figure 2 shows a plot of all the estimated sediment transport rates. Figure 3 shows a histogram of the mean net drift rates, with positive drift to the left when standing on the shore looking out to sea and negative drift to the right. Figures 4 to 10 show details of the interpreted sediment transport rates at different sections of the coastline, while Figure 11 shows a histogram of the interpreted (or chosen) drift rates (with the same sign convention as Figure 3).

11. REFERENCES

ABP, 2000. Humber Geomorphological Studies – Stage 2: 3D modelling of flows, salinity and sediment transport in the Humber Estuary. ABP Research and Consultancy Ltd Report R.854.

Andrews, J.E. et al., 2000. Sedimentary evolution of the north Norfolk barrier coastline in the context of Holocene sea level change. In: Holocene Land-Ocean interaction and environmental change around the North Sea. Geol. Soc. Spec. Publ. 166, 219-251.

Balson, P., Tragheim, D. and Newsham, R., 1998. Determination and prediction of sediment yields from recession of the Holderness coast, eastern England. Proc., 33rd MAFF conference of river and coastal engineers, Keele University. Pp 4.5.1–4.5.11.

Binnie Black and Veatch, 2000. Humber Estuary Geomorphological Studies, Phase 2. Report produced for the Environment Agency.

Birbeck College and Babtie, 2000. Spits and Nesses: basic processes and effects on long-term coastal morphodynamics. Report prepared for DEFRA by Birbeck College.

Bridges, E.M., 1989. Classic landforms of the north Norfolk coast. The Geographical Association.

CERC, 1984. Shore Protection Manual. US Army Corps of Engineers, Coastal Engineering Research Centre, US Government Printing Office, Washington DC.

Chambers, G., 1973. The Retreat of Unconsolidated Quaternary Cliffs. PhD thesis, Iniversity of East Anglia, Norwich. 2 Volumes.

Clayton, KM, McCave, IN, and CE Vincent, 1983. The establishment of a sand budget for the East Anglian coast and its implications for coastal stability. In Shoreline Protection, proceedings of a conference organised by the ICE. Thomas Telford, London. pp 91–96

De Boer, G, 1964. Spurn Head: Its history and evolution. Transactions of the Institute of British Geographers, 34: 71-89.

Department of the Environment, 1980. Coast protection survey.

Dobbie and Partners, 1990. Felixstowe town frontage – report on coast protection.

Halcrow, 1988. Holderness Joint Advisory Committee for Coastal Protection. Nearshore Environmental Studies Phase 2. Field Surveys 1987/1988.

Halcrow, 1998. Caister Beach Coast Protection. Engineer's Report. Issue 3, Revision B.

Halcrow, 1990. Sea defences Norfolk Happisburgh to Winterton. Final Report (two volumes)

Halcrow, 1995. Happisburgh to Winterton Sea Defences. (Godwin).

Halcrow, 1999. Gorleston to Lowestoft Coastal Strategy Study. Part Four – Appendices H to J. Consultation Draft.

Halcrow, 2001a. Happisburgh to Winterton Sea Defences. Stage three strategy review. Project Appraisal Report.

Halcrow, 2001b. Lowestoft to Thorpeness Coastal Processes and Strategy Study. Volume 2: Coastal Processes (Draft).

Halcrow, 2001c. Cobbolds Point to Landguard Point coastal process/strategy study: coastal processes (preliminary).

Hardy, J.R., 1964. The movement of beach material and wave action near Blakeney Point, Norfolk. Transactions of the Institute of British Geographers, 34: 53 – 69.

High Point Rendel, 1995. Coastal Planning and Management. Applied Earth Science Mapping: Cromer to Sea Palling, Norfolk. Rendel Geotechnics report R/H837 (for Department of Environment).

HR Wallingford, 1994. Sheringham Coast Protection Scheme 902. HR Wallingford Report EX 2888.

HR Wallingford, 1997. Harwich Channel Deepening: wave climate monitoring studies for 1996. HR Wallingford Report EX 3612.

HR Wallingford, 1998a. Great Yarmouth Outer Harbour: Impact of the Outer Harbour Development. HR Wallingford Report EX 3726.

HR Wallingford, 1998b. Hunstanton/Heacham Sea Defences: Specialist studies for beach nourishment at Heacham and Snettisham. HR Wallingford Report EX 3842.

HR Wallingford, 2001a. Cromer Coastal Strategy Study, interim report. HR Wallingford Report EX 4363.

HR Wallingford, 2001b. Ostend to Cart Gap Coastal Strategy Study. HR Wallingford Report EX 4342.

HR Wallingford, 2002a. Southern North Sea Sediment Transport Study, Phase 2, Sediment Transport Report. Prepared for Great Yarmouth Borough Council by HR Wallingford in association with CEFAS/UEA, Posford Haskoning and Dr. B. D'Olier. Report EX 4526, HR Wallingford.

HR Wallingford, 2002b. Overstrand and Mundesley Littoral Processes. HR Wallingford Interim Report, June, 2002. (To form part of Overstrand and Mundesley Strategy Study.)

IECS 1991. Filey Bay environmental Statement. The University of Hull, Institute of Estuarine and Coastal Studies.

IECS, 1992. Spurn Heritage Coast Study, Final Report. The University of Hull, Institute of Estuarine and Coastal Studies.

IECS, 1994. Holderness Coastal Defence. The University of Hull, Institute of Estuarine and Coastal Studies.

Ke, X., Evans, G. and Collins, M.B., 1996. Hydrodynamics and sediment dynamics of the Wash embayment, eastern England. Sedimentology, 43: 157 – 174.

Komar, P.D. and Inman, D.L., 1970. Longshore sand transport on beaches. Journal of Geophysical Research, 75(30): 5914 – 5927.

Leggett, D.J., Lowe, J.P. and Cooper, N.J., 1998. Beach evolution on the southern North Sea coast. Proceedings of the 26th International Conference of Coastal Engineering, Copenhagen Denmark. ASCE 2759 – 2772.

Maddrell, R.J., Home, R., Thurston, N. and Rennie, D., 1999. Impacts of changes to the bathymetry and wave energy rates on coastal erosion. Proceedings of the 34th MAFF Conference of River and Coastal Engineers, Keele. pp4.4.1 – 4.4.13

Mason, S.J. and Hansom, J.B. 1988. Cliff erosion and its contribution to a sediment budget for part of the Holderness coast, England. Shore and Beach, 56, 30-38.

McCave, I.N., 1977. Sediments of the East Anglian Coast. East Anglian Coastal Research Programme Report No. 6, University of East Anglia, Norwich, UK.

McCave, I.N., 1978. Grain-size trends and transport along beaches: example from eastern England. Marine Geology, 28: M43 – M51.

Motyka, J.A., 1986. A macro-review of the coastline of England and Wales, volume 2: the East Coast – the Tees to the Wash. HR Wallingford Report SR107.

Motyka, J.A. and Beven, S.M., 1987. A macro-review of the coastline of England and Wales, volume 3: the Wash to the Thames. HR Wallingford Report SR135.

