A Review of Current Knowledge

Sediments in the Marine Environment

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Review of Current Knowledge

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Front cover image Source: Eastern Coastal Partnership

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Review of Current Knowledge

Sediments in the Marine Environment

A broad sandy beach with groynes, outfalls and a jetty near Hartlepool, County Durham

Author: Dr E M Valentine

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1 Introduction

This review of current knowledge (ROCK) is concerned with the movement of sediments in the marine environment. This is an important subject with influence on all nations with a coastline. The ROCK provides an outline of the subject and a description of some of the methods used in the analysis of the many complex processes. However, for details of the analytical methods it is necessary to consult major text books on the subject.

The sediments of the marine environment are evident in natural coastal features such as beaches and coastal inlets, and in port dredging. Sediments are the result of erosion of the earth's surface over the history of the planet. They have been subject to periods of erosion and deposition, working of the material and long term deposition in deep water. The processes of erosion and deposition are natural phenomena which, in the past, were largely unaffected by man. However, as civilisations developed, these changes have intensified, particularly since the start of the industrial revolution.

Coastal sediments are in continuous motion, driven by waves, currents and tidal flows. The quantities of sediments which are moving vary according to the energy of the water motion and the availability of mobile sediment. Often, these sediments will be in dynamic equilibrium. However, when this equilibrium is disturbed by a change in conditions, or by human interference such as coastal development, there may be erosion or deposition on the coastline. This can cause significant problems to human use of ports and beaches. The success of civilisations has often hinged on the stability of their port sedimentation.

Knowledge of the sediment budget, that is the balance of supply and loss of sediment to marine systems, and of their motions in the marine environment, provides a means of predicting future changes as affected by the climate and the activities of man. For example, in port development, the ability to predict the volumes of maintenance dredging will determine the viability of the port and the project operating costs.

In Chapter 2 marine sediment, characteristics, sources and coastal sedimentary features are outlined in general terms.

Chapter 3 describes the mechanisms of sediment motion on beaches, in estuaries and in the wider marine environment due to waves, currents and tides.

The problems caused by sedimentation are discussed in Chapter 4, on both the natural coast and in harbour developments.

Chapter 5 outlines methods of estimating quantities of sediment in motion, erosion and deposition.

Some of the engineering methods of mitigating and controlling sediment problems are outlined in Chapter 6. Details of these techniques are too complex to be covered here and reference should be made to the literature.

Chapter 7 addresses future concerns which will affect the marine sediment environment.

A bibliography is provided to enable further reading.

2. Marine sediments

2.1 Sediment characteristics

All sediments transported in the marine environment by water and air have resulted from the weathering of rocks and have been delivered to the coasts by wind, rivers and glaciers. Sediment size, mineral composition, density, particle shape and consequent fall velocity (an important parameter in assessing sediment transport) depend on the parent material. The properties of both the individual particles and bulk properties of the sediment must be considered in order to estimate mobility.

Classification of marine sediments is based on size and origin. Size classification divides sediment by grain size, in progressively smaller sizes, into gravel, sand, silt and clay. Mud is a mixture of silt and clay. Origin classification divides sediment into five categories: terrigenous (land sources), biogenic (shellfish), authigenic (local bedrock), volcanic and even cosmogenic (extra-terrestrial) sediments.

Particle size is the most important property. The size range has significant influence on transport behaviour via porosity and fall velocity and controls whether the transport of sediment will be as bed load or suspension or some combination. In bed load transport the moving particles are in contact with the sediment surface, whereas suspended load remains entrained by the water. For transport types, the broad classification of coarse, fine and cohesive sediments is most useful. In most environmental hydraulics situations “coarse” refers to gravels, “fine” to sands and “cohesive” to silts and clays.

Factors that control sedimentation (deposition of sediments) and rates of erosion include the turbulent energy of the depositional environment as well as particle size. Average grain size at a location is an indicator of the energy of the depositional environment. High energy locations such as exposed beaches exhibit larger sizes, while silts and clays are characteristic of sheltered low energy areas such as estuaries.

Offshore, the ocean bed can be divided into the shelf (shallow and near a terrigenous source) and the deep ocean basin (deep and distant from a terrigenous source). Sediments deposited in the deep ocean are generally lost and no longer participate in the coastal system. Figure 1 illustrates the trend in particle size with distance offshore in the open sea.

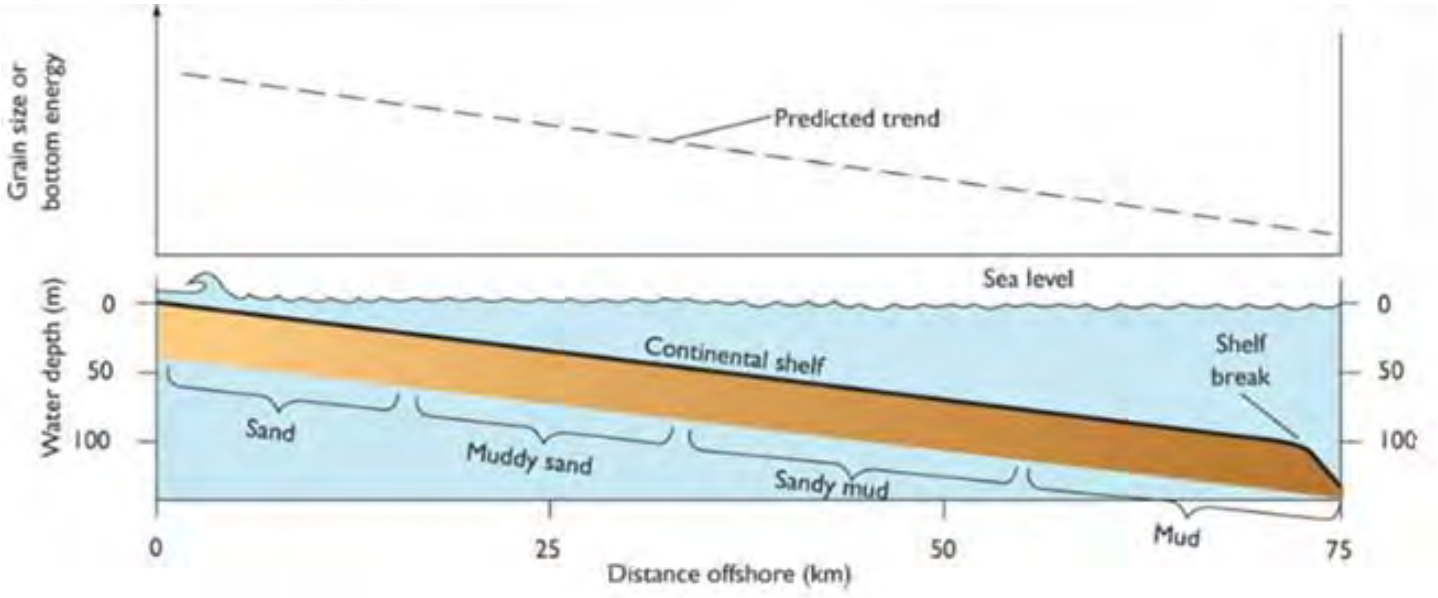

Figure 1 The distribution of sediment sizes over the width of the continental shelf.
Source: Neil Suits, Montana Univ.

2.2 Sediment supply

Globally, rivers discharge approximately 35,000km^3 of freshwater into the ocean annually. Transported in this flow is 15 to 20 billion (10^9) tonnes of sediment (**Milliman and Farnsworth 2013**). This sediment load is not distributed evenly across the world's rivers. The Asian and Oceanic regions account for 75% of the total sediment budget.

The changing rates of supply or replenishment from the fluvial systems is a dominant factor in controlling the rate of coastal erosion. While sediment production is increasing due to increased erosion rates, the delivery of this sediment to the coasts is decreasing. Human activities affect the discharge of water and sediment from a river to the coast in many ways. Deforestation, agriculture and urbanisation can increase the erosion of a river basin by as much as ten times. Freshly exposed soil is much less likely to resist erosion by rainfall or flowing water, especially in areas where land is often cultivated and rainfall rates are high.

Since the 1950s the number of dams in the world has increased more than sevenfold. The creation of reservoirs has significantly reduced the sediment yield of many rivers as sediment is trapped by these artificial barriers and the energy required to transport the material is diminished. (**White 2015)**. Removal of water from rivers for irrigation reduces the flow and therefore the sediment carrying capacity of the river. Agricultural and farming practices often require intensive

irrigation systems to achieve appropriate production levels. This creates a high demand on waterways as the flow is diverted to crops and pasture. The sediment transport capacity of the river is reduced and consequently sediment is deposited along the river and either takes much longer to reach the coastal zone, or never does so. The Colorado River in the United States is, perhaps, one of the most extreme examples of a river basin that has been subject to heavy water abstraction and consequent severe erosion of the river delta due to lack of sediment transport to the coast.

