Chapter 26. Land-Sea Physical Interaction

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1. Introduction

This chapter deals with how human activities have changed the physical interaction between the sea and the land. This physical interaction is important because about 60 per cent of the world's population live in the coastal zone (Nicholls et al., 2007). The "coastal zone" is defined in a World Bank publication as "the interface where the land meets the ocean, encompassing shoreline environments as well as adjacent coastal waters. Its components can include river deltas, coastal plains, wetlands, beaches and dunes, reefs, mangrove forests, lagoons and other coastal features." (Post et al., 1996)   In some places, natural coastal erosion processes cause damage to property, harm to economic activities and even loss of life. In other places, human activities have modified natural processes of erosion of the coast and its replenishment, through: (1) coastal development such as land reclamation, sand mining and the construction of sea defences that change the coastal alongshore sediment transport system; (2) modification of river catchments to either increase or decrease natural sediment delivery to the coast; and (3) through global climate change and attendant sea level rise changes to surface wave height and period and the intensity and frequency of storm events.

2. Natural coastal erosion and property damage

Coastal erosion is a natural, long-term process that contributes to the shaping of present coastlines, but it can also pose a threat to life and property (Rangel-Butrago and Anfuso, 2009). For example, the total coastal area (including houses and buildings) currently being lost in Europe through marine erosion is estimated to be about 15 km^2 per year (Van Rijn, 2011). Over 70 per cent of the world's beaches experience coastal erosion, some portion of which is a natural process (Dar and Dar, 2009). Other natural processes influencing coastal sediment dynamics include the supply of biogenic carbonate sand and gravel (see Chapter 7) and volcanism which can provide an important sediment source to some coastal areas, including some continental coasts, such as in Italy (de Rita et al., 2002) and to volcanic islands, such

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[1] The writing team thanks Kazimierz Furmanczyk for his substantive contribution to this chapter.

as in Polynesia, Indonesia, the Caribbean, the Azores and sub-Antarctic islands (e.g., Dey and Smith, 1989; Ross and Wall, 1999). Volcanic activity may supply sediments to the coast directly in the form of ash deposited as atmospheric fallout, or as lava flows or debris flows down the flanks of volcanoes that are adjacent to the coast (Fisher and Smith, 1991).

3. Impacts of anthropogenic climate change

The impacts on coastal ecosystems of anthropogenic global climate change (Jaagus, 2006; Jylhä et al., 2004) are associated with sea-level rise (Johansson et al., 2004 and increased storminess (Alexandersson et al., 1998) (Lowe et al., 2001; Masselink and Russell, 2006; Meier et al., 2004; Morton et al., 2005; Tõnisson et al., 2011; Suursaar et al., 2006; Wang et al., 1998). Coastal sedimentation and morphology are influenced directly by regional land morphology and composition and anthropogenic activities that affect the amounts and locations of precipitation, run-off from both point and non-point sources, sea level, and storm activity. In addition, aeolian (i.e., wind-blown) dust, especially from deserts in Africa and Asia, affects some coastal communities. Aeolian processes are discussed in Chapter 5 and will not be considered further here.

The Intergovernmental Panel on Climate Change (IPCC) (2013) has shown that the rate of global sea-level rise throughout the 20th century has increased, due to melting ice caps and glaciers and the thermal expansion of the oceans, both resulting from increased global temperatures. Local sea level is further affected by processes including sediment discharge and subsidence (the natural, gravitational sinking of land over time), hydrological management, fluid withdrawal, and tectonic activity (Millman et al., 1989; Reed and Yuill, 2009; Boon et al., 2010). The human response to sea-level rise will include armouring coastlines to protect real estate, thus cutting off the natural (landward) retreat path of coastal and intertidal organisms. Coastal development that has occurred on low-gradient, sandy coastlines is the most vulnerable, since the natural response of such systems is to retreat landward as sea level rises.

Another apparent response to the warming of the Earth's atmosphere is a change in the ocean wave climate, manifested as increased wave heights associated with more intense storm events (Carter and Draper, 1988; WASA Group, 1998; Gulev and Hasse, 1999; Allan and Komar, 2000). Changes in wave regime may affect the stability of sandy shorelines and potentially dramatic changes in coastal geomorphology may occur locally. For example, the transformation from tide-dominated to wave-dominated coastal systems is possible in some locations (Harris et al., 2002). Increased wave height and period translates into an increase in the water depth at which sediments may be mobilized, thereby fundamentally changing the character of the seabed habitat. For example, areas of sandy seafloor previously stable under the prevailing wave and current regime may become transformed into a different habitat type, subject to mobilizing forces of episodic storms (Hughes et al., 2010).

4. Impacts of coastal development

Increasing human encroachment, land reclamation, coastal development and economic activity (e.g., shipping, recreation, mining) are considered to be among the major anthropogenic impacts on the coastal environment. These impacts have both direct and indirect influences on the physical interaction of the ocean with the coast.

4.1 Land Reclamation

Land reclamation is a significant component of economic growth and development for many countries around the world. The need for space to accommodate an increasing world population, which is projected to exceed 8.1 billion by 2025 (United Nations, 2013), has been a contributing factor to the growing trend of large-scale reclamation projects in many coastal areas to provide suitable land for housing and recreation, industry, commerce, agriculture and, in some cases, to provide coastal protection for the adjacent coastline. Many land-reclamation projects are also found in coastal cities that are short of space for expansion, particularly for port activities.

Two methods of land reclamation are generally used: infilling and draining of tidal and submerged wetlands. Infilling is most common in coastal areas associated with dredging activities, either indirectly by utilizing dredged material form port and harbour development or directly from offshore sources. Improved dredging technologies over time have increased the scale efficiency, cost-effectiveness and value of the land created in reclamation projects (Kolman, 2012). Previously land reclamation was restricted to shallow near-shore environments; however, with improvements in dredging methods and technologies, land reclamation has progressed to deeper water.