Nairn, R.B. and Southgate, H.N., 1993. Deterministic profile modelling of nearshore processes, Part 2: sediment transport and beach profile development. Coastal Engineering, 19(1,2): 57 – 96.

Onyett, D. and Simmonds, A., 1983. East Anglian Coastal Research Programme Final Report 8: beach transport and longshore transport.

Pettitt, N., Guthrie, G., Cottle, R. and Dodson, I., 2001. Coastal Collaboration (working together for coastal defence). Proceedings of 36th DEFRA Conference of River and Coastal Engineers, Keele. Pp 02.4.1 – 02.4.12.

Posford Duvivier. 1992. Easington Coast Protection. Report for Holderness Borough Council.

Posford Duvivier, 1998. Humber Estuary Coastal Authorities Group Shoreline Management Plan, sub-cell 2a/2b, three volumes.

Posford Duvivier. 2000a. Coast Protection Scheme Strategy Plan Clacton-on-Sea. Report for Tendring District Council.

Posford Duvivier. 2000b. Hollesley to Bawdsey Sea Defences Coastal Processes Final Report. Report for the Environment Agency.

Posford Duvivier. 2000c. The Yorkshire Marina, Bridlington: Environmental Statement.

Posford Duvivier. 2001a. Tendring and Holland Tidal Defences Project Appraisal Report. Report for the Environment Agency.

Posford Duvivier. 2001b. Withernsea Coastal Defence Strategy Study. Report for the East Riding of Yorkshire.

Prandle, D., Lane. A. and Wolf, J., 2001. Holderness coastal erosion – offshore movement by tides and waves. Land-Ocean Interaction: measuring and modelling fluxes from river basins to coastal seas. IWA Publishing, pp209 – 240.

Robinson, A.W.H., 1964. The inshore waters, sediment supply and coastal changes as part of Lincolnshire. East Midlands Geographer 22: 316 – 318.

Robinson, A.W.H., 1968. The use of the seabed drifter in coastal studies with particular reference to the Humber. Zeitschrift fur Geomorphologie 7: 13 – 16.

Robinson, D.N., 1970. Coastal Evolution in north-east Lincolnshire. East Midlands Essays, 62 – 70.

Schans, H., Möller, I. and Spencer, T., 2001. Large-scale classification of the East Anglian coastline, UK. Coastal Dynamics '01. Proceedings of the 4th International Conference on Coastal Dynamics, Lund, Sweden. ASCE, 683 – 692.

Shoreline Management Partnership, 1995. Cobbolds Point Felixstowe – Longshore transport Evaluation. Report for Suffolk Coastal District Council.

Southgate, HN and Nairn, RB, 1993. Deterministic profile modelling of nearshore processes, Part 1: waves and currents. Coastal Engineering, 19(1,2): 27 – 56.

Steers, J.A., 1927. The East Anglian coast. Geographical Journal, 35: 24 – 48.

Steers, J.A., 1960. Scolt Head Island. Cambridge: Heffers.

Sunamura, T., 1992. Geomorphology of rocky coasts. John Wiley and Sons, Chichester, England: 302pp.

Taylor, H.R. and Marsden, A.E., 1983. Some sea-defence works in eastern England. In *Shoreline Protection*, Proceedings of a conference organised by the ICE. Thomas Telford, London. pp 91–96

Valentin, H., 1971. Land Loss at Holderness. Applied Coastal Geomorphology. Ed. Steers, J.A., MacMillan, London. pp116–137

Vincent, C.E., 1979. Longshore sand transport rates – a simple model for the East Anglian coastline. Coastal Engineering 3: 113–136

Wingfield, R. and Evans, C., 1999. The significance of the shoreface ramp for coastal development: Holderness, eastern England, UK. Proceedings of Littoral '99.

