Littoral Cell Definition and Budgets for Central Southern England

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ABSTRACT

Differentiation of natural process units is promoted as a means of better understanding the interconnected nature of coastal systems at various scales. This paper presents a new holistic methodology for the identification of littoral cells. Testing is undertaken through application to an extensive region of central southern England.

Diverse sources of information are compiled to map a detailed series of local sediment circulations both at the shoreline and in the offshore zone. Cells and sub-cells are subsequently defined by thorough examination of the continuity of sediment transport pathways and by identification of boundaries where there are discontinuities. Important distinctions are made between the nature and stability of different boundaries and a classification of types is devised. Application of sediment budget analysis to major process units helps to clarify the regional significance of different sediment sources, stores and sinks.

Within the study area, it is shown that sediments circulate from distinct eroding cliff sources to well defined sinks. Natural beaches are transient and dependent upon the continued functioning of supply pathways from cliff sources. Relict cells with residual circulations are identified as a consequence of interference.

Littoral cell boundaries separate independent coastal units from those that are partially, or totally dependent so the spatial impacts of various processes and practices can be discerned. They identify appropriate units for management, from which new co-operative groupings of local authorities can develop.

INTRODUCTION

Coastal management needs to be organised at scales which are fully representative of the dynamics of the coastal system. Past coast protection, sea-defence and planning arrangements in the U.K. concentrated upon site-specific or problem-specific issues that have resulted in comparative neglect at the larger regional scale (FLEMING, 1992). Partly a product of the fragmented and disparate organisation of shoreline protection and planning in the U.K., policies based on this perspective have delivered a legacy of developments and practices whose wider, or longer-term impacts were not anticipated (EVANS, 1992). Consequently, a more consistent framework for understanding and managing the coast as a system needs to be developed.

Differentiation of the coast through identification of process units offers great opportunities to develop a better co-ordinated approach (CARTER, 1988; BRUNSDEN, 1992). Nevertheless, significant difficulties remain in translating such concepts into operational units. This paper examines these problems by utilising a holistic approach to define littoral cells and their sediment budgets at a variety of scales. Aimed principally at shoreline management, such methods could form the basis for reappraisal of prevailing arrangements and activities. In this context, it is important that a consistent methodology be applied. Few previous studies have addressed these issues at regional scales.

The Systems Approach Applied to the Coast

A budgetary approach in which the coast is characterised by inputs, transfers, storage and outputs of materials and energy has long been advocated by coastal researchers (e.g., Bowen and INMAN, 1966; Krumbein, 1968; Davies, 1979; LAKHAN and TRENHAILE, 1989). The methodology recognises that coastal systems comprise a series of interrelated units linked by diverse transfer processes operating over different spatial and temporal scales. Differentiation of equilibrium and transient behaviour amongst units is critical to understanding the full implications and knock-
on effects associated with human interference (e.g., coast protection structures) or progressive natural change affecting external boundary conditions (e.g., rising sea-level).

Several appropriate scales representing a hierarchical structure of processes and forms have been distinguished for the study of coasts (STIVE et al., 1990; TERWINDT and WINBERG, 1991). However, it is the large scale variations in fluxes and storage covering decades and tens of kilometres that determine the net effects (CAMBERS, 1976; TERWINDT and WINBERG, 1991). Analysis at the large scale requires comprehensive data sets measured over long periods (DE VRIEND, 1991), limiting application to those few coastal units with appropriate monitoring records. Projects of this type have been initiated along extensive lengths of coastline, e.g., East Anglia, U.K. (FLEMING, 1989), the Netherlands (DE RUIG and LOUISSE, 1991) and the Pacific Northwest in the U.S.A. (ROSENFIELD et al., 1991), but these remain exceptional.

Appreciation of these problems in the late 1980's led to the formation of non-statutory regional groups of coastal authorities committed to mutual consultation; by 1992, eighteen co-operating groups had been established covering 98% of the coast of England and Wales (HOUSE OF COMMONS ENVIRONMENT COMMITTEE, 1992). SCOP AC—The Standing Conference on Problems Associated with the Coastline—is one such group comprising 29 local authorities and agencies covering a 200 km segment of the south coast. Formed in 1986, they instigated a programme of research to investigate sediment transport and sedimentation as a fundamental basis upon which to improve regional understanding, co-ordination and management of the shoreline environment of this coast. This paper presents the results of a holistic study based on diverse information sources to identify cells, their domains of activity, interdependence and sensitivity to change. The diverse nature of the coastal study area means that the methodology and results are potentially of wider significance. Indeed, since the production of the report from which this paper has been developed (BRAY et al., 1991), a strategic study of littoral cells at the national scale has been published by MAFF (MOTYKA and BRAMPTON, 1993).

The Study Area

A wide variety of coastal environments are covered (Figure 1). The range includes high, rapidly eroding, compound cliffs on the open coast to mudflats and saltmarshes in enclosed harbours. Predominant wave direction is from the south-west, coinciding with the maximum fetch which extends into the Atlantic. Inshore hydraulic conditions are strongly controlled by coastal orientation in relation to fetch. Variably sheltered by the Isle of Wight, a wide spectrum of conditions prevails around the Solent with its unique “double” tides and strong tidal currents (WEBBER, 1980).

Coastal geologic materials of Jurassic and Cretaceous age outcrop in the west with younger Tertiary and Quaternary sediments to the east (MELVILLE and FRESHNEY, 1982); most are highly erodible. Retreat has formed large embayments between harder lithological units where major headlands have developed. An important characteristic of this coast is the prevalence of gravel beaches composed of hard chert and flint materials originally derived from superficial deposits and from horizons within the Cretaceous strata (SCOTT, 1993). Many features are the legacy of the Holocene transgression (DEVY, 1982; CARR and BLACKLEY, 1974; WEST, 1980; BRAY, 1992a) and regional subsidence contributes towards continuing relative sea-level rise (EMERY and aubrey, 1985; SHENNAN and WOODWORTH, 1992). Much of the coast is densely populated and has a long history of protection and defence.

