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Lithohydrodynamic processes in the Tallinn Bay area

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Declaration: Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

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Contents

List of tables

List of figures

Introduction

Generally, there is certain dynamic equilibrium between the main coastal processes – sediment erosion, transport and accretion. Human activity in the coastal zone frequently changes this equilibrium and may often result in undesirable side-effects, for example, through enhanced sediment erosion, transport and accretion. Although the enhanced intensity of coastal processes could result from an increase in the frequency or severity of extreme hydrodynamic conditions (Orviku *et al.* 2003), the ever growing reason is that the principles of sediment dynamics are neglected during the planning and construction of coastal engineering structures (Dean and Dalrymple 2002).

Several options are available to prevent, minimize or mitigate the adverse effects caused by natural and anthropogenic factors. For example, in the course of environmental impact assessment (e.g. Morris and Therivel 2001) experts predict human impact to natural processes. Similarly, environmental monitoring gives information about unpredictable or predictable changes in the development area and in the vicinity. The monitoring often cannot distinguish the impact of the construction from the course of nature. Generally, various modelling approaches have to be used in order to foresee the potential changes caused by each factor and by specific combinations of driving forces. This process is more or less straightforward in case of smallscale constructions where natural processes are dominating. Considering the existing experience we can say that in case of larger objects anthropogenic impact prevails. The range of different effects, however, may be extremely wide, and extended analysis may be needed to estimate their tolerability for the community.

The current thesis focuses on several aspects of the use of contemporary concepts and methods of coastal processes and geomorphology in the context of Estonian beaches and nearshore. As the evolution of a large part of these beaches has stabilised due to postglacial uplift (Paper I), such coasts are often in an almost equilibrium state (Soomere and Healy 2009).

First, attempts are made to separate the natural and human-induced impact on almost equilibrium beaches. Anthropogenic influence is understood in a wide sense, which ranging from direct interference in the form of largscale direct intervention in sedimentation processes (e.g. dredging and disposal of dredged soil operations) over less direct impact, created by the erection of different coastal engineering structures (also called hydrotechnical structures in popular literature) in the coastal zone (such as ports, breakwaters and moles) to remote influence of waves from large ferries.

Contemporary methods of the analysis of various processes in shallow and nearshore areas provide in many cases a key towards identifying, managing and mitigating the adverse impact of human activities. The central element of their effective application is the appropriate knowledge of forcing factors (such as surface waves or nearshore winds) and the properties of the affected areas. Following from this line of reasoning in this thesis the analysis of the geological indicators (such as the sediment sources and texture) has been combined with studies of the local wave climate and properties of wave-induced sediment transport towards the description and analysis of nearshore morphology. This is one of the feasible ways to differentiate the natural course of sediment dynamics from the anthropogenically driven processes.

Human influence, which most frequently becomes evident through various coastal engineering activities, interferes with the course of nature. There is very small chance that a coastal engineering structure (except perhaps beach refill) would not affect the processes in the vicinity of the coast. Most likely it will induce certain changes or anomalies in the natural background, which will usually become evident as enhanced erosion or accretion. Since many of the existing structures have been constructed in the past when the awareness about their potential impact was vague, an important task of today's coastal science is to establish how the beach would have functioned without human interference. This is important not only from the theoretical perspective, but also in order to find decent ways of compensating the influence exerted on the beach by adequate countermeasures.

The natural course of coastal processes and related morphodynamic changes are at times important for the planning of various other economic activities, such as sand or gravel mining from underwater deposits. Although mining is usually not considered in the framework of classical coastal engineering, contribution from this discipline is extremely important for both localization of sand resources and mitigation of the adverse impacts of the mining process. The correlation of the sediment texture, wave-induced critical shear stress velocities and bathymetric information can simplify the prediction of sand accretion areas and largely facilitate prospecting for new sand deposits.

The application of standard modelling packages foreseen for the open ocean coasts is not always straightforward and sometimes even impossible in the Estonian littoral sea. The basic reason for their failure is that the nearshore of Estonia is atypical in many aspects. The Baltic Sea is a micro-tidal area hosting no strong stationary currents but with large-scale variations in the wave climate. Therefore there is an increasing need to differentiate more precisely the specific impact of planning and construction on the coastal processes and sediment dynamics in the context of Estonia. This information not only helps to avoid mistakes in the future decisions concerning coastal zone planning, but also contributes to the overall understanding of the functioning of almost equilibrium beaches.

North Estonian beaches

Beaches along the northern coast of Estonia form an interesting class of almost equilibrium, bayhead beaches that are often located in bays cut deep into the mainland in an almost non-tidal, highly compartmentalised coastal landscape and that develop mostly under the influence of wave action and sea ice (Orviku 1974; Orviku and Granö 1992). While large parts of the Baltic Sea coasts express relatively simple geomorphic and lithodynamic features (e.g. the almost straight eastern coast in some parts of Germany and from Poland up to Latvia or bedrock-based, extremely stable archipelago areas along the Swedish and Finnish coasts), the understanding of the physics and dynamics of lithohydrodynamic processes along the coasts of the Gulf of Finland is still a challenge. The southern and eastern coasts of the Gulf of Finland, belonging to a rare type of young, relatively rapidly uplifting beaches, are of greatest interest in this respect (Papers I, II).

These beaches, although suffering from a certain sediment deficit, are stabilised by relatively rapid postglacial uplift, the magnitude of which is from about 1 mm/year in the eastern part of Estonia near Narva up to about 2.8 mm/year in the north-western part of the coast (Vallner *et al.* 1988; Miidel and Jantunen 1992; Jevrejeva *et al.* 2000). Wave action normally impacts a relatively narrow nearshore band in the Baltic Sea conditions and additionally stabilises the bayhead beaches through littoral drift or finer sediment and gravel towards the bayheads. Aeolian transport and fluvial sediment supply are typically of very modest magnitude. In general, such beaches develop quite slowly and may be in an almost equilibrium stage even when the active sand mass is very limited.

The uplift, combined with a relatively low hydrodynamic activity and a limited supply of sand, has led to the formation of a specific type of “almost equilibrium” beaches (Soomere *et al.* 2009). The equilibrium is usually supported by a combination of factors (such as littoral drift that generally carries sediments to the bayheads, supply of sediments by rivers, the mouths of which are located at the bayheads, and the above-mentioned land uplift).

An important issue for sustainable management of such beaches is establishing the parameters of their equilibrium regime, the magnitude of sediment supply and the basic patterns of the natural sediment transport processes. This information combined with various mathematical methods, usually serves as the basis of well-justified decisions for their protection, controlled modification (for example, managed retreat, see Healy and Soomere 2008) or reconstruction (Papers I, II)

The combination of an almost equilibrium state of small, relatively vulnerable beaches and the damaging potential of heavy anthropogenic impact suggests that the beaches in question eventually are extremely sensitive to changes in external factors. For example, a rise in the global sea level, increased discharge during more pronounced spring floods in the future climate (The BACC Author Team 2008), construction of a dam to regulate the river flow (Velegrakis et al. 2008) or a new coastal engineering structure blocking the littoral drift (Paper II) may easily distort the balance.

This thesis mostly concentrates on the sediment transport properties and morphodynamical processes along the beaches of Tallinn Bay. This area is heavily influenced by various anthropogenic activities, ranging from different coastal engineering structures built over many decades (Paper II) to extensive wave loads from fast ferries starting from the turn of the millennium (Papers V and VI; Soomere 2005b).

Tallinn Bay as an example of a semi-sheltered bay

The beaches on the northern coast of Estonia form a highly interesting set of beaches with different characteristics, but still with a largely similar history, present and future. It is somewhat unexpected that no comprehensive description of general properties of these beaches is available in international literature (Paper I). There are, however, numerous publications, mostly in Russian and/or Estonian, treating both global and local features of the geological setting, properties of sediments and coastal processes at the southern coast of the Gulf of Finland (e.g. Orviku 1974; Lutt and Tammik 1992; Orviku and Granö 1992). Many interesting studies (e.g. Knaps 1976; Paap 1976; Orviku and Veisson 1979; Loopmann and Tuulmets 1980) are only available as manuscripts. Therefore here, some elements of the relevant knowledge and the geological setting in the Tallinn Bay region, are shortly presented mostly following Paper III. An overview of the geology and geological history of the entire Gulf of Finland area is given by Raukas and Hyvärinen (1992).

An interesting feature of the Gulf of Finland is that the beaches located on its southern and northern coasts have completely different nature. The northern coast is mostly characterised by "skären" type beaches, the evolution of which is very weakly affected by hydrodynamic factors (Granö and Roto 1989). On the contrary, the southern coasts of this gulf were formed and develop predominantly under the impact of wave action (Orviku and Granö 1992).

The most important landscape feature on the southern coast of the Gulf of Finland is the North Estonian Klint. This is an approximately 300 km long section of the Baltic Klint in North Estonia, between the Island of Osmussaar and the Narva River. The Baltic Klint is an app. 1200 km long system of erosional escarpments in Lower Palaeozoic (Cambrian to Ordovician) sedimentary rocks between the southern end of the Island of Öland in Sweden and Lake Ladoga (the estuary of the Syass River) in Russia (Suuroja 2005). The studies of the North Estonian Klint (e.g. Tammekann 1940; Suuroja 2005, 2006) provide useful information about the long-term development and source material of the beaches of Estonia.

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

The beaches along the Estonian coast of the Gulf of Finland 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, mostly classified as straightening coasts (group IIIA according to Kaplin 1973), obtained their contemporary shape only a few millennia ago. The most common types of coasts here are the straightening, accumulation, embayed coasts (type 20 according to Kaplin 1973).

The embayed beaches of the northern coast of Estonia are frequently divided into two sets. The features of the coast eastwards from the Viimsi Peninsula are mainly related to glacial and glaciofluvial formations and deposits of the foreklint lowland. The westward bays, including Tallinn Bay, however, are mostly associated with structural blocks and ancient erosional valleys in the bedrock (Orviku and Granö 1992, p. 221). The volume of sediment and the magnitude of littoral drift are modest for both subtypes that generally suffer from beach sediment deficit. This feature is the main reason why even the healthiest sections the of coast at the bayheads are from time to time subject to erosion, although littoral drift generally carries sediments to the bayheads.

Sandy shores are spread on a limited area of accumulation coasts. Most typical of the coasts of Tallinn Bay are bluff shores with a 1–2 m high bluff that normally lies above water level and is eroded only under conditions of high water level combined with strong wave activity, mostly during the autumn–winter period.

As the entire northern coast of Estonia generally suffers from sediment deficit (Orviku 1974; Orviku and Granö 1992), it is not surprising that certain net loss of sand at times occurs even at the bayhead of Tallinn Bay, in the Pirita area. This loss is partly compensated by postglacial land uplift (which is estimated to be 1.8 to 2.5 mm/year by Vallner *et al*. 1988 and Miidel and Jantunen 1992) which, over time, contributes to an increase in beach width. Moreover, there is no lateral sediment loss from Pirita Beach that exhibits, in general, low activity of coastal processes. Therefore, the concept of (almost) equilibrium beaches is apparently suitable for the analysis of its properties and development.

Outline of the thesis

The thesis is based on six academic publications which are referred to in the text as „Paper I"–"Paper VI" etc.:

Papers indexed by the ISI Web of Science:

Paper I Soomere, T., Kask, A., Kask, J., Nerman, R. 2007. Transport and distribution of bottom sediments at Pirita Beach. Estonian Journal of Earth Sciences 56(4), 233–254.

Paper II Soomere, T., Kask, A., Kask, J., Healy, T. 2008. Modelling of wave climate and sediment transport patterns at a tideless embayed beach, Pirita Beach, Estonia. Journal of Marine Systems 74 (Supplement 1), S133–S146.

Paper III Kask, A., Kask, J., Korneev, V., Okuntsov, E. 2008. Sedimentation conditions of marine Prangli and Naissaar sand deposits, the Estonian coastal sea. Baltica 21(1–2), 79–84.

Paper IV Kask, A., Soomere, T., Healy, T., Delpeche, N. 2009. Rapid estimates of sediment loss for "almost equilibrium" beaches. Journal of Coastal Research. Special Issue 56, 971–975.

Peer-reviewed papers in other international research journals:

Paper V Kask, J., Talpas, A., Kask, A., Schwarzer, K. 2003. Geological setting of areas endangered by waves generated by fast ferries in Tallinn Bay. Proceedings of the Estonian Academy of Sciences. Engineering 9(3), 185–208.

Paper VI Soomere, T., Põder, R., Rannat, K., Kask, A. 2005. Profiles of waves from high-speed ferries in the coastal area of Tallinn Bay. Proceedings of the Estonian Academy of Sciences. Engineering 11(3), 245–260.

The role of the applicant in these papers is as follows.

The applicant has the leading role in the collection of in situ and historical data, underlying analysis and writing Papers III and IV.

In case of Papers I and II, the candidate was responsible for the organisation of field works, compiled the overview of historical data, analysed the morphodynamical features of the study site, substantially contributed to the analysis and applications of the results of the studies and wrote the relevant text sections.

The basic contribution of the applicant to Papers V and VI consists in the organisation of and participation in all relevant field work, analysis of the gathered data from the viewpoint of sediment transport processes in different sections of Tallinn Bay and in writing the relevant parts of the text.

The main body of the thesis starts with the overview of the factors affecting sediment dynamics along the beaches of Tallinn Bay (Chapter 1). The basic hydrometeorological conditions are mostly outside the scope of this research and are described very shortly for the completeness of the information complementary to the material presented in the papers constituting the thesis. The main focus is on the properties of finer sediments in the nearshore, in an area strongly affected by surface waves, where the lithohydrodynamic processes are the fastest. As many of the contemporary features of the coasts stem from a long history of their development, some elements of the overall geological setting and history of the beaches are provided as well.

Along with this basic information, a more detailed discussion of the properties of the coasts and sediment texture in the nearshore and in the vicinity of the shoreline is presented. A large part of this information stems from original field studies, including estimates of the vulnerability of the coasts with respect to wakes from fast ferries (Paper V) and granulometric surveys made by the author or with an active participation of the author (see Papers I, V and VI for details).

The bathymetric properties of the nearshore constitute another important feature, largely defining the course of processes occurring in the nearshore and sediment transport pattern. From this viewpoint, the potential appearance of the foredunes and the dry beach area, beach profiles and underwater bedforms are equally important. A large part of the relevant properties is presented, based on the original studies made during the preparation of this thesis (Papers II, VI). The presentation focuses on three areas, for which original data have been obtained: Pirita Beach and its nearshore, and sand deposits near the islands of Naissaar and Prangli. A more qualitative overview of the other sections of the natural coasts surrounding Tallinn Bay is given in terms of their potential vulnerability with respect to the waves excited by fast ferries (Paper V). This topic is revisited in more detail for the coast of the Viimsi Peninsula in Chapter 3 from the viewpoint of the relevance of ferry waves to the dynamics of Pirita Beach, in particular, the present and past sediment sources for Pirita Beach.

Chapter 2 focuses on the dynamics of sediment in selected sections of the coast of Tallinn Bay. The main study site is Pirita Beach, a favourite recreational area located in the bayhead, in the neighbourhood of the city centre of Tallinn. This beach evidently suffers from severe, albeit indirect, anthropogenic influence. Although the beach is supported by a multitude of factors, it is a typical example of a beach whose evolution has been largely controlled by development works. In order to clarify the role of human interventions in its development, it is necessary to establish the basic features of its functioning, including sediment sources, spatial distribution of sediments in the nearshore and on the dry beach (Paper I), and sediment transport patterns and properties of the natural equilibrium of the beach. The parameters of the alongshore transport patterns are evaluated with the use of the classical Coastal Engineering Research Council (CERC) model (Paper II).

Another central topic of Chapter 2 is the analysis of the formation of relatively large (in terms of the Tallinn Bay scale) sand bodies in the nearshore of Tallinn Bay (Paper III). The key example is the actively accumulating sand deposit along the southern coast of Naissaar. This sand body is supported by sediment transport along both the eastern and western coasts of Naissaar and apparently increases in size at the expense of coastal bluffs of this island. As an example of a less rapidly growing sand body, certain features of a sand deposit located near Prangli in the adjacent Muuga Bay are analysed.

Chapter 3 contains an analysis of the consequences of various human interventions on sediment transport patterns along Pirita Beach and sand budget of the beach. This sandy coastal section with a length of about 2 km serves as a typical example of an almost equilibrium, bayhead beach of the North Estonian coast. The analysis is largely based on the concept of the Dean's Equilibrium (beach) Profile (DEP). The properties of this profile are estimated based on a combination of original bathymetric and granulometric surveys (Paper I) and a simulation of the local wave climate (Paper II).

A recently developed application for rapid estimates of the basic parameters of almost equilibrium beaches, based on a few relatively easily measurable or computable parameters, is used to quantify the sediment loss from Pirita Beach (Paper IV). It is demonstrated that net sand changes for such beaches can be estimated directly from the properties of the equilibrium profile, land uplift rate and loss or gain of the dry beach area. Finally, certain specific properties of wakes from fast ferries (such as their very long periods and shape that substantially deviates from sine waves) and their potential consequences are discussed on the basis of direct measurements of the water surface profile in such waves (Paper VI).

Approbation of the results

The main results described in this thesis have been presented in the following international conferences, symposiums and workshops:

The 10th International Coastal Symposium ICS2009, Lisbon, Portugal, 13–18 April 2009: poster presentation "Rapid estimates of sediment loss for "almost equilibrium" beaches" (in cooperation with T. Soomere, T. Healy and N. Delpeche).

The 33rd International Geological Congress, Oslo, Norway, 6–14 August 2008: oral presentation "Sediment transport patterns and rapid estimates of net loss of sediments for "almost equilibrium" beaches of tideless embayed coasts" (presented by T. Soomere, in cooperation with T. Healy) and poster presentations "Formation of sand deposits in Estonian coastal sea" (in cooperation with J. Kask) in the session EUR–10 The Baltic Sea Basin, and "Approximation of fine sediments transport" (in cooperation with A. Erm and V. Alari) in the session SES–01 General contributions to sedimentology.

The 6th Baltic Sea Science Congress, Rostock, Germany, 19–23 March 2007: poster presentation "Studies of composition of bottom sediments and bathymetric features of Pirita shore" (in cooperation with T. Soomere and J. Kask).

Joint workshop "Implications of climate change for marine and coastal safety" and "Applied Wave Mathematics" of Marie Curie networks SEAMOCS and CENS-CMA, and Eco-NET network "Wave Current Interaction in Coastal Environment", Palmse, Estonia, 10–12 October 2007: oral presentation "Large effects on small structures on coastal evolution".

The 5th Baltic Sea Science Congress "The Baltic Sea Changing Ecosystem", Sopot, Poland, 20–24 June 2005: oral presentation "The shape of wake waves from high-speed ferries in the coastal area" (in cooperation with K. Rannat and R. Põder, presented by T. Soomere).

The 8th Marine Geological Conference "The Baltic", Institute of Geology, University of Tartu, Estonia, 23–28 September 2004: poster presentation "Coastal processes in the inner part of Pärnu Bay" (in cooperation with J. Kask).

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1. Variability and vulnerability of the coasts of Tallinn Bay

The very basic description of the geological setting and bottom deposits of Tallinn Bay (Fig. 1.1) is presented on geological maps at a scale of 1:200 000 compiled out at the Geological Survey of Estonia (Talpas *et al.* 1994). The areas of predominant erosion and deposition have been identified by Lutt and Tammik (1992). These two sources, together with a generic description of the processes on the North Estonian coast (Raukas and Hyvärinen 1992), were the only scientific publications about coastal processes and bottom sediments in the Tallinn Bay area in the recent past which were available when the preparation of this thesis started. There are, however, numerous of manuscripts reporting the results of different measurement, surveying and monitoring works in this area (especially in the vicinity of Pirita Olympic Harbour; see, e.g. references in Paper I).

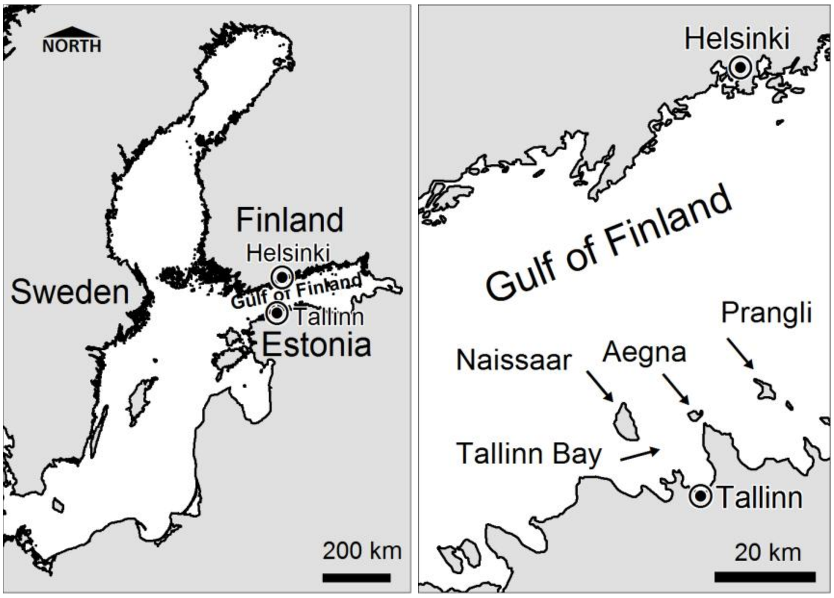

Fig. 1.1. Location scheme of the Baltic Sea, Gulf of Finland and Tallinn Bay

This chapter largely provides original data and observation results gathered within several measurement campaigns during 2001–2008. A rough classification of the vulnerability of the beaches of Tallinn Bay was performed in 2001–2003 in the framework of a study of the potential influence of wakes from fast ferries on the coasts of Tallinn Bay (Paper V). Detailed investigation of the sea bottom and sampling of the texture of potential sand deposits were conducted in 2003–2007 in the course of prospecting for potential sand mining sites (Paper III). These studies partially extended beyond Tallinn Bay, to a potential sand deposit near the Island of Prangli in the adjacent section of the Gulf of Finland. Finally, a series of different surveys and sampling studies was performed in 2006–2008 for the nearshore and dry beach in the vicinity of Pirita Beach (Papers I, II). As the listed investigations were concentrated in selected areas, unpublished data from other sources are frequently used below whenever possible. As historical studies have been carried out with the use of different classifications of sediments, not all the results are directly comparable.

Owing to quite different orientations of historical and underlying studies, different hydrometeorological and geological properties are used to quantify the results in separate locations. For example, the properties of sand are reported in quite general terms of fineness modulus (which is the decisive parameter for the quality of sand as a mineral resource) for Prangli and Naissaar deposits, but much more detailed textural analysis of sand has been performed at Pirita where spatial distribution of different fractions is important from both the recreational point of view and for potential beach nourishment activities.

