

Quantification of sediment loss from semi-sheltered beaches: a case study of Valgerand Beach, Pärnu Bay, the Baltic Sea

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ABSTRACT

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A systematic estimate of the sediment budget is presented for the northern coast of Pärnu Bay, the Baltic Sea, where the littoral drift of sand from Valgerand, an eroding sandy beach, is directed to the east and finally blocked by the jetties in the Pärnu River mouth. The estimate is based on an application of the theory of the equilibrium beach profile and a comparison of a map produced at the turn of the 19th and 20th century with contemporary maps. The eroding section is relatively short, about 1 km in length, and loses about 1000 m³ of sand annually. Most of the northern coast of Pärnu Bay shows features of longshore sand transport. The major accumulation area is located to the north of the Pärnu River mouth where up to 4000 m³ of sediment accumulates annually.

ADDITIONAL INDEX WORDS: *beaches, sediment transport, sediment budget, accretion, erosion*

INTRODUCTION

The problems related to the potential intensification of coastal processes and rapid erosion events at certain locations of the Baltic Sea (Orviku *et al.*, 2003; Eberhards *et al.*, 2006; Ryabchuk *et al.*, 2011) in the recent past are frequently associated with changes to the wave climate caused by the changes in cyclonic activity (Suursaar *et al.*, 2008; Orviku *et al.*, 2009). The relevant impacts are especially strong in the areas where the sea has normally been ice-covered during the windiest season and where the shortening of the ice season serves as a key agent of impact to sandy shores (Orviku *et al.*, 2003; Ryabchuk *et al.*, 2011).

The described processes have created a need for methods to estimate the status and future of beaches that are under heavy pressure. Many sandy beaches located in sheltered locations of semi-enclosed micro-tidal basins such as the Estonian Baltic Sea coast contain very limited amounts of sand and are therefore particularly vulnerable with respect to changes in forcing. The gradual shift in the directional distribution of winds in this area (Kull, 2005; Jaagus, 2009) that apparently is accompanied by similar changes to the wave directions (Räämet *et al.*, 2010; Kelpšaitė *et al.*, 2011) may seriously affect the sandy beaches that are open to a limited range of wind directions.

Valgerand (White Beach) is an example of an about 4 km long beautiful sandy beach with limited exposure to Pärnu Bay, in the south-west of Estonia (Figure 1). Sandy shores in Valgerand have suffered from erosion during a long time (Kask, 2000). The retreat has been, in some places by over 30 m within the last 50 years. Since the 1990s the average retreat is around a meter per year (Kask and Kask, 2002).

The geological structure of near-surface sediments and the general pattern of sediment transport in Pärnu Bay are well known (Orviku and Palginõmm, 2002). The orientation of Pärnu Bay is such that most of wave conditions cause littoral drift from Valgerand to the east, towards the Pärnu River mouth. The

eastward shift (about 500 m in 100 years) of the Audru River mouth is a clear indication for the longshore sediment transport.

Valgerand is located in the westernmost area of the northern coast of Pärnu Bay. To the west of Valgerand the coast is almost stable (geologically inactive) and therefore provides nearly no sand supply to the beach. In this sense, the coastal section from Valgerand to the Pärnu River mouth forms a more or less closed erosional-accretional littoral system, with prevailing drift to the east. The basic characteristic of the evolution of beaches is the rate of change of their sediment volume. This paper makes an attempt to estimate this rate for Valgerand based on the application of the theory of the equilibrium beach profile (EBP) (Dean, 1991) combined with a recently introduced inversion of the Bruun Rule (Kask *et al.*, 2009) and the analysis of historical data on the position of the coastline. The accuracy of calculations of the sediment loss is roughly estimated using the amount of eroded sediment from Valgerand that is carried along the shore and which has accumulated at the jetties of the Pärnu River mouth.

