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Lyme Bay and South Devon Coastal Group
1. INTRODUCTION

The coastline of this unit extends between the headlands of Holcombe (Photo 1) and Straight Point (Photo 2) and is interrupted by the estuary of the Exe (Photo 3). The orientation of both open and estuarine coastlines, where cut into bedrock is influenced by faulting and geological dip. A nearly north to south normal fault lies very close to the western bank of the Exe estuary, and passes beneath the proximal end of Dawlish Warren (Photo 4). The latter is a large south-west to north-east orientated sand spit, with a long and complex history of fluctuating erosion and accretion but which has suffered net loss of sediment over recent decades. Beneath the town of Exmouth is a smaller, apposition, spit that grew westwards across part of the mouth of the Exe estuary. The Exe approach channel is a dynamic feature delimited by offshore banks and characterised by a large tidal delta (Photo 3). The relative changes in the dimensions and volumes of Dawlish Warren and these several nearshore and offshore banks indicate that they are part of a dynamic system of exchange of predominantly sandy sediments.

The sources of beach and spit sediments include clifffine erosion of the various sandstones and breccias of the Permian New Red Sandstone, as well as shoreface/shelf stores that have been moved towards the present shoreline by Holocene sea-level transgression. Defences and protection structures that stabilise or control over 60% of this coastline now inhibit the supply of new inputs of sand (Photo 5), and as fresh inputs from offshore appear to have ceased, the sediment budget relies largely on the re-circulation of a finite, relict store of sediment. Several researchers have attempted to identify patterns of periodic, including cyclical, erosion and accretion affecting bars, banks, beaches and channels. This work has so far proved inconclusive and – to some extent – contradictory. Full understanding will involve improved knowledge of the combination of both wave-driven and tidal current transport and deposition that occurs at, and seawards of, the mouth of the River Exe. The several contemporary pathways of movement of sediment appear to resolve into a generalised pattern of clockwise circulation, with both large and smaller banks functioning as stores. Fine-grained sediments (silts, clays) either accumulate in the inner Exe estuary sink or are removed from the transport system in suspension. Gravel-sized sediment is present in relatively small quantities and is only moved under high-energy conditions to sites of temporary accumulation.

Littoral drift takes a southwest to northeast-directed pathway between Holcombe and the distal end of Dawlish Warren, with discontinuities imposed by minor intervening headlands at Dawlish and Langstone Rock (Photo 6). Between Orcombe Head (Photo 7) and Exmouth, the net movement of sediment longshore is approximately east to west, thus the mouth of the Exe is a drift convergence. Material arriving here is selectively moved offshore to an ebb tidal delta system, or further into the estuary, depending on grain size and prevailing energy conditions. The main mechanism accounting for confluent drift is the large-scale tidal eddy, or vortex, set up by the Exe tidal pass.

Morphosedimentary features and transport pathways create a set of subdivisions that have been used as a basis for discussion in this account. These are:

(i) The open coastline, interrupted at the Exe entrance.
(ii) The inner Exe estuary, between Exeter and Exmouth.
(iii) The outer Exe estuary, including the approach channel and offshore banks and bars.
Within (i), there are major contrasts between erosional and accretional forms. These features are not entirely complementary, as is evident from the evolution of Dawlish Warren. They are discussed in detail under appropriate topical headings. Aspects of the sedimentology and hydraulic regime within the inner Exe estuary are also covered separately, but are linked together by cross-reference.

1.1 Coastline Evolution

The framework for the geomorphological development of this coast, particularly since the mid-Quaternary period is given in the separate section covering the general Introduction to the South Devon coastlines. Additional local details are added here.

The Exe drainage basin is probably a long-established feature, perhaps dating to the late Tertiary (Dyer, 1980). However, evidence for the erosional history of the present-day estuary is limited to buried channels and their sediment infills. Durance (1969a, 1980) considered that the Exe was incised into underlying bedrock during the most recent (Devensian) glacial period, and possibly an earlier cold stage of the Quaternary. Clarke (1969) used a combination of offshore sea bed sediments types and morphology to postulate that in the early Holocene, when sea-level was at least –40 to –50 m OD, the River Exe flowed approximately parallel to the modern coastline between Dawlish and Berry Head. He reconstructed associated estuarine, beach and spit sediments that might represent an analogue to the present-day Exe entrance during an inferred stage of relative sea-level stability approximately 9,000 to 9,500 years before the present.

The evidence used by Durrance (1969a and b) consists of seismic refraction profiles beneath Dawlish Warren spit that reveal a series of sinuous channels orientated approximately north-west to south-east. The deepest, and presumably the oldest, occurs at just over –50 m OD, with a more recent channel at approximately –30 m OD. These are infilled with fluvial gravels, overlain by clays, sands and estuarine silts. The gravel suite closely corresponds in character with coarse deposits that occur very close to the surface at Bull Hill Sand, Pole Sand and beneath Warren Point. The younger gravels are partly a result of re-working of the older deposits, and both are associated with buried terraces at nine height-range elevations between –36 O D and –5.0 m O D. Each of these might represent a stage of either stillstand, or regression, during early to mid Holocene sea-level rise.

The appearance of sands, and then estuarine sediments, is interpreted from shallow borehole logs (Durrance, 1969a) as being evidence of the creation of a prototype form of Dawlish Warren spit. No specific date can be attached to this event, but it is presumed to be no later than early to mid Holocene. Its existence is due to the shoreward movement of large quantities of fluvially and/or periglacially deposited sand, driven by the advancing wave base as sea-level rise accelerated between 9,000 and 6,500 years before the present. Further important sources of sand came from (a) seabed abrasion and cliffline retreat, and (b) the re-mobilisation of the large ebb delta built further offshore at the mouth of the Exe during one or more low sea-level stages. The relative importance of these sources cannot be assessed, although at least 4-5 km of shoreline retreat appears to have occurred over no more than four or five millennia. Thus, longshore drift from the shoreline to the south west of Dawlish Warren would have been a significant feed to the growing volume of this spit, particularly before hard rock headlands such as Langstone Rock (Photo 6) became prominent features. Exmouth spit, growing in the reverse direction as an apposition structure, would also have
been sustained by substantial littoral transport of both sand and gravel moving westwards into the developing estuary entrance.

After approximately 5,500 Years Before the Present, the rate of sea-level rise declined, with a reduction in the quantity of offshore to onshore sediment transfer. It is the view of Kidson (1964) and others that the offshore reservoir of sand was either exhausted, or has become inaccessible, under prevailing hydrodynamic conditions over the most recent 2,000 to 3,000 years. The sediment budget of Dawlish Warren, Pole Sand and other banks, shoals and channels of the Outer Exe estuary has since depended on a finite, essentially “fossil”, resource subject to constant re-circulation. New inputs can now only come from off to onshore transport under very high magnitude storm conditions, and ongoing cliff erosion. Neither are considered significant sources of fresh supplies.

Durrance (1969b) has suggested that there may have been a complex sequence of events leading up to the modern configurations of Dawlish Warren and Exmouth spits. He has proposed that both spits grew rapidly towards one another, fed by convergent drift pathways separated by an anticlockwise tidal eddy at the increasingly constricted mouth of the Exe. Owing to reduced sand supply from offshore and increased exposure to wave overtopping events, Dawlish Warren was breached close to its proximal (attachment) end. This breach channel was close to one created by river incision in the Devensian. The main channel of the Exe used this new exit, whilst Exmouth spit – no longer so protected – extended well out across the line of the old main channel. However, Dawlish Warren was relatively rapidly reconnected and grew progressively across the wide estuary mouth, forcing the main channel to migrate in the same direction, back to its earlier position. (It is possible that a temporary sandbank became attached to Exmouth Spit, thus accounting for its apparent growth). During a later, but apparently relatively brief, stage, Exmouth Spit was eliminated altogether. Once the present relationship between the two spits was established they took up stable positions in relation to one another because the main channel of the Exe channel became confined between “anchors” of near surface rockhead outcrops. Although this is an interesting, and perhaps feasible, evolutionary hypothesis, Durrance (1969b) does not give detailed supporting evidence. Nor does he suggest a timescale for these postulated changes, although he hints that the former breach channel, discharging just east of Langstone Rock, was in use as recently as 1650. Recent behaviour of Dawlish Warren provides, at best, ambivalent support for the idea that the above sequence of changes could be repeated, ie that the spit has an inherent “cyclic” tendency towards growth, decay, collapse and regrowth (refer to Section 5.2 for further discussion).

From the mid or late Holocene, following the submergence of the lower valley of the Exe to create the present day estuary, sedimentation of fine-grained material (clays and silts) has been continuous. The estuary therefore represents a sink for fine sediment, with sand and gravel being deposited closer to its entrance. Inputs have come from both marine and fluvial sources, with the latter probably of much greater relative significance in the past than now. Riparian and catchment land use changes since at least Bronze Age times have been responsible for periodic accelerations in the rate of delivery of sediment by river discharge. Management controls have now substantially reduced these. See Section 4.1 and Section 5.3 for further discussion.
1.2 Hydrodynamic Regime

The tidal range increases slightly from east to west. At Exmouth, the mean spring range is 3.80m and the mean neap range is 1.48 m. Tidal current velocities are relatively weak along the open coast, but in the constricted entrance to the Exe estuary, and its approach channel, they are up to 3 ms\(^{-1}\) during spring tides and 1 ms\(^{-1}\) during neap cycles. These are high velocities, capable of moving large quantities of sediment, up to medium sized sand. Their significance is discussed in Section 5. Tidally induced transport in the inner estuary of the Exe is dominant, and is covered in Section 4.1.

There is an absence of validated quantitative data on the wave climate of the nearshore and offshore areas, although this situation could be improved if analysis of recently-acquired offshore wave rider buoy data is undertaken (one year deployment off Start Point for SMP – Posford Duvivier, 1998a). A theoretical wave climate for a point off Orcombe was produced by Posford Duvivier (1998a). The dominant wave approach direction is from the southwest, but attenuated swell waves moving up the English Channel are modified by refraction and diffraction around headlands between Start Point and Hope’s Nose. In addition, interactions with offshore and nearshore banks, bars and intervening channels further reduces the energy of waves from the west and south-west. Waves propagated across the east/south-east fetch are comparatively less depth-limited and introduce larger amounts of energy. Most storm waves arrive from this direction, and although they occur for less than 10% of the time during an average year they are responsible for substantial short-term changes in beach and bank volumes. Posford Duvivier (1991) and Hydraulics Research (1991) used developed a hindcast offshore climate and used a wave refraction computer model together with local bathymetric chart data to estimate certain inshore wave climate parameters. For waves approaching from the south-east, mean significant wave height (\(H_s\)) is 2.53 m for an annual return frequency, and 2.69 m for a 1 in 50 year recurrence. \(H_s\) (max) is 4.0 m and 5.3 m for the same periodicities. These figures were computed for the sector of coastline close to the proximal end of Dawlish Warren, in connection with revetment and rock armour design. Wave heights and periods for other parts of this complex nearshore/offshore area are likely to be somewhat different. A comprehensive and detailed numerical model of wave climate is an evident priority for future research.