1.1. Geological setting of the Tallinn Bay area

Different stratigraphic units crop out on the sea floor of Tallinn Bay. Cambrian sandstone is exposed sporadically in small areas, e.g. in the surroundings of the Paljassaare Peninsula, on the nearshore west of the Island of Aegna and the Viimsi Peninsula, and on Tallinn Bank (Lutt and Tammik 1992). This unit is usually overlain by a thin layer of sand and silt, whereas rest of finer sediment is carried away by waves (Lutt and Tammik 1992; Paper V; Kask *et al*. 2008).

Present-day sedimentation areas in Tallinn Bay have formed under the influence of several agents – large-scale circulation, nearshore currents generated by dominating winds, surface waves, impact of ice, sea floor topography, etc. While part of the seabed material, such as larger boulders, is mostly immobile or is overlying ancient marine and fluvial sediments (for example, at Pirita), the majority of contemporary finer, mobile sediment in the coastal zone has been mixed together from material eroded from different local coastal formations. As explained above, coastal material exchange with neighbouring bays has been very limited.

Pleistocene till and late- and postglacial clays are rather common. Late- and postglacial clays often crop out in areas of active sediment transit (western coast of the Viimsi Peninsula, underwater extension of the Kopli Peninsula, Kopli Bay, south-east and south-west of Naissaar). Postglacial clays are distributed on the western slope of a relatively deep trench in the central part of Tallinn Bay that opens to the central part of the Gulf of Finland (Fig. 1.1). Although deeper areas, formally, have depositional nature (Lutt and Tammik 1992), due to low hydrodynamic activity for a long time neither considerable deposition nor erosion has occurred in the above-mentioned areas. In some places a thin (less than 10 cm) layer of sand or gravel of unidentified origin or Fe-Mn nodules of various shape and size, are present.

Residual sediments (coarse fractions left after fine fractions have been carried away) of variable grain size (boulders to silt) form an independent sediment type. They overlie the bedrock or till and have formed mainly as a result of breaking wave activity in the surf and swash zones. Finer particles are transported to the deeper sea, while coarse material remains in the zone of wave activity, often forming a stone pavement on the sea floor. Such belts of boulders, cobbles and pebbles with some sand and gravel fill occur around Aegna, as well as in the coastal zone of the Kopli and Paljassaare peninsulas. The similar cobble and boulder pavement is common on the western coast of the Viimsi Peninsula and on the eastern coast of Naissaar, where it covers almost the entire coastal zone from the waterline to a depth of 5–6 m. Several areas covered with residual deposits are still subject to erosion and/or sediment transport and thus contribute to the sediment budget within Tallinn Bay.

In the shallow coastal areas which are subject to wave wash, erosion plays an important role. As a result of wave breaking, poorly sorted sand, less often gravel and pebbles may accumulate at the shoreline. In more than 10 m deep areas finely laminated or non-laminated silts are deposited.

In the central part of Tallinn Bay varigrained sand accumulates, which originates from the eroded shore sections at the ends of peninsulas. The varigrained sand south and south-west of the islands and banks has deposited in a similar way. The formation of areas covered with such deposits is controlled by prevailing winds, blowing from W-SW and N-NW (Soomere and Keevallik 2003). Such accumulation areas are for example the surroundings of Cape Hülkari on Naissaar. The cape and the sea floor south of the cape consist of sand which has been carried to this area from the eroded shores of Naissaar. Fine and medium sand is widely distributed in Tallinn Bay; coarse sand is found in shallow areas.

Fine deep-water (depths >20 m) sediments are represented by pelitic material which sporadically contains organic matter. Greenish-grey to black pelite with a high water content is found in seafloor depressions. The proportion of particles finer than 0.01 mm is about 70–80%, the silt fraction (less than 0.063 mm) is the main admixture. Generally darker (to black) pelite occurs in deeper areas (30–40 m), while a greenish variety is found in somewhat shallower sea areas. Such deposits are found in small areas only – west of Aegna where the maximum thickness of pelite is 6 m, to the south the sea floor is covered with silt, the thickness of which reaches 5–6 m. South-west of the islands of Aegna and Kräsuli the modern bottom deposits are only 0.20–0.30 m thick. This is apparently due to the coastal current in the southern Gulf of Finland which is directed to the east and partly passes the straits between Aegna, Kräsuli and the Viimsi Peninsula.

Eastwards of the Paljassaare Peninsula nearshore sediment transport is not observed and silt and pelite are deposited in relatively shallow water. The situation is similar in Kopli Bay, where sand accumulates in the eastern part of the bayhead, while in the western bayhead wave activity is less intense and silty and pelitic material is deposited.

1.2. Sedimentary compartments

Although Tallinn Bay is relatively small (approximately 10×20 km), its coast comprises several almost or entirely separated sedimentary compartments and a variety of beaches. For example, a steep till bluff can be found at Naissaar, a gently sloping till shore along many parts of the Viimsi Peninsula, a sandy coast at Pirita and at certain sections of Aegna, and long sections of artificial shore are also present.

The sediment system of the coasts of Tallinn Bay is characterised in Paper III. It consists of the following parts (Fig. 1.2). The mainland coasts of Tallinn Bay form a large compartment that is divided into two independent sedimentary cells by the harbours near the city centre of Tallinn. Western cell 1 is further divided into two subcells 1A and 1B by Katariina Jetty constructed in the 1910s, whereas eastern cell 2 (which before the 1920s extended from Tallinn Old City Harbour along the coast of the Viimsi Peninsula up to Aegna) has been even more extensively modified by coastal engineering structures of the 20th century. Its south-western part (2A) is nowadays an artificial shore. Since the 1970s the Port of Miiduranna divides the eastern part of cell 2 into two subcells 2B and 2C. Only the northernmost cell 2C (which may be partially connected with the adjacent cell in Muuga Bay through a narrow (about 300 m) and shallow (about 1 m before dredging) strait has been less affected.

Pirita Beach, one of the main objects of this research, forms the south-western part of cell 2B. The rest of the western coast of the Viimsi Peninsula (cells 2B and 2C) is mostly covered by coarse material (pebbles, cobbles, boulders). As typical of the northern coast of Estonia (Orviku and Granö 1992), it has a limited amount of gravel and sand participating in the littoral drift and its development takes place under sediment deficit. According to the classification of Lutt and Tammik (1992), erosion predominates in the entire nearshore of the Viimsi Peninsula northwards from Pirita Beach, up to a depth of about 10 m. Beach erosion, however, is usually modest since the stone pavement protects the shore (Paper V). 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.

The other basic sedimentary systems are located at the coasts of islands surrounding Tallinn Bay. Sand bodies 3A and 3B at Aegna (northwards from the island and in the strait between the island and the islets adjacent to mainland, respectively) are apparently separated from the mainland coasts. Cell 4 at the eastern coast of Naissaar (containing subcells 4A and 4B that are separated to some extent by a harbour) is completely disconnected from the mainland cells by a strait about 30 m deep. Still, it forms a sand accumulation area jointly with a sister cell located on the western coast of Naissaar.

In this thesis we study in more detail processes along Pirita Beach that forms the south-western part of cell 2B (Papers I, II) and in the joint accumulation area of two almost separated cells located at the eastern and western coasts of Naissaar (Paper III).

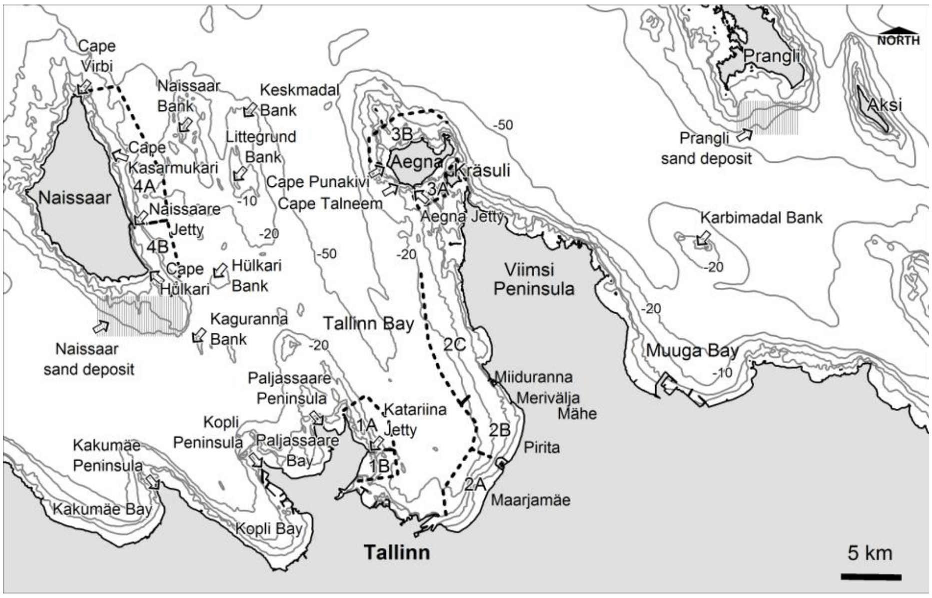

Fig. 1.2. Location scheme of of the study areas in Tallinn Bay and near Prangli based on the digital 1:50 000 Estonian Base Map from the Estonian Land Board (www.maaamet.ee). Dotted lines show cells of sediment transport: cell 1 along the western coast of the inner part of Tallinn Bay (divided into subcells 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 Aegna (subcells 3A and 3B at the southern and northern coasts, respectively), and cell 4 along the western coast of Naissaar (divided into subcells 4A and 4B by Naissaar Harbour)

1.3. Coastal zone of Pirita

Pirita Beach is located within the ancient Pirita River valley that extends down to Cambrian clay. The description of its main features is presented in Paper I. The contemporary Pirita River follows the ancient valley to some extent. The south-western border of the valley becomes evident at Maarjamäe (where Cambrian rocks are in places quite close to the contemporary surface) and the northward border at Merivälja (Fig. 1.3). A large number of similar ancient valleys and “klint bays" are found in northern Estonia. Many of them also contain contemporary beaches similar to Pirita Beach (Orviku 1974; Orviku and Granö 1992).

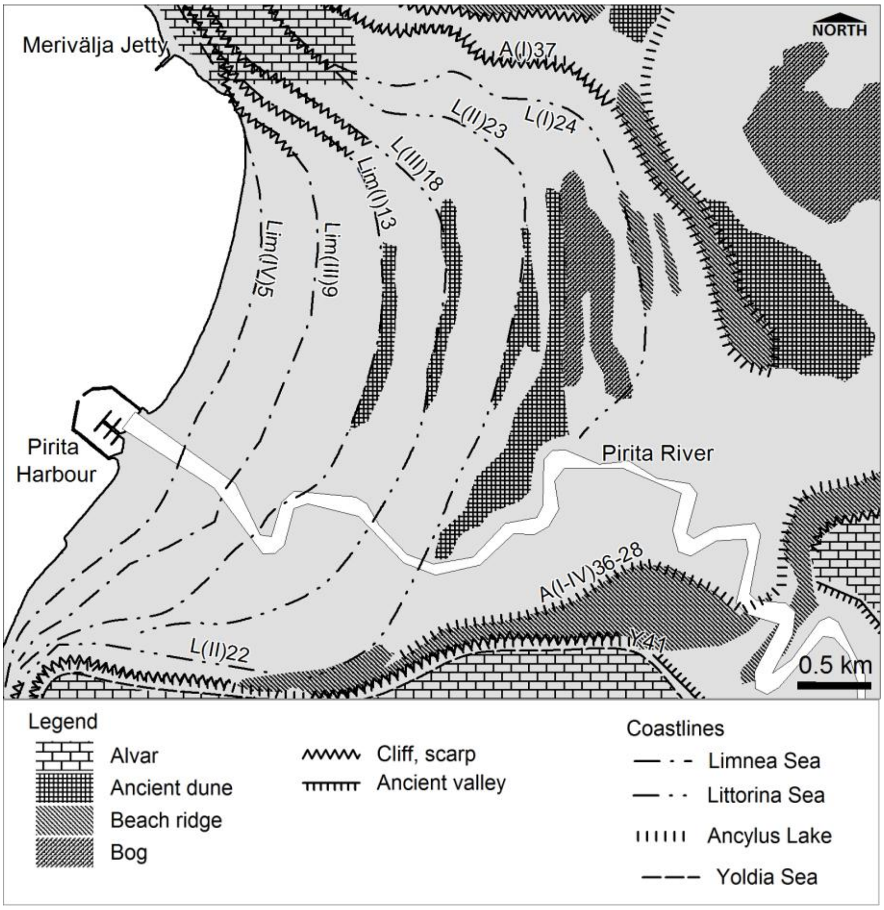

Fig. 1.3. Palaeogeographic map of the vicinity of Pirita Beach and the Pirita River mouth. Redrawn based on Tammekann (1940), Raukas *et al*. (1965), Kessel and Raukas (1967) and an unpublished manuscript (Kask 1997). In the nomenclature of ancient coastlines, Lim stands for Limnea Sea, L for Litorina 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 (Paper I)

An up to 35 m thick complex of limnoglacial Quaternary sand-clay deposits of different origin, lithological composition and consistence has been accumulated in the ancient Pirita River valley 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* is apparently representative for a large part of the ancient valley (although several layers are not necessarily present closer to the borders of the valley). Contemporary aeolian sand with a thickness of 2–2.5 m forms the uppermost layer that overlies older marine sand (about 8 m thick) and ice-lake deposits (Nugis 1971). A layer at a depth of 9–10 m contains a relatively large amount of clay particles and organic matter. A thin (0.75–1.60 m) layer of silt comes next overlying a 4.5–6.5 m thick loam that is apparently formed during the Ancylus Lake stage. These deposits are underlain by an about 9.5–10 m thick layer of ice-lake liquid loam or sandy loam, followed by about 2 m thick highly plastic striped clay, under which Cambrian blue clay is found.

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 south-western border in the Maarjamäe area.

The rugged landscape features of the ancient valley have been levelled off during many millennia. Today the area in question forms a part of the gently sloping Pirita(-Mähe) plane (Raukas *et al.* 1965; Kessel and Raukas 1967). The contemporary sandy beach (as well as the beach that existed southwards from the Pirita River until the 1970s) lies at the western boundary of the plane where the seabed is gently sloping until to 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. 1.3) when the 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 bluff close to Merivälja Jetty at a distance of about 2 km from Pirita Harbour. The thickness of recent foredune and marine sand is modest (usually 2–2.5 m). Dimensions of the marine sand layer diminish towards Merivälja and Maarjamäe, where a layer of till becomes evident either on the surface or below a thin layer of contemporary deposits. Noticeable foredunes with a maximum height of ~1.5 m only exist in the immediate vicinity of the sea coast. The major sea level changes can be recognised within the valley from much higher ancient dunes (Fig. 1.3) located about 1–2 km inland (Künnapuu 1958; Raukas et al. 1965).

1.4. Beach profile and bathymetry

The beach profiles available before studies described in Paper I 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 (Papers I, II). The same average slope holds for profile 3 in the central part of the beach. The mean slope is somewhat larger; about 1:150 in the vicinity of *Rannahoone*. 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 (Papers I, II). Shallow-water sand bars with a relative height of ~0.5 m are more frequent in the central part of the bay.

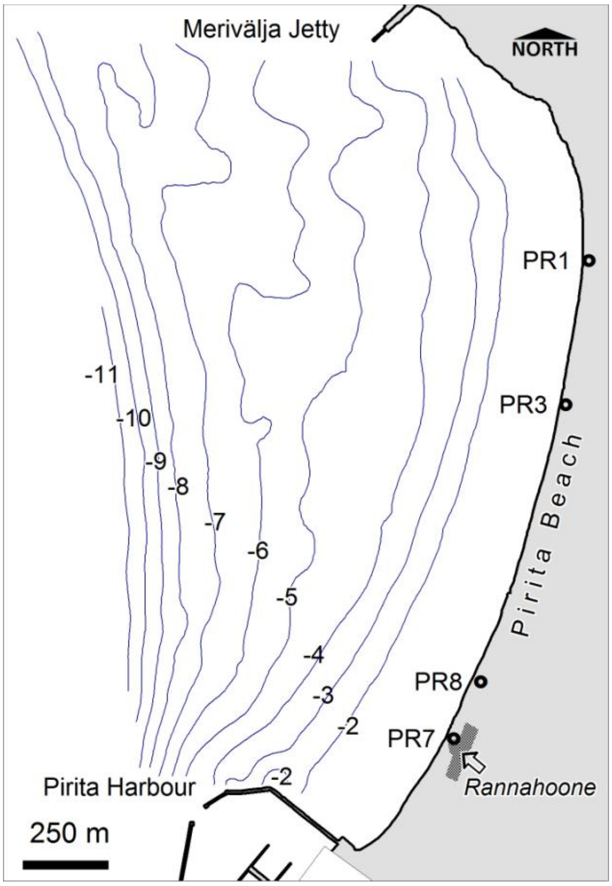

Fig. 1.4. Bathymetry offshore from Pirita Beach based upon the 2006 hydrographical survey (Paper I)

The water depth increases monotonically along the profiles in the southern and northern sections. Shallow-water sand bars seem to be 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.

Bathymetric mapping of the nearshore of Pirita Beach, down to 11 m isobath from the northern mole of Pirita Harbour to Merivälja Jetty, was based on field survey data by Gotta Ltd. 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 (Paper I).

The survey reveals that a gently sloping nearshore strip (evidently reflecting the equilibrium beach profile) stretches from the waterline down to depths of about 2–2.5 m (Fig. 1.4).
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 to 1:150 in the southern part.

Offshore from the beach, the water depth increases relatively fast between the seaward border of the above strip and the 4-m isobath. 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. A relatively gently sloping submarine terrace, some 500–800 m wide is located at depths of 4–7 m. The slope of this terrace is 1:200 in the central part of the beach. The water depth increases relatively fast from 7 m to over 10 m in 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 (Fig. 1.4), as well as to the till formations. As it can be identified also on the older maps of the 1980s, it probably is a long-term feature of the beach.

1.5. Spatial variations in seafloor sediment texture

A description of the properties of bottom sediments for the entire Tallinn Bay is given by Lutt and Tammik (1992). Previous studies of contemporary bottom sediments at Pirita are reported by Lutt (1992) based on 33 vibrocorer samples of sediments extending down to 2.1 m into the seafloor. 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 finer silt fractions[1] predominate (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. Quartz forms about 70% of the material, and feldspars—about 25%.

[1] The classification of fractions in Lutt (1992) mostly follows that of Friedman *et al.* (1992) 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 mm as coarse sand and fractions with the grain size >2.0 mm as gravel.

The sand layer is usually over 2 m thick. In the northern part of the beach it contains coarse or fine silt, or 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. The layered stratigraphy may reflect the attempts of beach fill; however, as mentioned above, 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 southwards from the river mouth. 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. About 200 m from 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 from the coast).

The transition between the 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 an appreciable amount of fractions of 0.05–1.0 mm, 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 and Tammik 1992; Kask *et al*. 2003).

Bathymetry and sediment texture at Pirita were mapped based on 18 samples collected in 2007 in the nearshore and on the waterline, and 51 samples from the upper 30 cm layer of bottom sediments taken in 2005 over the area between the 11 m depth contour from the northern mole of Pirita Harbour to Merivälja Jetty. The majority of the sampling points in 2005 which yielded about 10 samples are located along five profiles transversal to the coastline down to the 10 m isobath.

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 from the values of ϕ_{84} and ϕ_{16} (Dean and Dalrymple 2002, Chapter 2):

$$M_\phi = \frac{\phi_{84} + \phi_{16}}{2}, \qquad \sigma_\phi = \frac{\phi_{84} - \phi_{16}}{2}, \tag{1}$$

assuming the log-normal distribution of the grain size. The values of ϕ_{84} and ϕ_{16} (Fig. 1.5) represent the grain sizes, from which 84% or 16% of the entire sediment mass has a larger grain size. Their approximate values were found from the cumulative distributions[2] of the grain size (Paper I) with the use of linear approximation.

The sediment on the nearshore submarine slope consists mostly of fine sand in accordance with Lutt (1992) and Lutt and Tammik (1992). The dominating

[2] 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 (ϕ-values –1, 0, $\frac{2}{3}$, 1, 2, $2\frac{1}{3}$, 3 and 4, DIN 4022) was used in the analysis performed in the laboratory of the Estonian Geological Survey and in the Estonian Environmental Research Centre.

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 a depth of about 12 m where fine sediment usually 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 bluff). The average grain size in the nearshore of Pirita is close to 0.12 mm, in accordance with the predomination of fine sand in most of the beach. The sand is better sorted in the shallow nearshore where $\sigma_\phi \approx 0.6$ but poorly sorted in the rest of the beach (Paper I).

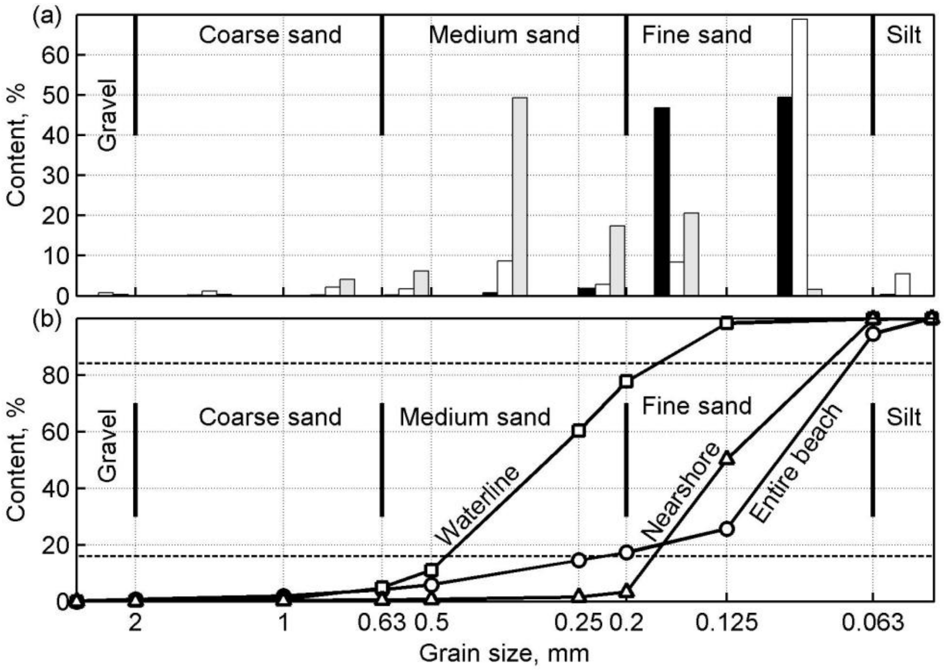

Fig. 1.5. (a) The content and (b) the cumulative distribution of different grain size fractions at Pirita based on samples collected in 2005 and 2007. The averaged properties are shown for sand along the waterline (grey bars, squares), in the area with a depth of ~1 m (nearshore in 2007, white bars, triangles) and for the entire beach (filled bars, circles). The horizontal dashed lines on panel (b) represent 16% and 84% of the sand mass (Paper I)

It is natural to expect several variations in the mean grain size and the content of the fractions within the study area. Deeper areas usually host the finest sediments and the coarser material is concentrated in the vicinity of the breaker line and at the waterline of sandy beaches (Dean and Dalrymple 2002). This is only partially true for Pirita, where a local maximum of the content of coarse sand is recorded solely in the vicinity of the waterline (where the maximum content of medium sand is up to 84% and the mean grain size is much larger than in the rest of the study area) and finer components are found in deeper areas indeed. A probable reason for this phenomenon is the intermittent nature of wave activity at Pirita (where mean wave conditions are very mild but severe wave storms may occur), under which the breaker line is poorly defined and the band of relatively coarse sand does not become evident. This feature is not entirely typical but also not very surprising (Dean and Dalrymple 2002, ch. 2.3.2). It may play an important role in planning 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 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 pattern of the alongshore variation in the content of the major fractions suggests, however, that the entire beach is not in perfect equilibrium. The potential sources of coarser material are located north of the beach (see below, Chapter 2), whereas fine sediments are supplied by the Pirita River mostly to the southern part. Supply of fine sediments was apparently enhanced by the pumping of deposits 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 in the equilibrium state and that the content of coarser sediments is larger in the northern part of the beach where unsorted material is occasionally abraded from the till bluff (Paper I).

