A study of hydrodynamic and coastal geomorphic processes in Küdema Bay, the Baltic Sea

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Abstract

The aim of the paper is to analyze relationships between hydrodynamic and geomorphic processes in a small bay in the West-Estonian Archipelago. The area consists of a Silurian limestone cliff exposed to storm activity, and a dependent accumulative distal spit consisting of gravel and pebble. Changes in shoreline position have been investigated on the basis of large-scale maps, aerial photographs, topographic surveys and field measurements using GPS. Waves and currents were investigated using a Recording Doppler Current Profiler RDCP-600 deployed into Küdema Bay in June 2004 and the rough hydrodynamic situation was simulated using hydrodynamic and wave models. The main hydrodynamic patterns were revealed and their dependences on different meteorological scenarios were analyzed. It was found that due to exposure to prevailing winds (and waves induced by the longest possible fetch for the location), the spit elongates with an average rate of 14 m/year. Major changes take place during storms. Vitalization of shore processes is anticipated due to ongoing changes in the regional wind climate above the Baltic Sea.
Keywords: shoreline changes, currents, waves, sea level, hydrodynamic models.

1 Introduction

Estonia has a relatively long and strongly indented shoreline (3794 km; Fig. 1), therefore the knowledge of coastal processes is of large importance for

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sustainable development and management of the coastal zone. During the last fifty years, intensification of coastal processes, including destruction of depositional coasts, e.g. sandy beaches has been observed in Estonia [1,2,3]. It is supposed to be an effect of climate change [4,5]. Time series analysis reveals a statistically significant increase in winter air temperatures, frequencies of westerlies and stormy days in Estonia [1,6]. A multidisciplinary working group for littoral dynamics was established in 2004 and a set of studies including meteorological, hydrodynamic, geomorphic and ecological aspects has been launched. The paper presents some preliminary results for a small (4 x 9 km^2) bay in West-Estonian Archipelago, Küdema Bay study site. The aim of the paper is to analyze relationships between meteorological, hydrodynamic and geomorphic processes, and to study past and possible future shoreline dynamics in relation to the changes in the regional wind regime and sea level rise.

2 Study area

The study site is located on Saaremaa (2671 km^2 in area), the largest island of the West Estonian Archipelago (Fig. 1). The main geomorphic features of Saaremaa's coastal zone reflect the features of preglacial and the last glacial phase relief, and postglacial isostatic and tectonic land uplift with the present rate of 2–2.5 mm per year [6]. Küdema Bay has a maximum depth of about 21 m. It has a relatively shallow (1–5 m) southern part.

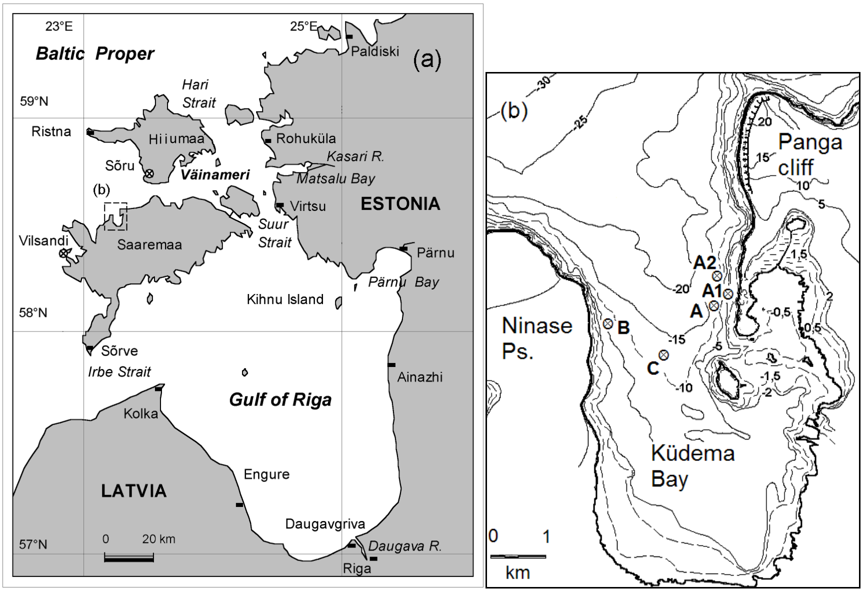

Figure 1: The locator (a) and the sketch-map of the study area (b). A – RDCP deployment site; A1 and A2 – sites of wave modelling, A, B, and C – sites of flow modelling.