Figure 2 is a satellite image of southern Britain showing sediment plumes from the major rivers and estuaries. While this sediment contributes to the coastal sediment, it is largely lost from cultivated land.

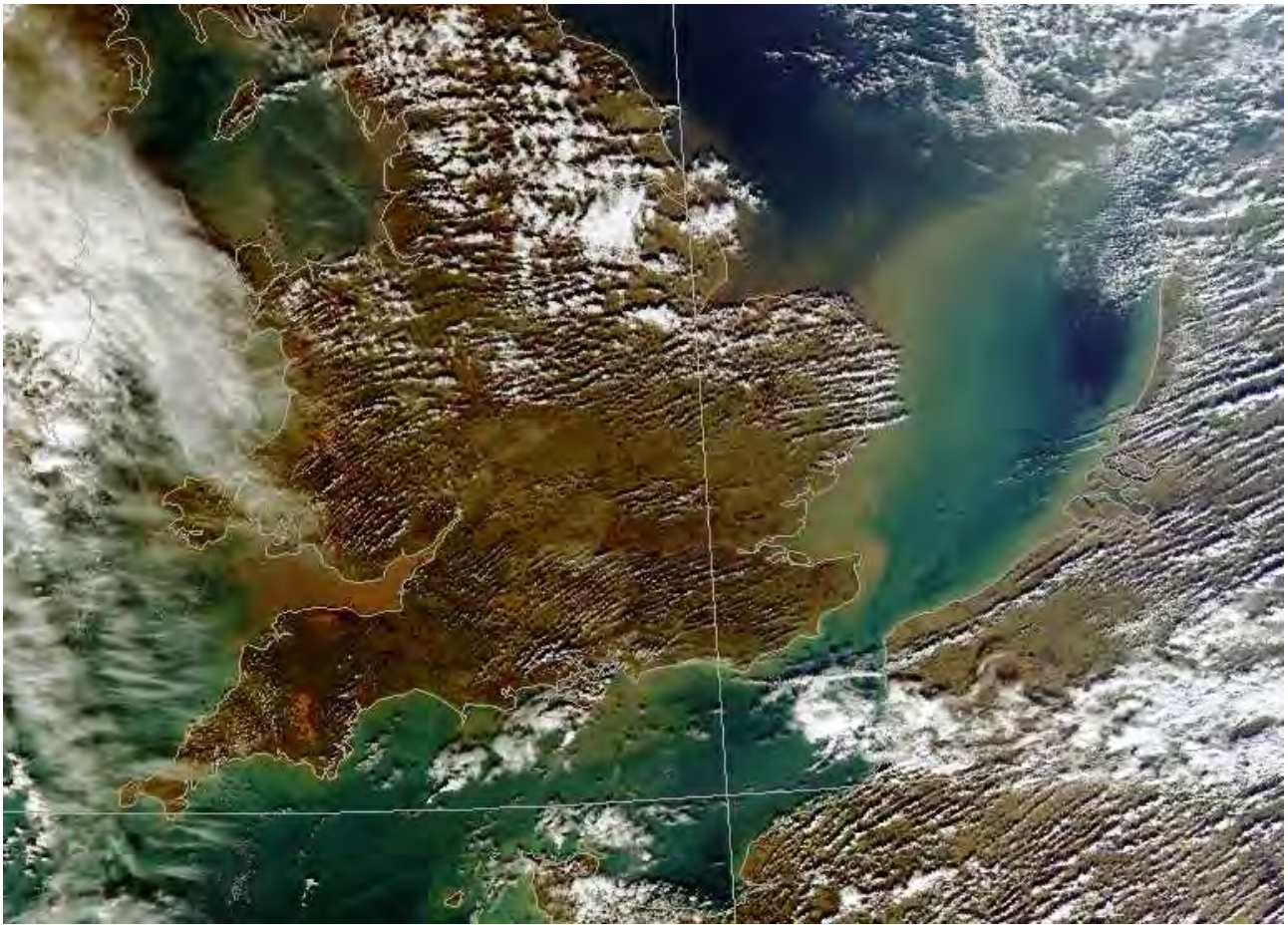

Figure 2 **A satellite image shows estuarine sediment plumes on February 16th, 2014**
Source: **Dundee Satellite Receiving Station**

2.3 Coastal sediment features

Coastline features are created by deposition of sediment. These include beaches, spits and tombolos, which are spits connecting an island to the mainland. Beaches are a common feature of the coastline. They are composed of eroded material that has been transported from elsewhere and deposited by sea waves and currents. Wave action is usually determined by seasonal conditions, building beaches and dune systems in low energy summer conditions and eroding these structures in high energy, stormy conditions. This cycle of erosion and deposition varies according to the climate variations but will tend to have an equilibrium condition. If the wave climate varies then so will the beach form.

The low energy “constructive” waves help to build up beaches. The material found on a beach (sand or shingle) depends on the geology of the area and the wave energy

The cross-section of a beach is termed the beach profile. The ridges, often shingle, found towards the back of a beach are called berms. The material found on a beach varies in size and type with distance from the shoreline. The smallest material is deposited near the average water level and larger sizes nearer to the back of the beach. The larger material is deposited during storms. Most waves break near the shoreline, so sediment near the water is more frequently transported and “worked” by wave action. Sandy beaches have gently sloping profiles and shingle and pebble beaches are steeper.

The sandy beach shown in Figure 3 is a typical sediment-rich Northumbrian beach which is contrasted with the pebble beach on the Yorkshire coast shown in Figure 4.

Figure 3 **A channel mouth and sandy beach features on the Northumbrian coast**
Source: **E M Valentine**

Figure 4 **A chalk pebble beach at Sowerby, near Bridlington, Yorkshire**
Source: **© Copyright Paul Allison**

A spit is an extended stretch of beach material projecting seaward from the coast. Spits are also created by deposition, formed where the prevailing wind, and hence wave action, is at an angle to the coastline. This results in *longshore drift* which is sediment transport along the beach. Spurn Head Spit (Figure 5) is an important and celebrated sand spit at the mouth of the Humber, fed by rapid erosion of the Holderness coast.

Figure 5 **Aerial view of Spurn Head Spit: an example of a coastal spit**
Source: **www.heritage-explorer.co.uk**

Spurn has developed as longshore drift has moved material and deposited it along the coastline. Over time, the spit has grown and developed a hook where the wind direction changes further out. In the lea of the spit, sheltered from waves, silt is deposited and mud flats or salt marshes form.

A tombolo is a spit that connects an island to the mainland. Chesil beach (Figure 6) which connects the Isle of Portland to the Dorset coast is an example of a tombolo. It stretches for 18 miles and lagoons have formed behind the stretch of beach material.

Figure 6 Satellite view of Chesil Beach
Source: Google Earth 2016

Generally, beach shape and planform are the outcome of the interplay between wave energy, other wave characteristics such as dominant direction, and the beach sediments. Beaches are usually in dynamic equilibrium, exhibiting changes in response to the recent wave conditions.

3 Movement of sediment in the marine environment

3.1 Sediment movement in the coastal zone

The sediments in the coastal zone are introduced through estuaries and by coastal erosion and are transported both by water motion and wind. The waters of the oceans, coastal waters and estuaries are in continual motion due to surface waves, tides, storm surge and nearshore currents. Coastal sediment transport results in the formation of characteristic coastal landforms such as beaches, spits and tombolos.

Wind-generated sea waves dominate the transfer of energy from the open sea to the coastlines. Wave energy drives the sediment transport process in the coastal zone. Sediment is entrained by waves moving across the increasingly shallow region of the coastal sea bed. Currents, produced by these waves and by tidal flows, provide the water motion which carries the sediments along. Winds play an important role in the coastal systems by mobilizing beach sands above the waterline. Typically, during storms, sediment is eroded from the beach face and deposited offshore in a sand bar. In calmer periods the sediment is transported back onto the shore rebuilding the beach. The most active region of sediment transport, the *nearshore zone*, extends from the seaward limit of the beach exposed at low tide to a water depth at which wave action during storms ceases to affect the sea bed. Above this, where fine sediments are in sufficient supply to the beach or nearshore system, *aeolian* or wind action contributes to the formation of dunes. Dunes form at the back of the beach and constitute a major component of natural coastal protection. They may be regarded as a store of protective sediment.

In addition to the forces acting upon the shore, the size distribution of the sediment controls how the beach develops. The interactions of the water motions generate a wide variety of beach shapes. Man also influences modification of these landforms. Some of these anthropogenic influences are due to measures which have been put in place to halt erosion or to prevent harbours from filling up with sediment. Development on dunes or overstabilisation often removes the contribution they make to the sediment supply which allows erosion in the beach head.