Sediments are more heterogeneous and the content of coarser material is greater in the northern sections of the beach. Somewhat surprisingly, the content of silt also increases northwards at greater depths. Heterogeneity may be partly induced by the sand bar stretching over the depths of 4–8 m, but may also reflect the selective blocking of the natural sand supply by coastal engineering structures (Merivälja Jetty and the Port of Miiduranna). The blocking increased the relative importance of the supply of unsorted sediments from the till bluff and the overall limited amount of sand in this area (Paper I). Apart from hydrodynamic factors, the beach refill and dumping of the material dredged from the river mouth and Pirita Harbour basins in the 1970s may have contributed to local variations in the grain size and the content of different fractions.

Based on 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, while there is no band of coarse sand in the surf zone.
- Most of the study area at depths from about 1 m to 6–8 m, extending to about 1800 m from Pirita Harbour, has more or less homogeneous distributions of sand fractions with a clear prevalence of fine sand.
- The deepest part of the nearshore (depths >6–8 m) mostly hosts even finer sand.

1.6. Vulnerability of the coasts with respect to ship wakes

The importance of sea traffic to the hydrodynamic activity of inland waterways and narrow straits was recognised long ago. Ship wakes can cause extensive resuspension of bottom sediments and essentially contribute to shoreline erosion (Nanson *et al.* 1994; Bourne 2000; Gaskin *et al.* 2003), trigger ecological disturbance and harm the aquatic wildlife (Ali *et al.* 1999; Lindholm *et al.* 2001). They may serve as a qualitatively new forcing component of the aquatic ecosystem in open sea areas with low natural wave activity, in particular, in non-tidal areas that are sheltered from long waves (International Navigation Association 2003, International Maritime Organisation 2004). The main concern is the possible impact of direct mechanical disturbances of bottom sediments (Soomere *et al.* 2003; Osborne and Boak 1999), which may lead to potential intensification of sediment transport and beach destruction processes (Parnell and Kofoed-Hansen 2001; Soomere and Kask 2003), and to an overall decrease in the water quality in the areas affected by ship waves (Erm and Soomere 2004).

Recent studies (e.g. Erm and Soomere 2006; Kelpsaite *et al*. 2009) have indicated that both wind waves and waves generated by fast ferries may play an important role in sediment distribution and erosion of the seafloor and shores in Tallinn Bay. There is evidence about rapid loss of sediment from a small mixed sand and gravel beach next to Aegna Jetty (Soomere *et al*. 2009a).

Sediment distribution on the floor of the Baltic Sea is determined by the combination of geological characteristics, the intensity and direction of natural waves and currents, the nature of short- and long-term sea level changes and ice conditions (Schwarzer *et al*. 2003). The influence of wind waves is greatest during the autumn–winter period when sea level is high, but the impact of waves generated by fast ferries is strongest during lower sea level in summer (Soomere 2005b).

The waves generated by fast ferries, having frequently a much longer period than wind waves, can influence the seafloor down to a depth of 20 m, that is, to larger depths than wind waves in strong storms in Tallinn Bay. Several studies (Hannon *et al.* 1999; Kirkegaard *et al.* 1998; Forsman 2001; Parnell *et al*. 2007) have predicted or described the destruction of shores as well as the seafloor by fast ferries' wakes. The fast ferry traffic in Tallinn Bay has greatly intensified since the turn of the millennium and has been considered as a possible reason for coastal destruction in several areas around Tallinn Bay (Soomere *et al*. 2003). Therefore it has become necessary to identify the influence of the ship-induced water movement on seafloor erosion, sediment transport and accumulation, to forecast the influence of waves of different origin and, if needed, to estimate the maximum tolerable anthropogenic wave load in vulnerable shore sections.

Within the framework of a study of potential influence of wakes from fast ferries on the coasts of Tallinn Bay, geological investigations were performed in three areas: the western coast of the Viimsi Peninsula, south-western coast of Aegna and eastern coast of Naissaar (Paper V). The investigations concentrated on the bathymetry, geological setting and structure of bottom sediments in the potentially endangered areas. Detailed works were carried out at smaller sites where high ship wave load was expected, and which were potentially vulnerable to increasing wave loads. On the Viimsi Peninsula the observed shore section extends from Meriválja to Rohuneeme Harbour (about 10 km). On Aegna detailed investigations were carried out on an about 2 km long eroded section north of Cape Talneem (length about 500 m), was considered. On Naissaar an about 7 km long section was studied on the eastern coast of the island. Detailed investigations were performed north of the harbour (ca 450 m long section) and north of Cape Hülkari (ca 500 m long section) in August–October 2001. Repeated observations (mainly by diving and bathymetric surveying) were carried out in all areas in March–October 2002 in order to identify the potential changes in the pattern of bottom sediment distribution. Owing to the extensive spatial coverage of this investigation (which virtually involved the beaches of Tallinn Bay), the results described in Paper V are mostly qualitative and largely based on visual observations.

Although a large part of the listed sections may be frequently affected by long and high waves from fast ferries (Torsvik and Soomere 2008, 2009; Torsvik *et al.* 2009), some of the changes may be of anthropogenic origin. In what follows a qualitative description of some features of the coastal changes along most of the natural coasts of Tallinn Bay is given. The sections considered comprise the south-western and western coasts of Aegna, the eastern coast of Naissaar and the western coast of the Viimsi Peninsula (Section 1.2, Fig. 1.2). The only section left out of consideration is the western coast of Tallinn Bay along the Kopli and Paljassaare peninsulas, which is relatively short and has been severely modified by human activity in the past (R. Nerman, personal information, 2007).

Processes on the western coast of the Viimsi Peninsula were first considered in the framework of the studies into wakes from fast ferries (Paper V), then revisited during investigation of potential sand sources for Pirita Beach (Paper I) and specifically for the study of properties of ship wakes at Aegna (Parnell *et al*. 2008). The eastern coast of Naissaar was re-examined in much more detail during the analysis of the sand deposit at the southern end of this coastal section (Paper III). For these reasons, coastal sections have been studied to a different degree, largely depending on particular purpose of the research. Part of this work is presented also in Chapter 2 in the light of potential changes in the littoral flow along the coast of the Viimsi Peninsula (Paper I).

First of all, the beaches exposed to ship wakes were reviewed and the erosion and accumulation processes were generally estimated. The sections undergoing considerable changes were photographed and mapped. The following sea floor investigations were carried out: bathymetric surveying and sea floor topography, mapping of the distribution of bottom deposits and their composition, occasional diving to describe in detail the character of the sea floor, drilling to determine the thickness and properties of the Quaternary deposits, geophysical surveying and laboratory studies.

The nearshore area and the seabed of the open sea area at the entrance of Tallinn Bay were investigated during two cruises of research vessels *Mare* and *Littorina* mainly by geophysical methods, but also bottom deposits were sampled. From *Mare* a 200 m wide stripe of the sea area around Aegna and Naissaar was studied using the boomer system EG&G, LC–100. From *Littorina*, more detailed investigations of sea floor topography and geological setting east of Naissaar were carried out using a Klein 595 side-scan sonar system and a boomer system (total of about 60 nautical miles). The bathymetric surveying and topographic investigations of the seafloor were conducted with an echo sounder-sonar Interphase PC/180 and echo sounder PEL–3, and navigator Garmin12XL with a differential block. Bottom deposits were sampled with a grip scoop and a corer specially designed for the sampling of soft deposits. More information on these studies is available in Paper V.

In the areas of detailed investigations the surveying of sea floor topography and mapping of bottom deposits were carried out. Grain-size analyses, of bottom deposit samples were performed to determine the distribution of different types of sediments. In the Aegna area 13 temporary piquets were established in order to register the changes in the shore bluff. For the Viimsi Peninsula, results of drill core studies of boreholes made by the drilling rig UGB–1VS of the Geological Survey of Estonia were used in analysis. The Quaternary sequences of the drill cores were described *in situ*. The coastal zones of all observation areas (and some places outside these sites) were investigated also by diving. Textural composition of bottom deposits was determined by sieving at the laboratory of the Geological Survey of Estonia.

Intense wave activity during severe storms may change both the appearance of certain sections of the shore and the sediment distribution, but the usual distribution pattern is generally restored in about 0.5–1 year. Two extreme events have occurred in the last decade: on 15 November 2001 and on 09 January 2005. During these storms the water level in Tallinn Bay reached about 130–150 cm above average and the accompanying intense wave wash eroded parts of shore that normally were not subject to erosion. Thus, large amounts of sediment were released and distributed on the shore and nearshore.

The bottom deposits on most of the natural coasts of the mainland section of Tallinn Bay have been formed under high wave action. There is evidence of intense transport of finer sediments in the entire nearshore. This is clearly reflected in the distribution of bottom sediments, which in the shallow nearshore substantially varies largely at different depths. The zone closest to the shoreline is usually affected by erosion and finer sediments are been carried away. The sea floor is thus mostly covered by pebbles, cobbles and boulders, with sand and gravel between them in only some places. The stone pavement protects the floor from further erosion. Seaward of the erosion zone the pavement alternates with areas represented by sand and gravel. This is apparently a zone of intense sediment transit, locally characterized by coarse sand (and even ripples) and gravel with few pebbles. Further seawards, at larger depths, the bottom deposits permanently consist of fine sand and silt.

1.7. Eastern coast of Naissaar

The eastern coast of Naissaar stretches from south to north-northwest. The shoreline is weakly dissected, except for a few eastwards extending capes, e.g. Cape Hülkari and Cape Virbi, as well as the harbour where sand has accumulated behind a jetty. The coast is relatively high, with some bluffs occur (Fig. 1.6). The forest usually extends to the upper border of the contemporary shore, except in the southern and northern parts of the island. Active littoral flow obviously takes place in the nearshore of the entire eastern coast of Naissaar. At 10–20 m water depth the sea floor is covered with silt, lying on till. Over a depth of 30 m a sediment complex of different Baltic Sea stages or glaciolacustrine deposits are exposed on the sea floor.

Keskmadal is a seafloor elevation covered with pebbles and cobbles, situated 7.2 km from Cape Pikasääre (minimum water depth above it is 1.4 m). Littegrund (minimum water depth 0.2 m) is located 5.2 km from Cape Hülkari, and Naissaar Bank 2.8 km north-eastwards of the island. The central part of Naissaare Bank is covered with pebbles and cobbles. The minimum water depth is 1.9 m. The nearshore on the eastern coast of Naissaar, together with the above-described as well as some other shallow areas, serve as a source for sediment material. The sea floor is covered with sand and silt that originate partly from the eastern coast of Naissaar and partly from the banks consisting of glaciofluvial deposits. The area between the eastern coast of Naissaar and the banks east of it can be treated as a closed system (Lutt and Tammik 1992, Paper I). Large amounts of new sediment material are not deposited here. As the share of fine material (grain size less than 0.063 mm) is small, almost no suspended matter is emitted from the sediments of the area.

Along the shoreline the underlying till is covered with an about 2.5 m thick layer of marine sand. Between the 4-m and 5-m depth contours the thickness of the sand layer abruptly decreases towards the sea. Drillcores from Naissaar and seismoacoustic measurements in the nearshore suggest that Cambrian blue clay occurs about 5.5 m below the sea floor. Approximately 700 m from the shoreline the bedrock surface rises for 10 m and the thickness of till and glaciofluvial sand and gravel decreases. Late- and postglacial clays are found under a thin layer of sand. Seismoacoustic sounding profiles show an ancient valley south-eastwards of Cape Hülkari. The present data, however, are insufficient for determining its extension and direction.

In the north-eastern part of the island, near Cape Virbi, abundant cobbles and pebbles are found in several places on the shore as well as in the nearshore. Such a shore built up of various coarse-grained material, spreads southwards, to the Jurka and Savikalda area. This shore is intensely developing. For example, the severe storm of November 2001 caused considerable changes in it and a bluff was eroded into the formerly flat shore.

On the north-eastern coast of Naissaar, near Savikalda, a more than 9 m high bluff is present in a typical erosion shore consisting of till and ancient marine sands (Fig. 1.6). The backshore in front of the bluff is relatively narrow (5–6 m). The foreshore is composed of pebbles, in some places cobbles. Sand and gravel are less common. The nearshore is gently sloping. The upper part of the bluff consists of 3 m thick medium sands that overlie till. The permeability of sand is high and therefore surface and groundwater flowing out at the boundary between sand and till may easily cause local landslides.

The development of the Savikalda shore bluff was monitored for the last five years. Changes have occurred mainly in spring when landslides happen as a result of winter storms, snow melt water and groundwater. The autumn and winter storms as well have largely contributed to the development of the bluff at Savikalda, whereas in summer changes have been small.

South of Savikalda there is a long, gently sloping, highly variably shore section covered with material of variable grain size. The nearshore is covered with pebbles and cobbles, locally with gravel and sand of different grain size between them, and underlain by till. There are short sections where sand is predominating among shore deposits (e.g. around Lehtmetsa), and some sections contain ancient beach ridges with dunes. In the landward part of the backshore low bluffs are often found in loose deposits, indicating the influence of earlier storms. The five years of monitoring, thus, proved that intense waves may considerably change the appearance of this shore section.

Fig. 1.6. A bluff on the NE coast of Naissaar (near Cape Kasarmukari) and SW coast of Aegna (near Cape Talneem), photos taken in 2002

One of the most extensive sandy shores on the eastern coast of Naissaar lies directly north of the harbour where the generally common pebbles and cobbles are covered by sand. The shore begins south of Sinkarka Reef and extends to the harbour mole. Partially, it has formed due to the existence of the harbour. Landwards of the present shoreline there are partly vegetated ancient coastal beach ridges built up mainly of fine to medium sand. Medium sand is presently found at the shoreline and in the upper part of shore. A narrow strip of coarse, well-sorted gravel occurs in the section closest to the harbour, which is likely subject to intense hydrodynamic activity. The sea floor, closest to the shoreline, is covered with fine to medium sand, while fine sand predominates in the deeper parts. At water depths greater than 10 m fine sand locally alternates with dense silt. The distribution of different sand fractions varies depending on hydrodynamic conditions, but the described zonation is the most typical. The sea floor lowers abruptly directly northwards of the quay of Naissaar Harbour. The 2-m depth contour is located about 30–40 m from the shoreline. The ground surface rises sharply landwards from the shoreline.

The morphodynamics around the harbour suggests that sand is carried from north to south, passing the harbour, because the area behind the jetty is already filled with sand. In relatively short time sand has filled also the mouth of Naissaar Harbour: in 1982 the water depth at the entrance to the harbour was 6.2 m, at the beginning of the 1990s only 2 m, but by 2008 it had decreased to 1–1.5 m. This shows that a large amount of sand was transported to the observation area.

A typical bluff shore lies south of the harbour. Its upper part (about 2 m of its total height) consists of marine sands, the lower part of till. The 2–3 m high bluff is active and its appearance may be substantially modified by autumn–winter storms. Like at Savikalda, surface and groundwater outflows occur at the upper till surface. The shore is narrow, composed of sand, gravel and pebbles. But also abundant cobbles and boulders are found in the coastal zone. The littoral drift is mostly directed southwards, towards Cape Hülkari where the bluff is replaced by a sandy shore with some gravel. This shore is also in active development. For example, the storm of 15 November 2001 caused considerable changes in this area. The landward boundary of the backshore was previously low and flat, but had become much higher, with a steep seaward side by the spring of 2002. This indicates that a large amount of sand had been carried away from this area.

Vessel-induced waves travelling from the ship lane towards Naissaar have to cross Keskmadal, Littegrund and Naissaar Bank. Calculations in Torsvik and Soomere (2008) and Torsvik *et al.* (2009) suggest that ship waves may heavily impact the southernmost section of the eastern coast of Naissaar. Their impact is apparently similar to that of natural storm waves and probably becomes evident as a certain enhancement of littoral flow to the south. An increase in water turbidity when the ship wake reaches the shore (Paper V) indicates that waves generated by fast ferries play some role in sediment transport in this area.

1.8. Western coasts of Aegna and the Viimsi Peninsula

The geological setting of the south-western and western coasts of Aegna is relatively simple. On the shore and in the nearshore area the bedrock is covered by till of the last glaciation, which is overlain by a thin layer of contemporary marine sediments. Further landwards the upper part of the Quaternary cover is composed of sand and in places foredunes occur. Finer sediments have been carried away from the coastal zone of till and a pebble and boulder pavement has formed.

In the northern part of the western coast of Aegna, from Cape Kurikneem down to Punakivi Bank, there is a wide accumulation shore built up of sand and gravel with partly vegetated foredunes. The coastal zone is wide and gently sloping, with abundant pebbles and cobbles. The water depth increases gently and the influence of wave wash on the sea floor is very small in the nearshore. No evidence of direct wave action has been recorded in this shore section and high water events together with heavy waves apparently cause only minor changes.

A 500–600 m long coastal section from Punakivi Bank to Cape Talneem is obviously the most actively developing section on the eastern coast of Tallinn Bay. Traces of erosion are observed in the shore bluff (Fig. 1.6). The shallow nearshore area is fairly narrow. The water depth increases abruptly and the breaker zone is close to the shoreline. The coastal zone consists mostly of pebbles and cobbles, while coarse sand and gravel occur sporadically. The stone pavement is underlain by till, which is spread also further offshore on the sea floor, but is covered by sand there. Although the till shore is protected by the pavement, it has likely been subject to erosion for a long time. In this area the nearshore is steeper and therefore a larger amount of wave energy reaches the shore, causing considerable changes during the high water events and in places formation of the 1–2 m high bluff.

An attempt was made in 2001 to estimate the retreat rate of the coast with the use of some piquets landwards of the bluff. In the autumn–winter period of 2001/2002 the retreat of the bluff was smallest in its south-eastern part (1–2 m), while in the north-western part it was approximately 2–3 m, in places up to 4 m. The retreat was largest in the areas where a pipeline was exposed in the bluff. As most of the changes took place during an extremely high water level, it may be assumed that usually the bluff recedes slower.

The coastal section around Cape Talneem, where the bluff is 2–3 m high, is in active development. Remnants of a stone construction are being largely destroyed by ice and waves. The till shore east of Cape Talneem is spread until Cape Kalavälja and is covered with abundant pebbles and cobbles with few boulders. The whole shore section is vegetated and coastal processes seem to be weak under conditions of average water level. There is, however, evidence of strong erosion that obviously occurs during high water stand when the wave activity influences areas far beyond the average shoreline.

East of Aegna Jetty, the shore exhibits a 2–3 m high bluff. In the vicinity of the harbour the bluff is flattened and vegetated, but is still at times eroded under conditions of high water stand and heavy waves. Pebbles and cobbles occur on the shore and in the nearshore.

A mixed, gravel and sand shore is spread between the jetty and Cape Kalavälja. The thickness of the sand layer is small and pebbles and cobbles are found on the foreshore. Most of this shore section suffers from sediment deficit and accumulation takes place only adjacent to the harbour mole. Small capes made of gravel and pebbles occur at the shoreline. Since 2001 the coastal bluff has retreated and the gently sloping beach has somewhat widened.

The sea floor of the nearshore area (water depth 6–10 m) of the south-western coast of Aegna is covered with pebbles and cobbles, with some gravel and sand. This pavement covers loamy till. At a depth of 10–12 m coarse sand is found sporadically, in places with ripples on its surface. The ripples indicate that waves do affect the sea floor. Unfortunately there is no information whether the ripples were present before the beginning of fast ferry traffic. At the depth of 12–14 m fine sand and silt are locally found on the sea floor.

In the coastal zone of the Viimsi Peninsula, ancient beach ridge systems alternate with exposures of till and Cambrian blue clay. On the shore till is spread from the Merivälja area to the end of the peninsula and is covered by a thin layer of younger deposits, often by sand. Near Pringi and Püünsi villages the thickness of till in the coastal zone decreases and in the northernmost part of the Viimsi Peninsula only 0.10–0.50 m of till lies on Cambrian blue clay. The upper surface of the till bed is inclined towards the sea. In the nearshore till is covered with varved clay and marine sediments. The thickness of contemporary sediments (sand and silt) is small, which indicates that no active sedimentation takes place here.

Most of the western coast of the Viimsi Peninsula northwards from Pirita Beach up to the northern end of this peninsula (cells 2B and 2C in Fig. 1.2) is covered by very coarse material (pebbles, cobbles, boulders). As typical of the northern coast of Estonia (Orviku and Granö 1992), here the amount of gravel and sand participating in the littoral drift is limited and the coast develops under sediment deficit. According to Lutt and Tammik (1992), erosion predominates in the entire nearshore of the Viimsi Peninsula north of Pirita Beach down to a depth of about 10 m. Beach erosion, however, is usually modest since 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 sandstone. Accumulation predominates in the deeper part of the nearshore and in the vicinity of Pirita Beach.

Coastal destruction may occur on the Viimsi Peninsula under conditions of high water level and intense wave action during severe storms. Sometimes a low bluff is formed in coastal sediments, while in other places sediments are accumulated on the shore. However, fine sediments are usually removed from the nearshore and either carried away to deeper sea or transported southwards, towards Pirita Beach.

The influence of storms on the studied shore sections was visually assessed directly after severe storms of 15 November 2001 and 09 January 2005. On the Viimsi Peninsula and Aegna, where the coastal monitoring areas of the state environmental monitoring programme are located, the changes in the abrasion bluff were measured (Paper V).