METHODS

A phased programme of research was devised to identify, compile and analyse information at several scales (Figure 2). Widespread archive searches were undertaken throughout all accessible organisations and individuals with statutory ownership and other regulatory coastal responsibilities or interests. Some 3,450 items were identified, including a wide variety of published works and a fragmented, but surprisingly extensive, unpublished literature comprising academic theses and numerous internal reports by local authorities, consultants and contractors. Systematic classification of these materials was undertaken to create a bibliographic database covering all aspects of coastal sedimentation (CARTER et al., 1989). These contents were used in a second phase of study to compile and analyse critically all extant evidence relating to sediment transportation (BRAY et al., 1991).

Details relating to processes and sediments were abstracted and individually assessed for reli-
ability according to the nature of their source data, its representativeness, and the availability of independent corroboration. All acceptable evidence was then pieced together to identify discrete sediment transport pathways, mapped in detail and comprehensively described in sixteen local reports covering the whole study area (Bray et al., 1991). A system of coded and coloured arrows was devised to show different information: the type of transport process, and its location; the type and volume of sediment in transit where quantitative data were available; net pathways and the reliability of the information (see Figure 3). Each process is coded with a letter and each component pathway is numbered, e.g., Q6. This provides linkage with the appropriate process statement in the local report which details the original sources. Finally, sediment sources, transport pathways, boundaries, budgets and inter-linkages were fitted together and analysed for the study area as a whole to create a synthesis not previously attempted at this scale. The identification of processes, pathways and cells is thus based on compilation of extant information and critical assessment of the evidence.

**CHRISTCHURCH BAY: A LOCAL SEDIMENT TRANSPORT UNIT**

Transport pathways identified within one relatively well researched coastal segment (Figure 3) demonstrate the basic type of results obtained throughout the study area at the local scale. The overall pattern in Christchurch Bay is a distinct clockwise net sediment circulation that has historically been sustained by coast erosion. Littoral drift (Q1 to Q6) transports material eastwards toward the shingle structure of Hurst Spit, a pathway supported by strong evidence derived from studies of wave refraction (Henderson, 1979; Lacey, 1985), aluminium pebble tracer experiments (Nicholls, 1985) and sediment budget computations based upon historical coastal changes (Nicholls and Webber, 1987a). A small accreting cuspate foreland at Hordle provides morphological evidence of a transport discontinuity that is supported further by the results of wave refraction and sediment budget studies. The proportion of sand upon the beach declines sharply from west to east, suggesting that fines supplied from the eroding cliffs are progressively winnowed.
offshore (WO2 and WO3) so that supply to the spit (Q6) is almost entirely shingle (Nicholls and Webber, 1987a).

Material drifting along Hurst Spit is lost offshore, entrained by strong tidal currents in Hurst Narrows and preferentially transported seaward (EO1) to the Shingles Bank gravel accumulation (Figure 3). These movements are inferred from tracer experiments (Nicholls, 1985), budget calculations (Nicholls and Webber, 1987b), residual tidal currents (Dyer, 1970), grain size analyses and from sonar observations of bedforms (Dyer, 1970; Velegarakis, 1991). Sand is transported further southwest onto Dolphin Sand (O3) and thence toward Durlston Head, Dorset (Dyer, 1970; Lacey, 1985; Fitzpatrick, 1987). Gravel is retained on the Shingles Bank which forms a major store estimated at 50–60 million m³ (Velegarakis, 1991). Wave refraction occurs over the elevated bank crest causing fluctuations in shoreline littoral drift potential (Henderson, 1979) and possible transport discontinuities, as at Hordle.

Christchurch Bay is not a fully self-contained sediment cell as it receives small inputs of sand drifting in from Poole Bay to the west (Hydraulics Research, 1986). Supply was previously much greater prior to almost complete protection of eroding cliffs along Poole Bay (Lacey, 1985; Lelliott, 1989). In fact, fluctuations in this supply source are strongly implicated in the growth and destruction of spits at the entrance to Christchurch Harbour (Robinson, 1955; Nicholls, 1984) and the present stable configuration is only maintained by coast protection either side of the inlet (Thurston, 1987). A co-ordinated programme of beach profiling within Christchurch Bay has revealed evidence of intermittent time-lagged sediment inputs associated with the major beach nourishment schemes undertaken at Bournemouth since the early 1970’s (Halcrow, Sir William and Partners, 1980; Lacey, 1985; Hodder, 1986; May, 1990).

Sediment inputs from eroding cliffs remain significant in central and eastern parts of the bay. Several long sections of cliffs have been stabilised and protected with consequent loss of supply (Lacey, 1985). Furthermore, protective structures and large rock groynes have intercepted beach drift and caused artificial compartmentalisation additional to that produced by the natural discontinuity at Hordle (Nicholls and Webber, 1987a).

Budget analysis has shown that these practices and their process impacts have caused a downdrift sediment deficit. This deficit has had serious implications for Hurst Spit, the terminal beach storage unit of the pathway (Nicholls and Webber, 1987a). Diminution of shingle volume through continued offshore loss without adequate natural replenishment has caused the spit to become increasingly susceptible to overtopping. Recent surveys have shown an acceleration of recession compared with historical rates. It has needed continuous material and technical inputs, soon to culminate in a major replenishment scheme (Wright, personal communication), to maintain the stability of the spit which protects much of the West Solent.
Figure 3. Christchurch Bay: local sediment transport pathways.
At a local scale, this type of study benefits investigations of specific problems by integrating an extensive, but hitherto fragmented, body of information to link processes and forms. It highlights information gaps which need to be filled by original research. It offers a broader perspective of interlinkages, showing in this example, that Christchurch Bay is the terminal sub-cell partly dependent upon a littoral drift pathway originating in Poole Bay. As such, it is sensitive to changes in management practice updrift, as well as within the bay itself. Hurst Spit, the terminal beach unit, is particularly vulnerable.

