EAST HEAD TO PAGHAM HARBOUR, WEST SUSSEX

SCOPAC
STANDING CONFERENCE ON PROBLEMS ASSOCIATED WITH THE COASTLINE

SOUTH DOWNS COASTAL GROUP

1. INTRODUCTION

The coastal zone of the Selsey peninsula is an exceptionally complex environment, not least because the well-defined headland of Selsey Bill separates shorelines with different orientations (Photo1). Because of spatial variation in wave climate, and the effects of both planshape and submerged relief on the local tidal current system, the apex of the peninsula functions as a regionally significant boundary between adjacent sediment transport cells. The presence of offshore and nearshore banks, bars, shoals and reefs adds unusual complications to the sediment budgets of each of the several distinct littoral transport sub-systems. Exceptionally rapid erosion over at least the last five millennia has resulted in the submergence of both natural and human-modified coastal landscapes. This legacy has not been fully explored, but has generated considerable speculation over the sequence of coastal evolutionary changes.

At the shoreline, a partially swash aligned shingle storm ridge and sandy lower foreshore extends the length of Bracklesham Bay to the Chichester Harbour Inlet. The eastern side of the Selsey peninsula is fronted by a drift aligned gravel beach. The hinterland is low-lying, but elevated slightly at East Wittering and Selsey. At Medmerry, the hinterland is close to or below mean sea level and is formed of soft alluvial deposits comprising a reclaimed estuary channel. A weak to moderate net shoreline drift transports sediments from the east to west, although actual drift of shingle is presently very low due to the widespread controlling effects of groynes.

It is only within the last 50 years that the majority of this coastline has been protected by formal defences and regulated by other shoreline management practices. Artificial control of beach volumes and sediment transport pathways has not succeeded in achieving conditions of shoreline stability at all points; indeed, there are several critical locations where, in future, it may be necessary to allow for natural shoreline behavioural tendencies and relax management controls (Posford Duvivier, 2001; HR Wallingford, 1995, 1997; Cobbold and Santema, 2001).

Coastal Evolution

The Selsey coastline is developed in Eocene (principally Bracklesham Group) sandstones and clays, overlain by Quaternary drift deposits. The former provide the substrate beneath the inter-tidal foreshore and are highly erodible; prior to the construction of comprehensive "hard" defences, coastline recession rates were up to 8ma^{-1} in places. Last Interglacial (Ipswichian stage) Raised Beach deposits (Photo 2) overlie earlier Quaternary deposits (Reid, 1892; West and Sparks, 1960; West, et al. 1984 and Bates, 1998 and 2000), but their formerly extensive exposure at the shoreline is now restricted to a few localities. Late Devensian or early Holocene loamy silt ('Brickearth') overlies the Raised Beach and provides the substrate to modern soil profiles. These deposits overlie the most recent of a sequence of marine erosional platforms that extend 25km inland. They have been interpreted as the product of successive Middle Pleistocene sea-level transgressions, punctuated by regressive stages and subsequently displaced by neotectonic movements (Bates, 1998, 2000; Hodgson, 1964; Bates, Parfitt and Roberts, 1997). Further detail is contained within the separate Section on the Quaternary History of the Solent.

During the last (Devensian) cold stage, sea level was at least –50 to –60mOD, and the regional shoreline some 5-7km seawards of its present position. Subsequent Holocene sea-level rise has therefore released a substantial quantity of sediment, including gravels derived from the ancestral Coastal Plain composed of Raised Beach, Coombe Rock (periglacial) and River Solent fluviatile (terrace) materials. Some of this continues to be available as scattered deposits on the seabed, but it is thought that much lies stranded offshore within submerged barrier beaches built during several stages of mid to late Holocene sea-level transgression. Wallace (1990 and 1996) has tentatively identified the foundations of several indurated barrier structures, some of which may have originally been independent barrier islands, separated by tidal passes. Others may have become “anchored” to the predecessors of modern reefs, such as the Mixon, and once extended as far eastwards as Bognor. Strongly indurated, stable cobble “ pavements” and large boulders of local Eocene and Oligocene rocks located in water depths in excess of 8m offshore the west and south-west coastlines might be the foundations of barriers that were submerged during one or more stages of rapid sea-level rise. Others continued to be driven landwards, probably by storms, to eventually produce modern barrier forms, as at Medmerry and Church Norton beach and spit. Overstepping of relict ebb deltas, banks and shoals, adjusted to earlier sea-level stillstands, is also likely to have occurred. Bone (1996) and Wallace (1990) offer several speculative dates for barrier breaching and reformation. Part of the substantial sediment resource of earlier gravel barriers has been redistributed to modern stores such as the Kirk Arrow spit; the Inner Owers; and the Pagham Harbour spits and tidal delta. Wallace (1990 and 1996) has attempted to fit a chronology of stages of sea-level rise to the apparent evidence of barrier breaching, breakdown and submergence. Evidence of brackish and estuarine sediments offshore Medmerry does suggest the former existence of a back-barrier lagoon that formed during a phase of sea-level stability; however, knowledge of the precise distribution and age of these sediments is insufficient to provide a more specific timeframe for barrier evolution.

Archaeological and sedimentological evidence supports the reconstruction of a continuous tidal creek linking Pagham Harbour with Bracklesham Bay (Heron-Allen, 1911; Millward and Robinson, 1973; Hinchcliffe, 1988; Wallace, 1990 and 1996; Castleden, 1998; Bone, 1996; Thomas, 1998). This may date back at least 2,000 years, perhaps resulting from a major breach of an earlier Bracklesham Bay barrier beach at Medmerry (Wallace, 1990). The Medmerry barrier is believed to have reformed and breached several times during subsequent centuries; at times isolating the Selsey peninsula as an island. Archaeological evidence demonstrates that the coastline was some 2 to 3km seawards of where it is now at about 5,000 years Before the Present (Cavis-Brown, 1910; White, 1934; Wallace, 1967, 1968 and 1996; Aldsworth, 1987; Goodburn, 1987; Thomas, 1998). Coastal erosion over this period must have occurred at a rate at least as fast as that recorded for the nineteenth and first half of the twentieth centuries (May, 1966). Documentary evidence for the medieval period (Bone, 1996) also indicates rapid coastline recession, especially during major storms. The latter probably caused the Medmerry barrier to repeatedly breach and break down, although there is reliable evidence that it was in place in the mid-sixteenth century. Stratigraphy from shallow boreholes into sediments infilling the former tidal creek isolating Selsey (Hinchcliffe, 1988; Wallace, 1990) clearly indicate oscillations between lagoon and brackish water conditions. A barrier spit may have connected Selsey Island with the mainland in the sixth century AD, but was permanently removed by a storm surge of exceptional magnitude in 1048.

Reclamation of some 120 hectares of saltmarsh occupying the tidal channel between Pagham Harbour and Medmerry was achieved when the Broad Rife sluice was built in 1884 (Photo3). This was undertaken in response to back barrier flooding resulting from a large pulse of gravel drift that blocked the Medmerry exit of this stream in 1880 (Bone, 1996). Further temporary blockages occurred in 1918, 1920 and 1924 before stabilisation of its present mouth in 1930.

The approximately triangular shape of the Selsey peninsula results from the protective presence of the Mixon reef some 2.5km seawards of Selsey Bill. This feature is composed of a relatively resistant Eocene calcareous Alveolina limestone cap rock overlying Bracklesham sands and clays. Wallace (1967, 1968, 1990 and 1996) has described a well-defined valley, up to 25m in depth and scoured by tidal currents, to the immediate south of the Mixon. The Outer and Malt Owers and The Streets are smaller bedrock reefs, but other offshore banks within 3km of the modern coastline appear to be sediment accumulations. They may be relict parts of a multistage barrier structure that was progressively segmented and submerged between 2,500 and 800 years before the present (Wallace, 1990; 1996). A remnant area of lagoonal and colluvial sediment that accumulated behind this structure survives inland of East Beach. Very fast erosion of this weak material occurred in the 50 years prior to the completion of costal defences in 1960.

Wallace (1990; 1996) has speculated that the Mixon reef formed a part of the coastline in early Romano-British times. It may have “anchored” the contemporary position of the barrier beach mentioned above. A 17m deep sediment-infilled v-shaped gap between the Mixon and Malt Owers mark the course of the ancestral River Lavant. The latter is likely to have discharged via what is now Pagham Harbour prior to its diversion to Chichester and Fishbourne by Roman engineers in the second century A.D. Wallace (1990) also suggests that the proto-Lavant followed the line of the buried channel that runs roughly parallel to the modern East Beach coastline some 300-400m offshore. This feature has been largely infilled with late Holocene sediments, but continues to act as a local trap of mobile gravel during winter months. Some of this material is stabilised by weed growth during summer months, and may subsequently be transported by rafting to supply the Inner Owers and Kirk Arrow gravel accumulations. The strike-directed east to west valley south of the Mixon may also have been part of the course of an ancestral Lavant river.

Barrier breaching and shoreline recession associated with rising sea-level and storm events caused The Mixon to become an offshore bank, or shoal, probably at about 950-1050 AD (Wallace, 1990). It would have been emergent during mean low water, whilst the Inner Owers would, by this time, have been fully submerged. The Mixon therefore acquired its reef-like form and function from early medieval times onwards as sea-level rose further and both tide and wave-induced currents caused bedrock scour.

Hydrodynamics

The tidal range is 4.9m (springs) and 2.7m (neaps) at Pagham Harbour mouth and at the entrance to Chichester Harbour, with the ebb phase shorter than the flood. The early ebb stage, gives rise to rectilinear, nearshore parallel, residual currents off the east-facing coastline. This stream moves towards the banks and reefs south of the Bill, where it is confined and movement is determined by their alignment. During the peak ebb flow, movement is north/north-eastwards. Maximum surface currents offshore the of apex of the peninsula are between 1.4ms^{-1} (springs) and 0.7ms^{-1} (neaps), reducing slightly at the seabed. Tidal currents adjacent to the west/south-west facing coastline flow predominantly eastwards/south-eastwards, as indicated by both float tracking and the morphology of patches of sand waves on the seabed (HR Wallingford, 1995, 1997, 2000). The protrusion of the Selsey peninsula into this net eastwards moving tidal stream creates an anticlockwise circulating gyre, (or "back-eddy") to the north-east, where residual current speeds are between 0.3 to 0.4ms^{-1} at the peak of the flood stage. A smaller, clockwise moving eddy between The Streets reef and Kirk Arrow spit is set up when the ebb tidal flow is east to west (Wallace, 1990).

The offshore wave climate is dominated by waves from the south and south-west with periodic episodes of less energetic waves from the south-east. However, the shoreline wave climates are complex, as the east and west facing coastlines have contrasting orientations and western parts of Bracklesham Bay are partially sheltered by the Isle of Wight. Selsey Bill and East Beach are directly exposed to waves approaching from the south and east, but they also receive highly oblique refracted and diffracted swell waves that propagate from the south-west (HR Wallingford, 1992; 1995; 19987; 1998). West and north-west of Selsey Bill, dominant wave approach is from the south-west and wave crests are frequently parallel to the nearshore contours and shoreline. Bracklesham Bay is therefore a swash aligned shoreline, whereas Selsey Bill to Pagham Harbour is a classic drift aligned shoreline.

Wave shoaling and refraction is complicated by the presence of the submerged offshore reefs, shoals, banks, scarps and troughs. The Mixon, in particular, protects the southernmost shoreline from waves from the west and south-west, but the high incident angle of their approach is least modified immediately west of Selsey Bill. Wave climate for any one location on this coastline is a result of complex relationships between offshore to inshore transformation as a function of shoreface width and water depth; seabed relief; approach angles and interaction between wave and tidally induced currents in the breaker zone. Generally, waves steepen where tidal currents flow in opposition to dominant wind wave direction of approach. Overfalls at specific tidal states add further complications.

Given this complexity, it has been difficult to develop a quantitative wave climate. HR Wallingford (1995), using the TELURAY model, calculated a maximum annual wave height of 2.85m for the shoreline west of Selsey Bill, and 2.11m for the area 500m offshore of the east-facing coast. For mean inshore wave heights, Posford Duvivier (2001) re-ran HR Wallingford's (1995) data, using additional values derived from field measurements in 1998 and further refinements based on ENDEC model results (HR Wallingford, 1998). For annual recurrence, the maximum wave heights obtained were:

Inner Owers:	2.8m
South-East of Selsey Bill:	2.10m
South-West of Selsey Bill:	2.17m
West Wittering:	1.24m

Maximum significant wave heights are substantially greater than this, in the order of 15-20m for offshore waves off Selsey Bill (Hydraulics Research, 1974; HR Wallingford, 1992, 1993); HR Wallingford (1995) report maximum Hs (metres) to be: 4.6 (East Beach); 3.94 (Pagham Harbour entrance); 3.87 (Medmerry); 4.32 (East Wittering) and 1.44 (East Head). Inshore breaking wave heights, and incident angle of approach, directly control potential rates of longshore sediment transport, and are one basic explanation for the spatial variations summarised in Section 3.

Bracklesham Bay was one of the locations for which wave modelling excercises were undertaken as part of the DEFRA Futurecoast Project (Halcrow, 2002). An offshore wave climate was synthesised based on 1991-2000 data from the Met Office Wave Model and then transformed inshore to a prediction point in Bracklesham Bay at –4.34m O.D. Potential sensitivities to likely climate change scenarios were then tested by examining the extent to which the total and net longshore energy for each scenario varied with respect to the present situation. Results suggested that a one to two degree variation in wave climate direction could result in a 2-4% variation in longshore energy and confirmed that the Bay was significantly more sensitive to this factor than most other south coast locations, as might be expected of a swash aligned coastline.