2. SEDIMENT INPUTS

2.1 Marine Inputs

F1 Onshore Sand Transport at the Exe Tidal Delta

All authorities are agreed that marine source is dominant, with both tidal currents and waves capable of moving both fine sediments (in suspension) and coarse material (as bedload) towards and the estuary entrance (Thomas, 1980; Merefield, 1982 and 1984; Posford Duvivier, 1998a and b). Fluvially derived sediment input is now low (see Section 2.2), but may have been of greater relative significance prior to catchment management measures introduced from the sixteenth century onwards. Some gravel and coarse sand may derive from erosion of sediment infills of earlier (Pleistocene) buried channels and valley terrace...
deposits. Breccia units within the underlying basement rock could also provide a source for coarse clastic material, most of which now occurs at tidal channel margins.

In their conceptual model of the transport regime of Pole Sand and the Exe channel, Posford Duvivier (1998a and b) propose movement of wave-driven bedload transport of sand across Pole Sand from the east, south-east and south. This represents “fresh” input from seabed/shelf reserves further offshore, and helps to account for the net gain of sediment since at least the mid nineteenth century. Kidson (1950; 1964) argued that Pole Sand must be the product of large quantities of sand moved shorewards during the Holocene, as sea-level rose. However, he inferred (Kidson, 1964) that net onshore supply no longer functions from evidence of the rapid erosion of Dawlish Warren spit during the preceding 30 years. Hydraulics Research Station (1965) also presumed that Pole Sand was now a finite reserve of sediment. This conflict of opinion has not been resolved, though the known presence of asymmetric bedforms is supportive of active wave transport. Posford Duvivier (1998b) also propose that wave-transported sand enters the outer Exe estuary, although the evidence for this assertion is not given. A proportion of this input appears to be carried into the estuary by the flood tide. It would explain the presence of the flood tidal delta (The Great Bull Hill) and shoals immediately upstream of the inlet (Photo 3) and also explain the generally sandy nature of much of the lower estuary (Photo 8).

As stated in the preceding section, transport across Pole Sand is predominantly by waves. This resolves into both net onshore and offshore components, the latter most likely to operate during storms. Posford Duvivier (1998b) suggest, based on hydrodynamic modelling, that almost one fifth of annual sediment transport flux may be accounted for by a single, high-energy storm. The relatively rapid migration of banks and bars may also be the result of substantial movements of sediment by storm waves. During these conditions, it has been observed (Sims, et al, 1995; Sims, 1998) that beach and foreshore erosion along Dawlish Warren coincides with crest flattening on Pole Sands – i.e. both loose sediment simultaneously. Normally, beach recovery takes place over succeeding weeks of “normal” conditions, thus suggesting that net onshore and offshore transfers may be in approximate balance.

The only distinctive type of sediment that gives strong circumstantial evidence of marine input is that of biogenic origin. Merefield (1982) calculated that 9% of the content of estuarine silts and clays is finely divided and well-mixed carbonate. Some of this, estimated at 4%, derives from lithoclasts in the New Red Sandstone, leaving some 5% that is likely to be introduced from the external marine environment. Microscopic analysis demonstrated that much of this carbonate is in the form of well-abraded grains, suggesting derivation from open coast beaches and near/off-shore banks. However, the ultimate source of this material is benthic organisms. Murray (1987) was able to identify the seabed of the central-western English Channel as the most probable origin of some foraminiferal tests present in samples of silts and clays obtained from the upper and middle reaches of the inner Exe estuary. Both of these studies, and Merefield (1987), thus suggest a long distance and long timescale pathway of estuary supply. It is probable that fine-grained minerogenic sediment is similarly transported, though no experimental work has yet been undertaken to substantiate this.
2.2 Fluvial Discharge

The major source of river sediment is from the River Exe. Posford Duvivier (1999) estimate an annual delivery of 1900 m$^3$ of fine grained sediment, all of which is incorporated into estuarine mudflats and saltmarshes. Coarse clastic input is considered to be less than 50 m$^3$ a$^{-1}$. Rendel Geotechnics and the University of Portsmouth (1996) calculate coarse bedload delivery to be 77 m$^3$ a$^{-1}$, some of which may move towards the estuary mouth. It is possible that significantly greater quantities could be delivered within flood events for extreme discharge events are a notable part of the river regime. There is also potential input of fine to medium sand and silt from: (i) Dawlish Water, which discharges at Dawlish and (ii) several streams draining small catchments along the east and west margins of the Exe estuary such as the R. Kenn and R. Clyst. None have been investigated, but are presumed to yield a very small cumulative quantity of sediment.

The quantities of fluvial sediment input are therefore small and do not make a significant contribution to the overall coastal sediment budget, although they would appear to be important to the budget of the Exe Estuary.

2.3 Cliff and Platform Erosion

E1 Holcombe to the Exe Estuary

The Dawlish Breccias and Lower Sandstones formations of the Permian period outcrop as a series of irregularly intercalated fine-grained breccias and sandstones between Holcombe and the proximal end of Dawlish Warren spit. Active marine erosion occurs at some sites between Holcombe and Dawlish, exemplified by the headland and stacks of the Parson and Clerk (Photo 1) and small-scale falls at Langstone Rock (Photo 6). At Coryton’s Cove there is a site of persistent cliff failure, with the slip surface located in a horizon of thinly-bedded mudstones within more coherent breccias. This may be a relatively recent re-activation of a relict shearing plane. For most of the length of this coastline, former marine cliffs are now confined behind the railway line constructed in 1849 (Photo 5 and Photo 9). Except for where the railway runs through tunnels behind headlands, these cliffs are now removed from the influence of wave erosion by seawalls, revetments, groynes, gabions and rock armour (Photo 10). Thus, much of the former input of sediment from cliff erosion has been curtailed.

Breakwaters at Langstone Rock (Photo 6), Dawlish (Photo 10) and elsewhere, designed to contain beach sediments transported by longshore drift, also provide some protection for otherwise exposed promontories. Although the cliff face behind the railway line has been stabilised, it remains subject to some weathering, gulleying and mass movement (Sims, 1998). This was experienced in February 2001, when ground water levels were exceptionally high and pore water pressures became critical. Sediment accumulates in small debris stores at the cliff base; when removed it is not transferred to the adjacent foreshore. For the limited areas of frontage that continue to be affected by marine erosion (mostly headlands composed of more resistant breccias), Posford Duvivier (1997; 1998a) estimate a recession rate of 0.5ma$^{-1}$. A small cave and fault-guided arch that have been eroded in the last 200 years into the north-east facing slope of Langstone Rock (Perkins, 1971) indicate ongoing cliff recession.
Small areas of shore platform have developed in front of headlands, used in places for the foundations of seawalls and breakwaters e.g. Langstone Rock (Photo 6).

**E2 Exmouth to Straight Point**

At Exmouth, the cliffline south to Orcombe Point has been protected from direct marine erosion by both land claim in front of The Beacon and Louisa Terrace and seawall construction. The promenade and seawall behind Maer Rocks (Photo 7) was constructed in 1914-15, and the upper cliff profile regraded in the 1920s. The seawall has been repaired since, with a set of groynes added in the 1970s (Posford Duvivier, 1998a; 1995; 1994), thus preventing sediment input to the beach from this source. However, weathering continues to operate over the lower, near vertical surface of the cliff face, although the upper slope facet is thickly vegetated and apparently stable. The west-facing side of Orcombe Point has not been protected, and has been the site of occasional rockfalls. A capping of gravel occurs at the High Land of Orcombe, that together with sand within the cliffs below provides a very small source of coarse beach sediment.

East of Orcombe Point (Photo 11), the cliffline is up to 55 m in height and is entirely developed in sandstones. A wide inter-tidal beach fronts much of this shoreline, with part of the Sandy Bay cliffs closer to Straight Point being protected by a narrow band of vegetated dunes at their toes. In the Bay sub-aerial denudation provides the main mechanism of continuing slope retreat and includes gulleying by overland flow, which has created a closely spaced set of ravine heads that recess the cliff top. Direct basal wave erosion occurs at and adjacent to, the headland formed by the High Land of Orcombe and around Straight Point. Occasional rock falls occur along the exposed steep slopes of Straight Point (Photo 2), evidenced by a boulder beach trapped between its twin headlands. A series of ledges run out at right angles to the cliff base, setting up localised wave refraction that reduces potential erosion rates.

Posford Duvivier (1994; 1997; 1998a) conclude from analysis of successive editions of 1:10,000 and 1:25,000 Ordnance Survey maps between 1880 and 1990 that there has been relatively little change in the position of the cliff top between Orcombe and Straight Points. The average erosion rate over this period of over a century has been 0.4 m a⁻¹. The cliff base may have advanced slightly in places due to the accumulation of talus. At Orcombe itself, a marginally higher mean rate of retreat of 0.5-0.6 m a⁻¹ has prevailed, with maximum short-term rate reaching up to 1.0 m a⁻¹ following small magnitude rockfalls. Although previous studies have not made calculations the 50m high Orcombe cliffs retreating over a 1500m frontage at an average rate of 0.4m would yield around 30,000 m³ a⁻¹ of sediment including a high proportion of sand. This undoubtedly explains the maintenance of the wide Sandy Bay beach and its backshore dunes.

Posford Duvivier and British Geological Survey (1999) estimate a total sediment loss of between 4,500 and 13,500 m³ a⁻¹ from the 1,000 m wide shoreface between Straight Point and the proximal end of Dawlish Warren. This is based on an assumed rate of vertical abrasion of between 1mm and 3mm a⁻¹ of the sandstone substrate. However, it is uncertain if the above figures were calculated from existing rock outcrop areas, or whether they also included estimated erosion from outer estuary sandbanks between these two elements of open coastline. If the latter is the case, the maximum figure quoted above is almost certainly well in excess of shoreface erosion on rock outcrops exposed to wave abrasion and tidal current.
scour. A more realistic estimate is probably 5,500 to 6,000 m$^3$ a$^{-1}$. Some of the material thus removed will be very fine sand, silt and clay, all of which is likely to move directly offshore in suspension.

In terms of platforms, the cliffline between Exmouth and Straight Point is developed in the Red Marls division of the Permian “New Red Sandstones.” This consists of marls with several thick sandstone units. The latter are relatively more resistant to marine erosion and are responsible for the headlands at the High Land of Orcombe and Straight Point, as well as platforms such as Conger, Orcombe and Maer Rocks. As the backshore element of platforms is normally concealed by beach sediment, they typically occur as foreshore outcrops that descend below mean low water. It is thought that the total (ie cumulative) extent of rock platform exposure may have reduced slightly from 1880 to 1990 (Posford Duvivier, 1995).

2.4 Aeolian Input

A1 Dawlish Warren

Sand dunes at the top of the backshore on Dawlish Warren (Photo 4) accumulate aeolian transported sand removed from the foreshore. However, foredune erosion also occurs when modified storm waves are incident on the beach, usually in association with rising tide. It is uncertain if these counter-acting processes are in balance, especially, as a range of dune conservation measures are now practised. Losses to inland, and into the Exe estuary marshes behind, due to wind deflation take place, but their quantitative importance is not known. Some of the dunes have been artificially created, and vegetated, as part of the flood defence strategy over the past 30 years.