LITTORAL SEDIMENT CELLS

The littoral cell concept based upon the continuity of sediment transport has been extensively applied to calculate budgets in different coastal environments (Stapor, 1971; May and Tanner, 1973; Vincent, 1979; Clayton, 1980; de Ruig and Louisse, 1991). Cells are identified according to morphological and process information and defined as relatively self-contained units within which sediment circulates. Their boundaries separate those parts of the coast that are interdependent from those that are independent in terms of physical processes. In many situations, cells are not so distinct, and there are problems differentiating between independent and dependent, or connected coastal units.

Identification and Classification of Cell Boundaries

Cell and sub-cell boundaries can be defined consistently by identification of discontinuities in rate or direction of sediment transport. This method was applied to the study area and numerous transport boundaries were identified from the full range of morphological, sedimentological, historical, hydraulic and process information assembled (Bray et al., 1991). Fundamental controlling characteristics based upon their physical permanence and their effect upon sediment transport were apparent throughout all boundaries. These qualities were exploited to develop a functional classification covering all types within the study area (Figure 4).

Fixed boundaries are those with a historical
record of stability covering at least the past 20 to 100 years. Typically, they are either headlands or inlets, but some major artificial structures maintained over long periods have had similar effects. *Transient* boundaries are generally of more diffuse character and limited stability. Typically, they are littoral drift convergences, divides or marked by discernible changes in transport rates, not necessarily associated with particular structures or morphological features. *Absolute* and *partial* boundaries are differentiated for each type according to their permeability to sediment (Figure 4). *Absolute* boundaries are barriers to all sediments, while *partial* boundaries permit bypassing or periodic throughput. Bi-directional and unidirectional transport regimes have been identified at *partial* boundaries, the former resulting in reduced sediment mobility, the latter causing dislocation so that the boundary acts as a one way “valve”.

The nature and occurrence of the different boundary types within the study area are mapped in Figure 5 and discussed as follows.

**Fixed Absolute Boundaries**

Eight *fixed absolute* boundaries were identified within the study area (Figure 5). Prominent hard rock headlands retreating at very slow rates (May, 1966, 1971) form obvious physical barriers of long-term stability in the west. Historically stable hydrodynamic boundaries are identified at equilibrium points within the Solent. Tidal flows and wave activity are delicately balanced so that incoming sediment circulates and net outputs are limited (Dyer, 1971, 1980). They function as sediment sinks stable under present conditions, but vulnerable to future changes affecting sea-level, wave and tidal parameters. Some inlet boundaries are of the fixed, absolute type, especially where deep channels are scoured by strong tidal currents or maintained for navigation by dredging, as at Portsmouth. Asymmetry of the semidiurnal tidal cycle results in ebb flow dominance, so that incoming sediment supplied by littoral drift is flushed offshore into sediment sinks with no bypassing (Harlow, 1979). The prominent, low-lying headland of Selsey Bill marks a boundary between divergent littoral drift pathways which are supplied from offshore sources (Joliffe and Wallace, 1973; Harlow, 1979). There is a long history of rapid erosion, and the present headland configuration has only been stabilised since the completion of improved coast protection structures in 1960 (Duvivier, 1961). These examples demonstrate that while some boundaries are clearly major natural features, others have unwittingly been reinforced by artificial means, their long-term stability dependent upon maintenance of these management practices. Finally, major artificial structures can create new boundaries where none have previously existed, as with the 500 m long breakwater of Brighton marina.

**Fixed Partial Boundaries**

Several distinct types have been identified throughout the region (Figure 5). Headland boundaries are most frequent in western parts, whilst inlets predominate in the low-lying eastern parts. Boundaries differ with respect to their effect upon sediment transport. Some allow transport in both directions along the shore, but the majority only permit transport in one predominant direction. A particular characteristic of these boundaries is the intermittent nature of bypassing transport which is often storm-related. By-passing of minor barriers appears to occur relatively frequently and is associated with normal storms as at Hengistbury Head (Hydraulics Research, 1986), or West Bay harbour, West Dorset (Joliffe, 1979). Larger barriers are less easily bypassed so that throughput may require exceptional storms and be highly intermittent. A particularly interesting situation develops on soft-rock coasts of high relief. Headland bypassing is controlled by a complex interaction between periodic major mass movements of the compound cliffs, which block beach transport pathways, and progressive marine erosion of the resultant fore-shore debris lobes, which reopens them (Bray, 1992b).

Zones of sediment depletion or shore erosion commonly occur downdrift of barriers and accretion is frequent updrift; however, the nature of the boundary is critical in understanding the dynamics of these processes. Coastal units adjoining “two-way” boundaries are interdependent. Where boundaries are “one-way”, downdrift coasts are highly dependent upon those updrifts, although the inverse does not apply. These concepts have been used to identify persistent sub-cells and recognise instances of unequal interdependence, between adjoining coastal units. There are important management implications, particularly where transport boundaries are adjacent to administrative boundaries as in Christchurch Bay (Wright, 1992). Unless there is close co-operation...
Figure 5. Littoral cells and transport bou
between neighbouring authorities, it is possible that different management policies will prevail on either side of the boundary; adverse impacts will inevitably be transmitted to the downdrift unit. Often the differences immediately updrift and downdrift serve to accentuate the boundary.