METHOD

The mathematical description of the evolution of beaches that reveal relatively small changes in the position of the shoreline compared to the width of the EBP can be largely simplified without the loss of generality and accuracy. Kask *et al.* (2009) show that for slowly evolving beaches the total sand loss or gain over a section of the beach can be approximately expressed using the shift Δy of the shoreline and the closure depth $h^*(x)$:

$$\Delta V = \int h^*(x) \Delta y \, dx \quad (1)$$

Here the x -axis is directed along the beach, the y -axis is perpendicular to the shoreline and both the shoreline shift and the closure depth may vary along the beach. The basic advantage of Eq. (1) is that the sand loss or gain in homogeneous beach sections

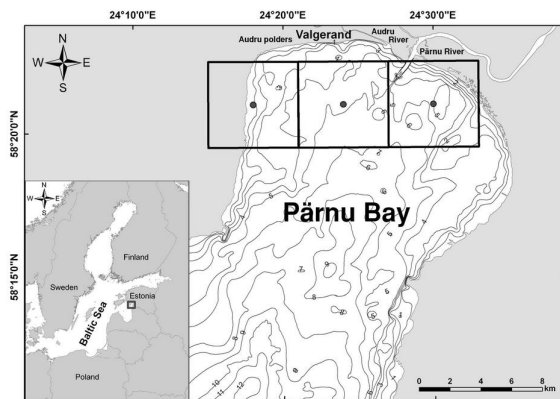


Figure 1. Valgerand in the south-west of Estonia in Pärnu Bay, Baltic Sea. Rectangles show grid cells of the wave model. Source: Pärnu Bay, map 1:50 000, Estonian Maritime Administration, 2009.

(where the closure depth is constant) only depends on the changes to the area of dry land:

$$\Delta V = h * \int \Delta y \, dx. \quad (2)$$

Equations (1) and (2) ignore the amount of sand eroded from (or deposited in) the berm and coastal scarp and ridges as well as sand transported beyond the seaward border of the EBP.

Most of the coastal forest and the backshore of the sandy strip of Valgerand have a very modest slope (Figure 2). An exception is a relatively short chain of ancient dunes to the east of the Doberan café (located in the central part of the sandy strip, Figure 3) that is currently eroding. There is little evidence of dune-building processes in most of the transitional area and in the accumulation area near the Pärnu River mouth. Minor foredunes are only being formed to the west of the contemporary location of the Audru River mouth. Therefore, it is reasonable to assume that the amount of sand eroded from the coastal scarp and dunes, and also sand deposited in the berm and foredunes near the Audru River mouth, can be ignored in calculations of sediment budgets.

The water depth in the northern part of Pärnu Bay is 3–4 m. The sea bottom is quite flat and mostly consists of varved clay. It is covered by thin (typically ~0.2 m) layer of soft Holocene



Figure 2. Valgerand, the area under erosion in 2007.

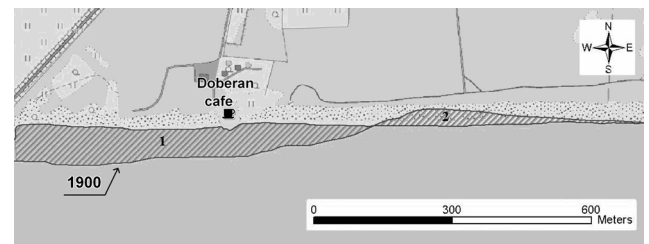


Figure 3. Map of Valgerand showing the variations in the position of the coastline from the beginning of the 20th century (denoted by 1900) until 2008 (Estonian Base Map). The striped areas mark erosion (1) and accumulation areas (2). Café Doberan was originally constructed in the 1920s far from the waterline but is located directly at the shoreline today. The sandy section starts from the polder located at the left border of the panel. Source: Estonian Land Board, <http://geoportaal.maaamet.ee/eng/> (accessed 05.12.2010).

sediments where the predominant material is fine sand (grain size >0.063 mm) and silt (<0.063 mm) with mud in some places (Kask, 1998; Orviku and Palginõmm, 2002). Sediments originate from the erosion of older sediments (till and varved clay). This suggests that there is very limited exchange of sediment between the wave-dominated coastal zone and current-dominated central part of the bay and that no extensive sand loss occurs from the active beach profile to the underwater slope.