3. LITTORAL TRANSPORT

LT1 Holcombe to Dawlish Warren

The net direction of littoral drift between the Parson and Clerk headland and Langstone Rock is southwest to northeast. This is evident from sand accumulation against the latter headland, and the breakwater deliberately built to encourage beach accretion against the wall protecting the coastal railway line (Photo 6). From the evidence of beach setback immediately north of Langstone Rock, it is effective in trapping sediment drifting north-eastwards, thus functioning as a large terminal groyne. However, as some bypassing would appear to take place during periods of high wave energy, it is classified therefore as a fixed, but partial, transport barrier. Over the last 140 years, railway engineers have experienced persistent problems with the exposure of the footings of the seawall, due to beach drawdown. This would suggest significant cross-shore transport involving both net onshore and offshore exchanges under varying incident wave conditions (Posford Duvivier, 1998a). Drawdown erosion is normally experienced during winter, and recovery (accretion) during summer. The longer-term trend would appear to be one of beach erosion, probably influenced by wave reflection from the seawall; however, quantitative evidence in support of this was not available for this study. The archive of beach levelling data, now held by the successor company to Railtrack, needs
to be analysed. Posford Duvivier (1998a) state in their analysis that MLW has moved landwards since 1890.

There are small pocket beaches, held between headlands, in coves between Holcombe and Dawlish. These are supplied by erosion of adjacent cliffs, with possible input from nearshore. Some bypassing of the headlands between Horse and Coryton’s coves may occur when high energy waves approach from the southwest. Posford Duvivier (1998a) estimated a net northward drift potential of 68,000 m$^3$ a$^{-1}$ at Holcombe by modelling transport using a hindcast wave climate. It almost certainly overestimates actual transport for it was assumed that all material was sand, abundant material was always available and that beaches were unimpeded. A net north-eastward potential drift of 13,300 m$^3$ a$^{-1}$ was estimated off Langstone Rock (Posford Duvivier, 1998a). These estimates suggest that drift should diminish along the pathway, although actual transport is low throughout as beaches are depleted and relatively little sediment is intercepted by groynes at Dawlish (Photo 12).

There are numerous observations, but relatively few measurements, of littoral drift along the seaward face of Dawlish Warren spit (Photo 4). All authorities are in agreement that the net direction is south-west to north-east i.e. from its proximal to distal end. This, of course, is evident from the orientation of this large accretion structure, although its evolution and present day morphodynamics are related to the complex pathways of sediment transport at, and seawards of, the entrance to the Exe estuary (Sims, 1998; Posford Duvivier 1998b). Further details are given in Section 4.1 and Section 5.1. Redfearn (1993) states that because the beach face of Dawlish Warren has progressively adjusted from a drift to its present day swash alignment, net longshore drift rates would be expected to be relatively low. This was confirmed by repetitive profiling either side of groynes functioning between 1987 and 1993. Turner (1996) came to a similar conclusion, and was further endorsed by analysis of beach profiles 1986-1994 by Posford Duvivier (1994, 1998b). The history of Dawlish Warren over the past four centuries (Kidson, 1950; 1964; Durrance, 1969; Sims Weaver and Redfearn, 1995; Sims, 1998) clearly indicates net erosion at the proximal “root” and accretion in the distal zone, but with major fluctuations in shape and volume.

Posford Duvivier (1998b) undertook a theoretical study of potential drift rates determined by wave hindcasting based upon recent wind speed and direction data. A rate of approximately 8,800 m$^3$ a$^{-1}$ was calculated for the central sector; a slightly higher rate, 9,100 m$^3$ a$^{-1}$, is suggested at the “root” of the spit, at Dawlish, in Posford Duvivier (1998a). Where the spit recurs to face into the Exe estuary, at Warren Point, Posford Duvivier (1998b) argue that the prevailing drift rate declines very abruptly to 1,100 m$^3$ a$^{-1}$. This is ascribed to the influence of Pole Sand attenuating and refracting nearshore waves. The above figures relate only to wave-driven inter-tidal beach transport; waves and tidal currents acting together potentially move substantially greater quantities of sand across the adjacent nearshore zone in the vicinity of the Exe inlet.

**LT2 Orcombe Rocks to The Point, Exmouth**

The sector of shoreline between Orcombe Rocks and The Point, Exmouth (Photo 3 and Photo 7) and has a well-documented history of fluctuation of beach levels and volumes (Hydraulics Research Station, 1963; Posford Duvivier, 1994; 1995; 1997, 1998a, b and c). There is no apparent direct supply of sand from the littoral drift system operating along Dawlish Warren. However, complex transport movements in the Exe approach channels and via offshore banks...
provide indirect supply from these sources (see Section 4.1 and Section 5.1). The presence of Pole Sand and Dawlish spit, and their complex fluctuations in size and shape over time, has been decisive in providing variable protection from, or exposure to, wave action. Waves approaching from the west or southwest are significantly affected by refraction, diffraction and transformation by shoaling and tend to be constructive. When waves from the east-southeast are dominant, beach drawdown, due to net on to offshore sediment movement, is usually experienced (Posford Duvivier, 1997, 1998b). Although, this is related to the presence of the Exe tidal channel, which abruptly terminates the foreshore, it is probably accentuated by basal scour induced by the seawall and promenade backing this frontage. The western end of this beach, now protected by a rock armoured revetment and groynes, has shown comparative stability over the most recent 10 to 15 years (Posford Duvivier, 1998b). Previously, it would tend to loose sediment in phase with erosion of the distal end of Dawlish spit (Warren Point). Most of the rest of this beach showed an erosional tendency in the 1980s and 1990s.

The net littoral drift pathway is east to west towards Exmouth spit, reflecting a combination of factors influenced by the presence of the Exe tidal inlet. These include local wave climate; sources of sediment feed and the role of coastline orientation in creating an anticlockwise tidal gyre. Most of the sediment moved is sand, but gravel can be mobilised when high wave energy impacts on the beach. Posford Duvivier (1998a) calculated the potential drift rate on the Maer Rocks frontage to be approximately $15,000 \text{ m}^3\text{a}^{-1}$, declining rapidly westwards to $4,500 \text{ m}^3\text{a}^{-1}$ between The Maer and the Lifeboat Station, Exmouth. These values for shoreline transport are an order of magnitude less than the sediment fluxed that were calculated to occur over the ebb tidal delta further seaward (Section 5.1). The sandy foreland of the Maer (Photo 3) with its dune system appears to be a product of long-term shoreline accretion that has produced a shoreline progradation of some 400m over a 1km frontage. Exmouth spit is the product of long-term westerly drift, but has been completely built over and can no longer accrete sediment via possible supply from offshore banks. It is composed of both sand and gravel, suggesting pulsed input of coarse sediment up until the end of the nineteenth century, when its natural dynamics were curtailed.

**LT3 Straight Point to Orcombe**

Both Orcombe and Straight Points are considered absolute boundaries for bedload transport of coarse sediment (Posford Duvivier, 1998a), but their role in impeding the movement of fine sands is uncertain and the former headland almost certainly allows some passage (Photo 7). Thus, the beach between the two headlands is relatively self-contained, with negligible littoral exchange with adjacent beach sectors. This is a wide sandy beach with a narrow backshore berm of coarser sediment supplied from local erosion of high sandstone and breccia cliffs. Cross-shore transport would appear to be more important than longshore in regulating beach morphodynamics, but knowledge is limited to inference from observation of profile changes. Foreshore width implies a net offshore to onshore pathway.

The prevailing direction of longshore drift is not certain, but a net eastwards movement is consistent with the increase in beach width towards Straight Point. However, this is not a consistent feature, indicating the probability of drift reversal in response to changes in the approach, and energy, of incident waves. The “terminal groyne” effect of Straight Point is especially pronounced, in comparison to Orcombe Point and gives a clear impression of the dominance of eastward drift. The accompanying map therefore indicates net eastwards
movement, thus identifying Orcombe Point as a divergence point for littoral drift. Not all evidence agrees with this view and Posford Duvivier (1998a) estimated a net westward drift potential of 10,000 m$^3$ a$^{-1}$ at Straight Point and 15,000 m$^3$ a$^{-1}$ at Maer Rocks (Posford Duvivier, 1998b) by modelling transport using a hindcast wave climate. It may be that the drift divergence actually occupies a zone between the Orcombe and Straight Point headlands rather than being represented by a precise location.

4. OUTPUTS

4.1 Estuarine Transport

EO1 Exe Estuary

The Exe estuary is ebb dominant and ebb tidal currents concentrated at its narrow inlet are considerably faster than the corresponding longer duration tidal flows (Halcrow, 2002). Sediments drifting into the inlet from the convergent Dawlish and Exmouth shoreline pathways are flushed several kilometres seaward until the ebb tidal current disperses and wave action tends to drive material back landward (Posford Duvivier, 1998b). Deposition occurs where the two opposing forces are evenly balanced forming the ebb tidal delta of the Pole Sand (Photo3). Wave action tends to drive shoreward the sediments of the delta so that they eventually drift back into the inlet and are again flushed seaward within an anticlockwise circulation system. The dynamics of this circulation and the morphological features produced are explained further within Section 5.1.

The following provides an account of sediment transport at the inlet and within the estuary:

All authorities are agreed that marine sediment are dominant, with both tidal currents and waves capable of moving both fine sediments (in suspension) and coarse material (as bedload) into and upstream of the estuary entrance (Thomas, 1980; Merefield, 1982 and 1984; Posford Duvivier, 1998a and b). Fluvially derived sediment input is now negligible (see Section 2.2), but may have been of greater relative significance prior to catchment management measures introduced from the sixteenth century onwards. Some gravel and coarse sand may derive from erosion of sediment infills of earlier (Pleistocene) buried channels and valley terrace deposits. Breccia units within the underlying basement rock could also provide a source for coarse clastic material, most of which now occurs at tidal channel margins.

The only distinctive type of sediment that gives strong circumstantial evidence of marine input is that of biogenic origin. Merefield (1982) calculated that 9% of the content of estuarine silts and clays is finely divided and well-mixed carbonate. Some of this, estimated at 4%, derives from lithoclasts in the New Red Sandstone, leaving some 5% that is likely to be introduced from the external marine environment. Microscopic analysis demonstrated that much of this carbonate is in the form of well-abraded grains, suggesting derivation from open coast beaches and near/off-shore banks. However, the ultimate source of this material is benthic organisms. Murray (1987) was able to identify the seabed of the central-western English Channel as the most probable origin of some foraminiferal tests present in samples of silts and clays obtained from the upper and middle reaches of the inner Exe estuary. Both of
these studies, and Merefield (1987), thus suggest a long distance and long timescale pathway of estuary supply. It is probable that fine-grained minerogenic sediment is similarly transported, though no experimental work has yet been undertaken to substantiate this.

