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Transport and distribution of bottom sediments at Pirita Beach

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Abstract. The basic factors affecting sediment supply for and transport processes at Pirita Beach, a sandy section of the southeastern coast of Tallinn Bay, are analysed. Observations of bathymetry, sediment properties and sources, sediment transport processes and their changes arising from coastal engineering activities are reported. The mean grain size is about 0.12 mm, with the fine sand fraction (0.063–0.125 mm) accounting for about 77% of the sediments. Coarse sand dominates only along the waterline. The content of coarser sediments is greater in the northern part of the beach. A number of coastal engineering structures have blocked natural sediment supplies. The beach suffers from sediment deficit now and has lost about 400 m^3 of sand annually from the dry beach between 1997 and 2005.

Key words: coastal processes, sediment transport, bottom sediments, Gulf of Finland, Tallinn Bay.

INTRODUCTION

Pirita Beach is one of the most popular recreational areas of the City of Tallinn, hosting more than 3000 visitors daily in warm summer days (Photo 1). It is located at the southeastern head of Tallinn Bay, the venue of the 1980 Olympic sailing regatta. The beach is aligned between the northern mole of Pirita (Olympic) Harbour and a till cliff located about 400 m south of Merivälja Jetty (Fig. 1). The length of the sandy area is about 2 km and the dunes are relatively low. The maximum height of the dune scarp is 1.5 m.

Beaches of the northern coast of Estonia generally suffer from sediment deficit (Orviku & Granö 1992). Thus it is not surprising that a certain net loss of sand at times occurs in the Pirita area. Only limited data are available about the earlier status of Pirita Beach that apparently was stable until the middle of the 20th century (Loopmann & Tuulmets 1980) and has suffered from damage since then. The stability of Pirita Beach has been discussed for several decades (e.g. Orviku & Veisson 1979; Orviku 2003, 2005). Potential reasons for beach destruction are, for example, the overall increase in the intensity of storminess in the Baltic Sea Basin from the 1960s (Alexandersson et al. 1998) or the increase in the intensity of NNW winds from the 1970s onwards (Soomere & Keevallik 2001). The former has generally been attributed to activation of coastal processes for several decades (e.g. Bird 1981; Orviku & Granö 1992) and has been found to cause intensification of coastal processes at several Estonian beaches (Orviku et al. 2003).

The most probable reason for the damage to Pirita Beach, however, is that its sand supplies have been affected by extensive coastal engineering activities. The largest natural supplies of sand are the adjacent Pirita River and littoral transport along the coast of the Viimsi Peninsula. Their magnitude evidently was reduced already by the end of the 1920s when the first groins at the Pirita River mouth and a small jetty at Merivälja were constructed. No evidence of changes in the beach is available from the 1930s to the 1960s, but a substantial shift of the isobaths closer to the shoreline was reported in the 1970s (Paap 1976).

Changes in the beach became noticeable after the construction of a port at Miiduranna and Pirita Harbour during the 1970s. Since then a gradual decrease in the width of the dry sandy beach, recession of the till cliff at the northern end of the beach, and extensive storm damages to the dunes have occurred despite rapid post-glacial rebound in this area (about 2.5 mm/year, Zhelnin 1966; Miidel & Jantunen 1992, p. 93) and attempts to refill the beach with material dredged from Pirita Harbour or transported from mainland quarries (Kask 1997; Orviku 2005). The largest damage to the beach was caused in November 2001 and January 2005 by high and long waves attacking the beach from the northwest or west, being accompanied by an exceptionally high water level (Photo 2).

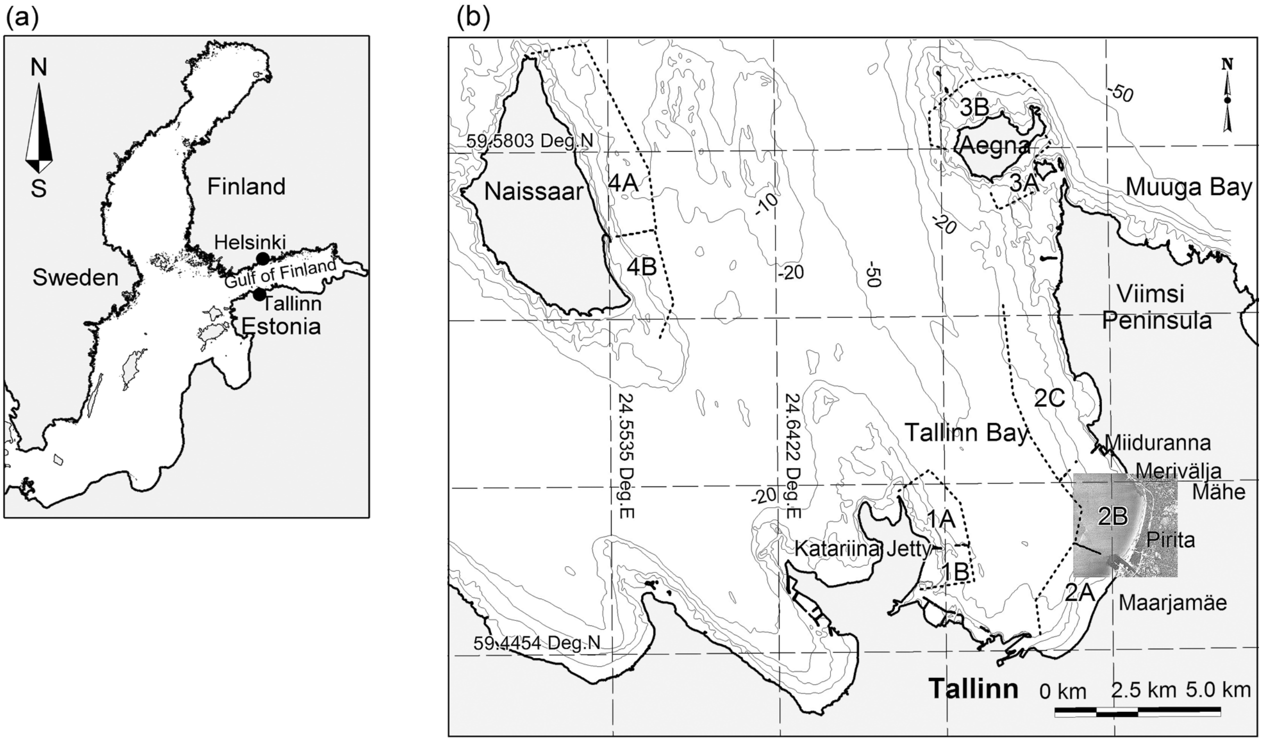

Fig. 1. (a) Location scheme of the Baltic Sea and the Gulf of Finland. (b) Location of Pirita Beach in Tallinn Bay based on the digital 1 : 50 000 Estonian Base Map from the Estonian Land Board (www.maaamet.ee). Dotted lines show cells of sediment transport: cell 1 along the western coast of the inner part of Tallinn Bay (divided into subcells 1A and 1B by Katariina Jetty); cell 2 along the eastern coast of Tallinn Bay (divided into subcells 2A, 2B, and 2C by Pirita Harbour and the Port of Miiduranna); cell 3 surrounding the Island of Aegna (subcells 3A and 3B at the southern and northern coasts, respectively), and cell 4 along the western coast of the Island of Naissaar (divided into subcells 4A and 4B by Naissaar Harbour). The step of the coordinate grid is 5 km.

The main purpose of this study was establishing the basic properties of sediments and factors affecting sediment supply for and transport processes at Pirita Beach. This is the first step towards quantification of the sand budget at Pirita with the use of the concept of the equilibrium beach profile (e.g. Dean & Dalrymple 2002). The properties of the profile are jointly defined by the properties of bottom sediments established in this study, and the local wave climate that will be described in a forthcoming study.

As no comprehensive description of beaches at the northern coast of Estonia is available in international literature, we present elements of the relevant knowledge and of the geological setting of the vicinity of Pirita Beach together with data about sediments at the beach and a qualitative description of sediment sources for this beach. Further we give an overview of the major coastal engineering activities potentially affecting the sediment transport processes and describe the results of the analysis of the texture and spatial distribution of bottom sediments, as well as the major bathymetric features based on surveys of 2005–2007. Finally, potential applications of the results from the viewpoint of beach protection are discussed.

THE COMPLEX OF SEDIMENTS AT PIRITA

The North Estonian coast, Tallinn Bay, and Pirita Beach

Descriptions of general properties of the beaches at the southern coast of the Gulf of Finland are mostly published in Russian or Estonian (Orviku 1974; Lutt & Tammik 1992; Orviku & Granö 1992). Many unique studies (e.g. Knaps 1976; Paap 1976; Orviku & Veisson 1979; Loopmann & Tuulmets 1980) are only available as manuscripts. An overview of the geology and geological history of the entire Gulf of Finland area is presented in Raukas & Hyvärinen (1992).

The beaches of Estonia have been catalogued based on a morphogenetic classification worked out in the former USSR (Ionin et al. 1964; Kaplin 1973; see an overview in Orviku & Granö 1992). An early scheme of the beaches of the entire Baltic Sea is presented in Gudelis (1967), and for Estonia in Orviku & Orviku (1961). An attempt at more detailed categorization (Morozova 1972) was improved and extended in Orviku (1974).

The beaches on the southern and northern coasts of the Gulf of Finland (Fig. 1a) are completely different. The northern coast is characterized mostly by "skären"-type beaches, whose evolution is weakly affected by hydrodynamic factors (Granö & Roto 1989).

On the contrary, the eastern and southern coasts of the Gulf of Finland were formed and develop predominantly under the effect of wave action (Orviku & Granö 1992). The beaches along the Estonian coast form a large erosional-accretional system, divided into compartments by rocky peninsulas and headlands. Many peninsulas, islands, and bays cutting deep into the land can be found in this area. The coasts obtained their contemporary shape only a few millennia ago and can be classified as straightening coasts (group IIIA according to Kaplin 1973). The volume of sediment and the magnitude of littoral drift are modest. The most common types of coasts here are the straightening, accumulation, and embayed coasts – type 20 according to Kaplin (1973).

The Viimsi Peninsula (Fig. 1b) divides the embayed beaches of the northern coast of Estonia into two sets. The features of the coast east of this peninsula are mainly related to glacial and fluvioglacial formations and deposits of the foreklint lowland while the westward bays (including Tallinn Bay) are mostly associated with structural blocks and ancient erosional valleys in the bedrock (Orviku & Granö 1992, p. 221). Both subtypes suffer from beach sediment deficit. Although littoral drift generally carries sediments to the bayheads, even the healthiest sections of the coast at the bayheads are from time to time subject to erosion.

