

associated increased risk of flooding of the low-lying areas behind. However, they added that redistribution of sand within the dune system should enable the dunes to be sustained.

- Future Coast (2002b) suggested that under rising sea level the offshore sand banks (Dunwich and Sizewell) may migrate inland maintaining similar levels of protection to the beaches as at present.
- Although the position of Thorpe Ness will continue to be partially controlled by the underlying geology, a future accelerated retreat is predicted due to relative sea-level rise and increased storminess.

5. THORPE NESS TO SHINGLE STREET

5.1 Thorpe Ness to Aldeburgh

Between Thorpe Ness and north Aldeburgh, a shingle beach barrier protects low-lying marsh behind. Aldeburgh is situated on a slight rise composed of Crag (>97% sand, James and Lewis, 1996), with a fronting cliff, over 1 km long and a maximum height of about 10 m. The cliff is defended by a seawall and fronted by a shingle beach. Prior to the late 19th century, the coast at Aldeburgh was eroding. Clayton (1987) refers to the loss of six streets since the 16th century. However, at Aldeburgh at present, a system of groynes is associated with a wide shingle beach, and the long-term erosion has been stopped (since 1886) (Future Coast, 2002c). This stretch of coast, therefore, marks a transition between erosion at Thorpe Ness and accretion at north Aldeburgh.

5.2 Aldeburgh to Shingle Street

The feed of shingle that is transported around Thorpe Ness moves south beyond Aldeburgh to form the beaches of Orford Spit and Ness. The spit diverts the course of the River Alde to join the River Ore, with a mouth at Orford Haven between Shingle Street and North Weir Point. The spit is backed by low-lying marsh through which the River Ore meanders. The shingle of the spit and ness is in the range 4 mm to 75 mm and is composed of a high proportion of highly resistant flint (Carr, 1970, 1972). A series of man-made saline lagoons occur on Lantern and Kings Marshes. They were former borrow pits, excavated to provide sediment for flood embankments. Another set of former gravel pit lagoons occurs within the main bulk of the shingle. Both sets of lagoons are fed by seawater percolation through the shingle, occasional overtopping and by rainfall.

The spit probably started to form after the rate of sea-level rise slowed several thousand years ago. It seems likely that a source of offshore sediment was gradually driven onshore. On reaching the shore, the dominant north-easterly wave climate forced the shingle southwards, whilst at the same time, the shingle was also being rolled back landward as sea level continued to rise. Since then, the growth of the spit is recorded by a series of ancient shorelines, which are preserved as shingle ridges with intervening lows.

Steers (1926, 1964) suggested that the construction of the castle at Orford in 1165 marked what was then the end of the spit, suggesting that ridges adjoining Stony Ditch were 12th to 13th century. Further ridges were added in the 14th century, with the higher, more seaward ridges formed in the period from the 17th century onward (Carr, 1970). Maps produced between the 1600s and 1800s show the spit to have grown beyond

Orford and Havergate Island (Carr, 1969). By the late 1800s the spit had grown almost to its present length. Over the last 180 years the length of Orford Spit has fluctuated over a distance of nearly 3 km, although evidence suggests that its alignment has remained unchanged (Carr, 1969, 1972). The present position of the end of the spit is close to its past known maximum.

Orford Ness is defined as a downdrift accretion ness (Birkbeck College and Babbie, 2000) with downdrift accretion accompanied by erosion on the updrift side. The erosion involves the "roll-over" of shingle on to the backing marsh, and old marsh sediments are exposed in places along the foreshore (Birkbeck College and Babbie, 2000). Between Slaughden and Lantern Marshes, the historical trend (before construction of defences) has been retreat of about 1 myr^{-1} (Clayton, 1987; Halcrow, 1995). Halcrow (2002) compared historic maps between 1886 and 2000 and suggested a lower value of around 0.45 myr^{-1} (an average of 50 m over the 114 year period). The analysis also indicated that the beaches at Slaughden have steepened with a foreshore reduction in width of about 50% over the 114 year period. Using beach profile data, Birkbeck College and Babbie (2000) measured average erosion rates of 3 myr^{-1} between 1991 and 1997. However, a storm event in February 1996 caused up to 15 m of erosion along the northern shore of the ness and reduced the height of the beach ridge by over 1 m. Washovers were pushed inland by up to 40 m. Losses of 5-6 m occurred at Slaughden during a single storm surge in October 1998. Clayton (1987) also suggested an erosion rate of $1.5\text{-}2 \text{ m yr}^{-1}$ immediately north of the ness and progradation of 0.3 m yr^{-1} immediately south of the ness (Halcrow 2002). The overall result of the erosion-accretion patterns is a gradual migration of the ness in a southerly downdrift direction (about 4 myr^{-1} , Clayton, 1987).

