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COASTAL ENGINEERING

Quantification of changes in the beach volume by the application of an inverse of the Bruun Rule and laser scanning technology

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Abstract. We address the possibilities of combining terrestrial (TLS) and airborne laser scanning (ALS) techniques with the classical concept of equilibrium beach profile to quantify the changes in the total sand volume of slowly evolving sandy beaches. The changes in the subaerial beach are determined from a succession of ALS surveys that were reduced to the same absolute height using a TLS survey of a large horizontal surface of constant elevation. The changes in the underwater sand volume from the waterline down to the closure depth are evaluated using an inverse of the Bruun Rule. The relocation of the waterline is extracted from the ALS scanning of elevation isolines of 0.4–0.7 m. The method is applied to an about 200 m long test area in the central part of Pirita Beach (Tallinn Bay, north-eastern Baltic Sea). The sand volume in this area exhibits extensive interannual variations. The annual gain of sand in the entire beach was about 2000 m^3/y in 2008–2010 and the annual loss was about 1100 m^3/y in 2010–2014. The changes in the underwater part of the beach are by a factor of 2–2.5 larger than the changes in the subaerial part.

Key words: equilibrium beach profile, coastal processes, Bruun Rule, laser scanning, Pirita Beach.

1. INTRODUCTION

The nature and appearance of beaches of the Baltic Sea (Fig. 1) reflect several specific features of this large, relatively young and shallow water body of extremely complicated shape [21]. The conditions governing their evolution vary substantially depending on the location of the beach and particularly on the exposure of the beach to predominant wind directions [22]. The most important driver shaping the beaches here is the wind wave field. Its impact is at times amplified by large variations in the water level [21]. While the impact of tides is negligible in the interior of the Baltic Sea, seasonal ice cover may considerably modify the hydrodynamic activity in the northern parts of the sea over the course of a year.

Small sandy beaches on the southern coast of the Gulf of Finland form an interesting pool of seashores [13]. Much of the shoreline here is locally relatively straight but follows the geometry of deeply indented bays cut into the limestone cliff [22]. Although many of these beaches overlie ancient dunes, the volume of the contemporary marine sand and the magnitude of the littoral drift are usually very modest [22,24]. The seashore is to some extent stabilized by the postglacial uplift (up to 2 mm/y) [18]. Most of these beaches suffer from sediment deficit [22,24] and are vulnerable to strong storms from certain directions.

Wave conditions in the Baltic Sea are highly variable with short but intense storms [15]. This feature is even more evident for the beaches in question. Although the entire southern coast of the Gulf of Finland is geometrically sheltered from one predominant direction of storms (south-west), large waves may approach from directions from which winds are not very frequent [30]. The described features have led to the development of 'almost equilibrium' beaches [29]. Their overall slow evolution is occasionally modified by rapid events when high waves approach from an unusual direction. If such waves are accompanied by a

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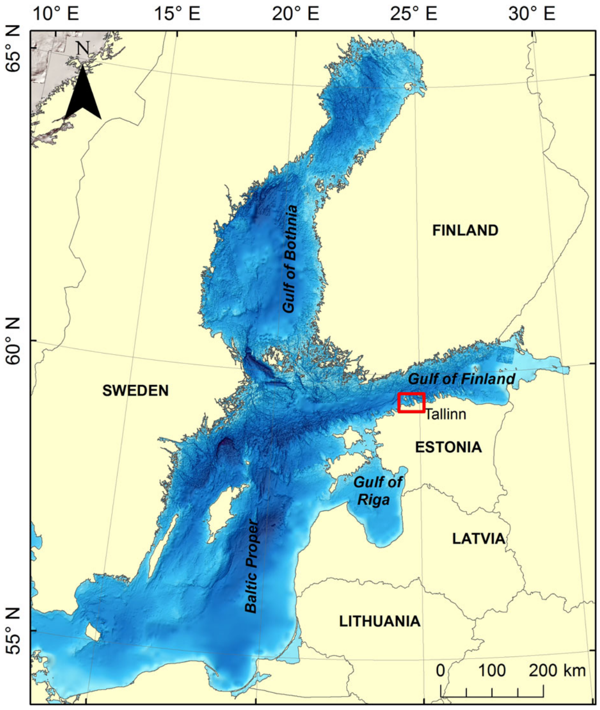

Fig. 1. The Baltic Sea and the Gulf of Finland. The box indicates the study area in Tallinn Bay in Fig. 2.

high water level and there is no protecting ice cover, substantial volumes of sand may be cut from the (fore)dunes relatively far from the usual waterline and distributed into the shallow nearshore [26,28].