The overall location and characteristics of Valgerand are such that the EBP theory is probably applicable for its description. It evolves quite slowly, with the total retreat over a century being much smaller than the width of the EBP (see below). Therefore, to a first approximation it can be considered to be in an almost equilibrium state, more or less continuously supporting an EBP, and the use of applications based on the existence of an EBP is reasonable, even when the active sand mass in some coastal sections is limited and rapid retreat occurs during some storms.

The key simplification from this approach is that the amount of data necessary for an adequate description of the sediment budget for almost equilibrium beaches is much smaller than the data sets needed to characterize non-equilibrium beaches. For such beaches the rate of change to the sediment volume can be simply estimated from Eqs. (1) or (2) based on only two sets of data: (i) the local wave regime (that defines the closure depth) and (ii) the change to the dry beach area. While a certain amount of data about sediment properties such as textural properties of sediment (that govern the mean slope and width of the EBP) and the availability of fine material in the retreating parts of the beach must come from *in situ* measurements, many necessary parameters can be estimated from the analysis of the nearshore wave climate and from comparison of historical maps or subsequent measurements of the position of the coastline. The necessary wave data set for the northern coast of Pärnu Bay has been constructed using long-term numerical simulations of the Baltic Sea wave fields (Räämet and Soomere, 2010). Also, there exist relatively detailed and reliable maps of the coastal areas of Estonia constructed more than 100 years ago.

We rely on the most widely used shape of the EBP that corresponds to the uniform wave energy dissipation per unit water volume in the surf zone (Dean and Dalrymple, 2002). The water depth $h(y)$ at a distance y from the shoreline along such a beach is expressed as

$$h(y) = Ay^{2/3}. \quad (3)$$

The details of such an EBP are defined by two parameters. The profile scale factor A depends on the grain size of the bottom sediment. Notice that Eq. (1) does not contain this parameter. The loss or gain of sand is determined by the other parameter – the closure depth h^* . We use the approximation of Birkemeier (1985) that explicitly accounts for the frequency of occurrence of rough wave conditions and the relevant wave period, and that has led to good results for semi-sheltered beaches in Estonia (Soomere *et al.*, 2008):

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

where $H_{s,0.137}$ is the wave height that is exceeded with a probability of 0.137 %, g is acceleration due to gravity and T_s is the dominant peak period in such wave conditions.

DATA AND RESULTS

Closure depth and width of the equilibrium profile

The closure depth for the areas in question is estimated using numerically modeled wave properties for the entire Baltic Sea with a spatial resolution of 3 nautical miles and a temporal resolution of 1 hour for 1970–2007 (Räämet and Soomere, 2010). The threshold $H_{s,0.137}$ and the accompanying value of T_s for use in Eq. (3) are calculated using two methods. Firstly, it was found as an average of a set of the relevant annual values for each of the 38 years of the simulation period. Secondly, it was estimated directly from the hourly time series of simulated wave heights. The results differed by a few mm. Wave data from the left-most grid cell in Figure 1 are used to characterize the eroding part of Valgerand (see below); from the middle cell – the short accumulation area in Valgerand and from the right-most cell – the vicinity of the Pärnu River mouth (Table 1).

An estimate of the width of the EBP described by Eq. (3) is based on the information about sediment grain size. We use this estimate only for a comparison of the changes to the coastline with the width of the EBP. For this purpose it is sufficient to use existing published data and to assume that the prevailing grain size insignificantly varies along the entire coastal section under consideration (because much of sand in the vicinity of the Pärnu River mouth has been transported from Valgerand).