The magnitude of these changes vary depending on the method of calculation. Indeed, beach profile data (1992-2000) suggest that sections of the coast between Aldeburgh and North Weir Point are subject to alternating trends of erosion and accretion with no discernible trends. The analysis also showed that annual variability was in excess of the average rates of change during the 8 year period, indicating that conclusions based on average trends, may not be indicative of longer-term trends, as a single years data may reverse the overall apparent trend.

Vincent (1979) calculated high potential net southerly longshore transport rates for sand of $80,000 \text{ m}^3\text{yr}^{-1}$ north of the ness and $195,000 \text{ m}^3\text{yr}^{-1}$ south of the ness. These values are well in excess of the available beach sediment supply. The beaches of Orford Spit are almost entirely shingle supporting these high potential transport rates (Halcrow, 1995). Pettitt (2000) suggested that the potential net longshore transport rate for shingle, immediately south of Orford Ness was $67,200 \text{ m}^3\text{yr}^{-1}$ in a southerly direction. At North Weir Point, this value is calculated to increase to $132,700 \text{ m}^3\text{yr}^{-1}$. Pettitt (2000) also suggested that bi-directional transport (in equal amounts) takes place north of Orford Ness due to the dominance of two wave directions. This indicates that north of Orford Ness, sediment is free to move in either direction, but once it passes Orford Ness it cannot be transported back. SNS2 (HR Wallingford 2002) suggests that the volume of shingle lost from the system at North Weir Point is greater than the volume entering at Aldeburgh, and so overall the system is losing sediment.

The history of Orford Spit and Ness is important with respect to its ecology. Of particular interest is the age of the ridges, their period without wave disturbance, and the roles of sea level, wave height and shingle supply in determining the profiles of the ridges and hollows (Randall and Fuller, 2001). The spit and ness are characterised by a steep upper beach, with relatively deep water on the upper beachface at high tide. The height

of the spit varies along its length with a tendency to increase in elevation where sea level has risen during the time of spit formation. Height variation also occurs due to build up of the beach ridges by storms. These ridges are roughly parallel to the shore, and have resulted in extensive areas of stable shingle, fringed by a more dynamic coastal ridge. Ridge heights vary from 3.1 m OD for the most landward (although old ridge crests lower than 1.5 m OD have been described), to around 4.0 m OD in the middle to up to 4.3 m OD to seaward (Carr, 1970; Randall and Fuller, 2001). The intervening lows are generally around 0.3 m lower than the ridge crests. Randall and Fuller (2001) showed that the established ridges contain fine shingle (<10 mm), while the lows between are coarse shingle, and this has had a major influence on the success or failure of plant colonisation. The fine shingle tends to be colonised whereas the coarse shingle is barren. The mechanism by which ridges and lows acquire different grades of shingle is unclear.

At Slaughden the diverted estuary approaches to within 50 m of the low water mark. This area constitutes the greatest danger of breakthrough of the spit, where the River Alde has cut into the landward side, while the sea has eroded the outer side. If the spit was breached at Slaughden, there is potential for the formation of a new mouth to the river with dramatic effects on the coastal morphodynamics of the area. The fragility of the spit at Slaughden was demonstrated by a breach at this point in 1963. About 250,000 m³ of shingle was transported to the site from the ness to repair the damage.