The changes in sedimentary beaches are commonly evaluated using measurements of the beach or seabed height over a small number of selected profiles during a long time interval. The direction of sediment motion is added based on various morphological and geological features [7]. This approach is valid for long and mostly homogeneous (along the coastline) beaches. It may, however, easily overlook certain features of the evolution of relatively small beaches along which the impact of waves is not necessarily homogeneous and long-term changes are often masked by short-term variability of morphological elements or temporary shifts of the waterline. The situation is particularly complicated when local sources (e.g. river flow or erosion of single spots) contribute to the sediment budget. The quantification of the resulting volume changes over the subaerial beach requires high-resolution measurement techniques.

The morphology of the nearshore is usually more regular along the shoreline than the appearance of the dry beach. Waves generally smooth out seabed features on scales from ripples to sand bars. Strong storms tend to support a relatively homogeneous, often universal underwater beach profile down to the closure depth. Its idealized appearance is called the (Dean's) equilibrium beach profile (EBP) [6]. Its parameters basically depend on the sediment texture (those that define the slope of the profile) and properties of the highest waves (those that define the closure depth, or equivalently, how deep the profile extends). The use of the concept of EBP makes it possible to roughly estimate the changes in the sediment volume in the nearshore based on a few parameters of sediment, wave climate, and relocation of the waterline [20]. This approach is particularly suitable for almost equilibrium beaches such as Pirita Beach [32] in Tallinn Bay or Valgerand Beach in Pärnu Bay [19] where only minor changes occur in the position of the waterline.

We address the possibilities of combining medium-range remote sensing methods such as terrestrial (TLS) and airborne laser scanning (ALS) [3] with the concept of the EBP to quantify the changes in the total sand volume of a typical almost equilibrium beach. High-resolution laser scanning data are used to build a sequence of Digital Terrain Models (DTM; in essence exact surface models of the study object or area) for different time instants (called epochs in the ALS literature) [17] and to detect inter-epoch volume changes. Depending on the altitudes of survey routes (often up to a few kilometres), the resulting spatial resolution (~0.1–4 points/m^2) is usually sufficient to adequately evaluate volume changes of sandy beaches [10,37].

The basic advantage of the ALS technique in coastal research is its ability to almost instantaneously gather accurate and high-resolution data over the entire surface of the beach [9,10,37]. Its limited spatial resolution compared to extremely high-resolution measurements over small areas can be complemented by the combined use of ALS and TLS data sets [16,17], which makes it possible to quantify the pattern of spatial changes in the subaerial beach.

In this paper we explore the potential of the laser scanning technique to quantify the total changes in the sand volume of an almost equilibrium beach during its slow evolution phase. The most significant limitation of this technique is that it normally does not recognize the underwater changes. This shortage can be to some extent circumvented using the concept of EBP and the Bruun Rule [4]. The basic idea is to evaluate the changes in the sand volume over the EBP using basic properties of the EBP, an inversion of the Bruun Rule [20], and the relocation of the waterline extracted from laser scanning data.