Posford Duvivier (1998b) postulate that waves and tidal currents introduce some 18,000 m$^3$ a$^{-1}$ of sand and gravel (predominantly sand) to the estuary entrance. An unquantified proportion of this feed is supplied by shoreline drift that is flushed off the distal points of Dawlish Warren and Exmouth spits. Much of this contributes to the flood tide delta of Great Bull Hill bank, where a proportion is retained (see Section 5.3). Perhaps some 900 to 1,000 m$^3$ a$^{-1}$ is moved into the upper estuary, where it is retained.

Referring to the estuary entrance, Thomas (1980) notes that flood tide velocities diminish rapidly upstream, thus the depositing of coarse to medium sand is restricted to this area under normal hydrodynamic conditions (Photo 8). However, exceptional storm waves at the mouth of the Exe can affect up-estuary transport of both coarse sand and gravel. The stronger ebb tide sweeps around The Point, Exmouth and moves substantial quantities of sand offshore, via the Inner Way. A large mussel bed has accumulated adjacent to the northwestern edge of Great Bull Hill Bank. This has a high surface roughness and assists in the trapping of muddy sand. After the mussels are harvested, rapid erosion of sand occurs, most of which appears to move upstream; most of this may be deposited and then re-entrained by the ebb current, resulting in no net sedimentation. Thomas (1980) reports the presence of dune structures on sandbanks either side of Great Bull Hill Bank, indicating a flux of tidally controlled transport and - probably - considerable re-working during each tidal cycle. “Normal” input by the flood current and output via the ebb stream may, however, be approximately balanced. This was also the provisional conclusion of Posford Duvivier (1998b). Thus, any net again - which is apparent from the gradual accretion of Great Bull Hill Bank (Section 5.3) and the presence of sandy deposits in parts of the middle estuary such as the Shagglies and Starcross Sand, must come from high magnitude storm events.

Thomas (1980) proposes that a division between dominantly marine and fluvially-derived sediment occurs close to the confluence of the River Kenn, on the western estuary shoreline. Although, no objective evidence, e.g. analysis of clay mineralogy, is provided in support of this, it is true that clay and silt is the dominant surface deposit in the upper estuary (Photo 13), north of a line between the mouth of the Kenn and Lympstone. Shell debris is relatively poorly represented here.

Although some localised losses may be occurring as a consequence of Spartina anglica “dieback” along the margins of some saltmarsh areas, the mudflats of the Exe are currently experiencing a slow net accretion (Thomas, 1980). The relative positions of the main channels have hardly changed over the past 130 years, suggesting that deposition is slowly raising mudflat elevation. Most of this input of fine sediment is via suspension transport by tidal currents, though internally generated wind waves may have an independent role in entraining sediment in shallow water areas. Waves certainly help to maintain sediments in suspension. Sims and Weaver (1990) report that a short sampling programme revealed suspended sediment concentrations, on the flood tide, to be between 3.52 and 9.9 mg. litre offshore the distal tip of Dawlish Warren; and between 6.52 and 25.07 mg. litre further into the lower estuary. Both sets of samples were obtained from close to channel boundaries, so are unlikely to be representative of the estuary as a whole. They do, however, hint that concentrations initially increase up-estuary, which could suggest that silt and clay-sized particles introduced from marine sources are not a dominant component of the total flux of
suspended load. It might be postulated that concentrations in the upper Exe estuary will be lower than they are closer to the entrance because of deposition in between due to clay particle flocculation. However, the evidence of the lack of conversion of remaining mudflats to more elevated saltmarshes following eighteenth and nineteenth century land claim suggests that rates of accretion are very slow. Thomas (1980) suggests that much of the sediment added to mudflats is in pelletised form, i.e. a result of ingestion and excretion of both organic and inorganic debris by infauna.

Most of the available evidence indicates that the overall estuarine sediment budget is in balance or is weakly positive due to inputs of marine suspended sediments and some sands at the entrance (Thomas, 1980). It is uncertain how much of the total sediment flux involves recirculation, and whether there are any sub-system periodicities affecting the storage of coarser sediments. The only piece of definite evidence is the recent, and continuing, accretion of the flood tide delta. This almost certainly involves the diversion to storage of sand introduced from nearshore and offshore sources.

The estuarine ebb flow is a significant source of sediment to Pole Sands, though not the only source. (see Section 5). Both waves and tidal currents combine to move sediment both up and down the Exe Channel as bedload. The ebb tidal stream is supplied by wave-driven sand moving towards, and then across, the eastern boundary of Pole Sand, especially under storm conditions. A further source, more constant but of less volumetric significance, derives from both flood tide and wave erosion of Warren Point. All of this sediment moves down channel, but some if it is reversed by waves moving into the outer estuary, and by the returning flood tide (Posford Duvivier, 1998b; Laming and Weir, 1991). Ebb and flood channels are independent of one another, though Laming and Weir (1991) suggest there might be a type of progressive cycle of erosion and accretion for each major channel. Thus, the “switching” or migration of ebb to flood function, and vice-versa, is an unproven possibility.

4.2 Dredging

Dredging is undertaken to maintain a navigation channel leading to Exmouth docks. The maintained channel is 100 to 200m in width and varies in depth from -12m CD at Exmouth Dock entrance to -1.5m CD in the eastern Maer Channel. Posford Duvivier (1998b) state that, for the past several decades, the average annual volume of dredge spoil has been about 500m$^3$. However, in 1986, 40,000m$^3$ was removed, in response to sandbank formation and general accretion over the previous 25 years. A similar quantity was dredged in 1996, because of the formation of several small banks, and their eventual merger into a shallow zone, during the previous 10 years. Laming and Weir (1992) calculated that some 156,000m$^3$ of sediment, most of it sand, were deposited in the channel system between 1986 and 1992. Spoil is dumped seawards of Spey Point, in a water depth of approximately 10m, and is probably re-distributed seawards into deeper water. It therefore represents a loss - albeit a small, relatively insignificant one - to the regional sediment budget. Its effect is to marginally reduce the size of the surplussediment entering the approach channel. Posford Duvivier (1998a and b) have pointed out that sustainable shoreline management would be enhanced if dredging could be undertaken periodically to provide material for local beach replenishments.
4.3 Reclamation

Considerable areas of the Exe estuary have been reclaimed causing impoundment of their intertidal sediments. Parkinson (1980) has examined the historical evidence for drainage and land claim in the Exe estuary, and concludes that saltmarsh may have occupied over 1,000 ha at the beginning of the medieval period. It was previously continuous along the margins of the lower Clyst estuary and the east bank from Exton to south of Lympstone. Land claim was a semi-continuous process between the early eighteenth and mid-nineteenth centuries, especially along the west bank between the River Denn and Exminster where up to 500 ha could have been involved. This process, together with the construction of the railway embankments along both banks (Photo 14), would account for the loss of tidal flats and much of the saltmarsh. Parkinson (1980) also notes that land claim throughout the estuary induced siltation, resulting in the infilling of numerous pre-existing creek channels. She does not offer a causal explanation, but the reduction of the estuary’s tidal prism is a probable major factor.

5. SEDIMENT STORES AND SINKS

5.1 Outer Exe Estuary

N.B. The major morphological features, and transport pathways, discussed in this section are diagrammatically illustrated on the accompanying enlarged map. In contrast to all other maps, its shows transport vectors unaccompanied by identifying letter notations. These arrows cannot, therefore, be used interactively. Generalised (net) sediment transport directions are, however, indicated by EO1 and F1 arrows on the smaller scale map covering this unit of coastline as a whole.

The outer Exe estuary is taken here to extend from The Point, Exmouth and the distal end of Dawlish Warren (Warren Point) eastwards to the end of Maer Channel (Orcombe Rocks) and for several km seaward to the outer margin of the ebb tidal delta (Pole Sand). Its main features are the extensive sandbank of Pole Sand, and the well-defined tidal channel of the Exe, which is deflected strongly towards the north-east (Exmouth) shore (Photo 3). Outcrops of Permian sandstones and breccias occur close to, and in places determine, the northern boundary of this channel. Examples include Conger Rocks, Maer Rocks and Checkstone Ledge. The Exe channel sharply truncates, causing the steeping of the foreshore slope in front of the Exmouth to Orcombe shoreline. Several independent sandbanks occur within the Exe estuary, causing subdivision into several minor channels that together create a type of distributary pattern. Most of these have fluctuated in size and position in recent years, such as Finger, Platypus and Boomerang Banks.

Until recently, there were few comprehensive or detailed studies of the Exe outer estuary system as a whole. However, an improved, though still uncertain - understanding has been achieved through studies undertaken by Posford Duvivier (1994; 1995, 1998b). The last was specifically commissioned as part of the regional Shoreline Management Plan (Posford Duvivier, 1998a).
Pole Sand

This extensive sandbank of Pole Sand is co-adjacent to the foreshore of Dawlish Warren spit, and extends several kilometres seawards. Its eastern boundary is sharply delimited by the Exe estuary channel, but its southern or outer edge is diversified by a sequence of embayments separated by low spurs, or ridges (Herrington Geoscience, 1995). Asymmetric sand waves and ripples are almost continuous across the eastern half, which is also somewhat lower in elevation that it is to the west. Superimposed over the surface of Pole Sand are smaller, distinct sandbanks whose dynamic behaviour indicates some independence from the “host” feature.

Analysis of Admiralty hydrographic charts back to the early nineteenth century indicates that although the overall shape of Pole Sand has been constant for nearly 200 years, it has steadily accreted sediment over this time period. Posford Duvivier (1998b) calculate approximately $1.8$ to $1.85 \times 10^6 \text{m}^3$ of sand has accumulated since 1840, whilst Sims, et al (1995) deduced a 42% increase in volume between 1888 and 1956. Evidence suggests that despite short-term fluctuations, this accretion tendency has persisted up to the present.

There is little detailed information on the sedimentology of Pole Sand. Harrington Geoscience (1995) state - apparently on the basis of a non-systematic collection of grab samples - that median grain size diminishes in a broadly west to east direction. Very fine sand is dominant across its south-easterly extremity. However, rapid sediment size coarsening occurs in the area immediately adjacent to the Exe tidal channel, with some additional presence here of fine gravel.

Exe Estuary Channel

The northern boundary of the Exe Estuary Channel is well defined by the Exmouth to Orcombe Point foreshore and several rock outcrops, but the southern boundary is more diffuse. This is due to the presence of several sub-parallel sandbanks and intervening shallow channels. All of these features are subject to fluctuations in both shape and volume. West of Conger Rocks the ebb and flood channels are independent, and are well incised in the entrance section known as the Narrows. The flood channel here is adjacent to the distal end of Dawlish Warren and continues to the west of the flood tide delta of Great Bull Hill Bank (see Section 5.3). Ebb tidal current velocities exceed $2\text{ms}^{-1}$ off Warren Point, sufficient to promote scour and prevent accretion of sand. There, may be some interaction with the flood current (Laming and Weir, 1991), although Finger Bank occurs between mutually evasive ebb and flood channels.