Large-scale land reclamation was pioneered in the Netherlands by the building of "polders" (areas of former swamp or intertidal land enclosed by embankments known as dikes). Since the 11th century, the Dutch have reclaimed marshes and fenland, resulting in some 3,000 polders nationwide enclosing about 7,000 km^2. About half of the total surface area of polders in northwest Europe is in the Netherlands. With the advent of modern machinery, such reclamation of wetlands is achieved much more readily. In West Bengal, India, 1,500 km^2 of the coastal Sundarbans wetlands have been reclaimed over the last 100 years (UNEP, 2009). In China, 9,200 km^2 (16 per cent) of the wetlands present in the 1970s had disappeared by 2007 (Zuo et al., 2013). At a more local level, 28 per cent of the tidal flats around the coast of the Yellow Sea were reclaimed between the 1980s and the late 2000s (Murray et al., 2014). Around the world, polder-type reclamation has been undertaken in Egypt, Morocco, Senegal and Tunisia in Africa, in Bangladesh, China, India, Indonesia, Iraq, Japan, Malaysia, Myanmar, the Republic of Korea, Pakistan, Thailand and Viet Nam in Asia; in Belgium, Denmark, Germany, Italy, Poland, Portugal, Romania, Spain and the United Kingdom of Great Britain and Northern Ireland in Europe; in The Russian Federation; in the south-eastern states of the United State of America in North America; and in Argentina, Colombia, Suriname and Venezuela in South America (MVenW, 1983). This reclamation work has particularly affected

mangroves and salt marshes (see Chapters 48 and 49).

In recent times significant large-scale dredging projects have been undertaken in several countries in Asia and the Middle East. Rapidly emergent economies, such as China, Japan, Singapore, and United Arab Emirates, have all undertaken large-scale reclamation projects as a solution to finding land for economic development (Glaser et al., 1991; Suzuki, 2003). Reclamation is no longer limited to near-shore coastal environments. Technological advances enabled the creation of the international airport of Hong Kong, China, Japan's Kansai airport and resort developments, such as the Palm Jumeirah, Palm Jebel Ali, the Deira Islands and other similar facilities that are now a prominent feature of the coastline of Dubai, United Arab Emirates.

Major projects, such as the creation of Hulhumalé Island in the Maldives between 1997 and 2002, have been used to relieve overpopulated urban areas and to enable urban expansion. More than 10 per cent of the developed land area of Hong Kong, China, is reclaimed from the sea (Jiao et al., 2001). Other examples of such urban land reclamation projects are: Rotterdam in Europe, New York/New Jersey Port Authority and San Francisco in North America, Rio de Janeiro and Rio Grande in South America, Shanghai, Singapore and Tokyo in East Asia, Chennai and Kolkata in South Asia, Bahrain and Dubai in West Asia, and Cape Town and Lagos in Africa. In special cases, such as the Principality of Monaco, reclaimed land forms 20 per cent of the land area of the State (Anthony, 1994).

Several examples of reclamation are found in China, where the primary objective was to provide suitable living space for a growing population and to promote economic development. Between 2003 and 2006, the Shanghai government spent 40 billion yuan (6.5 billion United States dollars) on the so-called Lingang New City Project to reclaim 133.3 km^2 of artificial land from the sea. From 1949 to 2000, China reclaimed about 12,000 km^2 of land. Land reclamation has also been used to tackle long-term coastal erosion problems from storm surges and extreme climatic events. For example, significant financial investments have been allocated to reclaim beaches along Florida's eastern coastline in the United States and support a major tourism industry. The Sand Engine[2] in the Netherlands is also an innovative example of an effort to alleviate long-term coastal erosion problems while at the same time boosting local biological diversity and the economy (Stive et al., 2013).

4.2   Environmental impacts of land reclamation
Land reclamation causes significant negative impacts on coastal habitats and the ecosystem services they provide (Wang et al., 2014; Wang et al., 2010). Degradation of wetlands, seagrass beds and coastal water quality is commonly associated with

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[2] The Sand Motor is an innovative method for coastal protection. The Sand Motor (also known as Sand Engine) is a huge volume of sand that has been applied along the coast of Zuid-Holland (the Netherlands) at Ter Heijde in 2011. Wind, waves and currents will spread the sand naturally along the coast of Zuid-Holland. This is called 'Building with Nature'. The Sand Motor will gradually change in shape and will eventually be fully incorporated into the dunes and the beach. The coast will be broader and safer. From: http://www.dezandmotor.nl/en-GB/.

large-scale reclamation projects. Examples of studies examining the impacts of coastal wetlands reclamation are available from, e.g., Hong Kong, China (Jiao et al., 2001), the Republic of Korea (Lee, 1998) and the Netherlands (Waterman et al., 1998).

Large-scale reclamation can also affect the regional groundwater regime, causing changes of the groundwater level and the modification of natural groundwater discharge to the coast. For example, Mahamood and Twigg (1995) conducted a statistical analysis of water table data to document a rise in the water table in areas of Bahrain associated with land reclaimed from the sea. Some of the problems related to land reclamation in coastal areas are reported by Jiao (2000) as including:

- Rises in water level will lead to reduction in the bearing capacity of foundations and in the stability of slopes.
- Ground water may also penetrate underground concrete and cause corrosion of steel reinforcements.
- An increase in water level may cause damp surfaces and superficial damage to the floors of residential buildings (Mahamood and Twigg, 1995).

Furthermore, aquifers behave like underground reservoirs and can receive only a certain amount of rainfall before they overflow. If the water level is increased as a result of land reclamation, the additional water storage capacity will be significantly decreased, resulting in increased rainwater run-off. Thus, aquifers that are full will increase the chance of flooding during heavy rainfall periods. As submarine groundwater input to the sea depends on the groundwater level relative to sea level, a change in the groundwater regime may modify the coastal marine environment and ecology (Jiao, 2000).