The coasts of Tallinn Bay possess several sedimentary compartments and a variety of different types of beaches. A steep till bluff can be found at the Island of Naissaar, gently sloping till shore along many parts of the Viimsi Peninsula, sandy coast at Pirita and at certain sections of the Island of Aegna, and long sections of the artificial shore around Tallinn. The compartment consists of the following parts (Fig. 1b):

1. The mainland coasts of Tallinn Bay form a large compartment that is divided into two independent sedimentary cells by the harbours of the City of Tallinn, namely
   (a) western cell 1 is divided into two subcells 1A and 1B by Katariina Jetty constructed in the 1910s, and
   (b) eastern cell 2 that before the 1920s extended from the harbours of the City of Tallinn along the coast of the Viimsi Peninsula up to Aegna. Coastal engineering structures have considerably modified this cell. Its southwestern part (2A) is nowadays an artificial shore. Miiduranna Port divides the eastern part of cell 2 into two subcells 2B and 2C since the 1970s. The more northward cell 2C may be partially connected with the adjacent cell in Muuga Bay (Fig. 1) through a narrow (about 300 m) and shallow (about 1 m before dredging) strait.
2. The sedimentary systems at the islands adjacent to Tallinn Bay consist of:
   (a) sand bodies 3A and 3B at Aegna (to the north of the island and in the strait between the island and the islets adjacent to mainland, respectively), which seem to be separated from the mainland coasts, and
   (b) the eastern coast of Naissaar (cell 4), which contains subcells 4A and 4B that are separated to some extent by a harbour. This cell is completely disconnected from the mainland cells by a strait with a depth of about 30 m.

Pirita Beach forms the southwestern part of cell 2B. The rest of the western coast of the Viimsi Peninsula (cells 2B and 2C) is mostly covered by very coarse material (pebbles, cobbles, boulders). As typical of the northern coast of Estonia (Orviku & Granö 1992), it has a limited amount of gravel and sand participating in the littoral drift and it develops under sediment deficit. According to the classification of Lutt & Tammik (1992), erosion predominates in the entire nearshore of the Viimsi Peninsula to the north of Pirita Beach and up to a depth of about 10 m. Beach erosion, however, is usually modest because the stone pavement protects the shore (Kask et al. 2003b). Finer fractions are only released in high water level conditions when waves directly act on unprotected sand, till, or limestone. Accumulation predominates in the deeper part of the nearshore and in the vicinity of Pirita Beach.

Quaternary deposits at Pirita

Pirita Beach is located within the ancient Pirita River valley that extends down to Cambrian clay. The contemporary Pirita River follows the ancient valley to some extent. The southwestern border of the valley becomes evident at Maarjamäe (where Cambrian deposits are in places quite close to the contemporary surface) and the northward border at Merivälja (Figs 1b, 2). A large number of similar valleys and "klint bays" are known in northern Estonia. Many of them also contain con-

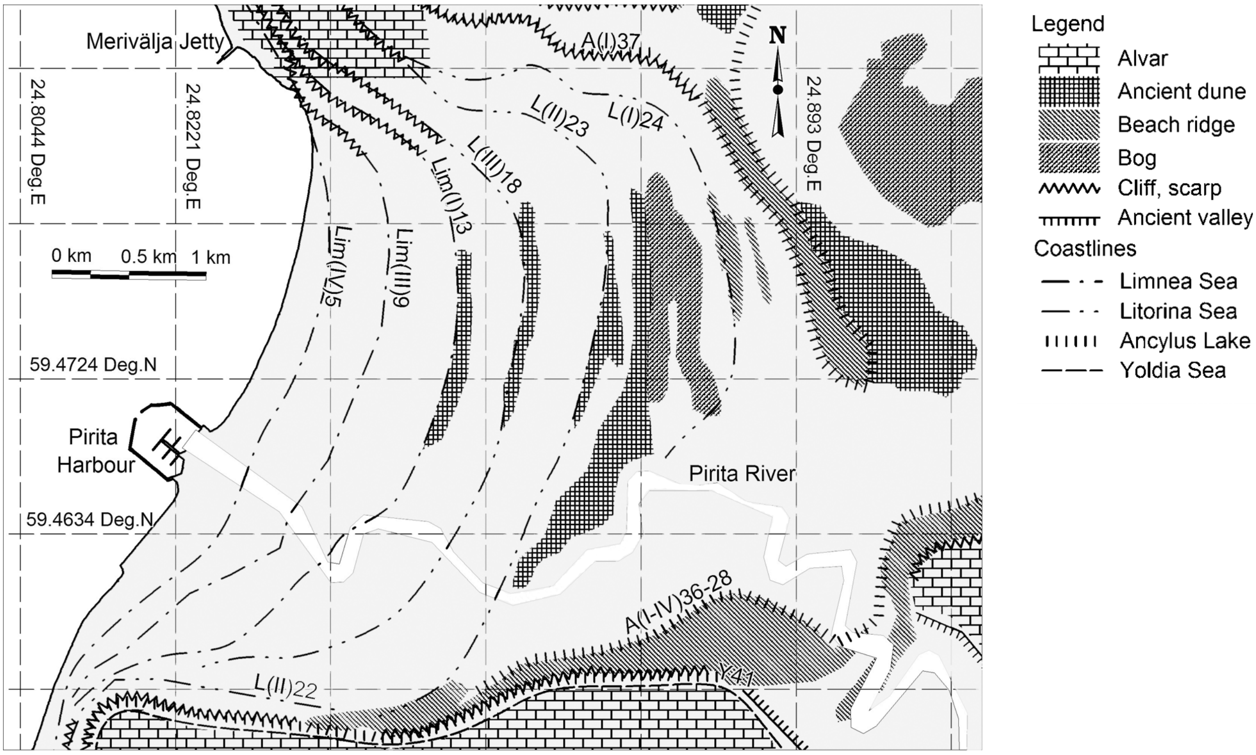

Fig. 2. Palaeogeographic map of the vicinity of Pirita Beach and the Pirita River mouth. Redrawn based on Tammekann (1940), Raukas et al. (1965), Kessel & Raukas (1967), and an unpublished manuscript Kask (1997). Alvar is a limestone area covered with a thin soil layer. In the nomenclature of ancient coastlines, Lim stands for Limnea Sea, L for Litorina Sea, Y for Yoldia Sea, and A for Ancylus Lake. The Roman number indicates the development stage of these water bodies and the Arabic numbers show the height of the ancient coastline above the contemporary mean water level.

temporary beaches similar to Pirita Beach (Orviku 1974; Orviku & Granö 1992).

An up to 35 m thick complex of Quaternary sand-clay deposits of different origin, lithological composition and consistence has accumulated in the ancient Pirita River valley during different stages of the Baltic Sea under the subsequent influence of river erosion, ice dynamics, sea level changes, and deposition of sediments. The vertical composition of sediments in the neighbourhood of the former restaurant Rannahoone (see Fig. 3) apparently is representative for a large part of the ancient valley (although several layers are not necessarily present closer to the borders of the valley). Contemporary dune sand forms the uppermost 2–2.5 m thick layer that overlies older marine sand (thickness about 8 m) (Nugis 1971). A thin (0.75–1.60 m) layer of silt follows, overlying 4.5–6.5 m thick sandy loam that apparently formed during the Ancylus Lake Stage. Below these deposits lies an about 9.5–10 m thick layer of loam. The lowermost beds consist of about 2 m thick highly plastic varved clay, underlain by Cambrian blue clay.

The thickness of the Quaternary complex diminishes and its vertical structure undergoes certain changes towards the borders of the ancient valley. At the northern border (at Merivälja), a layer of till becomes evident on the surface or below a thin layer of contemporary deposits. Till is in places also traceable under a thin layer of younger sediments on the sea bottom at the southwestern border in the Maarjamäe area.

The rugged landscape features have thus been levelled off during many millennia. Today the area in question forms a part of the Pirita(-Mähe) plane (Raukas et al. 1965; Kessel & Raukas 1967) that is gently sloping westwards. The contemporary sandy beach (as well as the beach that existed south of the Pirita River until the 1970s) lies at the western boundary of the plane where the seabed is gently sloping until a depth of about 7–8 m. The sandy area is limited by the extension of the ancient bay, which filled the ancient valley during different stages of the Baltic Sea and reached far deeper into the land in the past (Fig. 2), when the relative sea level was considerably higher.

The width of the sandy beach is up to 100 m at the northern mole of Pirita Harbour and gradually decreases northwards. Sand is replaced by a till scarp close to Merivälja Jetty at a distance of about 2 km from Pirita Harbour. Noticeable contemporary dunes and valleys only exist in the immediate vicinity of the sea coast. Major sea level changes can be recognized within the valley from much higher ancient dunes (Fig. 2), located about 1–2 km inland (Künnapuu 1958; Raukas et al. 1965).

Contemporary marine sand

The properties of bottom sediments for the entire Tallinn Bay are described in Lutt & Tammik (1992). Previous studies of contemporary bottom sediments at Pirita (Lutt 1992) are based on 33 sediment samples (Fig. 3) taken with a vibrocorer (Kudinov 1957). Drill cores extending down to 2.1 m into the seafloor (Lutt & Tammik 1992) provide a reliable stratigraphy of the upper layers of marine sand at Pirita (Fig. 4).

The seabed from the waterline down to depths of 2–3 m is covered with fine sand at Pirita. At depths down to 6–8 m relatively coarse silt is found. In deeper areas

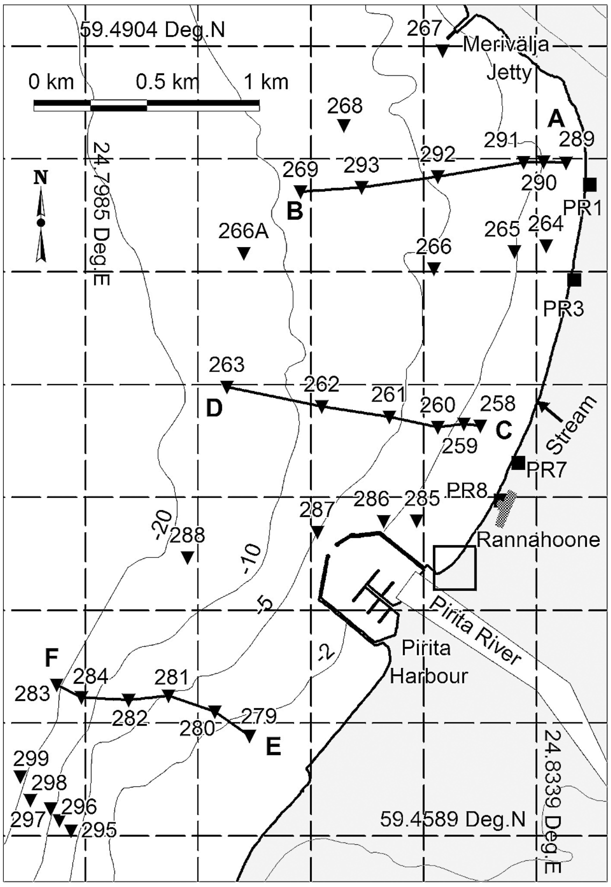

Fig. 3. Location of samples used for the construction of cross-sections A–B, C–D, and E–F (Fig. 4) of the upper sediment layers in Lutt (1992), Lutt & Tammik (1992), and for the analysis of properties of bottom sediments. Filled squares PR1, PR3, PR7, and PR8 denote the starting points of beach profiles 1, 3, 7, and 8 in Fig. 7. The box between Rannahoone and Pirita Harbour indicates the area represented in Fig. 8.

