4 The Baltic States

Estonia, Latvia and Lithuania

Hannes Tõnisson, Kaarel Orviku, Jānis Lapinskis, Saulius Gulbinskas
and Rimas Žaromskis

Overview

The three Baltic States (Estonia, Latvia and Lithuania) are among the smallest countries in Europe, but the shoreline length is remarkable – approximately 4,500 km. Moreover, due to their geographical location between major geological structures, the Fennoscandian Shield and East European Platform, they are rich in different shore types and valuable coastal ecosystems. All shores have been significantly influenced by changing sea levels as a result of different Baltic Sea levels during the last 10,000 years. Postglacial isostatic rebound since the Ancylus Lake period has resulted in up to 75 m of land uplift on the northern coast. The zero isobase of this land uplift runs SW–NE through Riga in Latvia and as a result, beaches formed north of that line are frequently backed by series of beach ridges and dunes often reaching tens of kilometres inland.

The composition of most Lithuanian and Latvian coastal sediments range from pebbles to silt. The variability is mostly in glacial till and the silt shores increase northwards towards Estonia. In addition to till shores along the whole of the Estonian coast, many limestone cliffs can be found on its northern coast and at Saaremaa Island.

The Latvian and Lithuanian Baltic Sea (exposed to the Baltic Sea proper) coast has been straightened by prolonged marine erosion and accumulation and favoured by the non-existent land uplift. The Gulf of Riga Latvian coast is generally straight but includes some gently sloping forelands, separated by shallow 4–6 km long bays. In contrast over two-thirds of the Estonian coast is crenulated in outline, with capes and bays being either hard bedrock or unconsolidated Quaternary deposits, notably glacial drift with the cliffed north-eastern coast being straightened by erosion. The north-western shore in Hiiumaa Island, and also the Gulf of Livonia, has been straightened by a combination of erosion and deposition whereas the beach-fringed Narva Bay has a smooth outline as a result of sediment accumulation.

Prevailing winds, and therefore most waves on the eastern coast of the Baltic Sea, approach from the south-west, which is reflected in sediment transport patterns from south to north (except the western coast of Cape Kolka). Those patterns are clearly visible from ancient coastal formations which can be found along the Baltic States coast. The longshore sediment drift is also known as the Eastern Baltic Longshore Sediment Flow and has existed since the late-Littorina period.

Coastal erosion, a global phenomenon, is also currently one of the most important problems of the Latvian and Lithuanian coast, but a much smaller problem in Estonia due to the continuous land uplift and diverse geological structure. The fact that all three countries were considered as a border zone for the old Soviet Union, decreased the importance of erosion to human activities, as for about 50 years it was not permitted to live or construct non-military buildings close to the shore. However, all three countries have some significant similarities as to the main agents causing coastal erosion. There are no tides but wind-induced storm surges can still range over 4 m in Estonia, 3 m on the southern coast of the Gulf of Riga and over 2 m on the open Baltic Sea coast (Eberhards, 2003), with the most drastic erosion events taking place during those extreme storm surges. The effect of winter storms is affected by cold season climate warming and amelioration in ground frost and ice conditions both in the open sea and nearshore zone.

The northern part of the Lithuanian coast currently experiences rapid erosion, reaching 60–70 m during the last 70–80 years in some sections (Gudelis, 1998). Erosion is also evident on the lagoon side of the Great Curonian dune ridge. As a result of a longer vegetation period, stronger westerly winds and forestation, the height of many active dunes has decreased and the Curonian Spit has shifted lagoonwards (Povilanskas *et al.*, 2009). The southern part of the Lithuanian coast is stabler and accumulation has reached up to 80–90 m during the last 100 years (Gudelis, 1995).

In stretches of low depositional Latvian coast which have coastal dunes, major storms, occurring once or twice a decade, can cause erosion of up to 30 m^3/m of sand material, while along certain stretches of high cliffs, this figure can reach up to 70 m^3/m. Increased erosion is connected directly or indirectly with human activities, e.g. harbour and coastal sea defences, and reduced river sediment discharge as a consequence of hydroelectric power plants.

There are no recent major projects along the Estonian coast concerning coastal erosion. The few that exist are privately funded or project based and exhibit localized measures. Similar situations can be found on the Latvian coast, most protection measures being established during the Soviet Union period. For example, there have not been any major foredune restoration projects in Latvia in recent decades – one of the most useful measures to protect the shores (Eberhards, 2003) – but only small localized protection measures, such as dune stabilization. The largest recent coastal engineering projects are related to the big harbours (Ventspils, Liepaja and Riga) and Jurmala beaches. Coastal erosion in Lithuania has been severely aggravated by human intervention such as construction of hydro-technical works, deepening of the Klaipéda harbour and recreational activities. The biggest problems appear to lie in popular tourist resorts in Palanga, where the sand beach has been almost completely eroded in the last ten years. To fight coastal erosion, all forests and dunes of the coastal zone have been classified as 'protected and preserved' according to the *Lithuanian Law of the Coastal Strip* since 2002. Furthermore, coastal forests cannot be cut down unless they are situated more than 1 km away from the coastline. Various soft protection measures have been carried out during the last decade including beach nourishment and dune stabilization. However, those measures suffered from a lack of funding until 2007, after which EU funds have been available to help extend soft protection measures.

Estonia

Introduction

Estonia is located in a transition zone between regions, having a maritime climate in the west and a continental climate in the east, and is a relatively small country (45,227 km^2), but its geographical location between the Fenno-scandian Shield and East European Platform and its comparatively long coastline (nearly 3,800 km) due to numerous peninsulas, bays and (>1,500) islands, results in a variety of shore types and ecosystems. The western coast is exposed to waves generated by prevailing westerly winds, with NW waves dominant along the north-facing segment beside the Gulf of Finland, contrasting with southern relatively sheltered sectors located on the inner coasts of islands and along the Gulf of Livonia (Riga).

The coastline classification is based on the concept of wave processes straightening initial irregular outlines via erosion of capes/bay deposition, or a combination (Gudelis, 1967; Orviku, 1974; Orviku and Granö, 1992). Much of the coast (77 per cent) is irregular with the geological composition of capes and bays being either hard bedrock or unconsolidated Quaternary deposits, notably glacial drift. The cliffed north-eastern coast around Ontika has been straightened by erosion, whereas beach-fringed Narva Bay has an outline smoothed by deposition (Orviku and Romm, 1992). Coasts straightened by a combination of erosion/deposition can be found on the northern shore of Kõpu Peninsula, the western part of Hiiumaa Island, and around the Gulf of Livonia. Orviku and Sepp (1972) have illustrated the stages in coastal landform evolution of the west Estonian archipelago.

Historical coastal evolution

Coastal evolution has been influenced by changing sea levels (Kessel and Raukas, 1967): the Ancylus transgression (9,500–8,000 years ago), followed by the Littorina transgression (8,200–7,000 years ago) and an ensuing regression (7,000–5,000 years ago). During the Littorina transgression there was extensive erosion, producing cliffs and shore platforms which generated large amounts of sand and gravel, with residual boulders occurring where glacial deposits (till) had been dispersed. During the ensuing regression sand, gravel and boulders on the emerging sea floor formed beaches, beach ridges and dunes by wave and wind activity.

Postglacial isostatic movements since the Ancylus Lake period resulted in land uplift ranging from *circa* 45 m in southern Estonia up to 75 m on the northern coast. Beaches formed are often backed by beach ridges and dunes and tilting has continued on either side of a zero isobase that runs SW–NE through Riga in Latvia, with land uplift of about 1 mm/yr at Pärnu, 2 mm/yr at Tallinn and 2.8 mm/yr on the north-western coast (Vallner *et al.*, 1988).

Main agents causing erosion

Waves and currents (especially during heavy storms), longshore drift, onshore winds, and human activity are the main agents of coastline evolution. Tides are negligible on the Estonian coast (<5 cm), with sea level generally higher in winter than summer. Rivers are small and alluvial deposition is very limited. Westerly and south-westerly winds predominate, producing waves from these directions on west-facing coastal sectors, but wave energy is low, especially in places where the nearshore is shallow and boulder-strewn. During storm surges, onshore

Figure 4.1 *Sea ice hummocks in a coastal forest at Paaste village, Saaremaa Island in 1997. (a) Hummocks of ice moved about 100 m inland within a 0.5 km wide sector of the shore as a result of north-westerly winds resulting in severe damage to a pine forest; (b) The results of the ice assault became evident in summer after the final ice melt: some boulders and sea bottom sediments have been transported to the damaged pine forest*

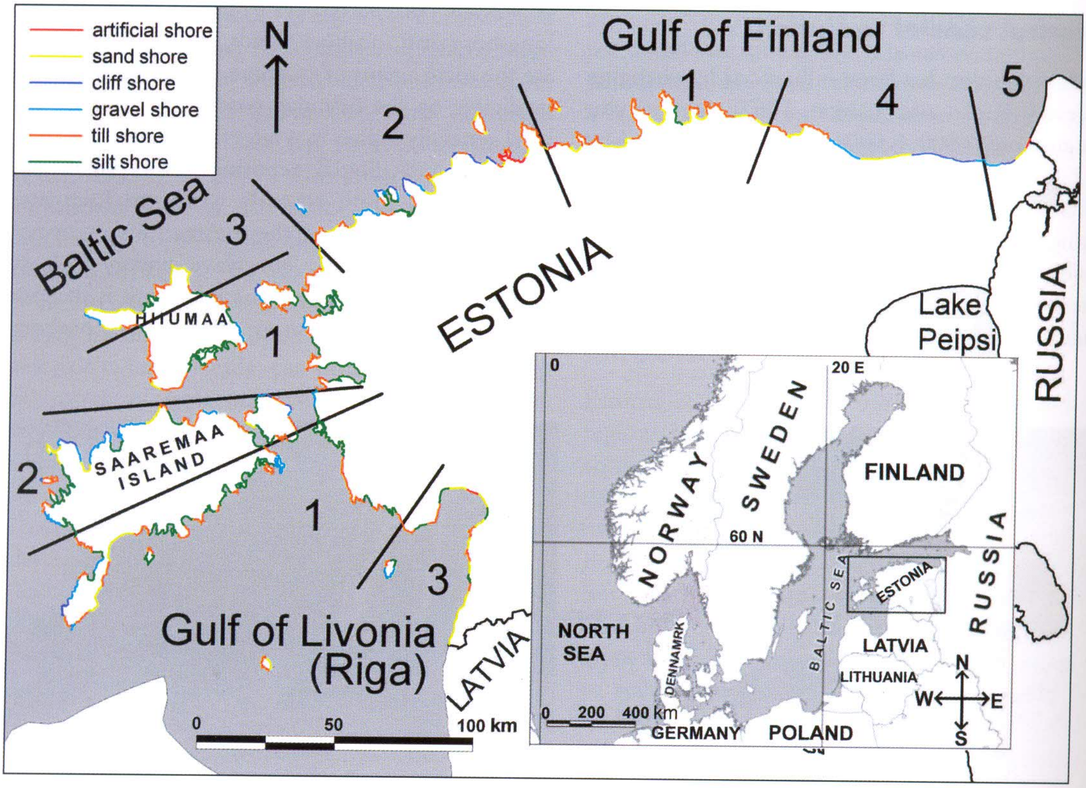
winds and low barometric pressure may raise sea level by nearly 3 m above the Kronstadt zero (benchmark for the eastern Baltic Sea), when major coast changes occur, with cliffs undercut at a higher level, high beach ridges formed, and large quantities of sand moved alongshore. During winter (November to April), a shore ice fringe develops which prevents wave activity, but on spring break up, waves may drive ice onshore, piling it up as 10–15 m high hummocks (Orviku 1965; Orviku *et al.*, 2011). Ice driven onshore scours sea floor sediment, displacing shoreward sand and gravel, and even boulders, damaging trees and buildings (Figure 4.1).