**Transient Partial Boundaries**

Discontinuities of this type fluctuate or evolve over quite limited timescales, and generally only retain stability over 1 to 20 year periods. Their unstable character and propensity for longshore migration mean that transient boundaries are by nature partial barriers and usually define minor sub-cells. They form at locations where hydraulic, bathymetric or oceanographic variations along the coast create discontinuities in littoral sediment transport potential. Frequently, littoral drift divides or converges; these boundary types have been identified in Poole Bay, Christchurch Bay (HENDERSON and WEBBER, 1979) and elsewhere (LOWRY and CARTER, 1982) through application of wave refraction analysis. Generally, they also have a morphological expression at the shore which can further assist in their identification (JACOBSEN and SCHWARTZ, 1981). Drift divides are marked by diffuse zones of erosion and/or onshore feed. Transient drift convergences are relatively rare along the south coast of England; most result from highly localised drift reversals and are associated with inlets, resulting in characteristic double spits at harbour entrances throughout the region (ROBINSON, 1955; DYER, 1980). Although there are historic records of instability, many navigable channels are now maintained by dredging so the status of inlets as transport boundaries has altered from transient to fixed. Transient boundaries may also be produced by simple acceleration or reduction in littoral transport rates resulting in zones of erosion or accretion as at Hordle Cliff in Christchurch Bay (Figure 3).

**Sediment Cell Budgets**

The major fixed boundaries compartmentalise the study area into nine relatively independent macro-cells (Figure 5), which are characterised by several distinct types of sediment budget (summarised in Table 1). The most dynamic budgets are on exposed southwest facing coasts. Rapid erosion of high, soft-rock cliffs produces rapid rates of input, throughput and loss and an overall negative budget. Sediment circulation can, nevertheless, be sustained, providing that these coasts remain free to erode and maintain inputs. These cell types are important contemporary sediment source areas and comprise the West Dorset (Cell 1), Purbeck (Cell 2) and southwest Isle of Wight (Cell 7) coasts. Durable gravels and coarse sands are retained at the shore, but finer materials yielded from these sources are removed seaward in suspension, possibly to contribute to the budgets of more sheltered estuarine cells. The Poole and Christchurch Bay (Cell 3) and Bracklesham, Hayling and Portsea (Cell 8) units were previously more dynamic systems; sediment circulation has diminished as their shores became more heavily protected and erosion yields were reduced (HARLOW, 1979; Lacey, 1985). These systems are now finely balanced and retain stability through reworking of stored sediments and through artificial beach nourishment. Consequently, they are sensitive to further interference and may become increasingly unstable as sediment stores deplete. The commonly recognised trend for beach steepening (BEAZLEY, 1982; HOOKE and RILEY, 1991) may be evidence of this response.

Cells in more sheltered locations are generally characterised by relatively low rates of sediment flux and by positive budgets. They are dominated by the sedimentation of suspended sediments which form estuarine mudflats and saltmarshes as within parts of the Solent (Cells 4, 5 and 6) and all the enclosed harbours of the study area. Although some fine sands are present, these environments are not sinks for coarser sediments, because tidal asymmetry throughout the region results in strong ebb tide flushing at inlets and concentration of materials in deltas on the open coast (HARLOW, 1979; WALLACE, 1988; HYDRAULICS RESEARCH, 1991). Slow process rates and dependence upon internal recycling of existing sediments mean that these environments may not adjust easily to variations in natural factors, *e.g.*, rising sea-levels.

Identification of budget types is a vital first phase in developing an analytical understanding of process interactions at the regional scale. For example, stabilisation and change in sheltered, low-flux cells are unlikely to impact on the budgets of adjoining open coast cells, because these environments are sediment sinks rather than sources. By contrast, cells with high-flux budgets (sediment source or “donor” cells) are themselves relatively stable in form, but even modest changes in process regime can have major impacts upon adjoining “recipient” sub-cells.
Table 1. *Macro-cell sediment budget components.*

<table>
<thead>
<tr>
<th>Macro-Cell</th>
<th>Inputs</th>
<th>Storage</th>
<th>Outputs</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Dorset</td>
<td>major cliff erosion</td>
<td>small pocket beaches;</td>
<td>fines transported seaward (approx. 80% of total inputs); history of beach shingle extraction</td>
<td>dynamic; negative sediment balance; Chesil Beach is an almost closed system of marginal stability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chesil Beach, a product of shingle accumulation throughout the Holocene</td>
<td></td>
<td>negative sediment balance; stability maintained by resistant hard-rock headlands shoreline sediment deficit is partly offset by nourishment; sediment circulation intercepted by protection structures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>shingle retained in small pocket beaches; Weymouth Bay is a sink for sand</td>
<td>fines transported seaward</td>
<td>uncertain net balance within complex pattern of erosion and sedimentation</td>
</tr>
<tr>
<td>Purbeck</td>
<td>cliff erosion</td>
<td>Studland Bay (sand sink)</td>
<td>shingle to West Solent</td>
<td>accretion in sheltered environments; shore erosion where exposed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shingles Bank (gravel sink)</td>
<td>fines transported seaward</td>
<td>low rates of sediment transfer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hurst Spit (gravel store)</td>
<td>sand transported S.W. to Swanage Bay</td>
<td>dynamic, negative sediment balance sediment deficit since cessation; re-working of sediment stores beach steepening; stability dependent upon protection</td>
</tr>
<tr>
<td>Poole and Christchurch Bays</td>
<td>erosion of limited unprotected cliff segments; beach nourishment</td>
<td>fines in saltmarshes and mudflats of N. coast; gravel banks in channel</td>
<td>historical dredging of mid-channel gravel banks; loss of sand to Brambles Bank</td>
<td>recycling of existing sediments; potential destabilisation resulting from <em>Spartina</em> die-back</td>
</tr>
<tr>
<td>Western Solent</td>
<td>cliff erosion of margins and channel bed; suspended sediments from Christchurch Bay</td>
<td>suspended sediments from West Solent and Spithead; erosion of margins</td>
<td>reclamation in Southampton Water, dredging of navigable channels</td>
<td></td>
</tr>
<tr>
<td>Southampton Water and Eastern Solent</td>
<td>saltmarshes in Southampton Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NE Wight</td>
<td>local shore erosion (low rates)</td>
<td>Ryde Sand (sink)</td>
<td>no information</td>
<td></td>
</tr>
<tr>
<td>SW and SE Wight</td>
<td>major cliff erosion</td>
<td>landslide debris in large undercliff stores; ebb tidal deltas associated with inlets; spits flanking inlets</td>
<td>fines transported seaward</td>
<td>dynamic, negative sediment balance sediment deficit since cessation; re-working of sediment stores</td>
</tr>
<tr>
<td>Bracklesham, Hayling and Portsea</td>
<td>coast erosion (in past); beach nourishment</td>
<td>beaches and minor spits at inlets</td>
<td>dredging of inlets and tidal deltas</td>
<td></td>
</tr>
<tr>
<td>West Sussex</td>
<td>beach nourishment; wave-driven and kelp-rafted shingle supply from offshore</td>
<td>saltmarshes and mudflats</td>
<td>sand loss from lower beach</td>
<td></td>
</tr>
<tr>
<td>Harbours (Poole, Portsmouth, Langstone, Chichester)</td>
<td>suspended sediments from marine sources and biological production of organic sediments</td>
<td>dredging of navigable channels; reclamation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sediment Sources