To protect the coast at Slaughden a rock revetment was placed at the back of the shingle ridge in 1987 followed by further works in 1989 and 1992. A continuous 15-year programme of recharge followed, whereby shingle was removed from the beach between Lantern Marshes and the point of the ness and placed on the foreshore at Slaughden. The average amount of recycled sediment amounts to 7000 m³yr⁻¹ (up to 10,000 m³yr⁻¹ maximum).

Randall and Fuller (2001) postulated that if a breach occurred, southerly longshore transport would be hindered and the shoreline at Aldeburgh would accrete, with the course of the River Alde to the sea steadily lengthening eastwards. The abandoned spit immediately south of Aldeburgh would "roll-over" Lantern Marshes, with enhanced accretion south of the present Orford Ness. Inside the spit, flows in the estuary would reduce and the channel would eventually silt-up.

The process regime at the mouth of the estuary is complex. Breaches through North Weir Point have occurred quite regularly and large shingle banks in the mouth form a route by which sediment is transferred southwards across to Shingle Street. Here, lower and far more ephemeral ridges (rarely exceeding 3.4 m high) are formed (Cobb, 1957; Carr, 1972, 1986), which are protected from all but southerly waves by North Weir Point, producing counter recurved spits, growing up-river, with remnants as far as Havergate. A series of natural lagoons occur at Shingle Street, which are formed by the build-up of shingle and enclosure of small bodies of seawater (Cobb, 1957). This system is subject to more dynamic conditions than the lagoons of Lantern and Kings Marshes and several have been lost through shingle movement since the 1970s. More recent photographs indicate that northerly drift into the estuary has either significantly reduced, or ceased (Pettitt, 2000). The inward pointing spits now appear to be only the inactive remnants of the original features and are being slowly eroded by wave and current action. This change itself is recognised as transitory. Towards Shingle Street, Pettitt (2000) calculated a potential net northerly longshore transport rate for shingle of 83,300m³yr⁻¹.

Orford Spit has grown in a “cyclic” fashion (Cobb, 1957; Carr, 1969, 1972, 1986) with periods of elongation intermittent with periods of shortening. According to Carr (1986) the cyclicity may be caused by fluctuations in the protection from waves afforded by nearshore sandbanks: Aldeburgh Ridge and Whiting Bank. The orientation and position of these banks provide protection in places and wave focussing in other areas (Future Coast, 2002c).

Steers (1926, 1964) calculated an average growth of 14 myr^{-1} from 1601 to 1897, although it wasn't necessarily continuous. During this period, Orford Spit is known to have undergone at least two periods of growth followed by collapse. Cobb (1957) and Carr (1969) stated that the spit reached a maximum length in 1811 and again in 1892. In both cases the most southerly location is reported to have been approximately opposite the Martello tower at the southern end of Shingle Street. This may represent the critical length of the spit, the maximum length that it can develop to before it becomes unstable and breaches (Cobb, 1957). This may suggest that limiting effects are local not nearshore. The 1892 cycle was ended by a severe storm in November 1893 (Cobb, 1957). This caused a breach, followed by progressive retreat in which the isolated portion of the spit formed a series of islands and banks. These were eventually driven onto the Shingle Street frontage by wave action initiating development of the lagoons (Cobb, 1957). By 1921 the spit had retreated to its most northerly location in this period (Carr, 1969, 1986). This 2.7 km retreat was almost twice the distance that occurred at the end of the 1811 cycle.

A number of mechanisms, by which a breach may occur have been suggested, including increased hydraulic gradient and direct wave attack. As the spit gets longer the hydraulic efficiency of the estuary decreases. This results in an increased hydraulic gradient across the spit (between its seaward and river sides), leading to increased seepage through the spit. This may be sufficient to cause a breach, probably by exploiting an existing weakness. A surge associated with a storm event could increase the hydraulic gradient. A storm may also result in changes to the estuary mouth bathymetry, possibly causing a partial blockage, and leading to an increased hydraulic gradient across the spit.