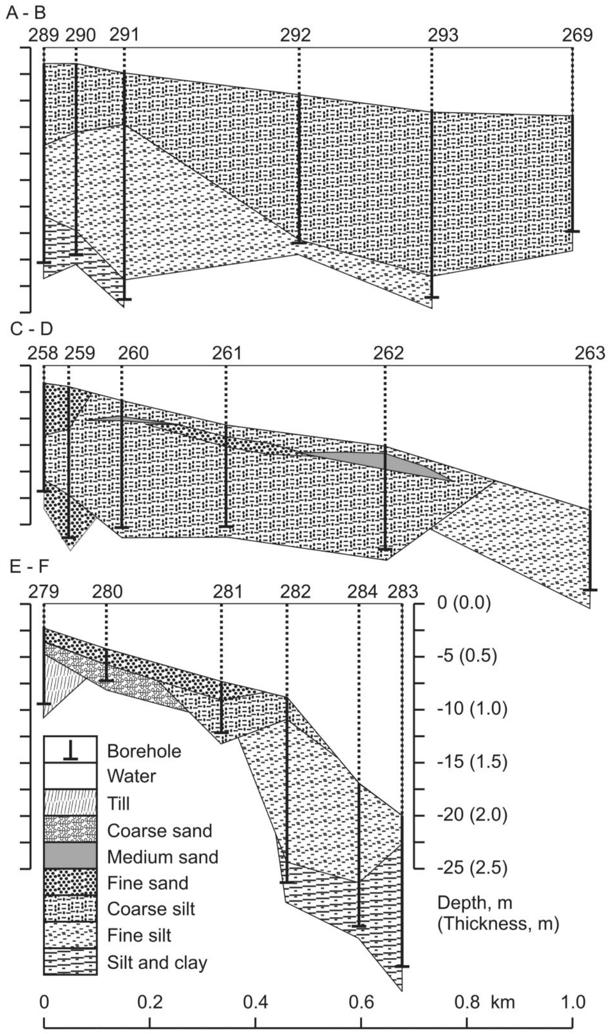

Fig. 4. Geological cross-sections of the beach area. Adapted from Lutt (1992) using the following nomenclature of the grain size: below 0.01 mm – silt and clay; 0.01–0.05 mm – fine silt; 0.05–0.1 mm – coarse silt; 0.1–0.25 mm – fine sand; 0.25–0.5 mm – medium sand; 0.5–1.0 mm – coarse sand. Location of the boreholes is given in Fig. 3.

finer silt fractions[1] dominate (Lutt 1992, p. 208). The light mineral components (with a specific weight of <2.89 g/cm^3) form more than 95% of the sand mass.

[1] The classification of fractions in Lutt (1992) mostly follows that of Friedman et al. (1992, pp. 335–340) except that different fractions of silt (with the grain size <0.063 mm) are called silty pelite (grain size from 0.01 to 0.063 mm) and pelite (grain size <0.01 mm). Fractions with the grain size from 0.063 to 0.2 mm are together referred to as fine sand, fractions from 0.2 to 0.63 mm as medium sand, fractions from 0.63 to 2.0 mm as coarse sand, and fractions with the grain size >2.0 mm as gravel.

Quartz forms about 70% and feldspar about 25% of the material.

The sand deposit is usually over 2 m thick. In the northern part of the beach (profile A–B in Fig. 4) it consists of coarse or fine silt, or of a mixture of silt and pelite (Lutt 1992, pp. 208–213). A thin-layered structure of the uppermost sediments exists at depths of 2–10 m in the central part of the beach (profile C–D in Fig. 4). The layered stratigraphy may reflect the attempts at beach fill (see below); however, such a depositional sequence of bottom sediments is also a typical feature of sandy areas next to North Estonian river mouths (Lutt 1992, p. 215).

Several medium- and coarse-grained sand bodies were detected in places under a thin sand layer southward from the river mouth (profile E–F in Fig. 4). Fine sand forms a thin layer (~20 cm) on the sea bottom from the waterline down to a depth of about 4 m at about 600 m from the coast. At the sampling point, located about 200 m off the coastline, fine sand overlies another thin layer (~15 cm) of coarse sand and till. Silt forms a more than 2 m thick layer at water depths of 15–20 m (800–900 m off the coast).

The transition between fine and coarse sand bodies is quite sharp at Pirita, whereas the transition between fine sand and different silt fractions is generally gradual. Coarser sand bodies are poorly sorted and contain appreciable amounts of 0.05–1.0 mm fractions, whereas finer sand bodies (with the typical grain size of 0.05–0.25 mm) usually have a narrow grain size range (Lutt 1992). These properties are common for the North Estonian sandy areas (Lutt 1985; Lutt & Tammik 1992; Kask et al. 2003a).

Local sediment transport

Sand transport in the littoral system is usually affected by a large number of various processes such as wave-induced oscillatory motions, wind-induced transport, coastal currents and wave-induced alongshore flows, variations of water level, sea ice, etc. The effect of ice is mostly indirect and consists in either damage to dune forest or in reducing the wave loads during the ice season. The tidal range is 1–2 cm in the Baltic Sea and the tidal currents are hardly distinguishable from the other motions. Water level at Pirita is mainly controlled by hydrometeorological factors. The range of its monthly mean variations is 20–30 cm (Raudsepp et al. 1999), but its short-term deviations from the long-term average are larger and frequently reach several tens of centimetres. Water levels exceeding the long-term mean more than 1 m are rare. The highest measured level at the Port of Tallinn is 152 cm on 09.01.2005 (Suursaar et al. 2006) and the lowest is –90 cm.

Fine sand that predominates at Pirita (see below) can be easily transported by wind when dry; however, winds sufficient for extensive transport are infrequent. The shoreline is parallel to the predominating winds (Soomere & Keevallik 2003). Strong onshore (NW) winds typically occur either during the late stage of storms or during the autumn months when sand is wet. Although wind carries a certain amount of sand to the dune forest, the overall intensity of dune building is modest. The height of the existing dunes is a few metres. The dunes are mostly covered with grass and forest. Only sand seawards from the faceted dune face actively undergoes aeolian transport. The role of aeolian transport has apparently been larger in the past, as suggested by a photo of a sandstorm at Pirita (Raukas & Teedumäe 1997, p. 291).

Coastal currents induced by large-scale circulation patterns are modest in the whole of the Gulf of Finland (Alenius et al. 1998). Their speed is typically 10–20 cm/s and only in exceptional cases exceeds 30 cm/s in Tallinn Bay (Orlenko et al. 1984). In the bayheads, such as the nearshore of Pirita Beach, current speeds apparently are even smaller (Loopmann & Tuulmets 1980). Local currents are at times highly persistent in this area (Erm et al. 2006) and may provide appreciable transport of finer fractions of sand that are suspended in the water column, even though the typical settling time of these fractions is only a few minutes at the coasts of the Viimsi Peninsula (Erm & Soomere 2004, 2006).

The magnitude of wave-induced bedload transport greatly exceeds that of the current-induced transport even at relatively large depths (8–10 m) in sea areas adjacent to Tallinn Bay (Kask 2003; Kask et al. 2005). Wave action in the surf zone therefore plays a decisive role in the functioning of Pirita Beach. This is a typical property of beaches located in microtidal seas.

Most of the waves affecting Pirita Beach originate from the Gulf of Finland. Western winds bring to the Pirita area wave energy stemming from the northern sector of the Baltic Proper. The wind regime in these areas is strongly anisotropic (Mietus 1998; Soomere & Keevallik 2003). Tallinn Bay is well sheltered from high waves coming from a large part of the potential directions of strong winds (Soomere 2005a). The local wave climate is relatively mild compared to that in the open part of the Gulf of Finland or in the adjacent sea areas. The annual mean significant wave height is as low as 0.29–0.32 m in different sections of Pirita Beach (Soomere et al. 2005).

Very high waves, however, occasionally penetrate into Tallinn Bay and cause intense erosion of its coasts (Lutt & Tammik 1992; Kask et al. 2003b). The significant wave height usually exceeds 2 m each year, but may reach 4 m in NNW and western storms in the central part of the bay and overshoot 2.5 m in the nearshore of Pirita Beach during NNW storms. The wave periods during such storms at Pirita match those in the central part of the Gulf of Finland and are usually up to 8–9 s (Soomere 2005a). The dominant waves approach the Viimsi Peninsula from the western or northwestern directions and thus cause southward littoral transport.

Waves from fast ferries form an appreciable portion (about 5–7% in terms of wave energy and 20–25% in terms of wave power) of the total wave activity since 1997. The daily highest ship waves belong to the highest 5% of wind waves in this area (Soomere 2005b). As ferry wakes are present during a relatively calm season and at times approach from directions not common for wind waves, they may induce sediment transport in a direction opposite to the natural littoral drift (Elken & Soomere 2004). Their role in beach processes, although potentially substantial under certain circumstances (Soomere & Kask 2003; Levald & Valdmann 2005; Valdmann et al. 2006), has been poorly understood to date.

Sediment sources of Pirita Beach

The above description suggests that major inflow of sand to Pirita Beach may occur owing to southward littoral transport of the material eroded from different sections of the Viimsi Peninsula. An aerial photo of the year 1951 (Figs 5, 6) demonstrates the presence of a well-defined ridge and runnel or multiple bar system along Pirita Beach. The number of sand bars and the width of the dry beach increase southwards, consistent with the net sand transport towards the southwest also along the beach. This is opposite to the usual eastward littoral drift along straight sections of the southern coast of the Gulf of Finland (Orviku & Granö 1992; Laanearu et al. 2007) and reflects a specific feature of semi-sheltered bayheads.

The Pirita River (Figs 3, 5), a typical small river among those flowing into the Gulf of Finland, is shallow and has a limited discharge (about 0.2 km^3 annually; Lutt & Kask 1992, p. 146). It provides about 1040 tonnes (about 400 m^3) of suspended matter annually (Lutt & Kask 1992, p. 149). Most of the material (74%) has a grain size of 0.01–0.05 mm, and about a quarter has a size of 0.0025–0.01 mm (Lutt & Kask 1992, p. 152). The river thus insignificantly feeds the gulf with coarse sedimentary material. A certain amount of bedload transport of coarser fractions probably occurs during spring and autumn floods; unfortunately no reliable data about its magnitude are available. Since the river-transported material is much finer than the beach sand, marine hydrodynamic processes probably transport this material farther to deeper areas.

Fig. 5. Basic sediment transport and supply processes at Pirita Beach in natural conditions: natural longshore transport (arrows along a continuous line), river-induced sand supply (small triangles) and scarp erosion at the northern end of the beach (bold arrows). The contemporary coastline (white line) is given according to 1 : 50 000 Estonian Base Map from the Estonian Land Board (www.maaamet.ee). The background aerial photo used by the courtesy of the Estonian Land Board.