Inputs or sources of “fresh” materials are vital to sustain sediment circulations within cells, especially where continuous losses to sinks are occurring. Coast erosion, offshore to onshore transport, fluvial inputs and artificial beach nourishment can be readily identified as potential sources of supply, although spatial and temporal variations in their respective contributions have important implications for individual budgets. Indeed, where there are serious shortages, residual sediment circulations can only be sustained by recycling of existing stores. Beach erosion and steepening is a likely result of this response.

Eroding coastlines are obvious sources of sediments, but the amounts yielded are critically dependent upon their retreat rate and land elevation (BRAY, 1992c). Integration of these parameters has enabled quantification of inputs at a number of sites (Table 2), although complete coverage has yet to be achieved. Unprotected soft-rock cliffs in exposed western and central parts of the study region (identified in Figure 6) are the major sources of supply. Results for other locations show that freedom to erode is important, and low-lying areas around the Eastern Solent and in West Sussex have been so extensively protected that very little yield of material is now possible.
Table 2. Coast erosion input.

<table>
<thead>
<tr>
<th>Location</th>
<th>Author</th>
<th>Period</th>
<th>Material</th>
<th>Total Input (m$^3$ a$^-1$)</th>
<th>Input Stable on Beach (m$^3$ a$^-1$)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Dorset</td>
<td>BHAY (1986, 1992b)</td>
<td>1901-1988</td>
<td>clay, sand, limestone, gravel</td>
<td>300,000</td>
<td>5,600</td>
<td>8,400 m$^3$ a$^-1$ limestone boulders temporarily stable</td>
</tr>
<tr>
<td>East Cliff, Burton</td>
<td>LAMING (1985)</td>
<td>1902-1962</td>
<td>sandstone</td>
<td>630</td>
<td>4,000</td>
<td>eventual abrasion and offshore transport mostly sand, only stable on lower beach and nearshore zone section protected by beach nourishment 1988</td>
</tr>
<tr>
<td>Hengistbury Head</td>
<td>LACEY (1985)</td>
<td>1984</td>
<td>sand, gravel</td>
<td>—</td>
<td>750</td>
<td>supply much reduced by coast protection includes gravel input from re-cession of Hurst spit</td>
</tr>
<tr>
<td>Double Dykes (Hengistbury)</td>
<td>LACEY (1985)</td>
<td>1974-1982</td>
<td>gravel</td>
<td>—</td>
<td>11,000-13,000</td>
<td>inputs now reduced by protection</td>
</tr>
<tr>
<td>Christchurch Bay</td>
<td>NICHOLLS (1985)</td>
<td>1978-1982</td>
<td>clay, sand, gravel</td>
<td>80,000</td>
<td>40,000</td>
<td>supply much reduced by coast protection</td>
</tr>
<tr>
<td>Ventnor Bay, Monks</td>
<td>SOUTH WIGHT BOROUGH COUNCIL (1985)</td>
<td>1896-1974</td>
<td>clay, sand</td>
<td>6,400</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Bay</td>
<td>BOHOLCH (1991)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R. Hamble to R.</td>
<td>BHAY et al. (1991)</td>
<td>1964-1978</td>
<td>clay, sand, gravel</td>
<td>8,000</td>
<td>4,000</td>
<td>pre 1964 supply significantly slower supply much reduced by coast protection</td>
</tr>
<tr>
<td>West Selsey</td>
<td>WALLACE (1990)</td>
<td>1875-1972</td>
<td>clay, sand, gravel</td>
<td>6,100</td>
<td>5,300</td>
<td></td>
</tr>
</tbody>
</table>

The longevity within the littoral zone of sediments supplied is not only determined by their size distribution and resistance to attrition, but also by environmental conditions at the point of supply. Beaches vary with respect to their exposure to wave energy and the minimum size of stable sediment increases at higher energy locations. Thus, on the exposed coasts, only coarse resistant materials are stable and a high proportion of supply is transported offshore (Table 2). A much larger proportion may be stable on lower energy coasts. Cliff geology is important and a greater residual contribution to the beach occurs where high proportions of coarse resistant sediments are delivered. Continued losses seaward may be significant; a few remote sensing studies suggest that clays yielded from erosion of open coasts may be a major source of suspended sediments in estuaries such as the Solent (SRIKENTHONG, 1982; MACFARLANE, 1984; LACEY, 1985).