In recent years, the Bay is primarily known as one possible site for the Saaremaa deep harbour with planned location on the north-western coast of Küdema Bay, at Ninase Peninsula. However, the investigation of geological and geomorphic features has much longer history in this Bay [8]. The relations between hydrodynamic and geomorphic processes should be particularly interesting, as the eastern coast of the Bay consists of a Silurian limestone cliff (the Panga cliff, length 2.5 km, maximum height 21 above sea level) exposed to wave erosion and currents, and a dependent accumulative distal spit. The spit of gravel and pebble is nearly 3 km long and up to 0.5 km wide [1]. Approximately 200 m offshore from the Panga cliff an underwater scarp is located. The base of the scarp is in the depth of 12–15 m, where dislocation of limestone boulders and pebble is negligible due to the relatively large depth. Sediment transport mainly occurs in the shallow wave break zone [8,9].

3 Material and methods

3.1 Hydrodynamic measurements

For studying hydrodynamic regime of the Bay, a Recording Doppler Current Profiler RDCP-600 from Aanderaa Instruments was used. The RDCP is a 600 kHz self-recording acoustic Doppler current profiler with 4 beams pinged by transducers. Three velocity components are calculated from the Doppler shifted backscattered signals. The self-contained RDCP 600 was deployed to the seabed using a bottom-mounted frame. The location (58°31.1'N, 22°16.6'E) was chosen close to the geomorphically interesting and quickly developing distal spit, about 200 m off the coast (A, Fig. 1b). The instrument was deployed for the period of two weeks, however, by accident only 19 hours of data was obtained from that field study. The mooring depth was 10 m. Considering a 2 m "blind" distance between the instrument and the lowermost measurable cell, plus 2–3 surface meters, which measurements are "contaminated" by wave motions, data from five depth layers was obtained. As a 2 m cell size with 50% overlap was used, "6 m depth" actually means 5–7 m depth interval, etc. Each current record included an average value of 300 pings (or individual measurements). Single ping had statistical noise of 9 cm/s, the setup of 300 pings used by us yielded standard noise level as low as 0.58 cm/s for the horizontal currents and 0.29 cm/s for vertical currents. In addition to currents, temperature, turbidity, conductivity, high accuracy pressure (i.e. relative sea level variations) and wave parameters were measured with the instrument. The measuring interval was set at 10 min.

3.2 Hydrodynamic modelling

Local currents, sea level variations and waves were investigated using simple hydrodynamic models. Sea level variations and wind-driven currents were modelled using a high-resolution shallow sea 2D hydrodynamic model, which was forced by the wind and open boundary sea level data. Due to the microtidal regime of the Baltic Sea (the amplitudes of M_2 and K_1 waves less than 2 cm near

Estonian coast) no tidal forcing was applied. The model is essentially the same as described in [10,11]. The previously applied 1 km grid step version of the Gulf of Riga (Fig. 1) model was validated in hindcast simulations using the flow and tide gauge measurements from 1999 [10].

The model application used in this study has a 74 m grid step, the model domain includes 4344 marine points. Wind stress was calculated from single-point measured data of the Vilsandi meteorological station with a 6 h time step. Both the wind drag description with the formula by Smith and Banke, and the quadratic bottom friction parametrization (with bottom stress coefficient k=0.0025) is common for such models. The wind stress was applied homogeneously over the modelled area. The hourly sea level time series obtained from the Sõru tide gauge were applied on the open boundary. The model equations were numerically solved using the finite difference method on a staggered Arakawa C grid. The model output included hourly sea level and current components data from the chosen points (Fig. 1b) calculated on the basis of realistic year 1999 forcing data. In addition, stationary flow and sea level patterns were calculated for different steady state wind directions. Current induced bottom stresses were calculated from the 2D model, and wave action was estimated at two selected points (Fig. 1b) using a simple first generation wave model based on the SMB method [12]. One (A2, depth 15 m) located about 1 km off the Panga cliff and the other near the spit (A1, depth 2 m). Time series of significant wave heights, orbital velocities and bottom stresses were calculated for the chosen points on the basis of the Vilsandi measured wind data. The algorithms of calculations considered the fetch depending on the headwind distances from the nearest shore in relation to the wind directions.