The interaction of the river flow and littoral transport has led to the formation of a more or less symmetric (with respect to the river stream) sill in the vicinity of the ends of the groins in the past (Fig. 6). This bottom feature apparently caused sedimentation of

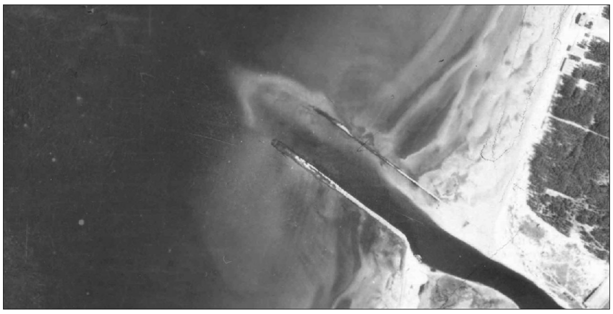

Fig. 6. The Pirita River mouth in 1951 (detail of the photo in Fig. 5) illustrating the joint effect of groins along the river coasts and the river flow on the formation of the sand bar at the end of the groins.

river-transported fine material in a relatively shallow area. Part of the material apparently entered the active sand body of the beach between the seaward end of the equilibrium beach profile and the dune toe, and probably contributed to the development of the extremely gently sloping sea floor in the southern part of the beach. As the artificial river mouth eventually was more affected by coastal currents which had no prevailing direction (Orlenko 1984), at times the transport of finer sediments from the river mouth was also northwards.

A local source of sediments is the till scarp between the beach and Merivälja Jetty. The scarp is frequently subjected to direct wave action. Sand may also be eroded from the dunes in the central and northern sections of Pirita Beach in high water level conditions. Dumped material has also increased the active sand mass of the beach.

COASTAL ENGINEERING STRUCTURES IMPACTING ON THE BEACH

Structures at the coast of the Viimsi Peninsula

Several major development works that indirectly but substantially affect the beach have been performed north of the beach (Table 1). Merivälja Jetty close to the northern end of Pirita Beach, today a simple straight construction that extends to about 3 m water depth, was built in 1925–1927 with a slightly different geometry (Nerman 2007). The jetty stayed largely damaged for over about two decades and was reconstructed at the end of the 1960s.

Merivälja Jetty has apparently blocked a large part of southward littoral drift of coarser sand since the 1930s, but evidently it had a minor role in the transport of finer sediments at depths over 3 m. Such selective

Table 1. Major development works in the vicinity of Pirita Beach and their influence on the beach

Object	Construction time	Affected depth, m	Time scale of the influence	Changes in the supplies of Pirita Beach
		To the north of the beach		
Merivälja Jetty	1925–1927	3	Long-term	Blocks bedload transport of coarse sediments; shelters the till cliff at the northern end of Pirita Beach
Miiduranna Port	1970s	6–8	Long-term	Blocks bedload transport of medium and coarse sediments
Revetment at the northern section of the beach	About 1980	–	Short-term (~10 years)	Probably increases erosion of sand at the toe of the revetment; partially protects the dune forest
Tanker quay at Miiduranna	About 2000	13	Long-term	Fully blocks bedload transport
Seawall at the till scarp	2006–2007	–	Long-term (expected)	Prevents erosion of the scarp; decreases supply of coarser sediments to the beach
		To the south of the beach		
Small groin north of the river mouth	1922	3	Short-term (<10 years)	Stopped southward littoral drift, probably enhanced filling of the river mouth, redirected the flow of fine river-transported sediments from the contemporary beach
Groins at the river mouth	1928	3	Mid-term (~20 years)	Temporarily stopped southward drift and blocked flow of fluvial sediments to the beach until filling the new river mouth. After forming a sand bar (Fig. 6) the processes recovered with certain modifications
Olympic Harbour	1976–1977	5	Long-term	Fully blocks alongshore sediment drift and supply of river sediments to the beach

blocking apparently is insignificant today when Miiduranna Port is the major obstacle. Although the jetty somewhat sheltered the till scarp at the northern end of Pirita Beach, the abrasion rate of the unprotected scarp section obviously increased.

Major changes in the littoral transport occurred after the construction of Miiduranna Port in the 1970s at an earlier landing place for small fishing boats. This large (in Estonian scale) complex was built as a fishing harbour and shipyard, and was also used for certain military purposes during the Soviet times. The depth of the basin and the fairway were 8.5–9 m and the quays extended out to the 6–8 m depth contour (EVA 1998). The depth of the fairway and the basin were extended to 13 m at the turn of the millennium.

The port practically cuts down the littoral drift of coarser sediments, because the closure depth at Miiduranna is only insignificantly larger than at Pirita (2.5 m). Active accumulation of sand and gravel takes place along its north mole. The fairway into the harbour acts as a sediment trap. A limited amount of sand probably bypassed the channel owing to propulsion-induced local turbulence when the channel depth was shallower. Sand bypassing through the contemporary entrance channel is negligible. The port eventually had a minor influence on the current-induced transport of suspended matter, but this transport does not substitute the cutdown of the littoral drift and supplies very little material to the active sand body of Pirita Beach.

A revetment was constructed from granite stones overlying limestone shivers along the dune toe in the northern section of Pirita Beach during the 1980s to protect the dune forest against high waves. It did not offer an effective protection: the dune forest has receded considerably since then. Remnants of the revetment are today located in the centre of the sand strip (Photo 3). This process is in agreement with the general experience that the presence of rigid structures may cause enhanced erosion of sandy beaches (Dean & Dalrymple 2002). The till scarp north of the beach was protected by a seawall in 2006–2007. Its effect on the functioning of the beach apparently is minor and consists in a certain reduction of the volume of the sand eroded from the scarp.

Structures at the Pirita River mouth

Natural hydrodynamic processes caused frequent obstruction of the Pirita River mouth in the past. At the beginning of the 20th century the river mouth was frequently almost closed by a sand bar (S. Roosma, pers. comm. 2006). The first industrial-scale attempts at protecting the mouth and dredging activities stem from the 1920s. A small mole was constructed along the northern coast of the river in 1922 by the Estonian Maritime Administration. This was a poor solution, since it apparently enhanced the obstruction of the river mouth owing to littoral drift.

The water depth at the river mouth was only 1.3 m after the winter ice broke up in the spring of 1928. This season roughly coincides with the spring flooding after which the sand bars at river mouths are reduced to their annual minimum size (Laanearu et al. 2007). Therefore the water depth might have been even less than 1 m during other seasons. Such a shallow fairway was only satisfactory for smaller vessels, whereas the steamship *Polaris*, with a draught of over 2 m, grounded at the river mouth (Nerman 2007).

Larger groins that extended out to 3 m deep water were built along the river coasts after the grounding of the *Polaris*. Assuming that the properties of the equilibrium beach profile have not changed since then, this groin extended to about 300–350 m from the natural coastline. Although the groins needed regular maintenance (Kask 1997), the structure maintained a navigable waterway and avoided rapid obstruction of the river mouth.

The groins apparently had a twofold role in coastal processes. They evidently interrupted the alongshore sediment transport, so that for some time the coastal processes in subcells 2A and 2B (Fig. 1) were completely separated. The fluvial sand transport for a while entered the over 3 m deep sea area that lay outside the equilibrium profile and from which fine sand was generally not transported to the coast.

On the other hand, the groins favoured the formation of a delta-like deposit (Fig. 6). Littoral drift gradually filled the sea floor adjacent to the groins and formed a bar in the vicinity at their ends (Fig. 6). Since then part of fluvial sediments again entered the active sand body of the beach and the subcells 2A and 2B (Fig. 1) were reconnected to some extent. Figure 6 suggests that this happened before the 1950s.

The river mouth was still gradually filled with sediments. During the 1950s, the water depth between the moles was again insufficient (Kask 1997). A suction dredge and pump were used to dredge the river mouth starting from 1958. There are no reliable data available about the structure and amount of the dredged material, and about the dumping location. Most probably, some 20 000–30 000 m^3 of material was removed from the river mouth. The material evidently had quite a small grain size and its trace is probably lost by today. About 15 000 m^3 of sand was removed from the river floor with bulldozers during a low water event in December 1959 (Kask 1997).

Observations in 1975–1977 showed that about 9000 m^3 of sediments accumulated along a 150 m long section of the river mouth during a two-year period (Loopmann & Tuulmets 1980). Since the river flow only transports about 400 m^3 of sediments annually (Lutt & Kask 1992), a large amount of marine sand apparently was carried and accumulated to the river mouth (Loopmann & Tuulmets 1980).

Substantial development works were performed at Pirita, related to the construction of the Olympic sailing harbour in the mid-1970s. The basin of the harbour was expanded considerably. The combined marina and a river harbour were designed for 750 vessels. The northern groin was lengthened and completely reconstructed. Another breakwater was erected to protect the southern side of the harbour.

Both marine hydrodynamic features and sand transport properties of the river flow were notably changed, although the seaward extension of the harbour is close to that of the earlier groins (cf. Figs 1, 5, 6). The water depth at the harbour entrance is about 5 m (EVA 1998). The coastal processes at different sides of the harbour are therefore practically disconnected. The river flow slows down considerably in the harbour basin, which acts as a sediment trap, and a much smaller amount of very fine sediments reaches the sea. The material still supplied to the sea is deposited into areas deeper than 4–5 m, far offshore from the equilibrium beach profile. The fluvial material thus has almost no chance to enter the active sand body of the beach.

The sea coast south of the Pirita River mouth was reclaimed using dredged sand to provide land for the Olympic village. The sandy beach was largely modified by the seawall of the new road to Pirita. There is a minimum amount of sand in this area now and we ignore it for estimates of the sediment budget.

To summarize, the extensive coastal engineering activities have largely blocked the littoral drift and supplies of sand to Pirita Beach. The remaining sources of coarser material are the till cliff at the northern end of the beach and the dunes. The intensity of their erosion depends mostly on the joint occurrence of high water level and intense waves. This misbalance of the supply of different fractions is expected to lead to a decrease in the dominant grain size and an overall worsening of the sand quality from the recreational viewpoint. On the other hand, the Olympic Harbour also prevents the lateral sand loss from Pirita Beach towards the bayhead and thus stabilizes the beach to some extent.

Changes in the beach

The coastline and the whole beach apparently were stable for at least a century until the 1970s. There were no identifiable changes to the coastline between the restaurant and Merivälja Jetty in 1940–1976 (Loopmann & Tuulmets 1980). No records of substantial changes also seem to exist from the last 200–300 years during which the largest events in this area have generally been documented.