Another measure of spit growth is the variation observed at Shingle Street. Aerial photographs show a “bulge” along the frontage, with an apex that has been moving in a southerly direction around 20 myr^{-1} (Pettitt, 2000). The bulge is the main location where sediment that has crossed the mouth of the estuary is being transported onshore. The location of the bulge is therefore an indicator of the position of the “effective end” of the spit, making allowances for the submerged banks at the tip. By extrapolation it is possible to predict that, assuming a linear growth, the spit will reach its critical length by about 2020 (Pettitt, 2000).

From a consideration of the predicted transport rates and observed growth of the spit, Pettitt (2000) was able to calculate how much sediment crosses the estuary mouth. The sediment transport analyses indicated that between about 70,000 and 130,000 m^3 of sediment moves in a southerly direction along the beach, south of the ness, every year. By assuming a typical cross-section for Orford Spit, Pettitt (2000) calculated that approximately $35,000 \text{ m}^3 \text{ yr}^{-1}$ of sediment is sufficient to sustain a growth rate of 20 myr^{-1} . This indicates that between 25% and 50% of the sediment transported along the beach contributes to the growth of Orford Spit. Therefore, the remaining sediment must cross the estuary mouth and reach the Shingle Street frontage, between 35,000 and 95,000 $\text{m}^3 \text{ yr}^{-1}$, depending on wave climates.

5.3 Future of the Thorpe Ness to Shingle Street coast

- Groynes at Aldeburgh will continue to maintain the beach along this stretch of coast. This coast will therefore remain stable, continuing to be slightly accretional. However, the groynes are unlikely to solve the long-term problems of a finite shingle supply.
- The diminishing supply of shingle to the north of Orford Spit, the continued steepening of the beach, relative sea-level rise and increased storminess will place increasing pressure on the Slaughden frontage, and increase the threat of breach.
- Future Coast (2002c) suggested that Orford Ness is a key control point and any changes in its form and position could have considerable impact for areas to the north and south. They argued that the entire foreland is undergoing large-scale re-alignment under a diminishing sediment volume regime.
- The accretional trend along the downdrift side of Orford Ness is expected to continue. There will continue to be a net loss of shingle from Orford Ness onto the coastline further south between Shingle Street and Felixstowe.
- Any significant increases in tidal volume and tidal flow, due to relative sea-level rise, are likely to change the pattern of sediment dynamics across Orford Haven, either due to a greater quantity of shingle being trapped in the mouth or due to premature or major rupturing of the shingle spit.
- North Weir Point is dynamic and known to vary by up to 3-4 km in response to breaching the spit. This cyclicity is likely to continue.
- Orford Spit is currently extending southwards parallel to the shore at a rate of approximately 20 myr⁻¹. In this process between 25% and 50% of the sediment is retained by the spit. It is predicted that this will continue well into the 21st century, until the spit becomes unstable. At this time (c. 2010 to 2030) the spit will probably breach and deposit a large shingle supply on the shore near Shingle Street, possibly creating another bulge.

6. ALDE/ORE ESTUARY

6.1 Alde/Ore Estuary

The estuary of the River Alde/Ore stretches from the normal tidal limit at Snape to Orford Haven. Between Snape and the cliffs at Iken, the southerly course of the Alde Estuary channel is fixed by a series of abandoned embankments, within which flows are generally slow. From Iken to Barber's Point the intertidal area widens to around 1 km with a narrow, meandering low water channel which is largely unrestricted. At Barber's Point the low water channel reaches its maximum width. Intertidal mudflats bordered by narrow saltmarsh dominate this area. Between Barber's Point and Slaughden the estuary narrows and forms several tight meanders, confined by both defences and natural high ground, before turning sharply south at Slaughden. In this reach, the flow velocities start to increase, particularly on the outer sides of the bends. From Slaughden to Shingle Street the estuary is confined between embankments (restricting any tendency for lateral movement) and flows parallel to the coast confined by Orford Spit. At Orford, the channel splits around Havergate Island. This division of the channel increases the flow area of the river and the general velocities decrease. The River

Butley joins the Alde/Ore Estuary at the south end of Havergate, where the two channels converge again. The tidal limit of the River Butley is at Butley Mills. Downstream of Havergate to its mouth, the estuary is at its widest, behind the spit. There is little scope for increase in width without cutting into the defences to landward or cutting back the shingle ridge on its seaward side.