Shingle feed from offshore is widely regarded as a major process that operated during the Holocene transgression when barrier beaches were driven onshore along the South Coast and elsewhere (e.g., CARTER and ORFORD, 1984). However, the evidence suggests that offshore supply sources are now largely exhausted at many sites within the study area, as at Chesil Beach (CARR and BLACKLEY, 1974; BHAY, 1992a), Christchurch Bay (NICHOLLS, 1985) and along the West Sussex coast (HARLOW, 1980; WALLACE, 1990; HYDRAULICS RESEARCH, 1993). The only significant source remaining is localised in the vicinity of Selsey, where gravel bars are intermittently driven onshore from nearshore banks. These bars are apparently replenished by kelp-rafting (JOLLIFFE and WALLACE, 1973). A mean input of 16,000 m$^3$ a$^-1$ was indicated by monitoring over the period 1959-1975 (JOLLIFFE and WALLACE, 1973; LEWIS and DUVIVIER, 1976; WALLACE, 1990).

Fluvial sediment input is not significant because many of the region's rivers are derived from predominantly Chalk catchments with consequent low sediment, high solute loads. Flows are invariably controlled by weirs, floodgates and other forms of regulation so that bedload transport is restricted, and supply is mostly suspended sediments which are deposited in harbours and estuaries. Historically, this source may have been more important as the sedimentary records of some estuarine marshes reveal fluvial influences (MAY, 1969).

Artificial replenishment of beaches has become an increasingly widespread practice since the mid-1970's and is now the dominant input in some sub-cells, as in Poole Bay (2.4 million m$^3$ in total to date) and Hayling Bay (0.5 million m$^3$) (HARLOW, 1985; MAY, 1990). Its significance as a
Figure 6. Principal sediment transport pathways and stores.
source of “fresh” sediment depends upon the origin of the material. Beach restorations from terrestrial sources or fossil offshore marine deposits represent new inputs to a littoral cell. Where material is derived from co-extensive mobile marine deposits (e.g., dredging of navigable channels close inshore), it constitutes a recycling of existing material within the cell. This latter type of operation is likely to become increasingly prevalent in the future as increasing requirements for beach nourishment materials will force greater competition with aggregate markets (RIDDELL, 1992). Wherever materials are artificially transported across cell boundaries, there is a possibility that “donor” cells will suffer permanent, destabilising sediment loss. Such practices may only be viable where donor cells are characterised by sediment surpluses or high rates of flux which can compensate.

The evidence reviewed on the South Coast indicates that cliff erosion is the major contemporary sediment source in the region and supplies material to beaches, the nearshore zone, and further afield in suspension. This situation probably became established during the late Holocene when it is thought that alternative supplies from seaward became exhausted (NICHOLLS, 1992). More recently, the extensive protection of some coasts, particularly in eastern parts, has led to an almost complete cessation of cliff erosion inputs. Many cells have readjusted by recycling existing littoral stores. This cannot be sustained unless stores are large and it has resulted in widespread beach depletion. Continued inputs from remaining high yield coasts are therefore needed to maintain the stability of present sediment circulation systems. Wherever such inputs are prevented by protection, increasing commitments to artificial beach restoration and recycling are entailed, if present sediment circulations and budgets are to be maintained.

Transport Pathways

A series of principal transport pathways have been defined by extracting details of the reliably identified littoral processes from the local studies, e.g., Christchurch Bay (Figure 3) and integrating them across the study area. The pathways mapped in Figure 6 summarise these net long timescale sediment circulations on beaches and in the littoral zone. Short timescale localised reversals and interruptions are characteristic of some pathways due to human interference and natural process variability. It is argued that the net long-term trends mapped here are the most important in understanding coastal systems and forms at the regional scale.

A notable finding is that only shoreline transport has been quantified consistently in any detail, although there is evidence of some significant offshore pathways. It means that the relative contributions of different processes and pathways are not easily assessed. Onshore to offshore transfer of materials in suspension is possibly dominant in many locations. It includes large quantities of fine sediments supplied by coast erosion; however, their ultimate fates are poorly understood.

The mapped pathways indicate marked convergence and seaward transport of sand and fines at some major headlands, e.g., Portland Bill (Figure 6). Coarser sediments are retained on interconnected pocket beaches in western and central parts where they are preferentially transported towards sinks, e.g., Chesil Beach and the Shingles Bank (Figure 6). The Solent appears to be an area of net sediment inputs from the coasts to the west and east. Net transport along many pathways in the east of the region has declined significantly over the past 100 to 150 years. The expanding use of protective structures has increasingly arrested coast erosion and intercepted drift. Hence, there are important intra-regional differences with active transport of sediment from source to sink areas in western parts, but with residual or discontinuous pathways in the east which function by recycling existing sediments through a spatial sequence of stores.

Sediment Stores and Sinks

Much of the available sediment along the South Coast is distributed in large sinks or stores which have accumulated at specific locations as mapped in Figure 6. A compilation of their characteristics reveals that these accumulations differ with respect to their size, mode of origin, sediment type and contemporary status (Table 3). Terrestrial accumulations take the form of: gravel barrier beaches, spits at inlets, cuspate forelands, or sand dune systems. Marine accumulations are frequently associated with tidal currents generated at: inlet entrances, e.g., Shingles Bank, East Winner, Chichester Delta (Figure 6); within confined channels, e.g., Solent Bank; or within vortices set up by tidal deflection from headlands, e.g., Shambles Bank associated with Portland Bill (PINGREE and MADDOCK, 1977a,b).

Many of the marine banks are associated with
Table 3. Principal stores and sinks.