The eastward boundary of Pole Sand is swept by the ebb current, but it is uncertain if the latter is able to restrain sedimentation. Indeed, it is probably more realistic to consider Pole Sand deflecting the ebb current (and also the flood, to a lesser extent) towards the Exmouth shoreline (Laming and Weir 1992, 1994; Herrington Geoscience, 1995). Sandy gravels floor at least parts of the ebb channel, with small sand “ribbons” aligned parallel to the direction of maximum velocity flow. In recent years (since approximately 1972), there has been progressive channel narrowing in the sector west of The Maer (Exmouth). For a longer period, at least since about 1950, the channel opposite the main town frontage has been slowly migrating landwards. In contrast, further out, opposite Orcombe Point, the channel has moved south-westwards over the same period (Posford Duvivier, 1994; 1998b). This has resulted in an increase in channel sinuosity, and confirms that scour close to The Point has
been replaced by differential erosion and deposition (Posford Duvivier, 1994; 1995; 1998b). Herrington Geoscience (1995) calculate, on the basis of analysis of detailed bathymetric chart evidence, that some 100,000m$^3$ (5,000m$^3$/a$^{-1}$) of sand accretion took place in the outer (Maer) channel between 1974 and 1994. However, the requirement to dredge the access channel to Exmouth Dock (see later) indicates that net accretion has been a feature of the inner channel, as well. Most of the outer sandbanks have grown northwards, i.e. towards the inner estuary entrance, since at least the mid 1980s (Posford Duvivier, 1998b). This is further evidence of an accretionary trend.

In their conceptual model of the transport regime of Pole Sand and the Exe channel, Posford Duvivier (1998a and b) propose wave-driven bedload transport of sand across Pole Sand from the east, south-east and south. This represents “fresh” input from seabed/shelf reserves further offshore, and helps to account for the net gain of sediment since at least the mid nineteenth century. Kidson (1950; 1964) argued that Pole Sand must be the product of large quantities of sand moved shorewards during the Holocene, as sea-level rose. However, he inferred (Kidson, 1964) that net onshore supply no longer functions from evidence of the rapid erosion of Dawlish Warren spit during the preceding 30 years. Hydraulics Research Station (1965) also presumed that Pole Sand was now a finite reserve of sediment. This conflict of opinion has not been resolved, though the known presence of asymmetric bedforms is supportive of active wave transport. Posford Duvivier (1998b) also propose that wave-transported sand enters the outer Exe estuary, although the evidence for this assertion is not given. A proportion of this input appears to be carried into the estuary by the flood tide.

The only other significant source of sediment input is via the ebb current discharging via the inner estuary through the Narrows, or Inner Way, and seawards to the vicinity of Maer Rocks. Beyond this it has insufficient energy to transport material as bedload (Laming and Weir, 1991; 1992; 1994). The composition and size of the flood tide delta of Great Bull Hill Bank is proof that both wave transport and the flood tide current independently introduce marine sediment into the inner-estuary (see Section 5.3).

**Sediment Transport Pathways and Rates**

Posford Duvivier (1998b) have presented an essentially conceptual view of the main pathways of bedload sediment transport. Tidal currents are considered to be significant sources of both erosion and transport in the inner section of the Exe channel, due to high velocities. The distal end of Dawlish Warren spit may be controlled by both flood and ebb tidal scour, though it is likely that wave-propelled movement of sand is also important here. Given its greater velocity, the ebb tidal current has more capacity for bedload transport, but an unknown proportion of sediment moved by it is returned via the flood stream.

As stated in the preceding section, transport across Pole Sand is predominantly by waves. This resolves into both net onshore and offshore components, the latter most likely to operate during storms. Posford Duvivier (1998b) suggest, based on hydrodynamic modelling, that almost one fifth of annual sediment transport flux may be accounted for by a single, high-energy storm. The relatively rapid migration of banks and bars may also be the result of substantial movements of sediment by storm waves. During these conditions, it has been observed (Sims, et al, 1995; Sims, 1998) that beach and foreshore erosion along Dawlish Warren coincides with crest flattening on Pole Sands - i.e. both loose sediment simultaneously. Normally, beach recovery takes place over succeeding weeks of “normal”
conditions, thus suggesting that net onshore and offshore transfers may be in approximate balance.

In addition to this on-offshore component, longshore transport is also largely determined by wave action in the nearshore and beach environments. This is discussed in Section 5, where it is suggested that convergent drift pathways at the entrance to the inner estuary may supply some of the sediment moved by tidal currents. There is no direct evidence that longshore transport can by-pass the main estuary channel, though it is a theoretical possibility in the outer estuary where tidal currents are weak.

Both waves and tidal currents combine to move sediment both up and down the Exe Channel as bedload. The ebb tidal stream is supplied by wave-driven sand moving towards, and then across, the eastern boundary of Pole Sand, especially under storm conditions. A further source, more constant but of less volumetric significance, derives from both flood tide and wave erosion of Warren Point. All of this sediment moves down channel, but some if it is reversed by waves moving into the outer estuary, and by the returning flood tide (Posford Duvivier, 1998b; Laming and Weir, 1991). Ebb and flood channels are independent of one another, though Laming and Weir (1991) suggest there might be a type of progressive cycle of erosion and accretion for each major channel. Thus, the “switching” of flood to ebb function, and vice-versa, is an unproven possibility.

Combined wave and flood tide sand transport may account for the landwards shift of a low bank towards Dawlish Warren between 1961 and 1990 (Posford Duvivier, 1994). Over this period, some 300m of movement was recorded accompanied by some net accretion. The recent movements of Boomerang Bank, detailed in Herrington Geoscience (1995) are a further example. Wherever there is gravel, or a mix of fine gravel and coarse sand, wave transport alone is implied.

Posford Duvivier (1998b) calculate potential rates of sand transport along the vectors shown on the accompanying (enlarged) map. For Pole Sand, waves introduce some \(116,000 \text{m}^3 \text{a}^{-1}\) at the eastern extremity, but less than \(13,000 \text{m}^3\) across the south-west boundary. These rates reduce to \(7,700 \text{m}^3 \text{a}^{-1}\) across the central area. The large difference is accounted for by either net offshore removal or deposition in the intervening area. The former is more likely. Some \(15,000 \text{m}^3 \text{a}^{-1}\) is moved by waves into the eastern extremity of the Exe channel, but the net sand transport rate off Exmouth Beach drops to \(4,500 \text{m}^3 \text{a}^{-1}\), with a westerly component. This reduction reflects both net accretion and the opposing influence of the ebb tidal current.

All of the above figures are derived from hydrodynamic modelling, using a range of sediment transport equations for an assumed median grain size of 0.5mm. There has been no field verification of processes, pathways, rates and volumes of sediment transport.

**Overall Sediment Circulation System**

Posford Duvivier (1998b) conclude that there are two distinct, though ultimately coupled, circuits of bedload sediment movement, namely:

(i) Wave-driven net onshore and longshore movements across Pole Sand towards Dawlish Warren. Closer to the shoreline there is a distinct northeastward component towards the eastern edge of Pole Sand. Flood tidal currents combine with waves to introduce sediment into the Narrows Channel (Exe inlet) between Warren Point and Exmouth.
(ii) Dominant ebb tidal transport southeastward along the Exe inlet channel to accreting sandbanks flanking the Maer Channel. Transport of this offshore moving sediment is reversed by waves in the outer estuary, where tidal currents rapidly lose transporting capacity. These sandbanks are thus driven northwestward by wave action providing much of the source material that feeds within circuit (i). This onshore-moving traction load is then available entrainment within the flood current as it approaches the Narrows, although it is much weaker than that set up by the ebb current.

The link between these two circuits occurs where the elongated salient of Pole Sand and the outer channel are adjacent (Photo 3). Not all of the principal pathways of transport are operating simultaneously, because of systematic variation of current velocities during each tidal cycle and more random variation of incident waves. For example, during storms, sand would be moved directly from Pole Sand into the Exe channel, possibly accounting for the deposition of gravel there. High-energy waves approaching from the east might also move sediment, both sand and fine gravel, towards Dawlish Warren. This, however, is less certain as accretion along the north-west edge of Pole Sands is probably due to the drawdown of the Dawlish Warren foreshore.

Posford Duvivier (1994; 1995) state that as Pole Sand and the Exe estuary channel show a tendency towards net accretion, the overall sediment budget is positive. This conclusion infers that “fresh” input must come from either offshore or longshore, possibly both. As the latter is a very small quantity, an offshore reserve of sand is the only feasible source. This, however, has not been proven, possibly influencing Posford Duvivier (1998a and b) to state that the two circulation systems - outlined in the previous section - are in approximate equilibrium, with losses and gains within each in balance. As these two systems are coupled, then this concept of budgetary balance may be applied to the transport system as a whole. Perhaps, over the longer timescale of a century - perhaps several centuries - steady accretion gains at various locations are cancelled out by large magnitude losses during major storms. The evidence is therefore insufficient to permit reliable conclusions concerning the status of the contemporary budget to be drawn. Much more research and monitoring is needed before a quantitative approach to the problem can be attempted.

An unanswered question concerns the origin of the large quantity of sediments stored within the banks around the entrance of the Exe estuary. Two probable sources are: (i) local cliff erosion between Straight Point and Holcombe, especially prior to protection of the Holcombe to Dawlish Warren frontage and (ii) inherited sediments combed up and driven landward by shoreline transgression across Lyme Bay during rising sea-levels of the mid to late Holocene. The indentation formed by the Exe valley would have sufficed to “capture and retain” available sediments. There sources are now either much reduced or exhausted, respectively.

5.2 Dawlish Warren

This large, south-west to north-east orientated sand spit is some 2.5km in length, and has an average width of 500m (Photo 4). Its mean elevation is approximately +1.4m, O.D. increasing to over +6.0m in the area of dune stabilisation adjacent to the north-central corridor linking its proximal and distal ends. Orientation abruptly changes where the spit is at its narrowest, creating a recurved distal point aligned nearly parallel to the adjacent flood tide channel at the mouth of the Exe estuary. The main factor controlling distal alignment is the
approach direction of waves from the east, south-east and south-west, which are refracted by the offshore presence of Pole Sand and other banks. However, the flood tide channel is well incised, having shown little change in position for nearly 200 years; it therefore constrains the position of the distal recurve, the seaward slope of which is steep.

Fine to medium sand constitutes the bulk of the sediment store composing Dawlish Warren, but with some coarsening at both its proximal and distal ends. At the former, coarse sand, with a small quantity of gravel, is less well sorted than along the main spit corridor (Redfearn, 1993); the coarsest fraction is probably derived from updrift sources, by-passing Langstone Rock. Although most of the sand making up the distal sector is finer in texture than it is updrift, a locally significant input of coarse clastic material occurs at the distal tip. This forms as beach which often has a multiblermed form, made up from particles composed of flint, chert, sandstone and quartz (Sims, 1998). These are almost certainly moved to and deposited at this site by storm waves, though peak flood tidal current velocities (over 3.0 ms\(^{-1}\)) probably also move both very coarse sand and fine gravel. Sims (1998) has recorded a coarse beach deposit along the eastern part of Inner Bay, which also has individual clasts of varied mineralogy. This is a probable storm beach, although there are no records of changes in morphology and/or clast composition/sorting following storm events. As there is also accumulation of broken shells at this point, it may derive in part from erosion of the flood tide delta of Great Bull Island Sand (Sims, 1998). Sub-surface stratification of alternating layers of coarse and fine material (of variable thicknesses) might point to fluctuations in wave energy, or more complex combinations of wave and tidal transportation.