The prevailing grain size in the coastal sediments along the northern coast of Pärnu Bay is in the range of 0.125–0.21 mm (Kask, 1998). This range corresponds to values of the profile slope parameter A from 0.07 to 0.1 (Dean and Dalrymple, 2002). Below we use the approximate value $A = 0.085$. With this value, the approximate width of the EBP is 120 m for Valgerand (area (i)), 130 m for area (ii) and about 200 m in the vicinity of the Pärnu River mouth (Table 1).

Changes to the coast

The rate of recession of the shoreline is usually estimated based on field measurements (repetitive profiles, GPS measurements), topographic maps, aerial photographs and orthophotos from different decades. The first map that more or less reliably depicts the location of the coastline of Valgerand comes from the beginning of the 20th century (Figures 3 and 4). The location of the coastline in this map is compared with the contemporary coastline (mapped in 2008). We also used several orthophotos and maps from different decades in order to establish the range of short-term variations in the shoreline, equivalently, to make sure that the identified long-term changes are credible.

Table 1: Parameters for the equilibrium profile for the northern coast of Pärnu Bay.

	Erosion area (i)	Accumulation area (ii)	Accumulation area (vi)
$H_{s,0.137}$, m	1.43	1.39	1.81
T_s , s	6.10	5.50	6.0
h^* , m	2.18	2.06	2.63
EBP width, m	130	120	196
$\int \Delta y$, m ²	46 600	10 460	133 600
ΔV_{Σ} , m ³	101 590	21 550	351 370

The northern coast of Pärnu Bay (Figure 1) from the western border of Valgerand to the Pärnu River mouth can be divided into six different sections: (i) an ~0.8 km long erosional stretch beginning at the Audru polder and including the Doberan café (area 1 in Figure 3); (ii) an ~0.6 km long accumulation area (area 2); (iii) a relatively long (~1.9 km) area of sand transport and weak accumulation (including some freshly formed foredunes); (iv) a sand transport area to the west from the Audru River mouth, where neither significant erosion nor accumulation is evident; (v) the Audru River mouth area mostly covered by reed beds (vi) the vicinity of the northern jetty of the Pärnu River, that is the key accumulation area over the entire beach section studied. This area apparently also had a positive sediment budget in the past but rapid accumulation has taken place since the jetties were built (Figure 4).

In calculations, we concentrate mostly on three sections in which substantial changes in the amount of sediment has occurred during the last century: erosion area (i) near the Doberan café, short accumulation area (ii) to the east from the café and major accumulation area (vi) adjacent to the northern jetty of the Pärnu River mouth.

Area (iii) is characterized by a large number of underwater sand bars and by very gently sloping shore. A comparison of maps and orthophotos from different times reveals several morphologic features that are typical for accumulation areas. Approximately 0.9–2.8 km to the east of the café, longshore sediment transport has separated the ancient coastal lagoon from the sea and slow accumulation into the narrow beach ridge takes place today. On the other hand, the presence of a swamp just behind a narrow sandy stretch separating the sea and an ancient lagoon suggests that this area acts as a transport section with very slow accumulation. Also, a very shallow nearshore region in this section at 24°24' E (Figure 1) probably reflects the presence of elevation higher base consisting of till or clay.

About 2.8 km to the east of the café is an area of intense transport where only very small net changes occur. Although several maps show some deviation of the coastline over the 20th century in this section, the very gently sloping shore and the absence of substantial dunes suggest that these deviations do not necessarily reflect the accumulation or erosion of sand. These deviations might be caused by the ambiguities or different methodologies used for mapping in the past. Also, relatively large weather-driven sea-level variations in this area (Suursaar and Sooäär, 2007) might have led to large variations of the instantaneous waterline on the shores with such a gentle slope. Therefore, we exclude this area from the calculations.