FIGURES

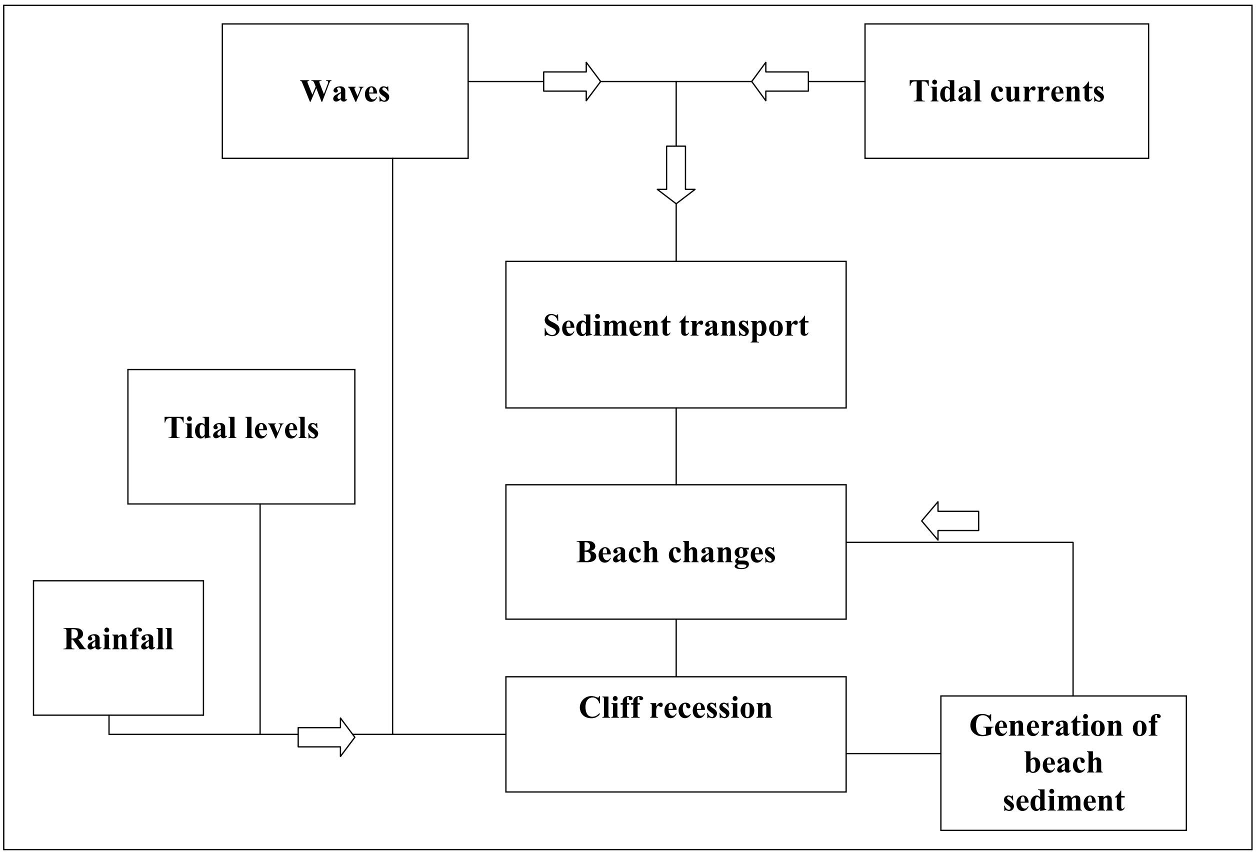

Figure 1 Simplified flowchart of littoral processes

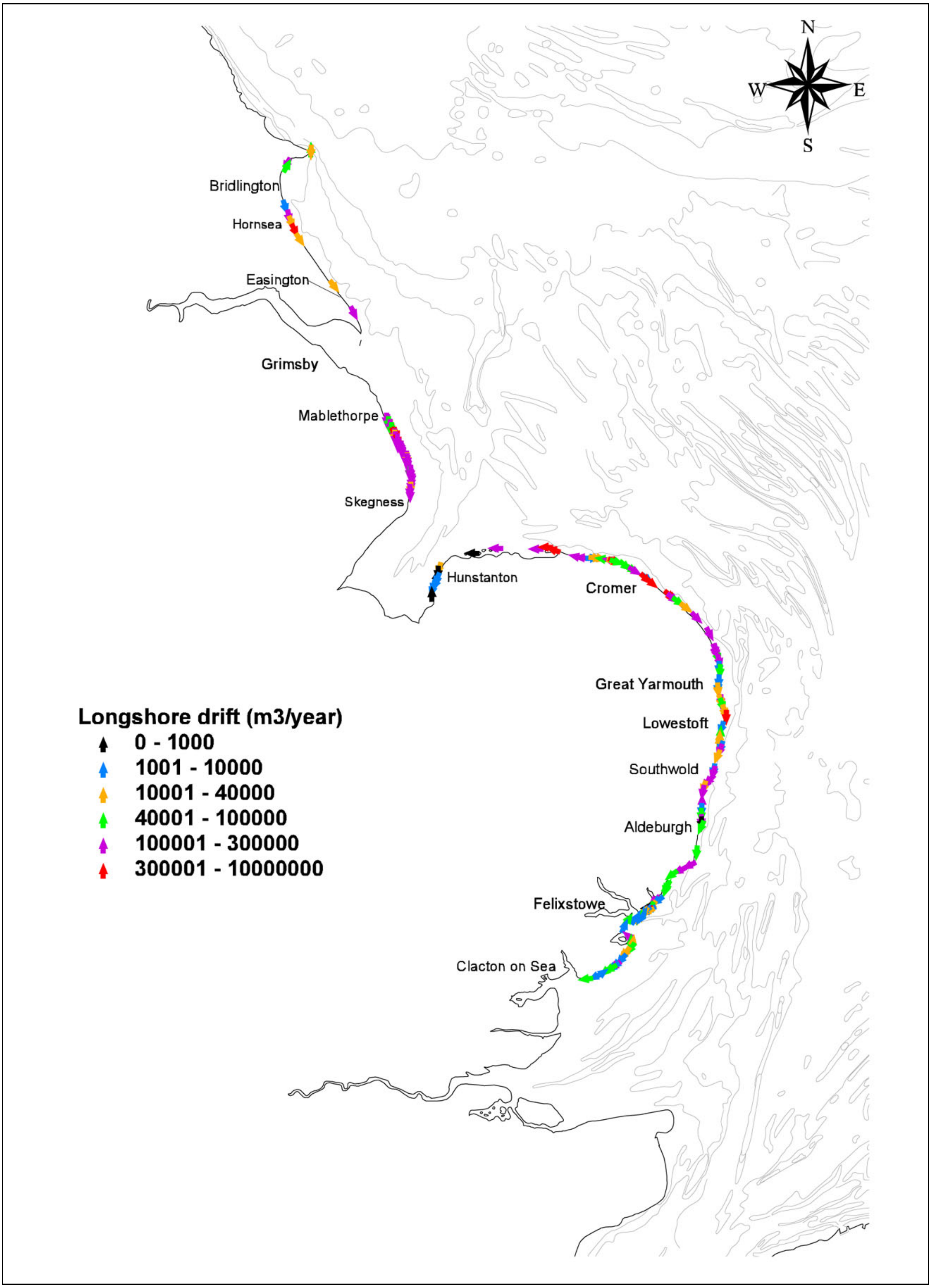

Figure 2 **All estimated longshore sediment transport rates included in the report**

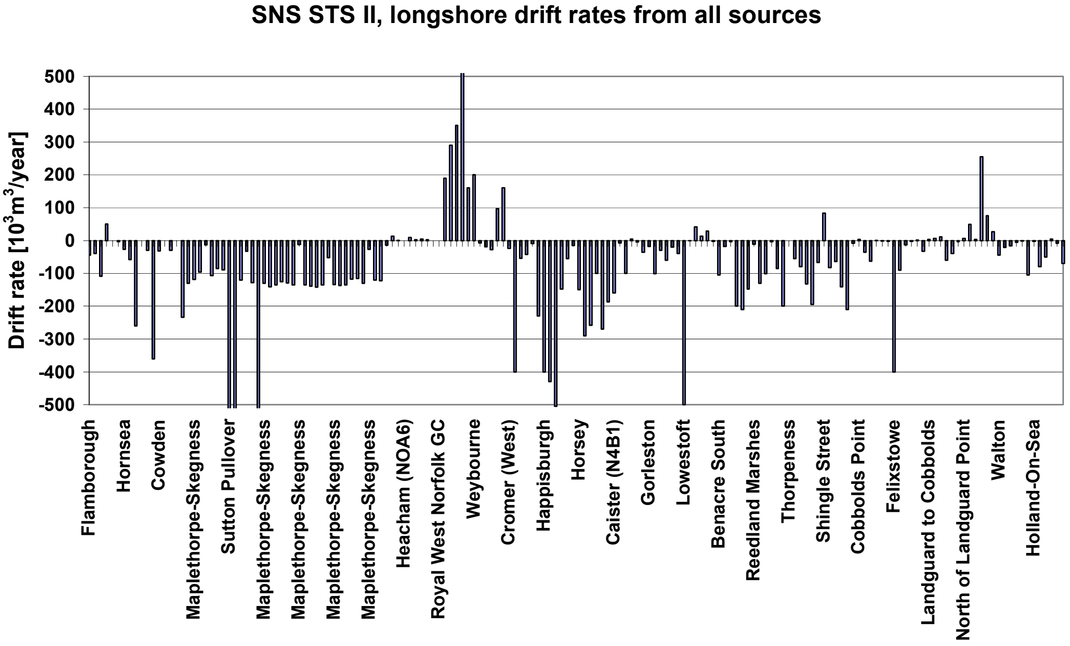

Figure 3 Summary histogram of all estimated mean net longshore drift rates. Positive drift is to the left when standing on the shore looking out to sea while negative drift is to the right