Noticeable changes only occurred in the vicinity of the Pirita River mouth owing to the joint influence of the groins and dumping of sediments from the basin of the Olympic Harbour. The width of the beach in its middle section in the 1960s (60–70 m, Soomere et al. 2005) was larger than nowadays (cf. also Raukas & Teedumäe 1997, p. 291). There are no reliable data to judge if this feature was natural or was induced by the groins. The width of the dry beach was relatively large in the southern part of the beach already by the 1950s (Fig. 5) and increased up to 200 m along the northern mole by the 1970s (Loopmann & Tuulmets 1980). A limited shift of the coastline seawards occurred at the southern mole and in a short section at Maarjamäe.

The combination of the engineering structures forms a probable background of bathymetric changes near Pirita Harbour, which were first identified in the mid-1970s. The isobaths at 2 m and larger depths were shifted by 40–50 m shorewards between 1958 and 1976 in a large area north of the harbour (Paap 1976). This process reflects a loss of a large volume of sand from areas adjacent to the new harbour at certain depths.

To mitigate the consequences of coastal engineering structures, an estimated amount of about 65 000 m^3 of the sand dredged from the basins of Olympic Harbour was dumped in the central and northern parts of Pirita Beach and into shallow water near Merivälja Jetty in the 1970s. It was expected that waves would transport the sand southwards to Pirita Beach. As sand in over 1 m deep water is not necessarily transported alongshore at Pirita (Soomere et al. 2005), it is unclear how much sand actually reached the beach. As the sand dredged from the harbour was quite fine (Orviku & Veisson 1979), a large part of it apparently was transported seawards and the width of the beachface decreased already by the 1980s (Kask 1997). Also, a certain amount of quarry sand was placed near Rannahoone about 500 m north of the Pirita River mouth. This considerably increased the sand volume and apparently prevented the central and southern parts of Pirita Beach from erosion.

The images in Figs 5 and 6 reflect the presence of a substantial amount of sand in underwater bars in 1951. Comparison with later images (Photo 4) suggests that the amount of active sand in bars has been reduced since then. Because the width of the contemporary beach is considerably smaller, a large amount of sediments apparently has been lost seawards. The nature of changes is different in different parts of the beach.

In the southern part, between the restaurant and Pirita Harbour, the width of the beach and the total sand volume have increased. This has resulted from beach renourishment and the influence of Pirita Harbour, which almost completely blocks the southward littoral drift. This apparently is a long-term trend, since even the most violent storms in 2001 and 2005 have not affected the beach width. The total width of the dry beach is up to 100 m. In elevation the beach extends up to 2 m above the mean water level. Waves did not reach the dune toe even during extreme water levels. This sector of beach therefore seems relatively stable and is characterized by gradual sand accumulation.

The central part of the beach (adjacent to the restaurant and extending to about 1 km from the Pirita River mouth) is in a near-equilibrium state. The bluff at the back of the beach is at times eroded to some extent in strong storms. Relatively intense aeolian sand transport into the dune forest occurs in this sector (Kask & Kask 2002). Although this may have an adverse effect on the dune forest, it can be interpreted as an expression of an excess of sand and a generally healthy state of the beach.

The northern part of the sandy beach, an about 1 km long sector, is changing actively. Strong western storms and high storm surges (Photo 2) caused extensive regression of the bluff in 1999–2005. The changes are marked to the north of the mouth of a small stream (that discharges to the sea about 900 m north of Pirita Harbour; see its location in Fig. 3) and are substantial in the northernmost part of the sandy beach. The recession of the bluff was on average 1–2 m (at a few sections even 3–5 m) in 1999–2001. The most intense erosion occurred at the interface between the sandy and till coasts. A large amount of sand was carried into the dune forest. Several dozens of pine-trees were destroyed and this additionally weakens the stability of the dunes.

The section of the coast between the northern end of the sandy beach and Meriválja Jetty embraces a till scarp about 400 m south of the jetty, which is intensively eroded during high water level conditions. Seawards from the scarp there is a gently sloping sea floor, with a width of the dry area up to 100 m in low water conditions, mostly covered by pebbles, cobbles, and boulders. This section illustrates intense sediment transit in high water level conditions.

Approximately 50% of Pirita Beach therefore suffers from substantial damage at times. One reason behind an apparent intensification of beach processes is the high frequency of storms experienced since the 1960s (Alexandersson et al. 1998). Still, a major threat to the beach is human activity that has considerably weakened the sand supply to the beach. Another potential threat is the influence of long waves from fast ferries on the seaward end of the equilibrium beach profile (Soomere 2005b). Given the circumstances, one cannot expect that Pirita Beach will further develop in a stable manner, although the natural variability of storms may provide relatively long periods during which the evolution is fairly slow.

Quantification of changes

The changes in the beach that have occurred since the mid-1970s can be roughly quantified by the comparison of maps stemming from different decades or the results of topographical surveys.

If the sand volume were constant at Pirita, the coastline would shift seawards and a gain of dry land would occur owing to the postglacial rebound. A rough estimate based on the comparison of the location of the waterline on a topographic map (1 : 25 000) from 1979 and the digital Estonian Base Map (1 : 50 000) from the end of the 1990s combined with an estimate of the effect of land uplift, suggests that the net sand loss at Pirita is about 1000–1500 m^3 annually (Soomere et al. 2005). The accuracy of the underlying information, however, is equivocal and this estimate should be considered as indicative only. A more detailed analysis of historical data is in progress and will be published elsewhere.

The above estimate only accounts for the changes in the sand within the equilibrium profile and in the till cliff, and ignores the potential changes in the amount of sand in berms and foredunes. The spatial patterns of these changes, inferred from beach profiles measured regularly within the framework of national coastal monitoring, are consistent with the qualitative analysis above (Suuroja et al. 2004). The erosion of the dry beach and the scarp is most evident in the northernmost section. For profile 1 (Fig. 7; see location of the profile in Fig. 3) the whole coastal profile is shifted by 10–20 m landwards. The central part of the beach is close to an equilibrium state (cf. profile 3 in Fig. 7). There is some sand accumulation in the southernmost beach sector as indicated by profiles 7 and 8.

A complementary estimate of the loss of dry sand can be derived based upon the comparison of isolines obtained from two subsequent topographic surveys of the beach. A comparison of the entire topography would be more exact, but the relevant data are not available.

The results of two high-resolution (1 : 500) topographical mappings from 1997 and 2006 suggest that no net changes in the dry land area occurred during this period, but systematic landward shift of the isolines of 0.5, 1.0, and 1.5 m took place (Fig. 8, Table 2). Such shifts suggest that the sandy beach has lost a certain

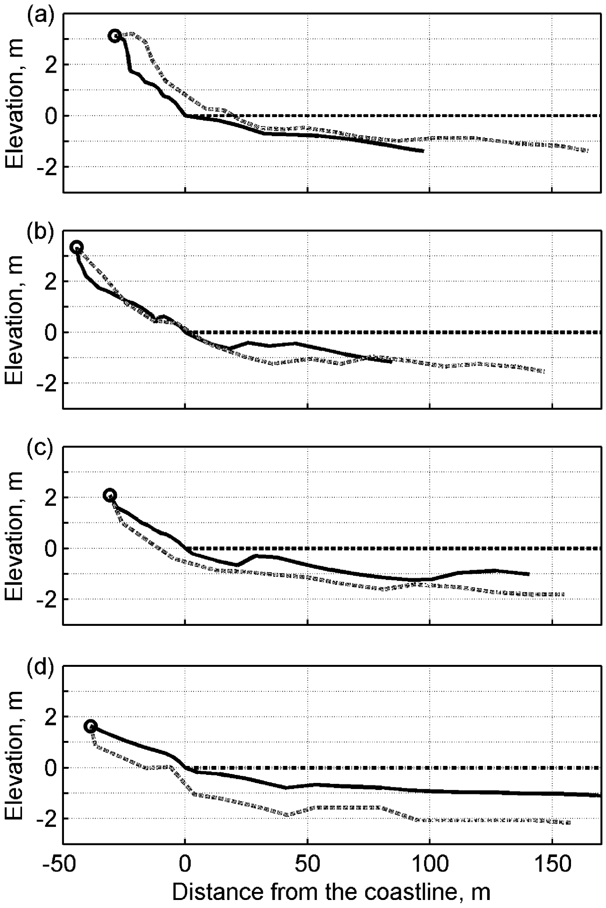

Fig. 7. Beach profiles 1 (a), 3 (b), 7 (c), and 8 (d) at Pirita on 9 Sept. 2003 (solid lines) and in 1994 (dashed lines) based on data from Suuroja et al. (2004). The profiles begin from the coastal scarp marked by a circle; refer to Fig. 3 for their location. The horizontal dashed line shows the mean water level.

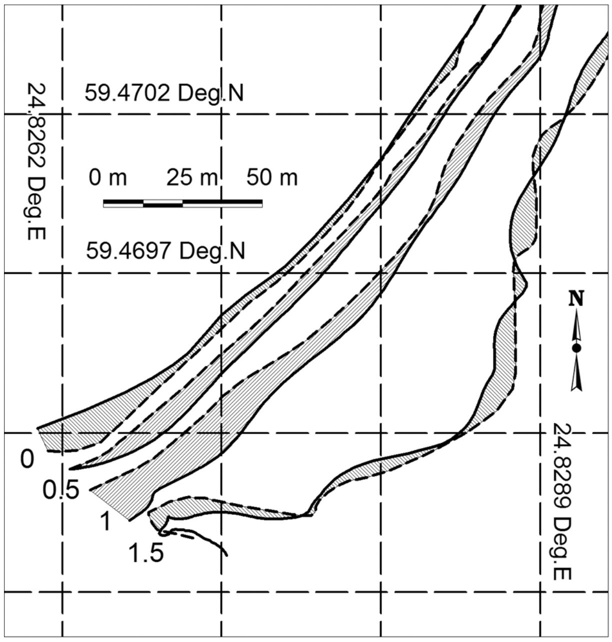

Fig. 8. Changes in the location of isolines of surface elevation in the southern part of Pirita Beach. Solid and dashed lines show the 0, 0.5, 1, and 1.5-m isolines according to surveys of 1997 by REIB Llc (Map 1 : 500 with technological networks. Harju County, Tallinn, Pirita District, Pirita Beach. Contract No. 06-612) and of 2006 by Hectare Llc (Map with technological networks. Survey of trasses of Pirita Beach. Contract No. TT-0249), respectively. The shaded area represents changes in the positions of the isolines between 1997 and 2006. The seaward shift of the 0.5–1.5-m isolines reflects sand accumulation in this area. The represented area is denoted by a box between Rannahoone and Pirita Harbour in Fig. 3.

amount of sand. As the landscape of the beach may easily undergo considerable changes in the immediate vicinity of the waterline, changes below the 0.5 m elevation may be temporary and are not accounted for. Sand loss may only occur from between the waterline and the dune scarp, the latter being represented by the 1.5 m isoline at Pirita.