2. STUDY AREA

The test area – a section of Pirita Beach – is located on the southern coast of the Gulf of Finland at the south-eastern bayhead of Tallinn Bay. It is a typical small, embayed beach at the bayhead of a haven that extends deeply into the mainland of Estonia (Fig. 2). The sandy

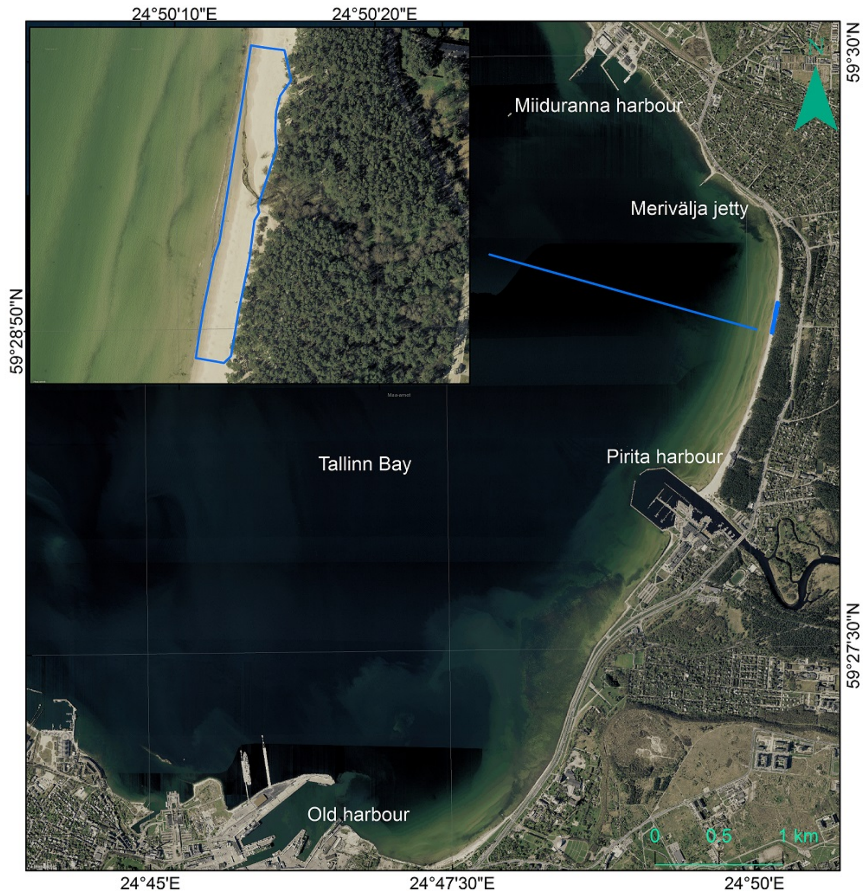

Fig. 2. The study area in Tallinn Bay.

beach with a total length of about 2 km stretches from the northern mole of Pirita (Olympic) Harbour until a moraine scarp located about 400 m southwards from Merivälja jetty. As is typical for beaches on the southern coast of the Gulf of Finland, the volume of the contemporary marine sand is quite limited, active foredunes are missing, and ancient dunes dominate the landscape inland. The overall intensity of coastal processes is low and the maximum height of the erosion scarp at the edge of the coastal forest is 1.5 m [31].

The coastal processes and the past and future of Pirita Beach have been the subject of discussions for decades [23,25,31]. The seashore is to some extent stabilized by the postglacial uplift (2.5 mm/y [18]) and by sediment supplies of the past. The stability of the beach is today threatened by a considerable decrease in the relative uplift rate and by the reduction of the natural sediment supplies [31]. The largest impact comes from the construction of Pirita Harbour, which has led to a substantial decrease in the supply of river sand to the beach.

Although the wave climate in the interior of Tallinn Bay is relatively mild and the closure depth along Pirita Beach is 2.4–2.6 m [33], single storms from unfavourable directions may cause severe destruction of the beach. The consequences of such storms in the 1970s have been mitigated by beach nourishment [23,25,31]. An increase in storminess in the second half of the 20th century [1] may have already overridden the stability of the eastern Baltic Sea beaches [26] and has caused severe sediment deficit on some beaches. Indeed, a gradual decrease in the beach width and recession of the coastal dune forest have continued in recent decades [17,31]. Approximately 50% of Pirita Beach, mostly its central and northern sections, suffers from damage at times [32]. The most significant damage to Pirita Beach in the recent past occurred in November 2001 and in January 2005 when high waves were accompanied with an exceptionally high water level [31].