<table>
<thead>
<tr>
<th>Location</th>
<th>Author(s)</th>
<th>Period of growth (years)</th>
<th>Study Technique</th>
<th>Sediment Type</th>
<th>Estimated Volume million m$^3$</th>
<th>Contemporary Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chesil Beach</td>
<td>CARR and BLACKLEY (1973, 1974), Bray (1992a)</td>
<td>from well before 7,000 BP</td>
<td>boreholes, profiles, sediment analysis; radiocarbon and pollen dating; diving surveys</td>
<td>shingle</td>
<td>16-60</td>
<td>fossil sediment sink since 1860's</td>
</tr>
<tr>
<td>Shambles Bank</td>
<td>PINGREE and MADDOCK (1977a,b, 1983), LANGHORN et al. (1982)</td>
<td>unknown</td>
<td>tidal modelling, sidescan sonar and sediment sampling</td>
<td>sand and shingle</td>
<td>—</td>
<td>mobile sediment store retained in present location by tidal eddy</td>
</tr>
<tr>
<td>South Haven Peninsula</td>
<td>ROBINSON (1955), DYER (1933), CARR (1971)</td>
<td>from 1721</td>
<td>historical maps, air photos</td>
<td>sand</td>
<td>—</td>
<td>terrestrial sediment sink, accretion continuing</td>
</tr>
<tr>
<td>Shingles Bank</td>
<td>DYER (1970), NICHOLLS (1985), VELKGRAKI (1991)</td>
<td>beginning 6,500-8,400 BP (upon breaching of West Solent)</td>
<td>sidescan sonar, sediment sampling, sub-bottom profiling</td>
<td>shingle</td>
<td>50-60</td>
<td>highly mobile nearshore sediment store, accretion continuing</td>
</tr>
<tr>
<td>Solent Bank</td>
<td>DYER (1971), HR (1977, 1981), WEBBER (1977)</td>
<td>beginning 6,500-8,400 BP</td>
<td>sidescan sonar, sediment sampling, chart comparisons, hydrographic survey</td>
<td>shingle and sand</td>
<td>up to 14 million tonnes removed by dredging since 1950's</td>
<td>mobile sediment store, seriously depleted by dredging</td>
</tr>
<tr>
<td>Hurst Spit</td>
<td>NICHOLLS (1985)</td>
<td>beginning 6,500-8,400 BP</td>
<td>boreholes, sediment sampling</td>
<td>shingle</td>
<td>less than 1.0</td>
<td>mobile store undergoing depletion and recession, major nourishment proposed</td>
</tr>
<tr>
<td>Bembridge Bar</td>
<td>GRANT et al. (1972)</td>
<td>major accumulation post 1874</td>
<td>sediment sampling, vibracoring sediment sampling</td>
<td>sand and shingle</td>
<td>minimum 1.5</td>
<td>fossil sediment sink; heavily dredged</td>
</tr>
<tr>
<td>Horse and Dean Sand</td>
<td>HARLOW (1980)</td>
<td>—</td>
<td>sediment sampling</td>
<td>sand and shingle</td>
<td>2.3 million m$^3$ dredged in 1971</td>
<td>marine sediment sink; negligible contemporary supply, fossil status</td>
</tr>
<tr>
<td>Gunner Point</td>
<td>HARLOW (1980)</td>
<td>post 1600</td>
<td>sediment sampling; map comparisons</td>
<td>sand and shingle</td>
<td>15</td>
<td>terrestrial sediment sink, accretion continuing</td>
</tr>
<tr>
<td>East Winner and Langstone Delta</td>
<td>HARLOW (1980), WEBBER (1984)</td>
<td>—</td>
<td>sediment sampling; chart comparisons</td>
<td>sand and shingle</td>
<td>—</td>
<td>mobile marine sediment store; possibly becoming a closed system or sink, accretion continuing</td>
</tr>
<tr>
<td>Chichester Bar tidal delta</td>
<td>WEBBER (1979), HARLOW (1980)</td>
<td>—</td>
<td>sediment sampling, chart comparisons</td>
<td>sand and shingle</td>
<td>25</td>
<td>mobile marine sediment store, dredging losses</td>
</tr>
<tr>
<td>Pagham Spits and Beach</td>
<td>WALLACE (1990), BARCOCK and COLLINS (1991)</td>
<td>post 1866</td>
<td>map and chart comparisons, air photos, sediment sampling</td>
<td>shingle</td>
<td>max 5</td>
<td>terrestrial sediment store, accretion continuing</td>
</tr>
</tbody>
</table>

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the Solent, so their formation must post-date the period 8400–6500 years BP. Sea-level had risen sufficiently for the Western Solent to become connected to Christchurch Bay, and the present hydraulic regime to be initiated (Nicholls and Webber, 1987b). In fact, the growth of many major shingle accumulations is closely associated with the early and mid-Holocene transgression when sediment was more freely available, e.g., Chesil Beach (Carr and Blackley, 1974; Bray, 1992a). These supplies are now largely exhausted, and sediment sinks of this type must be regarded as fossil, non-replenishable accumulations.

The majority of accumulations are mobile and subject to inputs and outputs as confirmed by numerous studies involving comparisons of maps and charts, bedform analysis and sediment sampling (Table 3). Dynamic stores of this type perform important coast protection roles by dissipating wave energy and can also release sediments to adjacent beaches, thereby providing a buffering effect to resist further shoreline changes. Most beaches are of very limited volume by comparison and are maintained by throughputs from contemporary sediment sources and recycling between major stores. In this context, it is easy to appreciate why beaches are so sensitive to coast protection structures which immobilise or intercept sources of sediment supply and to inshore dredging which interferes with natural recycling between dynamic stores.