2. SEDIMENT INPUTS

Two potential sources of sediment are identified for this coastline comprising offshore to onshore transport and shore erosion. These have been supplemented in recent decades by beach replenishment at several sites.

2.1 Offshore to Onshore Transport

Wave-transported sediment supply to the beaches of this coastline derives from several discrete sources, as detailed below. Tidal currents are not considered to be an independent mechanism of sustained onshore transport, but wave and tidal stream interaction creates complex patterns of turbulence that can entrain sediment.

F1 Onshore Gravel Feed From the Kirk Arrow Spit

The Kirk Arrow Spit is a mobile gravel bank with a mean volume of 20-40,000m^3 exposed at low water some 300-500 m offshore from Selsey Bill. The bank comprises mostly weed-rafted flint clasts deposited as a result of turbulence generated by interaction of waves and tidal currents off the apex of Selsey Bill (Jolliffe and Wallace 1973). The source of this material is gravel that "carpets" the sea floor south and east of Selsey Bill (see Coastal Evolution in Section 1). Some of this is so well compacted as to be immobile at bed stresses experienced here. It is believed that shingle is periodically transported onshore from the spit to feed adjacent beaches when waves approach from the south or south-west (Lewis and Duvivier 1977; Wallace 1990; Posford Duvivier, 2001). Evidence for this is mainly circumstantial and comprises reported observations and air photos. These sources suggest that beach levels opposite the spit are maintained by sudden onshore-directed influxes of shingle induced by high energy (storm) waves. A good example occurred between January and March 1999, when the beach to the west of the drift divide at Selsey benefited from a strong pulse of onshore gravel feed. This mechanism may be confirmed by the limited actual littoral drift, but substantial accretion to the north-east of Selsey Bill. However, an "outer circulation" of weed-dragged shingle may occupy an anticlockwise pathway that links several offshore banks and reefs with northern East Beach and Church Norton beach (Joliffe, 1978; Wallace, 1990). The circulation may be vital in replenishing the Kirk Arrow spit during intervals between onshore influxes. Estimations of this process are made especially complex by the fact that the main source area would appear to be a pavement-like area of well-consolidated cobbles that would not normally be disturbed by wave action. The growth of weed (kelp) holdfasts is therefore crucial to initial clast displacement, a process that will be dependant on fluctuations in water temperature, nutrient supply and other environmental controls in addition to wave and current induced stresses.

Air photos indicate gravel influxes from the bank to the shore during the periods 1959-60, 1971-72, 1986-92 and 1997-99 and corresponding extensions of the bank shoreward such that they temporarily attach to the shore. This suggests that gravel is transported onshore from the inshore end of the bank by shoaling waves approaching from the south. Lewis and Duvivier (1977) concluded that this feed occurs in pulses, separated by intervening periods of erosion, but averaged 5,000m^{3}a^{-1}. This estimate is based on the quantity of feed necessary to maintain beach levels over longer-term periods, in spite of output by littoral drift and beach drawdown under high-energy wave conditions. Gifford Associated Consultants (1997) propose the higher figure of approximately 10,000 m^3a^{-1}, but this also includes an estimate of the quantity gravel that is moved eastwards of the Selsey peninsula. HR Wallingford (1995) and Posford Duvivier (2001), using both recent and historical data, estimate that 80-85% of onshore deposition is subsequently moved rapidly eastwards, whilst the remaining 15-20% either remains in place or slowly drifts westwards.

Wallace (1990) examined accretion behind groynes constructed in 1989 at Selsey Bill and estimated 15,300 m^3 of gravel to have accumulated over a four month period (46,000 m^3a^{-1} if maintained over a year). Wallace (1990) also calculated that 5 million cubic metres of shingle have accumulated south of the entrance to Pagham Harbour since 1866, giving a mean rate of 41,677 m^3a^{-1}, a value that corresponds well with the four month estimate from 1989. The major sources are regarded as net onshore supply from both the Kirk Arrow Spit and from the nearshore Inner Owers bank (see below), and his figures would appear to include both.

It can be concluded that strong circumstantial evidence exists indicating significant but intermittent onshore transport of gravel from the Kirk Arrow Spit. The quantitative estimates of this feed are of medium reliability because it apparently occurs as high magnitude, low frequency pulses that are not easily measured. Additional information is required on the frequency, volume and duration of typical pulses, as well as on the pattern of changes in the shape and volume of the spit itself. Better knowledge is required of how it came to expand rapidly in the late 1980s to become habitually exposed during low water spring tides, thus creating a wide inter-tidal foreshore. However, during the previous three decades, it was detached and only rarely emergent. Ultimately, over a long timescale that cannot be determined at present, the Kirk Arrow Spit represents a finite source of supply, as there is a probability that its sources of replenishment will decline over time and eventually become exhausted.

F2 Onshore Feed From the Streets and Malt Owers Reefs

The Streets Reef and Malt Owers comprise two small denuded bedrock antiforms composed of a distinctive dark grey limestone. These interact with waves and a local tidal current gyre, causing turbulence, which can result in deposition of kelp-rafted gravel (Jolliffe and Wallace, 1973). Steep infacing slopes prevent offshore movement of mobile shingle, which tends to be driven along the strike of the beds by wave action and subsequently onto West Beach, Selsey (Harlow, 1980). The source of the kelp rafted gravel may derive from the “outer circulation” supplying East Beach (Wallace, 1990). Movement of kelp-rafted shingle, together with the pattern of deposition on the Streets, has been observed by divers (Jolliffe and Wallace, 1973; Jolliffe, 1978 and Wallace, 1990); thus, the reliability of this information is medium although quantitative details are lacking. This onshore wave driven feed has been deduced from observations of changes in beach volume at West Street, involving an estimated 1,000 m^3 annually (Harlow, 1980; Wallace, 1990). These volumetric calculations are based on indirect evidence and as few details of measurements are provided it is of low reliability.

F3 Onshore Feed From the Inner Owers

The Inner Owers are a series of mobile nearshore gravel banks, situated between East Beach, Selsey and Pagham Harbour inlet, which periodically migrate onshore. They are built onto the western margins the Pagham tidal delta and are characterised by a gentle offshore slope and a steeper inshore slope (Lewis and Duvivier, 1977). Their shape and form is determined by wave diffraction and refraction. Gravel is supplied to the local beaches in wave-driven pulses in a very similar way to Kirk Arrow Spit. The behaviour of these bars is analogous to that of swash bars that are widely associated with sand dominated estuaries in North America (Fitzgerald, 1996). The gravel supply process has been investigated by means of air photos and site observations (Lewis and Duvivier, 1977; Wallace, 1990). Based on estimations of the reasonably constant shape and volume of these gravel banks, observed during their migration phases, a total input of 10,000 m^3 was calculated for the period 1970-75; a longer term average input of 3,000-5,000 m^3a^{-1} is quoted by Lewis and Duvivier (1977). This process has been observed directly via diver surveys, and as its contribution to beach levels is evident, this information is regarded as of medium to high reliability. Further quantitative information is currently not available, so that research and monitoring over an appropriate timescale (at least 10 years) is necessary to determine long-term supply pathways and rates.

F4 Diffuse Weed Rafted Shingle Feed

The existence of this process was established by Jolliffe and Wallace (1973) and further confirmed by Harlow (1980). The evidence for shingle feed comprised diving observations of weed-attached shingle undergoing transport offshore and observations of beach shingle with attached holdfasts and/or kelp fronds. No further quantitative details are available.

F5 Input from the Chichester Tidal Delta

At Chichester Harbour Entrance, the ebb tidal current is of shorter duration, but significantly greater velocity, than the flood current. Net transport of all coarser bedload sediment moving into the channel is therefore offshore, thereby creating an ebb tidal delta comprising a major sediment accumulation extending up to 4km offshore (Harlow, 1980; Wallace, 1988; ABP Research and Consultancy, 2000; GeoSea Consulting, 2000). Between 1 km and 2 km offshore, the ebb tidal current diminishes and is increasingly opposed by wave action, so that shingle cannot be transported offshore beyond this point. Sand, however, can be transported further before deposition on the outer bar, some 3.0-3.5 km offshore (Webber, 1979; GeoSea Consulting, 2000). The sediment volume of the ebb tidal delta was estimated as being 25 million cubic metres by Webber (1979). Water depths over the delta are relatively shallow, particularly over the outer and inner bars (Webber, 1979; Harlow, 1980; Wallace, 1988; Geosea Consulting, 2000). Transport of sediments occurs on the delta by combined action of waves and tides with clear patterns of sorting. Sedimentological analysis of the delta deposits indicate that net transport of gravel from the tidal delta is westward resulting in accumulation in banks seaward of West Pole, Hayling Island (Harlow, 1980; GeoSea Consulting, 2000). It is uncertain whether a corresponding north-eastward pathway operates to deliver gravel from the delta back to the shore at West Wittering. By contrast, sand is more widely distributed both eastward and westward forming the outer bar deposits and a pathway of transport that operates towards West Wittering and East Head has been identified - see F6 (Webber, 1979; Harlow, 1980; GeoSea Consulting, 2000).

F6 Sand Feed from the Chichester Tidal Delta to East Head

Sand deposited on the outer Bar and East Pole Sands has the potential to be transported onshore by wave action to East Head (Webber, 1979; Harlow, 1980). Evidence for this is based upon (i) particle size variations over the tidal delta, which may involve a contribution from tidal currents during spring cycles (GeoSea Consulting, 2000); (ii) hydrographic chart evidence of up to 3m of erosion on the western margins of East Pole Sands, and 2-3m of accretion further east (ABP Research and Consultancy, 2000). This has occurred since 1923, and appears to have involved a change from a previously mobile gravel and sand surface to one, which is now stable. The latter feature was first reported by Webber (1979) and may be due to bevelling of the underlying clay substrate and its subsequent armouring by gravels.

2.2 Coast Erosion

Selsey Bill, East Beach and the coastline of Bracklesham Bay have a history of rapid erosion of low cliffs and the beach with several km being lost in historical times and a more recent maximum rate of 7.6 ma^{-1}, being recorded at East Beach, Selsey for the period 1932-51 (Duvivier, 1961; Millward and Robinson, 1973). The peninsula includes some spreads of raised beach deposits to the west and east of the Bill around Selsey. It is likely that these deposits were formerly much more extensive, but have been reduced greatly in extent as the headland has diminished. Erosion at such rapid rates necessitated installation of extensive and robust coast protection and defence structures, undertaken in the period 1945-61. These include groynes, revetments and seawalls, which have either halted cliff erosion or reduced beach losses. The only unprotected areas where natural recession of the shoreline continues are:

(i) East Head (Photo 4 and Photo 5)
(ii) A 300 m long cliff frontage from Hillfield Road to Medmerry, Selsey (Photo 2)
(iii) Several stretches between the proximal end of Church Norton spit and the Pagham Harbour inlet.

These sites are detailed below. In addition, erosion takes place across the approximately 2000m wide shoreface between Selsey Bill and East Head. Posford Duvivier (1999), using a modification of the Brunn Rule and assuming vertical erosion, principally by waves, of 1 mma^{-1} calculate an erosion yield of 19,000 m^{3}a^{-1} between Selsey and Bracklesham. This may increase slightly over the sector between East Wittering and East Head. The material released by shoreface erosion is believed to constitute fine sediments that are likely to be removed seaward in suspension.

E1 East Head see introduction to Coast Erosion

The morphological development of the East Head spit has been fully documented by Searle (1975), May (1975), Lewis and Duvivier (1977), Harlow (1980), ABP Research and Consultancy (2000) and Baily et al. (2002) (see Section 5). These studies have reported a clockwise rotation of the spit accomplished by very rapid recession of its seaward face, at 6.8 ma^{-1} during the period 1875-1896 and 2.3 ma^{-1} during the period 1896-1909. This rate had slowed by 1926 and by 1963 the spit was in approximately its present position. Although East Head as a whole has retreated very little since 1963 it cannot be regarded as stable for it was breached along its neck immediately north of "The Hinge" by a storm in 1963, was overtopped in 1987 and has experienced rapid thinning since the early 1990s (Photo 5). Its apparent stability has only been achieved by extensive use of artificial structures to stimulate dune growth (Searle, 1975; Baily et al. 2002). Most authorities agree that a combination of a spring tide and a severe storm could again breach the neck of the spit resulting in further recession and possibly its permanent breaching and ultimate destruction. Several alternative breach scenarios have been modelled and evaluated (HR Wallingford, 1995, 2000; ABP Research and Consultancy, 2000). The exact cause of the current phase of erosion at The Hinge is uncertain, but involves reductions in natural sand supply from updrift longshore and nearshore sources. An additional factor may be a continuing adjustment of cross-section of the Chichester inlet mouth to the tidal prism of the harbour (ABP Research and Consultancy, 2000). It has involved lowering since 1923 of the Winner sand and gravel bank by up to three metres allowing increased wave exposure and reducing the intertidal foreshore width in front of East Head.