Another argument for considering only three sections is that no reliable evidence is available for the behavior of sections (iii)–(v) between Valgerand and the Audru River mouth area, especially for the section with the ancient coastal lagoon and the very

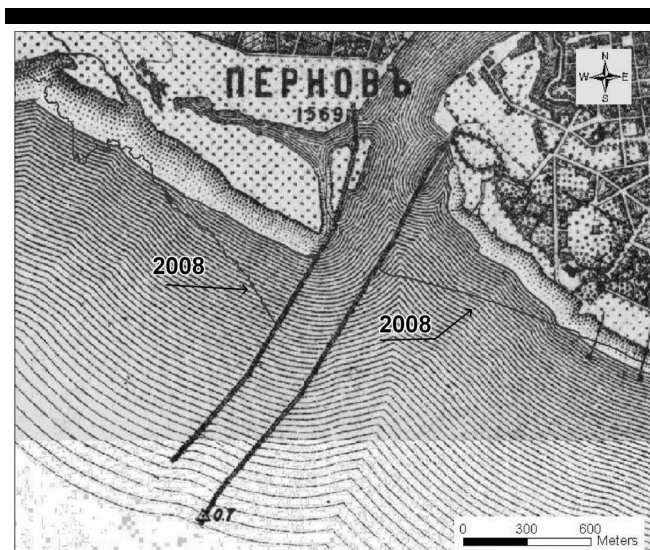


Figure 4. The Pärnu River mouth area in the beginning of the 20th century and the coastline of the Estonian Base Map (2008; Estonian Land Board, <http://geoportaal.maaamet.ee/eng/> accessed 05.12.2010).

shallow nearshore. It is natural to interpret the absence of external verification of changes to the coast in this relatively densely populated and actively used area as evidence showing that the coastline has been more or less stable.

Relatively large recession has occurred in section (i) of Valgerand from the polder to 0.3 km to the east of the Doberan café. The typical retreat rate is about 67 m within a century (6.7 m/decade). The total loss of dry land is about 46 600 m²/century, and that corresponds to the loss of about 100 000 m³ of sediment from this section of the coast (Table 1).

Further to the east of the Doberan café (0.3–0.9 km from the café, area (ii)) the beach has been widened to some extent (generally <20 m). The gain of dry land is about 10 000 m²; consequently, >20 000 m³ of sand has accumulated (Table 1). A comparison of orthophotos from 1994–2008 (not presented here) shows that the typical extension of natural variations in the position of the shoreline is about 10 m, that is, much smaller than the magnitude of the largest retreat. Therefore, the discussed long-term changes evidently are systematic.

Although there have been claims in the popular literature that the retreat rate has increased over recent years in Valgerand, our analysis suggests that the most intense erosion actually occurred in the vicinity of the café in the beginning of the 20th century. The retreat slowed down in the middle of the century. Although it apparently intensified again since the 1970s, its intensity evidently has not exceeded the rate of a century ago. This long-term pattern is consistent with variations in storminess in this region, being quite large at the beginning of the 20th century and decreasing substantially in the middle of the century. Although storminess has clearly increased again since the 1960s, it only reached its original level in the 1990s and probably is decreasing now (Alexandersson *et al.*, 1998; 2000).

The second largest changes have occurred in the vicinity of the Audru River mouth. Historical data and maps show that the river mouth has gradually moved eastwards, about 500 m/century, reflecting intense littoral flow to the east. The overall location of the coastline, however, has changed insignificantly.

Accumulation sand body at the Pärnu River mouth

The jetties (Figure 4) were built in 1864 to protect the port located in the river mouth from silting. Before their erection, the Pärnu River mouth was wide and low. The situation in the river mouth apparently was in dynamic equilibrium: sediment carried to the river mouth by littoral flow from both sides was either transported further offshore by the river flow or accumulated to the west of the river mouth.