Near Pringi village the vicinity of the shoreline is normally covered by a stone pavement with few boulders, but after several severe storms there was also much sand. In the neighbourhood of Pringi and Rummu villages, banks, boulders and cobbles are also found on the shore. An extensive shallow sea area, with boulders and cobbles, lies north-west of Rohuneeme Harbour.

The adjacent rather narrow seaward zone, where active sediment transit obviously occurs, consists of medium sand. After some storms the stone pavement covering the till was exposed and sand was present only sporadically. The usual sediment distribution pattern was restored within a few months, whereas changes were only minor during the summer period. More seawards a zone of pebbles and cobbles follows, but the pavement alternates with gravel and sand. Deeper the sea floor is covered by fine sand and silt, yet intense sediment accumulation is not observed. The amount of fine fractions (silt and pelite) is very limited in many nearshore sections of the areas in question, although this material is often eroded from the till shore. Thus, evidently these fractions are rapidly carried away from the areas of their release.

North of the Miiduranna area the coastal zone also often contains a pavement of pebbles and cobbles protecting the sea floor from erosion. Presently, some landing places for boats with moles were constructed of boulders on the shore bordering with Lahe Street. Due to these constructions the energy of waves decreases before they reach the shore and the erosion diminishes. Here the waves generated by fast ferries are usually 0.50–0.80 m high when they reach the shore. Depending on the wave length, the vessel waves may considerably influence sediment transport in certain shore sections. Due to the gently sloping foreshore and the abundance of stones, the waves generated by fast ferries have little impact on shore processes.

The above analysis shows that most of the nearshore of the mainland shoreline of Tallinn Bay is not vulnerable with respect to ship waves, mainly because it is protected by a pavement of boulders, cobbles and pebbles (Paper V). Only a few coastal sections of Aegna and the Viimsi Peninsula (sand, gravel, or mixed beaches) may suffer from the increased wave activity. On the other hand, high impact of ship waves on the coast of Naissaar (that generally has no such a protection) is probable. As the seabed at Naissaar is covered with a layer of relatively fine sediments starting from the depths of about 4–6 m, this area may be strongly affected by long ship waves (Soomere and Kask 2003).

2. Sediment dynamics

Modelling and quantification of nearshore sediment transport is an important challenge in contemporary coastal science. A large number of uncertainties are connected with inadequate knowledge of the properties (spatial distribution) of bottom sediments and bathymetry (e.g. Kuhrts *et al.* 2004). The properties of forcing factors are also usually known only approximately. In many applications, establishing the order of magnitude or direction of sediment transport is considered as a satisfactory result (e.g. Davies and Villaret 2002).

The uncertainties are particularly large in simulations of past events. For example, the resolution of historical wind data is ~22.5º for the wind direction and 1 m/s for the wind speed in the Gulf of Finland basin. The observations have been performed once in 3 or even 6 h. The directional resolution of the wave model used in Paper I (15º) therefore allows reproduction of the wave properties with an acceptable accuracy, whereas the wind data are the largest source of uncertainty. The sampling and survey of bathymetry described above have an effective spatial resolution of about 200 m at Pirita. This resolution allows an adequate representation of wave fields and transport properties for sections with a typical size twice exceeding this value; thus, using the spatial resolution, 470 m of the wave model matches the resolution of the bathymetry. Yet, the results of numerical simulations add valuable information that cannot be extracted from other sources.

In this study the most important numerically evaluated parameters are the largest significant wave height that occurs 12 h a year and which allows an adequate estimate of the width of the equilibrium beach profile. Also, an attempt has been made to reveal numerically the basic features of sediment transport in the vicinity of Pirita Beach. From a large number of factors affecting sediment motion (Soulsby 1997) only wave action in the surf zone is taken into account. This choice reflects the dominant role of wave-induced coastal processes in the evolution of beaches of this type. It also reflects the practical application of the studies that were used in planning the nourishment of Pirita Beach. Finally, the properties and development of two industrial-scale sand deposits near Naissaar and Prangli are discussed. The presentation mostly follows Papers II and III.

2.1. Driving factors of sand transport at Pirita Beach

Sand transport and recycling in a littoral system is usually driven by a large number of processes, such as wave-induced oscillatory motions, wind-induced transport, coastal currents and wave-induced alongshore flows, variations in water level, and, in the latitudes of Tallinn Bay, effects of sea ice. Sea ice may cause extensive damage to the dune forest at Pirita but usually it does not affect the equilibrium beach profile. 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. Tallinn Bay is practically tideless: the tidal range is 1–2 cm in the Baltic Sea and the tidal currents are hardly distinguishable from the other motions (Alenius *et al.* 1998). 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 (09.01.2005, Suursaar *et al*. 2006) and the lowest is –95 cm.

Given the essentially tideless conditions, surface waves play a particularly dominant role in the functioning of Pirita Beach. Since the variations in the water level are small compared to the area covered by sand at Pirita, waves almost always act upon the sandy part of the beach.

Fine sand that predominates at Pirita can easily undergo aeolian transport when dry; however, winds sufficient for extensive aeolian transport are infrequent. The shoreline is almost parallel to the prevailing south-western winds (Soomere and Keevallik 2003). Strong onshore (north-western) 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 foredunes are mostly covered with grass and forest. Only sand seawards from the faceted dune face undergoes active 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 and Teedumäe 1997, p. 291).

Coastal currents induced by large-scale circulation patterns are modest in the whole Gulf of Finland (Alenius *et al.* 1998). Their speed is typically 10–20 cm/s and in only 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 are obviously even smaller (Loopmann and 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 and 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 the decisive role in the functioning of Pirita Beach. This is a typical property of beaches located in microtidal seas.

Waves strongly influence the seafloor when the water depth is less than half the wavelength (Komar 1998). As the highest components of the waves generated by fast ferries are much longer than those of wind waves during even severe storms (Soomere *et al.* 2003), they affect also deeper zones of the nearshore. The periods of the largest waves generated by fast ferries are at least twice longer than the typical period of wind waves. The potential effects of such waves are described in Chapter 3.

The size of sediment particles is an important feature and largely controls sediment transport and distribution. The effect of cohesion is significant for determining the sediment properties if more than 10% of the sediment consists of grains smaller than 0.063 mm. Such mixtures are more resistant to erosion than, for example, pure sand (Soulsby 1997). The above has shown that the content of this fraction is very small in the surf zone along Pirita Beach where sand with the grain size of 0.063–2 mm prevails in the coastal zone and thus the impact of cohesion can be ignored to a first approximation.

Waves can transport sediment material in different ways (Soulsby 1997; U.S. Army Corps of Engineers 2002). Currents and turbulence raise the suspended sediment particles above the sea floor and carry it forwards. When waves break, alongshore currents are formed, which also carry sediments. Transportation may consist in grains rolling, hopping and sliding along the bed. This is known as bedload transport and is the main mode of transport for slow flows and/or large grains. If the flow is fast or the waves are large enough and the grains fine enough, sand will be forced into suspension up to a height of several metres above the sea floor and transported by currents. Such a transport mode is known as suspended load and often considerably exceeds bedload transport (Soulsby 1997). In what follows we do not distinguish these two transport types but use a model that accounts for both of them.

The above discussion has shown that the properties of bottom sediments are more or less homogeneous over the nearshore of Pirita Beach. This allows use of an average value for the grain size for the entire beach. Large storms may bring into motion 200–300 kg/m^2 of bottom sediments in the Baltic Sea (Jönsson 2005, IV-14), that is, the several tens of centimetres thick upper layer. The material presented above and in Paper I confirms that the upper 30 cm layer of sediments is mostly homogeneous at Pirita. Therefore it is reasonable to assume that the active sand layer in the nearshore of the sandy strip of Pirita Beach is homogeneous, except possibly the northernmost sector of the beach. Note that this assumption is not valid for the area north of the sandy beach where the sea bottom of the surf zone is mostly covered by the stone and gravel pavement, with minimal sediment transport.

The wind regime in the Gulf of Finland as well as in the entire Baltic Sea is strongly anisotropic (Mietus 1998; Soomere and Keevallik 2003). The most probable wind and storm direction is from the south-west. The NNW winds are less frequent but, statistically, the strongest in the northern Baltic Proper. During certain seasons strong easterly winds may blow along the axis of the gulf (Soomere and Keevallik 2003).

Tallinn Bay is well sheltered from high waves caused by strong winds coming from many potential directions. The waves affecting Tallinn Bay and Pirita Beach are primarily generated in distant sea areas of the Gulf of Finland. Westerly winds may bring to this area wave components excited in the northern sector of the Baltic Proper (Soomere, 2005a). Its wave climate is relatively mild compared to the open part of the Gulf of Finland and the sea areas adjacent to the bay. The annual numerically simulated mean significant wave height is as low as 0.29–0.32 m in different sections of Pirita Beach for 1981–2002 (Paper II). The significant wave height exceeded 0.3 m (0.6 m) with a probability of 25% (2.5%). The probability of the occurrence of wave heights >1 m was 1%, whereas in the open part of the Gulf of Finland wave heights 2–2.5 m occur with this probability.

The specific feature of Tallinn Bay is that occasionally very high waves reach its interior and cause intense erosion of its coasts (Lutt and Tammik 1992; Kask *et al*. 2003b). They directly attack Pirita during strong N-NW winds that occur with an appreciable frequency. This feature explains why extreme significant wave heights even in the inner region of the bay are comparable with those in the open part of the Gulf of Finland (Soomere 2005a). The significant wave height usually exceeds 2 m each year, may reach 4 m in N-NW and western storms, (Soomere 2005a) and may overshoot 2.5 m in the nearshore of Pirita Beach during NNW storms (Paper I). Dominating wave periods at Pirita in western and NNW storms are close to those in the central part of the Gulf of Finland and generally modest. The typical peak periods are 4–5 s for wave heights below 1 m, about 6 s for wave heights around 2 m and 8–9 s in only very strong storms when wave heights are 3 m or greater (Soomere 2005a; Broman *et al.* 2006). The dominant waves approach the western coast of the Viimsi Peninsula from the western or north-western directions and thus cause southward littoral transport.

2.2. Modelling of wave climate and closure depth at Pirita

The wave climate in the vicinity of Pirita Beach was estimated on the basis of a simplified scheme for long-term wave hindcast in 1981–2002 with the use of a triple-nested version of the WAM model (Soomere 2005a). This model, although constructed for open ocean conditions and for relatively deep water (Komen *et al.* 1994), gives good results in the Baltic Proper, provided the model resolution is appropriate and the wind information is correct (Tuomi *et al.* 1999; Soomere *et al.* 2008). Since waves are relatively short in Tallinn Bay (cf. Broman *et al.* 2006), the innermost model (24 evenly spaced directions, grid step about 1/4 nautical miles (about 470 m); covers Tallinn Bay and its vicinity) allows description of wave properties in the coastal zone, up to a depth of about 5 m and as close to the coast as about 200–300 m (Soomere 2005a). The wave model is forced with high-quality wind data from the adjacent open sea area. The calculations were performed by T. Soomere in the framework of studies towards optimum design of the beach refill and later used as source data for the analysis in Paper I which presents a detailed overview of the calculations of wave climate at Pirita.

The parameters of the nearshore wave climate were computed for five sections of Pirita Beach (Fig. 2.1, Table 2.1). The size of the sectors (470×470 m) matches the grid size of the innermost model. The simulations were performed for the years 1981–2002.

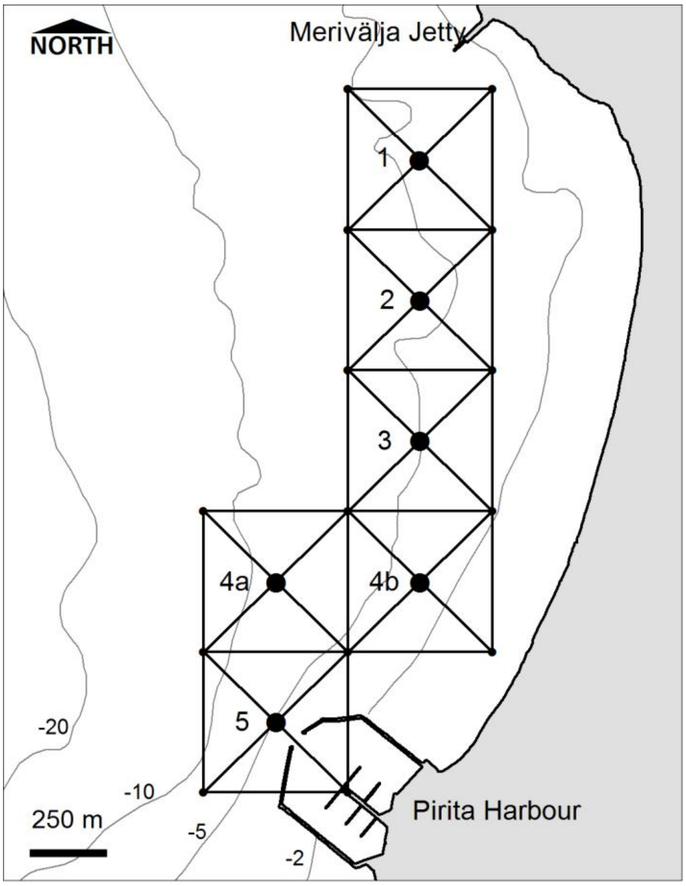

Fig. 2.1. Sectors of Pirita Beach for which wave properties were calculated (at the centroids of the sectors)

The highest waves (the significant wave height H_s, equivalent to the mean height of 1/3 of the highest waves, $H_s = 2.65$ m in the northern part of the beach, $H_s = 2.3$ m in the southern section, peak period about 8 s) apparently occurred at Pirita on 18–19 October 1998. During this night westerly winds of 22 m/s provided favourable wave generation conditions for the Pirita area. The 6-hour mean wind speed was even larger (23 m/s) on 15 November 2001 when the highest ever waves $H_s = 5.2$ were measured in the Gulf of Finland (Pettersson and Boman 2002; Soomere 2005a) but the fetch for winds from this direction (NNW) was much shorter

A significant wave height close to or exceeding 2 m occurred at Pirita about ten times during 1981–2002. Although in some of these cases the actual wave height was smaller than the modelled values because of the ice cover, the presented statistics suggests that the return period of the significant wave height ≥2 m is about two years.

Although a particular beach profile may undergo substantial changes owing to various hydrodynamic forcing, an average of the instantaneous profiles over a long period usually preserves a relatively constant shape called the (Dean's) Equilibrium Beach Profile (DEP, Dean 1991). The temporal and spatial resolution of available surveys (see above and Paper II) is too low for adequate estimate of properties of the DEPs at Pirita. For that reason we rely on theoretical estimates of the shape of the DEP based upon the concept of uniform wave energy dissipation per unit water volume in the surf zone (Dean and Dalrymple 2002, chapter 7). The water depth $h(y)$ along such profiles at a distance *y* from the waterline is

$$h(y) = Ay^{2/3}, \tag{2}$$

where the profile scale factor *A* depends on the grain size of the bottom sediments. Since the dominating grain size insignificantly varies along Pirita Beach, it is adequate to use a fixed value of the factor *A* that corresponds to the overall average grain size (Dean *et al.* 2001) of 0.12 mm (Paper I). The factor *A* is approximately 0.07–0.08 for the northern and about 0.063 for the southern part of the beach.

Another basic parameter of the equilibrium profile is the depth of closure $h*$. It is defined by Kraus (1992) as the depth where repeated survey profiles pinch out to a common line. It represents the maximum depth at which the breaking waves effectively adjust the whole profile. Seawards from the closure depth waves may occasionally move bottom sediments but they are not able to maintain a specific profile. Several authors have suggested empirical expressions for $h*$ based on measures of wave activity. It has been shown in Paper I that simple approximations such as the one proposed by Houston (1996) based on the annual mean significant wave height substantially underestimate the closure depth at Pirita. This is a generic feature: simplified models are frequently inappropriate for semi-enclosed, bayhead areas where the decisive factor in forming the wave conditions is the match of the geometry of the sea area with the anisotropy of the wave field (cf. Caliskan and Valle-Levinson 2008). In such areas the estimates of the closure depth should be based on more detailed information about the wave fields. At Pirita the reason is a specific feature of wave climate in the Baltic Sea: the average wave conditions are mild, but very rough seas may occur episodically in long-lasting, strong storms (Soomere 2005a; Broman *et al.* 2006; Soomere and Zaitseva 2007). Moreover, the strongest storms in the Gulf of Finland tend to blow from directions from which winds are not very frequent (Soomere 2005a; Soomere and Keevallik 2003).

It is demonstrated in Paper I that the expression (Birkemeier 1985)

$$h* = 1.75 H_{s,0.137} - 57.9 \frac{H_{s,0.137}}{g T_s^2} \tag{3}$$

gives a reasonable approximation for the closure depth h^*. Here $H_{s,0.137}$ is the threshold of the significant wave height that occurs 12 h a year, that is, the wave height that is exceeded with a probability of 0.137%, and T_s is the peak period in such wave conditions.

The existing wave data sets (Orlenko *et al.* 1984) and atlases (Lopatukhin *et al.* 2006) do not provide reliable information about the value of $H_{s,0.137}$ for sea areas adjacent to Pirita. Contemporary wave measurements in the central part of the Gulf of Finland (Pettersson 2001) cannot be directly extended to the Tallinn Bay area because of a specific combination of geometry of the bay and wind regime in this area. For the listed reasons, the numerically modelled properties of the local wave climate are used for an estimate of the closure depth in Paper I. The calculated time series of wave properties (significant wave height, wave period and propagation direction) along about 470 m long sections of the beach were used to estimate the closure depth and to evaluate the sediment transport patterns.

The threshold for the significant wave height occurring with a probability of 0.137% (12 h a year) is 1.45–1.58 m for different sectors of the beach. The typical peak period T_s in such storms is about 7 s (Paper II). These estimates lead to reasonable values of 2.36–2.57 m for the closure depth in different sections of the beach that match the bathymetric survey data (Paper I). With the approximate value of the scale factor $A = 0.07$, the width of the equilibrium profile is estimated to be about 250 m and its mean slope approximately 1:100 at Pirita.

The presence of ice is ignored in the calculations in Paper II. Statistically, the ice cover damps waves either partially or totally during the most windy winter season. Therefore, the computed annual mean parameters of wind waves are somewhat overestimated and represent average wave properties during the years with no extensive ice cover.

Since the wave modelling technique in use relies on the one-point wind from the central part of the Gulf of Finland, it may fail to represent correctly wave conditions in a few strong storms in which the wind speed in the northern Baltic proper may vary substantially from that in the Gulf (Paper II). Such a situation actually occurred in January 2005 (Suursaar *et al.* 2006). Therefore the above estimates should be interpreted as the minimum values of the closure depth.

2.3. Modelling of sediment transport at Pirita

Following the U.S. Army Corps of Engineers (2002), the intensity of alongshore sediment transport is estimated in terms of its potential rate Q_t in Paper I. This measure expresses the volume of sediments carried through a cross-section of the beach in ideal conditions within a unit of time. An equivalent measure is the potential immersed weight transport rate

$$I_t = (\rho_s - \rho) g (1 - p) Q_t , \qquad (4)$$

which accounts for voids between sediment particles and the specific weight of the sediment components. Here ρ_s and ρ are the densities of sediment particles and sea water, respectively, g=9.81 m/s^2 is the acceleration due to gravity and p is the porosity coefficient. The sign and the value of the integral of the transport rate show the dominant direction and the magnitude of net transport, respectively. The ratio of the net to bulk (the integral of the modulus of the transport rate) potential transport characterises the intensity of transit of sediments through the section in question compared to the back-and-forth motions.

The actual transport is usually much smaller than the estimated net or bulk potential transport. The difference is particularly large when the sediment layer is not continuous (as it is northwards from Pirita) or has a limited thickness. In fact, the difference between the estimates for different sections of the beach carries the key information about their particular role in sediment recycling and about their potential vulnerability to changes in sediment transport processes. Another key quantity is the ratio of net to bulk transport rates. It characterizes to some extent how vulnerable a section is with respect to changes at a particular side.

Details of calculations are presented in Paper II. The key method in use is the so-called CERC (*Coastal Engineering Research Council*) method to estimate the potential transport rate (U.S. Army Corps of Engineers 2002). It is based on the assumption that the potential transport intensity is proportional to the shoreward wave energy flux (also called wave power in some coastal engineering applications), with a proportionality coefficient reflecting the properties of sediments. The wave energy flux and the direction of wave propagation are estimated with the use of the above-described application of the WAM model. Since the majority of sediment transport occurs in the surf zone, these properties are found at the seaward border of the surf zone where the waves can be reasonably well described as long waves.

The results of the modelling of the potential rate Q_t of annual sediment transport based on wave conditions in 1982–2001 for three values of the mean grain size suggest that the transport rate (consequently, also the overall functioning of the sedimentary system at Pirita) only weakly depends on the particular grain size (Paper II). Sand transport at Pirita is thus almost entirely governed by the match of the wave propagation direction with the geometry of the coast, and potential changes in the transport patterns when the grain size is modified, e.g. through beach refill, are fairly modest.

The bulk potential transport rate in the northernmost sector evidently exceeds the actual transport by about two orders of magnitudes. The transport may have been more intense under natural conditions, before the Port of Miiduranna and Merivälja Jetty were constructed, but even then its actual intensity was much smaller than the estimated value because of the limited amount of finer sediments in the system. One could estimate the actual magnitude of littoral drift based on the accumulation rate in the vicinity of the Port of Miiduranna and the dredging requirement of its fairways – data which are currently not available.

The estimates of transport in the southernmost sectors do not necessarily match reality because of the blocking and sheltering effect of the moles of Pirita Harbour. The bulk rates of potential transport in the middle sections 3 and 4 of Pirita Beach are apparently reasonable and give a flavour of the intensity of coastal processes in the area whereas the net rates seem to be overestimated.

The ratio of bulk to net potential transport rates reveals a basic pattern of sediment transport (Paper II). The transport in the northernmost sector is almost (>90 %) unidirectional southwards. This sector therefore hosts intense sediment transit and any decrease in sediment supply generally leads to an acute sediment deficit and potential beach erosion. This is exactly what is observed in the area where the sandy strip ends. The till bluff is intensively eroded; in places at a rate of up to 1 m/year.

There is no predominating sediment transport direction in sector 2. The reaction of the beach to a decrease in sediment supply from the north is evidently milder. This sector possesses a revetment built in the 1980s along the dune toe. During the two decades, waves have eroded the protected part of the dune so that part of the revetment is located in the middle of the sandy strip today (Paper I).