The overall state of the beach, however, is not good: the isoline shifts indicate the loss of sand from large sections of the beach. The change in the areas of the relevant elevation is between 2000 and 5000 m^2. The largest changes have occurred at the elevations of 1–1.5 m. The relevant isolines are shifted 2–3 m landwards on average. As the typical width of the strip of dry sand is about 50 m, it means that, on average, at least 2 m^3 (about 5% of dry sand volume) of sand has been lost from each metre of the sandy area. It is interesting to notice that this loss is roughly equal to the estimated loss of finer sediments owing to wakes from fast ferries (Erm & Soomere 2004, 2006). Given the length of the surveyed section is 1800 m, the net loss of sand is about 3000–4000 m^3 and corresponds to the annual loss of sand volume of about 400 m^3.

Table 2. Changes in the dry land area and in the area of sections bordered by the isolines of 0.5, 1.0, and 1.5 m along a 1800 m long beach section at Pirita during 1997–2006

Isoline elevation, m	Loss, m^2	Gain, m^2	Balance, m^2
0.0	1860	1860	0
0.5	2600	360	–2240
1.0	4970	230	–4740
1.5	5400	1550	–3950

CONTEMPORARY BATHYMETRY AND BOTTOM SEDIMENTS

Mapping of sediment texture and bathymetry

The detailed sand budget of a beach is usually established based on long-term surveys. The situation is simpler for bayhead beaches such as Pirita Beach that (i) mainly serve as end points of littoral transport for which the lateral losses owing to alongshore transport are negligible, and (ii) which are subject to small seasonal changes and overall moderate wave activity. Such beaches are usually close to an equilibrium state. Many of their properties can be described with the use of a small number of parameters (e.g. Dean & Dalrymple 2002). One of the basic quantities is the typical grain size.

During the field campaign of 2005–2007, bathymetry and sediment texture were mapped in the nearshore between the waterline and the 11 m depth contour from the northern mole of Pirita Harbour to Merivälja Jetty. The total length of the study area (Fig. 9) along the waterline is about 2.5 km.

Granulometric (textural) analysis of Pirita Beach was performed on 51 samples from the upper 30 cm layer of bottom sediments taken during the 2005 campaign over the entire study area, and on 18 samples from the nearshore taken in 2007 (Fig. 9). The majority of the sampling points in 2005 are located along five profiles transversal to the coastline. Each profile contains about 10 samples from the waterline to the 10 m isobath. A selection from the standard set of sieves with the grid size of 2.0, 1.0, 0.63, 0.5, 0.25, 0.2, 0.125, and 0.063 mm (DIN 4022) was used in the analysis performed in the laboratory of the Estonian Geological Survey and in the Estonian Environmental Research Centre. The corresponding ϕ-values are –1.0, 0, $\frac{2}{3}$, 1.0, 2.0, $2\frac{1}{3}$, 3.0, and 4.0.

The mean grain size M_ϕ, its value in physical units d_{50}, and the standard deviation σ_ϕ of the grain size are found, as recommended in Dean & Dalrymple (2002, Ch. 2), from the values of ϕ_{84} and ϕ_{16}:

$$M_\phi = \frac{\phi_{84}+\phi_{16}}{2}, \quad \sigma_\phi = \frac{\phi_{84}-\phi_{16}}{2},$$

assuming the log-normal distribution of the grain size. The values of ϕ_{84} and ϕ_{16} represent the grain sizes, from which 84% or 16% of the entire sediment mass has a larger grain size. Their approximate values (Table 3) are found from the cumulative distributions of the grain size (Fig. 10).

Bathymetric mapping was conducted by Gotta Ltd with the echo sounder Bathy 500 MF and the DGPS system Trimble DSM 132 in April 2006. The measurements were performed along 20 transects perpendicular to the coast and separated by about 100 m, and 3 transects along the coastline. The spatial resolution of sampling along transects was about 1.5 m.

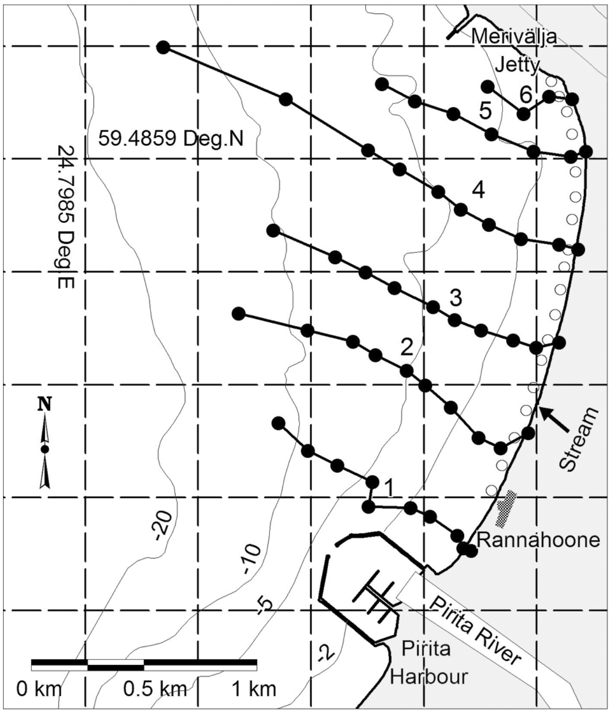

Fig. 9. Sampling points of bottom sediments at Pirita in 2005 (profiles 1–6) and 2007 (points in the nearshore, marked by empty circles). Isobaths of –2, –5, –10, and –20 m are shown based on the digital 1 : 50 000 Estonian Base Map from the Estonian Land Board (www.maaamet.ee).

Bathymetry

The available beach profiles (Fig. 7) confirm that the nearshore of Pirita Beach is generally very gently sloping (Suuroja et al. 2004). The slope of the profiles in the shallow water (depth <1 m) of the northern part of the beach is about 1 : 100 and well matches the estimates of the properties of the equilibrium beach profile (Soomere et al. 2005). The same average slope holds for profile 3

Table 3. Parameters of sand at Pirita Beach based on surveys of 2005 and 2007 (Soomere et al. 2007; Kask & Kask 2007). See text for explanation of symbols

Area	Property				
	ϕ_{16}	ϕ_{84}	M_ϕ	d_{50}, mm	σ_ϕ
Vicinity of the waterline	1.1ϕ	2.53ϕ	1.815ϕ	0.284	0.715
Entire beach	2.16ϕ	3.84ϕ	3.0ϕ	0.125	0.84
Nearshore (depth <1 m, 2007)	2.5ϕ	3.68ϕ	3.1ϕ	0.117	0.59

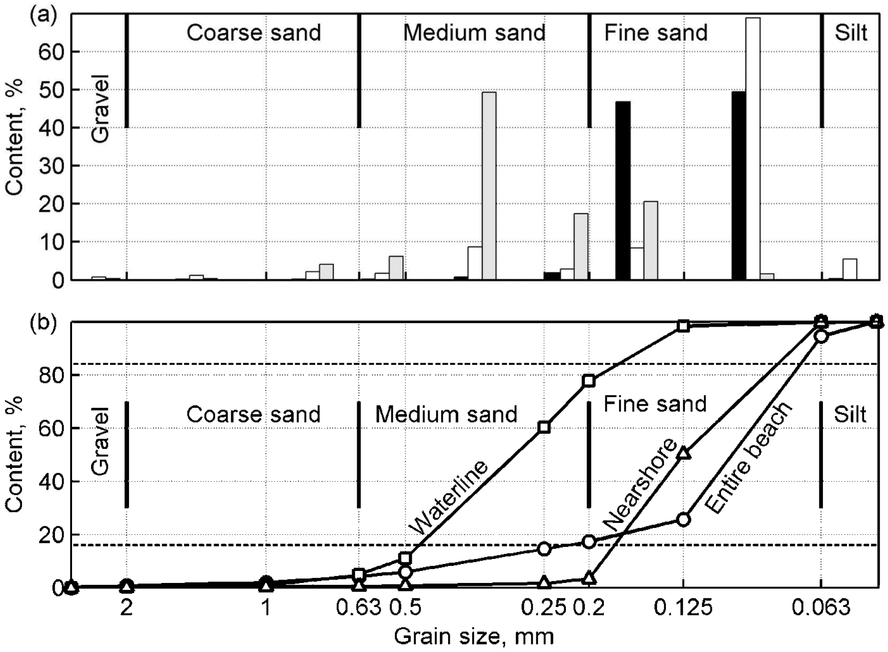

Fig. 10. (a) The content and (b) the cumulative distribution of different grain size fractions at Pirita based on samples collected in 2005 and 2007. Refer to Fig. 9 for sample locations. The averaged properties are shown for sand along the waterline (grey bars, squares), in the area with a depth of ~1 m (nearshore in 2007, white bars, triangles), and for the entire beach (filled bars, circles). The horizontal dashed lines on panel (b) represent 16% and 84% of the sand mass.

in the central part of the beach. The mean slope is somewhat larger, about 1 : 150 in the vicinity of the restaurant (profile 7). The gentlest slope (about 1 : 200) is found in the southern part of the beach along profile 8. These slopes not necessarily reflect the mean slope of the equilibrium beach profile that extends out to about 2.5 m deep water (Soomere et al. 2005).

The water depth increases monotonically along the profiles in the southern and northern sections (Fig. 7). Shallow-water sand bars are apparently more frequent in the central part of the bay, however, the situation may be different for different seasons and depths. The relative height of the bars on profiles 3 and 8 is up to 0.5 m.

The bathymetry survey reveals that a gently sloping nearshore strip stretches between the waterline and the 2-m isobath (Fig. 11). Its alongshore profile is nearly homogeneous in the northern half of the beach where the distance of the 2-m isobath from the coastline is 220–230 m. The strip widens to about 300 m in the vicinity of Pirita Harbour. Its mean slope is from about 1 : 100 in the northern part of the beach up to 1 : 150 in the southern part.

The water depth increases relatively fast between the seaward border of the above strip and the 4-m isobath (Fig. 11). This increase is also homogeneous along the coast: the distance of the 4-m isobath from the coastline varies insignificantly, between 400 and 450 m (Fig. 12). Located at depths of 4–7 m is a relatively gently sloping submarine terrace, some 500–800 m wide. The slope of this terrace is 1 : 200 in the central part of the beach. The water depth increases relatively fast from 7 to over

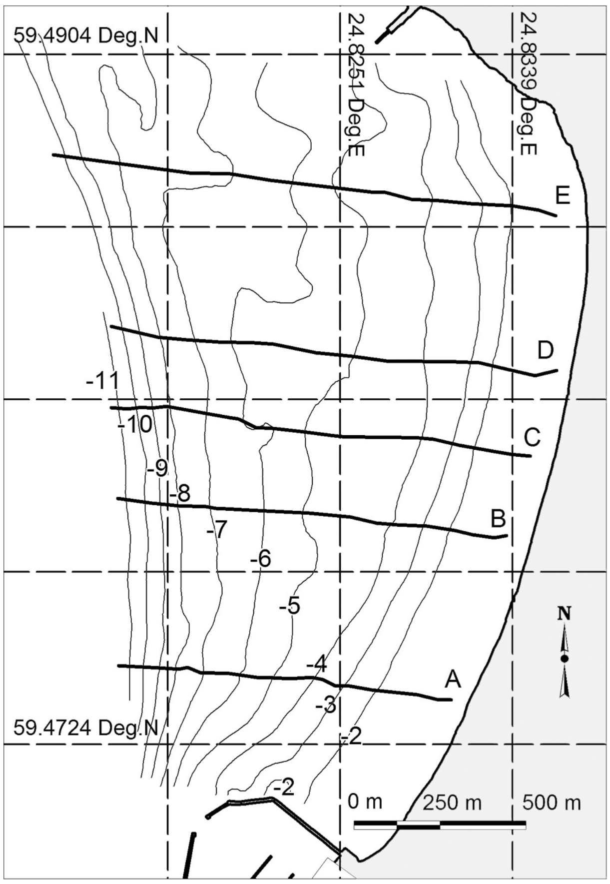

Fig. 11. Bathymetry of the nearshore of Pirita Beach according to the water depth survey in April 2006. The water depth along profiles A–E is given in Fig. 12. The coastline is shown based on the digital 1 : 50 000 Estonian Base Map from the Estonian Land Board (www.maaamet.ee).