4.3   Socioeconomic impacts of land reclamation

The significance of land reclamation to the development of local and national economies cannot be overstated. Land development is inextricably linked to rapid economic growth in many countries. For example, Small Island Developing States depend on coastal economies for their growth and development. Several islands rely heavily on the provision of suitable tourism infrastructure and seaports to maintain their development objectives. More generally, growth in international trade entails growth in shipping (see Chapter 17) both in volume and in the size of ships, which makes port expansion necessary (see chapter 18). In many cities, such port expansion can only be achieved by land reclamation.

As well as benefits, interference with other uses of the sea can occur For example, in Japan, part of Isahaya Bay on the Ariake Sea was cut off from the rest of the bay by a dike to reclaim land for agriculture and to create freshwater storage. Fishers and seaweed growers complained that the effects, especially on tidal flows, have harmed fish, shellfish and seaweed production, a view that a Japanese court upheld in 2010 (JT, 2014; AS, 2013).

4.4 Habitats, coastal development and coastal squeeze

Measured normal to the coast, the assemblage of coastal habitats ranges in width from only a few metres to tens of kilometres, offering very diverse environmental conditions to numerous plant and animal species. These habitats formed as a result of long-term stability in ecological conditions influenced by the constant distance from the shoreline. The influence of the sea decreases rapidly towards the land and biodiversity decreases rapidly just a few hundred metres from the shoreline as well. Therefore, it is noted that the loss of the land on the coastal zone often leads to the rapid decrease of biodiversity, especially on the uplifting regions (Kont et al., 2011).

Coastal vegetation (e.g., dune vegetation, reed-beds, mangroves, salt marshes) inhibits erosion, reducing the effect of storm surges and wave attack (Kathiresan and Rajendran, 2005), and serves as natural protection. Removing the vegetation for coastal development can increase coastal erosion (Waycott et al., 2009) and may add to the amount of sediment moving along the shore, causing siltation of harbours and burial of coastal and coastal sea habitats.

One of the most recent and most notable coastal defence structures is the 25-km-long Saint Petersburg Flood Prevention Facility Complex. The estimated cost of this structure was approximately 3.85 billion United States dollars (Reuters, 2011). Recent winter storms have caused extreme erosion events on the surrounding sandy beaches (Tõnisson et al., 2012).

Several countries in the world have legislatively defined shoreline locations, and major efforts are made to implement the laws. The most notable examples are Poland, the Netherlands and the United States of America. Today, over one-fourth of the 1032-km-long Polish coast is more or less engineered (www.climateadaptation.eu). For the period 2004-2023 a Long-Term Coastal Protection Strategy was developed for which 249 million euros has been secured (approximately 7.5 million euros per year). Approximately 3.5 million inhabitants live in the region that might be potentially affected by the sea in Poland (ec.europa.eu). This cost is rather big compared to what the Baltic States (which have a shoreline that is four times longer) altogether are spending on coastal protection. The only known cost is the Lithuanian Palanga nourishment project reaching 1.65 million euros per year (Gulbinskas et al., 2009).

Most of the effort in the Netherlands is focused on the flood protection, because over three-fourths of the Netherlands is less than 5 m above sea level. Approximately 9 million people live in the region at high risk from coastal flooding and over 50 per cent of GDP is generated in this region. In principle, the Netherlands addresses coastal protection activities in a comprehensive (national) approach to counteract flood risk (coast and river flooding). The total amount spent on flood-risk protection is estimated at 550 million euros per year. Over the period 1998-2015, measures to protect the Dutch coast against flooding and erosion and adapt to increased storminess and sea-level rise amount to 3.4 billion euros. The yearly expenditure on beach nourishments under the Sand Nourishment Programme has increased from 22 million euros in 2000 to 70 million euros in 2008 (ec.europa.eu).

Over 50 per cent of the population in the United States live in the coastal region and are more or less affected by changes in coastal processes. In the United States,

coastal erosion is responsible for approximately 500 million United States dollars per year in coastal property loss, including damage to structures and loss of land. To mitigate coastal erosion, the federal government spends an average of 150 million dollars every year on beach nourishment and other shoreline erosion control measures. However, it is estimated that despite the measures, every fourth house within an approximately 500-m-wide coastal zone will be destroyed by erosion by 2050 (NOAA, 2013).

Economic losses related to coastal erosion are more complex to assess. Detailed analyses carried out in Louisiana in the United States show that major disruptions in economic activities caused by coastal erosion and flooding might result in over 70,000 jobs lost in the United States and a long-term loss for the United States economy of approximately 10 billion dollars (dnr.louisiana.gov). Loss of coastal habitat in Louisiana results from three primary processes: control of the Mississippi River, which reduces the amount of replenishing sediment that rebuilds the coast, subsidence, and industrial activity.

The United States Army Corps of Engineers will be spending upward of 5 billion dollars on shore protection projects following Hurricane Sandy. The vast majority of these funds will be spent on pumping sand onto beaches from Delaware to Connecticut, an amount approaching 25 to 35 million m^3. This is an adaptation model that cannot be exported to most developing countries due to its cost, and it is doubtful that it can be maintained for an extended period of time in the United States of America (Young et al., 2014).

The use of initially less expensive hard protection measures (which are extremely destructive to surrounding shores and natural habitats) has decreased, whereas the share of soft coastal protection measures has significantly increased in recent decades. However, in light of global sea-level rise, researchers and coastal communities have started the debate on managed realignment. In the United Kingdom, realignment of private property and infrastructure occurred in a 66-km-long stretch of shoreline during 1991-2013. The United Kingdom government plans to reach 550 km (10 per cent of the United Kingdom coastline) by 2030 (Esteves and Thomas, 2014). These zones will function as natural buffer zones and reduce the risk of erosion and coastal defence costs to the surrounding coasts. Furthermore, most of the local communities are in favour of this measure and the strongest opposition is from those whose property will be most severely affected. This topic is also recognized by European Commission, and a new Horizon 2020 call (open until 2014 autumn) was issued on the topic: "Science and innovation for adaptation to climate change: from assessing costs, risks and opportunities to demonstration of options and practices", where realignment is considered as a key solution

(http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/).