Waves are created by the action of wind blowing over the surface of the sea. The highest part of a wave is the crest and the lowest is the trough. The difference between the crest and trough is the wave height. The distance between successive crests is the wavelength **(Kinsman 1965)**.

Figure 7 demonstrates how, as a wave moves onshore into shallower water, it affects the sea bed. Initially, in deep water, where the depth, *d*, is greater than half the wavelength, *L*, the wave is described as a *deep-water wave* and does not affect the sea bed. The oscillatory motion of the wave does not touch the bottom. As the depth reduces, the wave starts to affect the bed in the *transitional zone* and finally becomes a shallow water wave when the depth is less than *L/20*. In this zone, sediment transport is significant and eventually the wave breaks in the *surf zone*. Note that the speed of the wave is termed *celerity*, *c*. This is a function of depth in shallow water, so as the wave moves ashore it slows down leading to the distance between crests deceasing and the wave breaking. It is worth noting that the wave effect on the bed is dependent on the relationship of depth to wavelength. A tsunami, which is a wave cause by seismic movement, has a very long wavelength, so even although it may have a very small wave height, it will usually be a *shallow water wave* from inception and even in relatively deep regions of the ocean it may cause bed sediment motion.

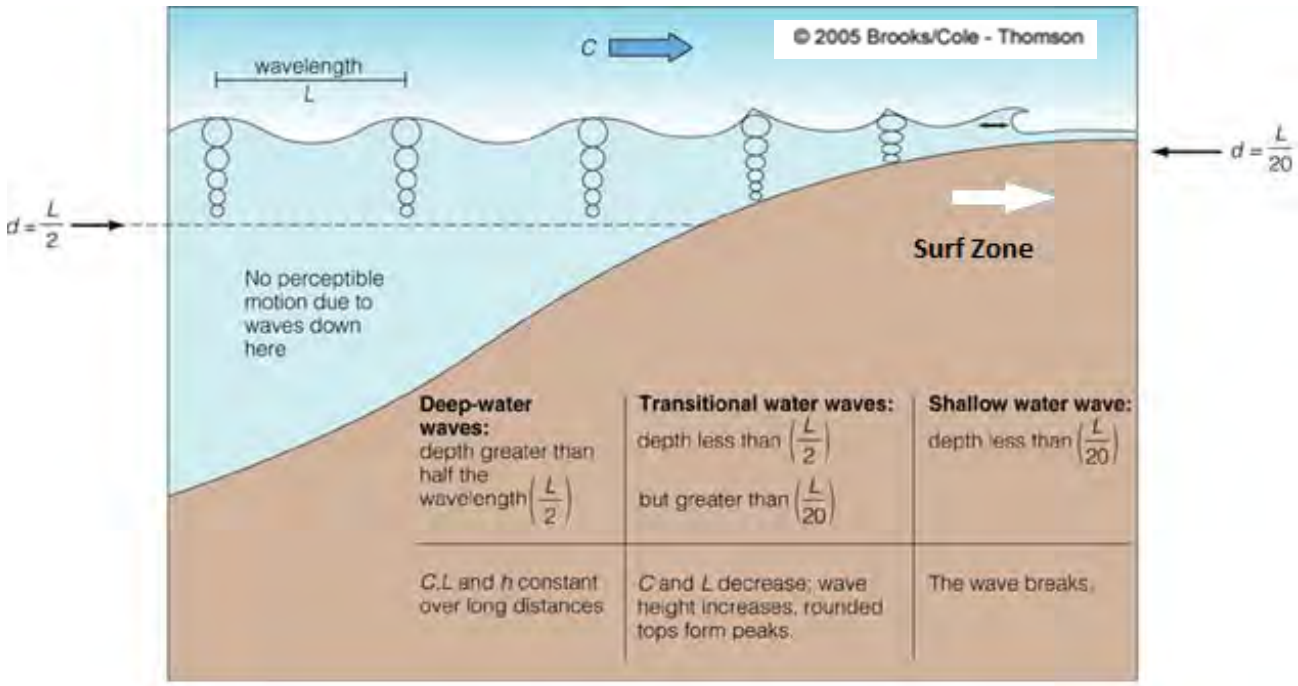

Figure 7 **Wave propagation and modification in shoaling water**
Source: **Adapted from Brooks/Cole**

Wave energy increases as the square of the wave height and will depend on wind strength, wind duration (how long the wind is blowing), water depth, and the fetch or maximum distance of open sea over which the wind blows. Therefore, storm winds of high velocity which blow for a sustained period over large distances produce the highest, most energetic waves which will transport most beach material on breaking on the shoreline. Waves break as they approach the beach as the depth reduces causing the wave to steepen. When a wave breaks, water washes

forward onto the shore and this so-called swash moves material up the beach. The backwash is the opposite action that returns water and sediment down the beach. The beach slope and wave steepness (relative height to length) control the way in which the wave breaks. A steep *plunging breaker* will expend more energy over a narrower *surf zone* than a *surging breaker* and will therefore create more intense sediment transport. (**US Army Corps of Engineers 2002** and **van Rijn 1984)**.

3.2 Littoral drift

Littoral drift, also known as *longshore drift* or *longshore transport*, is the process of transporting mostly non-cohesive sediments along the coast by waves which meet the shore at an angle. This depends on the prevailing wave direction, *swash* and *backwash*. As waves break on the beach, rip currents are produced as this water flows back down the shore (*backwash*) and sediment is progressively moved along the shoreline. The *swash* direction depends on the local instantaneous wave direction, so over long periods of time one direction may dominate, resulting in *net* longshore transport as explained in Figure 8. Currents may be caused by tidal flow and by wind and these can cause waves to be oblique to the coast, also causing longshore transport.

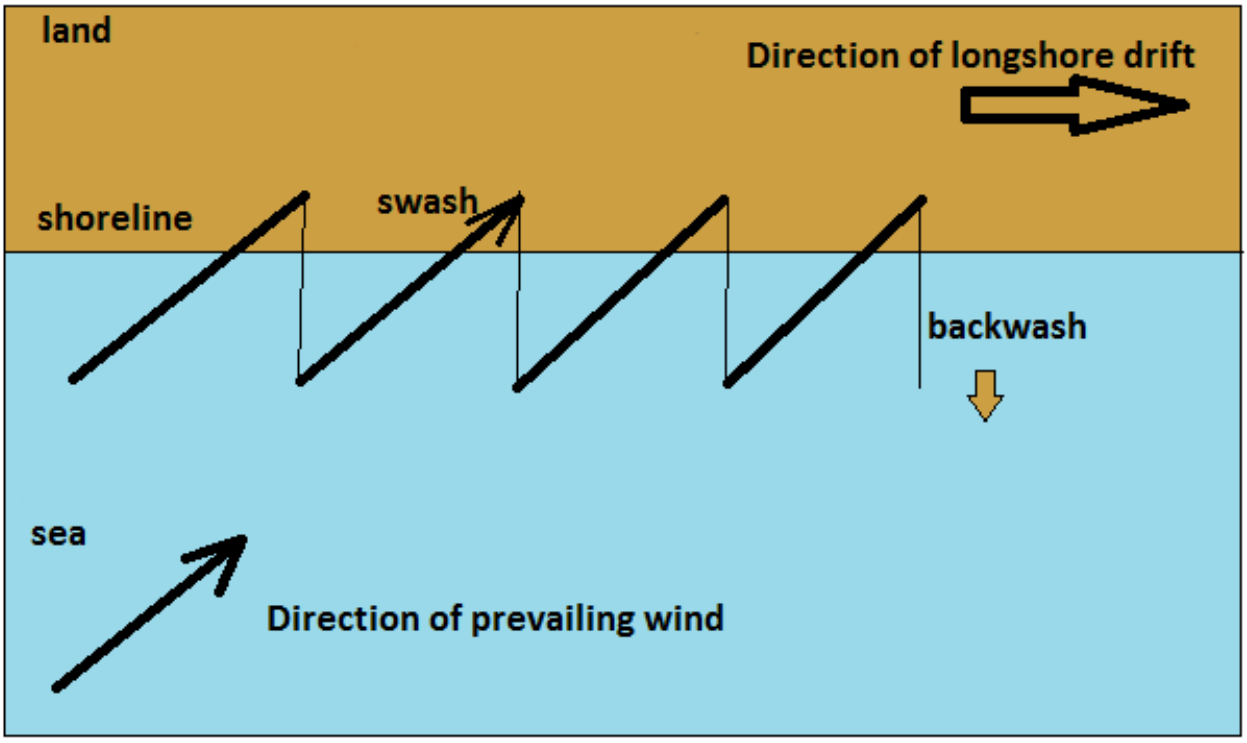

Figure 8 **Diagram showing longshore drift driven by wave direction**
Source: **E M Valentine**

3.3 Sedimentation in estuaries

Estuaries are the transition zones between rivers and marine environments which act as sediment traps or sinks. Sediment is transported from rivers to the sea through estuaries. They are subject to both the marine influences of tides, waves, the influences of saline water, and riverine influences of fresh water flows and sediment. The inflows of both seawater and fresh water provide high levels of nutrients in both the water column and sediment, making estuaries among the most productive of natural habitats.