The tides at Orford have spring and neap ranges of 2.9 m and 1.7 m, respectively (mesotidal). The present volume of water moving into and out of the estuary over a spring tide is around $9.6 \times 10^6 \text{ m}^3$ (Guthrie, 1999b), spread fairly evenly throughout the estuary. Guthrie (1999b) provided best estimate water levels of 2.05 m OD (1 year return period) and 2.80 m OD (100 year return period) for Snape, and 2.25 m OD (1 year return period) and 3.02 m OD (100 year return period) for the estuary mouth.

Tidal current flow velocities are generally symmetrical, with velocities varying in accordance with the tidal range and distance from the estuary mouth (ABP, 1996b). Peak surface velocity at Boyton Marsh has been measured as 1.2 ms^{-1} , whereas further upstream at Sudbourne Marsh the value lowers to 0.6 ms^{-1} , and in the wide intertidal section 0.25 ms^{-1} . Modelling in the wider upstream parts of the estuary show that the time for settlement of sediments at high water slack is increased in the wider marsh areas (ABP, 1996b). Any deposition therefore is more likely to add to the upper marsh levels than to the lower intertidal areas. The models also show that the velocities change very slowly in the mid-section of the estuary, but as soon as it widens the velocities drop by over 50% and continue to fall as the tidal limit is approached. Particle size along most of the estuary is dominated by mud (ABP, 1996b). Sand occurs where flow velocities are higher (Slaughden bend) and gravel occurs towards the mouth.

The estuary has a small freshwater inflow, with an average input of $0.62 \text{ m}^3\text{s}^{-1}$ (ABP, 1996b). There is a distinct seasonal pattern with flows in winter ($1.8 \text{ m}^3\text{s}^{-1}$) being six times higher than flows in summer ($0.3 \text{ m}^3\text{s}^{-1}$). On a spring tide, the tidal inflow at the mouth of the estuary is $1500 \text{ m}^3\text{s}^{-1}$ making the estuary system tidally dominant.

Over the past several thousand years the development of the Alde/Ore Estuary has been intimately linked to the development of Orford Spit and the land-claim of saltmarsh formed in the shelter of the spit. The main enclosure of saltmarsh took place in two phases, between the 11th and 13th centuries and in the 16th and 17th centuries (Beardall *et al.*, 1991). Beardall *et al.* (1991) estimated that 14.5 km^2 and 25.2 km^2 of saltmarsh and mudflat, respectively have been reclaimed and protected by embankments, leaving only 3.4 km^2 of saltmarsh and 5.4 km^2 of mudflat in the Alde/Ore/Butley system.

Between 1971 and 1992 there has been both loss and gain of saltmarsh, with an overall net loss (8.5% compared to 1971, ABP, 1996b). Most of the saltmarsh was lost from the middle estuary (75%) with 25% loss from the lower and upper estuary. The total area of saltmarsh in 1971 was 3.7 km^2 and 3.4 km^2 in 1992. The recent total area of pioneer saltmarsh is low (7.5% of total saltmarsh area) suggesting that little accretion is taking place. The loss of saltmarsh is considered to be due to excessive submergence caused by relative sea-level rise.

ABP (1996b) classified the Alde/Ore Estuary into four main process units based on morphological and hydrodynamic properties. Process Unit 1 comprises an area of wide intertidal mudflat and saltmarsh, which exhibits properties characteristic of a classic trumpet shaped estuary where the width and depth reduce exponentially up-estuary. The intertidal area is 0.5-1 km wide and is crossed by a narrow sinuous low-water channel. The power expenditure on the bed is very low, and hence, the unit is

marginally depositional in nature with potential for sedimentation on the higher mudflat and saltmarsh. Process Unit 2 is transitional between the banked channel downstream and unit 1, and has the morphological characteristics of an “inverted” estuary with the mouth at the upstream end. The power expenditure on the bed is constant and very low. It is an area of small net deposition. Both units 1 and 2 have internally generated waves, which are tidally dependent resulting in maximum stress at the edges of the saltmarsh and the embankments.