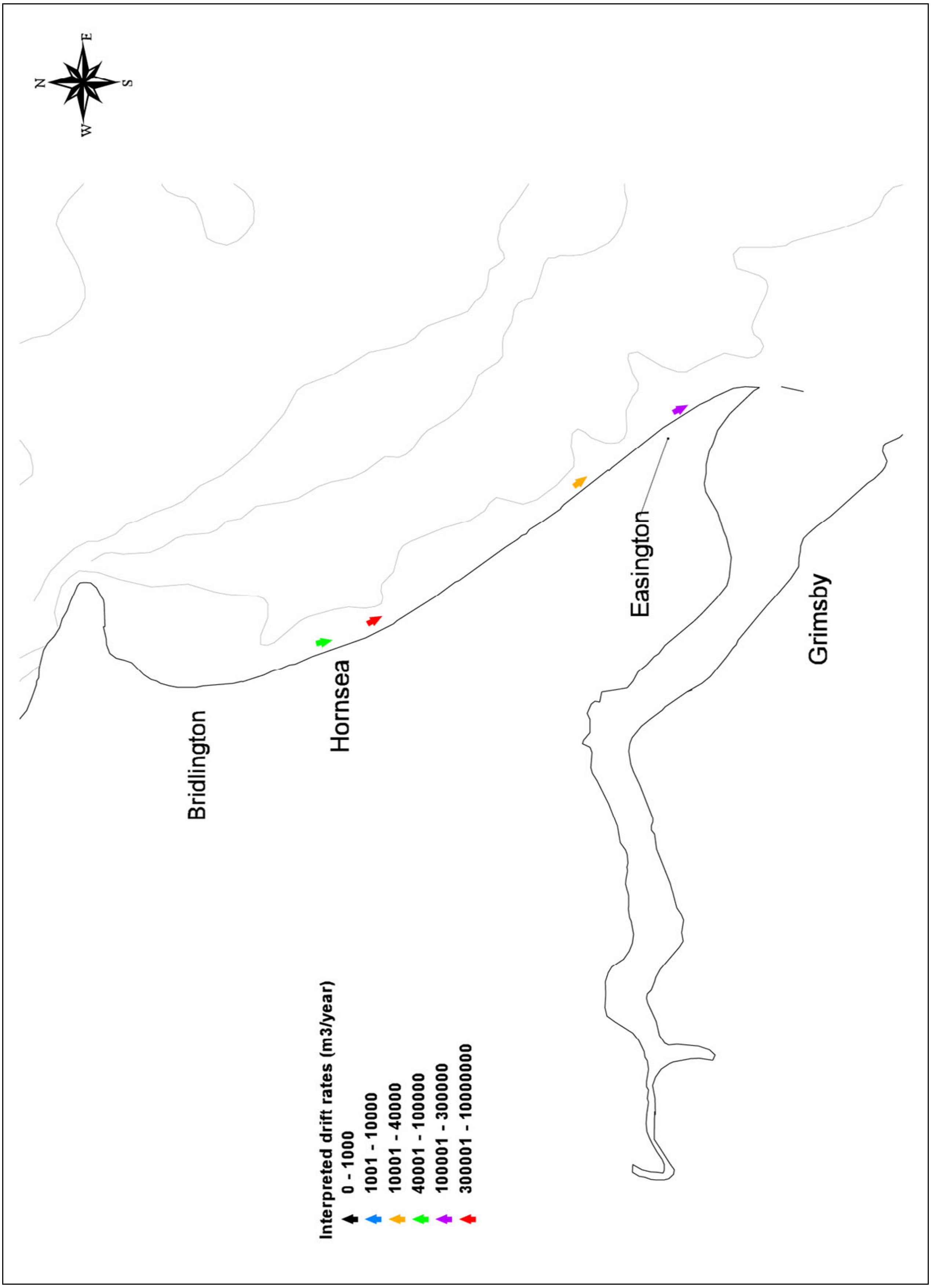

Figure 4 Longshore sediment drift rates along Holderness

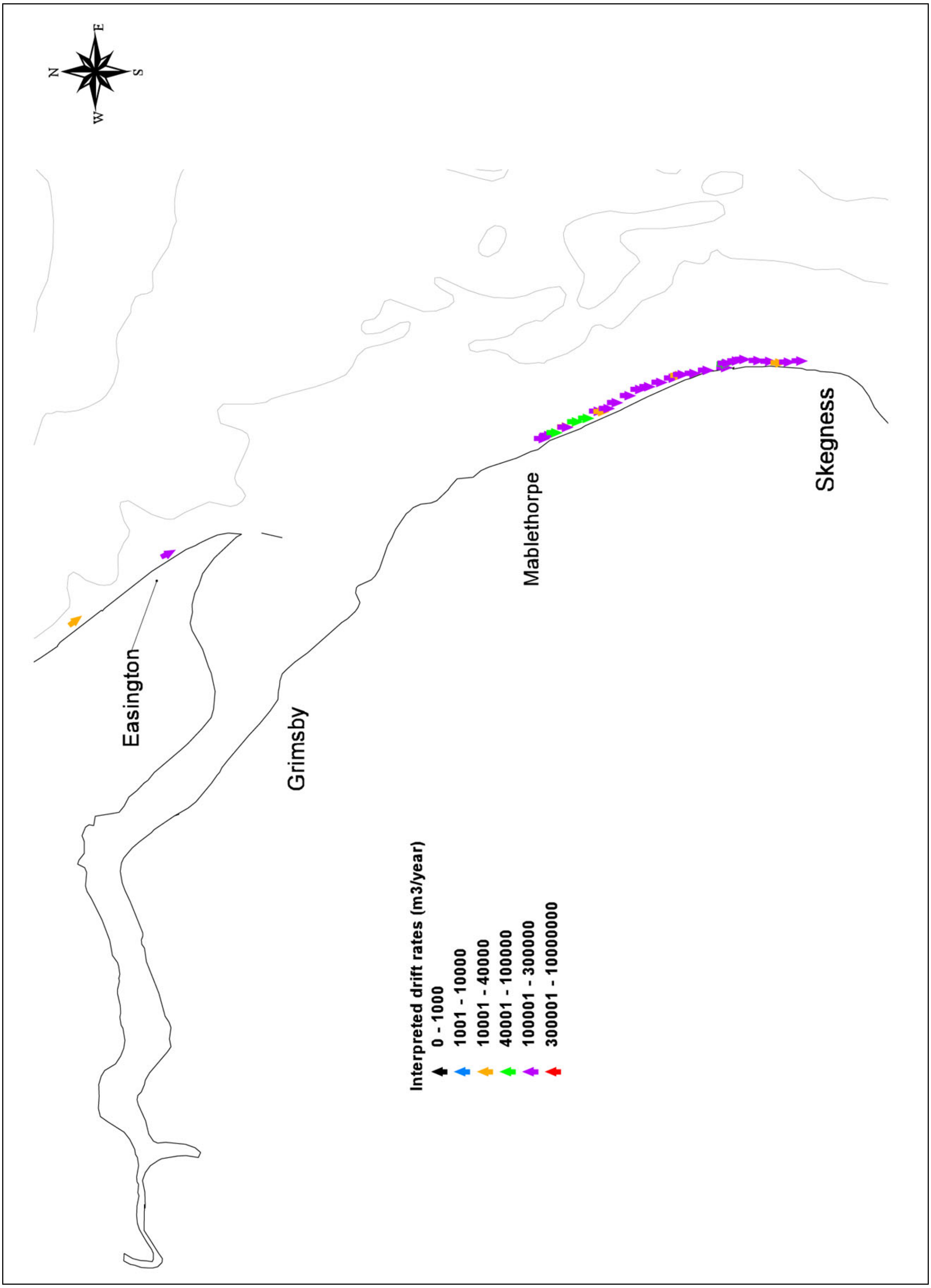

Figure 5 Longshore sediment drift rates for Lincolnshire

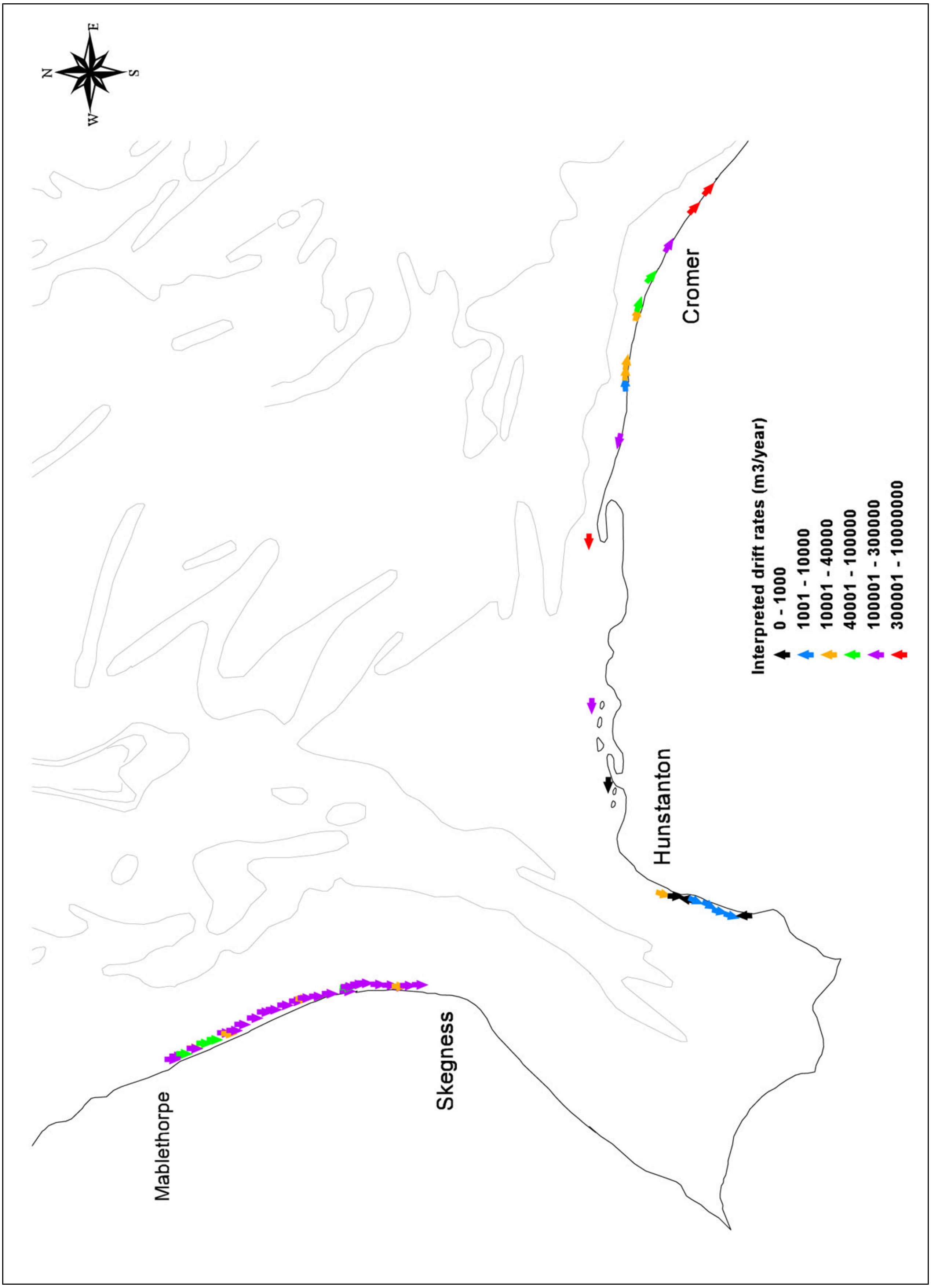

Figure 6 Longshore sediment drift rates for Lincolnshire, the Wash and North Norfolk