The flow conditions are complicated by the balance between river discharge and tidal range. As the sediment moves along the river to the estuary the grain size distribution is altered by deposition, re-entrainment and transport. This sorting process in the river deposits much of the coarser sediment on floodplains which is released only by floods (**Lee *et al.* 1995**). The finer material therefore is carried into the estuary where suspended sediment concentrations are high. These fine particles tend to be cohesive, tend to flocculate (clump together) and can be highly organic. The tidal and seasonal cycles create continual transport, deposition and erosion. So, even when little new sediment arrives from the river or coast, the working of the material within the estuary tends to cause silting of estuarine harbours and channels. The sediment features in estuaries are very mobile and strongly influence estuarine processes. The sediments are often fine grained clay materials which absorb pollutants which are then transported with the sediment. Understanding pollutant dispersion therefore depends on knowledge of sediment transport.

The sediment in an estuary is subject to several influences:

- Electro-chemical changes due to the salts in sea water. Increasing salinity causes flocculation which increases deposition of suspended sediment
- Impacts due to industrial effluents and shipping movements
- Repeated cycles of erosion, transport and deposition due to tides
- The effects of changing tidal currents through the range of conditions between spring and neap tides
- Flushing of the estuary due to fluvial flood event.

The result is the transformation of sediment into estuarial muds which are a complex cocktail of silts, clays, metals and other chemicals. This material may range from cohesive muds to non-cohesive sands which increases the complexity of the mobility of the sediment.

The form of estuaries depends on the relative volumes of sediment contributed by the river and the coastal system. Deltas form where river sediment discharge is high. The river valley fills, and sediment is discharged to the sea. Deltas are found where there is high seasonal river flow, commonly in the tropics, in monsoon areas and where snow melt flow is important. Where sediment discharge is lower, the estuaries are not filled with sediment and these locations still exhibit the main features of river valleys. This variety of estuarine forms means that there are diverse and complex processes dominating the movement and deposition of sediments. Dynamic equilibrium is controlled by whether the flood or ebb tide dominates.

The tidal range determines a capacity to move sediments. Estuaries are classified as microtidal (tides less than 2m), mesotidal (2-4 m) and macrotidal (greater than 4m).

In general, estuaries are shallow and are affected by tides and long term sea level changes. On geological timescales they are temporary features which are more common now than at other times because of relatively recent sea level rises. Sea level is rising by 3mm per annum (see section 7.1). This is expected to accelerate and estuaries will adjust their form as this occurs. It is also likely that sediment accumulation will increase with larger tidal ranges. However, the net results will be dependent on the balance of complex local influences.

4 Marine sediment issues

Human interference in coastal hydraulic systems is often necessary to maintain and extend economic activities related to ports and associated navigation channels. In many situations, engineering structures (**Novak *et al.* 2006**, **Reeve *et al.* 2004**) are required to stabilise the shoreline, shoals and inlets, to reduce sedimentation, to prevent or reduce erosion, or to increase the channel depth to allow larger vessels to enter a harbour basin. Coastal protection against floods and navigability are the most basic problems in estuaries.

Sediment problems are associated with the construction of artificial structures or the dredging of sediment from the bed to increase the depth or width of a channel. Of course, deposition and erosion are basic phenomena in natural sedimentation areas such as shoals, sand banks and bars. Interference with these natural features generally leads to large maintenance costs.

Sedimentation or deposition generally occurs at locations where the sediment transporting capacity of the hydraulic system is reduced due to the decrease of the steady (currents) and oscillatory (waves) flow velocities and related turbulent motions. This will occur at, for example, the expansion of the flow depth and width, perhaps due to dredging, or in flow circulation, dead water or in the lea of structures. Expansions of the navigational depth, or the expansion of vessel mooring basins in a harbour will reduce velocities and induce shoaling. Specific problems occur in navigation channels, inlet channels, harbour entrances, docks, in the up drift area of groynes (Figure 9) and around pipelines and breakwaters.

Figure 9 A large concrete groyne to reduce longshore drift adjacent to a stormwater outfall
Source: E M Valentine

4.1 Coastal erosion

Coastal erosion or retreat has significant implications for human habitat because 45% of the world's population lives within 100km of a coastline. The reduction in sediment supply to the coast generally, as discussed in section 2.2, results in increased rates of erosion as there is less nourishment of the beach profile. Over time, as storms "attack" the coastline removing sediment to offshore bars or from the system altogether, the problem develops of how to protect coastal infrastructure. Sea level rise is exacerbating this problem. For example, a recent storm has caused considerable damage in Sydney, depicted in Figures 10 and 11.

Figure 10 Collaroy Beach, Sydney, Australia following a storm in 2016
Source: UNSW with permission.

Figure 11 **Aerial views of Collaroy Beach, Sydney, Australia before (showing estimate property values) and after 2016 storm event**
Source: **UNSW with permission.**

4.2 Coastal deposition

While it is evident that coastal erosion is the dominant process, accumulation of sediments occurs where there is excess supply and the wave and current conditions permit net deposition. For example, areas of the Lincolnshire and Norfolk coasts are notable for the significant extent of their salt marshes, zones of extensive sediment deposition. A salt marsh is a coastal ecosystem in the upper coastal intertidal zone between land and open salt water or brackish water that is regularly flooded by the tides. It is dominated by dense stands of salt-tolerant plants such as herbs, grasses, or low shrubs. These plants are terrestrial in origin and are essential to the stability of the salt marsh in trapping and binding sediments. Salt marshes play a large role in the aquatic food web and the delivery of nutrients to coastal waters. They also support terrestrial animals and provide coastal protection.

Some areas of deposition presently support large populations. Since widespread cultivation of the loess plateaux in northern China began about 2400 years ago, the sediment transport in the Yellow River has increased more than tenfold. One implication of this large increase in the sediment discharge of Asian rivers has been the increased seaward growth of some deltaic areas over the past few millennia. The Yellow River delta has accreted hundreds of square kilometres over the past few decades. This process is building the coastline at a rate greater than

sea level rise and is depositing sediment faster than erosional processes can remove it. These areas have been developed by populations who are now occupying land areas which would not exist but for the increased upstream erosion and its delivery to the coastal system. They must, however, be regarded as vulnerable to future erosion.

4.3 Ports and harbours

It is widely recognised that an efficient transport system which allows the economic movement of goods, resources and people is vital for economic activity. It has been estimated that around 90 per cent of the global merchandise and commodity trade is transported by ship. It has therefore been necessary to provide a great deal of coastal infrastructure to accommodate ever larger vessels. This has inevitably affected the environment in many ways. A major issue concerns the control of sediment during construction of harbours and deepening of approach channels. Ports usually require maintenance dredging.

Dredging operations and the disposal of dredging wastes are one of the major sources of port-induced environmental damage. Dredging can destroy the habitats of marine species. Mud, silt and sediment dredged from channels or harbour bottoms is often highly polluted by hydrocarbons and heavy metals, although this pollution may not be the result of port operations but a legacy of land based agricultural, industrial and urban activities.

Sediment accumulations in Darwin Harbour, Australia are shown in Figure 12. How this type of problem is managed, is addressed in section 6.4.

Figure 12 Sediment accumulation in the Darwin Harbour, Northern Territory, Australia
Source: E M Valentine

5 Estimation of sediment movement in the coastal zone

Human interference in coastal hydraulic systems is often necessary to maintain and extend economic activities related to ports and associated navigation channels. In many situations, engineering structures are required to stabilise the shoreline, shoals and inlets, to reduce sedimentation, to prevent or reduce erosion, or to increase the channel depth to allow larger vessels to enter a harbour basin. Coastal protection against floods and maintaining navigability are the most basic problems in estuaries (**Reeve *et al.* 2004**).

Knowledge of the distribution of longshore sediment transport across the surf zone is important to the effective estimation of coastal sediment dynamics. The transport distribution is particularly important for the design of groynes, jetties, outfalls and to the migration of natural or artificially placed shoreline features. Due to the difficulties of measuring longshore transport (let alone understanding its complexities) most studies (**Bijker 1971**) have focussed on the total longshore transport rather than its distribution across the beach. A reliable method of estimating sediment behaviour on the coast is the examination of historical accumulation or erosion data such as survey or aerial photography. Of course, this is not always available.