E2 Hillfield Road to Medmerry see introduction to Coast Erosion

Low cliffs cut into raised beach pebble and sand deposits form a 300m long unprotected section (Photo 2) that has eroded relatively steadily at 1.09 to 1.25 ma^{-1} between 1875 and 1972 (Harlow 1980; Posford Duvivier, 1997). This rate was calculated from examination of successive OS 1:2500 map editions. Earlier maps suggest that erosion was more rapid in the period 1840-1880 (Harlow, 1980). Harlow (1979, 1980) attempted a calculation of sediment yield based on an appreciation of (i) the lithology of eroding raised beach and drift sediments, (ii) calculation of cliff height variation between successive periods over nearly one hundred years and (iii) an allowance for losses via suspended transport. He suggested that up to 1,480 m^3a^{-1} of gravel and 3,820 m^3a^{-1} of fine gravel and sand could be released and potentially contribute to the upper beach and foreshore. Posford Duvivier (1997) calculate a total supply of 1,000 m^3a^{-1} divided equally between gravel, sand and clay. Use of historical map sources coupled with Ordnance Survey maps enabled Lewis and Duvivier (1950) to calculate mean retreat at 1.34-1.82 ma^{-1} over the period 1778-1953, with a sediment yield of approximately 10,000 m^3a^{-1}. This higher rate probably reflects the more rapid erosion in the 18th and 19th centuries along a rather longer essentially undefended coastline so that the figures calculated by Harlow (1980) and Posford Duvivier (1997) are more representative of the present-day inputs. Unpublished local authority records (Lewis and Duvivier, 1950) report that between 1930 and 1952 annual rates of erosion between Medmerry and East Beach were as high as 8m. This was the highest rate recorded for any location in England during the twentieth century.

Selsey Bill see introduction to Coast Erosion

Prior to the construction of comprehensive 'hard' sea defences between 1962 and 1969 (Photo 1), much of the tip of the Selsey peninsula provided inputs of easily eroded sediment from wave-induced cliff and shoreface erosion. This has been the case for over 1300 years, thus accounting for over 2 km of coastline retreat since the second or third centuries AD (Ballard, 1910; Heron-Allen, 1911; White, 1934; Aldsworth, 1987; Wallace, 1990 and 1996; Castleden, 1996; Bone 1996; Thomas, 1998;). Shoreface erosion has accelerated over this period due to ongoing sea level rise and the lowering of protective off-shore rock outcrops. There is a rich, only partially explored, offshore archaeological legacy of submerged Romano-British, Saxon and early medieval landscape features, partially recorded in documentary and archival records (Heron-Allen, 1911; Wallace, 1990). Sediment yield derives not only from (former) rapid retreat of low cliffs, but abrasional scour of the complementary, expanding, shoreface platform. Hydraulics Research (1995) estimated that rapid erosion between 1850 and 1950 could have released as much as 2 million m^3 of gravel from raised beach deposits. Much of this resource has now become exhausted as the headland has diminished. Lewis and Duvivier (1977) calculate an annual volume of 7,500 m^3 of shingle for 1909-1962, feeding East Beach, Selsey. The quantity of sand was, and may continue to be, substantially greater, but is too fine to be retained on local beaches.

East Beach, Selsey see introduction to Coast Erosion

Posford Duvivier (2001) calculated that approximately 150m of recession of mean low water occurred between 1900 and 1950, with substantial beach drawdown and erosional loss along this south-east orientated shoreline. Losses could not be compensated by updrift littoral or nearshore transport, although some fresh supply of shingle may have derived from erosion of Raised Beach deposits periodically exposed in the back and mid shore areas. A series of successively landward relocations of the Lifeboat Station, 1909-1960, are described by Wallace (1990).

Church Norton and Pagham Harbour Inlet see introduction to Coast Erosion

Several specific sites have recorded past and recent beach erosion, considered (Gifford Associated Consultants, 1997; Posford Duvivier, 2001) to be between 4,000 and 8,000 m^3a^{-1}. These constitute changes in the beach sediment store and are not specifically regarded as inputs. Routine nourishment of the beach fronting Church Norton spit has taken place since the early 1980s to offset this loss and thus maintain the stability and integrity of Pagham Harbour.

2.3 Beach Nourishment and Re-cycling

Medmerry

The Environment Agency and its predecessors have conducted a long-term nourishment and re-profiling scheme at the critical Medmerry barrier beach site (Environment Agency, 1998a). This structure has a long history of intermittent landward migration. Its present form dates to approximately 1600, when it was reported to have blocked a former tidal inlet channel. Subsequently, it has breached and reformed on several occasions (Bone, 1996). However, in recent years it has exhibited increasing instability, and has experienced regular cutbacks, overtopping and breaching. It has necessitated increasingly urgent nourishment and profile reconstruction in order to maintain the present defence line (Photo 6 and Photo 7). This sector of beach is in a condition of chronic disequilibrium, unable to adjust to natural gravel losses and foreshore lowering. HR Wallingford (1995) demonstrate that it is located at a focal point for wave erosion due to refraction induced by complex offshore relief. The initial nourishment was in 1976 and comprised a pilot scheme involving deposition of 14,500m^3 shingle and extension of groynes to LWM. The main phase was conducted between 1976 and 1980, with the addition of 225,000m^3 of gravel obtained from inland gravel pits and delivered by truck to build the berm. This was preferred to dredged marine gravels that could be deposited on the lower foreshore because Hydraulics Research (1974) were unable to confirm that this material would move onshore. The nourishment material comprised nodular flint gravels significantly coarser and more angular than the indigenous beach material. The scheme also involved insertion of 38 groynes along a 3.8 km frontage and their extension to MLWST. The artificial beach was re-profiled to a slope of 1:10, with gravel that accumulated at the most westerly downdrift groyne subsequently being recycled updrift. Further replenishment and crest elevation was completed between 1989 and 1996, involving some 90,000m^3 to compensate for losses of 102,000m^3 over the period 1974-1992 (HR Wallingford, 1995; Environment Agency, 1998a). Several major storm surges during the winters of 1998-9, 2000-1, 2001-2 caused overwashing, crest lowering, beach drawdown, with a 300m breach in 1999. This has necessitated the emergency dumping (Photo 7) of over 500,000m^3 of gravel (again taken from inland sources), together with profile reconstruction. By the mid-1990s the groyne field had deteriorated and was virtually redundant as a mechanism for beach sediment conservation. A modest managed re-alignment of this barrier structure has been proposed (Posford Duvivier, 2001) as the only morphodynamically sustainable strategic defence option for this site. However, even if adopted, this would not avoid the need for future re-nourishment and control, albeit on a less intense basis dependent on distance of set back relocation.

Church Norton Spit

The beach fronting the southern (Church Norton) spit, protecting the entrance to Pagham Harbour, is replenished by routine artificial cycling of gravel, taken from the adjacent nearshore banks of the Pagham tidal delta, south-west of the inlet and from the Inner Owers. Since the early 1990s, this has averaged 15,000m^3a^{-1}, but reliable figures for the previous decade are not available. Profile reconstruction is also carried out as part of this routine practice.

3. LITTORAL TRANSPORT AND BEACH DRIFT

The longshore drift system involves both gravel and sand, but a significant quantity of fine sand is probably removed in suspension directly offshore (Posford Duvivier, 1999). Tidal gyres either side of Selsey Bill created by the intrusion of the headland into the pattern of rectilinear eastwards moving residual currents may result in locally complex transport of fines by tidal streams towards (i) East Beach and (ii) Medmerry Bank (Paphitis, et al., 2000; HR Wallingford, 1995; Gifford Associated Consultants, 1997). The littoral transport system is dominated by the influence of shoaling and breaking waves. Although there are well defined net transport pathways, short-term reversals occur, especially along the swash-aligned shoreline between between Selsey Bill and East Head (HR Wallingford, 1995). Monitoring of beach levels has revealed significant fluctuations in annual drift rates since the early 1970s (Posford Duvivier, 2001; HR Wallingford, 1995, 1998).

LT1 Bracklesham Bay (Selsey to West Wittering)

All authors agree that net drift of gravel is westward from West Street, Selsey to East Head. Lewis and Duvivier (1950) and Duvivier (1961) based this on visual observations and a wind vector analysis of 7 years of records from Thorney Island. Hydraulics Research (1974) derived the same conclusion from shingle tracer experiments undertaken over a 6 month period, and Harlow (1980) and Lewis and Duvivier (1977) estimated drift on the basis of beach volume and shoreline changes since 1868. However, detailed observations and transport modelling studies based on hindcast wave climates have revealed short-term and short distance reversal of the net drift direction as a result of varying incident wave approach (Posford Duvivier, 1992, 2001). Sensitivity to wave approach direction and the capacity for drift reversals are high because Bracklesham Bay is a swash-aligned shoreline (Halcrow, 2002).

Quantitative analysis has been attempted by assuming littoral drift to be the minimum sediment volume required to explain observed beach volume trends. Using this technique Harlow (1980) calculated a drift rate (all sediment grades) of 35-40,000 m^3a^{-1} for the period 1965-1973; 40-50,0000 m^3a^{-1} for 1933-65, but only 1,000-8,000 m^3a^{-1} for the period 1973-77. Between 1846 and 1896 it is estimated to have been of the order of 70,000 m^3a^{-1}. A present day mean drift volume of between 2,800 and 7,000 m^3a^{-1} is suggested for this unit as a whole (Posford Duvivier, 2001; ABP Research and Consultancy, 2000). The potential drift rate at West Beach, Selsey is 15,000-16,000 m^3a^{-1}, declining to 2-6,000 m^3a^{-1} at Bracklesham (Photo 8), because of the reduction in wave approach angle north-westwards (HR Wallingford, 1995, 1997). These, however, are net values, so that given the frequency of drift reversal, gross values are considerably higher. It should be noted that the lower rates of drift associated with more recent decades mostly reflect the role of defence structures in reducing fresh sediment inputs and intercepting transport.

Erosion of the proximal end of East Head spit since the mid 1990s suggests that the input of sediment via littoral drift updrift of the terminal groyne is virtually zero, although a net westwards drift here of 7,000m^3a^{-1} is suggested by Webber (1979), revised downwards by HR Wallingford (1995) to 2,600m^3a^{-1}. Through time, the drift rate has steadily fallen, a feature attributed both to fluctuations in the volume of onshore feed at Selsey and the effects of progressively more robust and comprehensive coastal protection structures in reducing supply from coast erosion and arresting beach drift. Lewis and Duvivier (1977), HR Wallingford (1995) and Posford Duvivier (1992, 2001) calculated a prevailing natural drift for the upper gravel beach of 2,000-5,000m^{3}a^{-1} downdrift of Medmerry, but added that this figure was only valid for the ungroyned coast; thus a negligible net drift rate of 300-500m^{3}a^{-1} was considered more realistic for the heavily groyned East Wittering to Bracklesham frontage (Photo 9) and 1,000-2,000m^{3}a^{-1} at West Beach, Selsey. In general, drift rates on this shoreline are determined by sediment availability and the condition of groynes, as deteriorating or overflowing structures can locally increase throughput for limited periods. Significant interruption to upper beach transport occurs at outfall sites, particularly Broad Rife (Photo 3), leading to immediate downdrift starvation. Thus, the downdrift benefits of the substantial gravel recharges of Medmerry beach have been surprisingly modest. Cross-shore rather than long-shore fluctuations have been dominant at Medmerry, varying between annual gains of up to 40,000m^3 to annual losses of over 60,000m^3 (net loss of 17,000m^{3}a^{-1} since 1974).

Volumetric assessments of littoral transport are based on minimum net drift values derived from assessing inter-tidal beach changes. Throughput, which causes no discernable beach volume change, cannot be detected so that absolute drift rates could be significantly greater. Modelling studies more effectively identify the natural littoral drift potential, such rates cannot be achieved due to the effects of groynes diverting sediments into storage.

LT2 Selsey Bill to Pagham Harbour

Littoral drift of gravel is from Selsey Bill north-eastwards to the entrance to Pagham Harbour (Photo 1). The main evidence for this comprises inter-tidal beach level observations and analysis of volume changes (Lewis and Duvivier, 1955; Duvivier, 1960; Wallace, 1990; HR Wallingford, 1995; Gifford Associated Consultants, 1997; Posford Duvivier, 2001) (see Section 5). Littoral drift pathways therefore diverge in the vicinity of Selsey Bill. Detailed analysis of maps, air photos and beach level measurements and observations in groyne compartments enabled Lewis and Duvivier (1976), Harlow (1980), HR Wallingford (1995, 1997) and Posford Duvivier (2001) to locate this regionally significant drift divide between Warner Road (net westward drift) and Hillfield Road (net eastward drift). At this point, groynes and a seawall have been constructed, either side of which erosion has occurred, thus forming an artificial headland. Between Hillfield Road and Selsey Bill the eastward drift rate is low as the beach is aligned closely to the dominant wave approach (Lewis and Duvivier 1977; Posford Duvivier, 2001). Immediately north-east of Selsey Bill the potential for drift is much greater due to the sudden change in shoreline orientation to face south-east. Beach drift is also hindered in the vicinity of the Bill by the seawall and numerous groynes, but periodic offshore to onshore influxes of gravel become piled against their west sides by the prevailing drift, so that overtopping and outflanking occurs. The eastern sides of groyne compartments are usually depleted, so that the operation of any significant counter (westward) drift is unlikely. However, the precise position of the drift divide fluctuates up to 300-400m, depending on prevailing wave conditions. Thus, the Bill operates as a “one way valve” facilitating net eastward gravel transport (Lewis and Duvivier, 1977; Posford Duvivier, 2001). Estimations of rates of drift have involved both assessments of changes in beach volumes and transport modelling approaches based on hindcast wave climates. The most effective studies have sought to compare the results of the two techniques. Studies have either focussed upon accretion of the Church Norton Spit (Photo 10), or upon beach volume changes throughout the pathway as follows:

Church Norton Spit Growth

The approach involves measurement of accretion immediately south of Pagham Harbour entrance and attribution of all material accumulating to littoral drift from Selsey and East Beach. Wallace (1990) determined a mean drift rate of 41,500m^{3}a^{-1} over the period 1866-1989, with a maximum of 76,000m^{3}a^{-1} in 1962. Lewis and Duvivier (1977) calculated the marginally higher potential rate of 50,000m^{3}a^{-1} for the period 1875-1909. Modelling using the LITPACK numerical model (Gifford Associated Consultants, 1997) suggests drift of 71,000m^{3}a^{-1} for all sediment grades Both studies neglect possible direct inputs to beaches flanking Pagham Harbour inlet from sources such as offshore gravel banks, and so probably overestimate actual drift rates. Their approaches also fail to allow for variations in supply resulting from both periodic upgrading of groynes and recharge operations. HR Wallingford (1995) calculated a drift rate of 33,000m^{3}a^{-1} for East Beach, reducing to 8,000ma^{-1} when adjusted for assumed groyne efficiency in their model studies. For Selsey Bill, their equivalent figures are 13,700 and 5,500m^{3}a^{-1}. Barcock and Collins (1991) have re-calculated the prevailing drift rate between East Beach and Pagham Harbour entrance to be between 24,000 and 42,000m^{3}a^{-1}. This is based data on the frequency distribution of wave heights and approach directions and considers sediment exchanges with Pagham tidal delta. Using HR Wallingford's (1995) DRCALC model, updated by later wave climate information, Posford Duvivier (2001) propose a potential drift rate of 32,000m^{3}a^{-1}. Actual rates are considered to be 25-30% of the above volumes because of the role of groynes.