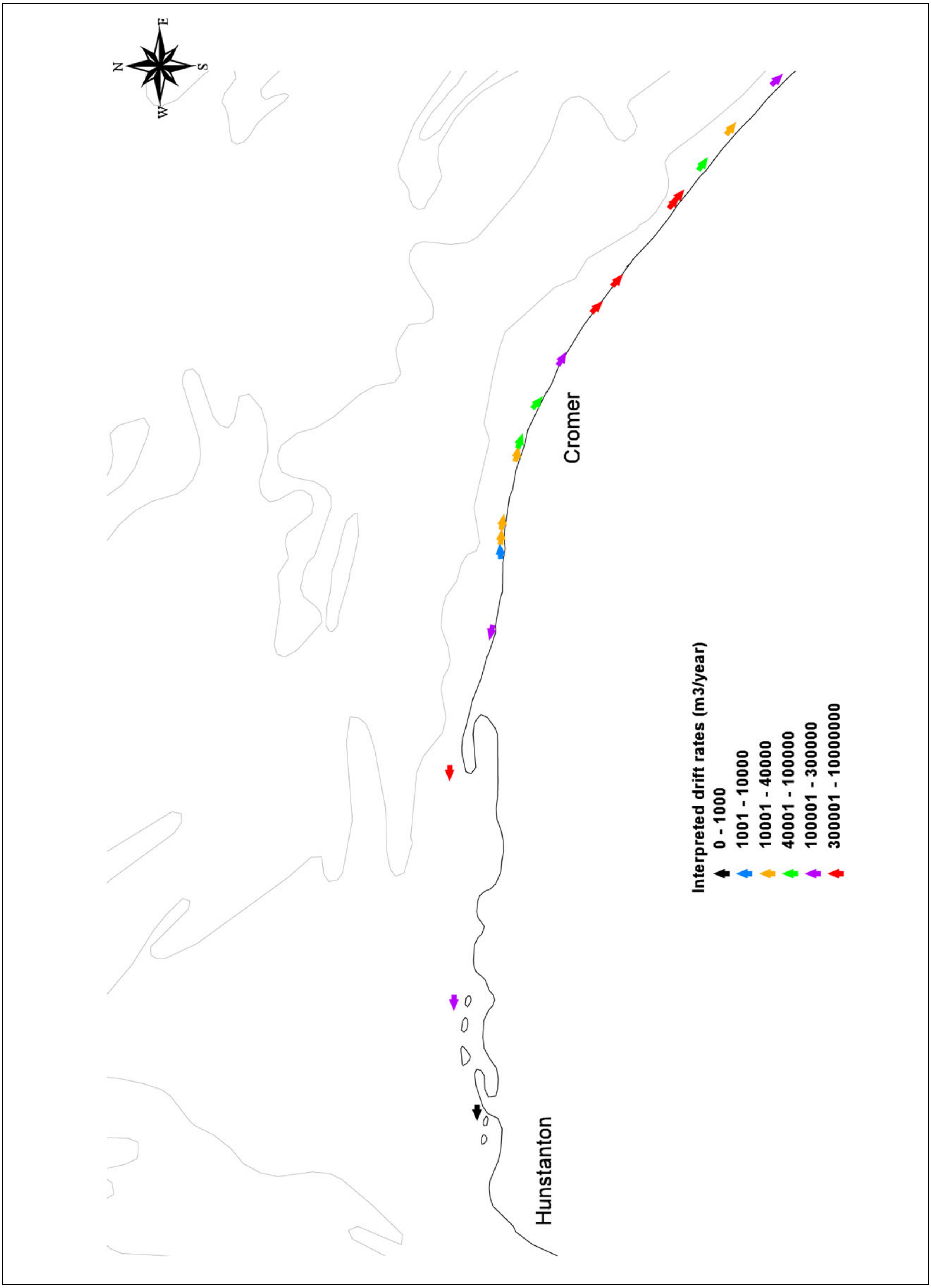

Figure 7 Longshore sediment drift rates for North Norfolk

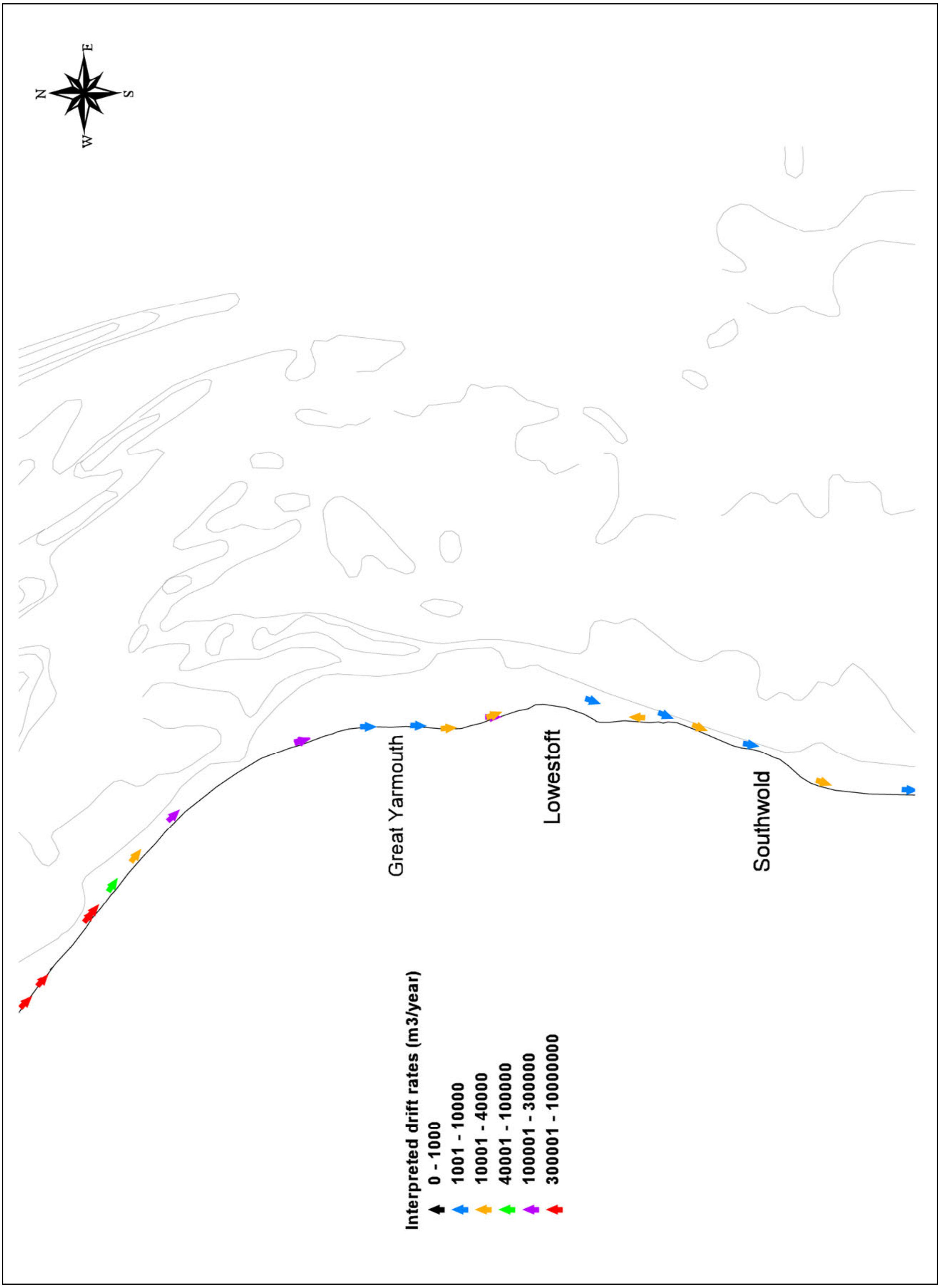

Figure 8 Longshore sediment drift rates for East Norfolk and North Suffolk (between Winterton Ness and Southwold)