5.1 Longshore sediment transport relationships

The simplest and most readily applied level of sediment transport estimation uses the longshore transport equations. The detailed application of these equations is beyond the scope of this review. However, an indication of the most common approaches is useful and further reading will enable the reader to pursue the methods.

There are several formulae that attempt to quantify longshore or littoral drift, the sediment transport caused by the action of waves on beaches (**Bayram *et al.* 2001**) The principal formulations are those of:

- **Bijker 1967, 1971**
- **Engelund and Hansen 1967**
- **Ackers and White 1973**
- **Bailard and Inman 1981**
- **Van Rijn 1984**
- **Watanabe 1992**

These formulae all provide different views of the processes that generate longshore drift and the sources are listed in the Bibliography.

Calculating nearshore sediment transport is challenging due to the complexity of the hydrodynamics and the variety of the governing phenomena. It is very difficult to estimate sediment fluxes on beaches due to the combination of steady flows (currents) and oscillatory flows (waves). Additional effects should be integrated, such as the variations in mean water level (tide, set-up and set-down due to waves affecting the mean level near the beach), breaking wave effects (turbulence, undertow), and topographic influence (mean slope and bed forms). These effects induce different types of transport (bed load, suspended load and sheet flow), with very different physical implications for the movement of sand. Most of the sediment transport formulas are functions of the bed shear stress and have been developed and calibrated on specific data sets. See for example, **Bijker 1971** and **Bailard and Inman 1981** who validated their formulae to field data for littoral drift; **Van Rijn 1984** whose formula is was compared to a large variety of laboratory and field data. Others for example have compared and fitted their formula to experimental flume data, simulating cross-shore dynamics (current opposite to incoming waves) for sheet-flow conditions.

5.2 Sediment budget

The sediment budget considers the balance of sediment supply and loss to a particular system. This attempts to evaluate the sources and sinks to estimate the net changes in storage and hence areal extents within the system. The sediment sources and sinks may be:

- Rivers
- Lagoons
- Eroding land sources
- Artificial sources such as nourishment
- Artificial sinks such as sand mining or extraction
- Offshore transport
- Deposition of sediment on shore.

This sediment then enters the coastal system and is transported by longshore drift. An example of the sediment budget and longshore drift interacting is in inlet ebb-shoals where sand which has been transported by longshore transport is stored. As well as storing sand, these systems may also transfer or bypass sand into other beach systems. Therefore, inlets with ebb-tidal shoals provide a source/sink for the sediment budget.

5.3 Shoreline models

Models for the prediction of short and long term shoreline evolution are important tools in coastal engineering. Ideally, these models use the local wave climate and sediment descriptions to predict the behaviour of the shoreline and offshore bathymetry over a chosen duration. Thus, if coastal structures are located or beach nourishment is to be carried out along a shoreline, the model would enable the evaluation of the effectiveness of these modifications. These models are also used by coastal planners for shoreline management (**DEFRA 2010**).

Engineers have analysed long term shoreline evolution using the following approaches:

1) **Measurement and analysis of historical shoreline position**.

Statistical analysis of data is the most accurate method to describe shoreline change. It does not provide a means of evaluating potential changes to the system caused by engineering activities (eg breakwater construction or beach nourishment) or major climate change.

2) **Models based on the conservation of sand volume**.

This is known as the *one-line* approach and has been the preferred model for evaluating shoreline change that may result from manmade or natural changes in the beach system. The concept is based on the premise that the beach profile shape remains constant as it advances or retreats so that volume change is directly related to shoreline change (**Frey *et al.* 2012**). Spatial and temporal variations in gradients in longshore transport cause shoreline advance or retreat. The assumptions common to all one-line models are:

- The beach profile shape remains constant
- The shoreward and seaward vertical limits of the profile are constant
- Sand is transported alongshore by the action of breaking waves and longshore currents
- The detailed structure of the nearshore circulation is ignored
- There is a long-term trend in shoreline evolution
- There is an adequate sand supply.

Many different models have been developed to simulate shoreline change since the first one-line model was proposed by Pelnard-Considère in 1956 (Figure 13, **Dean**

2002). For a more detailed summary of the history of one-line theory, refer to **Larson et al 1997**.

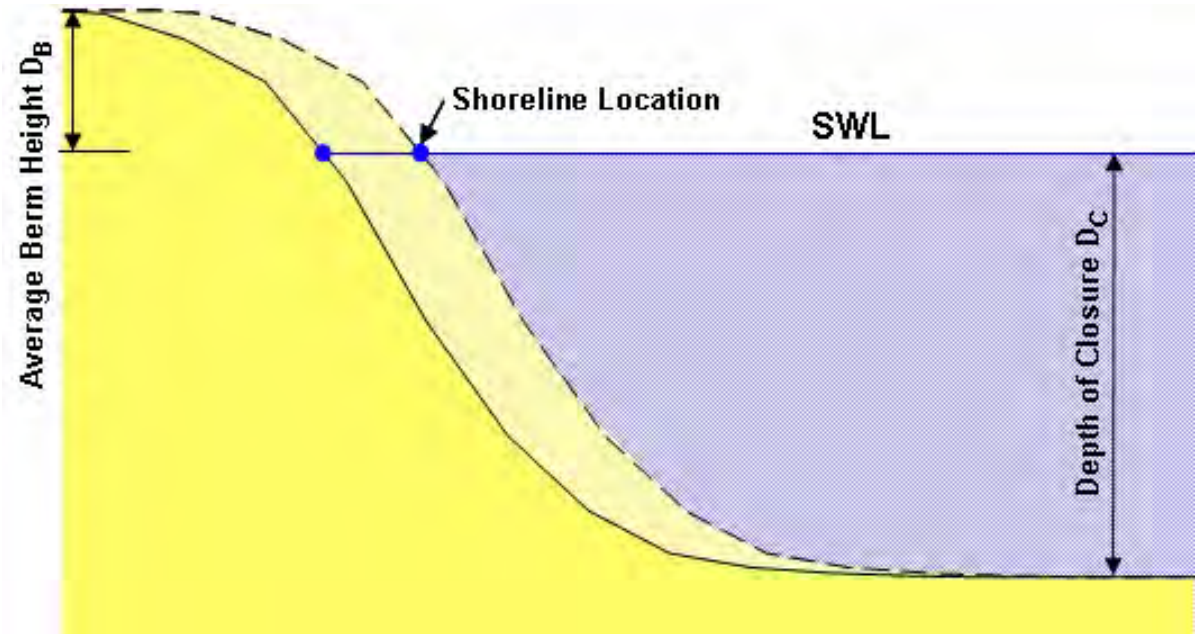

Figure 13 Shoreline change and associated bottom profiles in a One-Line model
Source: Dean 2002

3) Coastal morphodynamic models

Numerical models of the equations of motion (the equations describing the hydrodynamics of the water motion), the coastal morphodynamic models, in simple or more complete forms, require large computational resources. They are not well suited to the large spatial and temporal scales over which beaches evolve but are useful for indicating responses to engineering changes. An example visualisation of a beach evolution model is shown in Figure 14.

Equation-based models involve the solution of mathematical relationships which describe the phenomena in the coastal zone. The latter type includes numerical models which are solved using computers, and analytical models which are simpler but are useful conceptual tools to aid understanding.