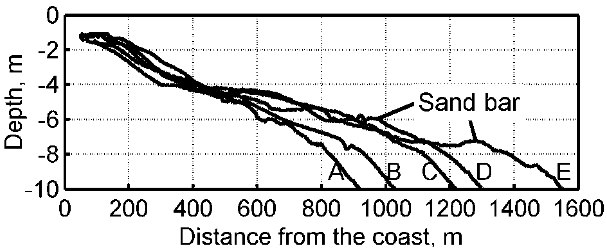

Fig. 12. Beach profiles (A–E) from the middle of the equilibrium profile to the 10 m isobath in April 2006. Refer to Fig. 11 for the location of profiles.

10 m at a distance of about 700 m in the southern part of the beach. The width of the area with a depth of <7 m extends to 1200 m in the central part of the beach.

A prominent feature of the submarine slope is an elongated elevation of moderate height (about 30 cm) extending through a large part of the deeper (>4 m) section of the study area. This feature, probably a large sand bar, is stretched obliquely with respect to the depth contours (Figs 11, 12) and to the till formations (Fig. 2). As it can be identified also on the older maps from the 1980s, it probably is a long-term feature of the beach.

Distribution of bottom sediments

The sediments on the nearshore submarine slope consist mostly of fine sand in accordance with the data in Lutt (1992) and Lutt & Tammik (1992). The predominating grain size constituents are fine (84%) and medium sand (13%). The proportion of silt is about 5.5%. Its content is largest (46%) in quite a deep area (at the seaward end of profile 4 in Fig. 9 at a depth of about 12 m) where usually fine sediment accumulates. Coarse sand also forms a small part of the sediments (3.9% on average). There is very little gravel in the study area (0.8% on average, maximally 11% in the immediate vicinity of the till scarp). The sand is better sorted in the shallow nearshore where $\sigma_\phi \approx 0.6$, but poorly sorted in the rest of the beach.

The average grain size in the nearshore of Pirita Beach is close to 0.12 mm, in accordance with domination of fine sand in most of the beach. An approximate value of the scale factor of the relevant equilibrium beach profile is thus $A = 0.07$ (Table 7.2 of Dean & Dalrymple 2002). The closure depth ranges from 2.4 to 2.6 m for different sections of the beach (Soomere et al. 2005). Therefore the width W of the equilibrium profile is expected to be about 250 m and its mean slope 1 : 100 at Pirita. This estimate well matches the results of the bathymetric survey. Notice that profiles in Figs 11, 12 cover only the seaward part of the equilibrium profile that ends at a distance of about 200 m from the coast and does not extend down to the underwater terrace located at depths of 4–7 m.

Several variations of the mean grain size and the content of the fractions should occur naturally within the study area. As waves sort the sediments and the finer fractions are gradually transported offshore, deeper areas usually host the finest sediments and the coarser material is concentrated in the vicinity of the breaker line and at the waterline (Dean & Dalrymple 2002). Coarser sand is found along the waterline (where the maximum content of medium sand is up to 84%) and finer components in deeper areas indeed (Fig. 13). The mean grain size along the waterline is much larger than in the rest of the study area (Fig. 10, Table 3).

The proportion of coarser sand generally decreases offshore (Figs 13, 14). The explanation is evidently related to the above-discussed highly intermittent nature of wave activity at Pirita (where mean wave conditions are very mild but severe wave storms may occur). The breaker line is poorly defined there and the relevant band of relatively coarse sand is not always apparent. This feature is not entirely typical but also not very surprising (Dean & Dalrymple 2002, Ch. 2.3.2). It may play an important role in the planning of beach nourishment activities because material with the grain size much smaller than the one at the waterline may be lost relatively fast. Moreover, relatively coarse and well sorted sand is

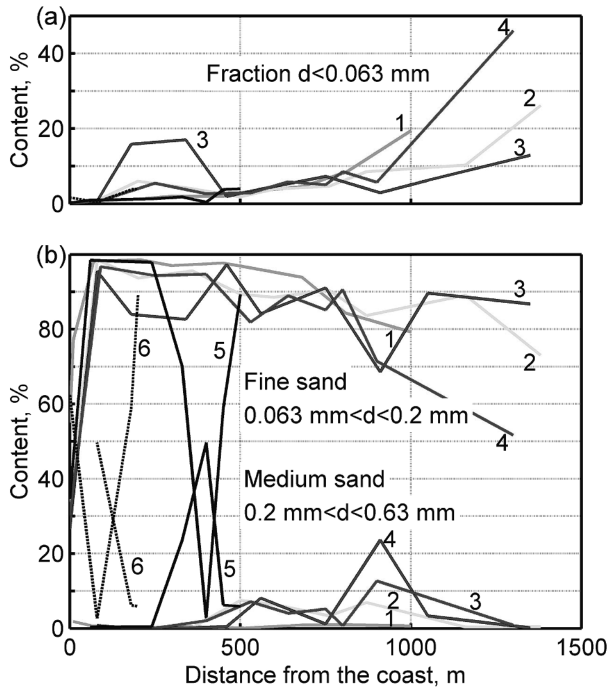

Fig. 14. Properties of different grain size fractions along beach profiles 1–6 in Fig. 9: (a) silt, (b) fine and medium sand.

perceived to be of the largest recreational value. In other words, beach fill with fine sand would lead to a decrease in the beach quality.

The potential sources of coarser material are located north of the beach whereas fine sediments are supplied by the Pirita River mostly to its southern part. This feature was apparently enhanced by the pumping of sediments dredged from the river mouth starting from the 1960s. Also, fine sand is more easily transported southwards by littoral drift. Thus it is natural that more fine sand is found in the southern sections of the beach (except at the waterline) and that the share of coarser sediments is larger in the northern part of the beach where unsorted material is regularly abraded from the till cliff and where gravel and coarse sand are mostly found. Also, the portion of medium sand is larger in the northern sections of the beach (Fig. 13), although a local maximum of its proportion is in the central part of the study area.

The alongshore variation of the size fraction properties along isobaths (Fig. 15) suggests that the entire beach is not in perfect equilibrium. Sediments are more heterogeneous in the northern sections of the beach (Figs 13, 14). This can be explained by the combination of supply of unsorted sediments from the till scarp and the overall limited amount of sand in this area. The heterogeneity may partly be induced by the sand bar stretching over the depths of 4–8 m. The dumping of the material dredged from the river mouth and harbour basins in the 1970s may also have contributed to the formation of local variations of the grain size and the content of different fractions.

An interesting feature is the difference of spatial distribution of sand fractions in relatively shallow (down to depths of 5–6 m) and deeper parts of the study area. The proportion of coarser sand decreases from north to south in the shallower part of the coastal slope (Figs 13, 15). On the other hand, the proportion of silt increases northwards at depths greater than 6–7 m (Fig. 15). This peculiarity may reflect the above-described selective blocking of the natural sand supply or dumping of fine sediments dredged from the Pirita River mouth to the vicinity of Merivälja Jetty.

On the basis of the maps of the distributions of mean grain size, the beach can be divided into four areas:

- The northernmost part has a relatively large proportion of inhomogeneously distributed coarser sediments.
- Relatively coarse sand is found along the waterline.
- Most of the study area at depths from about 1 m to 6–8 m and extending to about 1800 m from Pirita Harbour has a more or less homogeneous distribution of sand fractions with a clear domination of fine sand.
- The deepest part of the nearshore (depths >6–8 m) mostly hosts even finer sand.

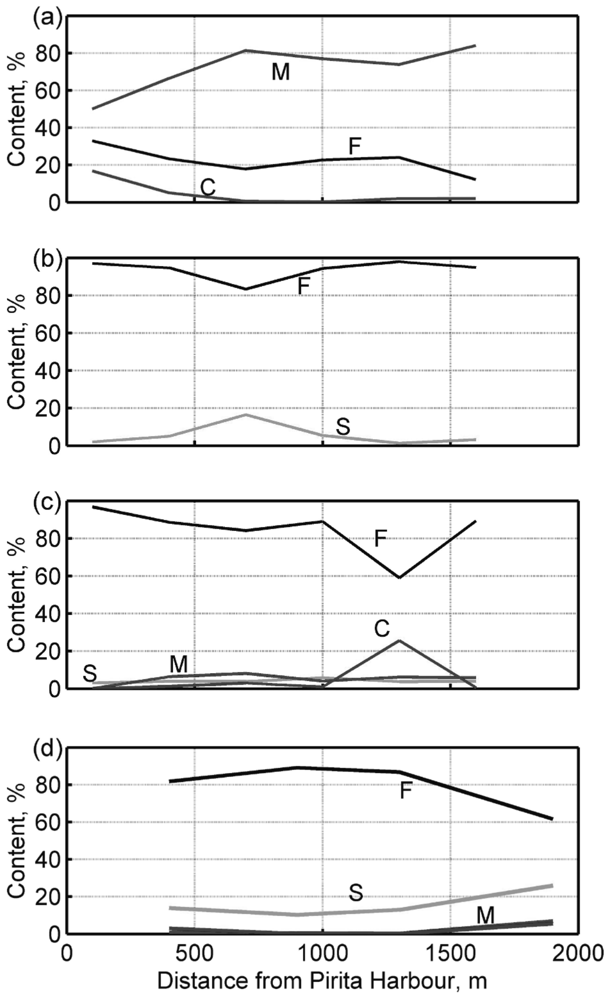

Fig. 15. Properties of different grain size fractions interpolated from sediment samples: (a) along the coastline, (b) along the 2-m isobath, (c) along the 5-m isobath, and (d) along the 10-m isobath. The letter C stands for coarse sand, M for medium sand, F for fine sand, and S for the fraction with the grain size <0.063 mm. Refer to Fig. 9 for sample locations.