The coastline

Shoreline classification

The following shore types (Figure 4.2) have been distinguished based on the initial relief slope, geological character of the substrate and dominant coastal processes, (Orviku, 1974; 1992; 1993):

- cliffed (approximately 5 per cent of shores) – an abrasion bluff in resistant Palaeozoic rocks (limestone, dolomite, sandstone);
- scarp (very short sections between other types) – an abrasion bluff in brittle unconsolidated Quaternary deposits (sand, gravel, till, etc.);



■ **Figure 4.2** *Distribution of shore and coastal types on the Estonian coast. Coastal types: (1) Straightening abrasion-accumulation coast in Quaternary deposits; (2) Straightening abrasion-accumulation coast in Pre-Quaternary bedrock; (3) Straightened abrasion-accumulation coast; (4) Straightened abrasion coast; (5) Straightened accumulation coast*

- till (35 per cent) – an abrasion sloping till;
- gravel (11 per cent) – depositional with beach ridges formed of gravel and pebbles;
- sand (16 per cent) – depositional with sand ridges often backed by foredunes or dunes;
- silt (31 per cent) – depositional with fine-grained (silt) sediments; usually it has a very flat nearshore and a tendency to become overgrown;
- artificial (2 per cent) – natural dynamics altered by anthropogenic constructions (breakwaters, protecting walls, berms).

For the above-listed types, the first three are erosional and the remainder mainly depositional shores (erosion might still occasionally occur); artificial shores may be either erosional or depositional (Figure 4.3 top). Classic examples are cliff formations outcropping in areas of carbonate rocks/sandstones, where initial topography was steep and waves sufficiently strong and till scarps subject to active erosion (Figure 4.3 centre; Orviku, 1982). As a result an erosion platform with boulders and cobbles formed on the sea floor or nearshore (Figure 4.3 bottom), acting as a natural breakwater, which considerably decreases storm wave influence on the scarp foot.

Explaining the formation of sand shores (Figure 4.4) is more difficult (Bird, 1985; Orviku *et al.*, 1995; Raukas *et al.*, 1994). The vast majority formed and developed because of alteration and re-sedimentation of old sand area deposits (buried valleys, landforms generated by glacier melt water, etc.). Small stretches of sand shores may also occur near artificial constructions, e.g. ports, where quays hinder natural sand movement. Sand origin on these shores is sometimes erroneously associated with erosion of neighbouring till shores, which is practically impossible because the till sand content is too low to enable formation of such shores.

Coastal types

Five different coastal types exist, which might include several different shore types and various coastal sediments but their evolution, geology and morphology follow similar patterns.

■ **Figure 4.3** *Cliff evolution. Top: Pakri cliff, northwestern Estonia. Centre: Erosional scarp formed in till in Mõntu, Sõrve Peninsula, Saaremaa Island. Bottom: Finer-grained sediments eroded by waves and remaining boulders, provide a good natural protection against further erosion (Abraded till shore on the western coast of Aegna Island, Tallinn Bay)*

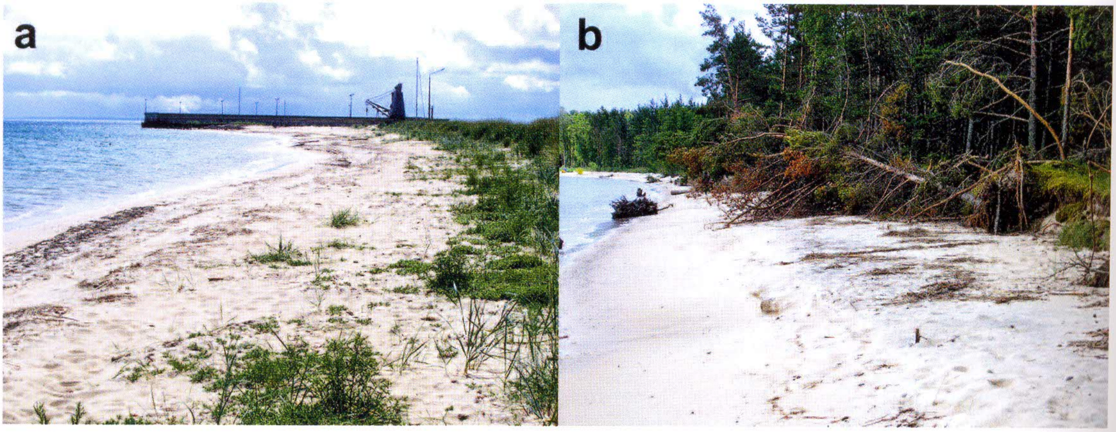


Figure 4.4 *(a) Accumulative sand beach with foredunes north to Lehtma harbour, Hiiumaa Island; (b) intensive erosion occurs south of the harbour jetty*

TYPE 1

Typical northern Estonian coastlines are large peninsulas separating deep bays. At the bay head there is usually a sand beach, backed by beach and dune ridges that rise landward. Erosion of glacial deposits has resulted in bay-head accumulation of sand and silt, with reeds and bushes colonizing silt flats. The coast consists of low scarps cut into glacial and fluvioglacial deposits, varved clays and gravel. Shore platforms cut into these soft sediments are strewn with erratic boulders fringed by reed beds. Bay-head beaches consist of sand and gravel, the finer silt and clays having been withdrawn seaward in suspension and deposited on the bay floor (Orviku, 1988).

Sections of Hiiumaa and Saaremaa Island are characteristically representative of type 1. The eastern and southern coasts of these large islands are low and flat, locally marshy, with pebble and cobble beaches. Large irregular inlets, open to this Baltic Sea sector sheltered by Hiiumaa Island, include many small rock islands. The southernmost bay (Matsalu) at the Kasari River mouth is bordered by extensive reed beds, which have spread rapidly seaward with the emerging nearshore area.

A sheltered low embayed coast made up of Quaternary deposits is also located between Saaremaa and the mainland where the offshore zone is very shallow. There are low marshy areas and occasional shingle beaches on the shores lined with boulders derived from glacial drift along with some low scarps, cut into till and fluvio-glacial deposits. Dunes are either poorly developed or missing (Orviku, 1974). Exposure to wind and wave activities increases southwards and reed beds occupy sheltered bays and have even spread onto sand beaches (Bird *et al.*, 1990).

TYPE 2

This coast is irregular, consisting of valley-mouth bays with sand beaches and reed beds with limestone headlands and cliffs. Between the capes, wide beaches have formed, backed by dunes and fronted by sand bars. The sand has been derived from Lower Ordovician sandstone in bordering cliffs. On Cape Pakri, a cliff has been cut into relatively soft Lower Ordovician sandstone, overlain by harder limestone. The limestone upper cliff is undermined by wave-cut notches (Figure 4.5a), which causes frequent cliff failure resulting in talus slopes (Figure 4.5b), subsequently reduced by wave activity and eventually gravel beaches.

The north-western coast of Saaremaa Island has up to 20 m high cliffs cut into Ordovician and Silurian limestone and the nearshore area is a bare rock shore platform with pebble and boulder beaches widespread near the cliffs. Sand and gravel beaches, derived from eskers and end moraines, are distributed by longshore drifting (Orviku *et al.*, 1995). Erosion of the Silurian limestone cliffs has yielded gravel deposits, which drifted into intervening bays to accumulate as bay-head shingle beach ridges. Because of continuous land uplift, cliffs are usually eroded only during heavy storms (Orviku, 1974). In recent decades, there has been erosion on parts of the shingle beaches and spit prolongation. The islands were much smaller during the Ancylus Lake stage and successively enlarged at Littorina Sea and Limnea Sea stages, with subsequent land uplift of the coastal plain. Each of the earlier coastlines is marked by bluffs and beach ridges, particularly on Saaremaa and Muhu Islands.

TYPE 3

As an example, a long and wide gently curving beach of fine sand rich in quartz and backed by low dunes has formed at the head of Pärnu Bay. Reed beds have spread over parts of the shore. Emergence following the Littorina transgression (up to 7 m above present sea level), resulted in formation of a coastal plain and shore fringed by boulders, sand beaches and segments of reed beds. Further south, as exposure to wave activity increases along the coast of the Gulf of Livonia, beaches are backed by lagoons overgrown with reeds. Similar processes and morphological features can be observed on the northern part of Hiiumaa Island.

TYPE 4

The Baltic klint (Ordovician limestone cliff) becomes higher (56 m) and westwards is located closer to this coastline type. It is cut into Cambrian sandstone, clay and shale and covered by Ordovician limestone, which is more resistant to erosion. There are accumulations of basal rock talus and beaches of cobbles and boulders derived from cliff erosion and the nearshore area is a boulder-strewn shore platform. The klint is generally stable and is now only locally and episodically attacked by waves.

TYPE 5

Close to the Russian border (Figure 4.2), this is epitomized by a long gently curving sand beach backed by numerous parallel beach ridges covered

Figure 4.5 *(a) The upper part of the limestone cliff is undermined by deep wave-cut notches in non-resistant rocks (e.g. glauconite sandstone), which crop out on the coast of Osmussaar Island; (b) wave-cut notches collapsed and forming a talus slope in front of Pakri cliff*

with dunes. The sand has come partly from cliff erosion to the west; partly from glacial and fluvioglacial deposits on the Kurgalovo Peninsula to the north; and partly from the Narva River, whose sediment yield has diminished after upstream dam construction. With a reduced sand supply, the seaward margin of these dunes is now in recession forming abrupt scarps. In the 1980s, the beach was re-nourished, and a breakwater built at the river mouth (Orviku and Romm, 1992).

Recent trends and changes

Estonia is sensitive to climate change manifestations such as an increase in cyclonic activity, westerly circulation and a northward shift of the Atlantic storm track over the past decades. There has been a storm increase (ten major storms from 1965–2010) with an intensity that had previously occurred only once or twice a century (Orviku, 1995; Orviku *et al.*, 2003; 2009; Tõnisson *et al.*, 2008; 2011). Changes in meteorological conditions have changed wave climate and sea-level conditions, as well as the rate at which shore processes occur. Frequent storm surges and a general absence of ice cover on the shore with unfrozen shore sediments in milder winter conditions, allow waves to attack the coast and shape beaches even in winter. Despite a tectonically uplifting coast, beach erosion attributable to increased storminess has become evident in recent decades.