The foreshore of the main spit axis shows seasonal fluctuations in cross-profile form, and is often characterised in summer by ridge - and - runnel sequences (Redfearn, 1993). Turner (1996) analysed sets of beach profiles, covering the full intertidal zone, measured between 1987 and 1995. He observed that the distal end experienced greater inter-annual volume changes than the proximal part, though both showed summer construction and winter drawdown. Sand dunes at the top of the backshore accumulate aeolian transported sand removed from the foreshore. However, foredune erosion also occurs when modified storm waves are incident on the beach, usually in association with rising tide. It is uncertain if these counter-acting processes are in balance, especially, as a range of dune conservation measures are now practised. Losses to inland, and into the Exe estuary marshes behind, due to wind deflation take place, but their quantitative importance is not known. Some of the dunes have been artificially created, and vegetated, as part of the flood defence strategy over the past 30 years.

Waves approach the central sector of Dawlish Warren at a shallow angle due to refraction by Pole Sand. This part, some 1850m in length, is swash-aligned. Longshore drift is therefore weak, but with net south-west to north-east transport between the ‘neck’ and the point where distal recurrature starts. Posford Duvivier (1998b) calculated the potential gross drift rate to be 8,400 m\(^3\)a\(^{-1}\) at the landward attachment of the neck of the spit, with a rapid reduction to 1,100 m\(^3\)a\(^{-1}\) at the tip. It is the result of extensive shoaling and refraction of typical incident waves over the East Pole Sand such that shoreline waves become reduced in energy and their crests become refracted to approach parallel to the shoreface contours. Hydraulics Research Station (1965) stated that reversals of the “average” direction of sand transport occur whenever waves from the south-east are incident. These are likely to be relatively short-lived, usually during the winter months. Posford Duvivier (1998b) assert that up to 20% of the annual drift “flux” can occur in a few hours of high energy storm waves. Where the spit
recurves into the mouth of the Exe, the net drift rates drop to a little more than 1,000 m$^3$ a$^{-1}$. (Posford Duvivier, 1998b)

The morphological character and dynamic behaviour of Dawlish Warren has shown considerable change over the past 230 years recorded by maps and charts. In the past 30 years, remotely sensed data has provided additional evidence of change, sometimes suggesting explanations for fluctuations in spit planform (Sims and Weaver, 1990). Summary reviews of the sequences of major changes, are provided by Motterhead (1986); Sims, et al (1995); Sims (1998) and Posford Duvivier (1994; 1998a and b). These draw on earlier, more detailed analyses by Kidson (1950; 1963 and 1964); Hydraulics Research Station (1963; 1965) and Durrance (1969a and b). Redfearn (1993) also gives a comprehensive review, supplemented by analysis and interpretation of original field measurements; Hodgson (1999) includes a summary of the major management interventions of recent decades that have served to restrain natural change.

There is no definitive evidence for the creation and progressive growth of Dawlish Warren spit during the Holocene. Kidson (1964) has suggested that it is the product of the landward movement of large quantities of sand introduced into the present day offshore area by sea-level rise. This would have created a precursor to Pole Sand, and possibly other banks within the Exe approach channel. Pole Sand thus provided a reservoir of sand from which Dawlish Warren was subsequently supplied. A tentative date for the appearance of an “ancestral” Pole Sand might be circa. 6,000 years B.P. At this time, updrift littoral transport, fed by the rapid erosion of Triassic sandstone cliffs, was unimpeded and also provided an input. If this is a valid explanatory approach, Dawlish Warren is not a conventional spit resulting from longshore drift; rather, it owes much to shoreward translation of a large sediment body. This is consistent with the development of coarse clastic barrier beaches along the Start and Torbay coastlines over approximately the same timeframe. The offshore source of sand supply is not known, but may come from sediment deposited during one or more stillstands during early to mid-Holocene sea-level transgression (Clarke, 1969), or during the low sea levels of the preceding Devensian and earlier cold (glacial) stages.

Durrance (1969b) has outlined a conjectural sequence of changes affecting Dawlish Warren, involving both proximal breaching and vigorous distal growth. He suggested that a prototype Dawlish spit was contiguous with Exmouth spit, only to be detached by tidal channel re-incision (see Section 1.1). This evolutionary concept has a “floating” timescale, with proximal detachment taking place in medieval times (Durrance, 1969b) as the last of a series of such events. Implicit in Durrance’s scheme is possible cyclic fluctuation of steady growth, rapid breakdown, dispersal and re-creation. This might have been repeated numerous times, possibly in response to “pulsed” sediment supply and a higher energy wave climate. Although further speculation is not productive, the progressive – if unsteady – erosion of Dawlish spit throughout much of the twentieth century might indicate a degenerate (post-maturity) stage (Kidson, 1964). This would imply some overall failure of supply from Pole Sand, despite the evidence for accretion of the latter feature (Section 5.1).

Kidson (1950; 1964) has provided a comprehensive analysis of the planform changes of the spit since the late eighteenth century. He draws upon earlier work, notably Martin (1872; 1876 and 1893) and Ussher (1878). Further analysis, of both OS maps and Admiralty hydrographic charts, is given in Posford Duvivier (1998b). The salient points are:
(i) Throughout the nineteenth century, Dawlish Warren consisted of two parallel components – the Inner and Outer Warrens – separated by a depression known as Greenland Lake. The latter was a brackish water inlet. Kidson (1950) suggested that the Inner Warren was built from sand removed from the Outer Warren, as in places it rested directly on a pre-existing mudflat surface. The fact that the elevation of the Inner Warren increased north-eastwards was regarded as confirmation of the role of dominant south westerly winds and waves, as the proximal end of the spit adjacent to Langstone Rock would have been relatively protected. It was the view of Martin (1872; 1876), however, that the Inner Warren was the product of the “trapping” of sand behind the Outer Warren, introduced by tidal currents and waves at the mouth of the Exe. Kidson (1964) found evidence of interbedded estuarine clays and sands below a part of the Inner Warren that tended to confirm Martin’s intuitive hypothesis. No researchers have indicated the possible role of aeolian transport from the Outer to the Inner Warren, though dunes were well established on the former in the mid-nineteenth century. One reference in Kidson (1964) suggests that the Inner Warren may have a gravel foundation, but this could be due to relict Pleistocene fluvial sediments (Durrance, 1969a and b), not an early coarse clastic barrier type spit, or conventional spit fed by longshore drift.

(ii) Throughout the second half of the nineteenth century, up until circa 1910, the Outer Warren maintained an overall length of slightly over 2000m. There were, however, short-term periods of both loss and gain in length (Martin, 1872; 1893). The distal end suffered a number of temporary breaches and fluctuated by some 350 m in position with respect to the stable boundaries of the Exe flood channel. Breaching also occurred at the proximal end in 1809 and 1851. From the 1860s, there appears to have been steady recession of the shoreline of the Outer Warren, at a rate of approximately 1.0 ma\(^{-1}\); this increased to 2.0 ma\(^{-1}\) between about 1880 and 1900. Fluctuation of both length and width up to 1850 were identified by Martin (1872; 1876) as evidence that the construction of the seawall protecting the railway line between Dawlish and Teignmouth, which was completed in 1849, was not a primary cause of subsequent erosion of the spit over the two decades that followed.

(iii) Between 1910 and 1932 continuous erosion of the Outer Warren caused its virtual extinction, with the distal sector retreating 160 m over this period. The first of a sequence of defence measures at the root of the spit was put in place in 1917, but failed to prevent on-going erosion. The length of the spit also reduced, by some 400 m, during this period.

(iv) Kidson (1950) described Dawlish Warren as it was in 1949, when the Outer Warren had disappeared and the Inner Warren formed the main morphological feature. At this time, axial length had reduced to 1600 m, but there was some net increase in width over the central sector (Redfearn, 1993). Starting in 1950 or 1951, there was an abrupt reversal of the erosional trend of the previous four decades. Between then and 1962, Dawlish Spit lengthened to 2250 m, although there was little change in mean width; distal re-orientation became more sharply defined. The need to defend against erosion, and a possible breach at the point of attachment to the mainland continued. Between 1950 and 1959, a set of “zig-zag” groynes were introduced, “rip-rap” laid down and dunes stabilised by the planting of grasses and shrubs and the building of brushwood fences. Kidson (1964), in reviewing the behaviour of the spit between 1950 and 1962, found no convincing evidence that there was a two-way, or balanced, exchange of sediment between Dawlish Warren and Pole Sand. It was his view that both simultaneously gained or lost material, for example as a result of storm wave action. Between 1960 and
1966, various sectors of the spit once again experienced rapid erosion, with a total retreat of 80 m along the main corridor, and up to 150 m at critical points close to and at the distal end. The defences put in place at the proximal end were either destroyed, or severely degraded, during these six years of erosional crisis. Hydraulics Research Station (1965) created a physical model of the spit and attempted a simulation of the local wave climate. This led to the recommendation to build a 320 m long impermeable groyne some 750 m south of the distal end as a measure to accumulate sand and widen the foreshore. This was not implemented; had it been built, its impact on the overall transport system linking Dawlish Warren to Pole Sand might have led to atrophy of the distal part of the spit. This, in turn, would have severely disturbed the sediment budget in the outer Exe estuary as a whole (Section 5.1).

(v) The period 1966 to 1972 was one of stability of form, but net erosion of the distal sector occurred during the rest of the 1970s. From 1980 through to the present day, the overall form of Dawlish Warren has been maintained, but with some significant net accretion at Warren Point at the end of the main distal recurve (Posford Duvivier, 1998b). During this period, the vulnerability of the proximal end to erosion, and potential wave overtopping was addressed through (a) the construction of a concrete revetment and gabions in 1973 (Photo 4), severely damaged in the severe storms of the winter of 1989/90; and (b) a wave return wall fronted with 35,000 tonnes of a rock armour (Sims, 1998; Posford Duvivier, 1991; Hydraulics Research, 1991). These various defence measures, by “fixing” the position of the neck of the spit may have been the main factor creating a small change in the orientation of its main axis between about 1975 and 1995 (Posford Duvivier, 1998b). By the early 1980s, the interbedded estuarine clays and sands that accumulated in Greenland Lake prior to the removal of the Outer Warren were exposed in the eroding foreshore.

It is uncertain if distal accretion during the most recent 20 years has been at least partially supplied by ongoing, if slow, erosion of the foreshore and dunes. Since the early 1960s, several measures have been used to stimulate dune growth and conserve their sand reserve (Section 5.4).