CONCLUSIONS AND DISCUSSION

Historical as well as recently collected data were analysed to specify the previous and the current state ot Pirita Beach and to estimate the sand budget there. Pirita Beach has apparently been stabilized by the postglacial uplift and natural sediment supplies until the middle of the 20th century. The littoral transport of material eroded from the coast of the Viimsi Peninsula and originating from the Pirita River were the major sand sources. Aeolian sand loss is minor in this area.

The results of bathymetric and textural studies form a basis for the quantification of the sediment transport processes. The overall changes of the predominating grain

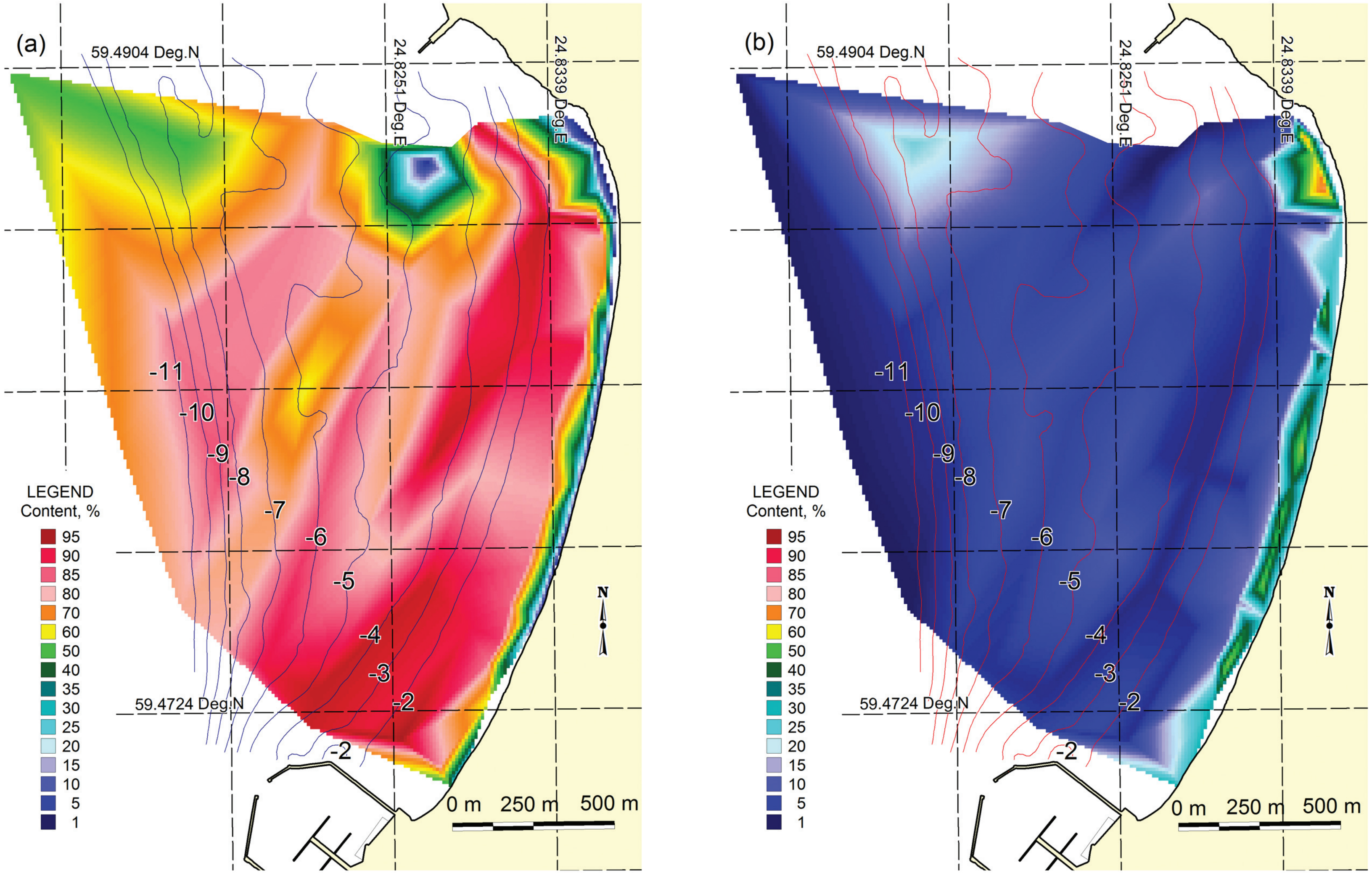

Fig. 13. Distribution of the dominant fractions in the study area: (a) fine sand (0.063–0.125 mm), (b) medium sand (0.125–0.2 mm). The background bathymetry is from the survey of April 2006 (Fig. 11). The coastline is shown based on the digital 1 : 50 000 Estonian Base Map from the Estonian Land Board (www.maaamet.ee).

Photo 1. View of southern Pirita Beach and Olympic Harbour into which the Pirita River discharges. Photo by A. Kask.

Photo 2. Erosion and loss of pine forest on the low dune during a strong storm in January 2005. Photo by I. Kask.

Photo 3. Remnants of the revetment originally constructed at the dune toe at the north end of Pirita Beach at the beginning of the 1980s. Photo by A. Kask.

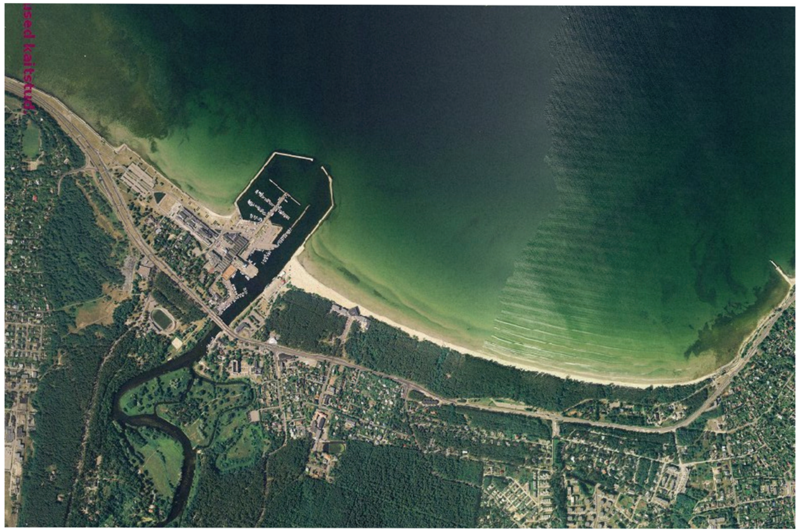

Photo 4. Aerial photo of Pirita Beach in 2000. Courtesy of the Estonian Land Board.

size are fairly minor at Pirita. This feature allows using a fixed value of the shape parameter of the equilibrium beach profile for this beach.

Major changes in the sand budget occurred when (i) Miiduranna Port and its fairway largely blocked the littoral transport, and (ii) when Pirita Olympic Harbour drastically decreased the river-induced sand transport to the littoral system.

The deficit of relatively fine river-transported material (about 400 m^3 annually) has to some extent been compensated by the pumping of the material dredged from the river mouth to the beach.

The blocking of littoral drift of coarser sediments by Miiduranna Port and Meriválja Jetty probably is the main reason for the sediment deficit in this area. The decrease in the littoral transport also led to an overall sediment deficit southwards from Merivälja Jetty, and evidently to more intense erosion of the scarp in the northernmost part of Pirita Beach. This change, apparently, is not compensated by the total blocking of the lateral sand transport by Pirita Harbour. It can be speculated that the specific deficit of coarser material leads to undesirable gradual decrease in the grain size in the southern part of the beach.

Since 1997, apart from the above sediment deficit, another 400 m^3 has been eroded annually from the dry beach. The erosion process of the beachface, dunes, and scarp in the northernmost part of the beach may have been less intense in the past, because the littoral transport previously carried more sand to this area.

In general, sand supply from the north, sand dredged from the Pirita River mouth and the basin of the Olympic Harbour, beach fill activities in the 1970s, and the relative land uplift have kept Pirita Beach more or less stable during the recent decades. Other beach protection measures such as construction of a revetment in the northern part of the beach have been ineffective.

Extensive damage by storms in November 2001 and January 2005 to the beach scarp and to the dune forest behind it, accompanied by seaward sand loss (cf. Orviku et al. 2003), suggest that the natural recovering mechanisms of Pirita Beach are no longer sustainable and that the beach has become very vulnerable. The positive influence of the beach fill from the past is probably over, and an increase in the net sand loss from both the dry beach and the nearshore is likely in the future. Therefore, construction activities in the vicinity of the beach or its sand supply channels, even if designed as beach protection measures, may lead to adverse effects and to an increase in the net sand loss. For example, if the till cliff north of the beach will be further stabilized by construction of a seawall, less material will be supplied to the beach and the net sand loss will likely increase. It is also likely that a rigid wall will enhance the sediment deficit in the northernmost section of the sandy beach.

A feasible way of restoring the sand balance at Pirita and to make the beach stable consists in increasing the sand volume at the beach. The fastest result would be by utilizing classical beach renourishment methods. This would involve placing high-quality, relatively coarse sand (extracted, e.g., from Naissaar Harbour, Kask & Kask 2007) either on the dry beach area or in the immediate vicinity of the shoreline. An artificial dune of moderate height (about 1.5 m) along the existing coastline would effectively protect the dune forest and not distort the sea view (Soomere et al. 2006). The dumping of sand to the nearshore is ineffective owing to the relatively small closure depth. Filling the beach with sand from the Pirita River mouth, from the Olympic Harbour basin or from the coastal slope of Pirita Beach should be undertaken with great care (Soomere 2007), because the sand there is relatively fine. Another feasible way, which would bring to good results, consists of sand bypassing to the southern side of Miiduranna Port. Doing so would eventually compensate the sediment deficit along the coast at Merivälja, reduce the coastal erosion in this area, and deliver medium and coarse sand to Pirita Beach.

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Põhjasetete jaotus ja transport Pirita rannas

Tarmo Soomere, Andres Kask, Jüri Kask ja Robert Nerman

Töö eesmärgiks on identifitseerida Pirita ranna setete allikaid ja settetransporti mõjutavad peamised tegurid. On vaadeldud Pirita lähistel paiknevate sadamate kujunemist, ranna batümeetriat, setete omadusi, allikaid ja transpordi peajooni ning hüdrotehniliste rajatiste mõju ranna funktsioneerimisele. Setete keskmine terasuurus on ligikaudu 0,12 mm. Peeneteraline liiv (fraktsioon 0,063–0,125 mm) moodustab 77% pealiskihis paiknevast liivast. Suurema terasuurusega liiv on valdav vaid rannajoone vahetus läheduses. Jämedamat liiva on rohkem ranna põhjaosas. Sadamad ja muulid on blokeerinud loodusliku liiva juurdevoolu. Praegu liiva hulk rannas väheneb; sh on aastail 1997–2005 keskmisest veepiirist kõrgemalt ära kantud ligikaudu 400 m^3 liiva aastas.