Somewhat surprisingly, numerically modelled net sand transport shows certain prevalence of northward flux in the middle and southern sectors (3–5) of the beach, although observations suggest a slight domination of southward sediment flux. The inconsistency may reflect specific conditions within different study periods. It may also stem from the uncertainties of modelled wave fields, caused by the use of the single-point wind field from a remote measurement site and by an insufficient resolution of the propagation direction of waves approaching Pirita. As explained above, much of these uncertainties are connected with generic vagueness of the existing wind data. Another potential source of error is the spatial resolution of the innermost wave model (1/4 miles). Although the grid is uncommonly fine for open sea wave studies, it may still not be sufficient for proper resolving of effects of wave refraction on small-scale bathymetric features of Tallinn Bay. In general, it is clear that estimates of the sediment transport direction for Pirita Beach are very sensitive with respect to the accuracy of numerical reproduction of wave parameters.

Generally the small ratio of the net to bulk potential transport rates indicates that no predominating transport direction exists in the area. This feature, combined with the overwhelming prevalence of southward transport in the northern sectors, implies that sand accumulation should take place in the middle and southern sectors of the beach. While certain accumulation indeed occurs in the southernmost sector, the middle sectors show no obvious accumulation features. The position of the shoreline has remained almost unchanged since 1980, although land uplift together with accumulation should have led to the widening of the dry beach. On the contrary, a certain amount of dry sand has likely been eroded from this section between 1997 and 2006 (see Paper I and Chapter 3).

The above discussion, together with the evidence of apparent sand loss from the area, suggest that an interesting (albeit somewhat speculative) pattern of sand motion may characterize Pirita Beach. If the northward transport actually slightly predominates, sand loss to offshore mostly occurs from the middle sections 2 and 3. This feature may be one of the reasons why beach renourishment by placing sand in the middle of the beach had limited positive influence (Paper II). This hypothetical pattern may also support the existence of the wide and low sand bar at medium depths, which seems to stem from the middle section of the dry beach.

Table 2.1. Potential transport rate along Pirita Beach for different sectors (Fig. 2.1). The rates are presented for the following fractions: $d_{50} = 0.063$ mm (fall velocity 5.1 cm/s), $d_{50} = 0.1$ mm (fall velocity 6.4 cm/s) and $d_{50} = 0.2$ mm (fall velocity 9.1 cm/s)

Sector No.	$d_{50} = 0.063$ mm			$d_{50} = 0.1$ mm			$d_{50} = 0.2$ mm		
	Potential transport rate 1000 m^3/year			Potential transport rate 1000 m^3/year			Potential transport rate 1000 m^3/year		
	Bulk	Net	%	Bulk	Net	%	Bulk	Net	%
1	626	–574	–92	610	–560	–92	592	–543	–92
2	191	0.2	0	184	2	1	176	4	2
3	170	17	10	164	18	11	156	18	12
4a	202	26	13	194	27	14	186	28	15
4b	174	22	13	168	22	13	161	23	14
5	187	36	19	180	36	20	173	37	21

2.4. Sand deposits in the nearshore of Prangli and Naissaar

The results of the studies of Prangli and Naissaar sandbanks (Fig. 1.2) are described in detail in Paper III. These banks are overlying somewhat different bedrock formations. In the region of Prangli, the crystalline basement is covered by the sandstones of the Kotlin Stage (Vendian) (Suuroja *et al.* 2002). Vendian sandstones form the cores of almost all islands and banks in the area. The Vendian Kroodi Formation of the Vendian is represented by weakly- to medium-cemented yellowish-grey sandstone. At different levels up to 1 m thick interbeds of argillaceous siltstone are found. In places an up to 2 m thick basal bed, consisting of coarse-grained sandstone, gravellite, fine conglomerate or mixtite lies at the lower boundary of the Kroodi Formation, In the upper part of the Kroodi Formation the up to 8 m thick Kannuka Member is distinguished, comprising coarse-grained siltstone to medium sandstone.

In the region of Naissaar, the bedrock is represented by the Vendian (Upper Proterozoic) and Cambrian terrigenous complex. The Vendian rocks are mainly sand- and siltstones with argillaceous interbeds, while the Cambrian rocks are represented by the clay of the Lontova Stage.

The formation and distribution of sand deposits have been related to the Quaternary deposits covering the seafloor in the surroundings of Prangli and Naissaar (Suuroja *et al.* 2002). The older Quaternary deposits are found in small areas only but also in the depressions eroded into bedrock. On Naissaar and Prangli, the till is covered with glaciofluvial deposits. The older tills are overlain by the till of the Järva Formation of variable thickness. The tills in the region under discussion contain a large proportion of pelite fraction, less well-rounded, coarse-grained fraction, and an equal percentage of sand and silt. The Järva Formation is divided into two parts: glaciofluvial (Naissaar) and glaciolacustrine (Prangli) deposits.

The till of the last glaciation (Järva Formation) and glaciofluvial deposits are covered with late glacial varved clays and postglacial clays. The topmost layer of the seafloor deposits consists of deep-water pelite and silt, probably formed during the Litorina and Limnea Sea stages.

The field work described in Paper III was carried out from the research vessel *Junikon* which has equipment for both remote geophysical investigations (continuous seismoacoustic profiling and echosounding) and drilling. The upper portion of bottom deposits was investigated by continuous profiling that allowed defining the boundaries of the seabed layers of different density with a resolution of 0.3–0.5 m. The results were interpreted together with the drilling results in order to determine the thickness of sand layers. Drilling was performed by the vibratory (in total 30 points in the Prangli and in 46 points in the Naissaar sand deposit) and, when necessary, rotary methods down to the varved clay base of the sand deposit. The drilling points were selected on the basis of seismoacoustic profiling results. A detailed description of the work and technical parameters of the devices is presented in Paper III. Using the bulk sampling method, 70 samples were taken from the Prangli and 64 samples from the Naissaar sand deposit.

The main quality indicators of sand in this context are the fineness modulus and the content of the <0.05 mm fraction (silt and pelite). See Annex 5 of the regulation of the Minister of the Environment of the Estonian Republic no. 29 of 22 June 1995 "Guidelines for applying the requirements of mineral exploration for sand and gravel."

The grain-size distribution of the samples collected was determined by sieve analysis on the board of *Junikon* and at the Laboratory of the Geological Survey of Estonia. The sieving was carried out according to the requirements of "Guidelines" mentioned above. The set of sieves with the sieve size (in mm): 10, 5, 2.5, 1.25, 0.63, 0.315, 0.16 and 0.05 was used. The fineness modulus F_m of sand was calculated as $F_m = (A_{2.5} + A_{1.25} + A_{0.63} + A_{0.315} + A_{0.16})/100$, where $A_{2.5}$ etc. is the fully retained mass of sand on the sieve. The "Guidelines" establish that the sand qualifies as building sand if the fineness modulus is 1.3 or more and the share of the <0.05 mm fraction is less than 10%. The classification of sand applied in this study (Table 2.2) is based on the fineness modulus.

Table 2.2. Classification of sand according to its fineness modulus

Class of sand	Fineness modulus
very coarse sand	>3.0
coarse sand	2.5–3.0
medium sand	2.0–2.5
fine sand	1.5–2.0
very fine sand	1.0–1.5
extra fine sand	<1.0

The results of the analysis confirmed that both Prangli and Naissaar deposits contain sand of various grain sizes forming layers with highly variable thickness.

At Prangli a narrow stripe of very coarse to fine sand surrounds the outcrop area of till in the north-western part of the sand deposit. In the northern part of the deposit a layer of coarse sand (about 0.5 m thick) and in the north-western part very coarse sand (thickness up to 0.3 m), overlie extra fine sand. The thickness of the sand deposit increases towards Prangli and achieves its maximum (extra fine sand, 7.8 m) in the northernmost part of the study area. In the western part of the sand deposit, closer to Prangli, a lens of sand with a fineness modulus of >1.3 occurs. In the seaward part of the cross-section, there is a lens of sand with a fineness modulus <1.3, which wedges out.

The base of the Naissaar sand deposit consists of till or glaciolacustrine varved clay, irregularly alternating within the investigation area. The thickness of sand (fineness modulus mainly <1.3) varies greatly, reaching a maximum of 9.7 m in the eastern part of the deposit.

The sand with a fineness modulus of <1.3 occurs probably as lenses, because, it is missing in some areas. Within the Naissaar deposit, this sort of sand is covered with somewhat coarser sand (fineness modulus >1.3), up to 8.8 m in thickness (south-eastern part of the deposit). The greatest total thickness of the sand complex is 11.2 m in the south-eastern part of the deposit. Unlike in Prangli, the sand in the Naissaar deposit usually shows no clear lamination. This feature is evidently connected with the difference in the processes that have driven the formation of these two deposits.

Extra fine (fineness modulus <1) and fine sand (fineness modulus 1.5–2.0) predominates in the Prangli sand deposit. Medium and very coarse sands form each 3.1% of the samples collected and the share of coarse sand is 1.5%. In the Naissaar deposit, the sand is mostly very fine (fineness modulus 1.0–1.5). Very coarse sand (fineness modulus >3), however, occurs sporadically in the upper part of the deposit. The fineness modulus is greatest (4.23) in the north-western part of the Naissaar sand deposit, where very coarse sand lies on till. The smallest fineness modulus (0.22) was recorded in the south-western part of this deposit. In general, coarse and very coarse sand are distributed in the central part of the deposit, fine to extrafine sand dominate in its south-western part.

2.5. Formation of Prangli and Naissaar sand deposits

The above-described sand deposits at Prangli and Naissaar are located in similar geomorphic conditions, near the southern ends of medium-sized islands (Fig. 1.2), and in basically similar wave conditions. Therefore it is natural to assume that these deposits have apparently formed as a result of wave erosion in the coastal zones of these islands. The coarse-grained material of till (pebbles, cobbles and boulders) remained in the coastal zone, while waves and currents carried finer particles (gravel, sand and silt) to the south. This process usually results in the formation of vertically quite homogeneous sand bodies. The difference in the vertical structure of the two deposits, however, raises the question whether the deposits have developed under similar conditions.

The above description of the properties and main geomorphic features of the eastern coast of Naissaar suggest the following basic sediment transport pattern in the coastal zone of the island. Like the eastern coast of Naissaar, the deeper underwater part of its western coast is covered with a pebble and cobble pavement and the backshore is often covered with sand. The typical direction of approaching large waves is such that this sand is carried to the sea and southwards during high water stand and intense wave activity. The northern and southern coast of the island are sodden till shores, which serve as a source of finer sediment. As said above, in the coastal zone on the eastern coast of Naissaar the material is of variable grain size – ranging from sand to boulders. In two places abrasional bluffs in till and ancient dunes are found. Large areas on the seafloor are covered with sands of various grain sizes.

The southward transport of sand along both the western and eastern coasts of Naissaar is one of the main reasons for the formation of a prominent accumulation area of sand near Cape Hülkari in the south-eastern part of Naissaar. Very likely its core is a till ridge, extending towards the southeast. Waves and currents have carried the sand fraction of eroded material to this area. Due to active hydrodynamic processes a large amount of the material eroded in the coastal zone has been first well sorted along its long way on the coast, and finally deposited on the seafloor to the southeast and south of Naissaar. The World War II bombshell cases buried at a depth of several metres in sand and the overall small vertical variations in the properties of sand.

The western and northern coasts of Prangli are mainly covered with a pebble and cobble pavement. Wave erosion is insignificant these areas, the sea floor is only weakly eroded and sediment transport is small. The eastern coast of Prangli contains several sandy beach sections, but pebbles and cobbles are also found in the deeper underwater part of these sections. The capes formed on the south-eastern and south-western coasts of Prangli prove that sediment flow is from north to the south, although the magnitude of this flow seems to be quite limited.

The layered structure, however, is a fairly typical feature of different sand deposits located along the North Estonian coast. While in the Pirita Beach area such a layering may partially reflect attempts at beach fill (see below and Paper II), a qualitatively similar depositional sequence of fine bottom sediments occurs also in sandy areas next to North Estonian river mouths (Lutt 1992, p. 215, Paper II). It may therefore be hypothesized that part of the sand deposit at Prangli has been formed under conditions similar to those that have shaped sand bodies on the northern coast of Estonia – although one could expect that the properties of sand deposits at Prangli and Naissaar are more similar to each other.

The deposit at Prangli has apparently been formed in varying hydrometeorological conditions where different layers and/or sand with different properties have been deposited under different dominating processes. The deposit at Naissaar, however, has evidently been formed predominantly under the influence of wave-driven erosion of the coastal bluff, followed by littoral drift and sand recycling and sorting under wave action.

3. Anthropogenic impact

It has shown above that Pirita Beach is an example of a bayhead beach, the natural evolution of which takes place mainly under wave action in almost tideless conditions. In natural conditions sediment accumulation predominates in the deeper part of Tallinn Bay and in the vicinity of Pirita Beach (Lutt and Tammik 1992). Although this process is of modest intensity because the amount of finer sediment is limited, the beach apparently developed in a stable manner until the 1970s. Since then, its stability has been discussed for several decades (e.g. Orviku and Veisson 1979; Orviku 2003, 2005). The common opinion is that Pirita Beach has obviously suffered from sediment deficit during the last decades and its active sand volume is seems to be decreasing.

One of the potential reasons for beach destructions is the overall increase in the storminess in the Baltic Sea basin since the 1960s (Alexandersson *et al.* 1998). This process may be reflected in the increase in the intensity of NNW winds from the 1970s (Soomere and Keevallik 2001). The waves excited by NNW winds and high water conditions may cause substantial damage to Pirita Beach, as was observed after the storm of 15 November 2001. For several decades such changes in natural forcing have been considered to activate coastal processes in general (e.g. Bird 1981; Orviku and Granö 1992) and also at several Estonian beaches (Orviku *et al.* 2003).

Another most probable reason for the damage to Pirita Beach is the anthropogenic influence: its sand supplies have been considerably affected by extensive coastal engineering activities.

In this chapter the major sand supplies to Pirita Beach are analysed and qualitative changes in their magnitude caused by different coastal engineering structures are described. Further on a quantitative estimate of the resulting net sand loss from the sandy beach is constructed, based on the theory of the equilibrium beach profile and its properties at Pirita established in Chapter 2. Finally, some specific properties and potential impact of wakes from fast ferries in the nearshore of Tallinn Bay are discussed.

3.1. Sediment sources for Pirita Beach

The largest natural supplies of sediment to Pirita Beach in the past have been the adjacent Pirita River and littoral transport along the coast of the Viimsi Peninsula (Fig. 3.1). A local source of sediments is the till bluff between the northern end of the beach and Merivälja Jetty. The bluff is frequently subject to direct wave action. Sand may also be eroded from the foredunes 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 (Paper I).

The above description of the basic properties of the wave climate in the nearshore of the beach and estimates of the intensity and direction of the littoral flow suggest that major inflow of sediment to Pirita Beach takes place owing to southward littoral transport of material eroded from different sections of the Viimsi Peninsula.

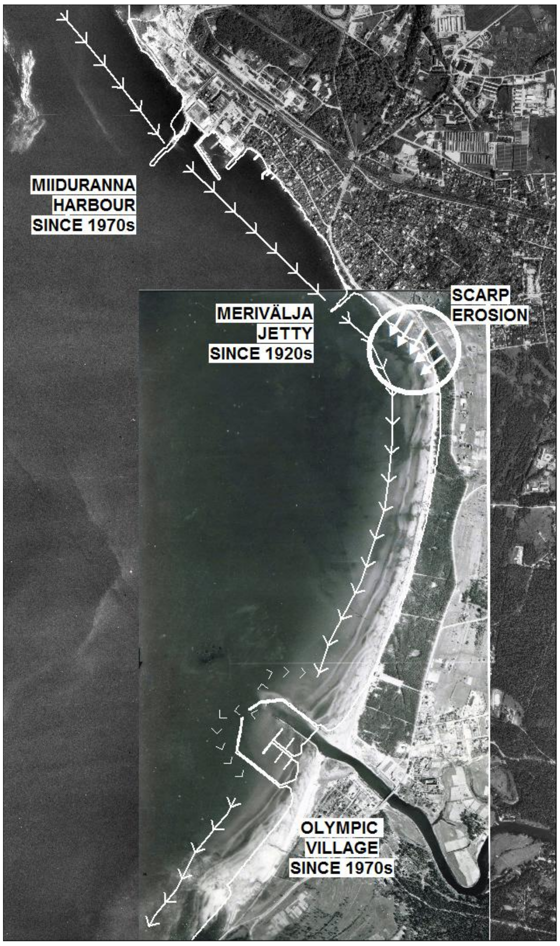

Fig. 3.1. Basic sediment transport and supply processes at Pirita Beach in natural conditions: natural alongshore transport (arrows along a continuous line), river-induced sand supply (small triangles) and bluff erosion at the northern end of the beach (bold arrows). The contemporary shoreline (white line) is given according to 1:50 000 Estonian Base Map from the Estonian Land Board (www.maaamet.ee). From Paper I

The nature of the shore has undergone very limited changes north of the Port of Miiduranna. The coastal zone of this peninsula is built up mainly of till of variable content of coarse-grained material (see also above, Section 1.8). The till shore begins in the Merivälja area and spreads up to the end of the Viimsi Peninsula. Plants grow in the upper part of the backshore which indicates that the intensity of shore processes is low. In several places on the shore there exist beach ridges made of sediment material of variable grain size – from fine sand to boulders. Abundant pebbles, cobbles and boulders occur almost everywhere on the shore and in the nearshore protect them from further erosion.

Finer sediments (clayey material, sand and gravel) are usually found in places between the pebbles and cobbles both on the shore and in the nearshore. This feature suggests that the amount of finer sediment participating in the littoral flow is fairly limited. The most vulnerable with respect to wave action are the former onshore bluffs that may be severely eroded under joint influence of high water level and large waves. Sediment accumulation occurs only locally in some coves.

A shallow bay with a sandy backshore lies between Miiduranna and Pringi. In the landward part of the shore there occur foredunes covered with plants. The sandy shore continues up to Cape Pringi. The nearshore is wide and gently sloping, therefore high waves break before they reach the shoreline and even the strongest autumn and winter storms usually do not considerably influence the shore processes. A presently flattening and vegetated bluff on the southern coast of Cape Pringi gives evidence of former intense erosion.

Northwards of Pringi Harbour the shore is more exposed and subject to (more) intense wave activity. Great changes have taken place close to Pringi Harbour and the bluff has retreated for about 1 m during the November 2001 storm. Further northwards, on the shore in front of the Viimsi open-air museum, the till shore, although mostly covered with a protecting pebble-cobble pavement, is subject to both erosion and accumulation. The shore bluff is eroded in ancient beach ridges. Further northwards from the Viimsi museum, the shore is sheltered by a shoal located a few hundreds of metres from the coastline and extending almost to the south-western end of Aegna. The nearshore is gently sloping and wave breaking usually occurs far away from the shoreline. The appearance of the shore changes only a little even in very strong storms.

In recent years, several small landing places and harbours have been built or reconstructed on the western coast of the Viimsi Peninsula. They may have locally changed the hydrodynamic processes in the coastal zone, but obviously their influence on the entire littoral system is minor.

Dominant waves approach the Viimsi Peninsula from the west or north-west (Soomere 2005a) and thus cause southward littoral transport. This direction becomes visible also from accumulation features north-westwards from the Port of Miiduranna and Merivälja Jetty. The potential rate and variability of the littoral transport were established in Paper II.

The magnitude of this flow is limited by the amount of available sediment in the system. Technically, erosion predominates in the entire nearshore of the Viimsi

Peninsula northwards from Pirita Beach out to a depth of about 10 m (Lutt and Tammik 1992). Beach erosion, however, is not necessarily active since the vicinity of the shore is mostly covered by an armoured or lag pavement of pebbles, cobbles and boulders (Paper V) and postglacial uplift favours the increase in the dry land area. The nearshore has a limited amount of gravel and sand, as is typical of the northern coast of Estonia. Finer fractions are only released from the bluff during storm surges when waves directly affect unprotected sand or till.

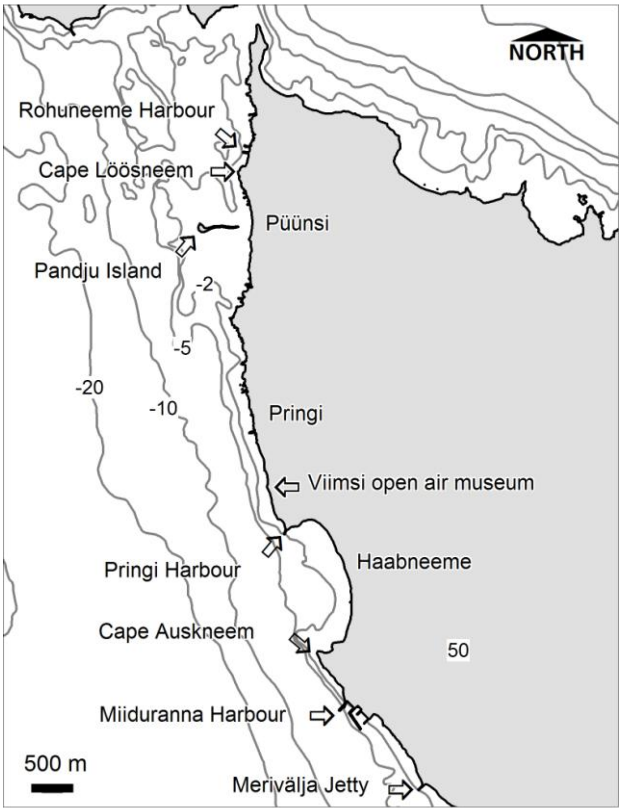

Fig. 3.2. North-western coast of Viimsi Peninsula

An aerial photo of 1951 (Fig. 3.1) demonstrates the presence of a well-defined ridge and a runnel or multiple bar system along Pirita Beach. Contemporary surveys show clearly less sand bars. Its geometry of a single bar in the north splitting to multiple bars in the south is consistent with the southward net littoral drift and greater available sediment in the beach system trapped by the mole.

This is opposite to the usual eastward littoral drift along straight sections of the southern coast of the Gulf of Finland (Orviku and Granö 1992; Laanearu *et al.* 2007) and reflects a specific feature of the semi-sheltered bayhead which is only attacked by waves coming from a few directions.

The Pirita River, a typical small river among those falling into the Gulf of Finland, is shallow and has a limited discharge (about 0.2 km^3 annually, Lutt and Kask 1992, p. 146). It provides about 1040 tonnes (about 400 m^3) of suspended matter annually (Lutt and Kask 1992, p. 149). Most of the material (74%) has a grain size from 0.01 to 0.05 mm and about a quarter has a size from 0.0025 to 0.01 mm (Lutt and 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 further to deeper areas.