Beach Volume Changes from Selsey Bill to Church Norton

The approach involves estimation of drift from a consideration of all beach volume changes between Selsey Bill and Church Norton. Using this approach Wallace (1990) recorded movement of 15,300 m^3 in 4 months at Selsey Bill, and Lewis and Duvivier (1977) deduced an average input close to Selsey Bill of 5,000-6,000m^{3}a^{-1} (1959-75) composed mainly of pulses of gravel onshore from the Kirk Arrow Spit. Posford Duvivier (2001) estimated a drift rate of 13,700m^{3}a^{-1} at Selsey, reducing to 5,500m^{3}a^{-1} once groyne performance is factored in. Drift potential was found to increase north-eastwards on East Beach, where it is between 15,000 and 25,000m^{3}a^{-1}. Much of this beach frontage is managed, so that actual drift depends on groyne performance and sediment availability. HR Wallingford (1995, 1997) state that a mean quantity of 5,000m^{3}a^{-1} is supplied from the Kirk Arrow Spit and is augmented by a further 5,000m^{3}a^{-1} from the Inner Owers, giving a total drift potential of 25-30,000m^{3}a^{-1}. This figure is based on the fact that on formerly unprotected stretches erosion of up to 10,000m^{3}a^{-1} occurred to maintain drift rates; it corresponds closely with the estimated gravel input from erosion behind East Beach before coast protection. The sediment supply and transport system had previously achieved an equilibrium so that no net beach erosion occurred between East Beach and Church Norton. Terminal scour and thus some downdrift starvation has been a significant past problem at the north-east end of this protected frontage. HR Wallingford (1995) use a modelling approach informed by measured beach level changes to calculate drift to be approximately 32,000m^{3}a^{-1} along the Church Norton spit, although the rate is less than 17,000m^{3}a^{-1} for the upper gravel beach alone.

Overall, there is some variation in rates of processes along this complex frontage and numerous alternative estimates of drift have been produced. There is some consensus that potential drift in recent decades of all sediments approximates to around 30,000m^{3}a^{-1} with actual drift being in the range 7,000 to 11,000m^{3}a^{-1} being controlled by beach management practices. The mean rates reported above make assumptions on the magnitude and frequency of pulses of supply and the overtopping of groynes. Despite this, the overall pattern and volume of drift has been established at medium to high reliability with moderate to good correspondence between modelled and observed processes.

The effect of sustained long-term unidirectional north-east drift along this sector, over at least the last millennia, has been to deliver much sediment to build the southern spit that helps to define the entrance to Pagham Harbour (Photo 10). It has a history of fluctuation, thus indicating temporal variation in littoral and offshore drift supply (see Section 5). It is currently in a phase of depletion, but potential erosion losses are offset by deliberate cycling of gravel from co-extensive nearshore bars, at a rate of approximately 11,000m^3a^{-1} since the late 1980s. The northern (Pagham) spit is the product of a local 'counter' drift, resulting from a transport divide some 2000m north-east of the harbour entrance. This itself is the outcome of interaction between tidal currents generated by the inlet and complex wave refraction over the Pagham tidal delta (Geodata Institute, 1994). With a maximum SW drift throughput of 5,000m^3a^{-1} (Barcock and Collins, 1991; Collins, et al., 1995), this northern spit has had less capacity for growth and change than its southern counterpart.

Offshore tidal current transport of sand, inferred from sample surveys of bedforms and numerical modelling (Barcock and Collins, 1991) is considered to be towards the south-west, or west, in water depths of less than 15m.

LT3 Reversed Littoral Drift of Sand in Bracklesham Bay

Experiments employing fluorescent sand and shingle tracers at Medmerry (Hydraulics Research, 1974) have indicated that sand transport may be reversed on the lower foreshore, seaward of groynes, due to strong eastward residual tidal currents. Any reversal was, however, considered to be local to the study site because the westward tidal current increases in velocity west from Medmerry so inducing net sand transport westward to East Wittering; a transport divide may therefore exist in the vicinity of Bracklesham. The tracer experiments were only conducted over a 6 month period so it is possible they were unrepresentative of typical conditions. The experiments offer the only direct information on this component of sediment transport, although HR Wallingford (1995) state that an anticlockwise circulating tidal eddy exists outside the entrance to Chichester Harbour that transports sand from the foreshore between East and West Wittering onto East Pole Sands. Other studies fail to acknowledge such a net drift reversal and Lewis and Duvivier (1977) argued that all sand transport on the lower foreshore was, on balance, westward (i.e. in the same direction as the shingle of the upper foreshore). Their evidence was sand distribution observed within groyne compartments, analysis of residual offshore currents, and the lack of sand at Selsey contrasted with its abundance at East Pole Sands and East Head. Modelling by HR Wallingford (1995) computed the transport rate for sand to be some 25,000$m^3a^{-1}$from east to west

LT4 Drift Divergence North of Pagham Harbour Entrance

A local reversal of drift occurs at the eastern boundary of this frontage for the net direction of drift immediately east of Pagham Harbour inlet is considered to be westwards over a 500-700m long frontage at an approximate rate of 5,000m^3a^{-1}. The Pagham Harbour ebb tidal delta and wide, accreting foreshore sets up complex local wave refraction and provides protection against the dominant south-westerly waves enabling a very local dominance of south-easterly waves (Barcock and Collins, 1991; Gifford Associated Consultants, 1997; Posford Duvivier, 2001). A drift divide marked by a zone of persistent beach erosion is therefore identified in the vicinity of Pagham Beach estate (Wallace, 1990; Posford Duvivier, 2001).

4. SEDIMENT OUTPUTS

4.1 Estuarine Outputs

EO1 Chichester Harbour Entrance

Eastward shoreline drift from Hayling Island and westward drift from West Wittering and East Head converge at the harbour entrance (Photo 11). Sand and gravels entering the Chichester tidal channel are flushed offshore by the strong ebb residual tidal current and deposited at varying distances from the entrance depending upon sediment size, wave conditions and water depth. This is confined by the orientation and shape of bar topography (HR Wallingford, 2000) and sediment trend analysis (Geosea Consulting, 2000). Gravel can be transported a maximum of 2km offshore and sand a maximum of 3.5km offshore (Webber, 1979). The result of this offshore flushing of sediments has been the accumulation of some 25 million cubic metres of sediment within a major ebb tidal delta (Webber, 1979). Sediment sampling by Harlow (1980) and GeoSea Consulting (2000) revealed a series of sedimentary zones and potential transport pathways, suggesting that wave action can mobilise sediments on the tidal delta and drive them back shoreward towards Eastoke, Hayling and West Wittering. The net result of these processes appears to be an anticlockwise circulation in the east of Chichester entrance as reported by ABP Research and Consultancy (2000). Part of this circulation is depicted in Photo 11.

The volume of sediment transported and deposited offshore by tidal currents has not been calculated, but fresh supply to the tidal delta could be estimated from littoral drift inputs at the entrance. Drift inputs to the tidal channel were undoubtedly greater in the past (over $70,000m^3a^{-1}$), but have substantially declined over the past 100 years as coast protection has intercepted and reduced drift along the shoreline of Bracklesham Bay (Harlow, 1980; Posford Duvivier, 2001). Not only have inputs to the delta reduced, but losses due to dredging of Chichester bar have increased since 1973 (see Section 4.2). In fact, analyses of bathymetric data have suggested that the ebb tidal delta suffered a net loss of 1.4 million cubic metres from 1974 to 2000 (Posford Duvivier, 2001).

The rotation and recession of East Head during the nineteenth century (Section 5.3) caused the formerly deep entrance channel close to the east shore of Hayling Island widen eastwards along a north to south axis, thus reducing the Winner Bank. This may continue a long-term trend, as the absence of drift deposits beneath Sandy Point (Hayling Island) suggests that the harbour channel was further west at least two or three millennia Before the Present.

Analysis of the hydraulic regime at the entrance channel, via hydrodynamic modelling (ABP Research and Consultancy, 2000; HR Wallingford, 1998) has shown that there has been a rather variable pattern of channel narrowing and deepening; widening and shallowing since the mid-nineteenth century. The channel initially decreased in size, as the Winner bank accreted, 1887-1923; but overall, given the rotation and retreat of East Head and subsequent lowering of the Winner, the cross-sectional area of the channel has increased over the last 150 years. This suggests that it is adjusting towards a new equilibrium condition, but is below its optimum cross-sectional area given the tidal prism of Chichester Harbour. It stimulates the suggestion (ABP Research and Consultancy, 2000) that the harbour mouth has adjusted, or is adjusting, to a change from a wave-dominated littoral transport fed sediment budget to one which is controlled more strongly by tidal currents.

EO2 Pagham Harbour Entrance

Currents generated by tidal exchange at the Pagham Harbour entrance are effective in interrupting littoral drift (Photo 10). As at Chichester Harbour entrance, the ebb current (1.0-1.5ms^{-1}) is more powerful than the flood (0.4ms^{-1}) so sediment movement into the entrance channel by littoral drift is mostly flushed seaward to a significant ebb tidal delta (Barcock and Collins, 1991). Between 30-75,000m^{3}a^{-1} is potentially available at the entrance to the harbour comprising convergent longshore transport from the south-west and north-east. A proportion of this becomes stored in the beaches that make up the twin spits, potentially leaving around 24-40,000m^{3}a^{-1} to enter the entrance channel (Gifford Associated Consultants, 1997). Based on an assumption of bedload transport rate at the harbour entrance and calculation of the tidal prism, output to the delta by ebb current flushing is likely to be between 16-40,000m^{3}a^{-1} (Gifford Associated Consultants, 1997). However, a significant proportion of this quantity represents material introduced into the entrance channel by wave transport of gravel and coarse sand from landward migrating offshore banks that are already components of the tidal delta (Geodata Institute, 1994; Barcock and Collins, 1991).

Ebb tidal currents are moderate and their influence does not extend very far seaward compared to those generated at the much larger Chichester Harbour. Wave action is modified by local refraction induced by complex bathymetry, but HR Wallingford (1993) calculated a mean significant wave height of 1m, and a maximum of 4.5m, at Pagham Harbour Entrance. Wave induced currents oppose seaward transport and tend to drive material back landward where ebb tidal currents are weak. A consequence is that the ebb tidal delta is located close to the inlet and is relatively small. Sediment therefore has a short residence time within the delta and is liable to being driven back ashore within swash bars to the west and east of the inlet.

Net seaward discharge that generates accretion of the ebb tidal delta at Pagham entrance is in the order of 16,000m^{3}a^{-1} representing the balance estimated between landwards (flood tide and wave-driven) input of 18,000m^{3}a^{-1}, and seawards removal of 34,000m^{3}a^{-1} (Geodata Institute, 1994).

Flushing processes and the ebb delta sediment budget have undoubtedly changed over the past four centuries due to reduction of the tidal prism of the harbour as a consequence of land claim. The earliest record of this process is in 1580, with the first major flood ebmbankment constructed in 1637 (Brown, 1981; Cavis-Brown, 1910; Graves, 1981; Environment Agency, 1998). Approximately 1.26km^2 were reclaimed between 1672 and 1809 and the remainder was reclaimed in 1877. Breaching in 1910 led to rapid inundation of the present harbour area of 2.83km^2. It can be postulated that the ebb tidal would have reduced in size and area as the tidal prism was reduced and it is likely that much sediment was driven ashore from 1876 to 1910 when there was no active inlet.

4.2 Dredging

Dredging across Chichester Bar, on the ebb tidal delta, is carried out routinely to maintain a channel for navigation; some of the material is used for beach renourishment on south-east Hayling Island. Dredging for aggregates, on a small scale on The Winner, was carried out between the early nineteenth century and about 1920. Dredging for navigation access, however, did not become significant until 1973.