For example the Kiipsaare study site, located on the north-westernmost tip of Harilaid Peninsula, NW Saaremaa Island is exposed to the Baltic Sea proper. This is a small (4.3 km^2) peninsula connected by a tombolo to the larger Tagamõisa Peninsula. The primary landform is a glacio-fluvial ridge. A coastal scarp borders the 50 m wide sand beach, reaching 3 m a.s.l. in the NW part where shore processes are strongest. The area is most influenced by waves from the SW, W, NW and N, and the sea bottom is particularly flat and shallow, north-west of Kiipsaare, the 5 m isobath being 4 km from the shoreline. The steepest underwater shore slope occurs north-east of the peninsula where the 5 m isobath is 350 m offshore.

In 1933, the Kiipsaare lighthouse was erected approximately 150 m from the shoreline and in the middle of the Cape. Estimates of the shore retreat speed between 1933 and 1955 are not possible, but the mean annual velocity of shoreline retreat at Cape Kiipsaare is about 2 m/yr from 1955–1981. More rapid retreat is revealed when comparing aerial photographs from 1981 and 1990 (Figure 4.6). During that decade, the lighthouse 'shifted' from a safe distance near the erosion scarp. Shoreline retreat during these ten years was up to 30 m and by 1995, the lighthouse was in the middle of the beach. Even more severe storm damages occurred from 2001– 2010, when the shoreline receded approximately 50 m. Today the lighthouse stands over 50 m offshore. Former beach ridges explicitly show the position of earlier shorelines along the western coast. These shorelines are not parallel to the current one, as would be typical of sand beaches, but a 45° intersection of the current shoreline with the axis of former beach ridges is clearly visible in freshly formed scarps – evidence of rapid changes in the direction of shore processes. Additional evidence of the north-eastward migration is given by shipwrecks on the western coast of the Cape (Figure 4.6), probably wrecked on the north-eastern coast of the Cape 150 years ago. Sand later buried the wrecks, which were re-exposed on the western coast and consequently the Cape has 'rolled over' the shipwrecks.

Figure 4.6 *Shoreline changes during the period from 1900–2010 (shipwrecks found in 2000 and 2010 are also indicated).Key: black = 1900; Purple = 1955; Yellow = 1981; Green = 1988; Lilac = 1998; Light blue = 2002; Red = 2008; Dark blue = 2010*

Coastal defence

The Baltic Sea is a relatively shallow water body and its small dimension restricts wave size and reduces the erosion risk to shores. Major damage takes place during extreme events once or twice a century. Previously, the main coastal zone economical activities were fishing and agriculture, which did not need much shoreline infrastructure, and therefore all bigger infrastructures were planned further away at higher elevations. Lightweight buildings built close to the shoreline were easy and cheap to rebuild after extreme events. Humans lived in harmony with nature and there was no need for coastal protection.

Everything changed as a result of World War II. The Soviet occupation began at the end of the war in 1945 and continued for nearly half a century, during which time the coast was the western border of the Soviet Union and different degrees of restriction were established depending on location. On the mainland, east of the west Estonian archipelago, restrictions were not as stringent as on islands exposed to the Baltic Sea proper. Strict limits were established on sea-borne navigation and even land movement. Local people on small islands and in many villages situated on larger islands, were deported from their homes and many older buildings and infrastructure were taken over by Soviet border guards, with the result that many unused buildings collapsed after 50 years (Figure 4.7). Due to the restricted border zone regime, no developments were permitted close to the sea, so no coastal protection existed and natural processes reigned free.

After regaining independence in 1991, the coast became a popular recreation area, which affected coastal land use; it is now a popular place for summer-houses and even residences. According to legislation it is declared as a *force majeure* (Government has absolved itself for possible losses caused by coastal erosion) when erosion endangers houses or private infrastructure and this has more or less kept developers away from the shoreline. Therefore, most of the coast is akin to a natural laboratory and natural processes can be allowed with no threat of financial or human loss.

Moreover, the country is experiencing land uplift of up to 2.8 mm/yr and the shoreline is shifting slowly seaward. However, a few examples of recent coastal protection still exist. In Tallinn Bay, there are 4 km of breakwaters and jetties, and in 1980, a 2.5 km long sea wall was built purely to enclose and reclaim a shallow bay-head area for highway construction and the 1980 Olympic Yachting Centre (Martin and Orviku, 1988). Nearly 30 years later, because of relatively low wave energy, this construction is still in good shape, apart from a few ice attack events that bent some steel bars on the construction top (Orviku *et al.*, 2011).

Very close to the above is Pirita, where a seawall protects the roadway (Figure 4.8) and an artificial sand beach has been created. Pirita River sediments once fed the beach but at present have more or less stopped because of river mouth marina construction. Pirita beach has suffered repeatedly due to extreme storms (1967 and 1975/76). Approximately 30,000 m^3 of additional sand was brought from inland sources to nourish the beach for the 1980 Olympic Games (Orviku, 2010). Many more extreme storms have taken place since, including the November 2001 storm and January 2005 storm (Gudrun) which caused extensive erosion. In addition to wave

Figure 4.7 *The former lighthouse keeper house has been destroyed by various factors, including Soviet army destruction and purely natural processes. Eventually, it will be completely destroyed by coastal erosion*

Figure 4.8 *Seawall protecting Pirita roadway in Tallin Bay*

erosion, some sand was carried inland by wind to the pine forest. Pirita beach needs to be urgently renourished in the near future, as it is approximately 30 years since the last nourishment and the beach has lost much of its natural protection – every storm attack makes the beach more vulnerable.

The last of the coastal protection measure examples in Estonia is the area surrounding a former nuclear waste depository near Sillamäe town, north-east Estonia (Figure 4.9). At the beginning of the twentieth century, boat houses and summer cottages were the most common buildings here (according to a 1934 map), and the shoreline was stable. The first artificial changes appeared when the so-called 'Swedish harbour' was established at the end of the 1930s on the eastern side of Cape Päite. The harbour jetty became a sediment trap for gravel-pebble longshore transport from west to east. Sediments trapped behind the jetty accumulated on the northern shore of Cape Päite and the sediment amount in front of Sillamäe (east of the harbour) and the character of shore processes changed. Former accumulation gave way to erosion and the shoreline moved landwards, especially in the area of the current Sillamäe town. The town itself and a highly specialized chemical and metallurgy plant were constructed in 1946 (Orviku *et al.*, 2008). It was forbidden to outsiders in 1947–1991, as fuel rods and nuclear materials for the Soviet nuclear power plants and weapons were produced. Uranium enrichment finished in 1989, but enrichment of rare metals (such as niobium) still exists. On the immediate shore of the Gulf of Finland, is a 50 ha nuclear waste depository established since 1959, where some 1,200 tonnes of uranium, 800 tonnes of thorium enrichment residuals and other hazardous substances are buried.

The depository did not cause much change in the shoreline or coastal processes; accumulation was still dominant in front of the depository due to the Swedish harbour jetty. The most drastic changes, at the beginning of the 1980s, were related to construction of an ash depository whose northern tip extends up to 200 m into the coastal sea and therefore interferes with the longshore sediment transport pathway. As a result, the longshore transport of gravel-pebble from west to east has been artificially impeded forming a 200 m long and more than 20 m wide complex system of beach ridges. The process is similar to one caused by the harbour jetties. Simultaneously, the northern shore of the waste depository started to erode, caused by a lack of sediments from the west, which intensified longshore transport. Due to security concerns, the jetty at the Swedish harbour was demolished in 1984, which triggered massive amounts of formerly trapped sediments to move eastward. These sediments quickly formed a spit in the south-eastern direction. Rapid spit development was probably caused by intensive storm periods (the estimated average speed of the accumulation of the distal part of the spit was 700–800 m^3/yr). Sediments formerly trapped behind the jetty, which protected the shores in front of the nuclear waste depository, were transported to the spit and left the north-eastern depository area without natural protection. By 1996, gravel-pebble ridges formerly fronting the northern shore of the nuclear waste depository were completely eroded, giving storm waves free access to the gravel terrace built at the nuclear waste base, allowing subsequent erosion to reach the nuclear waste's protective dam. It has been known only since 1989 that annually, some 4,000 tonnes of ammonia has leaked into the Gulf of Finland through the broken protective dam (Orviku *et al*, 2008).

Intensive wave activity caused the gravel terrace of the Sillamäe nuclear waste depository to erode, which, in turn, forced emergency repair work to be carried out to the foundation using whatever materials were available. These repairs were not effective and erosion continued until closure of the waste depository in 1998–2008. It was one of the highest priority environmental projects in the whole Baltic Sea basin. The dam has been reinforced and leakage through to the sea should be negligible. Currently, the northern shore of the nuclear waste depository is well protected from wave activity, as a result of conserving and construction of Sillamäe harbour in front of the dam (Figure 4.9). Intensive accumulation is current on the west of the western jetty. Unexpectedly, erosion has not intensified east of the harbour and accumulation has dominated during the last decade. This might be caused by changes in

Figure 4.9 *Location of Sillamäe and directions of sediment transport (Base image with permission from the Estonian Landboard, compiled by H. Tõnisson)*

hydrodynamic conditions, as the longest fetch at Sillamäe is for waves coming from north and north-east. As a result of changes in wind climate, such as increases in westerly and decrease in northerly winds, over the last few decades, wave activity has decreased near Sillamäe (Tõnisson *et al.*, 2011).

Conclusions

The annual maximum sea-level on the Estoninan west coast has increased during the last decade. Fewer storms seemingly affect the coast but in western Estonia, they have become significantly more intense, resulting in an escalation of shore processes. Measurements at various study sites in western Estonia show that the current rate of coastal change is many times higher than in the 1950s. These factors are responsible for acceleration in the rate by which such coastal processes occur. Each subsequent storm reaches an already vulnerable beach profile. In addition, higher sea levels during storms have also caused the erosion area to move further inland with subsequent storms. Even accumulative shores (sand shores, gravel shores) in normal conditions have now become erosional in many locations (Tõnisson, 2008; Tõnisson *et al.*, 2011).

Latvia

Introduction

Latvia, with a coastline of about 496 km in length, is located on the eastern Baltic Sea shore. The Baltic Sea open coastline is approximately 183 km; the Irbe Strait coastline 57 km; while the Gulf of Riga total seashore length is 256 km. Because of Atlantic autumn/winter storms, high waves and storm surges occur especially on the Kurzeme coastline, which faces the open Baltic Sea. River flood plains, as well as lagoon remnant lakes specific for this particular area, created suitable environments for settlements to form and trade to develop. Today, three major ports exist (Riga, Ventspils and Liepāja), as well as eight smaller ports, which have had a significant effect on the intensity of coastal erosion rates. Isostatic processes began at the commencement of the postglacial period and have slowed considerably, so that at present it has little effect on coastal processes (Ulsts, 1998). In terms of a morphogenetic classification, the coast generally belongs to a class of coasts straightened by erosion and deposition (Gudelis, 1967).

Coastal morphology and geological history

The coastline is comparatively straight with no explicit headlands and gulfs, but at some headlands the orientation changes by more than 30°, e.g. at the Capes of Akmeņrags, Ovīsrags, Kolka and Ragaciems. The Late Pleistocene relief has been modified through alternating periods of accumulation and erosion during former stages of development of the Baltic basin and also during the last 2,800 years, when sea levels have been comparatively stable. During this period, the Earth's vertical crustal movements have been activated and catastrophic events relating to basin water exchanges caused by de-glaciation process have occurred, all resulting in comparatively frequent and sharp water level changes. The intensity of coastal processes during the Baltic Ice Lake period (12,600–10,300 radiocarbon years BP) was significantly higher than today (Veinbergs, 1986).