Process Unit 3 is a narrow gently meandering bank-parallel section. This unit has evolved due to the historical development of Orford Spit and anthropogenic influences, being constrained on both sides by embankments. The power expenditure is larger than units 1 and 2 but smaller than unit 4. The channel division around Havergate Island reduces the overall energy expenditure reducing the erosional effects on the bed and embankments compared to those up and down estuary. The unit has a small depositional potential with respect to sand and a net potential for erosion of mud. Internally generated wave heights are generally uniform and small. Process Unit 4 is a straight narrow bank-parallel section, which is characterised more by coastal processes rather than estuarine processes. The unit has a high potential for deposition of sand and a high potential for erosion of mud and therefore has the most potential for overall change. Waves are dominated by those generated at sea into the entrance and there is little evidence for the formation of tidal deltas at the entrance.

6.2 Future of the Alde/Ore Estuary

There are several factors that will impose constraints on the development of the estuary as relative sea level rises in the future. These are, first, the degree to which at any point in the estuary its width is constricted, and second, the degree to which a change in alignment of the channel is constrained. Following a postulated rise in sea level of 0.5 m, the following predictions have been made (ABP, 1996b; Guthrie, 1999b).

- The frequency of return of extreme water levels is predicted to increase by a factor of 10 or more. At Snape, the water level of the 1 year event would increase from 2.05 m OD to 2.55 m OD and the 100 year event from 2.8 m OD to 3.3 m OD. Correspondingly the water levels at the estuary mouth would increase from 2.25 m OD to 2.75 m OD (1 year event) and from 3.02 m OD to 3.5 m OD (100 year event).
- The peak ebb velocities will increase by about 0.1 ms^{-1} from the estuary mouth to the confluence with the Butley river, thus increasing the potential to scour the bed and banks in this section. However, an increased sediment load through the area may cause deposition of coarser sediment at times of lower flows.
- Power dissipation at the channel bed in all areas of the estuary is predicted to increase. The greatest increases will occur in the relatively narrow channels south of Aldeburgh increasing the likelihood of morphological change.
- The tidal volume would increase from $9.6 \times 10^6 \text{ m}^3$ to $13.82 \times 10^6 \text{ m}^3$ (144% of present volume) assuming all defences remain intact.
- In the wide intertidal area, the increase in tidal prism is likely to lead to only a small increase in velocities, because the area is tolerant of large changes in tidal volume due to the limited constraint of the channel. The velocity increase may be too small to cause any significant increase in erosion in the area.

- The saltmarsh areas of the estuary are gradually being eroded, and this trend will probably continue with relative sea-level rise.

7. SHINGLE STREET TO PORT OF FELIXSTOWE

This stretch of coast differs geologically (dominated by London Clay) and hydrodynamically (lower energy dissipative environment) from the Suffolk coast further north. Longshore transport is dominantly to the south towards Woodbridge Haven, where sediment is temporarily held in The Knolls and spits at the entrance to the Deben Estuary. Offshore banks provide varying degrees of protection to the coast, and during north-east storms, sediment from the banks is redistributed onto the beaches along the Felixstowe frontage.

7.1 Shingle Street to Felixstowe Ferry

The northern part of this stretch of coast is generally low-lying, formed of marsh fronted by mixed sand-shingle beaches. The southern part is dominated by 3 km of generally unprotected eroding cliffs, up to 16 m high, composed of sands and gravels of the Red Crag (up to 13 m thick in places) resting on London Clay (generally less than 3 m thick) (James and Lewis, 1996). The cliffs at Bawdsey are the most northerly exposure of London Clay on the East Anglian coast. The Red Crag has a significant gravel component, varying from 25-30%. The beach is highly mobile and, in places, London Clay outcrops on the foreshore. Halcrow (1998) argued that the onshore movement of sediment is critical to maintaining beach levels.