The beach apparently lost, on average, 1000–1250 m^3 of sand per year between 1986 and 2006 [20,32]. Its most vulnerable part is an approximately 1 km long northern section where an extensive regression of the bluff occurred between 1999 and 2005. The recession was up to 3–5 m in a few sections from 1999 to 2001 [17]. The most stable section is in the south where the width of the beach is up to 100 m and the sandy strip reaches an elevation up to 2 m above the mean water level. The central part of the beach is in an almost equilibrium state.

The northern part of the beach has an almost unidirectional sand transport to the south whereas the transport direction is highly variable along other sections of the beach. The central area of the beach, selected as the test region for this study, is apparently the most sensitive with respect to changes in the hydrodynamic forcing and sediment supplies. Recent research has demonstrated that this area is extremely variable (both in time and space) with respect to erosion and accumulation [17]. The reader is referred to [31,32] for a detailed overview of the recent status of the beach, the local wave regime, and the properties of wave-induced sediment transport processes along the beach.

3. METHODS

3.1. Laser scanning techniques

Laser scanning technology has been suggested as an accurate and reliable method to quantify the coastal processes [9,10,37] and to evaluate the location of the shoreline [34]. The largest problem in using the ALS technique for the evaluation of sand volume is how to accurately determine and eliminate the systematic elevation errors between data sets measured from an aircraft in different surveys [9,17]. A combination of the TLS and ALS data sets makes it possible to remove the relevant bias, to reduce all the measured data sets to the one reference surface, and to accurately establish the absolute height of the sand surface in different scans [8,14]. Together with enhanced temporal resolution, this step is essential for an accurate evaluation of sand volume changes and for recognizing the internal structure of changes in the subaerial beach [17].

The elevation data of Pirita Beach from 2008 to 2013 were retrieved from the database of ALS measurements performed and pre-processed by the Estonian Land Board. Only points classified as ‘ground’ were used in this study. These ALS data sets, measured from an altitude of 2400 m and with an average density of 0.45 points/m^2, were complemented with TLS data with a much higher resolution of about 2 cm × 2 cm [17] gathered in 2013 and 2014.

All ALS surfaces were reduced to the reference surface using corrections derived from the exact elevation of a large car park near Pirita Beach. This area was measured using the TLS technology in December 2013 [17] and linked to the measurements at the beach. The resulting DTMs were suitable for estimating the changes in the absolute height of the beach and sediment volume along the beach. For technical details the reader is referred to [17]. During the TLS survey in 2013 the water level was relatively high (+0.4 m compared with the long-term mean). As the swash zone covered a significant part of the subaerial beach, this data set was not suitable for estimations of shoreline changes. Another TLS survey was performed in late spring 2014 when the water level was relatively low (–0.2 m).

3.2. Bruun Rule

As the laser scanning technology is not able to measure the location of the seabed, a first approximation of the changes in the sand volume in the underwater part of a beach was obtained using the theory of the EBP [6]. An extension (inversion) of the Bruun Rule makes it possible to evaluate these changes from the associated shift $\Delta y(x)$ of the shoreline and closure depth $h^*(x)$. The change in the volume ΔV_Σ over the EBP can be expressed as [20]:

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

Here the x-axis is directed alongshore and the y-axis is perpendicular to the shoreline. In general, both closure depth and the shift of the waterline may vary along the shoreline. As the closure depth along the entire Pirita Beach varies insignificantly (2.4–2.6 m [2]), it can be considered as constant $h^*(x) = h^*$ in the short test area (Fig. 2). In this case the change in the sediment volume over the EBP is equal to the product of the closure depth and the total change of the dry land area. This approach ignores the sand volumes transported to deeper areas from the seaward end of the EBP and the relocation of sand in the immediate vicinity of the waterline. For small relocations of the waterline on gently sloping sandy beaches these amounts are usually minor compared to the total changes in the sand volume.