Because of gradually increasing water levels during transgressions, modification of very flat coastal underwater slopes occurred in numerous places, mobilising and moving shorewards significant sediment amounts. Later, with a lowering of water levels, material on the upper coastal slope accumulated as barrier spits and accumulative terraces (Ulsts, 1998). Currently, underwater slope areas eroded during the Littorina Sea (7,000–5,000 BP) transgression phases, contain almost no fine sediment fractions, but gravel and boulders, which play significant roles in seashore dynamics. In shallow, sediment-active areas, sand bars are present (up to four sub-parallel bars in the Irbe Strait coast). Along major parts, the seaward depth increase is comparatively steep, but beyond a 4–8 m depth the slope becomes flat.

Along the major part of the coastal areas, the bedrock surface lies beneath sea level; hard rock cliffs outcrop only in Devonian sandstone and clay on the eastern shore of the Gulf of Riga. The bedrock is covered with Quaternary sedimentary deposits up to 60 m thick. These consist, mainly, of moraine and outwash deposits covered and in some places, replaced by silt, sand and gravel from the Baltic Ice Lake (average thickness of 2–8 m) and Yoldia Sea (10,300–9,500 BP); Ancylus Lake (9,500–8,000 BP) and Littorina Sea sediments cover them. The most widespread (almost along the entire coastline) are Littorina Sea sediments, often exposed at the surface and involved in present day coastal processes. Significant volumes of Post-Littorina period coastal area deposits are found in northern Kurzeme on the shoreline of the Strait of Irbe, where these, along with more ancient sediments (in particular, those of the Littorina period) form accumulation terraces (Ulsts, 1998; Figure 4.10). A major depositional headland occurs at Kolka on the Kurzeme peninsula's tip, whose morphology has changed numerous times; today, coastal retreat occurs at the headland.

Littorina Sea stage and Post-Littorina dunes are present along the major part of the coastline (approximately 80 per cent), reaching up to 30–40

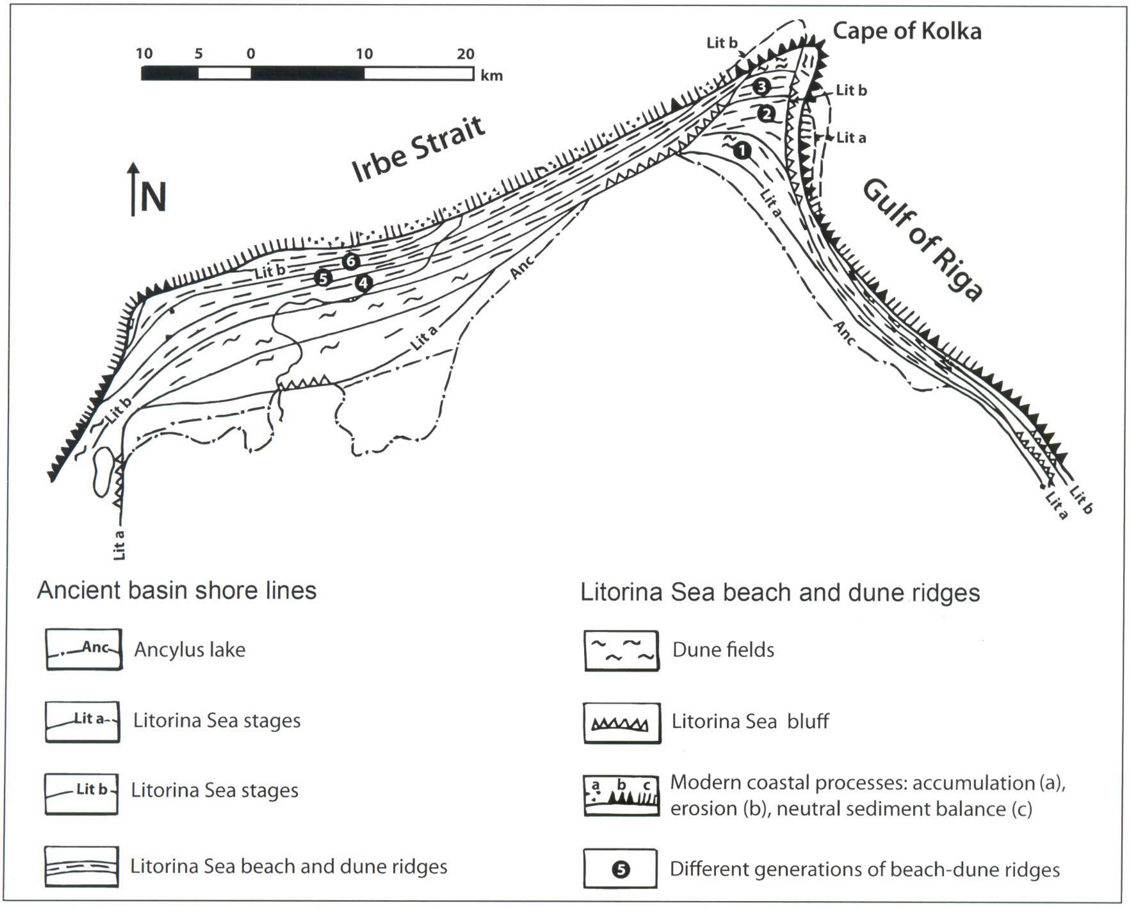


Figure 4.10 *Generalized palaeogeographical map of the Littorina Sea accumulation terraces and Cape Kolka (Ulsts, 1998)*

m above sea level (Figure 4.14). Lagoons, separated from the sea during the Littorina Sea stage, have been transformed into shallow, actively overgrowing remnant lakes (Pape, Liepāja, Babīte, Engure, etc.), or have been partially eroded while the coastal system adapts to new conditions. The water level in several lagoon remnant lakes has been artificially lowered for agricultural development. At the same time, at the southern end of the Gulf of Riga, a depositional coast developed because large sediment volumes obtained from the major rivers (Daugava, Gauja and Lielupe) were moved by longshore sediment drift. Wave-dominated deltas were also built at the mouths of the rivers Daugava and Gauja.

All Latvian coastal sections possess several common peculiarities in that the:

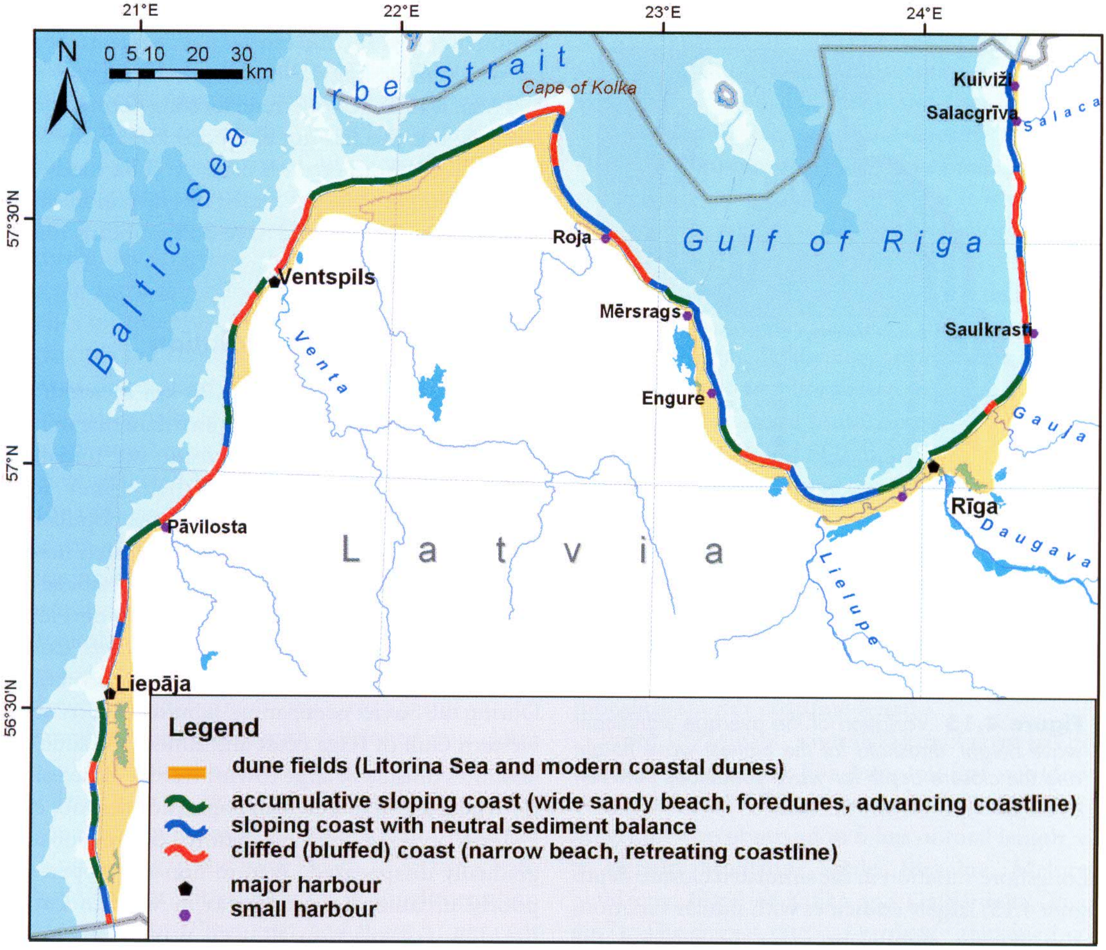
- majority are formed of unconsolidated Quaternary sediments, except an approximately 8 km long section in the eastern part of the Gulf of Riga;
- seashore is comparatively low and flat (height mainly does not exceed 15 m);
- underwater coastal area has a gentle slope, covered with an amount of 'active' sediment material;
- entire coastline, with few seasonal exceptions, has a beach;
- longshore sediment drift reaches one million m^3/yr in the open Baltic Sea coast.

Figure 4.11 *Soft cliff (bluff) in Quaternary deposits on the Baltic coast central section*

Irrespective of the comparatively homogeneous geologic structure, the coastal geomorphology is changing and as a result, areas can be found where continuous accumulation of deposits has occurred on flat shorelines (about 140 km of total length) together with coastal erosion, where cliffs/bluffs (about 150 km in length), with different heights and different geological structures (Figures 4.11, 4.12 and 4.13).

Figure 4.12 *Sediment-deficient slowly retreating coast on the northeastern side of the Gulf of Riga*

Figure 4.13 *Accumulative coast with sand beach and growing foredunes on the central part of the Irbe Strait coast*



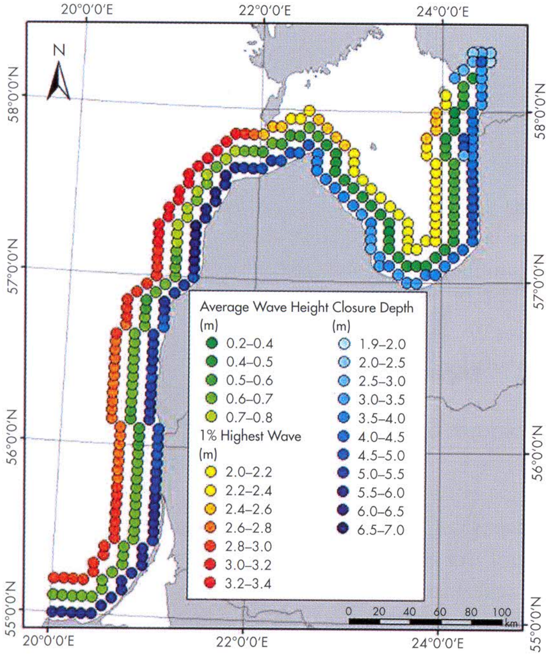
■ **Figure 4.14** *Coastal types along the Baltic Sea and Gulf of Riga*

Along other sections of the coast (about 200 km), conditions are stable. In some places, sediment movement occurs at a very slow rate, e.g. the north-east and north-west of the Gulf of Riga.