A total of 600,00m^3 of gravel was thus removed over the period 1974-1982 (Harlow, 1985) and between 1988-1996 dredging was permitted up to an annual limit of 20,000 tonnes (12,500m^{3}a^{-1}). Analysis of hydrographic surveys indicated that water depths increased over the dredged area in the 1970s (Webber, 1979). Despite this, it was difficult to attribute this change solely to dredging because the Chichester tidal delta is a large sediment reservoir (25 million m^3) characterised by major natural internal fluctuations and sediment redistribution (ABP Research and Consultancy, 2000). From bathymetric information (Posford Duvivier, 2001) it can be concluded that the Chichester tidal delta has more recently lost material due to reduction of littoral supply from Bracklesham Bay in combination with outputs by dredging. For the period 1974 to 2000 this can be estimated at 1.4 million cubic metres. This quantity is quite significant in comparison to the total estimated volume of the delta, particularly when it is considered that the bulk of output comprises gravel from the inner bar whilst much of the estimated stored volume comprises sand on the outer bar. Continued dredging and onshore feed might therefore be expected to deplete reserves, such that natural onshore feed could reduce in the near future (or may already have done so).

5. SEDIMENT STORES

Sediments are stored along this shoreline within its beaches, spits and within ebb tidal deltas associated with harbour inlets.

5.1 Beach Morphology and Sedimentology

Along much of this coast the upper beaches are steep and composed of flint gravel, whilst the lower foreshore has a relatively shallow slope and is composed of medium and fine sand (Hydraulics Research, 1974; Lewis and Duvivier, 1977; Harlow, 1980; Posford Duvivier, 2001). Patchy gravel frequently overlies foreshore sand, which in turn normally conceals the sandy clays of the Eocene Bracklesham Series. The main beach morphodynamic and sedimentary features are distinctive along the several discrete sectors of this coastline, namely:

(i) **East Head**: The seaward side is composed of a wide gently sloping sandy foreshore (ABP Research and Consultancy, 2000), which narrows abruptly at the point of distal curvature. Here, a steep convex shingle beach has become a more established feature in recent years, and may represent the re-exposure of the original shingle platform on which the spit has been developed. A very narrow shingle backshore beach at The Hinge has been eliminated by recent erosion, but has been retained immediately updrift by groynes.

(ii) **Bracklesham Bay**: Beach crest levels are typically maintained at around 5.4m above Ordnance Datum (AOD). An exception to this is along and immediately west of the Medmerry frontage (Photo 6) where maximum levels exceed 6m AOD due to artificial profile reconstruction or "beach scraping" (Harlow, 1980; Hydraulics Research, 1974; Posford Duvivier, 2001). Beach width decreases south-eastwards whilst the slope of both the upper and lower foreshore increases north-westwards. Beach sediment sampling between 1km west of Selsey Bill and 0.5km east of Bracklesham indicated that backshore pebbles were generally larger than those on the foreshore and at Bracklesham (Photo 8) mean size was larger than at Selsey (Cole, 1980). No statistically significant sorting trends were detected across the profiles other than for size. Although the measurements and analyses were carried out carefully, the spatial extent of sampling was limited and the temporal variability of the beach sediments was not considered in this study. Harlow (1980) sampled beach sediments from 124 sites between Gilkicker Point (Gosport) and Selsey Bill. Surface sediment samples were collected after a storm affecting the shoreline between East Wittering and Selsey in an attempt to describe the form to which the beach is tending in response to dominant waves. He noted that: (a) gravels on both the upper storm beach and the mixed midbeach increase in size from east to west. (b) Medium sand on the midbeach showed limited coarsening westward from Selsey Bill. (c) Fine to medium sand on the lower foreshore showed no sorting trend. It should be noted that the sedimentology of this beach would have been affected considerably by the numerous beach replenishments and beach scraping undertaken for coastal defence

(iii) **West Beach, Selsey and Selsey Bill**: The beach is generally narrower and steeper than the Bracklesham Bay frontage and is backed by hard defences. It is usually fairly empty of gravel in the vicinity of Hillfield Road (the littoral drift divide), but gravel accumulations increase both eastward and westward from this point (Lewis and Duvivier, 1977). Sand is only of significance at the lower beach fronting Selsey Bill, though it is not a constant feature (HR Wallingford, 1997).

(iv) **East Beach, Selsey**: The beach has been frequently described as dominantly gravel, and steeper and narrower than West Beach (Duvivier, 1961; Hydraulics Research, 1974; Posford Duvivier, 2001). Immediately east of Selsey Bill, Lewis and Duvivier (1977) reported that the beach was composed of loose gravel sloping steeply down to a gravely pavement near or below LWMST. Further north-east, a variable proportion of sand was an impersistent feature of the lower foreshore. In this vicinity there were exposures of clay and other in-situ strata after winter storms, which tended to be concealed in summer by renewed beach accretion. Mean grain size is reported to increase rapidly northwards for the sandy-gravels of the foreshore, suggesting selective longshore transport, but is fairly constant for the upper beach (Gifford Associated Consultants, 1997). Quantitative analysis of beach sediments has not been undertaken, although Duvivier (1964) noted that Selsey Beach consisted predominantly of rounded flint clasts. Attrition tests were carried out by placing weighed samples in a revolving steel drum and re-weighing and resieving the residue at intervals. This technique established that attrition rate was inversely related to pebble size.

(v) **Church Norton and the Pagham Entrance Spits**: The beach at Church Norton is composed mostly of flint shingle (Lewis and Duvivier, 1977; Wallace, 1990; Posford Duvivier, 2001). Barcock and Collins (1991) report that Pagham Beach (the north eastern shingle spit) consists of a steep upper beach, a shallower mid-beach, and an extensive low gradient foreshore. This beach is mostly flint gravel, but grades to coarse sand and granules on the lower foreshore. The series of closely-spaced ridges that make up much of the Church Norton and spit beaches may result from the bifurcation of the ebb channel immediately seaward of the harbour entrance. The abandoned channel then fills with gravel, forming a linear bank that subsequently migrates on shore. Repetition of this process creates the pattern of multiple ridges (Barcock and Collins, 1991). Beach morphology along this sector has been considerably modified by nourishment and profile reconstruction.

5.2 Beach Volumes

Volumetric information has been collected by a variety of sources and covers most of the area:

(i) **East Head.** The total volume of material (sand and gravel) comprising the inter-tidal beaches of East Head has been calculated for a variety of dates using MHW and MLW on successive OS maps (Harlow, 1980). Its volume was 499,400m^3 in 1846, increased to 894,000m^3 by 1965, and remained stable up to 1975. The total volume of sand comprising the entire spit and dune system exceeds 2.2 million m^3 (ABP Research and Consultancy, 2000), but there are no recent calculations of beach volume alone. The volume of gravel on East Head beach was calculated independently by Webber (1978) and Jarosz (1979). Webber measured 7 profiles and estimated volume at 22,000m^3, while Jarosz measured 3 profiles and estimated volume at 21,183m^3. Direct measurement of sediment thickness (depth) was not employed in either of these investigations thus the volumes quoted are approximate. The similarity of estimates by Jarosz and Webber suggests the quoted volumes may be representative, but the study by Harlow (1980) indicated that inter-tidal sediment volume can vary greatly at East Head according to incident winds and waves. The foreshore of the Winner in front of East Head has eroded and lowered by up to 3m since 1923 (ABP Research and Consultancy, 2000).

(ii) **West Wittering to West Beach, Selsey.** A series of profiles were measured at monthly intervals along this frontage by Hydraulics Research (1974). Beach volume was calculated above 0.16m OD, a level equivalent to the toe of Medmerry Beach. Calculated beach volumes revealed seasonal variations, with significantly larger volumes in summer. Mean quantities (i.e. inter-annual values) were:

West Wittering:	135,000m^3
East Wittering:	167,000m^3
Medmerry:	450,000m^3
West Beach, Selsey:	30,000m^3

Distinction was not made between gravel and sand, for the two were frequently intermixed on the foreshore and their relative proportions at depth were unknown. The temporal representativeness of these volumes was moderate to low because profiles were only measured during a 9 month period, insufficient to include exposure to the full range of wave energy states. Severe winter storms were observed to remove all foreshore sediment and expose the underlying substrate to wave abrasion (Lewis and Duvivier, 1977). However, much of this material was recovered during the following summer so that the operation of seasonal "cut" and "fill" cycles is likely to be an inherent feature of this sector of coastline.

Analysis of beach levels, 1973-1995 (HR Wallingford, 1995 and Gifford Associated Consultants, 1997) using Environment Agency ABMS profiles revealed that the upper gravel beach was narrow at Bracklesham (Photo 8), and did not appear to derive much benefit from up-drift replenishment. Further north-west it was more substantial, although there were site-specific variations in width and height reflecting groyne trapping efficiency. The lower foreshore appeared to have maintained its form, but levels dropped progressively throughout the above period, especially at West Wittering, Bracklesham and Medmerry. High rates of volume loss and profile flattening along the Medmerry frontage, associated with storm waves, have been offset by intensive renourishment and reprofiling (see Section 2.3). This has been especially marked in the late 1990s (Posford Duvivier, 2001).

(iii) **Selsey Bill**. HR Wallingford (1995), using ABMS extending data back to 1973, identifed a steady lowering of foreshore levels, particularly west of Hillfield Road. At this point, and north-west to West Beach, there is no direct feed from the Kirk Arrow Spit. The narrow depleted strip of upper gravel beach is also a result of wave reflection from backing seawalls. Further east, towards and at Selsey Bill, the shoreline is less exposed to waves from a wide approach sector. This is apparent from the comparatively wide mixed shingle and sand beach, though substantial drawdown occurs when there are incident waves from the south-east. The foreshore close to the Bill (Photo 1) has tended to resist the trend towards depletion, showing some modest accretion in recent years probably due to receipt of influxes of gravel from the Kirk

Arrow Spit since 1997 (Posford Duvivier, 2001). HR Wallingford (1995) calculated an overall upper beach gravel loss of 1,000 m^3 for 1973 to 1992 prior to the recent gravel influxes. Hydraulics Research (1974) calculated that the beach at Selsey Bill (Hillfield Road) stored some $65{,}000m^3$ of sediment; this is a mean value that accounted for seasonal fluctuation.

(iv) **East Beach, Selsey**. Lewis and Duvivier (1977) note that beach volume is variable spatially and temporally, but estimate that $50{,}000$-$55{,}000m^3$ of material is permanently retained on the beach. This calculation was undertaken using aerial photographs (1972-75) and beach morphology observations. Analysis is complicated by the fact that there are significant differences in beach levels north and south of the lifeboat station. Gifford Associated Consultants (1997) calculated a net loss of $40{,}000m^3a^{-1}$, 1972-1992, for the entire sector between Selsey Bill and Pagham Harbour entrance, based on application of the LITPAK numerical model. For East Beach alone, a loss of $6{,}000m^3a^{-1}$ was derived from analysis of ABMS beach profiles for the same period (HR Wallingford, 1995). Taking into account the complexities of loss and gain on this beach, especially nearshore and inshore exchanges and the retention of gravel by closely-spaced groynes, annual depletion over this period is considered to be close to $4{,}000m^3a^{-1}$. This, however, is substantially less than the rate of loss between 1900 and 1950, when recession at about $3ma^{-1}$ occurred prior to the construction of defences. During this period, underlying Raised Beach deposits were intermittently exposed, thus adding to sediment supply and helping to offset losses (Posford Duvivier, 2001). Under present hold the line policies this source is no longer available.

A number of specific locations on East Beach, Selsey, involving both upper and lower beaches, have exhibited net depletion and lowering over the most recent 30 years (HR Wallingford, 1995). However, profiles at Inner Owers and Church Norton have been characterised since the early 1900s by net periodic accretion at rates of up to $4{,}800m^3a^{-1}$ ($100{,}000m^3$ between 1970 and 1994), probably due to sequential "welding" of onshore moving bars (Barcock and Collins, 1991; HR Wallingford, 1995). Depletion, here, and on the Pagham spit, was apparent between 1910 and 1940 and by the mid-1980s; the latter was losing material at a minimum rate of $2{,}000m^3a^{-1}$, necessitating gravel recycling and re-profiling in an attempt to resist beach losses. These trends are a continuation of those measured by Lewis and Duvivier (1977), using aerial photography, for the period 1967-1975. However, small scale spatial variability of net accretion/depletion patterns are apparent, and appear to be most directly related to groyne re-construction, the inshore movement of gravel banks and bars and spatial variation in exposure to wave energy. Terminal scour at the easternmost groyne was evident before the latter was buried following replenishment.

The erosion losses from East Beach need to be placed in an historical context. Excepting locations subject to irregular nourishment, LWM has retreated at a rate of between 0.3 and 3.0 ma^{-1} since 1875 (Gifford Associated Consultants, 1997). As HWM is held static by seawalls and embankments along much of this frontage, this has led to a long-term trend of profile steepening. Foreshore width has diminished by up to 650m over the past 125 years at the most rapidly receding locations. The fastest rates of retreat at specific points occurred within a few years of the completion of seawalls, which was undertaken in piecemeal fashion between 1910 and 1969.

Taking the sector from Selsey Bill to Pagham Harbour entrance as a whole, beach budgets are negative, with groyne-assisted accretion and gravel recycling along the sector north of East Beach only partly counteracting overall losses of beach volume further south. Details of site-specific gains and losses, 1973-1992, are given in HR Wallingford (1995).