For simplicity we employ the most widely used shape of the EBP that corresponds to the uniform wave energy dissipation per unit water volume in the surf zone [7]. The water depth at the distance y from the waterline down to the closure depth is $h(y) = Ay^{2/3}$. The profile scale factor A (which depends on the predominant grain size) is immaterial for the quantification of volume changes in Eq. (1).

The Bruun Rule is valid for virtually any realistic coastal profile of sandy beaches where the overall cross-section is approximately linear. The existing observations and simulations [17,20,31,32] suggest that both the concept of EBP and the inversion of the Bruun Rule are applicable for Pirita Beach. Regular monitoring of beach profiles between 2003 and 2012 by the Geological Survey of Estonia [35] indicates that the height of underwater sandbars is modest (around 30 cm). Although the sandbars seem to move onshore by about 4 m/y [17], their presence introduces minor deviations of the real profiles from the EBP.

The implementation of Eq. (1) requires the knowledge of two parameters. The change in the waterline position can be estimated based on repeated ALS or TLS scannings as demonstrated below. Another key parameter is the closure depth h^*. Similarly to the EBP, it is a concept rather than a simply measurable quantity [2]. It is defined as the maximum depth at which the breaking waves effectively adjust the whole profile [11,12]. This definition suggests that the closure depth is a function of the wave climate and to some extent also of sediment texture. It is usually assumed that the closure depth is governed by the most severe wave conditions that persist for a reasonable time. In our context the conservative viewpoint is to use the values of closure depth from [33], which are evaluated on an annual basis [12]:

$$h^* = 1.75 H_{s\,0.137\%} - 57.9 \frac{H^2_{s\,0.137\%}}{gT_s^2}, \tag{2}$$

where $H_{s\,0.137\%}$ is the significant wave height that is exceeded during 12 h/y (with a probability of 0.137%), T_s is the dominant peak period in such wave conditions, and g is acceleration due to gravity.

4. INTERANNUAL VARIABILITY OF THE SUBAERIAL BEACH

To demonstrate the capacity of the ALS and TLS techniques to quantify changes in the test area, we present a brief insight into the largest changes that occurred in 2008–2014. The rich spatial structure of the sand accumulation between 2008 and 2010 (erosion was observed only in a few spots) was superposed by substantial differences between the northern and southern segments of the test area (Fig. 3a). The entire subaerial beach gained about 500 m^3 of sand per year [17]. The height of the beach typically increased by 20–30 cm.

The changes had an almost totally opposite pattern between the ALS survey in 2010 and the TLS survey in May 2014 (Fig. 3b). The subaerial beach mostly lost sand in an amount almost equal to the total gain in 2008–2010. The changes in the beach height were distributed unevenly. The described features are coherent with the changing pattern of storms in 2008–2013 [17]. It is likely that in the period from 2008 to 2010 relatively mild wave conditions with a comparatively large proportion of swells, favourable for the recovery of the beach, dominated the coastal processes [17]. The autumn and winter of 2011/2012 and 2012/2013 were comparatively stormy [36] and Pirita Beach was frequently impacted by severe wave conditions.

These differences in wave properties are consistent with the spatial structure of the measured changes [17]. The overall pattern of changes matches the common ‘cut-and-fill’ cycle of sandy beaches. Under severe wave conditions and high water levels waves erode unprotected sediment from the upper part of the beach. As waves approach Pirita Beach almost incidentally, the eroded material is mostly deposited within the EBP [7]. This material is brought back into the vicinity of the waterline either by the onshore motion of sandbars or by regular swells. It is thus not surprising that the resulting