Many countries do not have the economic resources to protect their coast actively through engineering solutions, which are very expensive and often not technologically successful.   Effective non-engineering solutions are available such as restoring the processes that were in place before human intervention, improved urban planning, and orderly retreat strategies.   The cost of not dealing with coastal

erosion can be even more costly over the long-term. For example, in 2006, Mozambique requested 3 million US dollars from the international community to carry out engineering coastal protection countermeasures for potential flooding. This request was turned down in 2007, and since then, the international community has spent over 90 million dollars to address extreme flooding in the region (Ashdown, 2011).

5. Impacts of catchment disturbance

5.1 Decline in marine sedimentation as a result of water management

On a global basis, the natural (pre-Anthropocene) sediment load to the oceans from rivers is estimated to be about 15×10^9 tons; the majority is supplied by mountain rivers with steep catchments (Milliman and Syvitski, 1992; Ludwig and Probst, 1998; Syvitski et al., 2005). Over the last few centuries, the global annual sediment flux into the coastal zone has increased by 2.3×10^9 tons due to anthropogenic soil erosion and decreased by 3.7×10^9 tons due to retention in reservoirs: the net effect is a reduction of sediment input by 1.4×10^9 tons (Syvitski et al., 2005). A major environmental consequence of river sediment starvation is erosion of the coast and attendant loss of habitat; conversely, the consequence of increased sediment input is elevated coastal and estuarine turbidity and smothering and burial of biota. Many examples of the two opposite consequences are documented from different places around the world (Fig. 1).

A well-documented example of the first problem (sediment starvation) is the Mississippi River, which is controlled by the United States Army Corps of Engineers and has one of the most diverse and largest watersheds in the world. Over the Holocene period (the last 10,000 years) the Mississippi deposited the largest deltaic coastal complex in North America. Prior to European settlement of North America, the sediment load of the Mississippi was around 400 million tons per year, but at present it is around 100 million tons per year as a result of the construction of around 45,000 water reservoirs in the catchment (Syvitski, 2008). The decreased sediment load contributes to loss of wetlands in the delta; this loss peaked between 1955 and 1978 at 11,114 ha/year and declined to 2,591 ha per year from 1990 to 2000. Reductions in sedimentation, compounded by sea-level rise, water abstraction (causing subsidence), oil and gas extraction (also causing subsidence), tidal erosion and storm surges, have resulted in an approximate total land loss of 113,300 acres of the coastal Mississippi delta over the past 60 years (Morton et al., 2005).
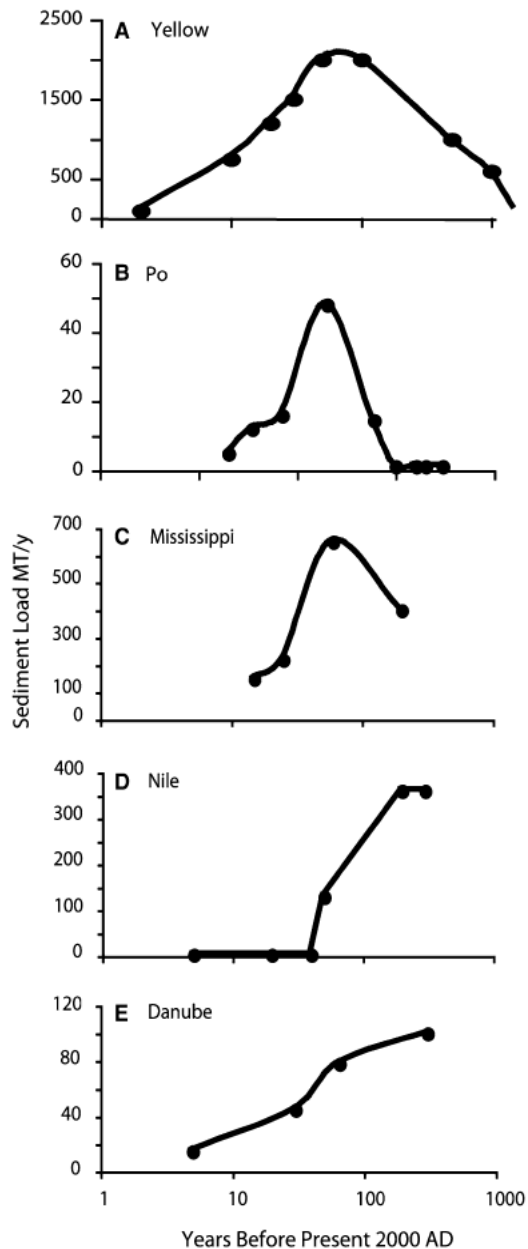
Figure 1. Change in the sediment load in millions of tons per year (MT/year) delivered to the deltas of five rivers over a period of 1,000 years: (A) Yellow; (B) Po; (C) Mississippi; (D) Nile; and (E) Danube (from Syvitski, 2008). In some cases an initial phase of catchment clearing and disturbance, characterized by increased sediment load, is followed by a reduced sediment load phase attributed to dam building (A, B and C). In other cases the curves indicate only a steady decrease in sediment load attributed to dam building (D and E) (Source: Syvitski, 2008).

Other examples of river systems that have undergone a similar pattern of anthropogenic sediment retention that has reduced the sediment discharge of the river to below pristine conditions include the Yellow, Indus, Colorado, Nile and Danube Rivers (Syvitski, 2008). In extreme cases the sediment load is reduced to near zero (e.g., the Nile, Indus and Colorado Rivers). The Volta River in West Africa had a sediment load of 11 million tons per year prior to the construction of the Akosombo Dam, but after the dam's completion in 1963, this load was reduced to nearly zero (Milliman and Meade, 1983). With the recent construction of another dam on the

Volta River (the Kpong Dam), its sediment yield has diminished further, starving the delta and coast of sediment input.