The role of wind-induced sediment transport and aeolian foredune recovery has apparently been larger in the past when the coastal forest was young, the sandy strip was wider and local sandstorms occurred (Raukas and Teedumäe 1997). The contemporary narrow beach is oriented parallel to the dominating south-western winds (Soomere and Keevallik 2003) and is partially sheltered by the ever increasing number of high buildings of the city of Tallinn. Strong onshore (north-western) winds typically blow either during the late stage of storms or during the autumn months when sand is wet. As a result, the intensity of foredune building is modest and the height of the existing dunes is a few metres.

Dumped, at least partly sandy, dredged material has also increased the active sand mass of the beach in the past. From the late 1950s, sediments from the river mouth were pumped to the northern side of the mole, but no reliable data are available about the sediment size and volume of the dredged material (Paper II).

3.2. Changes to the littoral flow and river-induced sand supply

A number of coastal engineering activities have largely modified the nature and magnitude of sediment sources to Pirita Beach during the last century. A detailed overview of such works is given in Paper I.

Several major development works (such as the construction of Merivälja Jetty, the Port of Miiduranna, and a revetment and seawall at the northern end of Pirita Beach) that indirectly but substantially affect the beach have been performed northwards of the beach. As a result, the littoral drift has also undergone major changes.

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 (Fig. 3.3).

Fig. 3.3. Remnants of the revetment in the northern part of Pirita Beach

The till bluff north of the beach, which was subjected to direct wave action under storm surge conditions, was protected by a seawall in 2006–2007. Its effect on the functioning of the beach is apparently minor and consists in a certain reduction of the volume of finer sediment eroded from the bluff.

Merivälja Jetty close to the northern end of Pirita Beach, today a simple straight construction that extends out to about 3 m water depth, was constructed in 1925–1927 with a slightly different geometry. The jetty was extensively damaged over about two decades and was reconstructed at the end of the 1960s.

The local shore processes are evidently influenced by Merivälja Jetty. Northwards of the latter a small amount of mixed gravel and sand sediments has been deposited on the shore. This accumulation feature obviously is not yet in equilibrium, because it usually widens after large storms such as the November storm of 2001 (Kask and Kask 2002). The jetty somewhat shelters a short coastal section nearby, where the erosion of the shore bluff has diminished and the old erosion bluff was partly grown over with plants around the turn of the century. In November 2001, however, the bluff was eroded again, sediments were loosened from its lower part and the upper part fell down. More southwards of the jetty erosion predominates, but the massive pebble-cobble pavement protects the shore.

Merivälja Jetty probably largely blocked southward littoral drift of coarser sediment from the 1930s onwards, but evidently had a minor role to the transport of finer sediments at depths >3 m. Such selective blocking is obviously insignificant today when the Port of Miiduranna (see below) is the major obstacle. Although the Jetty somewhat sheltered the till bluff at the northern end of Pirita Beach, the abrasion rate of the unprotected bluff section may have increased.

While the construction of Merivälja Jetty diminished the transport of coarser sediments, major changes to the littoral transport occurred after the construction of the Port of Miiduranna in the 1970s at an earlier landing place for small fishing boats. This large (in Estonian scale) complex was built as a fish harbour and a basis for ship maintenance, 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 a natural depth of 6–8 m (Estonian National Maritime Board 1998).

The depth of the fairway and the deepest basin were increased to 13 m at the turn of the millennium.

The port almost completely blocked the littoral drift of coarser sediments, because the closure depth at Miiduranna is only insignificantly larger than at Pirita (2.5 m). 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 seems to be 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.

As a direct consequence of cutting down the littoral drift, the shore bluff is frequently eroded between the jetty and Miiduranna area during high water level and intense wave conditions. Directly southwards of the Port of Miiduranna the shore has retreated for a long time since the port was built. The intensity of erosion is still limited by the pebble-cobble pavement.

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, personal communication 2006). The first industrial-scale attempts to protect the mouth and dredging activities stem from the 1920s. A small mole was constructed along the southern coast of the river in 1922 by the Estonian Maritime Administration (Paper I, historical facts provided by R. Nerman). This solution apparently enhanced 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. Therefore the water depth might have been even less than 1 m during other seasons. A larger groin that extended out to 3 m deep water was first built along the northern river coast. 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 seem to have had a twofold role in the coastal processes. They evidently interrupted for some time alongshore sediment transport. For a certain time, the coastal processes in sediment transport subcells 2A and 2B (see Chapter 1, Fig. 1.2) were completely separated. Fluvial sand transport for a while entered the over 3 m deep sea area outside the equilibrium profile, 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. 3.4). Later 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 and Tuulmets 1980). Since the river flow only transports about 400 m^3 of sediments annually, a large amount of marine sand was likely carried to the sea floor adjacent to the groins and accumulated in the dredged river mouth (Loopmann and Tuulmets 1980). Since then part of the fluvial sediments again entered the active sand body of the beach and subcells 2A and 2B (Fig. 1.2) were reconnected to some extent.

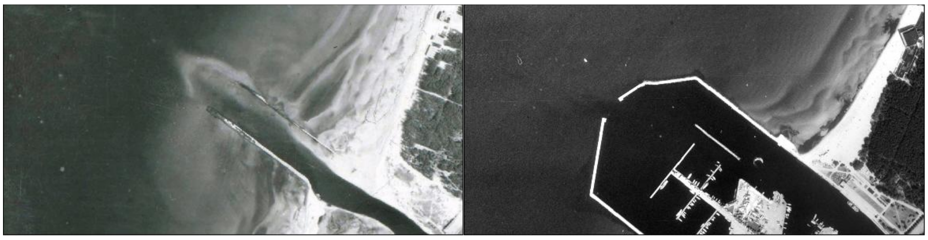

Fig. 3.4. The Pirita River mouth in 1951 (detail of the photo in Fig. 3.1), illustrating the joint effect of groins along the river coasts and the river flow on the formation of the sand bar at the end of the groins

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. No reliable data are 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 the use of bulldozers during a low water event in December 1959 (Kask 1997).

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 notably enlarged. 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 harbour from the southern side.

Both marine hydrodynamic features and sand transport properties of the river flow were largely changed, although the seaward extension of the harbour is close to that of the earlier groins. The water depth at the harbour entrance is about 5 m (Estonian National Maritime Board 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, which is far offshore from the equilibrium beach profile. The fluvial material thus has almost no chance of entering the active sand body of the beach.

The sea coast southwards from the river mouth was reclaimed using dredged sand to provide land for the Olympic village. The coast further southwards from the Pirita River mouth was strongly modified by the seawall of the new road to Pirita. There is very little sand in this area now.

About 65 000 m^3 of sand dredged from the basins of the harbour was dumped near Merivälja Jetty in the 1970s on the expectation that waves would transport it southwards to Pirita Beach. It is not known how much of that sand actually reached the beach.

To summarize, the extensive coastal engineering activities of the past century have essentially blocked the major supplies of sand to Pirita Beach. The remaining sources of coarser material are the till bluff 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. The potential misbalance of the supply of different fractions is expected to become evident as a gradual decrease in the dominant grain size of the beach, resulting in an overall worsening of the sand quality from a recreational viewpoint. On the other hand, Pirita Harbour blocks the lateral sand loss from the beach. The beach profile, therefore, should be relatively stable and the concept of the equilibrium beach profile is accordingly an appropriate tool for its analysis.

3.3. Qualitative changes to the beach

The coastline and the whole beach have likely been stable during at least a century until the 1970s. No identifiable changes occurred in the coastline between the location of *Rannahoone* and Merivälja Jetty between 1940 and 1976 (Loopmann and Tuulmets 1980). Records of substantial changes in the last 200–300 years, during which the largest events in this area generally have been documented, are lacking as well.

Noticeable changes took place only in the vicinity of the Pirita River mouth owing to the joint influence of the groins and dumping of sediments from the basin of Olympic Harbour. The width of the beach in its middle section in the 1960s (60–70 m) was larger than nowadays (cf. also Raukas and Teedumäe 1997, p. 291). There are no reliable data to judge whether this feature was natural or was induced by the groins. The width of the dry area was relatively large in the southern part of the beach already in the 1950s (Fig. 3.1) and increased by up to 200 m along the northern mole by the 1970s (Loopmann and Tuulmets 1980).

The combination of the engineering structures forms a probable background of changes in the bathymetry 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 apparently reflects a loss of a large volume of sand from areas adjacent to the new harbour at certain depths.

To mitigate the consequences of the coastal engineering structures, a portion of the sand dredged from Olympic Harbour was dumped in the central and northern parts of Pirita Beach in the 1970s. Also, a certain amount of quarry sand was placed near *Rannahoone* about 500 m northwards from the Pirita River mouth. This considerably increased the sand volume and apparently prevented the central and southern part of Pirita Beach from erosion. Since the sand dredged from the harbour was quite fine (Orviku and Veisson 1979), a large portion of it was evidently transported seawards and the width of the beachface decreased already by the 1980s (Kask 1997).

Several older images (see Paper I) reflect the presence of a substantial amount of sand in underwater bars in 1951 (Fig. 3.1). Comparison with later images suggests that the quantity of active sand in bars has decreased, whereas a large portion of sediments possibly has been transported seawards. The nature of changes is different in different parts of the beach.

In the southern part, between the *Rannahoone* and Pirita Harbour, the width of the beach and the total sand volume has increased. This tendency is likely a long-term one, since even the most violent storms of 2001 and 2005 did not affect the beach width. The total width of the dry beach is up to 100 m. The height of the beach is up to 2 m above the mean water level. Waves did not reach the dune toe even during extreme water levels. This sector of the beach therefore seems relatively stable and is characterised by gradual sand accumulation.

The central part of the beach (adjacent to *Rannahoone* 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 during strong storms. Relatively intense aeolian sand transport into the pine forest occurs in this sector (Kask and Kask 2002), which can be interpreted as an indicator 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 caused extensive regression of the foredune toe in 1999–2005. The changes are notable northwards from the mouth of a small stream (about 900 km northwards from Pirita Harbour) and 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 erosion was most intense at the interface between the sandy and till coasts. Several dozens of pine-trees were destroyed, and this additionally weakened the stability of the beach.

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

The spatial patterns of these changes, inferred from beach profiles (Fig. 3.5) measured regularly within the framework of coastal monitoring, are consistent with the qualitative analysis above (Suuroja *et al.* 2004). The erosion of the beach and the bluff is most evident in the northernmost section where the whole coastal profile is shifted by 10–20 m landwards. The central part of the beach is close to an equilibrium state. Some sand accumulation is observed in the southernmost beach sector.

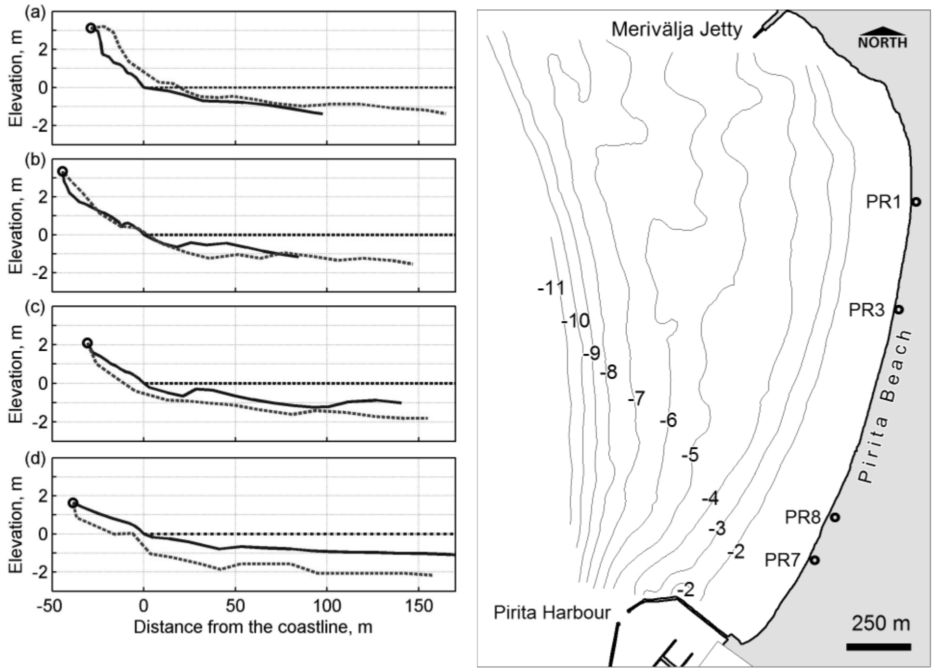

Fig. 3.5. Beach profiles 1 (a), 3 (b), 7 (c) and 8 (d) at Pirita on 9 Sept. 2003 (solid lines) and in 1994 (dashed lines) based on data from Suuroja et al. (2004). The profiles begin from the coastal bluff marked by a circle. The horizontal dashed line shows the mean water level

Approximately 50% of Pirita Beach therefore occasionally suffers from substantial damage. As discussed above, one reason behind an apparent intensification of beach processes is the high frequency of storms experienced during the last decade. Still a major threat to the beach is human activity that has considerably reduced 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 and Kask 2003; Soomere 2005b). Under these 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.

A feasible way of restoring the sand balance at Pirita and making the beach stable consists in increasing its sand volume. The fastest result would be obtained by utilizing classical beach renourishment methods. This would involve placing high-quality, relatively coarse sand (extracted, for example, from Naissaar Harbour, see Paper I and references therein) either on the dry beach area or in the immediate vicinity of the shoreline. An artificial foredune of moderate height (about 1.5 m) along the existing coastline would effectively protect the coastal forest and not distort the sea view. 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 should be undertaken with great care (Paper I), because the sand there is relatively fine. Another feasible way, which would bring to good results, consists in bypassing sand to the southern side of the Port of Miiduranna. 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.

3.4. Quantification of changes to almost equilibrium beaches

Obtaining an accurate sediment budget normally requires long-term measurements of sediment transport, or sediment trapped at a groin, or historical geomorphic and bathymetric changes, and is thus time-consuming and costly. The problem, however, may be greatly reduced for certain beaches that are close to an equilibrium state. Such beaches only reveal small-scale (and frequently temporary) changes in their bottom profile. The properties of their long-term evolution are mostly governed by a small number of parameters. The nearshore profiles of such beaches are usually close to the equilibrium beach profile (Dean 1991; Dean and Dalrymple 2002).

Since no reliable data about changes in the sand volume and the intensity of sand sources in the Pirita Beach area are available, an alternative way must be used for estimating the gain or loss of sand at the beach. Several features affecting its dynamics, in particular, local postglacial uplift combined with the current sea level rise and very limited lateral sand loss from the area, are favourable for creating an equilibrium regime as shown in Papers I and II.

The applications of the concept of the equilibrium profile are mainly directed at estimating the reaction, either recession or progression, of a natural profile and/or the shoreline to water level rise or storm erosion (e.g. Kriebel and Dean 1985; Callaghan *et al.* 2009). Solving the inverse problem of changes in the sediment volume of the beach profile is usually not possible, because the sediments are redistributed between different bodies such as foredunes, berm, sand bars and the sloping bottom (Dean *et al.* 1993).

Sometimes an inverse application of the concept of the equilibrium profile to obtain a rough estimate of sediment loss or gain is reasonable (Soomere and Healy 2009). This approach is justified, for example, when (i) the lateral sediment losses are minor and (ii) the local water level change and sediment loss or gain cause oppositely directed shoreline shifts. Such situations frequently occur in the case of small bayhead beaches where the loss of sand from the equilibrium profile area is balanced by littoral drift or other sand supplies. The above has demonstrated that Pirita Beach satisfies these conditions: it is a bayhead beach with relatively low activity of littoral drift and coastal processes where, sand loss is nearly balanced by relative water level fall.

The method of rapid estimation of sand loss or gain relies on the existence of the more or less persistent beach profile. In essence, it is an inverse version of the Bruun Rule (Bruun 1962). Originally, this rule was derived to predict shoreline retreat resultant upon water level rise for any sort of equilibrium profile. It is usually expressed as the following linear relation between the shift Δy of the shoreline and the relative water level rise ΔS, the proportionality coefficient of which is the inverse mean slope of the equilibrium profile $\tan\theta$:

$$\Delta y = -\frac{\Delta S}{\tan\theta}. \quad (5)$$

Equation (5) does not rely on any particular beach cross-section and remains valid for any shape of the equilibrium profile with the mean slope $\tan\theta$.

Consider now a situation in which a certain loss of sand from the equilibrium profile has occurred and the entire profile has been shifted shoreward (Fig. 3.6). For simplicity, in Paper IV it is assumed that the equilibrium profile has the shape of the classical Dean's Equilibrium Profile (DEP).

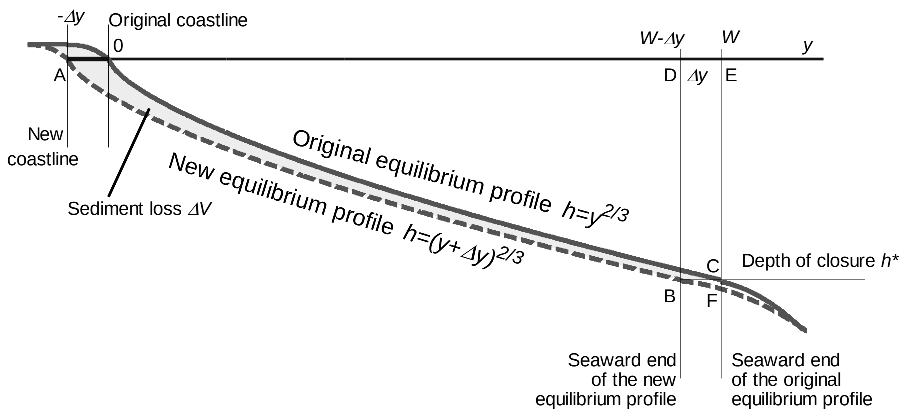

Fig. 3.6. Calculation of the change in the sand volume for small changes of the position of the coastline (Paper IV)

The volume of sand loss can be easily expressed in terms of the profile parameters. For small changes in the shoreline position the slope of the dry beach can also be ignored. It is then straightforward to recognize that the curved trapezoids ABD and 0EC are identical. Therefore, to a first approximation, the cross-section of the entire profile has been shifted to the left and the volume of the lost sand is

$$\Delta V \approx h^* \Delta y, \quad (6)$$

where depth $h*$ is the closure depth,. This depth for different sections of Pirita Beach has been estimated in Chapter 2 (Paper I). Details of the derivation of Eq. (6) and further discussion of the method are presented in Soomere *et al.* (2009).

The main advantage of the described approach is that the problem of calculation of sand loss can be been reduced to determination of the shift of the shoreline and the closure depth. The simplest application of this method in Paper IV neglects the amount of sand between the seaward ends of the original and the shifted equilibrium profile and the changes in the amount of sand in the dry beach area. This assumption is adequate in the case of Pirita Beach where the typical slope at the seaward end of the equilibrium profile is smaller than the mean slope.

The resulting sand loss over a beach section (along which the closure depth $h*(x)$ may vary) can be expressed as:

$$\Delta V_{\Sigma} = \int h*(x) \Delta y \, dx . \tag{7}$$

The basic advantage of Eq. (7) is that the sand loss or gain in homogeneous beach sections (where the closure depth is constant) depends only on the changes in the area of the dry land:

$$\Delta V_{\Sigma} = h* \int \Delta y \, dx . \tag{8}$$

Consequently, Eqs. (7, 8) predict that a shift of the shoreline by one metre at Pirita (equivalently, each square metre of gain or loss of the dry land) means the change in the volume of sand within the equilibrium beach profile by $\Delta V \approx 2.5$ m^3 per linear metre of beach. Realistic values representing long-term gain or loss can obviously only be obtained for beach sections of considerable length, along which the integrals in Eqs. (7) or (8) are calculated.

As the temporal and spatial resolution of existing depth surveys at many beaches (also at Pirita) is too low for an adequate estimate of the properties of the equilibrium profile from the measured profiles, an alternate method for defining the parameters of the equilibrium profile is used in Paper IV. This method implements the parameters of the local wave climate.

The most widely used shape of the DEP corresponds to the uniform wave energy dissipation per unit water volume in the surf zone (Dean and Dalrymple 2002, chapter 7). The water depth $h(y)$ at a distance y from the waterline along such a beach is expressed by Eq. (1): $h(y) = Ay^{2/3}$ (see Chapter 2). The properties of an equilibrium beach profile are defined by two parameters. First, the profile scale factor *A* that, to a first approximation, depends on the grain size of the bottom sediments and the value of which for Pirita Beach is established in Chapter 2 (Paper I). Another decisive parameter is the closure depth, the calculation of which is presented in Paper II.

Small variation in the closure depth along Pirita Beach (Chapter 2, Paper I) suggests that the wave regime along the beach is more or less homogeneous and the use of Eq. (8) for volume loss calculations is justified.

3.5. Rapid estimate of sand loss from Pirita

Based on the theory presented in the previous Section, the changes in the sand volume can be easily estimated from the changes in the dry land area, provided the parameters of the equilibrium profile and the relative water level changes are known. As an example of the application of this idea, the calculation of sand loss from Pirita Beach has been performed in Paper IV. The use of this method basically means that the changes in the beach since the mid-1970s can be roughly quantified by the comparison of maps stemming from different decades or the results of topographical surveys.

Although the estimate of the volume of sand loss does not explicitly depend on the slope of the equilibrium profile, it has a key role in estimating the potential shift of the coastline owing to land uplift or subsidence.

In the framework of the concept of the DEP, the slope is defined jointly by the closure depth and the profile scale factor. When the closure depth has been defined, the mean slope $\tan\theta = h^*/W$ of an equilibrium profile is the ratio of the closure depth h^* to the width W of the profile. The width is usually treated as the distance from the coast at which the water depth reaches the closure depth and does not include the subaerial part of the beach profile. While the closure depth can be estimated, to a first approximation, from wave properties only (Chapter 2, Paper II), the width of the profile also depends on the properties of bottom sediments.

In the case of a DEP, the profile width can be estimated using closure depth and the profile scale factor *A*. To a first approximation, this factor depends only on the sand grain size. The typical grain size in the nearshore of Pirita Beach is 0.12 mm and varies insignificantly in the nearshore of most of the beach (Paper I). Consequently, it is adequate to use a constant profile scale factor $A = 0.07$ in the whole beach area (Dean *et al*. 2001; table 7.2 of Dean and Dalrymple 2002).

The values $h^* = 2.36$–2.57 m of the closure depth established in Chapter 2 (Paper I) define the width and the mean slope of the DEP as $W = (h^*/A)^{3/2} \approx 200$–225 m and $\tan\theta \approx 0.012$, respectively. These estimates give the local Bruun Rule for the recession or recovery rate of the shoreline:

$$\Delta y \approx -85\Delta S . \qquad (8)$$

As an example of the application of this simple, rapid method to estimate sediment loss from almost equilibrium beaches, we assessed the net loss of sediment from Pirita Beach from the mid-1980s to the present. As high-resolution surveys are not available from the 1980s, the position of the shoreline before 2000 was digitized from topographical maps produced at different times. The position of the coastline in the mid-1980s was found from the 1:25 000 scale, formerly classified sea map “Tallinn Bay”, published in 1986 by the Directorate of Navigation and Oceanography, Ministry of Defence of the USSR based on topographical surveys performed obviously in 1983–1985. An analogous, but more recent map has apparently been surveyed about the turn of the century, i.e. some 15 years later.