3.3 Geomorphology

Topographic maps and aerial photographs from different times were used to identify past changes in the shoreline positions in the region of the spit. Maps from 1904 (1:42000), 1917 (1:25000), 1955 and 1988 (1:10000), as well as aerial photographs from 1957, 1985 and 1998 were used. The maps and photos were registered with *MapInfo* software using certain control points together with their Cartesian coordinates. In addition, shore dynamics were traced on the basis of levelling surveys in relation to local benchmarks, and topographic measurements of coastal formations on the spit since 2000 were carried out using GPS. Field observation records and photos taken by Dr. Orviku in 1960-2004 served as an additional source for analysis [1,8]. The calculations of changes in matter volumes were performed using *Vertical Mapper* software.

4 Results and discussion

4.1 Hydrodynamical features of Küdema Bay

Weather conditions during the survey in June were relatively calm. According to the data from the Vilsandi meteorological station, the average wind speed of 1.9 m/s (max 3.5, min 0 m/s), mainly from the north-west was measured.

Consequently, wave activity was also low (wave heights below 0.4 m). Despite calm weather conditions, the maximum horizontal current velocity reached 17 cm/s (average 5.4 cm/s) and the vertical velocities with average modulus of 0.53 cm/s were directed mainly downwards (with an average speed of –0.21 cm/s).

The *in situ* measuring period was too short for revealing hydrodynamic properties of the Bay. It allowed, however, verifying the hydrodynamic model, which was mainly used in the further studies. The agreement with the model forced by the same wind conditions was relatively good (Fig. 2a,b), when looking at averages. Due to different time steps (10 min *vs.* 1 h model output created with 6 h wind forcing) no agreement in fluctuations can be expected. The measurements also showed quite homogeneous behavior of horizontal currents over the depth range (Fig. 2c), which allowed us to use the 2D model.

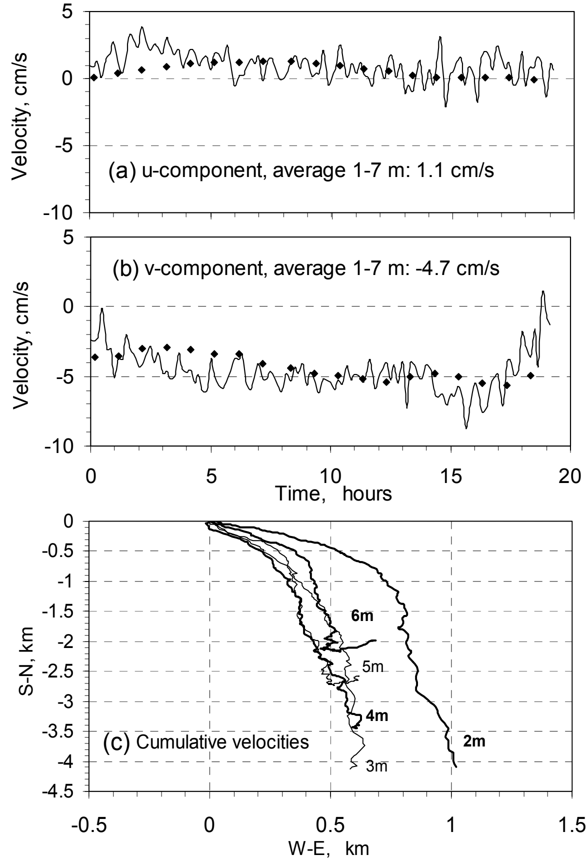

Figure 2: Comparison of measured (lines) and modelled (dots) depth-averaged velocity components (a,b). Positive directions are E for (a) and N for (b). Progressive vectors of measured horizontal current velocities in different layers on June 1, 2004 (c).