5.3 Stores: spits and estuarine sediments

The principal stores are the spits at either side of the entrance to Pagham Harbour; East Head Spit, the ebb tidal delta offshore of Pagham Harbour, and the estuarine sediments within Pagham Harbour.

Pagham Harbour Spits

Pagham Harbour (2.83km^2) is a product of Holocene sea-level submergence of the former mouth of the river Lavant prior to its diversion in Roman times (Wallace, 1990). However, its present extent is the result of storm surge inundation on 6th December 1910 following complete enclosure and land claim in 1876 (Environment Agency, 1998b). Sitlation of the original larger estuary and progressive, piecemeal, reclamation took place earlier, the latter commencing in the seventeenth century (Graves, 1981; Brown, 1981).

The convergent gravel spits that define the Pagham Harbour entrance channel have behaved in a highly dynamic fashion over at least the past seven centuries (Robinson, 1955; Robinson and Williams, 1983; Barcock and Collins, 1991; Geodata Institute, 1994; Gifford Associated Consultants, 1997; Environment Agency, 1998b; Posford Duvivier, 2001). The earliest reasonably reliable map evidence (1587) suggests that the southern (Church Norton) spit had a configuration similar to the present, possibly in response to one or more breaches dating back to 1340-1410. Between 1672 and 1724, it extended some 90 m northeastwards, with a rapid acceleration in this extension of almost 900 m between 1774 and 1885. Episodes of breaching interrupted the spit extension in 1820, 1829 and 1840. As the spit extended and thinned during this 100 year period, there may not have been a significant supplementary supply from inshore sources (i.e. migratory bars associated with the tidal delta). The main source of sediment feed was probably delivered by littoral drift along the shoreline from the south west. Rapid shore erosion occurring around the Selsey peninsula at this time would have provided a local source of sediment. Over this same period, the northern (Pagham) spit, the product of ‘counter drift’ determined by a transport divide north-east of the harbour entrance, experienced net erosion and recession. The entrance channel cut into the low clay cliff on the northern side, resulting in 170m of coastline retreat at this point between 1780 and 1840.

Natural change ceased in 1876, when both spits were partially stabilised and the inlet channel closed to effect the final land claim of Pagham Harbour in 1877. Although this helped to create almost 120m of foreshore progradation, a major storm in December 1910 breached the Church Norton spit, creating a 160m wide channel near Church Norton and flooding the newly reclaimed area. Subsequent events have been documented by the sources mentioned above, notably the Environment Agency (1998b), as follows. Further north-eastwards growth of the Church Norton spit narrowed the entrance and deflected it some 700-800m to the NE towards Pagham. The deflected entrance began to threaten bungalows built on the Pagham spit in the 1920s, so a new narrow entrance, close to the 1910 breach, was established artificially in 1937. The pre-1937 entrance gradually closed becoming marked by a low gravel berm. A further breach over a wide front between the 1937 and pre 1937 inlets occurred shortly after 1955 and by 1958 the entrance was some 700m wide. Rapid drift thereafter led to a further extension of the Church Norton spit across the inlet narrowing it to 250m by 1961. Following continued narrowing a stabilisation of the entrance channel by a training wall along the distal end of the Pagham spit was completed in 1963, and this situation has been maintained subsequently. Events from 1955 to 1966 are presented in Photo 11 and the present configuration is depicted by Photo 10

The high instability of the Pagham inlet has been determined to result from the relatively small tidal prism of the harbour and the potential for rapid west to east drift along the shoreline (Geodata Institute, 1994). Inlet narrowing and deflection occur when drift exceeds the flushing effects of tidal exchange. Breaching occurs when storm surges overwash the spits and lower them sufficiently to allow tidal exchange that can maintain permanent inlet channels.

East Head Spit

The evolution of this spit can be traced in some detail from the end of the sixteenth century, using old maps, charts, successive Ordnance Survey map editions and (since 1945) aerial photographic cover and other remote sensing imagery. Searle (1975); May (1975); Edwards, (1994); Baily and Nowell (1996); ABP Research and Consultancy (2000) and Baily et al.(2002) all indicate that East Head has grown, over at least the past 200-300 years, from an embryonic or possibly ancestral gravel spit form following the east-west trend of the immediate updrift shoreline. Growth, however, has been a long-term trend superimposed on short term fluctuations. It is currently more than three times the area (measured from mean low water) that it occupied in circa. 1850 (May, 1975), with a total volume of about 2.2 million m^3 of sand and gravel (ABP Research and Consultancy, 2000).

The spit has experienced progressive recurvature since about 1880, possibly in several stages of re-orientation, in response to changes in (a) incident wave energy; (b) near and offshore topography and (c) both longshore and nearshore sediment supply. Posford Duvivier (2001) indicate that greatest wave heights are currently associated with winds blowing from the south or south-east over a fetch of some 150km. During this period of growth and establishment, the gravel foundation was overlain by sand, and the current dune field accreted. The events were the product of a change of the local sediment budget, and cannot be wholly ascribed to the impact of updrift protection measures. Changes in planform were particularly marked between 1880 and the early 1950s, but throughout its recent history the spit has been ‘fixed’ at its proximal point (“The Hinge”) whilst rotating clockwise and converting from swash to drift-alignment.

Re-orientation of the spit resulted in exposure of a low sand and gravel intertidal forshore (the Winner) across central and eastern parts of the widening entrance to Chichester Harbour. It served to dissipate wave energy approaching the spit and its wide intertidal expanse formed a key source for wind entrainment and supply of dune-building sands to the spit. However, since 1923 lowering of the Winner has occurred by up to three metres, allowing increased wave exposure and reducing the intertidal foreshore width in front of East Head. The lowering of the Winner is due mainly to the requirement of the cross sectional area of the

Harbour mouth to increase. This increase has been in response to the reduction in littoral drift from the east, which has occurred over at least the 100 years following the widespread provision of defences updrift (ABP Research and Consultancy, 2000).

Since 1945, The Hinge has become progressively narrower, and now constitutes a tenuous, and vulnerable, connection to the updrift coastline. This was made apparent in 1963, when it was breached by storm waves; and again in 1987 when it was overtopped. Some 10m of recession of the seaward face of The Hinge occurred between 1978-94 (Burgess, 1994), with rates of over 3-5 ma^{-1} since 1994, necessitating the insertion of a concealed rock barrier in 1999. A further 6m of recession occurred between July and October 2000. Almost all researchers ascribe erosion at 'The Hinge' to the very substantial reduction of sediment supply from littoral transport along Bracklesham Bay. It results from the progressive extension of longer, higher and more frequently spaced groynes along this updrift shoreline since the late nineteenth century. There is currently almost no natural bypassing by gravel, of the terminal groyne adjacent to East Head (Photo 11). A further cause of erosion at the 'Hinge' is the reduction in height of the adjacent Winner Bank, which appears to have been continuous since at least the early 1920s (ABP Research and Consultancy, 2000). This has reduced sediment supply and has introduced greater wave energy owing to increased nearshore water depths. HR Wallingford (2000) have modelled the hydraulic conditions that would promote breaching for three specific water level, wave and tidal height combinations. Simulation of wave set-up and water levels revealed potentially high wave energy at The Hinge, with wave-induced northwards net transport along the 'open' shoreline to the north most apparent when spring tides combine with a high oblique angle of wave approach (i.e. from the south-west). Several combinations of conditions were identified that could lead to opening of permanent breaches that had a potential to cause sedimentation effects in the main channel (ABP Research and Consultancy, 2000).

Whereas the spit neck has eroded, the width and volume of the distal part of East Head has expanded in stages, with the rapid development of a broad triangular shape between 1911 and 1933. By 2000, East Head, as a whole, was significantly larger than it was in the mid-twentieth century, although its generally bulbous shape has been achieved through major accretion at the head and local erosion of the neck. The accretion is largely the result of deliberate management measures (brushwood windbreak fences) introduced from 1967 to stimulate new sand dune growth and stabilise the existing vegetation cover (Searle, 1975; Doark et al. (1990); Baily and Nowell, 1996; ABP Research and Consultancy, 2000; Baily et al., 2002). However, this trend towards distal enlargement may also be a function of an effective sand supply by net northwards littoral drift along its beach face, fed by an increase in wave and tidal current transported sand inside the mouth of Chichester Harbour (Photo 11). Some sand also appears to be lost from the extreme northern spit tip and transported NW towards the Emsworth Channel. These pathways are suggested from sediment trend analysis of inter-tidal samples from the western and northern shoreline of East Head (Geosea Consulting, 2000).

Pagham Tidal Deltas

A body of sediment has accumulated immediately seaward of the Pagham Harbour entrance forming an ebb tidal delta (Photo 10). Its total volume is estimated to be of the order of 0.5 million m^3 (Barcock and Collins, 1991) and results from the complex feedbacks between longshore sediment transport along the spits and in the nearshore, tidal flushing from Pagham Harbour, wave refraction set up by bank itself and net onshore transport by wave-induced currents (including kelp-rafted shingle). See Section 4, EO2 for further details.

A small flood delta exists just inside the harbour entrance composed of sand and gravel shoreline sediments driven into the harbour during storms in combination with flood tides. It may become reworked by coastal recession, but otherwise cannot readily contribute sediments back to the open coast and is a sink for shoreline sediment over a 50 year timescale. It forms an important area of raised and stable topography which can afford stability to any spits or barriers which migrate landward it.

Pagham Harbour: Estuarine Sediments

The total volume of estuarine sediment infill has not been calculated, and coring undertaken to investigate sediment stratigraphy (Hinchcliffe, 1988; Geodata Institute, 1994; Cundy et al., 2002) only penetrated a few metres. The latter two works revealed relatively coarse sediments at the mouth, and sands close to the ebb/flood channels, suggesting a small flood delta composed of marine-derived sediment. These progressively fine up-estuary to clays and clayey-silts at the heads of creeks, thus demonstrating the dominance of tidal currents on contemporary sedimentation. At an unknown depth, estuarine sediments are replaced by biogenic and minerogenic alluvial/colluvial sediments that accumulated when Pagham Harbour was part of the lower floodplain of the River Lavant (Wallace, 1990). These are known to occupy the buried channel of the proto-Lavant, which extends beneath the offshore tidal delta and thence southwards some 3-500m seawards of the eastern shoreline of the Selsey peninsula (Wallace, 1990).

Geodata Institute (1994) and Cundy et al. (2002) report stratigraphical marker horizons at around 0.5m depths in the northern harbour that are interpreted as the 1876-1909 reclaimed agricultural surface. Subsequent tidal sedimentation has occurred at a rate of between 4.7-8.3mma^{-1}. This is likely to have been highest during the period of expansion of *Spartina* anglica-dominated lower saltmarsh, from 1919-1948. Extensive swards of Spartina anglica that colonised from 1919, expanded to cover 130 ha. in 1948 and then suffered slow die-back to 102 ha. in 1971 and 97 ha. in 1984. Losses were mostly due to recession of the outer marsh margin. Unusually for the Solent, the dieback trend appears to have reversed recently with some renewed expansion of Spartina along the Sidlesham and Norton margins to cover 107 ha. by 2001 (Bray and Cottle, 2003). Dieback has continued in other areas and HR Wallingford (1997) noted locally severe losses adjacent to the wall delimiting the northern reaches of the harbour. Mudflats and scattered sand and gravel banks and bars cover 220ha. Their morphology is determined by tidal currents, although wave abrasion may be of some significance in the upper harbour. Posford Duvivier (2001) calculated a maximum significant wave height of 0.6m, occurring at least once a year, adjacent to the wall of Sidlesham.

As there is negligible freshwater discharge into the harbour, input of terrestrial sediment can be regarded as effectively zero. The sediment budget is therefore determined by the balance between flood tide input and ebb tide output together with any primary production by the flora. Thus, the 0.5m thickness of sediment that has accumulated since 1910 would appear to provide evidence of a net input from marine sources.

6. SUMMARY OF SEDIMENT PATHWAYS

1. This coastline is characterised by a dominant west to east directed littoral drift pathway (drift aligned) operating to the east of Selsey Bill and a less well defined east to west pathway operating within the swash aligned Bracklesham Bay.
2. The drift pathways have been sustained by sediment inputs from the Kirk Arrow spit and the Inner Owers. Rapid coastal retreat in the past has provided important sources of fresh sediment derived from erosion and/or transgression of the sand and gravel sediments of the Selsey peninsula, but these are now almost completely reduced by widespread coastal defences.
3. The sediment budget is dominated by storage and transfer of sediments at the shoreline within a system of dynamic beaches, spits and nearshore banks, especially the Chichester and Pagham ebb tidal deltas. Movement of gravels inshore from relic deposits by a kelp rafting mechanism is thought to be an important means by which fresh gravels accumulate as banks (*e.g.* Kirk Arrow Spit) in water sufficiently shallow for them to be driven ashore by wave action. Following storage, most shoreline sediments are transported eastward or westward out of this coastal area by drift and few long-term sinks are evident (except deposition of fine sediments within the harbours). In consequence, the natural budget of shoreline sediments is negative, although this imbalance has been reduced in recent years by the practice of beach replenishment..
4. Intensive management involving the holding of a largely fixed line of coastal defence for the past 100-150 years has inhibited the natural tendancy for landward migration of the shoreline. It has greatly reduced the supply of fresh sediments from coastal retreat and extensive groyne fields have intercepted much of the drift of gravels and coarse sand on the upper beaches.
5. Beach management operations throughout this shoreline involving gravel recharge, and re-profiling together with control structures now largely control sediment transport and attempt to maintain beach stability. Given the low-lying and erodible nature of this shoreline, its modest natural sediment supplies and the potential for sea-level rise and climate change impacts there are some uncertainties relating to the sustainability of trying to hold the present defence line in the long term (Halcrow, 2002)

7. COASTAL HABITATS AND DEFENCE INTERFACE ISSUES

In a fully natural condition this coastline would provide a wide range of mobile and partly mobile shingle habitats together with extensive sheltered estuarine intertidal areas around Pagham, Sidlesham and Medmerry. However long established practices of coastal defence and reclamation together with a historical trend of natural recession, narrowing and steepening of gravel beaches, has had some negative impacts on habitat survival and development. The key contemporary habitats are vegetated shingle (Pagham Spits and intermittently along Bracklesham Bay), sand dunes at East Head and intertidal mudflats and saltmarsh in Pagham Harbour and behind East Head spit. Some coastal grazing marshes exist on the low-lying reclaimed land between Pagham Harbour and Medmerry.