**DISCUSSION**

The sediment cells identified by this study are designed to improve our understanding and management of the shoreline. They focus upon material coarse enough to remain on the beach-face, or on the nearshore bed in appreciable quantities. Precise offshore limits of cells and a grain size “cut-off” for sediments under examination are not easily defined. This is because fine materials contribute to the shoreline in sheltered (saltmarsh) environments. They are transported in suspension and are relatively unaffected by littoral boundaries in more exposed situations. Nevertheless, sediment cells have been identified on some tidal mud flat coasts (Zhang, 1992). Barrier effects clearly vary according to sediment size and different cells are appropriate for different sizes. Independent cells for fine materials are likely to be much larger than those defined above. Following examination of the east coast of England, it has been suggested that an appropriate process cell would encompass almost the whole of the central, southern North Sea (Pearce, 1993).

Identification of littoral cells is traditionally restricted to the shoreline. Here it is shown that transport connections may be traced to offshore banks that constitute the major sediment stores throughout much of the region. The increasing availability of details of bedforms and sediment texture and improvements in the understanding of bed stresses produced by interacting tidal currents and waves (Hydraulics Research, 1993), makes the extension of sediment cells to include such regions feasible. However, there is presently insufficient evidence to resolve boundaries in such detail as is possible for their shoreline counterparts.

The long-term stability of transport boundaries is an important criterion affecting use of coastal cells to define appropriate shoreline management units. Hence, macro-cells should be based as far as possible on fixed boundaries. Differentiation of fixed from transient boundaries is therefore invaluable. Some fixed boundaries are dependent for their stability upon management practices, and others may become unstable as natural conditions change, e.g., rising sea-levels or variable wave climates. Several potentially unstable boundaries are identified within the study area and also elsewhere in the U.K. as at Spurn Head, North East England.

Distinctive cell budgets are identified along the south coast. Materials inherited from the Holocene transgression remain important in some fossil budgets, e.g., Chesil Beach; the majority are controlled by contemporary processes and owe their distinctiveness to alteration by management practices. High flux budgets fed by major inputs from high eroding cliffs are particularly important because other sediment sources along the south coast are either exhausted, or have been adversely affected by management practices. Many natural beaches are maintained by sediment throughputs from such systems and are highly sensitive to interference. Wherever formerly renewable fresh sediment sources have been “impounded” or intercepted by protective structures, an increasing sediment deficit develops and materials are re-worked from remaining mobile stores causing erosion of beaches and nearshore banks. Such budgets can only be sustained as littoral sediment circulation systems if beaches are artificially replenished or recycled. Sediment shortfall may also be serious for low-flux estuarine systems where
marine sources sustain the input of suspended sediment. This factor may contribute toward a widespread erosive trend that threatens saltmarshes within the region. Sediment supply needs to be considered alongside other controlling parameters, notably tidal regime, wind-wave climate, relative sea-level and marsh vegetation (Allen and Pye, 1992).

The availability of natural sediment sources is particularly important in view of estimates of increasing rates of sea-level rise and possible storm climate variation likely to result from global warming (Warrick and Oerlemans, 1990; Wigley and Raper, 1992). Impact assessments within the study area indicate potential problems unless coasts become more heavily protected, or can adjust naturally (Ball et al., 1991; Bray et al., 1992). Models suggest that sediment yields from eroding soft-rock cliffs are likely to increase correspondingly, provided they remain unprotected (Bray et al., 1992). Such sources will be vital in facilitating natural readjustments to shore profiles (Leatherman, 1990; Komar et al., 1991), so there is a strong case for advance planning for a managed retreat of cliffs through development controls and setback zoning (Kay, 1990, 1991; English Nature, 1992). Where coast protection is a necessity, it may be possible to retain, or restore sediment supply by permitting coast erosion updrift. These types of action can only be articulated where there is sufficient understanding of littoral cells to identify source areas and their linking pathways.

CONCLUSIONS

In this study, a detailed classification of sediment transport boundaries has been developed according to the continuity of sediment transport and the temporal stability of process-form interactions. Applied regionally, the method has proven effective in identifying dependent hierarchies of littoral cells which are representative of natural processes. It is important not only to identify local transient boundaries and sub-cells along otherwise undifferentiated coasts, but also to consider the longer timescale stability of major fixed boundaries and their possible responses to alterations in natural conditions and/or management practice. The scale of definition is also dependent upon the sediment size under consideration, so that larger dependent cells must be identified for fine sediments. The methodology facilitates an improved understanding of the dynamics of coastal change, the timescale of responses, and the relative importance of human and natural factors.

There are important applications because the littoral cells identify appropriate management units, setting out for the first time a coherent basis for shoreline management according to a large-scale understanding of the physical system. They indicate clearly the new groupings of authorities (Figure 5) which will need to cooperate and share joint responsibilities for particular cells, providing opportunities for resolving inconsistencies of approach at administrative boundaries within prevailing arrangements. An advantage of this perspective is that complex analysis is not necessary; a relatively simple methodology based upon compiling and utilising existing, but hitherto unconsolidated source information has proven effective within this study area. It means that the methods presented are more widely applicable to other developed, or partially developed coastlines where similar levels of process information are available.

Improvement in the understanding of littoral systems along the south-central coast of England has been achieved. Sediments circulate from distinct eroding cliff sources to well defined sinks, whereupon they become unavailable to large sectors of the downdrift shoreline. Beaches throughout the region are dependent upon supply pathways from eroding cliffs and are very sensitive both to interference and natural change. Such analyses have obvious implications for avoiding adverse impacts and facilitate the future management of littoral sediment as a valuable resource. In this context, an appreciation of sediment cells and their budgets will become increasingly important in assessing the regional and local impacts of sea-level rise, and in appraising the implications of possible ameliorative strategies, including managed retreat and widespread artificial beach nourishment.

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