In general, coastal types can be defined by differences in sediment volume distributions, which, in its turn, is a function of many factors, the main being the Littorina Sea period heritage, coastline orientation against prevailing winds and anthropogenic factors (Eberhards, 2003). Artificial coasts (harbours, 8 km and shore protection structures, 4 km) represent 2.4 per cent of the entire coastline (Lapinskis, 2010).

Wave climate

The main Baltic Sea storm period is the autumn/winter season, when maximum wind waves in the open Baltic Sea can in exceptional cases reach heights of 13 m. Maximum wave height in the Gulf of Riga is 8.5 m in its southern part away from coastal areas. Waves arrive at the coast predominantly from a south-western and western direction and underwater sand bars, usually found on the flat coastal underwater slope, significantly affect wave transformation.



■ **Figure 4.15** *Variation of the average significant wave height, threshold for the highest wave height and the closure depth for wave conditions between 1970–2007 (Soomere* et al.*, 2011)*

Longshore variation in the simulated closure depth (Figure 4.15) largely coincides with similar variations in the average significant wave height and the threshold for the 1 per cent of highest wave conditions. The highest wave values are found along the western coast of the Kurzeme Peninsula (about 5.4 m); the smallest ones at the western Gulf of Riga coast (3.5 m). Wave climate differences in the Gulf of Riga evidently reflect the anisotropic nature of wind fields in this region.

The average breaking zone width is from 600 to 1000 m starting from a depth of 7–8 m. In the Baltic Sea and, in particular the Gulf of Riga, sea level changes are mainly caused by wind pressure (storm surges). Maximum storm surge levels along the open Baltic seashore were observed in 1967, when +174 cm was registered near Liepāja. In the Gulf of Riga, the highest water level (+247 cm) was registered in 1969 in Skulte. Wind speeds of 28 m/s have a return period of five years, and ten years is the return period for winds exceeding 32 m/s (Ulsts, 1998).

There is an increasing trend for long-term sea level changes, but this has not exceeded 10–15 cm since the end of the nineteenth century (Eberhards and Purgalis, 2008). Changes caused by gravitational tides do not exceed 15 cm and have no significant role in coastal area evolution.

Coastal settlement evolution

Within a coastal area of about 20 km in width (15 per cent of Estonia's area) live more than one million inhabitants, usually located outside the initial sea adjacent to a 100–200 m area/belt. They form approximately one half of the whole population, mainly because the capital, Riga, is located here, a function of Latvian history. Due to various social and political restrictions, there are no densely developed areas in the *direct* seashore vicinity and there exists a comparatively small number of civil infrastructures. During the Soviet occupation, significant parts of the western Gulf of Riga coast and almost all Baltic Sea seashores outside of large towns, were a 'closed area', for which access to a civilian population was not easy. Fishing villages existing before the occupation gradually disappeared. Within non-developed and poorly urbanized coastal areas in western Latvia, the only construction allowed was in relation to protection of the outer USSR borders. Therefore, paradoxically, the Soviet occupation 'saved' Latvia from various coastal management problems that seem specific to Western Europe, and the 255 km of protected natural areas located along the coast are partially a 'present' of the Russian occupation.

In the beginning and middle of the sixteenth century, demand for timber and firewood in all areas sharply increased (urban construction, shipbuilding, lighthouse fire, industry, warfare) and as a result, extensive areas of forests were harvested. The degraded areas were exposed to aeolian processes and inland dune migration followed, especially along the Kurzeme coast. Dune migration continued for centuries, causing significant damage and requiring much effort for replanting but sand movement stopped in the mid twentieth century (Eberhards, 2003).

Until the end of the nineteenth century, coastal areas, except river mouths, were very sparsely populated because of the coastal lowland's low fertility. The main source of subsistence for people living in coastal villages and farmsteads was fishery. At the end of the nineteenth century, along with industrial development, the first significant anthropogenic intrusion into coastal processes occurred when construction of large ports commenced. During the last century, because of a coastal retreat of 50 to 200 m, many small rural population centres in areas originally located a safe distance from the coast are now at risk. During recent decades, Latvia has been affected by a common worldwide trend: inhabitants gradually moving closer to the coast mostly to previously undeveloped areas. This rapidly increasing human impact on sensitive, but in most areas still intact, coastal belt ecosystems, is such that the typical natural landscape is being transformed and degraded.

However, significant coastal areas are still vacant. The total coastline length with developed areas closer than 500 m from the shore is *circa* 11 per cent. The total length of sections with a low or very low building density forms about 28 per cent (mainly in the Gulf of Riga); the total length of sections with no building, but with significant seasonal recreation load forms about 10 per cent, and about 51 per cent are those minimally affected by people (except erosion caused by harbours).

Coastal erosion

The most significant source of new material in the sand, gravel, shingle coastal system is erosion of cliffs/bluffs and sediments from the coastal underwater slope. These are moved laterally by longshore currents, but dredged sediment from harbours is lost to the system because of being transferred to offshore dump areas away from the active coastal zone.

Analysis of available materials show that since 1935 (the oldest qualitative cartographic material for the entire seashore; Eberhards, 2003), to 1992, shoreline retreat at an average rate of 0.5–2.0 m/yr has occurred in wide areas in the western part of Kurzeme, but only for some specific short sections in the Gulf of Riga (Figure 4.16; Eberhards and Lapinskis, 2008). The impact of Ventspils and Liepāja harbours is especially important, since ship entrance channels reach large depths, e.g. at Ventspils it is −19 m and these have completely stopped longshore sediment drift.

For over the past 20 years, more than 35 million m^3 of sediment has been buried in offshore dumps or inland. To the north from both Liepāja and Ventspils harbours, shoreline retreat has been of the order of 200 m whilst south, accretion has exceeded 350 m at Liepāja and 800 m at Ventspils. The total length of seashore formed due to harbour excavation is significantly less than the length of the eroded retreating sections (35 km). For example, the approximate sediment deficit volume north of Ventspils harbour exceeds 50 million m^3. In the Gulf of Riga, the role of ports affecting coastal dynamics must be considered significant, though the ports affect significantly shorter coastline lengths.

From 1992–2011, some 120 km of coast has been affected by erosion. For some 60 km withdrawal occurs at a rate >0.5 m/yr. Much higher rates (>2 m/yr) may be observed in 6 km of total length, e.g. at Bernāti headland, Šķēde, Jūrkalne, Melnrags, Staldzene, Cape of Kolka and Gauja delta (Figure 4.17). The retreat rate has probably remained constant for the central shoreline, but eroded lengths seem to have been extended (Eberhards *et al.*, 2009)

In the long term, certain adverse impacts have been caused by boulder removal from beaches and underwater slopes, these being used to fortify the subaerial coast (in the central part of the western Gulf of Riga and the south-east part of the Gulf of Riga). Additionally foredune trampling has resulted in deflation because of recreation overload, especially in the southern part of the Riga Gulf.

In the second half of the last century, extraction of, for example, sand-gravel for economic needs, hydropower dam construction, etc. has led to a decrease in alluvial sediment input from the major rivers (Daugava, Lielupe, Venta and Gauja), resulting

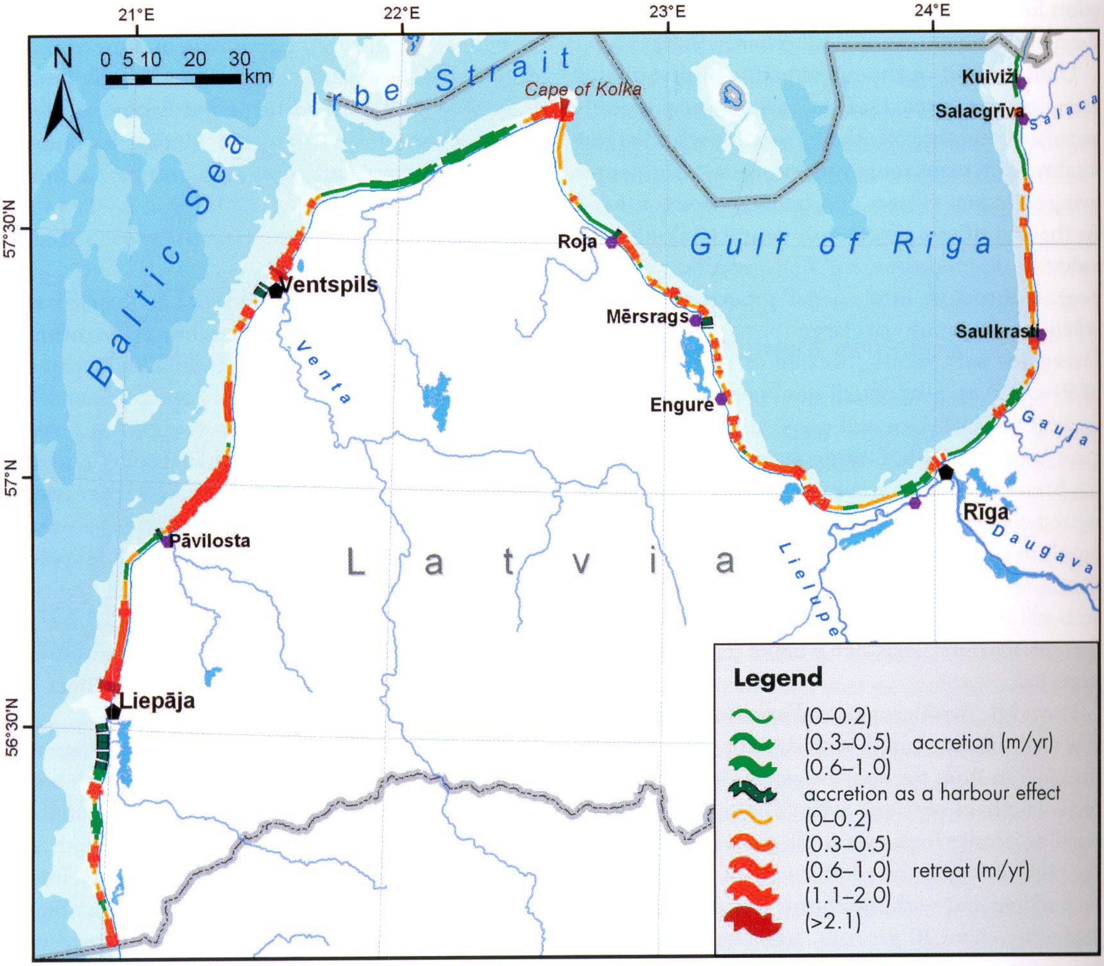


Figure 4.16 *Shoreline retreat and accretion in the Gulf of Riga and Baltic Proper in 1935–1992*

in coastal erosion acceleration of some 6 km (Eberhards and Lapinskis, 2008). During recent decades, due to climate change, there has been a sharp reduction in the sea ice duration time (Meier *et al.*, 2004) along with a reduction in the number of days with sub-aerial frost on the shore (Briede, 2006). The result, particularly on the Gulf of Riga shore during winter storms, is that ice is not acting as a natural 'protective barrier'. For instance, during the hurricane-strength winds of 8–9 January 2005, when there was no ice cover, the volume of material washed into the sea reached 3.1 million m^3 and about 90 ha of territory was lost (Eberhards *et al.*, 2006).