The current rate of the postglacial rebound at Pirita Beach is about 2.5 mm/year (Vallner et al. 1988). If the sand volume were constant at Pirita, the expected coastline shift within approximately 15 years would have been close to 4 m according to Eq. (8). The gain of dry land in the entire sandy beach would be about 8000 m^2. The actual gain of land has been much less, about 3000 m^2. Large sections of the sandy beach have become narrower (Papers I and II). As discussed above, erosion of the beach is most evident in its northernmost part along a ~200 m long section. The maximum recession is in places up to 25 m and only the central and southern areas of the beach have been stable (Papers I and II).

Consequently, the net loss of sand is about 5000 $m^2 \times 2.5$ m=12 500 m^3. The net annual loss of sand from the beach is thus of the order of 1000 m^3. Since this rate has been derived from indicative data, it should be interpreted as an estimate of the magnitude of sand loss.

A more exact estimate can be obtained from the comparison of two high-resolution surveys of 1997 and 2006 (Fig. 3.7).

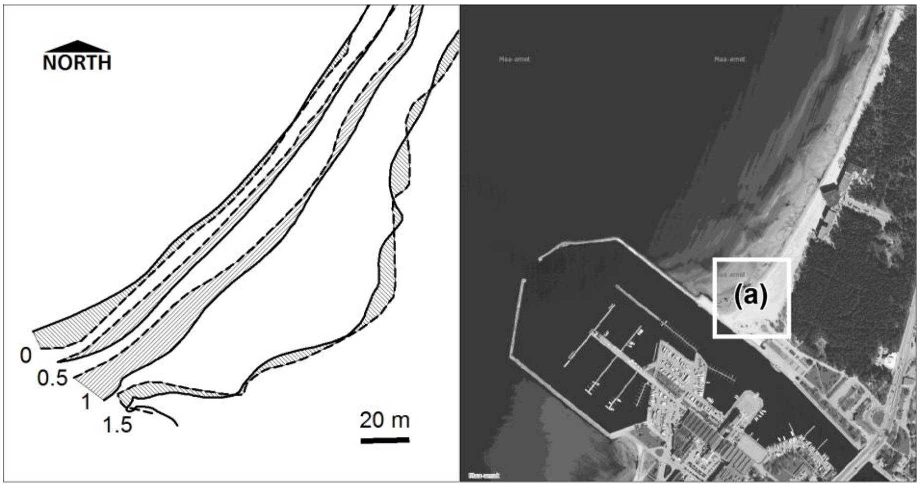

Fig. 3.7. Changes in the location of isolines of surface elevation in the southern part of Pirita Beach (left panel). Solid and dashed lines show the 0, 0.5, 1, and 1.5 m isolines according to surveys of 1997 by REIB Llc (Map 1:500 with technological networks. Harju County, Tallinn, Pirita District, Pirita Beach. Contract No. 06-612) and of 2006 by Hectare Llc (Map with technological networks. Survey of infrastructure 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 (a) between *Rannahoone* and Pirita Harbour in the right panel

As during the previous period, no net changes in the dry land area occurred between 1997 and 2006. The expected shoreline shift within 10 years would have been about 2.5 m and would have resulted in the gain of about 5000 m^2 of dry land. In fact, the area of dry beach has remained practically unchanged in 1997–2006. Consequently, the net loss of sand during these years was also about 12 500 m^3. The net annual loss of sand from the beach was thus about 1250 m^3 during this decade.

The proposed method allows making rapid estimates of net sediment gain or loss for beaches which are more or less in equilibrium within the limits of the active beach profile with the use of a small number of external parameters – gain or loss of the dry beach area and the closure depth. In essence, it is a version of an inverse method of the Bruun Rule and, as such, is applicable to any type of equilibrium profile. The change in the sediment volume is expressed as the product of the change in the dry beach area and the closure depth.

The method is suitable in cases where the net alongshore transport is negligible and the shoreline change owing to sediment loss or gain is more or less balanced by the variation of the relative sea level. Such a situation frequently occurs in bayhead beaches located in an area of isostatic rebound.

The described method has been applied to a class of beaches for which the loss of sediment is approximately balanced by the postglacial uplift. The scope of its applications is obviously much wider, for example, bayhead beaches in which sand loss is approximately balanced either by littoral transport or beaches in estuaries where sediment loss is balanced by sand supply by river flow. It can also be applied in cases of subsiding beaches, supported by intense littoral drift or current-induced or fluvial sediment supply.

The above estimate only accounts for changes in the sand within the equilibrium profile, and ignores potential changes in the amount of sand in berms and foredunes. A complementary estimate of the loss of dry sand in 1997–2006 is derived in Paper I 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 surveys of 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 (Table 3.1). Such shifts suggest that the dry beach area has lost a certain amount of sand from between the waterline and the dune bluff, the latter being represented by the 1.5 m isoline at Pirita. The change in the areas of the relevant elevation is between 2000 and 5000 m^2. The greatest changes have occurred at the elevations of 1–1.5 m. The relevant isolines are shifted 2–3 m landwards on average. Since 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 and Soomere 2004; 2006). Given that 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 3.1. 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	Change, m^2
0.0	1860	1860	0
0.5	2600	360	–2240
1.0	4970	230	–4740
1.5	5400	1550	–3950

3.6. Properties and potential impact of wakes from fast ferries

The relative impact of wake waves substantially depends on the properties of nearshore sediments, the nature and vulnerability of the sea coasts and properties of wakes. This Section describes the results of early studies of specific properties of wake waves in the coastal zone (Paper VI).

In the case of fast ferry waves the formation of intense alongshore currents and rip currents is unlikely, because the duration of wave packages (some minutes) (Soomere *et al.* 2003) is too short (Kirkegaard *et al.* 1998).

Orbital velocity of water movement under the wave crest is higher than under the wave bottom, consequently, more sediment is transported under the wave crest. As a result of the described processes sediment material is normally transported in the direction of wave travelling (generally towards the shore). Sediment transport by the waves generated by fast ferries is probably more intense than by wind waves of the same height, since the profile of ship waves is often strongly anisotropic (Kirkegaard *et al*. 1998; Peltoniemi *et al*. 2002; T. Kõuts, personal communication 2001). Water masses move in the direction of wave movement and sediment material is carried in the same direction. Thus, it is frequently argued that sediment transport by fast ferry waves generally occurs perpendicular to the shoreline (Kirkegaard *et al*. 1998).

Due to their length, fast ferry waves often create relatively large near-bottom orbital velocities far from the waterline, therefore they mobilize fine sediments more intensely into the deeper part of the nearshore than wind waves do (Soomere and Kask 2003). This may cause considerable changes in the balance of sediment distribution. During the periods of fast ferry traffic, generally low water level predominates, therefore the waves induced affect even deeper parts of the seafloor.

Waves from fast ferries have formed an appreciable portion (about 5–7% in terms of wave energy and 20–25% in terms of wave power) of the total wave activity in Tallinn Bay since 1997. The daily highest ship waves belong to the highest 5% of wind waves in this area (Soomere 2005b). Since 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 directed opposite to the natural littoral drift, as hypothesised by Elken and Soomere (2004). Their role in coastal processes, although potentially substantial under certain circumstances (Soomere and Kask 2003; Levald and Valdmann 2005; Valdmann *et al.* 2006), is still poorly understood.

The excessive influence of wakes of high-speed ships occurs when wake waves are much longer than wind waves (Kirk McClure Morton 1998; Soomere and Rannat 2003) For example, typical wave periods in Tallinn Bay are 2–4 s and rarely reach 6–7 s (Soomere 2005a). The leading wake waves have frequently a height of about 1 m and a period of 10–15 s (Soomere and Rannat 2003). Such waves occur extremely seldom in natural conditions in certain regions of semi-enclosed seas. They are qualitatively similar to long-period ocean swell. Together with wind waves, they may form bi-modal wave systems, which may have much higher impact on various coastal processes than wave systems with a single spectral peak and a comparable total energy (Coates and Hawkes 1999; Hawkes 1999).

The shape of the waves is extremely important, because many properties of water particles in long linear and weakly nonlinear waves (in particular, velocity components) linearly depend on the surface displacement. The purpose of Paper VI was to study the actual appearance of long ship waves approaching shallow coastal areas.

In summer 2003, a series of experiments was carried out in a shallow area near Aegna Jetty. A pillar was rigidly fixed to the bottom in a vertical position so that its top reached out of water about 1 m above the calm sea level. It was slender enough (diameter 5 cm) not to create considerable reflected waves, and was stabilised with the use of three ropes. The fluctuations of the water surface along a scale on the pillar were recorded on the videotape. The resolution of the scale allowed detecting the position of the water surface with an accuracy of 1–2 cm.

Measurements were conducted in calm days in order to reduce the possible influence of wind waves. The analysis of ship wave properties was performed with the use of record segments containing a full profile of single waves at least 10 cm in height. Profile of single waves were recorded in the morning of July 20 at a measurement site about 30 m in the SSW direction from Aegna Jetty where the water depth was 3.6 m. Their total length is about 16 min and they represent 3 different wakes from ships sailing from Tallinn to Helsinki.

The water level in the frames was located and typed in manually by Reio Põder, a co-author of Paper VI. Changes in the water level were slow as compared to the frequency of recorded frames and only every 5th frame was digitised. The resulting time series shows the profile of the ship wake at this point. The shape of even the highest recorded waves was generally regular and symmetric with respect to their crests and troughs, thus the waves were far from breaking.

The height of the highest wake was about 95 cm, thus about 90% of the expected daily largest height of long waves at this site (Soomere and Rannat 2003). Other wakes had the highest waves of about 50 and 40 cm. The mean height of the analysed waves was 26 cm. The period of the largest waves was 11–12 s whereas some waves had periods of 15–17 s and a few waves even had periods >20 s. Therefore, the recorded waves well represent properties of ship waves at the measurement site. The details of the analysis are presented in Paper VI.

The classical linear wave theory reasonably reproduces the wave shape of only relatively small ($H \leq 30$ cm) ship waves. The water surface elevation and dropdown in such waves are practically symmetric with respect to the calm water level. Higher waves are often asymmetric and the classical wave theory systematically and considerably underestimates the maximum elevation at wave crests and overestimates the dropdown at wave troughs for waves with $H > 30$ cm (Fig. 3.8). The crest of a larger ship wave is narrower and its trough is flatter than those of a sine wave with the same height and length. Therefore, the maximum velocity of water particles in such waves greatly (up to several times for the highest waves) exceeds the velocity predicted by the classical sine wave theory.

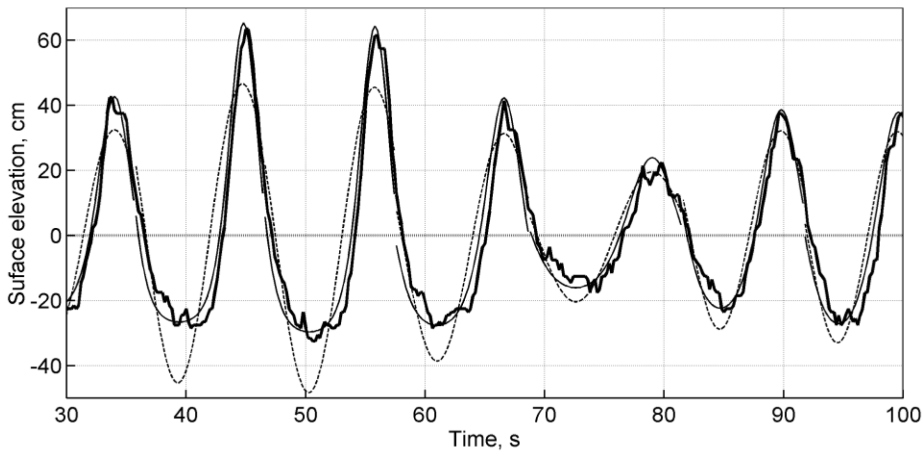

Fig. 3.8. Water surface time series (bold line) in a ship wake with a maximum height of 0.95 m, the shape of cnoidal waves corresponding to the depth of the best fit (solid line) and the corresponding sine line (dashed line). From Paper VI

An important outcome of the studies described in Paper VI is that properties of single waves from each ship wake have a large scatter. The shape of some waves is very similar to highly cnoidal waves whereas other waves of comparable height and length from the same wake are practically sinusoidal. The general tendency is that the shape of the leading (that is, the longest and the highest) waves substantially deviates from the sine wave.

As such waves evidently cause large near-bottom velocities, the influence of a part of long ship waves on the seabed, offshore structures and local ecosystem in certain parts of the coastal slope is apparently much larger than expected from the linear wave theory. Since ship waves are a new component of water dynamics in many areas, an extensive reaction of the benthic layer and fine bottom sediments to frequent occurrence of nonlinear waves is likely in the affected regions. Although species that prefer a rocky or sandy bottom may benefit from the increased hydrodynamic activity, the concern is that abrupt changes in forcing conditions usually have an adverse effect on the local ecosystem. The reduced water transparency, an obvious feature of such reaction (Erm and Soomere 2004, 2006), may have strong suppressing feedback on the bottom vegetation, and suspension and re-sedimentation of finer sediments may considerably worsen fish spawning conditions.

The results described in this Section motivated repeating similar experiments in 2008 with the use of professional, high-resolution water surface profiling instruments (Parnell *et al*. 2008).

Conclusions

Summary of the results

The coasts of Tallinn Bay are characterized by several sedimentary compartments and a variety of beaches. A steep till bluff is most widely distributed and can be found at the Island of Naissaar. The gently sloping till shore occurs along many parts of the Viimsi Peninsula, sandy coast at Pirita and at certain sections of the Island of Aegna. Long sections of artificial shore are found around Tallinn. Most of the coasts are covered with pebble and cobble pavement which to some extent protects them from further erosion. There are, however, a few coastal sections (usually sandy beaches) that are vulnerable with respect to changes in the intensity of drivers of coastal processes.

Most of the nearshore of the interior of Tallinn Bay is protected by a stone pavement and is not vulnerable to ship waves. Only a few sections of the coast of Aegna and the Viimsi Peninsula (sand, gravel, or mixed beaches) may suffer from vessel-induced changes to wave activity. Long ship waves may, however, largely contribute to the processes at the deeper nearshore (5–20 m) where the seabed is mostly covered with fine material. Considerable impact of ship waves on the coast of Naissaar (that generally has no such protection) is probable.

The study of two major sand deposits in the vicinity of Tallinn Bay located in almost similar geomorphic conditions (south of Prangli and Naissaar) shows that their development has been quite dissimilar. While the Prangli deposit was obviously formed in varying hydrometeorological conditions where different layers have been deposited under different dominating processes, the deposit at Naissaar was evidently formed under the predominant influence of wave-driven erosion of the coastal bluff followed by littoral drift and sand recycling and sorting under wave action.

The historical as well as recently collected data were analysed to specify the previous and the current state and sand budget of Pirita Beach. This sandy area with a typical width of a few tens of metres is limited to a ~2 km long section. Aeolian sand loss is minor in this area. Littoral transport of the material eroded from the coast of the Viimsi Peninsula and sediments originating from the Pirita River were the major sand sources for this beach which has apparently become stabilised by postglacial uplift and natural sediment supplies by the middle of the 20th century. The interaction of the river flow and littoral transport led to the formation of a sill in the vicinity of the river mouth in the past, which possibly caused sedimentation of river-transported fine material in a relatively shallow area. A large portion of the material evidently entered the active sand body of the beach and played a role in the development of the extremely gently sloping sea floor in the southern part of the beach.

Major changes in the sand budget at Pirita occurred when the Port of Miiduranna largely blocked littoral transport, and Pirita Olympic Harbour drastically decreased the river-induced sand transport to the littoral system. Although gradually losing some sand, Pirita can be characterised as an almost equilibrium beach. The blocking of littoral drift of coarser sediments by the Port of Miiduranna and Merivälja Jetty is probably the main reason for the sediment deficit in the area south of Merivälja Jetty. Moreover, the specific deficit of coarser material may lead to undesirable gradual decrease in the grain size in the southern part of the beach.

The results of bathymetric and textural studies, and modelling of the local wave climate are used to establish the properties of the Dean's equilibrium profile for Pirita Beach and to quantify the sediment transport processes. The average grain size at Pirita is about 0.12 mm and its spatial variations are fairly minor. This feature allows using a fixed value of the shape parameter $A = 0.07$–0.08 of the equilibrium beach profile for this beach. The closure depth is about 2.5 m along the entire beach and the width of the equilibrium profile is therefore about 200 m. Pirita Beach can be divided into four areas. The northernmost part has a relatively large proportion of coarser sediments. Relatively coarse sand is found along the waterline, while there is no band of coarser sand in the surf zone. Most of the seafloor at depths from about 1 m down to 6–8 m extending to about 1800 m from Pirita Harbour is covered by mostly homogeneous fine sand. The deepest part of the nearshore (depths >6–8 m) hosts even finer sand.

An estimate based on the comparison of the location of the waterline on a pair of maps from the mid-1980s and from the very end of the 1990s, combined with an estimate of the effect of land uplift, suggests that the annual net sand loss from the underwater part of Pirita Beach is about 1000 m^3. Since 1997, another 400 m^3 has been eroded annually from the dry beach. The erosion process of the beachface, dunes, and bluff in the northernmost part of the beach may have been less intense in the past, because littoral transport previously carried more sand to this area.

A method is proposed for rapid estimation of net sediment gain or loss for beaches which are more or less in equilibrium within the limits of the active beach profile. A small number of external parameters are used – gain or loss of the dry beach area and the closure depth. In essence, it is a version of an inverse method of the Bruun Rule and, as such, is applicable to any type of the equilibrium profile. The change in sediment volume is expressed as the product of the change in the dry beach area and the closure depth.

Based on the direct recording of water surface time series in ship waves, it is shown that the shape of a large number of waves from fast ferries in the coastal area of Tallinn Bay substantially deviates from that of sine waves. For a wave with a given height and length, such "deformed" waves apparently cause considerably larger velocities of water particles than predicted by the linear theory. For typical ship waves in the coastal zone of Tallinn Bay the difference may be a few times. Therefore, possible adverse influence of long ship-generated waves may be much larger than its estimates based on the classical wave theory.

Main conclusions proposed to defend

1. Analysis of the geological setting and shore types shows that generally wakes from fast ferries do not cause direct erosion of the shores of Tallinn Bay, which are mostly covered with a protecting stone pavement. Only a few sections of gravel and sand beaches are vulnerable with respect to ship wakes. Long ship wakes may, however, largely contribute to the processes at the deeper nearshore (5–20 m) where the seabed is mostly covered with fine material.
2. The structure of sand bodies at Naissaar and Prangli differs considerably. The layered structure of the Prangli deposit is qualitatively similar to the depositional sequences in sandy areas next to North Estonian river mouths. This deposit may thus have been formed under highly varying driving forces.
3. The sand mass in the Naissaar deposit usually shows no clear layered structure and has evidently been formed under the influence of wave-driven erosion of the coastal bluff, followed by littoral drift and sorting under wave action.
4. Based on maps of spatial distributions of the mean grain size, Pirita Beach can be divided into four areas: (i) the northernmost part that has a relatively large proportion of coarser sediments; (ii) relatively coarse sand along the waterline; (iii) most of the seafloor at depths from about 1 m down to 6–8 m, which is covered by mostly homogeneous fine sand; (iv) the deepest part of the nearshore (depths >6–8 m) which mostly hosts even finer sand.
5. Extensive coastal engineering activities of the past century such as the Port of Miiduranna or Pirita Harbour have greatly affected the natural supply of sand to Pirita Beach. The potential misbalance of the supply of different fractions to the beach is expected to become evident as a gradual decrease in the dominant grain size, resulting in an overall worsening of the sand quality from a recreational viewpoint.
6. Owing to the stabilizing effect of postglacial uplift and blocking of the lateral sand loss from the beach by Pirita Harbour, the beach at Pirita is still relatively stable and the concept of the equilibrium beach profile is an appropriate tool for its analysis.
7. The basic parameters of the equilibrium beach profile (scale factor ~0.07–0.08 and closure depth ~2.5 m) have been estimated for Pirita Beach based on an original survey of sediment texture and calculations of the local wave climate.
8. A method has been derived for estimating net sediment gain or loss for „almost equilibrium" beaches based on the use of the gain or loss of the dry beach area and the closure depth. The method has been used to quantify the net sand loss from Pirita (about 1000 m^3/year) during the last decades. Since 1997, another 400 m^3 has been eroded annually from the dry beach.
9. The shape of waves from fast ferries higher than 0.3 m often substantially deviates from the sine wave. As the maximum velocity of water particles in such waves greatly exceeds the velocity predicted by the classical sine wave theory, they may have strong impact on the seabed.

Recommendations for further work

As the entire northern coast of Estonia generally suffers from a sediment deficit, it is not surprising that a certain net loss of sand at times occurs in the Pirita area. Prior to the mid 20th century the beach was apparently stabilised by postglacial uplift and natural sediment supply. In general, sand supply from the north, sand dredged from the Pirita River mouth and the basin of Olympic Harbour, beach fill activities in the 1970s and relative land uplift have kept Pirita Beach more or less stable during recent decades. Other beach protection measures, such as construction of a revetment in the northern part of the beach, have been ineffective.

During recent decades, however, a gradual decrease in the width of the dry beach, rapid recession of the bluff at the northern end of the beach, and extensive storm damage to the forest have occurred despite postglacial uplift and attempts to renourish the beach with material dredged from Pirita Harbour or transported from mainland quarries. Great damage caused by recent storms (November 2001, January 2005) to the beach bluff and the forest suggests that the natural recovering mechanisms of Pirita Beach are no longer sustainable and that the beach has become very vulnerable.

Alterations in natural conditions such as large-scale changes in storminess in the 1960s (Alexandersson *et al.* 1998), may have caused increasing loads on Baltic beaches (Orviku *et al.* 2003). Yet, a more probable reason for large-scale recent changes at Pirita Beach is directly or indirectly related to a number of major coastal engineering structures. For example, the construction of the Port of Miiduranna has essentially blocked all littoral transport from the north since the 1970s, while the construction of Pirita Harbour substantially decreased the supply of sand by the river. Pirita, therefore, is a typical example of a beach whose evolution has been largely controlled by development works. Construction activities in the vicinity of the beach or its sand supply channels, even if designed as beach protection measures (such as stabilisation of the till bluff north of the beach), may lead to adverse effects and to an increase in the net sand loss. It is also likely that a rigid wall will enhance the sediment deficit in the northernmost section of the sandy beach.

