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Rapid Estimate of Sediment Loss for “Almost Equilibrium” Beaches

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ABSTRACT

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A simple method is proposed for a rapid estimate of the net sand loss or gain for beaches where the sediment loss or gain is balanced by tectonic uplift or downsinking, and the beach is close to Dean’s equilibrium beach profile conditions. The method is based upon inverting the Bruun Rule. Sediment loss or gain is expressed in terms of the changes of the dry land area, the width of the equilibrium beach profile, and the uplift or downsinking rate. Information necessary for applying the method consists of (i) the basic properties of the local wave climate, (ii) changes of the location of the coastline, (iii) grain size along the beach and (iv) uplift or downsinking rate. An example of the sediment budget for Pirita beach on the Estonian coast of the Baltic Sea is presented. Details of the local wave regime and nearshore sand transport patterns along this tideless beach have been investigated utilizing high-resolution modelling of wave properties combined with bathymetric and topographic surveys of the coastal slope and the dry beach, and sediment textural analyses of the beach and nearshore sea floor. The proposed 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.

ADITIONAL INDEX WORDS: *Sediment transport, equilibrium beach profile, Bruun Rule*

INTRODUCTION

To obtain accurate sediment budget normally requires long-term measurements of sediment transport, or sediment trapped at a groin, or historical geomorphic and bathymetric changes, and thus is 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 of their bottom profile. The properties of their long-term evolution are mostly governed by a small number of parameters. Although the instant profile may undergo substantial changes owing to various hydrodynamic factors, an average of the instantaneous profiles over a long period usually tends toward a practically constant shape. This shape is called the “equilibrium beach profile” (Dean, 1991; Dean and Dalrymple, 2002).

The majority of applications of the concept of equilibrium profile are directed towards estimates of 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 of sediment volume of the beach profile usually is not possible, because the sediments are redistributed between different bodies such as dunes, berm, sand bars, and sloping bottom (Dean *et al.*, 1993).

An inverse application of the concept of equilibrium profile to obtain a rough estimate of the sediment loss or gain based on the shift of the shoreline is reasonable in certain cases. This approach is justified, for example, in cases when (i) the lateral sediment losses are minor, (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. A type example may be found around the bayhead beaches of the isostatically rebounding northern Baltic Sea where the sand loss is nearly balanced by the relative water level fall.

It is shown that in such cases the changes of the sand volume can be easily estimated from the changes of the dry land area provided the parameters of the equilibrium profile and the relative water level changes are known. We present the relevant mathematical justification of an inverse of the Bruun Rule in the particular case of the Dean’s Equilibrium Profile and discuss the set of parameters necessary for such estimates. As an example, we present the calculation of sand loss from Pirita Beach in Tallinn Bay, the Baltic Sea.

Study area

The Baltic Sea is an almost tideless basin with quite limited current velocities, normally not exceeding 10–20 cm/s. Therefore the main factor shaping the beaches is surface waves. The overall wave activity in the Baltic Sea is also quite modest and coastal changes mostly occur during infrequent high storm surges accompanied by high waves.

Pirita Beach is a typical small, embayed beach with about 2.4 km long sandy strip of the southern coast of the Gulf of Finland, located in the south-eastern section of Tallinn Bay, Estonia (Figure 1). The seashores adjacent to Pirita Beach are largely protected by boulders cobbles, and pebbles. For the listed reasons, the overall activity of littoral drift and coastal processes is relatively low. As the entire northern coast of Estonia generally suffers from sediment deficit (Orviku and Granö, 1992), it is not surprising that a certain net loss of sand at times occurs in the

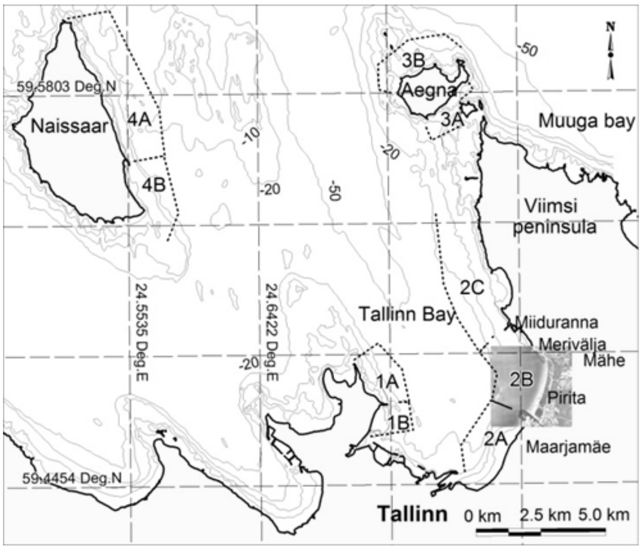

Figure 1. Location scheme of Pirita Beach in Tallinn Bay showing identified cells of sediment transport after SOOMERE *et al*. (2007) and isobaths of –2, –5, –10, –20, and –50 m. Reprinted with permission from the Estonian Academy Publishers.