This whole stretch of coast is presently held in position by a gun emplacement at East Lane which acts as a "strong point" maintaining a coastal configuration which would not naturally occur (Halcrow, 1998; Pettitt, 2000). East Lane acts as an artificial promontory, which has become more pronounced as the "soft" coastline to either side has eroded. This erosion has been markedly more severe on the south of East Lane due to the promontory intercepting the net southerly longshore sediment transport (Pettitt, 2000). Aerial photographs show that there has been little overall change to the frontage south of Shingle Street towards East Lane over the last fifty years. Pettitt (2000) suggested that the promontory acts as a longshore transport regulator; sediment cannot supply the downdrift side until it has built up sufficiently on the updrift side. This is likely to lead to periods of erosion on the downdrift side prior to a sufficient build up on the updrift side. At Bawdsey, the potential net longshore transport rate for shingle is $141,000 \text{ m}^3\text{yr}^{-1}$ to the south (Pettitt, 2000).

According to Halcrow (1998) the processes at the Deben Estuary mouth are poorly understood. The main complicating factor is the presence of The Knolls, a series of mobile, transient shingle bars to the north and south of the mouth supplied by sediment from the north. Halcrow (1998) suggested that there is a greater potential for sediment movement into the area from the north, than there is for sediment loss to the south, and so The Knolls are accreting. Their configuration is influenced by the interaction of waves, tides and sediment supply, and depending on their configuration, they provide varying degrees of protection to the downdrift coast. The interaction and stability of the bars depend to a large degree on the volume of flow into and out of the estuary. There is evidence that the bars develop within limits beyond which growth is restricted by wave action and the outflow from the estuary. They accrete over a period of time, gradually becoming unstable, before a storm event drives sediment across the channel and onto the Felixstowe Ferry frontage, which is then redistributed by wave action on to the Felixstowe beaches (BMT Ceemaid, 1990). This has led to general stability along the

coast south of the estuary. There is no mechanism for transport northwards across the estuary, and so it is a one-way transport boundary. These processes result in steady erosion of the Felixstowe Ferry frontage followed by significant accretion over a very short period of time. Overall, there appears to be a balance between discreet accretion events and the long-term erosion trend along the frontage (Pettitt, 2000).

During storm conditions, The Knolls rapidly change shape, orientation and location, with a resulting change in the tidal flows in the lower estuary. They can be breached and eroded, and no longer act as a wave protection system, enabling waves to propagate into the lower estuary. The ebb channel breaks through The Knolls altering the orientation of the ebb flow, reducing the length of The Knolls and providing further supply of sediment to be transported away.

BMT Ceemaid (1989a, 1989b, 1990) showed that The Knolls have undergone periods of both accretion and depletion over the period 1950 to 1988. ABP (1996c) showed that the shoals were at their greatest extent in 1913 and again in 1985. The smallest volume was in 1960. BMT Ceemaid (1990) suggested that there may be a 15 year cycle, consisting of growth of The Knolls and steady erosion along the southern shore, followed by collapse and accretion along the southern shore. Aerial photographs from 1953 illustrate the effect that a major storm can have on The Knolls. The event appears to have driven a large quantity of sediment onshore, towards the frontage in front of the Martello tower.

7.2 Felixstowe Ferry to Landguard Common

The Felixstowe coast has historically been protected from erosion by revetments and seawalls, and groynes maintain the beach. From Felixstowe Ferry to Cobbolds Point, the coast consists of low cliffs, composed of Red Crag resting on London Clay (generally less than 3 m in thickness) (James and Lewis, 1996). The cliffs contain over 75% sand. About 4 km of cliff front the coast with a maximum height of about 17 m, although cliff elevation is variable with heights down to 2.5 m. At Felixstowe the cliff turns inland away from the coast to leave a lower lying coast to the south, formed of a variety of morphological types. The beach between Felixstowe Ferry and Landguard Common is typically mixed sand-shingle with outcrops of London Clay in places along the foreshore.