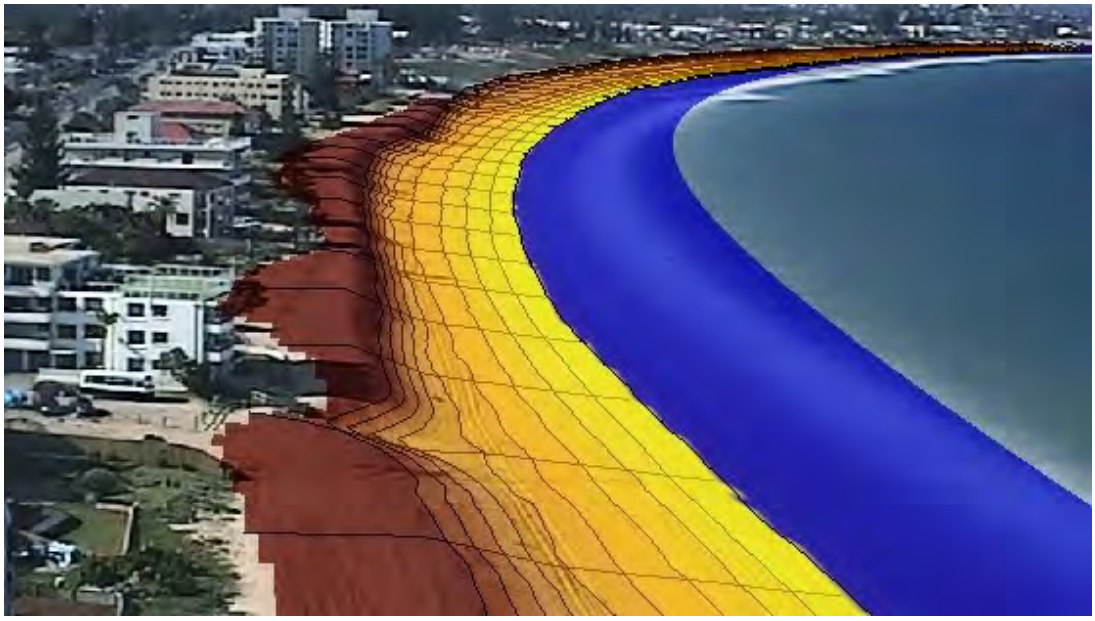

Figure 14 A graphic of a beach evolution model showing the computational elements of the beach and berm system
Source: Courtesy of UNSW, Sydney.

4) **Physical models**

Physical models are reduced scale representations of the prototype. They use scaling techniques for sediment to simulate the motion of particles in water waves. This is an art as well as a science. They are suited to local analysis but are prohibitively expensive to apply to very large areas or large scales.

Future direction? No fully satisfactory shoreline model exists at present. This is because our understanding of the physics of shoreline sediment transport is limited. There are also uncertainties in representing the wave environment over long and short periods and in describing the complex wave dynamics in the surf zone. However, models have been developed partly to test how well our level of knowledge provides a representation, partly to identify weaknesses in the description, and partly to provide the best possible tools for the present.

In the future, it is expected that the most successful models will be numerical ones. These allow flexibility in the initial and boundary conditions and the representation of the forces driving the processes. These models are readily modified as knowledge improves. Although these models are progressing, the equations describing the shoreline behaviour are too complicated to be captured in an analytical model. Physical models are hampered by scaling constraints and high costs.

Numerical models, complemented by good judgement based on field experience, provide the best available predictions (**Novak *et al.* 2010**).

6 Methods of marine sediment control

Man's activities have increased sediment in rivers through practices that increase soil erosion. Simultaneously, the sediment flux to the coastal environment has decreased because of dam construction and reduced river flow due to abstraction. The net result is a global reduction in the overall sediment flux to the coast. This impact on coastal erosion will be further accelerated as sea level rises. Given the modern levels of sediment loads, over 100 billion tonnes of sediment has been deposited in artificial reservoirs. This explains why the effects in the changes in upstream fluvial conditions are included in coastal zone management plans. The management of the coastal zone must account for both the effect of human activities and the impacts resulting from changes in the coastal zone (**DEFRA 2002**).

6.1 Coastal planning

Incorporating a sediment budget into a coastal management plan is becoming critical (**DEFRA 2010**). Today, a large majority of the global population live close to the coast. One of the essential components which may be drawn from a sediment budget is the prediction of morphological changes that are likely to occur on a coastline over time. This is especially relevant to the effects of major environmental change such as sea level rise. A sediment budget has been recognized as important in coastal planning for finding information relating to hazard zones, beach property protection, and coastal erosion as well as the effectiveness of current management strategies. A problem with using the sediment budget for management is its complexity (**Environment Agency 2010**).

6.2 Coastal protection

When protecting the coastline, it is important to understand how the sediment budget can be affected when implementing appropriate coastal protection techniques. Often, management plans for coastal erosion have seen the use of 'hard' engineering structures as a means of protecting coastlines from recession. Frequently, groynes are used to trap the longshore drift of sediment that often depletes a beach. Groynes are simply timber or concrete walls across the beach which are used to change the sediment motion along the beach by trapping sand. The up drift beaches accrete while the down drift beaches are starved. These approaches have become less popular as a better understanding of coastal dynamics has led to the promotion of 'soft', more natural solutions such as nourishment and preservation of natural systems such as dunes.

6.3 Management of coastal erosion

Many coastlines are managed in order to prevent or minimise coastal erosion. These management strategies often require the use of coastal defences to fix the location of the land-sea boundary or reduce the impact of erosion. Coastal defences may use either 'hard' or 'soft' engineering methods (**Novak *et al.* 2006, Reeve *et al.* 2004**).

Soft engineering is often regarded as a more sustainable, long-term and potentially cheaper approach to coastal defence, working with the natural processes to protect the shoreline.

A beach is itself a coastal defence, as it reduces wave impact and prevents inland flooding. However, the beach may need to be managed to ensure it is wide and high enough to prevent overtopping during high tides or storm surge levels. This can be done through beach replenishment (see cover picture) where beach grade sediments are used to 'top-up' the beach, increasing its level of protection.

Beach replenishment or nourishment is a short term fix for a long term problem. It treats the immediate symptoms of coastal erosion by dumping sand either just offshore or on the beach directly. It can be an expensive and time consuming process as it requires regular maintenance. While it may appear aesthetically pleasing it does not solve the problem as the beach may have lost its source of natural nourishment. Artificial nourishment is an appropriate short term solution on small scale restoration projects.

This type of coastal erosion management has been applied all over the world. An example of this is Mount Manganui beach on the North island of New Zealand. This beach had experienced erosion, resulting in coastal dune retreat of 20 m. When dredging at the adjacent Tauranga Harbour entrance began, the opportunity was taken to use the sediment to re-nourish the beach. The sediment was deposited in the nearshore zone promoting beach accretion by this supply to the offshore berm. It has been successful, as most of the 80,000 m^3 of sediment added to the nearshore zone made it ashore to re-nourish the beach and even out the past sediment deficit. Nourishment can be regarded as a fast fix option to reverse a sediment deficit. However, it is important that it is on-going to ensure the sediment budget remains balanced.

Hard engineering usually has higher capital costs. It is generally more intrusive than soft engineering and can often cause more problems elsewhere by creating wave reflection and higher local rates of sediment transport. The methods used

extend from large fixed concrete walls, through so-called ‘flexible’ structures which consist of loose but interlocking stone or concrete elements, to structures designed to limit longshore transport and so sustain the beach material in the locality.

Examples of hard engineering methods:

Sea walls and revetments are structures with respectively vertical or near vertical, and sloping seaward faces which are used to reduce the landward migration of the beach due to coastal erosion. Wave energy is limited by the structure to reduce the erosive power of the wave action. They may be constructed from concrete, stone or asphalt. The structure must have a crest high enough to stop wave overtopping during a storm event.

Breakwaters are offshore sloping or vertical structures that reduce incoming wave energy arriving at the coastline. As well as reducing erosion, they are used to create calmer waters for harbours and shipping. Breakwaters may be constructed of concrete or rock.

Groynes (Figure 15) are barriers extending from the beach offshore to below low water, usually placed at intervals along a beach in some relation to the wave conditions and beach slope. As observed earlier, they are used to slow the loss of beach material by inhibiting longshore drift. They can be constructed of timber, stone or concrete depending on the size of the native beach material. Although they act to reduce local erosion, they usually starve down drift locations and may exacerbate problems there.

Sea dykes are large land-based structures used to prevent overtopping during high tide and storm events. Instead of protecting from wave action, sea dykes fix the land-sea boundary in place to prevent inland flooding. They are typically built from sand, clay or mud, often with a grass covering. These structures occupy large areas due to the flatter berm slopes required for stability.

Figure 15 **An example of successful groynes where the beach has accreted to the extent that the top of the groynes is just visible**
Source: **E M Valentine**

Managed retreat. It must be acknowledged that beaches and estuaries are dynamic and that in some situations the protection of a coastline may be impossible to achieve within acceptable economic limits.

Managed retreat or *managed realignment* is an approach that involves altering the location of the line of defence, to provide a more sustainable position from which to manage flood and erosion risks. It can involve advancement (moving forward), set back, or breach of the existing coastal defence line. Most commonly, it involves establishing a new set back line of defence on the coast or within an estuary. The creation of coastal habitat such as saltmarsh helps to absorb wave energy. The result can be an effective and sustainable solution to flood and erosion risk at the coast.