5.2   Increase in marine sedimentation as a result of catchment disturbance

In many instances, dam building and sediment entrapment in reservoirs does not offset the impacts of land clearing and soil disturbance in the catchment, such that river sediment loads exceed pristine levels in spite of dam building. The data presented in Figure 1 for the Yellow River 10 years ago and for the Po and Mississippi 100 years ago all showed this effect. Another example is the coast of northeast Queensland in Australia adjacent to the Great Barrier Reef; modelling work by Brodie et al. (2003) indicates that the total suspended sediment load of rivers draining into the Great Barrier Reef region is currently about 16 million tons per year, compared with pre-European settlement estimates of around 2 million tons per year. This is in spite of the fact that nearly all of the rivers in the region have been dammed. Consequently, increased sedimentation (with attendant inputs of nutrients and pesticides) to the ecosystem are affecting inshore areas of the Great Barrier Reef, causing increased algal growth, accumulation of pollutants in sediments and marine species, reducing light and smothering corals (GBRMPA, 2009).

One other key point noted by Milliman and Meade (1983, p. 19) is that "much of the sediment probably accumulates on the subaerial parts of subsiding deltas, never really reaching salt water. Along coastlines that include a number of large estuaries, most of the inflowing river sediment is trapped in embayments." Hence a significant proportion of sediment discharged by most rivers is trapped within the coastal biome. Nevertheless, more widespread impacts of increased sediment loads may occur during flood events, when buoyant river plumes extend across the continental shelf. The input of fine-grained sediment in historical times may also have increased the turbidity of the coastal zone above pristine environmental conditions, affecting some light-dependent species.

5.3   Modelling Coastal Sedimentary Processes

Computer models have assisted in improving our understanding of sedimentation processes in the near shore (Syvitski and Alcott, 1993; Syvitski and Alcott, 1995; Mulder et al., 1997; Syvitski and Milliman, 2007; Chu et al., 2013). Computer algorithms provide process-related information to understand flow dynamics, particulate and chemical distributions, and the overall oceanography of coastal environments.

5.4   Impacts of increased sediment input on coastal habitats

The impact of sediments has been recognized by both global reviews and the United Nations Environment Programme (UNEP/GEMS, 2008).   These impacts include:

- Smothering of marine communities and, in severe cases, complete burial leading to suffocation of corals, mangrove stands and seagrass beds.

- Decreases in the amount of available sunlight, which may in turn limit the production of algae and macrophytes, increase water temperatures and reduce growth of natural vegetation.

- Injuring fish by irritating or scouring their gills and degrading fish habitats as gravel containing fish eggs becomes filled with fine particles, thus reducing available oxygen

- Reducing the success of visual predators, and may also harm some benthic macroinvertebrates.

- Infilling watercourses, storm drains and reservoirs, leading to costly dredging and an increased risk of flooding.

- Many toxic organic chemicals, heavy metals and nutrients are physically and/or chemically adsorbed by sediments, so that an increase of sediment loading to the marine environment can also lead to increased deposition of these toxic substances that result in further negative impacts such as eutrophication.

It is important to recall that human impacts on marine habitats rarely (if ever) act in isolation (Lotze et al., 2006; Harris, 2012). Therefore it is difficult, if not impossible, to attribute specific changes in species composition or abundance to single, specific impacts, such as increased sediment loads of rivers caused by human activities. Nevertheless, increased sediment loads of rivers have evidently affected the marine environment, and this section reviews these effects as far as possible.

Coastal habitats and species that are most affected by increased sediment loads of rivers are those which are least tolerant of rapid sediment deposition and high turbidity (in relation to natural background levels), and changes in sediment grain size and composition. Among such ecosystems, coral reefs and estuaries with their associated mangrove, salt marshes and sea grasses are among the most vulnerable habitats.

In the Caribbean, Burke et al. (2004) reported on the assessment of more than 3,000 watersheds across the region that discharged into an area where coral reefs were present. They found that 20 per cent of coral reefs in the region are at high threat, and about 15 per cent at medium threat from damage caused by increased sediment and pollution from agricultural lands and other land modification.

Sediment input to temperate ecosystems also affects habitats and associated species. For example, eelgrass meadows, which provide important near-shore marine habitat for fish, shellfish, and invertebrates, as well as food for waterfowl and detritus feeders, can be buried or fragmented by increased sediment delivery associated with river-delta channelization (Lotze et al., 2006; Grossman et al., 2011). Increased turbidity is a particular problem because seagrasses require some of the highest light levels of any plant group in the world, approaching 25 per cent of incident radiation in some seagrass species, compared with 1 per cent or less for other angiosperm species (Dennison et al., 1993).

Therefore, even small increases in turbidity can cause significant reductions in seagrass cover over a short time span (Orth et al., 2006).

Changes in sediment grain-size composition can also affect ecosystems. For example, many shellfish beds and forage-fish spawning beaches depend on a specific sediment grain-size composition that is linked to land-use activities and hydrological conditions that release and carry sediment into coastal waters (Gelfenbaum et al., 2009). Water quality, near-shore and offshore habitats, and aquatic ecosystem health are affected by contaminants and nutrients that preferentially adsorb to fine sediments. Specialized organisms that have adapted to fine sediments, high sedimentation rates, and mobile substrate utilize estuaries. The macroinvertebrates that are found at the bottom of estuaries are much smaller than those found in streambeds with larger particle sizes, and they tend to be opportunistic species (Schaffner et al., 1987). Within the estuary, the density of fauna is commonly greater in the freshwater tidal areas than in parts of the estuary having (tidally) varying salinity (Schaffner et al., 1987). The species diversity of macroinvertebrates is usually lower in fine sediments than that in sediments with coarser particles. The diversity and evenness of species decline with an increasing percentage of silt/clay and organic matter (Junoy and Vieitez, 1990). However, fine-sediment beds are important for burrowing tube-building invertebrates and other burrowing species (Minshall, 1984).