Cobbolds Point forms a protected promontory, which is exposed to high energy wave action. Consequently there is a narrow beach of fluctuating width. The sediment transport regime at Cobbolds Point is presently under debate (Future Coast, 2002d). One argument suggests that the point is an area of net sediment transport divergence with sediment moving north and south from the point. Another argument suggests that net sediment movement is southwards, but that reversals do occur. At Cobbolds Point, Future Coast (2002d) suggested that the sand fraction of the beach is more responsive to reversal in sediment transport and is moved both north and south. However, shingle is moved southwards by high energy waves from the north-east. Pettitt (2000) calculated a potential net longshore transport rate for shingle of $62,700 \text{ m}^3\text{yr}^{-1}$ to the south.

The volatility of the beaches along this stretch of coast is linked to changes in channel and bar configuration at the Deben Estuary mouth. The cross-channel component of sediment transport from The Knolls is therefore critical to the maintenance of beach levels.

7.3 Landguard Common to Landguard Point

This stretch of coast is low-lying, formed of Landguard Spit and shingle beach, fronting marsh that has been land-claimed from the Orwell Estuary. The end of the spit is held in position by Landguard Point Jetty, which acts as a terminal groyne, and from the point a shore normal shingle bank extends offshore. Until the mid 1980s, sediment was extracted from the beach at Landguard Point (typically $10,000 \text{ m}^3\text{yr}^{-1}$) to reduce the need for dredging of the Harwich Harbour approach channel. This practice has now stopped. The jetty limits the amount of sediment moving into Harwich Harbour, and allows the beach to remain relatively stable. Historical evidence suggests that if sediment was not trapped behind the jetty, it would be transported into the mouth of the Orwell Estuary, rather than building out across the estuary (SNS2 HR Wallingford 2002). It was identified that the probable extent of drift along the shoreline was in the order of 20,000m3yr to 30,000m3yr based on the dredging record from immediately within the mouth of the estuary. There is no evidence of material moving from the Felixstowe frontage across the main Harwich channel. This view was supported by Futurecoast (2002)

The onshore-offshore movement of sediment was believed to be important to beach level maintenance along this coast (Halcrow, 1998). From Landguard Point, sediment was thought to move offshore to Cork Sand where it was believed to be stored temporarily. IECS (1993) suggested that Cork Sand marks the ebb tidal delta of the Orwell-Stour-Harwich Harbour system. Easterly or north-easterly storms were thought to move the sediment onshore towards the Naze where a longer term store exists. Mouchel (1997) suggested that around $70,000 \text{ m}^3\text{yr}^{-1}$ was input to the Naze, most of which coming from Cork Sand, while some ($10,000 \text{ m}^3\text{yr}^{-1}$) is derived from the cliffs at the Naze. Measurement work undertaken as part of SNS2 (HR Wallingford 2002) demonstrated no substantial link between Cork Sands and the Naze.

7.4 Future of the Shingle Street to Port of Felixstowe coast

- The future evolution of the shoreline between Shingle Street and East Lane depends to a large extent on the behaviour of the East Lane promontory. If it is removed or retreated then the coast would erode and release significant quantities of sediment into the system, probably to feed The Knolls and Felixstowe beaches. The shingle ridge to the north would gradually be stripped of sediment and possibly draw more sediment off Orford Spit.
- Sediment would still be transported intermittently through East Lane and across the mouth of the Deben via The Knolls.
- Under rising sea levels there is likely to be increased rollover of the shingle beaches over the low-lying marshes to the south of Shingle Street.
- Future relative sea-level rise and increased storminess are predicted to increase erosion rates along the cliffed section at Bawdsey, releasing larger quantities of fine sand and mud to the nearshore system. Most of this sediment may be lost offshore.
- With relative sea-level rise the beach on Landguard Spit may retreat, but the continued build-up of sediment behind the jetty will ensure that retreat is limited.