Pirita area. This loss is compensated by postglacial land uplift which is estimated to be 1.8 to 2.5 mm/year (VALLNER *et al*., 1988; MIIDEL and JANTUNEN, 1992) and which, over time, contributes to an increase in beach width.

Prior to the mid 20th century the beach was considered to be stabilized, almost in equilibrium state, or even showing features of sand accretion. Several coastal engineering activities in its vicinity, however, have influenced the sediment dynamics. The Miiduranna port north of the beach this port has essentially blocked all littoral transport from the north since the 1970’s and the construction of Pirita Harbor substantially decreased the river supply of sand (SOOMERE *et al*., 2007). During recent decades a gradual decrease of the dry beach width and rapid recession of the till cliff at the northern end of the beach at a rate of up to 1 m/year suggest that the beach seems to lose sand.

Since no reliable data about changes of the sand volume and the intensity of sand sources in the beach area are available, an alternative way must be used for estimates of the gain or loss of sand at the beach. Several features of the local dynamics, in particular, relatively fast postglacial uplift combined with the overall sea level rise and very limited lateral sand loss from the area, are favorable for creating an equilibrium regime (SOOMERE *et al*., 2007; 2008). A feasible way consists in the use of the proposed technique to approximately determine the net sand loss of the beach.

METHOD

The method of rapid estimate 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, the Bruun Rule was derived to predict shoreline retreat resultant upon water level rise for any sort of equilibrium profile. Usually it is 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 $\tan\theta$:

$$\Delta y = -\frac{\Delta S}{\tan\theta} \,. \tag{1}$$

Equation (1) 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 has occurred from the equilibrium profile and the entire profile has been shifted shoreward (Figure 2). For simplicity, we assume that the equilibrium profile has the shape of the classical Dean’s Equilibrium Profile (EBP).

The volume of sand loss can be easily expressed in terms of the profile parameters. For small changes of the shoreline position the slope of the dry beach can also be ignored. Then it is 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 lost sand is

$$\Delta V \approx h^* \Delta y \,, \tag{2}$$

where depth h^* is equivalent to so-called closure depth, defined as 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. Details of the derivation of Eq. (2) and further discussion of the method are presented in (SOOMERE *et al*., 2009).

The problem of calculation of sand loss has therefore been

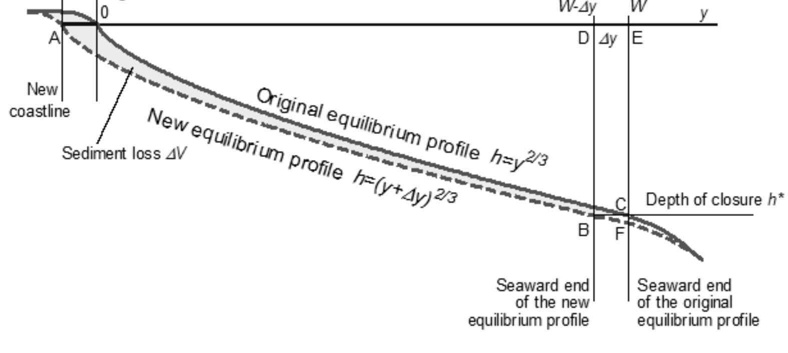

Figure 2. Calculation of the change of sand volume for small changes of the position of the coastline.

reduced to determination of the shift of the shoreline and the closure depth. By doing so we have neglected the amount of sand between the seaward ends of the original and the shifted equilibrium profile. Since the typical slope at the seaward end of both the profiles is smaller than their mean slope, this volume is smaller than

$$V' = \frac{1}{2}\Delta y \tan\theta \tag{3}$$

and obviously can be neglected for small coastline changes.

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

$$\Delta V_\Sigma = \int h^*(x)\Delta y \, dx \, . \tag{4}$$

The basic advantage of Eq. (3) is that the sand loss or gain in homogeneous beach sections (where the closure depth is constant) only depends on the changes of the area of the dry land:

$$\Delta V_\Sigma = h^* \int \Delta y \, dx \, . \tag{5}$$

Consequently, Eqs. (4, 5) predicts that a shift of the shoreline by one meter (equivalently, each square meter of gain or loss of the dry land) means the change of the volume of sand within the equilibrium beach profile by $\Delta V \approx 2.5$ m^3 per linear meter of beach. Realistic values representing long-term gain or loss obviously can only be obtained for beach sections of considerable length, along which the integrals in Eqs. (4) or (5) are calculated.