The impacts of increased sedimentation from river input will differ between deltas and estuaries (Harris and Heap, 2003). Estuaries and deltas formed along coasts at the end of the last Ice Age when sea level reached its present position, around 6,500 years ago. Deltas evolved in places where river sediment discharge filled the palaeo-river valley to form a deltaic protrusion from the coast. The formation of a delta relies on the river supplying sediment to the coast more rapidly than can be redistributed by waves and tides, causing seaward progradation. For estuaries and lagoons, slow rates of sediment delivery to the coast results in the palaeo-valley remaining partially un-filled. Waves and tides produce deltas and estuaries with distinctively different shapes in plain view (e.g., Harris and Heap, 2003; Syvitski, 2008).

Prograding coastlines, characterized by deltas, strand plains and tidal flats, export most of their sediment load to the sea and generally have a naturally low sediment-trapping efficiency. They contain a suite of habitats that will not be significantly affected by sedimentation. In contrast, transgressive coastlines, characterized by estuaries and lagoons, have a high sediment-trapping efficiency (Fig. 2). They are, therefore, more susceptible to the accumulation of particle-associated contaminants such as heavy metals. They also contain a suite of habitats that will change (evolve) as they infill with sediments (Roy et al., 2001), and are therefore more susceptible to catchment perturbations that affect river sediment loads. The water contained in tide-dominated deltaic distributary channels, estuaries, and creeks that drain intertidal flats, is naturally turbid and generally well mixed. In contrast, water contained in wave-dominated deltaic distributary channels, estuaries, and lagoons is naturally clear (low turbidity) and exhibits mainly stratified (estuarine) circulation patterns (Fig. 2).

In arid regions of the Earth, this circulation is often of the inverse (negative) type, driven by high evaporation rates. From a management perspective, therefore, human activities that give rise to higher turbidity levels are likely to have a greater impact in wave-dominated systems (that have naturally low-turbidity, clear water) than in tide-

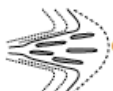dominated systems that are naturally turbid (Harris and Heap, 2003).
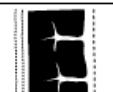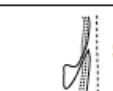
Type of Coastal Environment	Sediment Trapping Efficiency	Turbidity	Circulation	Habitat Change due to Sedimentation
Tide-dominated Delta	Low	Naturally High	Well Mixed	Low Risk
Wave-dominated Delta	Low	Naturally Low	Salt Wedge/ Partially Mixed	Low Risk
Tide-dominated Estuary	Moderate	Naturally High	Well Mixed	Some Risk
Wave-dominated Estuary	High	Naturally Low	Salt Wedge/ Partially Mixed	High Risk
Tidal Flats	Low	Naturally High	Well Mixed	Low Risk
Strand Plains	Low	Naturally Low	Negative/ Salt Wedge/ Partially Mixed	Low Risk
Lagoon	High	Naturally Low	Negative/ Well Mixed	High Risk

Figure 2. Diagram showing different types of coastal depositional environments in relation to four common management issues: sediment trapping efficiency, turbidity, water circulation and habitat change due to sedimentation (from Harris and Heap, 2003).

5.5   Coastal erosion caused by sediment starvation of coasts attributed to dam building and impacts on habitats

When sediment delivery to the coast is reduced by dam building in the catchment, critical near-shore habitat and beaches can be eroded by natural coastal processes and lost (Malini and Rao, 2004; Warrick et al., 2009). Erosion along pristine sedimentary coastlines will cause a landward retreat of habitats, such that an ecological succession is observed at a fixed observation point. For example, supratidal vegetated dunes give way to intertidal salt marsh and tidal flats. Thus the entire suite of habitats is preserved, but laterally displaced.

Several factors can complicate this simple view. In some cases the space that could allow habitats to retreat is simply not available (so-called coastal squeeze; Doody, 2013; Pontee, 2013) For example, in a modelling study of continental United States coastal habitats, Feagin et al. (2005) found that beach erosion resulted in the disappearance of sand dune plants or in their confinement to a narrow belt because existing coastal development (or coastal defences like seawalls) occupies the

available space landward of the dune zone. This results in a breakdown of the successional process in built-up areas along the coastal zone.

An example of loss of habitat attributed to coastal erosion induced by dam building was reported for mangrove habitat of the Godavari Delta, India (Malini and Rao, 2004). Elsewhere, coastal erosion caused by a combination of factors has been attributed to loss of habitat (see Box 1). For example, loggerhead turtle nesting areas in southern Italy have been affected by coastal erosion (Mingozzi et al., 2008). Although numerous examples exist from around the world where coastal erosion and habitat loss have occurred, it is often not possible to single out dam building as the single (or even the dominant) cause of coastal erosion. This is because of complicating, often related factors, such as subsidence, diversion of freshwater input, coastal development and land-use changes, (e.g., Syvitski, 2008). For example, the loss of wetlands in the Mississippi Delta region is a famous example of habitat destruction caused by human interference with a major river system (see Box 2), but the loss of habitat has not been caused so much by dam building as by diversion of the river channel by the construction of artificial levees and dredging activities (Shaffer et al., 2009).

Other responses to sediment starvation of the coast from dam building also occur (see Box 1). Erosion of a once stable or prograding coast can transform the composition and character of the subtidal habitat such that it no longer supports the original community. For example, erosion of the Elwa River delta in Washington State, USA, transformed a sedimentary terrace in front of the delta from a sandy habitat colonized by molluscs into a cobbled substrate hosting a different ecosystem (Warrick et al., 2009).