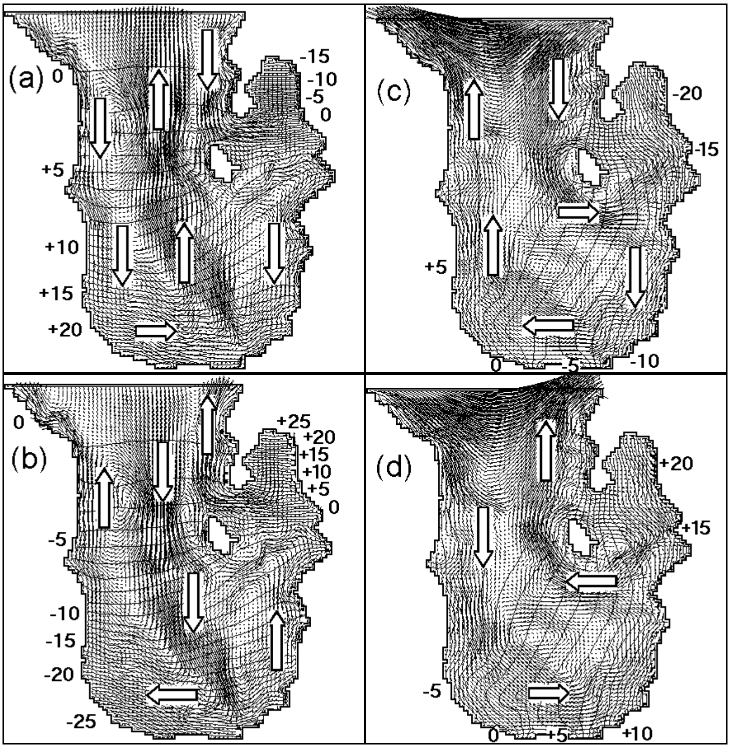

Figure 3: Flow patterns (average volume fluxes over vertical profiles) in Küdema Bay produced by the 20 m/s stationary wind from the north (a), south (b), east (c) and west (d). Contours represent local sea levels in relation to open boundary sea level.

The four modelled quasistationary flowfields (Fig. 3) show cyclonic and anticyclonic circulation cells and patterns with downwind flows near the shallower coastal areas and compensatory flow against the wind along the deeper middle section of the Bay. Near the spit northward flows occur in wind directions between 100° and 270°, while southward motions appear between 280° and 90°. The highest velocities among the selected points were found at point B (Fig. 4b). The maximum velocity modula reached 66 cm/s in the point A in 1999 hindcast simulations (Fig. 4a). Such velocities are capable of transporting coarse sand particles. In the point A the sums of north- and southward flows and bottom stresses were practically equal (with a difference about 1%) in 1999, while in the point B, northward flows clearly prevailed (73% *vs*. 27%, Fig. 4b). Average compensatory inflow along the axis of the Bay existed (Fig. 4c).

Another valuable outcome of the 2D model runs is reproduction of the sea level variations (Fig. 4d). Due to the small size of the Bay, the modelled sea levels followed the Sõru measured input sea levels with local differences of up to ±20 cm.