PARAMETERS OF EQUILIBRIUM PROFILE

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 which implements the parameters of the local wave climate.

The most widely used shape of the equilibrium beach profile (EBP) 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

$$h(y) = Ay^{2/3} \, . \tag{6}$$

The details of an EBP 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. Another decisive parameter is the closure depth.

Closure depth

A specific feature of semi-enclosed beaches is that the simplest approximations of the closure depth h^* based on average wave parameters of wave regime usually lead to inconsistent results. For example, HOUSTON (1996) argues that an acceptable estimate for the closure depth is

$$h^* \approx 6.75 H_s^a \, , \tag{7}$$

where H_s^a is the annual mean significant wave height. This approximation underestimates the closure depth at Pirita. The reason is that the proportion of rough wave conditions that are able to support the entire equilibrium profile, implicitly used in this estimate, does not necessarily hold in coastal areas with complex geometry, in particular, in semi-enclosed seas such as the Baltic Sea (SOOMERE, 2005; CALISKAN and VALLE-LEVINSON, 2008). For that reason, approximations that explicitly account for the frequency of occurrence of rough wave conditions should be used in this region.

BIRKEMEIER (1985) suggests the following expression for the closure depth:

$$h^* = p_1 H_{s,0.137} - p_2 \frac{H_{s,0.137}}{gT_s^2} \, , \tag{8}$$

where $H_{s,0.137}$ is the threshold of the significant wave height that occurs 12 hours a year (that is, the wave height that is exceeded with a probability of 0.137 %), g is acceleration due to gravity, T_s is the dominant period in such wave conditions, and the coefficients p_1 and p_2 depend on the particular type of problem and time scale. For example, NICHOLLS *et al.* (1996) have generalized expression (7) for any time frame of interest with the choice $p_1 = 2.28$, $p_2 = 68.5$. For Pirita, however, the best fit of the numerically estimated values of closure depth give the values suggested by BIRKEMEIER (1985)

$$p_1 = 1.75 \, , \; p_2 = 57.9 \, . \tag{9}$$

Local wave regime

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 we use the numerically modeled properties of the local wave climate for an estimate of the closure depth (SOOMERE *et al.*, 2008). The wave properties are 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. The innermost model has a grid step of about 1/4 nautical miles (about 470 m) and allows correct description of wave properties up to a depth of about 5 m and as close to the coast as about 200–300 m in the conditions of Tallinn Bay (SOOMERE, 2005). The wave model is forced with high-quality wind data from the adjacent open sea area. The presence of ice is ignored. 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. Detailed overview of the calculations of wave climate in the vicinity of Pirita Beach is presented by SOOMERE *et al.* (2008).

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 value of $H_{s,0.137}$ is 1.45–1.56 m in different parts of the beach and the typical peak period $T_s \approx 7$ s in such storms (SOOMERE *et al.*, 2008). The closure depth, estimated from Eq. (8), therefore varies between 2.36–2.57 m in different sections of the beach. This estimate well matches the similar depth of about 2–2.5 m, estimated from a bathymetric survey about one year after a major storm (Figure 3).

The small variation of the closure depth along the beach suggests that the wave regime along the beach is more or less homogeneous and the use of Eq. (5) for volume loss calculations is justified.

In order to estimate the closeness of the beach to the equilibrium conditions, alongshore sediment transport patterns were calculated based upon a long-term time series of wave properties along the beach, and the CERC formula applied to beach sectors each about 500 m long. Southward transport dominates in the northern section of the beach whereas no prevailing transport direction exists in the southern sections and the entire beach is close to an equilibrium state (SOOMERE *et al.*, 2008).

Profile scale factor and local Bruun Rule

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

In the framework of the concept of EBP, 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 width W of the profile and the closure depth h^*. 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, the width of the profile also depends on the properties of bottom sediments.

In the case of an EBP, 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 the Pirita beach is 0.12 mm and insignificantly varies in the nearshore of most of the Pirita beach (SOOMERE *et al.*, 2007). 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 above values $h^* = 2.36 - 2.57$ m of the closure depth define the width and the mean slope of the EBP 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 coastline:

$$\Delta y \approx -85\Delta S\,. \tag{10}$$

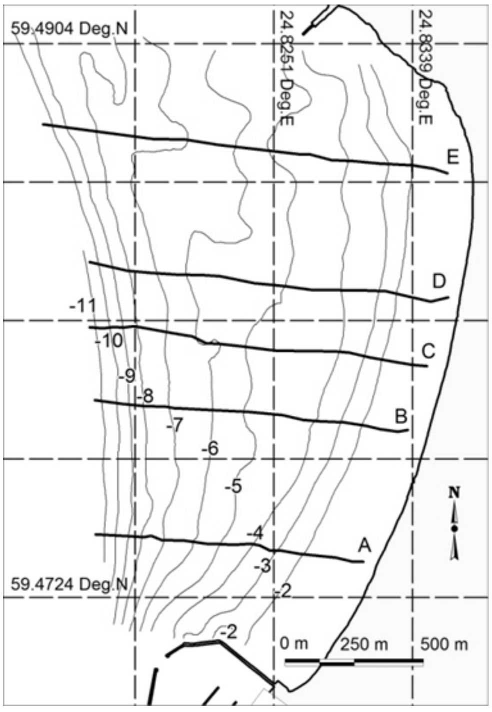

Figure 3. Bathymetry of the nearshore at Pirita in April 2006 (SOOMERE *et al.*, 2007; reproduced with permission from the Estonian Academy Publishers)

RESULTS

As an example, we estimate the net loss of sediment from Pirita Beach from the mid-1980s to the present. As high-resolution surveys are not available from 1980s, the position of the coastline before 2000 is digitized from topographical maps produced at different times. The position of the coastline in the mid-1980s is 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 Defense of the USSR based on topographical surveys performed apparently in 1983–1985. An analogous, but more recent map has apparently been surveyed about the turn of the century, i.e. about 15 years later.

The rate of the postglacial rebound at Pirita Beach is about 2.5 mm/year (VALLNER *et al.*, 1998). 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. (9). The gain of dry land in the entire sandy beach would be about 8,000 m^2. The actual gain of land has been much less, about 3,000 m^2. Large sections of the sandy beach have become narrower (SOOMERE *et al.*, 2007). Erosion of the beach is most evident in its northernmost section along a ~200 m section. The maximum recession is at places up to 25 m and only the central and southern parts of the beach have been stable (SOOMERE *et al.*, 2007; 2009).

Consequently, the net loss of sand from the beach is about 5000 $\mathrm{m}^2 \times 2.5\ \mathrm{m} = 12{,}500\ \mathrm{m}^3$. The net annual loss of sand from the beach is thus of the order of 1,000 m^3. Since this rate has been derived from indicative data, it should be interpreted as an estimate of magnitude of the sand loss.

A more exact estimate can be obtained from the comparison of two high-resolution surveys from 1997 and 2006 (Figure 4). As during the previous period, no net changes of the dry land area occurred between 1997–2006. The expected coastline 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 been practically unchanged between 1997–2006. Consequently, the net loss of sand during these years is also about 12,500 m^3. The net annual loss of sand from the beach is thus about 1,250 m^3 during this decade.

CONCLUSIONS AND DISCUSSION

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 for any type of equilibrium profile. The change of sediment volume is expressed as the product of the change of the dry beach area and the closure depth.

The proposed 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.

It should be noted that simplified formulae for estimating the closure depth based on the average wave height only (e.g., HOUSTON, 1996) may frequently be inappropriate for semi-

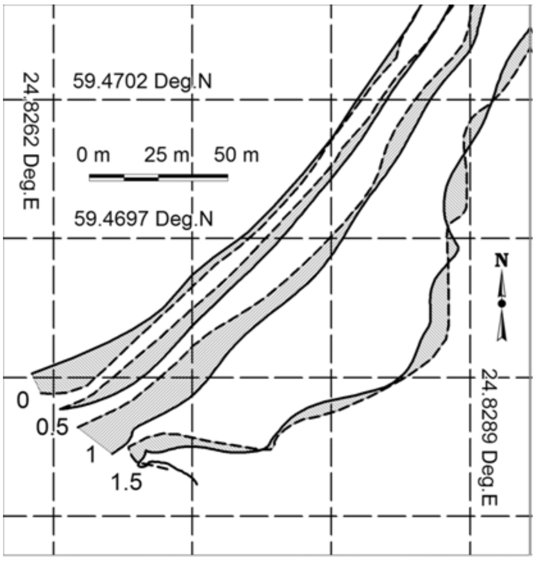

Figure 4. Changes in the location of isolines of surface elevation in the southernmost section of Pirita Beach. Solid and dashed lines show the 0, 0.5, 1, and 1.5-m isolines according to surveys of 1997 by REIB Llc (Map 1:500 with technological networks. Harju County, Tallinn, Pirita District, Pirita Beach. Contract No. 06-612) and of 2006 by Hectare Llc (Map with technological networks. Survey of Pirita Beach. Contract No. TT-0249), respectively. The shaded area represents changes in the positions of the isolines between 1997 and 2006 (Soomere *et al*., 2007; reproduced with permission from the Estonian Academy Publishers).

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. For that reason, the properties of the local wave climate defining the closure depth should be extracted from high-resolution simulations of the wave fields.

The method has been applied for 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 the 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 downsinking beaches supported by intense littoral drift or current-induced or fluvial sediment supply.

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