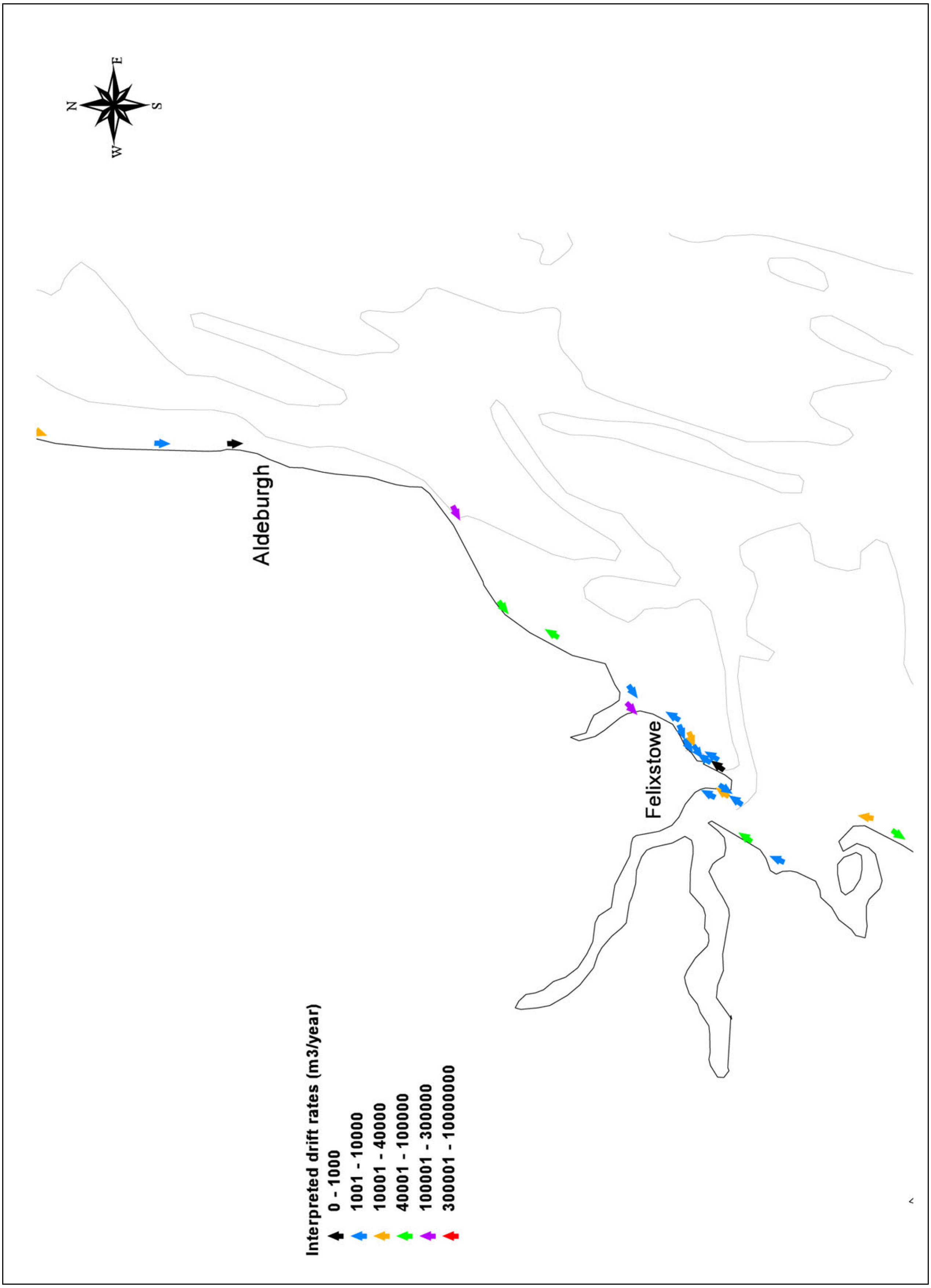

Figure 9 Longshore sediment drift rates in Suffolk (between Southwold and Felixstowe).