The general consensus today (Posford Duvivier, 1998a and b) is that the sediment budget of Dawlish Warren is directly dependant on supply from Pole Sand. The latter is a substantial store that receives sand eroded from the spit and returns it under specific hydrodynamic conditions. It is the view of Posford Duvivier (1998b) that there is an “approxim ate time-averaged balance” between these two stores. The above assertion conceals several uncertainties. These include explanations of why there have been frequent, and apparently non-periodic, switches between phases of net erosion and accretion at various parts of the spit. Reasons for this spatial variability are not understood, nor the dynamics linking erosion and deposition to axial lengthening and shortening. Whilst Dawlish Warren has exhibited a history of instability over at least the past 150 years, Pole Sand has grown progressively in volume over the same period. The concept, expressed by Kidson (1963, 1964) that Dawlish Warren is a “late stage” degenerate form, thus remains unproven. The construction of “hard” defences at its proximal end may have reduced its ability to respond dynamically to forcing factors; this may in the future directly affect the distal sector, by subjecting it to more frequent and higher magnitude fluctuations. One point, however, agreed by all authorities is that the supply of new sediment input via longshore drift is negligible. Although cliff inputs have been halted by protection for some 150 years the earlier emergence of Langstone Rock
as a barrier to transport, would also have intercepted the coarser elements of the potential sediment supply.
5.3 Estuarine Mudflats, Banks and Saltmarsh: Exe Estuary

The extensive inter-tidal and sub-tidal mudflats; saltmarshes and, close to its entrance, sand and shell banks of the Exe estuary are evidence of progressive accumulation of sediment over the past 6 to 8,000 years. For fine-grained sediment, the estuary functions as a sink, but for coarser material it is more appropriately classified as a store. The major sources of input have been, and continue to be:

(a) Fluvially-transported sediment mainly from the Exe and Clyst rivers;
(b) Bank side and estuary bed abrasion of the underlying rock substrate.
(c) Marine sources, including sand and gravel from the ebb tidal delta driven through the entrance and a small quantity of sand derived from deflation of Dawlish dunes.

The Joint Nature Conservation Committee (1997) states that the Exe estuary has an intertidal area of 1,201 ha and a shore length of 47.8 km. Mudflats and sandflats occupy 1,135 ha, and saltmarsh 66 ha. The mean spring tidal range at the estuary head, at Topsham, is 4.1 m. Most of the length of the estuary margin is embanked, protecting the railway lines on both sides (Photo 14). Groynes add some further protection in places, with revetments and walls along the urban frontage at Exmouth.

The intertidal flats are composed predominantly of silt and clay, becoming slightly sandier towards the mouth (Photo 8). Behind Dawlish Warren spit, sand is added by wind deflation of the dunes. Great Bull Hill bank, immediately inside the estuary entrance between the distal points of Dawlish Warren and Exmouth Spits is a flood tide delta, with a recent history of accretion. (Laming and Wier, 1994; Posford Duvivier, 1998b see Section 4.1). Its planform has remained relatively constant since the early 1930s, although Shelly Bank composed mostly of mussels, has been added on the northern and western sides. Accretion is estimated at $120,000m^3$ over the past 70 years, giving a potential gain of 16,000 to 17,000 m$^3$ a$^{-1}$ (Posford Duvivier, 1998b). Most of this gain of sediment has contributed to crest elevation, although Laming and Wier (1994) assert that 0.5 m of crest lowering occurred between 1974 and 1990. Various estimates suggest that actual annual rates of deposition have been variable, often well below potential rates. Although now a well-established and stable feature, Kidson (1964) states that it was only a minor form in the mid nineteenth century. Sims, Weaver and Redfern (1995) calculated that Great Bull Hill Bank increased some 17% in area between 1888 and 1968, with most growth occurring up to the 1930s.

The ebb and flood channels at the estuary entrance define its boundaries, although flood flow inundates it at and close to maximum spring high water. Both ebb and flood currents have sufficient peak velocities to scour the bank margins. Tidal transport is the main mechanism providing new sediment inputs, but as coarse sand and gravel is present this must be periodically aided by wave-induced transport. Erosion losses take place during occasional severe storms, but both gravel and shell armouring provide some protection. No research on the sediment budget of this major accretion form has been undertaken, but its long-term history of accretion, together with sediment composition, suggests that marine inputs via the flood tide current system exceed those via ebb tide transport.

Some of its sand supply may derive from material moved by littoral drift to the end of Dawlish Warren spit and then entrained by flood tidal currents. This has not been experimentally proven and Great Bull Bank is in all other respects independent of dynamic
changes affecting Dawlish Warren, Pole Sand and other accretion forms in the Outer Exe estuary. It is also well adjusted to the hydrodynamic regime at the Exe entrance.

Much of the area of intertidal mudflats, which is more extensive on the eastern side of the estuary, is undissected by creeks. It is separated from the estuary margins by limited area of Saltmarsh, particularly: (a) behind Dawlish Warren spit (Photo 4); (b) along the western shore, between Turf and Topsham, and (c) fronting the eastern shore between the lower Clyst river and Exton (Photo 13). A small, fragmented area also survives behind The Point, at Exmouth. The reasons for the absence of saltmarsh along the middle reaches of the estuary are not clear; increased wave erosion resulting from exposure to a larger fetch is suggested by Proctor (1980). Others have suggested that extensive former saltmarshes have been largely lost to land reclamation (Parkinson, 1980).

Parkinson (1980) has examined the historical evidence for drainage and land claim in the Exe estuary, and concludes that saltmarsh may have occupied over 1,000 ha at the beginning of the medieval period. It was previously continuous along the margins of the lower Clyst estuary and the east bank between Exton to south of Lympstone. Land claim was a semi-continuous process between the early eighteenth and mid-nineteenth centuries in this latter area and especially along the west bank between the River Denn and Exminster where up to 500 ha could have been involved. This process, together with the construction of the railway embankments along both banks (Photo 14), would account for the loss of tidal flats and much of the saltmarsh. Parkinson (1980) also notes that land claim throughout the estuary induced siltation, resulting in the infilling of numerous pre-existing creek channels. She does not offer a causal explanation, but the reduction of the estuary’s tidal prism is a probable major factor. The saltmarsh behind Dawlish Warren was planted with 1000 setts of *Spartina townsendii*, taken from Poole Harbour (Dorset) in 1935, to help to arrest mudflat erosion and protect the Inner Warren sand ridge.

Reviews of the floristic composition and community zonation of the saltmarshes of the Exe estuary are given in Gillham (1957) and Proctor (1980). The first account concentrates on the relationship between water salinity and zonation patterns, noting that soil solutions are often higher than seawater on falling tides. At that time – the mid-1950s – the upper estuary marsh was dominated by *Spartina ssp*, *Scirpus maritimus* and *Phragmites communis*, in order of tolerance of saline conditions. *Scirpus maritimus* was also present over areas of poorly consolidated mud close to the western shoreline. Gillham (1957) noted that the *Spartina* planting in the lee of Dawlish Warren had proved very successful, having spread via a series of original “patches”. Substrate stability had been achieved, possibly assisted by the addition of wind-blown sand from the adjacent spit.

Proctor (1980) adds further details on local saltmarsh plant community structure, together with a brief inventory of the distribution of *Zostera augustifolia* (Eelgrass) in the sub-tidal environment. This was most widespread between The Point (Exmouth) and south of Lympstone, occupying an area of not less than 80 ha. This source documents the spread of the hybrid *Spartina anglica* over the low marshes between the mid 1940s and early 1970s, and the appearance of edge dieback in 1972/3 in the lower estuary. In the upper estuary, *Spartina* was still invasive in the late 1970s, having commenced its colonisation of bare mud surfaces in the late 1950s. This pattern of invasion is somewhat different to, and much later than, that experienced in the estuaries of Poole Harbour and the Solent (see appropriate sections of other volumes of this study for details). The effect of the expansion of *Spartina anglica* has been to reduce the floristic variety of the Exe saltmarshes, regarded by Parkinson
(1980) as “immature”. *Halimione portulacoides* (Sea Purslane) survives on sandier substrate, with local dominance of *Salicornia dolichostachya* (Proctor, 1980), but a *Spartina*-dominated monospecific sward is now established north of Exton (below the inner cliff) and at Topsham and the lower Clyst. Over 60% of the saltmarsh adjacent to Dawlish Warren is now *Spartina anglica*.

Above the low and mid-marsh communities, described above, a cover of mixed grasses tolerant of saline conditions occurs. This would seem to be a local variant of upper saltmarsh, probably significantly modified by land claim, drainage, canal and railway bank construction, etc. A low bluff cut into estuarine muds occurs in places below upper marsh areas. It is uncertain if this represents a previous phase of erosion, temporarily arrested by *Spartina* colonisation.

No research has been conducted on the role of *Spartina* in stabilising and accreting fine sediment and this point is not raised in the review of sediment transport in the Exe estuary by Thomas (1980). Some of the suggested controls on plant zonation, other than salinity that are suggested by Gillham (1957) – such as channel geometry and substrate texture – deserve attention.

### 5.4 Sand Dunes

There are two sites where relatively small areas of sand dunes have accumulated, viz (i) Dawlish Warren spit, and (ii) Exmouth, on the opposite shoreline. Their collective area is estimated at 52 ha, although foredune erosion and accretion is a constant process at Dawlish. (Turner, 1996; Holder and Woolven, 1990, Sims, 1998). Well-defined dune ridges and intervening slacks are a feature of the dunes that extend across Dawlish Warren (Photo 4), where sand has been fixed by vegetation colonisation dominated by Marram grass (*Ammophila arenaria*). The plant community in the slacks is a product of complex fluctuations of the groundwater table, currently subject to monitoring by a research group from the University of Plymouth. Some 20 ha of fixed dune grassland have been converted to a golf course and a car park. The effects of trampling resulting from heavy recreational pressure have accelerated natural erosion. Conservation management has introduced several measures to reduce this, including gabions, wire mesh netting, marram grass and tree lupin planting brushwood litter and boardwalks. Semi-fixed and mobile dunes adjacent to the open shoreline of Dawlish Warren allow some mutual exchange with the backshore beach. However, in recent years, there has been a small net loss of dune sand due to blowouts behind the main dune ridge and as a result foredune recession.

Dunes at Exmouth have accumulated at the Maer foreland, south of the Lifeboat Station (Photo 3), where the original dune belt varies between some 170 and 400 m in width and would have covered some 25ha. Total dune area is now less than 6ha having been reclaimed for use as recreational land, thus forming a local sediment sink. Sand supply derives from the wide intertidal foreshore exposed during the ebb tide, with sand drift often partly concealing the promenade and adjacent road. The latter is periodically cleared and returned to the foreshore (Posford Duvivier, 1994). Marram grass provides stability, but some mobile sand moves inland. Sand fences have been constructed to encourage accretion and reduce public risk.
6. COASTAL DEFENCE AND HABITAT INTERFACE ISSUES

The main habitats present include vegetated soft rock sea cliffs, sand dunes, intertidal mudflats and saltmarshes within the Exe Estuary. Extensive reclaimed margins of the Exe estuary have developed into important coastal grazing marshes.