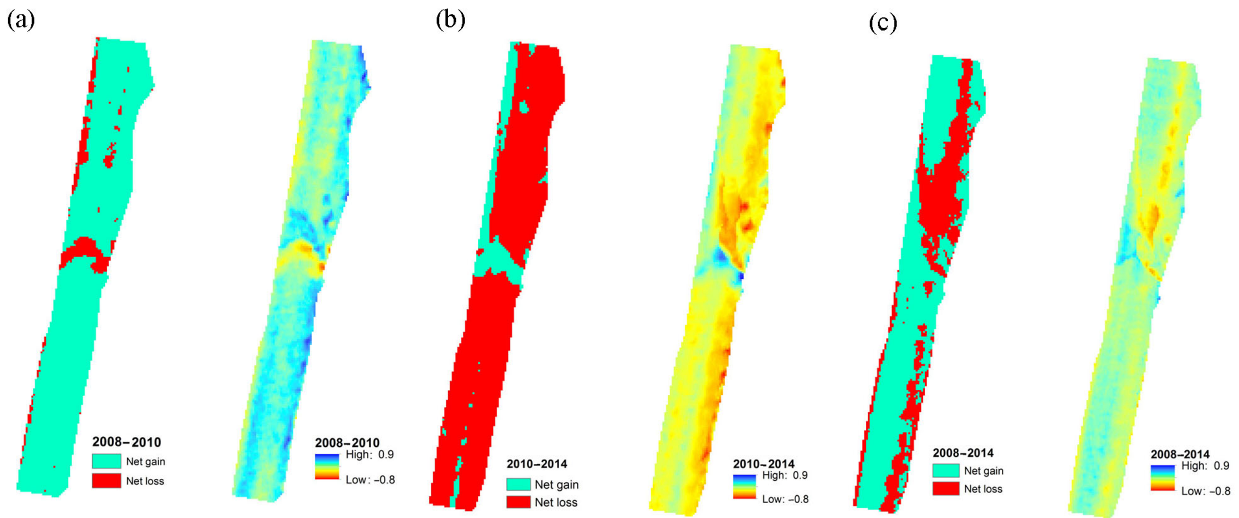

Fig. 3. Changes in the beach height: (a) in 2008–2010, (b) 2010–2014, (c) 2008–2014. The scale shows the differences in the beach height (m, right) and the relevant erosion (red) and accumulation (blue) areas.

changes in the sand volume of the subaerial beach during the six years from spring 2008 to spring 2014 were fairly minor (Fig. 3c). The only exception is the vicinity of the mouth of a small stream [17] where the changes are evidently connected with its relocation and are not representative of the processes in other parts of the study area.

The described technique is thus capable of highlighting fairly small changes (of the order of a few centimetres) in the sand surface height. The changes in the beach height in 2008–2014 are predominantly less than ±12.5 cm (Fig. 3c). Consistently with the overall pattern of wave-driven sediment transport to the south in Pirita Beach [32], a certain amount of sand has been accumulated near the waterline in the southern part of the test area while almost the entire northern part of the beach has lost sand.

5. CHANGES IN THE UNDERWATER SAND VOLUME

Equation (1) suggests that the change in the underwater sediment volume over the EBP is, as a first approximation, proportional to the gain or loss of the dry beach area [20]. The shape of the beach in the vicinity of the waterline and the location of the waterline itself may be subject to rapid and essentially random variations (e.g. when a sandbar reaches the shoreline or when extensive cusps are formed) and thus are not always representative of the changes in the underwater sand volume. The appearance of a beach between the landward end of the swash zone and foredunes is often much more homogeneous. For this reason the position of the waterline is evaluated based on the shift of isolines of 0.3 m, 0.4 m, 0.5 m, 0.6 m, and 0.7 m on the dry beach (Table 1). These elevations are often impacted by waves during autumn storms and their relocation apparently follows the shift of the waterline.

Part of the estimates for the elevation heights of 0.3 m substantially deviates from the rest of the estimates, signalling that processes at this elevation may be considerably modified by local or short-term features such as the ‘beaching’ of a sandbar. The use of several isolines allows uncertainty associated with the results to be reasonably evaluated. The relevant estimates for the elevation heights of 0.5 m and 0.6 m almost coincide (Fig. 4) and are highly coherent for all isolines of 0.4–0.7 m. Below we use the average of the relocation of these four isolines to represent the shift of the waterline. The largest deviation of the area change based on a single elevation from this average is 10% in 2008–2010 and 80% in 2010–2014.