Box 1 - Case Study – West African Coastal Erosion

The West African coastal zone stretches from Mauritania to Cape of Good Hope in South Africa and consists of a narrow coastal zone backed by a gradually rising Precambrian landmass that is drained by several rivers. The rivers carry sediments, nutrients and water to the coastal areas. The major rivers responsible for most of the sediment load are the Congo, Niger, Volta, Benue, Gambia, and the Orange. Of these rivers, the Congo, Niger and Orange are classified among the 10 largest rivers in the world in terms of sediment and water yield (Milliman et al., 1983). Minor rivers, such as Senegal, Ouémé, Mono, Bandama and Calvally, collectively contribute significant amounts of sediments and water to the coast because of their basin size, length, and flood plains as compared to rivers such as the Niger, Congo and Orange (Fig. 1).

The ability of these rivers to effectively nourish the coast is hindered by climatic, environmental and anthropogenic factors that determine the amount of sediments, nutrients and water delivered, and include different origins of sediments, and climate variability in the catchment areas. (Folorunsho et al., 1998; Awosika et al., 2013; Awosika and Folorunsho, 2014).

Sediments carried to the coast by the major rivers and ephemeral rivers are derived predominantly from the weathered Precambrian rock complex comprised of schist, gneiss, and granite. The rock complex has now been reduced by erosion to piedmonts that dot most of the West African region. Younger sedimentary rock types in the lower Niger River and flood plains have also been eroded along the river courses and carried to the coast. Suspended sediments, comprising fine silt and fine sand blown from the Sahara desert through the savannah and the Equatorial region, constitute another major sediment type in the region.

The large-scale impoundment of upstream reservoirs has reduced downstream flow volumes and velocities. As a consequence, the strength of the Niger River in its downstream segment is reduced. The reduction in flow velocity encourages sediment deposition within river channels, and is reflected in shallower river cross-sections and enlarged sand bars. Assessment of the spatial distribution and relative sizes of sand bars indicates increased deposition over the years of impoundment. The sand bar just north of Patani on the Forcados River increased from 0.1701 km2 in 1963 to 0.486 km2 in 1988. The sand bar at Anibeze, east of Patani on the same river, increased from 0.3645 km2 to 0.9315 km2 in the same period. A similar trend is observed on the River Nun, where the sand bar just south of Odoni increased its size by 100 per cent between 1963 and 1988. The sand bar opposite Odi not only increased in size, it also expanded in the upstream direction.

At Sampor, a major river channel completely silted up. Several other sand bars on the river between Onitsha and the bifurcation of the Niger into the Forcados and Nun Rivers have evolved into larger sand bars, thereby significantly modifying the river morphology. The NDES environmental change atlas for this area (NDES, 2000) confirms that changes have largely been confined to the flood plain. This channel modification has adversely affected the economy of the river channel and the Nigerian Federal Government's plan for large-scale dredging of the River Niger.

<div style="border: 1px solid black; padding: 10px;">

Box 2: Coastal Louisiana and the Mississippi River Delta, USA, and the Impact of Hurricane Katrina

The Mississippi River Delta provides the primary buffer for inland communities within the State of Louisiana and is a major resource for fisheries. Land loss resulting from subsidence has historically been replenished by the deposition of silt from the Mississippi River. However, human activity, including resource exploitation, such as petroleum extraction and controlling the flow of the Mississippi River by the U.S. Army Corps of Engineers, has resulted in reduced sediment flow and significant loss of land. It is important to note that whereas southeast Louisiana contains 37 per cent of marsh habitat in the United States, it has the highest rate of land loss of any region of the country (Glick et al., 2013).

This land loss resulted in the increased landward incursion of seawater during Hurricane Katrina in 2005, flooding coastal communities and eroding and displacing habitat. In addition, the Mississippi River Gulf Outlet provided a channel through which seawater flowed, overtopping the levees that protected the City of New Orleans, causing billions of dollars of damage to property and economic activities and loss of life (Shaffer et al., 2009).

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5.6   Significant environmental, economic and/or social aspects in relation to changes in sediment input

The social and economic aspects of loss of specific habitats include loss of livelihood (where important fish-food sources and access to croplands have been displaced or where tourism assets are lost), homes and communities (for example, where coastal erosion and shoreline retreat have damaged or destroyed buildings), and habitats of cultural or amenity values. The concept of waterfront property value is also linked to tourism, as it is often the case that the aesthetic and cultural aspects driving property values and tourism are the same (Phillips and Jones, 2006). Many of these issues are described in relation to the specific habitats involved in other parts of this Assessment (coral reefs, see Chapter 43 and 44; estuaries and deltas, see Chapter 44; kelp and seagrass, see Chapter 47; mangroves, see Chapter 48; and salt marshes, see Chapter 49).

Shaffer et al. (2009) note in relation to the cost of restoring wetlands on the Mississippi Delta (estimated to be about 5,300 US dollars per hectare) that "the most significant twenty-first century public works projects will be those undertaken to correct environmental damage caused by twentieth-century projects." In other words, the cost of restoring damaged habitats is often much greater than the cost of the projects that caused the damage in the first place. The cost of maintenance of coastal protection infrastructure is estimated to be about 300,000 dollars per mile (1.8 km) of coast in the United States (Dunn et al., 2000). Along coasts that are eroding, the cost of allowing the coastline to retreat is immense. If the coast of Delaware in the United States were allowed to recede at its present pace (without shoreline defence engineering works), the cost of lost property by 2050 has been estimated by Parsons and Powell (2001) to be about 291 million dollars (year 2000 dollars), which the authors argue justifies the dollar cost of defence.

6. Gaps in Capacity to Assess Land/Sea Physical Interactions

The assessment of land/sea physical interactions is multidisciplinary, requiring expertise in all aspects of oceanography (physical, geological, chemical, and biological) and concomitant terrestrial counterparts. Local, regional, and basin-wide scales must be considered, along with implications of climate change and sea-level rise. Ultimately, the natural sciences must inform and serve the social realities of economic and infrastructural needs. This section is arranged according to gaps in knowledge of coastal processes, gaps in knowledge of ocean processes, and gaps in capacity to apply existing science to effective decision-making. Some examples are taken from the Caribbean; however, the discussion is global, with many areas of extrapolation.