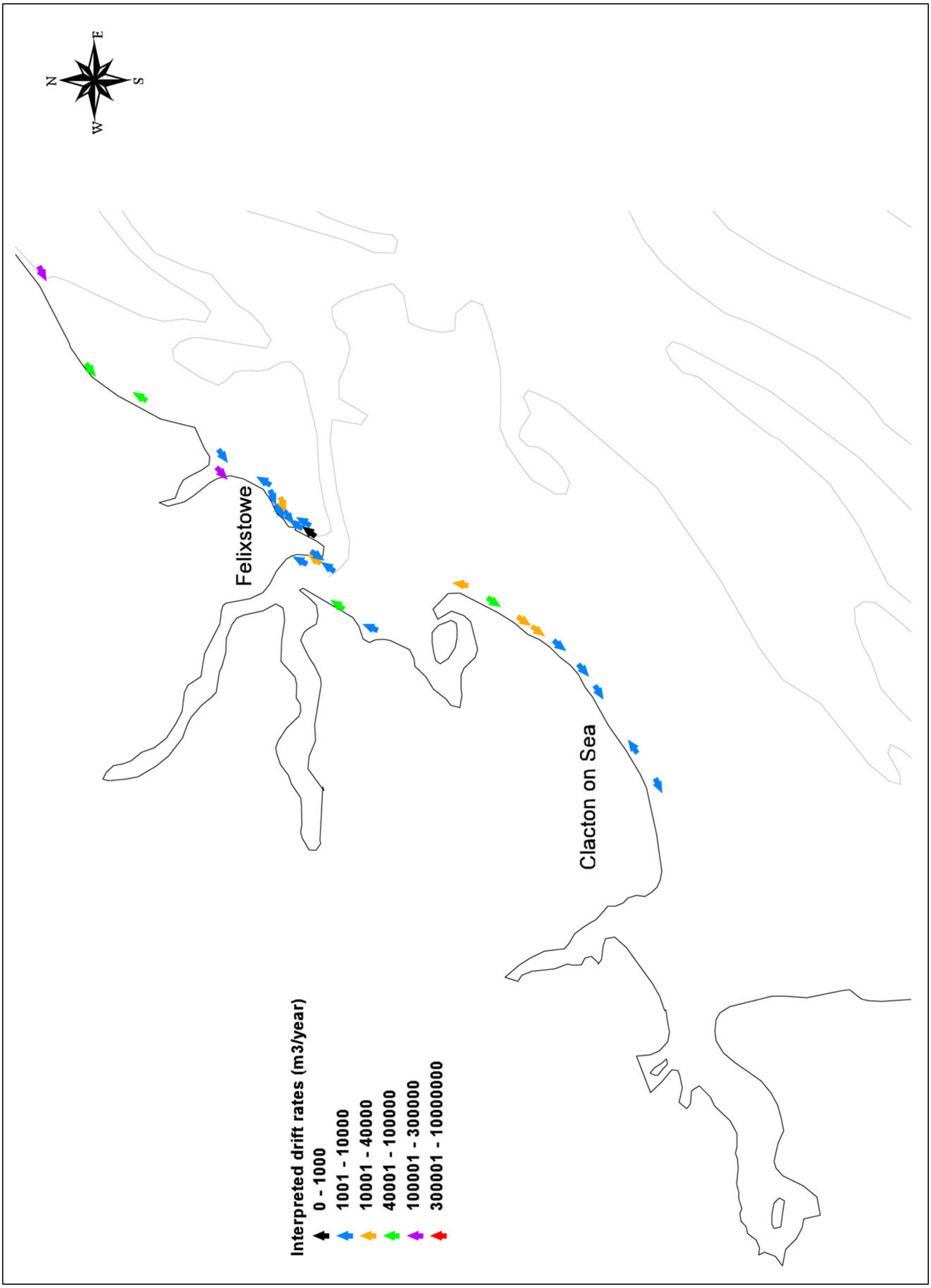

Figure 10 Longshore sediment drift rates in Essex

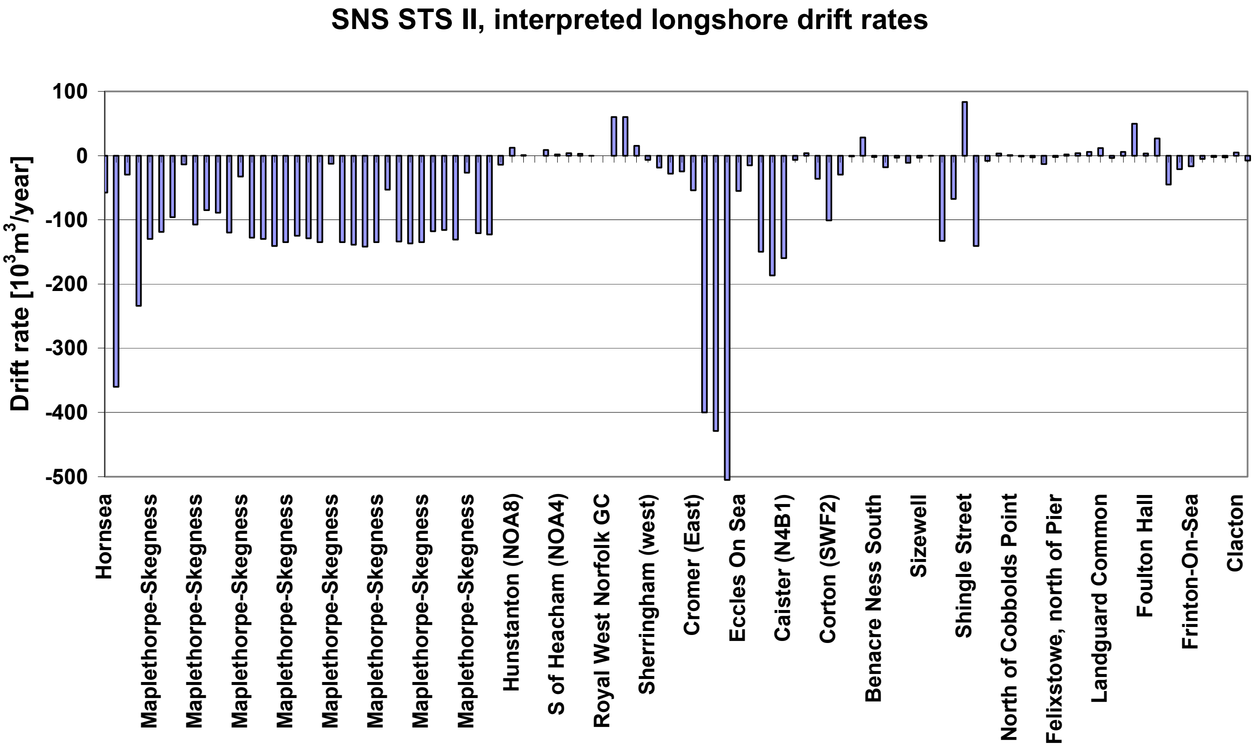

Figure 11 Summary of interpreted mean net longshore drift rates. Positive drift is to the left when looking out to sea, negative to the right

ANNEX A. COSMOS MODELLING OF DRIFT RATES AT HORNSEA

The COSMOS model

HR Wallingford's coastal profile model COSMOS 2D was used to model sediment transport (sand) at Hornsea. COSMOS models nearshore hydrodynamics and sediment transport and includes:

- Linear wave transformation by refraction, shoaling, Doppler shifting, bottom friction and wave breaking.
- Wave set-up from the radiation stress gradient
- Driving forces for longshore wave-induced currents from the spatial distribution of wave energy dissipation
- Longshore currents from pressure-driven tidal forces and wave-induced forces.
- A three-layer model for cross-shore undertow
- Wave breaking transition zone
- Cross-shore and longshore sediment transport rates using Bailard's energetics approach.
- Seabed level changes due to cross-shore sediment transport.

The model assumes a straight coastline with parallel depth contours. It is quick to run and relatively simple to set-up and operate. Details of the model were published by Southgate and Nairn (1993) and Nairn and Southgate (1993).

Beach profile

COSMOS requires a beach profile to operate. This was acquired from two principal sources:
1. Beach profile surveys around Hornsey, kindly provided by East Riding of Yorkshire Council
2. Bathymetry extracted from the TELEMAC model and based on digitised Admiralty charts.

The cross-shore bathymetry used is shown in Figure A.1. The angle of the shoreface ramp was very close to that suggested by Wingfield and Evans (1998).

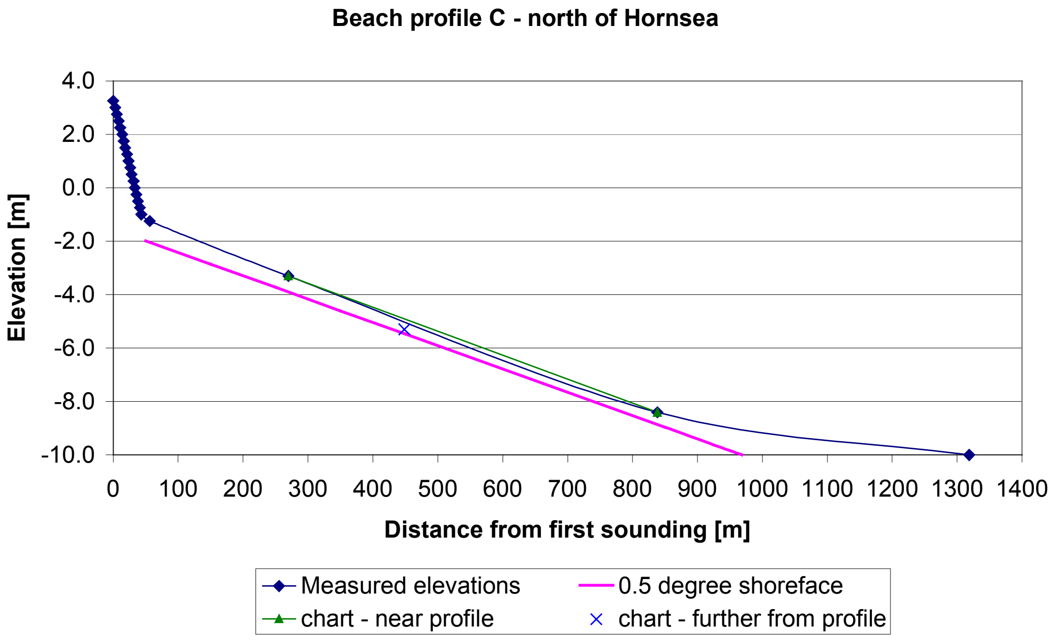

Figure A.1 Beach profile at Hornsea

Tide and wave forcing