Coastal protection

According to estimates of coastal erosion, some 160 households, municipal or industrial (including cemeteries, 6 km of roads, electro transmission lines and several historical and cultural objects) are located within the 50 year risk zone, of which about 40 are located within the 15 year risk zone (Eberhards *et al.*, 2009).

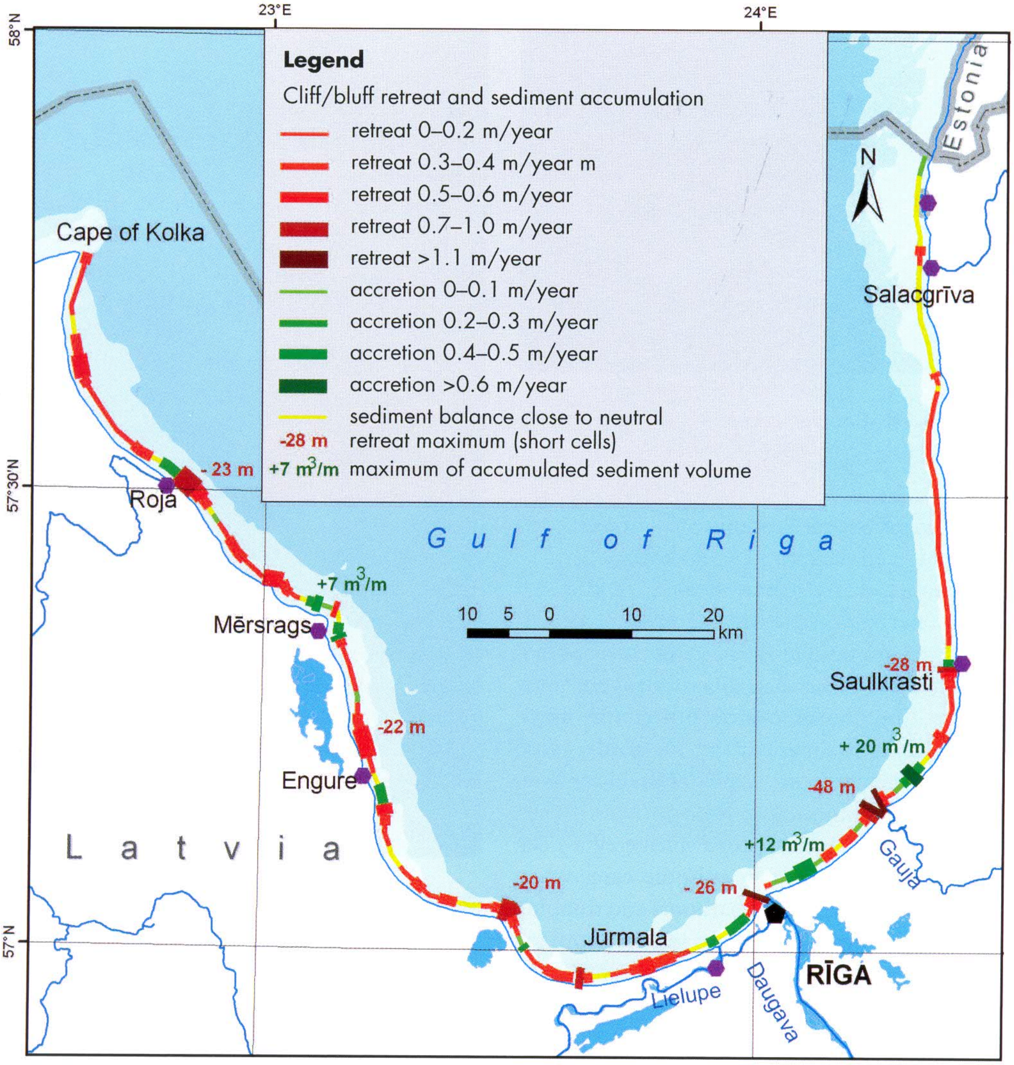


Figure 4.17 *Shoreline retreat and sediment accumulation in the Gulf of Riga in 1992–2011*

Protected shoreline sections are comparatively short, their total length is small (about 4 km), and usually built from local natural material, e.g. many Gulf of Riga fishing villages have boulder revetments (Figure 4.18). Similar in function, though more solid, are structures formed of reinforced concrete prisms or tetrapods, placed near several lighthouses on the Kurzeme coast (Figure 4.19). In many cases, revetment section installations placed parallel to the shoreline for only a few 100 m have caused beach disappearance and erosion intensification of nearby sections. One major coastal protection structure with a length of 500 m was installed in 2006 at the Liepāja wastewater treatment plant (Figure 4.20). The chosen solution, an inclined wall of gabions, has still preserved its original function but caused significant

Figure 4.18 *Boulder revetment at Valgalciems (western coast of the Gulf of Riga)*

intensification of coastal erosion to the north away from the protected section.

The massive military fortifications formed in the beginning of the twentieth century and located north of Liepāja port are unique in the context of coastal erosion. Despite being partially destroyed, they continue to function as coastal protection units, maintaining the coastline and further north, cause typical consequences of beach instability and intensification of erosion (Figure 4.21).

No soft shore protection projects have ever been executed in Latvia, except in episodic cases when material excavated from small harbours and shipping channels with volumes exceeding several thousand m^3 have been transferred to the nearest beach vicinity to the port. No groins, detached or submerged structures have been constructed along the Latvian coast. The shoreline length covered by coastal protection structures is very small and all belong to passive structural types (seawalls and revetments). The end result is that scour, which increases reflected wave energy and end wall erosion, has occurred at all sites. Around 40 per cent of the existing coastal protection structures can ensure only short-term or partial protection of the endangered objects, since they are inappropriate for local situations and are in critical conditions (Lapinskis, 2009).

In several comparatively densely populated sections experiencing high anthropogenic stress and

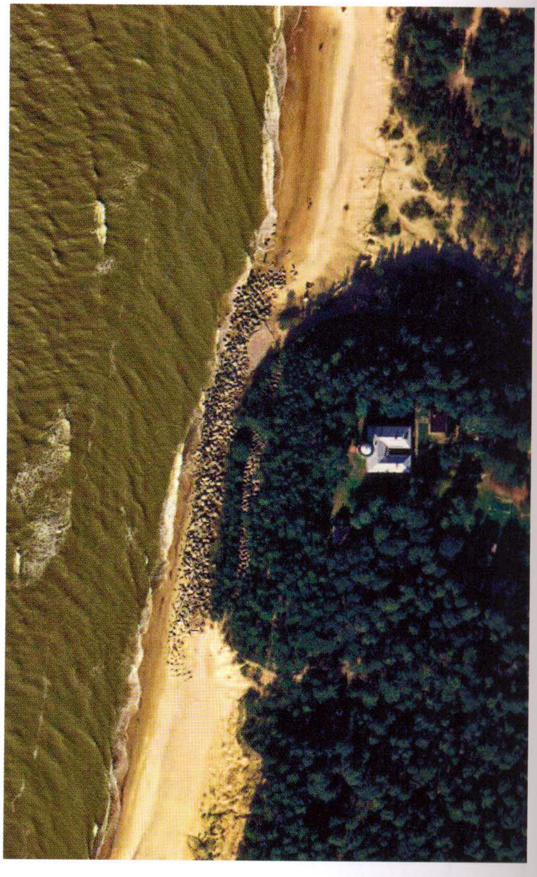


Figure 4.19 *Tetrapods around a lighthouse on the Kurzeme coast (aerial photograph by Metrum Ltd.)*

Figure 4.20 *Liepāja wastewater treatment plant revetment*

■ **Figure 4.21** *Old military fortification north of Liepāja port*

where significant amounts of sand are available (e.g. Ventspils, Jūrmala), dune planting of osier and marram grass has been practised since the 1960s (Figure 4.22). It was carried out to enhance aeolian foredune accumulation and to accelerate depositional processes after erosion episodes, as well as to enhance any recreational qualities of the beach.

■ **Figure 4.22** *Dune planting close to the southern jetty of the port of Ventspils*

Conclusions

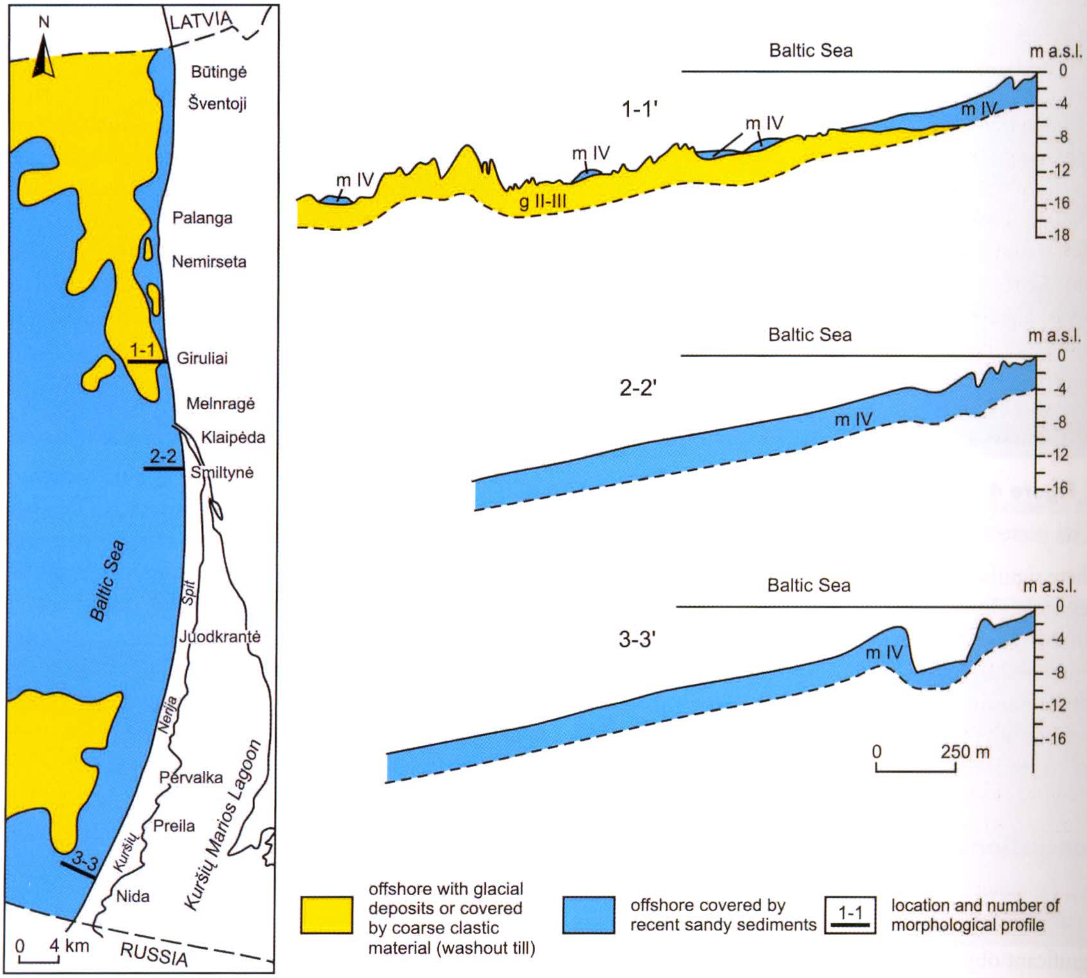
Coastal sections with landscape-valuable bluffs, as well as broad sand or pebble-gravel beaches, are significant objects for a coastal tourism industry. By artificially restricting natural processes, the intrinsic value of these objects may decrease or even disappear.