Globally, coastal engineering science has evolved dramatically during the last century, from the application of crude coastal protection measures such as the *ad hoc* placement of rocks and other natural materials, to the well-modelled and sophisticated coastal structures built today. These changes are mainly due to some improvement in understanding of coastal processes, such as the interaction of nearshore waves with littoral sediment transport paths. However, methodologies are still developing, linking changes in sea level to changes in shape, sediment volume, and beach width. New models have been developed, and produce better results when validated than the Bruun model (DECCW, 2010). Since the 1950s, the Bruun model has been used to model coastal retreat caused by increases in sea level, in spite of its apparent limitations as a two-dimensional representation of a multi-dimensional process (Cooper and Pilkey, 2004).

In developed countries, such as the European Union Member States, the United States and Canada, permanent, extensive coastal and nearshore monitoring ensures that the body of data required for modelling coastal processes is readily available. An abundance of information exists on the sources and sinks of sediment, and on sediment transport processes. However, the situation is different in many African and Asian coastalstates, and in Small Island Developing States, where capacity and technologies for widespread monitoring are limited. The UNESCO Sandwatch programme has enabled establishment of beach profile monitoring in many developing countries by non-governmental organizations and school students (UNESCO, 2010).

Development of a specific global framework for land/sea physical interaction assessment needs to be initiated. This could include improving capacity of persons who collect and analyze existing and new data at local, regional, and basin-wide levels. Ultimately, a standardized training programme, through an inter-institutional network, should be established. Support is needed for ongoing *in-situ* measurements and for the re-establishment of discontinued data collection programmes, and for initiating new studies. Above all, the scientific questions should be clearly articulated. Forecasting ocean processes is a necessary capability for addressing climate change and sea-level rise.

Many countries, including small island States, are susceptible to climate change impacts, many of which will directly affect land-sea interaction (Carter et al., 2014). Inundation of coastal lowlands and small islands will lead to the loss of mangroves, seagrasses, and coral reef habitats and ecosystems. It is also postulated that rainfall patterns over the region will be altered, changing river discharge and non-point-source sedimentation. It is also thought that hurricanes will become less frequent but more intense, posing a particular threat to the coasts of island States. The global Integrated Coastal Area Management (ICAM) programme of IOC-UNESCO is designed to assist countries in their efforts to build marine scientific and technological capabilities as a follow-up to Chapter 17 of Agenda 21, and to Chapter IV of the Mauritius Strategy. The main objectives of ICAM are to increase capacity to respond to change and challenges in coastal and marine environments through further development of such science-based management tools as marine spatial planning, ecosystem-based management, and the Large Marine Ecosystem (LME) approach.

Activities include syntheses of scientific information and preparation of methodological manuals, a strategic alliance with the International Geosphere-Biosphere Programme (IGBP) and its core project on Land-Ocean Interaction in the Coastal Zone (LOICZ), and a project on the development and application of indicators for integrated coastal and ocean management.

In the same way the SPINCAM (Southeast Pacific Data and Information Network In Support to Integrated Coastal Area Management) project was designed to establish an ICAM indicator framework at national and regional levels in the countries of the Southeast Pacific region (Chile, Colombia, Ecuador, Panama and Peru), focusing on the state of the coastal and marine environment and socioeconomic conditions, to provide stakeholders with information and atlases on the sustainability of existing and future coastal management practices and development. The SPINCAM model is proposed for replication in other regions.

With respect to gaps in knowledge of ocean processes, it is noted that anthropogenic climate change will affect wave climate, sea level and ocean acidification (OA). Impacts of the latter are discussed in chapter 5, and the production of beach sand is discussed in chapter 7. However, given that the science on OA is now developing, significant gaps exist in knowledge of this phenomenon and its effects. Thus far only certain regions of the world's oceans are being studied, e.g. off North America, Canada and New Zealand. The Global Ocean Acidification Observing Network (GOA-ON) is striving to assist in the development of standards, and of capacity for researchers in other countries.

Sea-level monitoring and research is quite mature; almost all coastal States participate in the collection of sea-level data. Instrumentation is easily accessible and States utilize data for early warning of coastal hazards. The Global Sea Level Observing System has improved monitoring in regions not previously monitored. The main gaps in knowledge are in the use of sea-level data in models to determine changes in coastal processes and changes in shorelines.

Other gaps in capacity relate to the application of existing knowledge to inform the development of coastal areas. An understanding of coastal dynamics is vital in design and construction of coastal infrastructure. Diversion of sediment pathways through dam building, port/harbour construction, and infrastructure development constructed on dunes and sand spits may result in losses following coastal erosion.

Land reclamation may destroy habitat and ecosystem services that protect the coast from sea-level-related hazards such as storm surge and tsunamis. One significant gap in capacity is in coastal engineering, especially in Small Island Developing States. Once capacities in physical oceanography and coastal engineering are linked, ocean and coastal processes may be better understood for application by coastal developers.

Even where capacity in Small Island Developing States exists, such as in Barbados, the challenge is to develop a comprehensive succession planning framework that maintains that capacity over time. Additionally, the costs of appropriately located, designed and constructed coastal infrastructure may be prohibitive. Currently, Barbados is undertaking a Coastal Risk Assessment and Management Programme (CRMP) of 42 million US dollars through concessional loan financing. The aim of this project is to conduct diagnostic studies of ocean and coastal processes, in order to determine the impact of sea-level rise and other coastal hazards on the country's coastal assets (IDB, 2011). Thus, the costs of monitoring, including maintenance and calibration of instrumentation, and training, are a factor in the application of existing science for effective coastal planning.

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