Vegetated shingle along Bracklesham Bay and the eastern side of the Selsey peninsular is potentially threatened by squeeze between fixed residential developments to landward and the natural tendency of the beaches to migrate. Re-profiling and recycling of gravel on Church Norton Spit has the potential to disturb existing vegetation communities and prevent communities from re-establishing on the managed shingle. Mapping of the distribution and characteristics of vegetated shingle has been undertaken by the West Sussex Vegetated Shingle Project (2003). The project has sought to increase general awareness of the local resource; it has provided guidance for contractors working on vegetated shingle (relevant to Church Norton spit and Medmerry Beach) with further guidance produced for residents with shingle gardens (relevant to Bracklesham Bay and East Beach Selsey).

In Pagham Harbour, moderate saltmarsh dieback from 130 ha. in 1948 to 97 ha. in 1984 appears to have reversed recently with some renewed expansion of marsh along the Sidlesham and Church Norton margins to cover a total 107 ha. by 2001. However, the *Halimione* dominated mid-marsh that fronts many embankments is diminishing and *Spartina* and *Salicornia* species are encroaching into areas abandoned by *Halimione* so that the transition between the lower and mid marsh is migrating landward (Bray and Cottle, 2003). Such a process is indicative of coastal squeeze and suggests that the flood defences around the perimeter of Pagham Harbour are affecting habitat quality. It suggests also that opportunities should be sought for habitat creation.

There are several positive opportunities for the managed set-back or re-alignment for parts of this coastline, that are assessed in detail in Posford Duvivier (2001) and Bray and Cottle (2003). In particular, there are opportunities for the expansion of intertidal habitats in areas of land claim, such as the former channel connecting Pagham Harbour to Medmerry and around the perimeter of Pagham Harbour. Alternatively, there is the more radical option of planning for a major inundation so as to reinstate the full extent of the former 17th Century estuary to create an intertidal area some 4-5 times larger than at present (Bray and Cottle, 2003). Indeed, the potential is such that the area could be considered for mitigation projects arising from the need to compensate for losses in adjoining areas such as the harbours of the eastern Solent. The inundation of Pagham Harbour, in 1910, represents an excellent analogue of managed retreat as a means of expanding subtidal, mudflat and saltmarsh environments (French, 1991; Cundy et al., 2002). Immediately following submergence significant sedimentation occurred and lower saltmarsh regenerated rapidly, possibly due to the presence of a seedbank in reclaimed soils. This was accentuated after about 1925 with the arrival and spread of the fertile hydbrid cord grass, *Spartina anglica*. *Zostera* ssp also became well established over a large area of harbour mudflats (Geodata Institute, 1994). Based on this example the prospects for successful creation of intertidal habitats would appear to be good, although there are a wide range of other critical issues that would need to be addressed (Posford Duvivier 2001). Geodata Institute (1994) address the issues of ecosystem response to anthopogenically forced changes to vegetation communities in Pagham Harbour. These would apply, with some modifications, to the deliberate re-creation of new, or substitute, habitats.

The sand dune habitat, of East Head, although not entirely natural, exhibits a regionally significant set of ecological gradients and characteristic communities (Doark et al, 1990). The continuation of sand supply to the foreshore is critical to the maintenance of the present scale and variety of dune forms and ecological diversity. A permanent breach at the ‘Hinge’ would intercept sand and potentially reduce inputs to the established dunes at the head of the spit causing long-term loss of habitat integrity. The present strategy of strengthening this vulnerable area is subject to monitoring and periodic review. This approach may need to be supplemented by detailed ecological modelling of the impacts arising from the breaching scenarios outlined by HR Wallingford (2000). An alternative possibility is to permit retreat of the West Wittering frontage with the aim of improving the longshore sediment supply to East Head. The conservation values of East Head, and the range of alternative options, are examined in further detail in Posford Duvivier (2001) although further feasibility studies would be required to support some of the more radical options. More detailed mapping and frequent monitoring of critical factors, such as soil chemistry, may be needed before a final choice can be made.

8. OPPORTUNITIES FOR CALCULATION AND TESTING OF LITTORAL DRIFT VOLUMES

Estimates of gross and net littoral drift derived from numerical modelling based upon wave hindcasting are available at numerous points along the shoreline due to previous studies in support of Coastal Defence Strategy Plans (HR Wallingford, 1995 and Posford Duvivier, 2001) and the two overlapping SMPs (HR Wallingford, 1997; Gifford Associated Consultants, 1997). The overall patterns and volumes of drift have been established with medium reliability with moderate to good correspondence between modelled and observed processes. However, there are several uncertainties and different studies have on occasion yielded differing results.

Difficulties encountered in applying these models included the problem of selecting a representative sediment gain size on the mixed sand and gravel beaches (sediment mobility is highly sensitive to grain size), the need to estimate (or ignore) the extent to which groynes on the upper beach intercepted any potential drift, problems of tidally induced transport around Selsey Bill and the need to incorporate estimates of offshore to onshore inputs of gravel. Furthermore, this frontage has a long history of beach management operations including intensive episodes of emergency recharge and re-profiling. Such operations are not always carefully recorded and their possible effects are difficult to represent within modelling studies. For these reasons, the shorelines of this frontage are rather unsuited for definitive studies of drift. This however does not obviate the need to generate valid predictive models for testing of beach management options e.g. design of recharge schemes and appropriate control structures, but the data generated from these studies has to be interpreted especially carefully. With this in mind it is important that beach volume changes continue to be monitored with the Environment Agency ABMS and good records should be maintained of all beach management activities undertaken.

9. KNOWLEDGE LIMITATIONS AND MONITORING REQUIREMENTS

There has been an impressive increase in both the quality and quantity of knowledge and understanding of the coastal sediment transport process system on this frontage over the most recent 10 years. The two overlapping SMPs (HR Wallingford, 1997; Gifford Associated Partners, 1997) and Coastal Defence Strategy Studies (HR Wallingford, 1995 and Posford Duvivier, 2001 have reviewed, synthesised and contributed to this much of this information. Furthermore, many of their recommendations are in the process of implementation by the Strategic Regional Coastal Monitoring Programme, a consortium of coastal groups working together to improve the breadth, quality and consistency of coastal monitoring in South and South East England (Bradbury, 2001). A Channel Coastal Observatory has been established at the Southampton Oceanography Centre to serve as the regional co-ordination and data management centre. Its website at *www.channelcoast.org* provides details of project progress (via monthly newsletters), descriptions of the monitoring being undertaken and the arrangements made for archiving and dissemination of data. Monitoring includes directional wave recording, provision of quality survey ground control and baseline beach profiles, high resolution aerial photography and production of orthophotos, review and continuation of Environment Agency ABMS to incorporate new ground control, LIDAR imagery and nearshore hydrographic survey. Data is archived within the Halcrow SANDS database system and the aim is to make data freely available via the website.

On this basis, the recommendations for future research and monitoring here attempt to emphasise issues specific to the reviews undertaken for this Sediment Transport Study and do not attempt to cover the full range of coastal monitoring and further research that might be required to inform management as follows:

1. The effective application of numerical modelling studies of beach behaviour and sediment transport processes requires the input of high quality **nearshore bathymetric survey data**. This is especially important for those sectors of the near and offshore environments with complex landform and sediment associations, e.g. between East Head and East Wittering, around the Selsey peninsular and the Pagham tidal delta. Surveys should be completed with reasonable frequency and ideally be combined with some sea bed sediment sampling. The latter would ultimately provide more reliable knowledge of potential onshore sediment transport through the compilation of large-scale maps of sediment distribution, grading patterns, etc. With the exception of some of the areas covered by seabed mobility studies (Hydraulics Research, 1993) present knowledge is based on ad hoc sampling and divers observations, so future work needs to be more systematically organised. It would be most valuable for surveys to be interpreted so as to extend the pioneering work of Wallace (1967, 1968, 1990, 1996) in identifying geological, geomorphological and archaeological features of the recently submerged marine landscape. Interpretation should focus on identifying the extents and compositions of relict landforms and sediment stores. The latter may have particular relevance to understanding kelp-rafting as well as offshore and nearshore transport by tidal currents. It might, in particular, throw light on the important question of whether offshore to onshore gravel supply is a sustainable process under the contemporary hydrodynamic regime.

2. Studies of beach planform and volumes, especially volume changes, provide valuable insights into the rates of operation of littoral transport and the effectiveness of beach

management. These have been facilitated by routine Environment Agency ABMS **aerial photography** since 1973, with subsequent photogrammetric measurement of profiles. There are have been some uncertainties in the past relating to the reliability of parts of the profile data so that it is important both to validate the historical data and to introduce robust methods for future profile data collection. It is understood that the Environment Agency initiated such work in 2002 and intend to incorporate the new ground control provided by the Strategic Regional Coastal Monitoring Programme into their profile measurement procedures.

3. Once the quality and consistency of the ABMS profile data sets have been assured it will be important to consider how the profiles should best be **analysed**. It will be important to identify indicators of beach health such as sediment volume, crest height and crest position. It is anticipated that different criteria may apply to free-standing barrier beaches or spits as opposed to beaches retained in front of sea walls or other control structures. Volume is especially important, but can be difficult to monitor reliably using widely spaced profiles on groyned coasts. Furthermore, an error analysis should also be undertaken so as to identify the minimum volumetric change that can be resolved with the techniques. Past trends in these indicator parameters (decadal, annual and seasonal) need to be established and a system of routine analysis instituted that would provide early warning of “unusual” trends. It may be that local engineers could identify critical thresholds, or minimum values of these parameters that could be applied to trigger specific warnings. To effectively interpret the trends recorded, it will also be vitally important to maintain good records of all beach management activities undertaken.

4. To understand beach profile changes it is important to have knowledge of the **beach sedimentology** (gain size and sorting). Sediment size and sorting can alter significantly along this frontage due to beach management, especially the practices of recharge and recycling. Ideally, a one-off field-sampling programme is required to provide baseline quantitative information along this shoreline together with a provision for a more limited periodic re-sampling to determine longer-term variability. Such data would also be of great value for future modelling of sediment transport, for uncertainty relating to grain size is often a key constraint in undertaking modelling.

5. **Kelp-assisted shingle rafting** is of unusual significance as an input into the longshore transport system, compared with most locations on the south coast. Current estimates of the volumes and periodicities of supply are subject to wide uncertainties and margins of error, and it would be highly relevant to undertake a long-term programme of monitoring and measurement. It would also be valuable to promote research on the mechanisms of this process, despite evident logistical problems. In this context, the Selsey peninsula may offer exceptional opportunities to study a process that may operate more commonly along gravel shorelines than is currently appreciated.

6. The recent application of several numerical and conceptual models to the quantification of rates and volumes of longshore sediment transport (e.g. HR Wallingford, 1995; Gifford Associated Consultants, 1997; Posford Duvivier, 2001) has resulted in some significant advances of understanding. Nonetheless, empirical data is relatively scarce, and carefully targeted **sediment tracing** would be of real value in verifying existing theoretical understanding. This approach would need to select (i) critical locations where transport discontinuities exist; and (ii) shoreface zones where historical and

recent analyses of beach shape and volume have created uncertainties over the relevance of past to future trends.

7. Most beach budgets are currently negative, with renourishment, recycling and groyne control structures serving to reduce deficits. This shortfall may be partly due to progressive loss of offshore sediment reserves. It is therefore clear that longshore transport throughput depends heavily on inputs from nearshore banks and bars, especially the **Pagham tidal delta** and **Kirk Arrow Spit**. These features require careful **monitoring** of changes in shape and volume. This knowledge would help to inform planned beach management practices over intermediate time periods.

10. REFERENCES

ABP RESEARCH AND CONSULTANCY LTD (2000) *Geomorphological Analysis of East Head and Chichester Harbour*. Report R.893. Report to Chichester Harbour Conservancy, English Nature and the National Trust, 29pp., 5 Tables, 31 Figures and 2 Appendices.

ABP RESEARCH AND CONSULTANCY LTD (2001) *East Head Research Study: Summary Report*. Report R.895. Report to Chichester Harbour Conservancy, English Nature and the National Trust, 17pp. and 12 Figures.

ALDSWORTH F G (1987) Prehistoric and Roman Selsey, *Sussex Archaeological Collections,* 125, 41-50.

BAILY B and NOWELL D (1996) Techniques for Monitoring Coastal Change: A Review and Case Study, *Ocean and Coastal Management,* 32(2), 85-95.