Negative effects of artificial protection features are seen adjacent to structures. Excavation related to port shipping channels has stopped longshore drift and large amounts of excavated sediment has been lost to the system by being dumped offshore. Transfer of excavated uncontaminated sediments from shipping channels and ports to sediment deficiency areas, should be mandatory. If existing harbour management practices continue, an extension can be expected with respect to the lengths of coastal erosion sections.

Lithuania

Introduction

Lithuania has one of the shortest coastlines (90.6 km) among all European countries, only three other European countries – Montenegro, Slovenia and Belgium – have shorter marine coastlines (Gudelis, 1967; Boldyrev *et al.*, 1976). With respect to geology and geomorphology the Baltic coast, which is shaped by wave-induced processes, can be divided into two



■ **Figure 4.23** *Lithuanian coastal area of the Baltic Sea and typical nearshore profiles* different segments: a sand peninsula (the Curonian Spit), and the continental coast (mainland). They are separated by the narrow Klaipėda Strait that connects the Curonian Lagoon to the Baltic Sea, stretching north from Klaipėda (Figure 4.23), the third biggest Lithuanian city and one of the biggest Baltic Sea ports. The coast is important for nature conservation with the Curonian Spit protected as a UNESCO World Heritage Site. Intensifying use of coastal resources, especially port development and increase in recreational activities, are some of the most important factors causing coastal erosion resulting in application of coastal protection measures.

Coastal morphology

The Curonian Spit is the largest accumulative coastal landform in the Baltic Sea, being 95 km in length. The northern 51 km is in Lithuania, while the remaining 44 km is part of Kaliningrad Oblast, Russia. The spit width varies from a minimum of 380 m in Russia to a maximum of 3.8 km in Lithuania. Spit development started some 8,500–8,300 years ago at the end of the Ancylus Lake formation stage of the Baltic Sea and took its present shape in the Littorina Sea phase, 6,900–6,300 years ago (Bitinas and Damušytė, 2004; Damušytė, 2009). The barrier sand spit formed on the remnant of a glacial moraine, as a result of sand accumulation by longshore sediment transport. Historically, the Curonian spit has continued to evolve by dramatic changes in natural processes which took place during the 1700s and 1800s, when ancient parabolic dunes, which had prevailed since Holocene times, were completely destroyed by drifting sand and replaced by barchan dunes (Gudelis, 1995, 1998).

Different relief sections occur along the spit: beach, foredune ridge, blown sand plain, blow-out dune remnants, great dune ridges and the shore of the Curonian Lagoon (Gudelis, 1995). The most dominant element of Curonian spit relief is the ridge of high drifting dunes (Figure 4.24 top), stretching for some 80 km. The ridge width varies from 0.3 to 1 km and average dune height is 30 m, with some reaching 50–60 m. The 31 km long ridge of 40–60 m high migrating dunes is the longest coastal drifting dune ridge in Europe (Povilanskas and Chubarenko, 2000).

■ **Figure 4.24** *Main landscape forms of the Curonian Spit: great dune ridge (top) and foredune (bottom) (Photograph by G. Gražulevičius)*

Another important element is the foredune ridge, a man-made protective beach dune, whose construction started 200 years ago. It stretches along the entire spit length (Figure 4.24 bottom) with heights varying from 7–8 m at Juodkrantė to 15 m at Kopgalis (in the northern spit) the width ranging from 50–60 m to 90–100 m. The presence of ravines and pits on the foredune top provides evidence of intensive blowout processes. Behind the protective foredune is a vegetated, blown sand plain. The Curonian Spit nearshore is characterized by very specific underwater topography and the presence of two or more 4–6 m high sandbars in water depths of up to 8–9 m (Figure 4.25; Gelumbauskaitė, 2003).

Three morpholithodynamic sectors may be distinguished on the Curonian Spit coast:

1. southern – erosional and accumulative (in the Russian part);
2. central – transitory (stable);
3. northern – accumulative (Kirlys and Janukonis, 1993).

The Lithuanian section includes both transitory and accumulative shoreline sectors.

The current state of the Curonian Spit depends very much on the functioning of the longshore sediment transport which occurs in a 3–4 km wide zone. Prior to the 1950s, the sediment flow intensity was distributed as follows: 350–400×10^3 m^3 of sand was transported along the spit; 500–700×10^3 m^3 of sediments reached Klaipėda and only 150–200×10^3 m^3 continued northwards from Klaipėda towards the Latvian border (Knaps, 1969). After the 1950s the amount of sand in the nearshore zone has decreased considerably (Žaromskis, 2007b), mainly through stabilization of the Sambian peninsula shores and depletion of erosional sediment sources on the Baltic Sea bottom (Zhamoida *et al.*, 2009). This resulted in an increased length of abrasive spit segments, particularly in the Russian sector.

The Curonian Spit and mainland coast are separated by the narrow mouth of the Curonian Lagoon known as the Klaipėda Strait. The Curonian Lagoon (surface area 1,584 km^2) is the biggest shallow semi-landlocked freshwater basin located in the south-eastern part of the Baltic Sea. The Nemunas River (catchment basin of 97,864 km^2) drains into the lagoon on its way to the Baltic Sea and the Klaipėda Strait water area is occupied by one of the biggest sea ports in the Baltic region. Breakwaters and a permanently deepened port entrance channel act as a trap for longshore sediment transport, thereby affecting the state of the mainland coast.

The continental coast consists of alternating erosional and depositional zones. Several different lithologies occur, but sand or till deposits are dominant. While sand sediments, formed mainly in the Littorina and Post-Littorina phases of the Baltic Sea development, prevail in the northern part (Šventoji, Palanga), the southern part of the mainland

■ **Figure 4.25**
Beach dunes between Palanga and Šventoji

coast (Nemirseta, Giruliai) is characterized by glacial (till) deposits (Bitinas *et al.,* 2005), that mainly form eroded cliffs. A natural foredune stretches along the entire continental coast. This varies from a height of 4–6 m and a width of 50–60 m at Būtingė or Melnragė to a height of 9–10 m and a width of 100–130 m to the south of Šventoji (Figure 4.25). In several places, especially in the northern part near the Latvian border during the last 30 years, the foredune has been heavily destroyed and intensification of foredune erosion is related to an increasing frequency of storm events and recreational loadings.

Evolution of coastal settlements and coast usage

The first coastal settlements were created from 3–4,000 BC (Rimantienė, 1999). A convenient trading road connected Semba and Kuršas (Strakauskaitė, 2004) and in the thirteenth to sixteenth centuries AD the biggest settlements were created along this road. During spit deforestation due to overgrazing, timber harvesting and boat-building in the eighteenth century, dunes were activated and entire villages buried. The prevailing westerly winds reworked the parabolic dunes to form the single dune ridge which was supplemented by sand from the western part of the spit (Gudelis, 1998).

Between 1706 and 1846, 14 villages were buried beneath the sand (Gudelis, 1998). The massive sand movement was mitigated by large scale revegetation and reforestation efforts. Since the middle of the nineteenth century, the Curonian Spit has become known as a famous Lithuanian holiday resort with unique landscapes (Armaitienė *et al.,* 2007) and the whole territory of the Curonian Spit (including the Russian portion) has protected area status. Since 2000, the Curonian Spit has been on UNESCO's World Heritage List under cultural criteria "V", an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change (WHC-2000/CONF.204/21). In addition to its conservation value, the Curonian spit is an important national and international tourism destination. In the Lithuanian part there are four resorts (Nida, Preila, Pervalka, Juodkrantė), integrated into one town.

Klaipėda's history began in 1252, when Memelburg castle was founded by the Order of Crusaders along the Klaipėda strait and the Danė river. In 1808, Klaipėda, for a short period, even became the capital of the Kingdom of Prussia. The territory of Klaipėda, which was densely populated by Lithuanians, was officially connected to Lithuania in 1923 and after this date the port developed rapidly. After World War II, the port fulfilled the primary needs of the Soviet Union and during Soviet times, most of the coastal zone was a closed military area. Sea access was possible only during the day and in narrow coastal strips designated for recreational purposes. When Lithuania regained its independence in 1990, the coastal area became fully opened to the public.

Currently the coastal region is characterized by the fastest economic growth in the country. The GDP per person is 1.5 times higher than in other regions (Žaromskis, 2006), one of the main reasons being the successful operation of Klaipėda port. In 1995, cargo turnover at the port was 12.7 million tonnes and in 2010 it had increased to 31.3 million tonnes (Figure 4.26). Moreover, Klaipėda developed as an attractive tourist destination. The northern part of the Curonian spit (Smiltynė and Kopgalis), as well as recreational settlements on the mainland coast (Melnragė, Giruliai), belongs to the municipality of Klaipėda.

A large part of the continental coast belongs to Palanga, which also includes Šventoji settlement. Palanga is the most popular resort on the Lithuanian coast, famous for its high quality sand beaches. At the end of the nineteenth century there was an attempt to establish a port in present-day Palanga and a breakwater was constructed (Žaromskis, 2006). Unfortunately, the quay rapidly filled with sediment, while the breakwater eventually became the promenade pier (Figure 4.26 centre). Dam construction had a major impact on further developments of the Palanga coast.