The dry beach area therefore increased in the period from 2008 to 2010 and decreased to a lesser extent between 2010 and 2014. Consistent with the above analysis, the increase in the beach width is more pronounced (up to 7 m) in the southern part than in the northern part (up to 5 m) of the test area. The imbalance between the increase in 2008–2010 and the decrease in 2010–2014 (~25% of the entire pool of changes, Table 2) characterizes the uncertainty of the entire approach. Part of the widening of the beach is evidently connected with the decrease in the relative sea level owing to the postglacial uplift. This process apparently contributes about 1.5 m to the dry beach width [32], or equivalently, about 350 m^2 to the total dry beach area in 2008–2014.

Changes in the sand volume over the EBP (Table 2) are evaluated using Eq. (1), the average change in the dry beach area (Table 1), and the average closure depth $h^* = 2.5$ m for the study area [33]. Similarly to the subaerial beach, the underwater part of the beach also gained sand between 2008 and 2010 and lost sand between 2010 and 2014. The amount of sand gained and lost within these time intervals is almost equal (±4000 m^3). The relative uncertainty of the estimates (the imbalance of volumes for 2008–2010, 2010–2014, and 2008–2014) is obviously the same (about 25%) as for the changes of the dry beach area.

Interestingly, changes in the underwater sand volume are substantially (by a factor of up to 2.5) larger than over the dry beach. The annual gain of sand in the entire (subaerial and underwater) beach in the period from 2008 to 2010 is relatively rapid, about 2000 m^3/y. The annual loss in the period from 2010 to 2014 is less intense, about 1100 m^3/y. As these estimates are for only a short section of Pirita Beach, they are not directly

Table 1. Changes in the subaerial beach area (m^2) based on the shift in the height isolines in 2008–2014

Time interval	Elevation height, m					
	0.3	0.4	0.5	0.6	0.7	Average for 0.4–0.7
	Surface change, m^2					
Spring 2008 to spring 2010	1055	1207	1259	1227	995	1172
Spring 2010 to spring 2014	−170	−698	−1020	−1041	−733	−873
Spring 2008 to spring 2014	840	749	513	509	551	581

Fig. 4. Changes in the position of the waterline (0.5 m and 0.6 m isolines) from 2008 to 2010.

Table 2. Changes in the sand volume (m^3) over the subaerial beach and down to the closure depth in the test area in 2008–2014

Time interval	Subaerial beach	Underwater profile	Total
Spring 2008 to spring 2010	1514	2930	4444
Spring 2010 to spring 2014	–1188	–2183	–3371
Spring 2008 to spring 2014	302	1453	1755

comparable with earlier estimates of sand deficit over the entire beach [32]. As the changes in question are much larger than similar changes for the subaerial beach, the uncertainty of the entire estimate mostly depends on the accuracy of the evaluation of the sand budget over the EBP.

6. DISCUSSION AND CONCLUSIONS

The presented results support the conjecture that it is possible to highlight quite subtle changes in the absolute height and appearance of slowly evolving sandy beaches by means of combining various laser scanning technologies [17]. We have further expanded the scope of the use of laser scanning techniques beyond its classical limitations – towards the evaluation of the changes in the sand volume in the underwater part of the beach. The progress is achieved by means of the evaluation of the relocation of the waterline from the shift of a selection of isolines of the elevation of the sandy beach and the subsequent application of the theory of EBP and an inverse of the Bruun Rule. The major advantage of this approach is a small amount of data required for the analyses. To a first approximation, the changes in the underwater sediment volume can be estimated using a quantity derived from the local wave climate and changes in the position of the waterline.

The established synchronization of changes over the EBP and the subaerial beach is an unexpected feature of the test area. The conventional beach theory suggests that erosion on the upper profile (i.e. over the subaerial beach or from its upper part) during a stormy period is commonly accompanied by accumulation of sediment on the lower profile (e.g. in deeper sections of the EBP). This phase of the common cut-and-fill process is reversed during milder wave conditions, which bring sediment back from the deeper sections of the EBP to the shore and from where winds move it further to the upper beach. It is, though, unlikely that sand was added to the entire system in 2008–2010 and then removed in 2010–2014 because the seabed deepens relatively rapidly offshore from the closure depth and temporary deposition of large sand volumes in this part of the nearshore is not likely. It is more likely that, owing to the common large approach angles of storm waves in the Baltic Sea basin, sand was moved back and forth over the entire Pirita Beach. This conjecture is implicitly supported by the large variability in the simulated alongshore sand transport direction along this beach [32].