An important issue for sustainable management of Pirita Beach is establishing the parameters of its equilibrium regime, the magnitude of sediment supply, and the basic mechanism of the natural sediment transport processes. Based on this information, well-justified decisions can be made for its protection or reconstruction. Since the sediment transport processes have already been substantially modified by various development works, more elaborate methods of numerical modelling allowing for detailed analysis of both alongshore and cross-shore sand transport and the potential changes in the local morphology are necessary to simulate the natural situation and to specify the best means for the coastal management.

A feasible way of restoring the sand balance at Pirita and making the beach stable consists in increasing the sand volume at the beach. The fastest result would be obtained by utilising classical beach renourishment methods. This would involve placing high-quality, relatively coarse sand (extracted e.g. from Naissaar Harbour) either on the dry beach area or in the immediate vicinity of the shoreline. An artificial foredune of moderate height (about 1.5 m) would effectively protect the dune forest and not distort the sea view as suggested in Paper I. 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 should be undertaken with great care, because the sand there is relatively fine. Another feasible way, which would provide good results, consists in bypassing sand to the southern side of the Port of Miiduranna. This procedure would eventually compensate the sediment deficit along the coast at Meriválja, reduce the coastal erosion in this area and deliver medium and coarse sand to Pirita Beach.

Another important tool for sustainable management of vulnerable beaches is simple, rapid methods for estimating of the basic features of beach development and consequences of different human activities. The method for a rapid estimate of the sand budget of almost equilibrium beaches belongs to this pool of tools. Although it has been applied in this study to a class of beaches for which the loss of sediment is approximately balanced due to postglacial uplift, the scope of applications is obviously much wider, for example, to bayhead beaches where sand loss is nearly balanced by littoral transport or to beaches in estuaries where sand supply by river flow has balanced sediment loss. It can also be applied in cases of subsiding beaches, supported by intense littoral drift or current-induced or fluvial sediment supply. In general, this method is suitable when the net alongshore transport is negligible and the shoreline change owing to sediment loss or gain is more or less balanced by the variation in the relative sea level.

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Papers constituting the thesis

I. Soomere, T., Kask, A., Kask, J., Nerman, R. 2007. Transport and distribution of bottom sediments at Pirita Beach. Estonian Journal of Earth Sciences 56(4), 233–254.

II. Soomere, T., Kask, A., Kask, J., Healy, T. 2008. Modelling of wave climate and sediment transport patterns at a tideless embayed beach, Pirita Beach, Estonia. Journal of Marine Systems 74 (Supplement 1), S133–S146.

III. Kask, A., Kask, J., Korneev, V., Okuntsov, E. 2008. Sedimentation conditions of marine Prangli and Naissaar sand deposits, the Estonian coastal sea. Baltica 21(1–2), 79–84.

IV. Kask, A., Soomere, T., Healy, T., Delpeche, N. 2009. Rapid estimates of sediment loss for “almost equilibrium” beaches. Journal of Coastal Research. Special Issue 56, 971–975.

V. Kask, J., Talpas, A., Kask, A., Schwarzer, K. 2003. Geological setting of areas endangered by waves generated by fast ferries in Tallinn Bay. Proceedings of the Estonian Academy of Sciences. Engineering 9(3), 185–208.

VI. Soomere, T., Põder, R., Rannat, K., Kask, A. 2005. Profiles of waves from high-speed ferries in the coastal area of Tallinn Bay. Proceedings of the Estonian Academy of Sciences.Engineering 11(3), 245–260.

Abstract

Natural and anthropogenic lithohydrodynamic processes on the coasts of Tallinn Bay have been studied from the viewpoint of development of sandy beaches and sand deposits in a semi-sheltered environment with relatively low hydrodynamic activity and limited sediment supplies. The main study objects are (i) Pirita Beach, a ~2 km long sandy bayhead area with a typical width of a few tens of metres, (ii) actively evolving sand deposits at the islands of Naissaar and Prangli and (iii) changes in the sediment supplies of the listed objects under anthropogenic pressure. The development of the two sand deposits located in almost similar geomorphic conditions has been dissimilar. While the layered structure of the Prangli deposit has evidently been formed in varying hydrometeorological conditions, the largely homogeneous deposit at Naissaar has apparently been shaped by wave-driven erosion and sorting.

It is shown that most of the coasts of Tallinn Bay are covered with a stone pavement which to some extent protects the shore from further erosion and naturally limits the magnitude of sediment sources for the listed areas. This implies that the vicinity of the waterline, as a rule, is less vulnerable with respect to changes in the intensity or properties of natural and anthropogenic drivers of coastal processes such as wind or ship waves. Extensive impact of ship waves is probable in some sections of the coast of Naissaar which have no such protection, and in deeper areas (depths >4–6 m), usually covered by relatively fine sediments. As the shape of the longest ship waves in the nearshore substantially deviates from the shape of sine waves, the possible adverse influence of long ship-generated waves may be much larger than its estimates based on the classical wave theory.

It is demonstrated that Pirita Beach is an almost equilibrium bayhead beach, the natural development of which has been disturbed by the impact of a number of coastal engineering structures that have largely blocked its natural sand sources. The littoral transport of material eroded from the coast of the Viimsi Peninsula and sediments originating from the Pirita River were the major sand sources that together with the postglacial uplift stabilised the beach in the past.

The analysis of historical as well as recently collected data together with numerical modelling of coastal processes has been used to quantify the sediment transport processes and specify the sand budget, spatial variations of the proportion of different sand fractions and the properties of the Dean's equilibrium profile. The average grain size of sand at Pirita is 0.12 mm and varies insignificantly along the beach. The closure depth is about 2.5 m and the width of the equilibrium profile about 200 m. Finally, an inverse method of the Bruun's Rule is proposed for rapid estimation of net sediment gain or loss for "almost" equilibrium beaches like Pirita, based on a small number of external parameters – gain or loss of the dry beach area and the closure depth. The annual net sand loss from the nearshore at Pirita is about 1500 m^3. Since 1997, another 400 m^3 has been eroded annually from the dry beach.

Resümee

Väitekirjas käsitletakse looduslike ja antropogeensete tegurite koosmõjus kulgevaid litohüdrodünaamilisi protsesse Tallinna lahe rannavööndis ja selle läheduses paiknevate liivalasundite kujunemist. Lähemalt vaadeldakse Naissaare, Aegna saare ja Viimsi poolsaare randu. Detailselt analüüsitakse setete ruumilise jaotuse ja transpordi küsimusi madala hüdrodünaamilise aktiivsuse ja piiratud settematerjali hulga tingimustes kujunenud Pirita rannas ning selle ümbruse rannaprotsessides arvestades inimmõju tulemusel toimunud muutusi.

Looduslike protsesside käiku vaadeldakse Prangli ja Naissaare liivalasundite näitel. Kuigi need paiknevad sarnastes geomorfoloogilistes tingimustes, on lasundite iseloom erinev; seejuures Prangli lasundil on sarnaseid jooni Eesti põhjaranniku lahtedes paiknevate liivalasunditega.

Valdavat osa Tallinna lahe rannavööndit katab moreenist moodustunud veeriste, munakate ja rahnude vöönd. Veetaseme, lainetuse ja jää dünaamika koosmõjul on peeneteralisem settematerjal moreenist välja pestud. Sillutisetaoline madalmere põhi kaitseb rannasetendeid edasise kulutuse eest. Selline rand on veepiiri läheduses reeglina vähemtundlik nii looduslike kui ka antropogeensete mõjurite (sh. laevalainete) suhtes. Kiirlaevalainete suhtes on tundlikud mõned rannalõigud Naissaarel, kus taoline vöönd puudub. Neljast meetrist sügavamal, kus merepõhja katavad enamasti peeneteralisemad setted, võivad laevalained põhja märgatavalt mõjutada. Madalas vees erinevad kiirlaevalained siinuslainest, mistõttu võib nende mõju mere-põhjale olla oluliselt suurem kui klassikalisel laineteoorial tuginevates hinnangutes.

Väitekirjas on näidatud, et Pirita rand on suhteliselt aeglaselt muutuv, pärastjääaegse maapinna kerke poolt stabiliseeritud peaaegu tasakaaluline lahepära rand. Minevikus moodustasid valdava osa Pirita randa toitvatest setetest piki Viimsi poolsaare läänerannikut kantavad setted ja Pirita jõest tulev materjal, mille liikumist tänapäeval takistavad hüdrotehnilised rajatised nagu Miiduranna ja Pirita sadamad, mõjutades seejuures oluliselt Pirita ranna dünaamikat.

Varasemate andmete, välitööde tulemuste ja rannaprotsesside numbrilise modelleerimise abil on määratud Pirita ranna setete bilanss, lõimise ruumiline jaotus ja nn. tasakaalulise rannaprofiili parameetrid. Settematerjali keskmiseks terasuuruseks on 0,12 mm. Tasakaalulise rannaprofiili sulgemissügavus (rannanõlva merepoolseim sügavus) on 2,5 m, millele vastab kaugus ligikaudu 200 m keskmisest veepiirist. Pirita ranna näitel on välja pakutud Bruuni reegli pöördmeetod kuhjunud või ära kantud setete mahu määramiseks peaaegu tasakaalulistes randades. Vajalikeks lähteandmeteks on vaid ajuveeranna laius ja sulgemissügavus. On näidatud, et aastane liiva kadu Pirita ranna veealusest osast on ligikaudu 1000 m3. Alates 1997. aastast on igal aastal keskmiselt ära kantud ka ligikaudu 400 m3 liiva ajuveerannast.

Appendix A. Curriculum vitae

1. Personal data

Name	Andres Kask
Date and place of birth	27.07.1980, Tallinn

2. Contact information

Address	Hindreku 6, Muraste, Harku vald, 76901, Harjumaa
Phone	(+372)5256483
E-mail	andres@altakon.ee

3. Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn University of Technology	2005	applied geology / Master of Engineering Science
Tallinn University of Technology	2004	applied geology / Bachelor of Engineering Science

4. Language skills (fluent; average; basic skills)

Language	Level
Estonian	native language
English	average
Finnish	basic skills
Russian	basic skills
German	basic skills

5. Further training

Period	Educational or other organisation
August 2007 – September 2007	Summer School “Waves and Coastal Processes”, Tallinn, Estonia
July 2000	Participation in a scientific cruise with Christian-Alberts University of Kiel research vessel *FK Littorina*
June 2000 – July 2000	Participation in an expedition with The Leibniz Institute for Baltic Sea Research, Warnemünde; research vessel *Professor Albrecht Penck*.

6. Professional employment

Period	Organisation	Position
2007–	Ltd Altakon	Environmental expert
2005–2007	Marine Systems Institute at Tallinn University of Technology	Researcher
2004–2005	Marine Systems Institute at Tallinn University of Technology	Engineer
2003–2004	Marine Systems Institute at Tallinn University of Technology	Technician
2003–	Ltd Altakon	Member of board
1999–2003	Geological Survey of Estonia	Technician

7. Scientific work

7.1. *Conference presentations*

International Geological Congress. Oslo, Norway, 6–14 August 2008. Session EUR-10: The Baltic Sea Basin. ”Formation of sand deposits in Estonian coastal sea.” Session SES-01: General contributions to sedimentology. ”Approximation of fine sediments' transport” (2008);

Joint workshops “Implications of climate change for marine and coastal safety” and “Applied Wave Mathematics” of Marie Curie networks SEAMOCS and CENS-CMA, and Eco-NET network “Wave Current Interaction in Coastal Environment”, Palmse, Estonia, 10–12 October 2007: “Large effects on small structures on coastal evolution” (2007);

6th Baltic Sea Science Congress, Rostock, Germany, 19–23 March 2007, ”Studies of composition of bottom sediments and bathymetric features of Pirita shore” (2007);

5th Baltic Sea Science Congress The Baltic Sea Changing Ecosystem. Institute of Oceanology PAS. Sopot, Poland, 20–24 June 2005, ”The shape of wake waves from high-speed ferries in the coastal area” (2005);

The Baltic: The 8th Marine Geological Conference. Institute of Geology, University of Tartu. ”Coastal processes in the inner part of the Pärnu Bay” (2004)

7.2. *Publications*

Kask, A., Kask, J., Korneev, V., Okuntsov, E. 2008. Sedimentation conditions of marine Prangli and Naissaar sand deposits, the Estonian coastal sea. Baltica, 21(1-2), 79–84.

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Erm, A., Kask, A., Kõuts, T., Soomere, T. 2007. Optical detection of wave-induced resuspension of sediments. In: Lectures: Rostock: Rostock University, 2007, 96. In: Baltic Sea Science Congress Rostock 2007: March 19–22, 2007 at Rostock University. Rostock, 2007, 96.

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Kask, J., Perens, H., Perens, R., Suuroja, S., Kask, A. 2001. Comparison of geological settings at possible deep harbour sites, north-western Saaremaa Island. Proceedings of the Estonian Academy of Sciences. Engineering, 7(2), 99–125.

8. Defended theses

Bachelor`s degree thesis ”Sand deposits of Naissaar and Prangli and the environmental impact related to extraction from these deposits”.

Master`s degree thesis ”Sand accumulation in Tallinn Bay and Muuga Bay areas”.

9. Main areas of scientific work/Current research topics

Coastal morphodynamics, sediment texture and dynamics, anthropogenic influence on sediment dynamics

10. Other research projects

Leader of projects

Assessment of the environmental impact of the dredging of the Hiiumadala sand deposit Hiiumadala II mining claim (2008)

Assessment of the environmental impact of the Pirita Beach nourishment project (2008)

Assessment of the environmental impact of the Kakumäe Harbour reconstruction project (2007)

Geological investigations of shoals west, north and north-west of the Island of Hiiumaa (2007)

Geological investigations of the Diomid shoal research area (2007)

Assessment of the environmental impact of the Toila Harbour reconstruction project (2006)

Assessment of the environmental impact of the Kelnase Harbour reconstruction project (2006)

Assessment of the environmental impact of the Leppneeme Harbour reconstruction project (2006)

Geological investigations of the sand deposit in the north-eastern part of Ihasalu Bay (2006)

Geological investigations of the sand deposit south-east of Naissaar Island (2005)

Geological investigations of the sand deposit in the eastern part of Ihasalu Bay (2005)

Appendix B. Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi	Andres Kask
Sünniaeg ja -koht	27.07.1980, Tallinn

2. Kontaktandmed

Aadress	Hindreku 6, Muraste, Harku vald, 76901, Harjumaa
Telefon	(+372)5256483
E-posti aadress	andres@altakon.ee

3. Hariduskäik

Õppeasutus	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2005	Rakendusgeoloogia; tehnikateaduste magister
Tallinna Tehnikaülikool	2004	Rakendusgeoloogia; tehnikateaduste bakalaureus

4. Keelteoskus (alg-; kesk- või kõrgtase)

Keel	Tase
Eesti	emakeel
Inglise	kesktase
Soome	algtase
Vene	algtase
Saksa	algtase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
August 2007 – September 2007	Rahvusvaheline suvekool „Lained ja rannikuprotsessid“, Tallinna Tehnikaülikool
Juuli 2000	Osalemine teaduslikus ekspeditsioonis Christian-Alberti Kieli Ülikooli uurimislaeval *FK Littorina*
Juuni 2000 – Juuli 2000	Osalemine teaduslikus ekspeditsioonis Warnemünde Läänemere Uuringute Leibnizi Instituudi uurimislaeval *Professor Albrecht Penck*

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2007–....	OÜ Altakon	Keskkonnaekspert
2005–2007	Tallinna Tehnikaülikooli Meresüsteemide Instituut	Teadur
2004–2005	Tallinna Tehnikaülikooli Meresüsteemide Instituut	Insener
2003–2004	Tallinna Tehnikaülikooli Meresüsteemide Instituut	Tehnik
2003–.......	OÜ Altakon	Juhatuse liige
1999–2003	OÜ Eesti Geoloogiakeskus	Tehnik

7. Teadustegevus

7.1. Konverentsi ettekanded

International Geological Congress. Oslo, Norway, 6–14 August 2008. Session EUR-10: The Baltic Sea Basin. ”Formation of sand deposits in Estonian coastal sea.” Session SES-01: General contributions to sedimentology. ”Approximation of fine sediments' transport” (2008);

Joint workshops “Implications of climate change for marine and coastal safety” and “Applied Wave Mathematics” of Marie Curie networks SEAMOCS and CENS-CMA, and Eco-NET network “Wave Current Interaction in Coastal Environment”, Palmse, Estonia, 10–12 October 2007: “Large effects on small structures on coastal evolution” (2007);

6th Baltic Sea Science Congress, Rostock, Germany, 19–23 March 2007, ”Studies of composition of bottom sediments and bathymetric features of Pirita shore” (2007);

5th Baltic Sea Science Congress The Baltic Sea Changing Ecosystem. Institute of Oceanology PAS. Sopot, Poland, 20–24 June 2005, ”The shape of wake waves from high-speed ferries in the coastal area” (2005);

The Baltic: The 8th Marine Geological Conference. Institute of Geology, University of Tartu. ”Coastal processes in the inner part of the Pärnu Bay” (2004)

7.2. Publikatsioonid

Kask, A., Kask, J., Korneev, V., Okuntsov, E. 2008. Sedimentation conditions of marine Prangli and Naissaar sand deposits, the Estonian coastal sea. Baltica, 21(1-2), 79–84.

Parnell, K., Delpeche, N., Didenkulova, I., Dolphin, T., Erm, A., Kask, A., Kelpšaite, L., Kurennoy, D., Quak, E., Räämet, A., Soomere, T., Terentjeva, A., Torsvik, T., Zaitseva-Pärnaste, I. 2008. Far-field vessel wakes in Tallinn Bay. Estonian Journal of Engineering, 14(4), 273–302.

Soomere, T., Kask, A., Kask, J., Healy, T. 2008. Modelling of wave climate and sediment transport patterns at a tideless embayed beach, Pirita Beach, Estonia . Journal of Marine Systems 74(Supplement 1), S133–S146.

Kask, A., Kask, J., Soomere, T. 2008. Formation of sand deposits in Estonian coastal sea. Abstracts cd-rom of International Geological Congress. Oslo 2008, August 6-14. Session EUR-10: The Baltic Sea Basin.

Soomere, T., Healy, T., Kask, A. 2008. Sediment transport patterns and rapid estimates of net loss of sediments for "almost equilibrium" beaches of tideless embayed coasts. Abstracts cd-rom of International Geological Congress. Oslo 2008, August 6–14. Session EUR-10 The Baltic Sea Basin.

Kask, A., Erm, A., Alari, V. 2008. Approximation of fine sediments' transport. Abstracts cd-rom of International Geological Congress. Oslo 2008, August 6–14. Session SES-01 General contributions to sedimentology.

Soomere, T., Kask, A., Kask, J., Nerman, R. 2007. Transport and distribution of bottom sediments at Pirita Beach. Estonian Journal of Earth Sciences, 56(4), 233–254.

Kask, A., Soomere, T., Kask, J. 2007. Studies of composition of bottom sediments and bathymetric features of Pirita shore. Baltic Sea science conference 2007. March 19–23. Poster abstracts. 2007, 119–119.

Erm, A., Kask, A., Kõuts, T., Soomere, T. 2007. Optical detection of wave-induced resuspension of sediments. In: Lectures: Rostock: Rostock University, 2007, 96. In: Baltic Sea Science Congress Rostock 2007: March 19–22, 2007 at Rostock University. Rostock, 2007, 96.

Valdmann, A., Kask, A., Kask, J., Rannat, K. 2006. Sustainable planning of underwater sand mining and beach protection in vulnerable semi-enclosed sea areas under heavy anthropogenic pressure. Geophysical Research Abstracts, 8, Paper 05578, 4 pp.

Kask, A., Kask, J., Soomere, T. 2006. Environmental impact assessment of offshore sand mining in Estonian coastal sea. Proceedings of the Estonian Maritime Academy 3, 19–31.

Kask, A., Kask, J. 2006. Väikesadamate rajamise ja süvendamise keskkonnamõju hindamisest. Eesti Väikesadamate Liit. Väikesadamate Infoleht, 22–24.

Soomere, T., Kask, A., Kask, J. 2006. Modelling of sand transport at Pirita beach and formulation of principles of beach nourishment. In: The Baltic Sea Geology : The Ninth Marine Geological Conference, August 27–September 3, 2006, Jurmala, Latvia, Extended Abstracts (Lukševičs, E., Kalnina, L., Stinkulis, G., eds), pp. 93–95. Riga: University of Latvia, 2006,.

Soomere, T., Põder, R., Rannat, K., Kask, A. 2005. Profiles of waves from high-speed ferries in the coastal area of Tallinn Bay. Proceedings of the Estonian Academy of Sciences. Engineering 11(3), 245–260.

Kask, A., Kask, J., Kornejev, V. 2005. Liivamaardlad Eesti rannikumeres. In: Ehitusmaterjalide kaevandamine ja varud: Eesti mäekonverentsi 2005.a kogumik. Tallinn: Tallinna Tehnikaülikool, 2005.

Rannat, K., Kask, A., Põder, R., Soomere, T. 2005. The shape of wake waves from high-speed ferries in the coastal area. In: 5th Baltic Sea Science Congress The Baltic Sea Changing Ecosystem: Book of Abstracts, Sopot, Poland, 20-24 June 2005: Sopot: [Institute of Oceanology PAS], 2005, 99–100.

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8. Kaitstud lõputööd

Bakalaureuse töö „Prangli ja Naissaare liivalasundid ning nendest kaevandamisega seotud keskkonnamõjud“

Magistritöö „Liiva kuhjumine Tallinna ja Muuga lahe piirkonnas“

9. Teadustöö põhisuunad

Ranniku morfodünaamika, setete omadused ja dünaamika, liivalasundid meres

10. Teised uurimisprojektid

Projekti juhina projektides:

Hiiumadala liivamaardla Hiiumadala II mäeeraldisest kaevandamise keskkonnamõju hindamine (2008)

Pirita rannakaitse rajamise keskkonnamõju hindamine (2008)

Kakumäe sadama rekonstrueerimise keskkonnamõju hindamine (2007)

Hiiumaast läände, põhja ja loodes asuvate madalate geoloogiline uuring (2007)

Diomidi madala uuringuruumi geoloogiline uuring (2007)

Toila sadama rekonstrueerimise keskkonnamõju hindamine (2006)

Kelnase sadama rekonstrueerimise keskkonnamõju hindamine (2006)

Leppneeme sadama rekonstrueerimise keskkonnamõju hindamine (2006)

Ihasalu lahe kirdeosa geoloogiline uuring (2006)

Naissaarest kagus asuva liivalasundi geoloogiline uuring(2005)

Ihasalu lahe idaosa geoloogiline uuring (2005)