This process has been blocked by the jetties that act as extremely long groins (with a total length of about 2 150 m, Orviku and Palginõmm, 2002) almost completely separating the sedimentary systems to the east and to the west of the river mouth. The major change is twofold: (i) sand transported to either side of the river mouth is intercepted by the jetties; (ii) almost no marine sand enters the river and practically all sand is accumulated in the vicinity of jetties. The resulting changes to the coastline are clearly visible in Figure 4. The thickness of the layer of contemporary marine sediment decreases rapidly along the jetties. At the tip of the eastern jetty the thickness of the sand layer is about 1 m, but is about 1.95 m at the end of the western jetty (Kask and Kask, 2002).

The shoreline has advanced, on average, by more than 360 m seawards in a period of approximately 100 years. The advancement is much larger (up to 700 m) in the immediate vicinity of the jetty. Accumulation has evidently occurred in the form of a sequence of low sandy ridges. The ridges were in places separated by shallow lagoons that have later been filled by other sources of sediment and partially by human activities. The height of the ridges and the depth of lagoons usually are below 0.5 m, thus, much smaller than the entire thickness of the layer of marine sediment (about 3 m), and we neglect the presence of ridges and lagoons in our estimates. The entire gain of dry land is more than 130 000 m² and therefore about 400 000 m³ of sediment has been accumulated in this section. The thickness of the contemporary marine sediment may be smaller (approximately 1.5 m) at some places under the accumulation area, potentially reflecting the presence of elevation higher base consisting of ancient sediments to the west of the Pärnu River mouth and suggesting that the accumulation rate may be overestimated to some extent.

CONCLUSIONS AND DISCUSSION

The comparison of the contemporary coastline with the position of the coastline about a century ago shows that the retreat rate in Valgerand has been about 0.67 m/year in the 20th century. The eroding section is relatively short (about 1 km in length) and most of the northern shore of Pärnu Bay shows features of either sediment transport or accumulation.

The total net sand loss from the sandy area of Valgerand is about 100 000 m³. The annual loss of sand, therefore, is about 1000 m³ which is close to the typical loss rate for Estonian beaches located in relatively sheltered locations (Soomere *et al.*, 2008). It is very likely that this sand is mostly transported to the east, passes the Audru River mouth and accumulates in the vicinity of the northern jetty of the Pärnu River mouth. The estimated rate of sand gain in this accumulation feature exceeds by several times the loss from Valgerand. The typical rate of advancement of the shoreline exceeds 3 m/year in that area. This difference apparently stems from the sand inflow from the Pärnu and Audru rivers. The presented data suggest that these sources may provide up to 3000 m³ of sand per annum. This estimate is consistent with data from the much smaller Pirita River on the northern coast of Estonia that delivers about 400 m³ of fine sediment per annum to Tallinn Bay (Soomere *et al.*, 2008).

The credibility and usefulness of the estimates obviously depends on whether or not it is acceptable to apply the theory of Dean's equilibrium profile and the inversion of the Bruun Rule (that has been derived for relatively small variations in the location of the shoreline, Kask et al., 2009) for the area in question and for the relatively large changes in the shoreline location near the Pärnu River mouth. Another criterion of credibility is the ratio of typical short-term variations in the position of the shoreline and its long-term changes.

The identified changes to the shoreline in the key erosion and accumulation areas (typically 70 m and larger than 300 m, respectively) substantially exceed the range of short-term variations (about 10 m) and thus are reliable. The typical magnitude of shoreline changes at Valgerand is much smaller than the width of the EBP in this region whereas this magnitude exceeds by several times the EBP width for the major accumulation area. This feature suggests that the presented estimates are basically reliable for the eroding sections but may overestimate the amount of sand accumulated near the Pärnu River mouth.

Another concern with this type of analysis is the credibility of older maps. In general, one should be extremely careful using maps from the end of the 19th century. However, long history of the use of the coast and backshore in this region together with several fixed objects in the vicinity of the shoreline on both maps suggest that the accuracy of the map used was quite high in the light of standards of the past and acceptable also today.

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