Managed retreat may have serious social consequences and requires thorough community engagement. Examples are at Medmerry in Sussex, Abereiddy in Pembrokeshire and Steart in Somerset. **(ICE website).**

6.4 Dredging

Dredging is the removal of sediments and debris from the bottom of waterways, rivers, harbours and ports (**Herbich 1992**). Maintenance dredging is the periodic removal of shoals or sediments from existing navigational channels, berths, swinging moorings etc. to maintain an appropriate safe depth of water for navigation, construction or operational purposes. It is a routine necessity because of sedimentation – the natural process of sand and silt washing downstream from rivers and driven by tidal currents around harbour basins. The sediment deposits, and gradually fills, the deepened channels and harbour areas Dredging is an excavation activity usually carried out underwater in shallow seas with the purpose of removing bottom sediments and disposing of them at a different location. It may be used as a source to replenish sand on public beaches, where sand has been lost because of coastal erosion.

Dredging is often focussed on maintaining or increasing the depth of navigation channels, anchorages, or berthing areas to ensure adequate draught for vessels. Ships require a certain navigational keel clearance which has increased as larger and larger ships are commissioned. Dredging is also performed to reduce the exposure of fish, wildlife and people to contaminants and to prevent the spread of contaminants to other areas of the water body. This *environmental dredging* is often necessary because sediments around cities and industrial areas are frequently polluted. These pollutants may come from point sources such as sewer overflows, municipal and industrial discharges or from non-point sources such as stormwater runoff or atmospheric deposition. Sediment arriving in marine zones may require management to mitigate environmental damage.

Dredged material is usually disposed of at sea in licensed areas, the criterion being to deposit sediments in areas deep enough to be stable. However, the process of dredging results in some material being entrained at the dredge and deposit sites. This also has environmental impacts which may be controversial if not addressed.

Dredging activities have the potential to change the environment. At the sites of dredging and disposal, the seabed and associated benthic communities are disturbed, and for some distance suspended sediment may cause turbidity in the water column and increased sedimentation on the bottom.

Between 20 and 40 million tonnes of material is dredged from English and Welsh ports, harbours and their approach channels every year, and in 1994 the amounts dredged were estimated at some 40 million tonnes (**Lee *et al.* 1995**).

However, the levels of dredging that take place varies greatly from port to port and from year to year. For example, while Milford Haven may only have a minimum requirement to undertake maintenance dredging in some years, in other years the oil companies in the Haven have dredged substantial amounts. The ports of the Severn Estuary were reported to dredge around 4.5 million tonnes of sediments in a typical year (**Severn Estuary Strategy 1997**), whereas in Strangford Lough (Portaferry Harbour) only 2,000 tonnes were dredged a year. In contrast, no dredging is undertaken at Millbay Docks and Sutton Harbour in Plymouth Sound, although small amounts of maintenance dredging activity is undertaken within the Dockyard Port of Plymouth.

In addition to undertaking maintenance dredging to improve or extend navigable depths in ports, harbours, marinas and shipping channels, it is also an important activity adjacent to lock and dock gates to ensure there is efficient operation and continued access to dry docks and basins. The aerial photograph in Figure 16 illustrates the effects. Very large ships carry the bulk of goods around the globe and consequently dredging plays a vital role in the economy.

Figure 16 Dredging operations at the mouth of the Swan River at Freemantle, Western Australia
Source: The Dredge Research Collaborative

7 Future concerns

7.1 Climate change and sea level rise

Sea level rise is one of the most significant effects of global warming. The highest projected rates of future sea levels have captured the attention in low-lying coastal areas. Some Pacific islands which are already threatened by inundation and erosion are planning population migration. The consequences for global coastal erosion and modification are enormous.

Global Mean Sea Level Rise (GMSLR) between 1901–2010 can be accounted for by ocean thermal expansion, ice loss by glaciers and ice sheets, and change in liquid water storage on land. It is very likely that the 21st-century mean rate of GMSLR will exceed that of 1971–2010 due to the same processes. Rates up to 2100 can be projected with medium confidence, including the contribution from ice-sheet rapid dynamics. A significant increase in the occurrence of future sea level extremes due to storm surge is expected. It is virtually certain that global mean sea level rise will continue for many centuries beyond 2100, with the amount of rise dependent on future emissions (**IPCC, 2013**). The GMSLR projections are shown in Figure 17. Figure 18 indicates that the level increases will not be uniform but will depend on location due to complex factors of tidal flow and local atmospheric pressure.

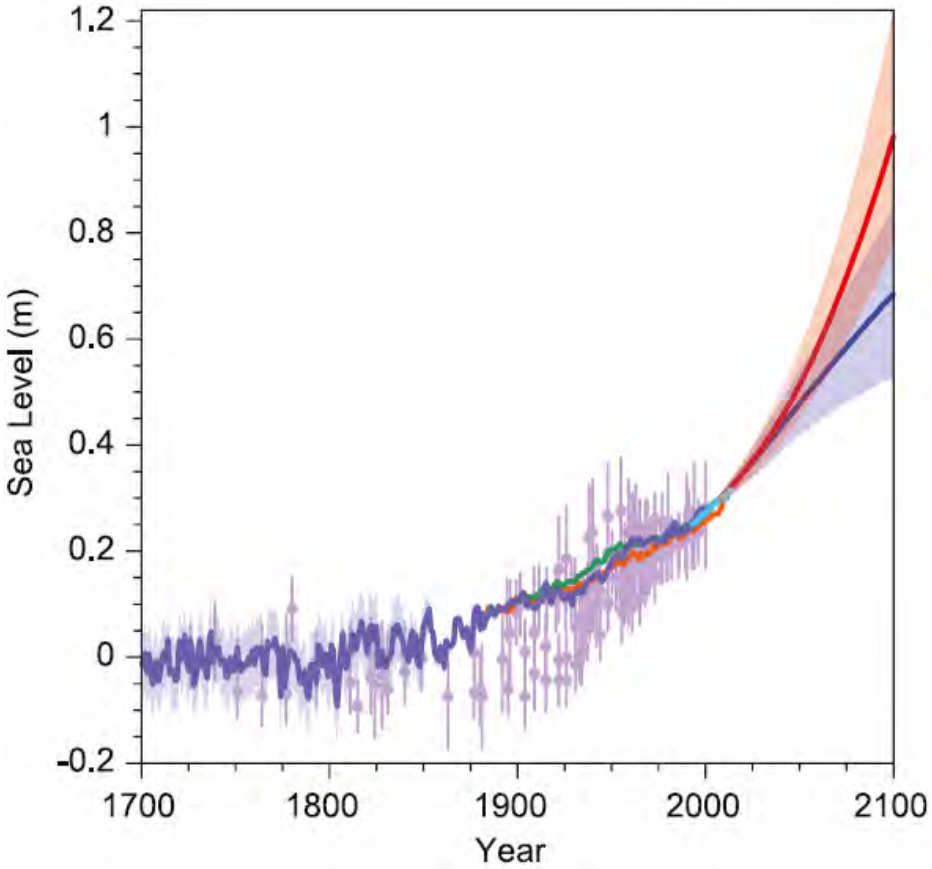

Figure 17 **Past and future sea-level rise. For the past, proxy data are shown in light purple and tide gauge data in blue. For the future, the IPCC projections for very high emissions (red, RCP8.5 scenario) and very low emissions (blue, RCP2.6 scenario) are shown**

Source: **IPCC AR5, 2013.**

Increased sea level and the forecast increased storminess will cause changes in wave climate and increases in storm surge levels. This will have serious effects on coastal flooding and sediment dynamics, contributing to coastal erosion rates (**DEFRA 2002)**.