BAILY, B.; HOOKE, J. and BRAY, M.J. (2002) East Head spit, West Sussex Southern England: identifying past change and monitoring future trends. *Shore and Beach*, 70 (3), 41-47.

BALLARD A (1910) The Sussex Coastline, *Sussex Archaeological Collections*, 53, 215-225.

BARCOCK N W S and COLLINS M B (1991) *Coastal Erosion Associated with a Tidal Inlet: Pagham Harbour, West Sussex.* Report No: SUDO/TEC/91/3NC. Department of Oceanography, University of Southampton. Report to Arun District Council and National Rivers Authority, 172 pp.

BATES M R (1998) Pleistocene Sequences at Norton Farm, Chichester, West Sussex, in J B Murton et al. (Eds.) *The Quaternary of Kent and Sussex: Field Guide, Quaternary Research Association*, 168-177.

BATES M R (2000) Late Middle Pleistocene Deposits at Norton Farm on the West Sussex Coastal Plain, Southern England, *Journal of Quaternary Science*, 15(1), 61-89.

BATES M R, PARFITT, S A and ROBERTS M B (1997) The Chronology, Palaeoecology, and Archaeological Significance of the Marine Quaternary record of the West Sussex Coastal Plain, Southern England, UK, *Quaternary Science Reviews*, 16, 1227-1252.

BONE A E (1996) The Shaping of the Selsey Coastline: A Review of the Geomorphology, Archaeology and History. *Tertiary Research,* 16, 5-14.

BROWN A R (1981) The Changing Geography of the Harbour, in: R W Rayner (Ed.) *The Natural History of Pagham Harbour,* Bognor Regis Natural History Society, 1-13.

BRADBURY, A.P. (2001) *Strategic monitoring of the coastal zone: towards a regional approach.* Report to SCOPAC, South Downs Coastal Group, South East Coastal Group and Environment Agency, 91p.

BRAY, M. J. and COTTLE, R. (2003) *Solent Coastal Habitat Management Plan, Volumes 1 and 2.* Report by Posford Haskoning and University of Portsmouth to English Nature and

Environment Agency. Volume 1 Summary of Habitat Change 66p. Vol 2 Technical Report 219p.

BURGESS, J.T. (1997) *East Head, Chichester Harbour: erosion on the seaward side near "the Hinge."* Report to Chichester Harbour Conservancy, 7p plus Appendicies.

CAVIS-BROWN J (1910) Selsey or Pagham Harbour, *Sussex Archaeological Collections,* 53, 5-25.

CASTLEDEN R (1998, 2nd Edition) *Classic Landforms of the Sussex Coast*, Sheffield: Geographical Association, 48pp.

COBBOLD C and SANTEMA R (2001) *Going Dutch on the Manhood Peninsula*. Rotterdam: van Walsberge, 79 pp.

COLE M J S (1980) *The Abrasion of Beach Materials. A Study on Bracklesham Beach, West Sussex.* Unpublished BSc Final Year Project Report, No. 23, 79/80, Department of Civil Engineering, Portsmouth Polytechnic, 48 pp.

COLLINS M B, FITZPATRICK J and GAO S (1995) *A Tracer Experiment for Defining Transport on a Beach at Pagham,* Department of Oceanography, University of Southampton. Report to Arun District Council, 9 pp.

COOPER S M (1984) *Tidal and Wave Regime at East Beach, Selsey, and Its Implications for Sea Defence,* unpublished BSc Dissertation, Department of Civil Engineering, University of Southampton, 61 pp.

CUNDY, A. A.B. LONG, A. HILL, C. SPENCER, C. and CROUDACE, I. (2002) Sedimentary response of Pagham Harbour, southern England to barrier breaching in AD 1910. *Geomorphology*, 46, 163-176.

DOARK, C. HEADLEY, S.M. and WOOLVEN, S.C. (1990) *Sand Dune Survey of Great Britain, Site Report No 81: East Head, West Sussex*. Report to Nature Conservancy Council.

DUVIVIER J (1961) The Selsey Coast Protection Scheme, *Proceedings of the Institution of Civil Engineers*, 20, 481-506.

DUVIVIER J (1964) Attrition Tests of Natural and Redeposited Shingle Beaches, *Proceedings of the 9th International Conference on Coastal Engineering (Lisbon)*, 289-298.

EDWARDS, S. (1994) *East Head Change Analysis.* Solent Mapping and Charting, University of Portsmouth. Report to Chichester Harbour Conservancy.

ENVIRONMENT AGENCY (SOUTH) (1998a) *Summary of Shingle Recharge at the Medmerry Frontage*. (Internal Report).

ENVIRONMENT AGENCY (SOUTH) (1998b) *Historic Maps of Pagham Harbour, 1847-1973*. Report. (Internal document).

FITZGERALD, D. 1996. Geomorphic variability and morphologic and sedimentologic controls on tidal inlets. *Journal of Coastal Research*, Special Issue 23, 47-71.

FRENCH P W (1991) *Natural Set-Back at Pagham Harbour*. Report to West Sussex County Council, n.p.

GEODATA INSTITUTE, UNIVERSITY OF SOUTHAMPTON (1994) *Pagham Harbour. Review of Physical and Biological Processes.* Report to English Nature, National Rivers Authority and West Sussex County Council, 87 pp.

GEOSEA CONSULTING (CANADA) LTD (2000) *A Sediment Trend Analysis (STA) at the Entrance to Chichester Harbour: Implications for Long-Term Behaviour of East Head.* Report to ABP Research and Consultancy, Ltd, 10pp., 5 Figures, 2 Tables and 3 Appendices.

GIFFORD ASSOCIATED CONSULTANTS (1997) *South Downs Shoreline Management Plan – Final Report*. Report to South Downs Coastal Group (lead authority: Arun District Council).

GOODBURN D M (1987) Medmerry: A re-assessment of a Migration Period site on the south coast of England, and some of its finds, *International Journal of Nautical Archaeology and Underwater Exploration,* 16(3), 213-224.

GRAVES J C (1981) The reclamation of Pagham Harbour Through the Centuries, *Journal of West Sussex Archives Society*, 20, 2-5.

HALCROW, 2002. *Futurecoast: research project to improve the understanding of coastal evolution over the next century for the open coastline of England and Wales.* Report and CD-ROM produced by Halcrow-led consortium for DEFRA.

HALL I D (1982) *Sedimentary Survey of Bracklesham Bay, using Sidescan Sonar and Sediment Sampling,* unpublished MSc Dissertation, Department of Oceanography, University of Southampton, 50 pp.

HARLOW D A (1979) The Littoral Drift Budget between Selsey Bill and Gilkicker Point, and Its Relevance to Coast Protection Works on Hayling Island, *Quarterly Journal of Engineering Geology*, 12(4), 257-265.

HARLOW D A (1980) *Sediment Processes, Selsey Bill to Portsmouth*, unpublished PhD Thesis, Department of Civil Engineering, University of Southampton.

HERON-ALLEN E (1911) *Selsey Bill: Historic and Prehistoric: A Map and Guide to Selsey.* London.

HINCHCLIFFE J M (1988) *Late Flandrian coastal changes at Pagham Harbour,* unpublished BSc Geography Dissertation, Department of Geography, University of Durham.

HODGSON J M (1964) The Low-Level Pleistocene Marine Sands and Gravels of the West Sussex Coastal Plain, *Proceedings of the Geologists' Association*, 75, 547-561.

HR WALLINGFORD (1992) *Selsey Bill: Effects of Dredging on Nearshore Wave Conditions.* Report EX 3121. Report to Kendall Bros Ltd and United Marine Dredging, 13 pp.

HR WALLINGFORD (1993) *UK South Coast Shingle Study.* Reports SR 319 and SR 323. Report to Crown Estates Commissioners and SCOPAC.

HR WALLINGFORD (1995) *Pagham to Portsmouth Harbour (Coastal) Strategy Study.* Report EX 3121. Report to Pagham to River Hamble Coastal Group (Lead Authority: Havant Borough Council).

HR WALLINGFORD (1997) *East Solent Shoreline Management Plan,* 4 Volumes. Report to East Solent Coastal Group, Report EX 3441.

HR WALLINGFORD (1998) *Pagham Harbour to East Head, Sussex: Wave and Beach Modelling.* Report Ex 3929. Report to Posford Duvivier.

HR WALLINGFORD (2000) *Numerical Modelling Studies at East Head, Chichester Harbour.* Report EX 4260. Report to Chichester Harbour Conservancy, 6pp. and 30 Figures.

HYDRAULICS RESEARCH (1974) *Selsey Bill: Protection of a Shingle Bank*, Report EX 643, 18pp.

JOLIFFE I P and WALLACE H (1973) The Role of Seaweed in Beach Supply and in Shingle Transport Below Low Tide Level, *Science Diving International* (Proceedings of the 3rd Symposium of the Scientific Committee on the World Confederation of Submarine Activities, Monaco, 8-9 October 1973), 189-195.

JOLIFFE I P (1989) The Rafting of Shingle under the Agency of Seaweed, *Progress in Underwater Science,* 13, 79-96.

JAROSZ E S (1979) *Effectiveness of Groynes at West Wittering*, unpublished internal report. Chichester District Council.

LEWIS and DUVIVIER (1950) *Report on Coastal Protection.* Report to Chichester Rural District Council, 42pp.

LEWIS and DUVIVIER (1955) *Report on Pagham Harbour.* Report to Chichester District Council, 9pp.

LEWIS and DUVIVIER (1977) *Study of Littoral Movements, Selsey Bill to Pagham Harbour.* Report to Chichester District Council and Southern Water Authority, 25pp. (and supplementary report, 17pp.).

MAY V J (1966) A Preliminary Study of Recent Coastal Changes and Sea Defences in South-East England, *Southampton Research Series in Geography*, 3, 3-24.

MAY V J (1975) *The Physiographic History of East Head, Sussex.* Unpublished report to the National Trust, 13pp.

MILLWARD R and ROBINSON A (1973) The Coastline of the Selsey Peninsula, in: R Willward and A Robinson, *The Channel Coastlands,* Basingstoke: MacMillan, 86-98.

PAPHITIS D, VELEGRAKIS A F and COLLINS M B (2000) Residual Circulation and Associated Sediment Dynamics in the Eastern Approaches to the Solent, in: Collins M and Ansell K (Eds) *Solent Science – A Review*, Amsterdam: Elsevier Science, 107-110.

POSFORD DUVIVIER (1992) *Coast Protection: East Head; East and West Wittering*. Report to Chichester District Council, 14pp.

POSFORD DUVIVIER (1997) *SCOPAC Sediment Inputs Research Project: Phase 2: Cliff Erosion.* Report to SCOPAC.

POSFORD DUVIVIER (1999) *SCOPAC Research Project: Sediment Inputs into the Coastal System*. Summary Document, 54pp.

POSFORD DUVIVIER (2001) *Pagham to East Head Coastal Defence Strategy Plan. Final Report and Supporting Documents Volume*. Report to Arun District Council, Chichester District Council and Environment Agency (South), no separate pagination, 14 Appendices.

REID C (1892) The Pleistocene Deposits of the Sussex Coast, and their Equivalents in other Districts, *Quarterly Journal of the Geological Society of London*, 48, 344-361.

ROBINSON A H W (1955) The Harbour Entrances of Poole, Christchurch and Pagham, *Geographical Journal*, 121(1), 33-50.

ROBINSON D A and WILLIAMS R B G (1983) The Sussex Coast: Past and Present, in: (Anon, Ed) *Sussex: Environment, Landscape and Society*. Gloucester: Alan Sutton, 50-66.

SEARLE S A (1975) *The Tidal Threat: East Head Spit, Chichester Harbour*. Chichester: The Dunes Group, 24 pp.

THOMAS M S (1998) New Evidence for a Late Bronze-Age Occupation of Selsey Bill, *Sussex Archaeological Collections*, 136, 7-22.

WALLACE H (1967) Geological Report on the Structure of the Mixon Reef and Adjacent Submerged Cliff Face, One Mile South-East of Selsey Bill, Sussex, *Scientific and Technical Newsletter, British Sub-Aqua Club, August 1967*, 24-33.

WALLACE H (1968) The Search for Roman Selsey, in K McDonald (Ed) *The Underwater Book,* Havant: Pelham Books, 135-145.

WALLACE H (1990) *Sea-Level and Shoreline Between Portsmouth and Pagham for the past 2,500 years.* Privately-published by the author, 61 pp. (Re-published as a series of separate booklets in 1996).

WALLACE, H., (1996) *Sea-level and Shoreline between Portsmouth and Pagham for the past 2,500 Years. Part 2 Chapters 1 to 4* . Published privately by author.

WEST R G and SPARKS B W (1960) Coastal Interglacial Deposits of the English Channel, *Proceedings of the Royal Society of London*, Series B, 240(701), 95-133.

WEST R G et al. (1984) Pleistocene Deposits at Earnley, Bracklesham Bay, Sussex, *Philosophical Transactions Royal Society of London*, Series B, 306, 137-157.

WHITE G M (1934) Prehistoric Remains from Selsey Bill, Antiquaries Journal, 14, 40-52.

WEBBER, N.B. (1979) *An Investigation of the Dredging in Chichester Harbour Approach Channel, and the Possible Effects on the Hayling Island Coastline.* Report to Havant Borough Council, Chichester Harbour Conservancy and Francis Concrete Limited, 56pp.