At Hornsea the tidal forcing for COSMOS was provided by the TELEMAC model that produced the sediment transport area modelling results in the Southern North Sea Sediment Transport study. The wave modelling was driven by a wave climate produced from wind records between October 1986 and March 2001 so a 14.5 year long record was used. HR Wallingford's offshore wave prediction model HINDWAVE was used to predict a time series of wave conditions at an offshore point, in deep water. The offshore wave conditions were transformed into nearshore conditions using HR Wallingford's wave ray tracing model TELURAY. A wave rose was created from the time series. This shows the percentage of the total time series at each combination of wave height and direction. A period was associated with each of the wave conditions, by assuming an equal wave steepness, $s = 2\pi H_s/gT_z^2 = 0.03$, where H_s = significant wave height and T_z is the average wave period. The significant wave height, average period, wave angle and probability of occurrence were entered into the COSMOS model for each wave condition. The longshore transport rate was calculated at each point along the coastal profile for each wave condition, averaged over a tidal cycle. In additions, the longshore transport rate was accumulated in space from the nearshore point. To give a measure of the total transport rate between the top of the beach and each position. A weighted average of the mean longshore transport rate from all conditions was then calculated (weighted by the probability of occurrence) as was the weighted average of the transport rate, accumulated in space from the nearshore point.

Three results were presented for the nett annual longshore drift derived from considering the sediment transport due to waves and tidal currents out to different distances from the mean water line.