Some 66 ha of saltmarsh and 1200 ha of intertidal flats are recorded within the Exe estuary and up to 500 ha of grazing marshes are also estimated. Studies have not been undertaken to formally quantify the detailed distributions of all of these estuarine habitats, review their “health,” or determine whether they could be affected by maintenance of existing defences. Due to extensive 18th and 19th century reclamation, defences protect much of the low-lying estuary perimeter so that natural estuarine/terrestrial transitions are rare. In particular, the Exeter – Plymouth and Exeter - Exmouth railways run along the western and eastern shores so that their protected embankments (Photo 14) could contribute to “squeezing” of fronting intertidal habitats as sea level rises. Although the reclaimed land is mostly undeveloped and would appear to offer opportunities for realignment of defences, much is valuable grazing marsh that would be threatened by tidal inundation. These types of issue have been studied within the national Living with the Sea Project (English Nature et al, 2003), where it has been suggested that the most sustainable long-term option would be to attempt to relocate grazing marshes to within river valleys away from coastal areas.

The Exe Estuary Project, a partnership of responsible authorities and interest groups has developed to promote the integrated management of the estuary. It has prepared an Estuary Management Plan (Exe Estuary Project, 1998) to promote the sustainable use of the Exe Estuary and provide a framework for co-ordinated management, including an action plan. The document is due for review in 2003. The management plan together with further details of the Exe Estuary Project is provided at the project website at:
http://www.exe-estuary.org/index2.htm

7. OPPORTUNITIES FOR CALCULATION AND TESTING OF LITTORAL DRIFT VOLUMES

The discontinuous nature of the shoreline of this unit with its headlands, defences, pocket beaches, Exe tidal inlet and nearshore banks means that it is unsuited generally for definitive studies of drift. There are, however, opportunities to study drift occurring on the amenity beach between Dawlish and Langstone Rock. An initial approach would be to extend the Posford Duvivier (1998a) numerical model studies of littoral drift potential based on an analysis of a long-term (greater than 20 years) hindcast wave climate. Uncertainties encountered in applying numerical model studies would include:

(a) Imprecision in the selection of synthetic wave climates in the absence of field validation of inshore waves. The east facing orientation and the tendency for significant wave energy to approach from several different direction sectors introduces complexity in the waves actually experienced at the shore;

(b) The problem of selecting a representative sediment gain size on the mixed sand and fine gravel beaches (sediment mobility is highly sensitive to grain size);
(c) Uncertainty relating to the extent to which the rocky headland of Langstone Rock (photo 6), with its breakwater and shore platform, intercepts drift and acts as a barrier to transport.

The resulting potential littoral drift volumes could then be tested by means of a thorough examination of the budget of beach sediments, especially that which accumulates immediately to the south of Langstone Rock. This method would assume that long-term transport can be inferred from changes in beach volume and would offer an independent check on modelling results. For this to be feasible, it is important that beach volumes should be monitored and historical beach volumes and cliff erosion sediment inputs are reconstructed (e.g. using map comparison, historical documentary evidence, perhaps supplemented by photogrammetrically derived data from historical air photos dating back to the 1940s).

8. RESEARCH AND MONITORING REQUIREMENTS

The SMP (Posford Duvivier, 1998a) and Exmouth Approach Channel Study (Posford Duvivier, 1998b) have summarised existing knowledge and added various original insights into the complexities of wave and tidal current-driven sediment transport in the nearshore zone. Several of the observations and provisional conclusions deserve further investigation and there are many uncertainties, requiring focus concentrated on the following issues:

1. Quantitative assessment of the wave climate at a series of inshore points along the unit such as Dawlish Town, Langstone Rock, Dawlish Warren, The Maer, and Orcombe Point. An initial examination of data collected by Posford Duvivier (1998a and 1998b) should attempt to identify the extent to which suitable data already exists, together with any additional studies needed to fill gaps. It ideally requires a representative long-term hindcast offshore wave climate based on some 20-30 years of wind data, together with shoaling and refraction analysis to derive inshore climates for the points selected. Temporary inshore field measurements of waves would be beneficial to validate model studies of the effects of refraction and diffraction on waves approaching from different directions. A magnitude-frequency analysis should also be linked to a quantitative study of the recurrence probabilities of extreme water levels. This is considered important for it is storm waves and storm tidal surges in combination that appear to cause erosion events and sandbank lowering along Dawlish Warren as well as defining overtopping criteria along the Dawlish sea wall.

2. Complementary to the above point, bathymetric surveys of most sectors of the nearshore zones are needed. The main benefit would be to provide more precise input to modelling of the contribution of wave refraction to inshore wave climate. Better knowledge of offshore seabed relief would improve to the planning of other research surveys, such as sediment sampling. Regular bathymetric re-surveys are carried out over the approach channels to Exmouth, and in the entrance of the Exe estuary. This work needs to be maintained, if possible, at greater spatial resolution, and extended to adjacent areas of complex seabed relief. In practice, it would be time and cost-effective if bathymetric surveys could combine the acquisition of seabed sediment and suspended transport samples; side-scan sonar or other types of remote sensing of bedforms, and tidal current metering. In both logistical and financial terms, multipurpose survey work of this nature needs to be very precisely planned with prioritisation based on maximum
perceived return of both theoretical and practical knowledge. In this context, the outer estuary of the Exe is the key location. Whilst recent work (e.g. Posford Duvivier, 1998b) has advanced understanding of the nature of the complex sediment flux here, several critical questions have yet to be resolved. These include: (i) the interaction of tidal and wave-induced currents in moving sediment, of various grades, towards and then away from the estuary entrance; (ii) the relative importance of flood and ebb tide currents in the overall circulation of sediment in and between channels; (iii) the stability (or, conversely, the mobility) of banks, bars and shoals; and (iv) whether the overall sediment budget is determined by a closed or open system, and whether it is in balance, excess or deficit. This last issue will require a long-term programme of morphological mapping, sediment sampling and process measurement/monitoring. However, the ultimate benefit will be a fully-informed long-term strategic approach to problems of shoreline management at locations such as Dawlish Warren and the Exmouth frontage. Historically, they have been addressed on an ad hoc basis.

3. A particular need is to undertake seabed sediment sampling in the area of the Exe ebb and flood tidal deltas around the estuary entrance. It would provide additional valuable information on the potential for onshore sediment transport through the compilation of large-scale maps of sediment distribution, and analyses of particle size and sorting to derive bed transport vectors as was undertaken for Chichester Harbour entrance by Geosea Consulting Ltd (1999). It might, in particular, throw light on the important question of whether offshore to onshore sand supply is a sustainable process under the contemporary hydrodynamic regime, or whether its sources could suffer interception and/or exhaustion.

4. The independent contribution of tidal currents to sediment transport in the inner and outer estuaries of the Exe has not been systematically studied. Linking with point no. 2 above, it would be beneficial to determine the depth-averaged current velocities, and of stresses imparted by flow interaction with the seabed at selected stages of both ebb and flood tides during spring and neap cycles. This data would then provide input into theoretical transport equations appropriate to calculating the potential capacity of tidal currents for both suspended and bedload transport.

5. Whilst there has been a certain amount of beach profile monitoring, particularly along the shoreface of Dawlish Warren and between The Point, Exmouth and Orcombe Rocks, most of this type of data collection has been short-term. The morphodynamic response of regional beaches to forcing factors expressed as seasonal fluctuations of profile form and volume is only known in general terms. Crossshore sediment exchange has been implied, but knowledge remains conjectural. A systematically organised programme of beach profile monitoring is therefore needed, which will need to operate continuously for several years to give results representative of the full range of forcing conditions. This might be achieved as part of a region-wide aerial photographic survey similar to the ABMS undertaken by the Environment Agency (South Region), although this would need to be complemented by baseline ground surveys. Changes in seabed topography occurring over the full active profile “envelope” are required ideally, thus necessitating periodic bathymetric surveys several hundred metres seawards of the intertidal profile lines to water depths where there is limited sand mobility. Measurements before, and immediately following, major storms would give quantitative insight into their role in moving large amounts of sediment. Correlation between (a) the drawdown and recovery of inter-tidal beaches; and (b) nearshore sediment storage would be more objectively
understood as a result. The relationship between Exmouth Beach and storm-driven removal of sand into the Exe channel is a key problem. So, too, is the coupling of Dawlish Warren foreshore and Pole Sand – does the reduction of one result in an increase in the other? If this is so, what is the time lag of response? Is there a longer-term trend towards erosion and depletion of Dawlish Warren spit, as suggested by several researchers? The type of comprehensive monitoring approach initiated in south and southeast England (Bradbury 2001) co-ordinated by the Channel Coast Observatory – see website at: [http://www.channelcoast.org](http://www.channelcoast.org) provides an excellent model.

6. 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 crossshore and longshore transport and could also be affected by beach management. Ideally, a one-off field-sampling programme is required to provide baseline quantitative information 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. It would also provide insights into potential transport paths (via grain size and sorting analyses) and likely sediment provenance.

7. Whilst net pathways of longshore sediment transport are qualitatively well established, estimates of actual rates and volumes of movement are lacking. Most existing numerical assessments derive from the application of theoretical equations, and may be misleading. Drift reversals occur quite rapidly in response to changes in incident waves, but their overall significance in reducing rates of net unidirectional transport has not been evaluated. Tidal current transport becomes a significant mechanism close to the Exe estuary entrance, although whether or not it combines with breaking waves – especially at the distal end of Warren Point – is not known. Gross rates of transport, over a period of one or more years, are likely to be well in excess of net rates. However, this can only be determined by repeated surveys of the volume and distribution of sediment size-range in inter-groyne compartments or against other confining features. The approach of validating model estimates of transport against known changes in beach volume is recommended (see Section 7)

8. All of the above research and/or monitoring initiatives will contribute to more detailed knowledge of the Holocene, and possibly earlier, geomorphological history of this coastline. In this context, borehole samples would provide potentially helpful knowledge. The latter can rarely be specifically commissioned, but archival records should be searched. Although this might appear to be acquisition of knowledge of only academic value, its main value would be to indicate if the larger sediment stores (e.g. Dawlish Warren; Pole Sand) are composed of material from offshore reserves that are no longer being supplied. In other words, does the sediment circulation system in the outer Exe estuary involve “fossil” material that has been drawn from a finite reserve? If research could provide an answer to this long-standing crucial question, it would provide a strong basis for future approaches to sustainable shoreline management.

9. Baseline surveys of the extents and qualities of the estuarine habitats are needed covering the Exe estuary. For forthcoming SMP revisions, it is likely that future intertidal habitat changes and the possible influences of defences will need to be assessed.
It is acknowledged that it is unlikely to be feasible to complete all tasks immediately, indeed, some will require the accumulation of quality monitoring data. Thus, it is recommended that the profile monitoring relating to Dawlish town to Dawlish Warren and Exmouth to Orcombe Point should be prioritised. Remaining tasks should be factored into the preparatory work for the forthcoming SMP revision, or progressed soon thereafter as part of the implementation of that Plan.

9. REFERENCES


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