The results indicate that changes in the underwater part of the beach, from the waterline to the closure depth (about 2.5 m for the test area at Pirita Beach), are much larger (by a factor of 2–2.5) than similar changes in the subaerial part of the beach. Although this feature may reflect the small amount of the contemporary marine sand in the subaerial part of the study area, it suggests that underwater processes in the nearshore may predominate the evolution and fate of almost equilibrium beaches of the north-eastern Baltic Sea. Moreover, this proportion raises a serious question about the credibility of the estimates of the total changes in Table 2. In essence, the presented approach combines an extremely accurate way of measuring changes in the subaerial beach with a very coarse, almost conceptual application of the Bruun Rule and the equilibrium profile, both of which have been quite critically reviewed in the literature [5,27]. As the results based on the basically conceptually modelled data dominate the final outcome and there is no verification from another method, the quantitative outcome should be interpreted with care.

The variation in the course of coastal processes (intense accumulation in several years and almost equally intense erosion during several subsequent years) demonstrates that a comprehensive understanding of the functioning of beaches in this region requires long-term (at least on decadal scales) observations and simulations. The possibility of severe damages to beaches during extreme storms and changes in the duration of the ice season add complexity to the system and considerably reduce its predictability. Another source of uncertainties of the entire procedure stems from the nature of the concept of the EBP. This time-averaged property is applied here at relatively short (annual and intra-annual) scales at which the real profile may considerably deviate from the long-term average.

Even though the presented approach relies on the idealized concepts of the EBP and closure depth, the discussed results suggest that it may provide a feasible option for an inexpensive monitoring of almost equilibrium beaches over longer time intervals and for recognition of major changes that may impact the functioning of the entire beach system.

The concept implicitly relies on the separation of processes over the EBP and in deeper areas of the nearshore. Therefore, strictly speaking, it is directly applicable only in coastal segments where the EBP is clearly evident and the seabed rapidly deepens starting from the closure depth (as is the case in the deeper part of Pirita Beach [31]). We are looking forward to the validation of the outcome of this approach, for example in locations where the natural alongshore sediment transport has been blocked by a recent large coastal engineering structure.

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Laserskaneerimise ja Bruuni pöördreegli kombineerimine rannaliiva mahu muutuste hindamiseks

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Liiva koguhulga muutusi aeglaselt arenevate randade veealusel rannanõlval ja liivarannal hinnatakse erinevatel aegadel läbi viidud maapealse ning aerolaserskaneerimise andmestike kombineerimise kaudu klassikalise tasakaalulise profiili teooriaga. Muutused ajuveealas ja eelluidete piirkonnas tuvastatakse kord aastas tehtud aerolaserskaneerimise andmestikest, mis taandatakse samale absoluutkõrgusele muutumatu kõrgusega pinnal (parkimisplatsil) maapealse seadmega sooritatud täppismõõdistuste abil. Liiva mahu muutused veealusel rannanõlval veepiirist kuni sulgemissügavuseni arvutatakse Bruuni pöördreegli alusel. Arvutuste aluseks on veepiiri nihkumine, mis leitakse erinevate aastate aerolaserskaneerimise andmetest 0,4–0,7 m samakõrgusjoonte ümberpaiknemise kaudu. Meetod on rakendatud ligikaudu 200 m pikkusele lõigule Pirita rannas. Liiva hulk testalal varieerub ulatuslikult aastate lõikes. Aastail 2008–2010 lisandus testalale ligikaudu 2000 m^3 liiva aastas, samas vähenes seal liiva maht aastail 2010–2014 ligikaudu 1100 m^3 võrra igal aastal. Muutused veealusel rannanõlval olid kuival rannaosal asetleidnud muutustest ligikaudu 2–2,5 korda suuremad.