Ten kilometres north from Palanga, at the mouth of the Šventoji River, there was an ancient port,

■ **Figure 4.26** *Hydrotechnical constructions on shore: Klaipėda sea port breakwaters (top); Palanga promenade pier (centre); old Šventoji port filled with sand (bottom) (Photographs by V. Karaciejus, Klaipėda State Sea Port Authority and A. Tirlikas, PC ORLEN Lietuva)*

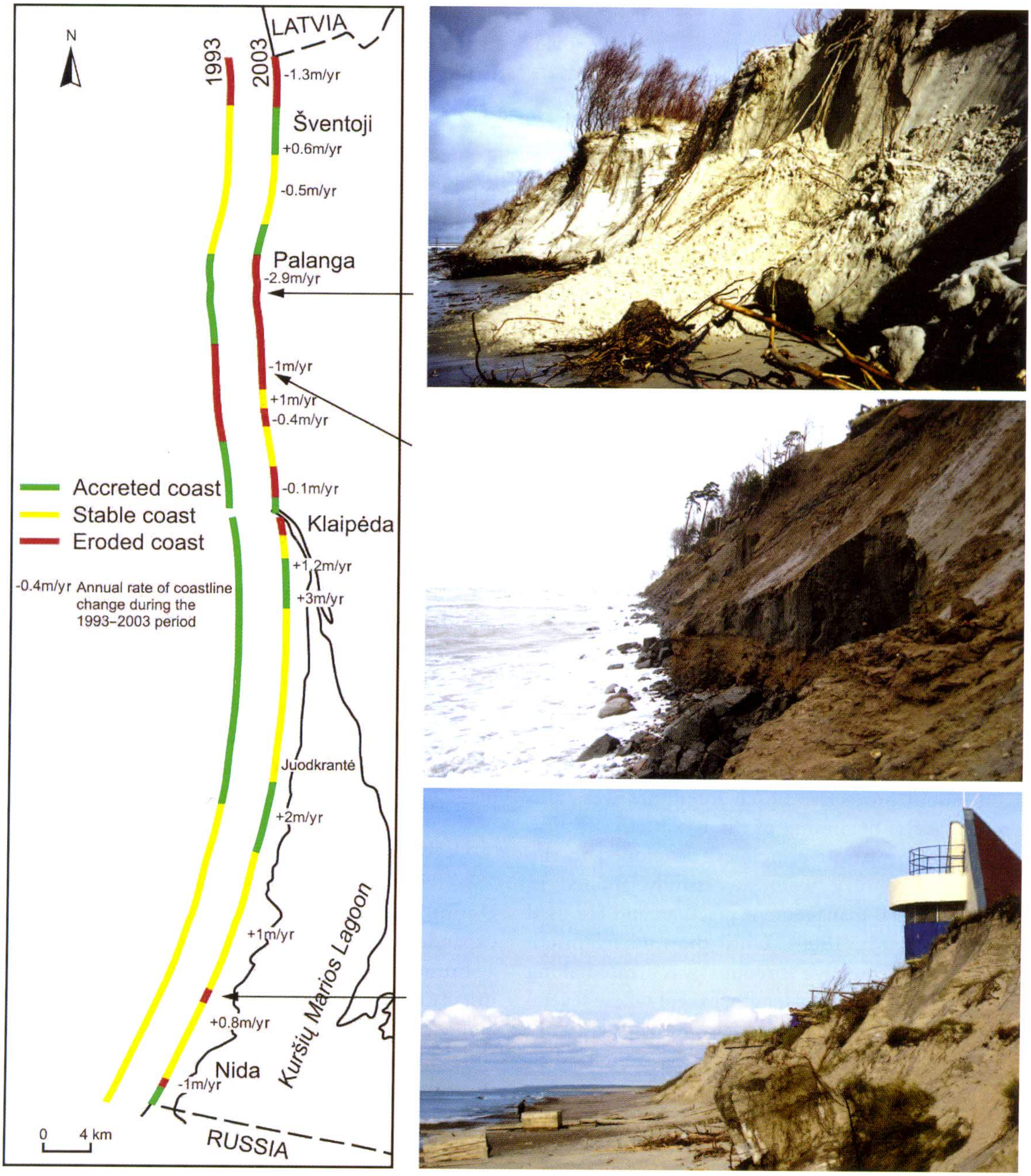
which is no longer used. Intensive port construction took place during 1924 to 1939, but stopped suddenly because of World War II. Afterwards construction works were discontinued and the port was covered with sand (Figure 4.26 bottom). After much discussion it was decided to reconstruct the port in 2011 for recreational fishing purposes.

Since 2000, the Būtingė Oil Terminal, near to the Šventoji settlement commenced operations with an annual turnover of 10 million tonnes per year. The terminal is the only one of its kind in the Baltic Sea, because tanker moorage, as well as cargo handling, takes place using a single point mooring (SPM) buoy, installed 7 km from the coastline in 20 m of water, crude oil being pumped to inland facilities via a pipeline.

Most of the coast is now under some form of protected area designation, which influences coastal zone usage possibilities; e.g. the entire Curonian Spit and part of the continental coast (Seaside Regional Park) are NATURA 2000 territories.

Beach erosion

This was already serious some 40 years ago (Žilinskas, 2005) and since then awareness has increased yearly, the length of eroding coastline moving from 18 per cent to 27 per cent between 1990 and 2003. By contrast, the proportion of accreting coast fell from 40 per cent to just 12 per cent over the same period, while the stable coastline rose from 42 per cent to 61 per cent (Figure 4.27). There are several reasons for the above. First, there was a significant reduction of sediment supply because of changes in long-shore sediment transport in the SE Baltic Sea region. There was a dramatic decrease of sand availability in the northern nearshore of the Sambian Peninsula, where sediment movement was blocked after shore stabilization involving hard structures (Zhamoida *et al.*, 2009). Geomorphological development was also influenced by human activity, particularly the operation of Klaipėda port. Breakwaters and the deep entrance channel intercept more than half the longshore sediment drift, resulting in the continental coast suffering an additional sand deficit (Žaromskis, 2007a).



■ **Figure 4.27** *Shore dynamics and eroded beach segments*

Climate changes also affect shoreline stability and acceleration of relative sea level rise has been observed on the Lithuanian coast (Jarmalavičius *et al.*, 2007). Between 1970 to 2000, the Baltic Sea level rose by more than 15 cm (Johansson *et al.*, 2001; Dailidienė *et al.*, 2006) and long-term investigation of sea level rise in the Lithuanian Baltic Sea shows an annual increase of 6,5 mm. A rise of sea level up to 60 cm would cause significant problems for inhabitants and the land infrastructure (Žaromskis, 2001).

More frequent storms (wind speed >24 m/s) have caused sand loss from the coastal zone (Žaromskis and Gulbinskas, 2010). Formerly, deep cyclones occurred every six to eight years, but recently this frequency has changed to every two to three years, so that the coast has no time to restore its equilibrium profile (Žilinskas, 2008).

Shore protection

Coastal protection has a long history, even though the first coastal protection measures were not aimed to stop erosion, but rather to mitigate impacts of aeolian processes (Žaromskis, 2007b). In the Lithuanian part of the Curonian Spit, such works were first initiated in Klaipėda in 1810 and later (1825) activities were also undertaken in Nida. Continuous protective beach foredunes were also created at the beginning of the twentieth century. Foredune formation principles, developed in the nineteenth century were successfully applied in modern coastal management practices and are used today (Gerhardt, 1900). Until the mid twentieth century the protective foredune was created along almost the whole coastal length, except where several sectors had moraine cliffs (north from Klaipėda Strait).

Shore protection regulation

Coastal management is based on laws, long-term coastal management programmes and implementation of coastal protection projects. According to Lithuanian Law on the coastal strip, the coastal zone is that part of the coast including the nearshore and extending not less than 100 m inland, extending from the border of Latvia to the northern breakwater of Klaipėda port, including part of Curonian Spit up to the Russian border and the Baltic Sea part of territorial waters up to 20 m in depth (Seimas of the Republic of Lithuania, 2002).

The main principles of coastal protection are stated in the Lithuanian Baltic Sea coastal protection strategy (Ministry of Environment of the Republic of Lithuania, 2001) and are as follows:

- coastal protective measures can be applied only in strips where coastal erosion endangers human activities, protected areas and natural or cultural heritage values;
- priority should be given to the preservation of natural landscape and natural coastal formation processes;
- there is a need to ensure complex coordination of coastal protection and coastal use.

Long-term coastal management programs specify application of coastal protection measures according to functional priorities and natural coastal dynamics. Coastal segments are distinguished by their functions, coastal erosion rates, recreational capacities, etc. in order to identify the problem sectors, before agreeing to any final coastal protection and management measures (Gulbinskas *et al.* 2009).

Shore protection by elementary measures

During recent years, coastal protection works have expanded. The protective foredune is maintained by a brushwood flooring of foredune slopes and installation of brushwood fences, which help catch and accumulate sand, which builds up faster when surface roughness is increased and wicker fences at the dune base facilitate this process. Other measures include construction of wooden stairs and footpaths in recreational areas, planting of greenery in dunes, as well as maintaining natural processes (Figure 4.28).

Figure 4.28 *Foredune maintenance by elementary measures near Palanga*

Hard constructions

Hard constructions are limited and used only for protection of a small segment at the centre of Palanga. For over 100 years, the impermeable Palanga promenade pier acted as a sediment trap and was dismantled in 1998 when a new permeable pier was erected. This changed the coastal dynamics and stimulated intensification of coastal erosion. In order to restore the former situation it was decided to build a stone groin in place of an old sea pier. A semi-permeable groin was built in 2005 (Figure 4.29a), but due to a relatively low height (*circa* 1 m above water level) it does not disturb longshore sand drift during strong storms, but traps sand brought by small waves.

Nearshore and beach nourishment

Beach and nearshore nourishment works commenced in 2001, sand extracted offshore and during the dredging of Klaipėda's port entrance channel being used for beach nourishment. Large volumes of sand are dredged from the Klaipėda sea port entrance channel (Figure 4.29a) and this sand is proposed to be used as a compensation measure to restore the sand balance disturbed by the port breakwaters. As a result the nearshore strip, north from the port entrance channel is regularly supplemented with dredged sediments. During the last ten years the nearshore has been nourished by a sand volume of 850×10^3 m^3.

Palanga resort is the most problematic coastal sector with regard to coastal erosion. At the end of the nineteenth century, the width of Palanga beaches was 150–180 m but in the mid twentieth century, because of decreasing sand supply, beach width declined to 60–80 m. The most intensive erosion took place between 1993 and 2007, when average sand loss was calculated at 13.0 m^3/m/yr (Žilinskas, 2008). At the beginning of 2005, the beach width in some places decreased to 10–15 m.

Palanga beach nourishment was implemented in several stages. In 2006 the central part (800 m length segment) was replenished with 40×10^3 m^3 of sand, brought from an inland quarry (Figure 4.29b). As a result beach width increased up to 40 m. In 2008 the beach (1,200 m length segment) was nourished with $\sim 111 \times 10^3$ m^3 of sand, brought from the seabed (Figure 4.29c). This time the coastal sector width increased by up to 70 m. The third stage of beach nourishment was supplemented in 2011–2012 and the 2.4 km long Palanga beach sector nourished with 424×10^3 m^3 of sand. Monitoring confirmed that beach nourishment had a positive effect on reducing erosion, resulting in an increase in beach width, stabilization of the coastline and nearshore sand accumulation.

Figure 4.29 *Palanga beach regeneration area (right): building of groin (a); beach nourishment (b, c)*

Conclusions

Early coastal development was characterized by a large sand supply and a south–north longshore sediment drift, which created a dominance of accumulative sand coasts. However, during recent decades degradation and further disappearance of sand beaches was observed, mainly because of intensive human activity. Lithuanian coastal management gives priority to environmental protection and preservation of natural coastal dynamics. Coastal protection strategy and measures are selected according to functional coastal usage. Seeking to ensure harmonized nature and human interaction, the following soft coastal protection measures have been applied on sensitive coastal areas in Lithuania: 1) maintenance of the protective foredune using traditional 'soft engineering' measures; and 2) nearshore and beach nourishment.

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