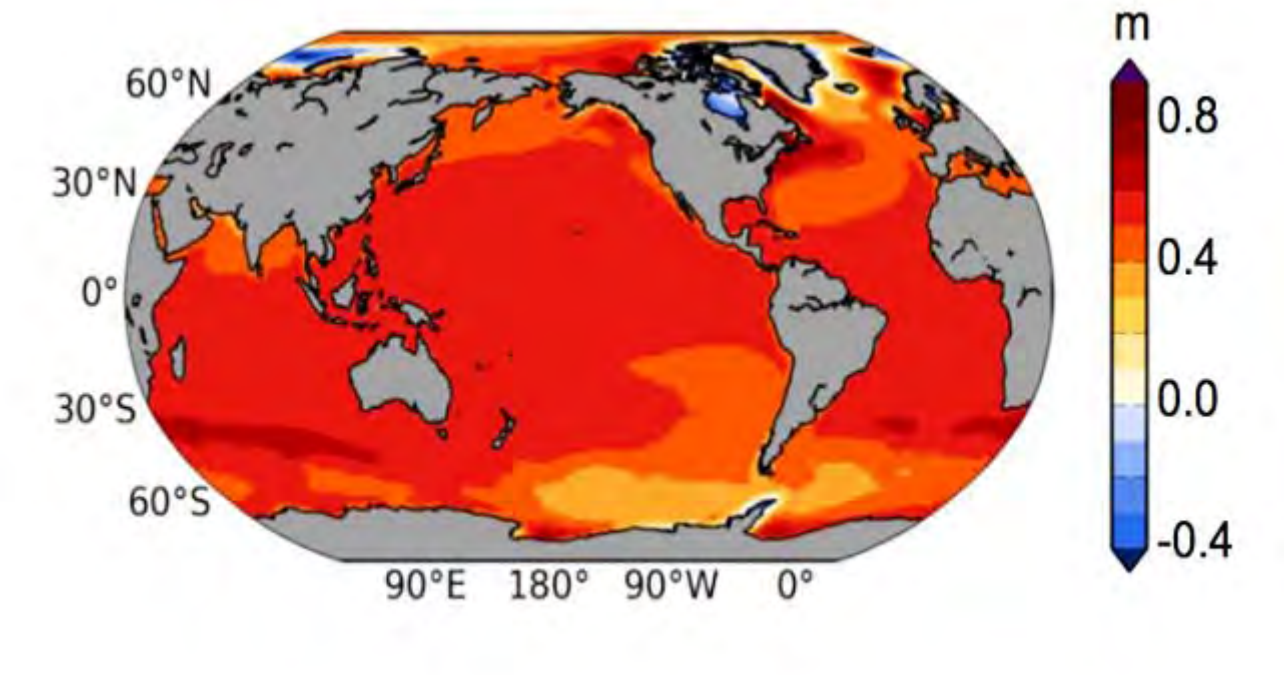

Figure 18 **Regional sea level rise projected for a moderate emissions scenario to demonstrate that sea level rise will vary depending on location**
Source: **IPCC AR5, 2013.**

7.2 Coastal response to sea level rise

In the British Isles coastal erosion is a significant issue. It is estimated that 17% of the UK and 20% of the Irish coastline is eroding. Of the 3,700km of the coastline of England and Wales 28% is receding at a rate greater than 100mm per annum.

A notable example of cliff erosion is the Holderness coastline in Yorkshire which runs between the Humber Estuary in the south and Flamborough head (**www.urbanrim.org.uk/Holderness)**. It has the unenviable reputation for the highest rate of erosion in Europe. In stormy years, waves from the North Sea have removed between 7 and 10m of the cliffs over considerable distances (Figure 19). The longshore drift is predominantly to the south, so much of the eroded material is contributing to the accretion of the Lincolnshire coast where salt marshes are continuing to develop.

The natural response of coastal systems to sea level rise is to migrate landward, through erosion of the lower part of the nearshore profile and deposition on the upper part. This so-called *roll-over model* is applicable to beaches, estuaries, barriers and tidal flats. Rocky coasts are called erosional coasts because there is little material in the sediment balance and by their nature retreat even under stable sea-level conditions. Where the coast is protected by engineering structures, coasts are generally experiencing a steepening of the intertidal profile.

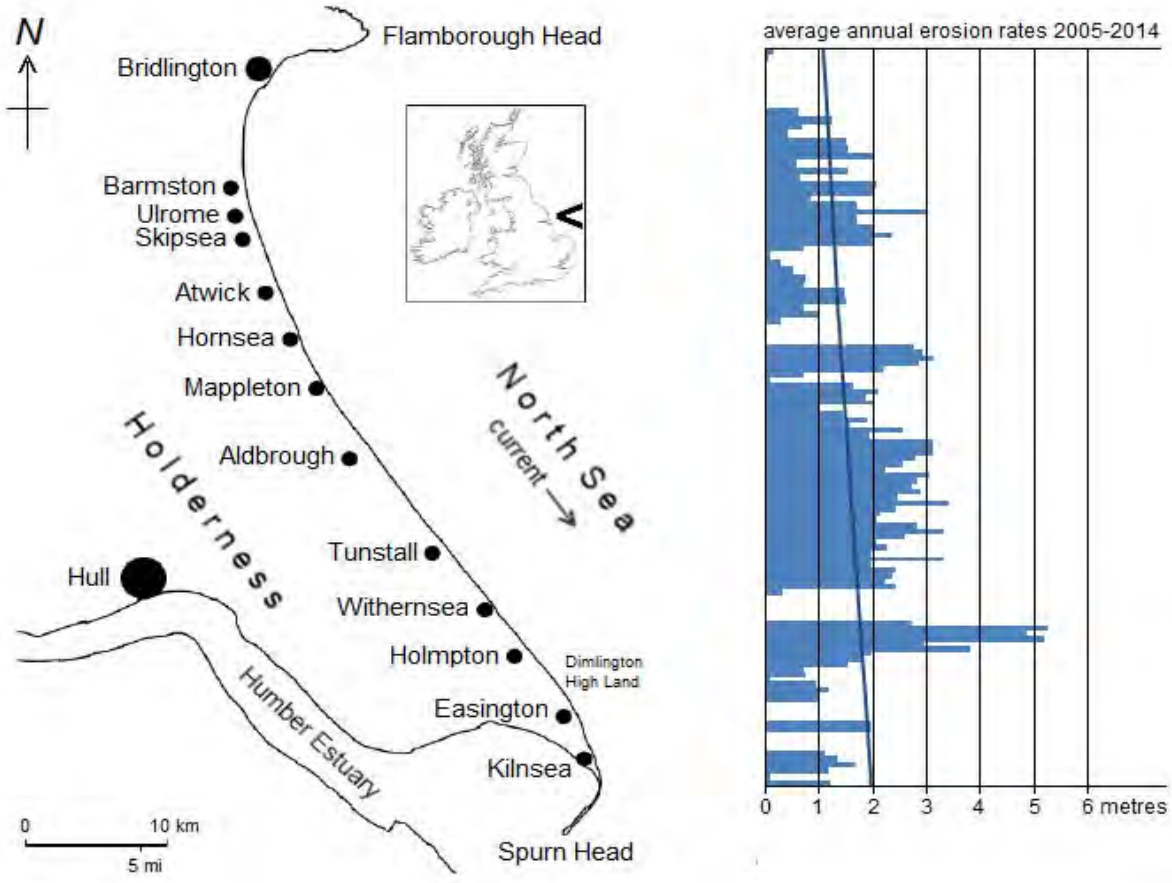

Figure 19 **Rates of erosion on the Holderness coast in Yorkshire, England**
Source: **www.urbanrim.org.uk/Holderness**

Coastal response to sea-level is strongly determined by site specific factors and usually it is these factors that dominate over global changes in sea level or a regional change in wave climate. Predictions of general coastal response due to climate change therefore have a low confidence. However, if a detailed study is conducted and long term coastal change data are available, then local or regional predictions of coastal response to climate change can have improved confidence.

In the absence of a clear understanding of the coastal processes, and therefore a reliable predictive tool, the default position is to assume that the present coastal change will persist. However, it is very likely that stretches of coast which are presently experiencing erosion will suffer increased rates of erosion due to sea-level rise.

The coastal management strategy (e.g. hard coastal defences, beach nourishment, managed realignment) is also key in determining the long term response of the

coast to climate change, including sea-level rise. Managed realignment is likely to increase in the future as a management strategy. Although this will result in increased local erosion, the sediment supplied to the system can benefit other sections of coast by reducing erosion or even causing accretion. Adaptation is emerging as the key management response to cope with coastal erosion.

7.3 Sediment and water quality

The sediments in receiving estuarine and coastal systems can be a repository for contaminants that may be discharged or seep through groundwater from coastal facilities. These contaminants have the potential to affect benthic biota though bioaccumulation.

Discharge from coastal facilities into marine systems or the disturbance of contaminated sediments can affect water quality. This can result in toxicity or bioaccumulation in marine species.

The Foresight project on flooding and coastal defence for the UK (**Foresight project 2004**) provides an indication of future risks from flooding and coastal erosion based on scenarios of socioeconomic development and climate change. The analysis suggests that risks could increase significantly over the next 30 to 100 years, but there are significant variations between the different scenarios and considerable uncertainty inherent in looking so far into the future.

7. 4 Where to now?

The reader will appreciate that understanding sediment transport is difficult. The complexities of the marine hydraulics environment render the problem even more difficult. The engineering community has been very successful in understanding the physics of environmental hydraulics and in applying computational models to practical problems. Large projects on the coast and in estuaries, such as the Øresund Bridge from Denmark to Sweden, have benefited from extensive state-of-the-art morphological models to determine the effects of the infrastructure on tidal flows and hence the channel sea bed. Future projects, such as a potential Severn Barrage will require application of the most sophisticated models to demonstrate long term viability, largely due to important effects on the sediment regime.

It must be acknowledged that our understanding of the mechanics of how currents and waves drive sediment transport in the marine environment remains incomplete. Despite the enormous progress in modelling the marine sediment environment, it remains a major research area.

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