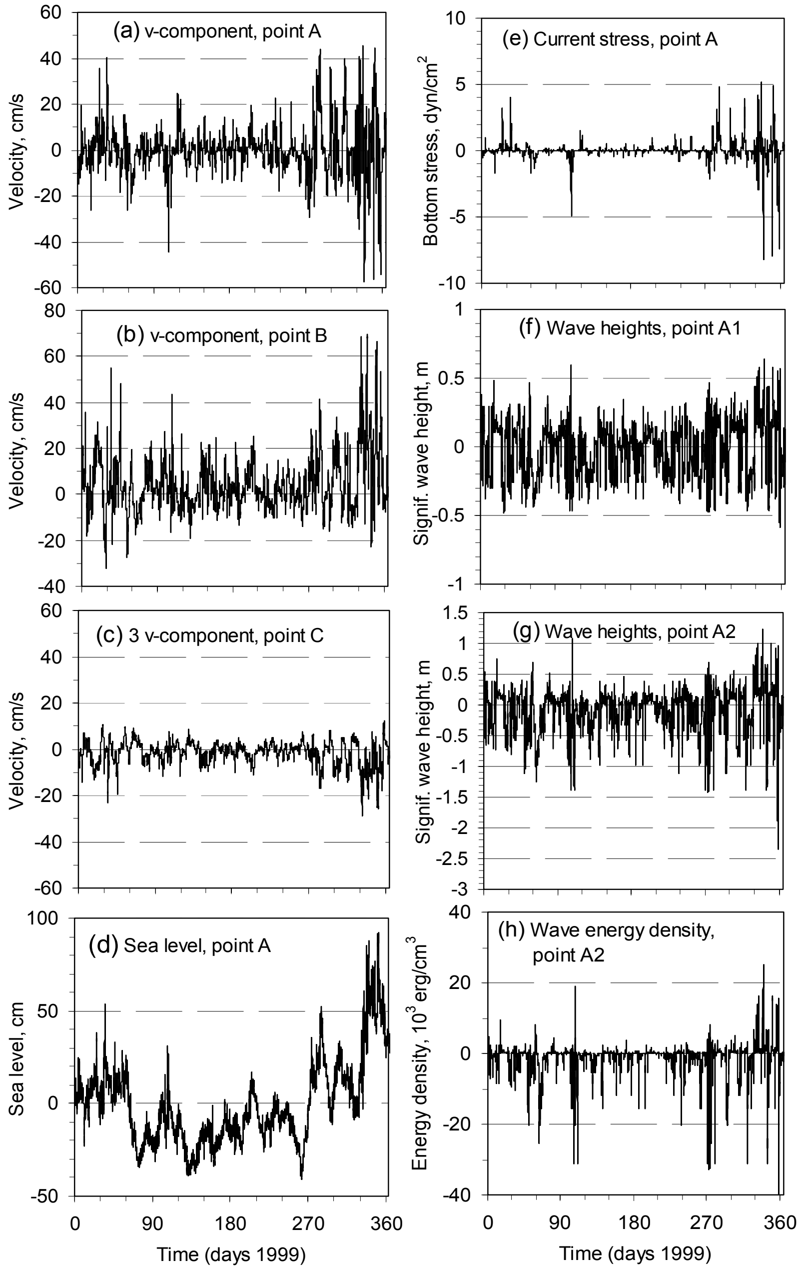

Figure 4: Modelled time series of wind driven currents (a,b,c), sea level variations (d), bottom stresses (e), significant wave heights (f,g), and wave energy densities (h). Positive direction of motions (a–c), or forces in the coastal zone (e–h) is North.

In general, westerlies and northerlies elevate, and southerlies–easterlies lower the sea level in the point A in relation to the input sea level. The Sõru tide gauge sea level itself mainly follows the sea level variations of the Baltic Proper with minor local additions. The sea level near Küdema spit fluctuated between -40 and +92 cm around the average. The variability range is relatively small, when compared to some other bays in the coastal waters of Estonia. For example, Pärnu Bay had sea level variations between –49 and +146 cm in 1999 [10]. However, sea level height is an important feature in coastal geomorphic processes. It appears that the higher waves appear together with high sea levels both in the previously studied Pärnu Bay [11], and near the Küdema spit as well (Fig. 4d,f,g). Comparison of Figs. 4e and 4h suggests that the wave motions are much more energetic. However, coastwards wave energy gradually decreases. Some of it transforms into onshore movements and smaller proportion turns into alongshore movements. Rough estimates yield that the wave energy in the shallow coastal zone is an order of magnitude bigger than the energy of wind-driven currents in the Küdema Bay area. While the wind-induced currents show roughly equal north- and southward motions, the alongshore wave energy is predominantly directed southwards. About 81% of the stresses created by the wave's motions were conditionally directed southwards. It is not exactly the physical entity responsible in coastal abrasion and sediment transport, but still gives us a rough idea about the proportions of the forces. In addition, processes of wave break should be studied more carefully in the future.

4.2 Geomorphic developments of the Küdema spit and their relations to meteorological conditions

Fig. 5 shows the variations in shoreline positions near the Küdema spit in different periods. The spit has gradually formed as a result of along- and onshore transport of sediments eroded mainly from the cliff [8]. Erosion occurs along the whole extension of the cliff and nowadays also in the root-area of the spit, whereas in the southern part, accumulation and elongation mainly occurs. Erosion also occurs on the nearshore area on the limestone bench in front of the Küdema spit. Eroded material is moving mainly onshore, which has filled the sea between the small islands in the past. As a result of this onshore movement, the growth speed of the spit was much quicker. In the beginning of the 20th century the spit grew also due to joining up of the small islands with the mainland, (nowadays the positions of these island can be identified due to U-shaped gravel ridges [8]). In the present stage, the areal increase mainly occurs as a result of formation of new beach ridges of gravel and pebble (Fig. 5b). The new beach ridges most prominently appear after stormy periods, they consist of coarser material in comparison with the material between the ridges. Higher old (inland-) ridges are already smoothened by waves and ice action. They are naturally vegetated to a large extent and not active anymore. The ridge formations are up to 1.4 km long and their total volume makes up 180 000 m^3 [9]. The annual area increment of the spit has been about 380 m^2 with the average elongation rate of 14 m per year between 1985 and 1998. The average rate was about 4-5 times slower in the period of 1963-1972 [2].

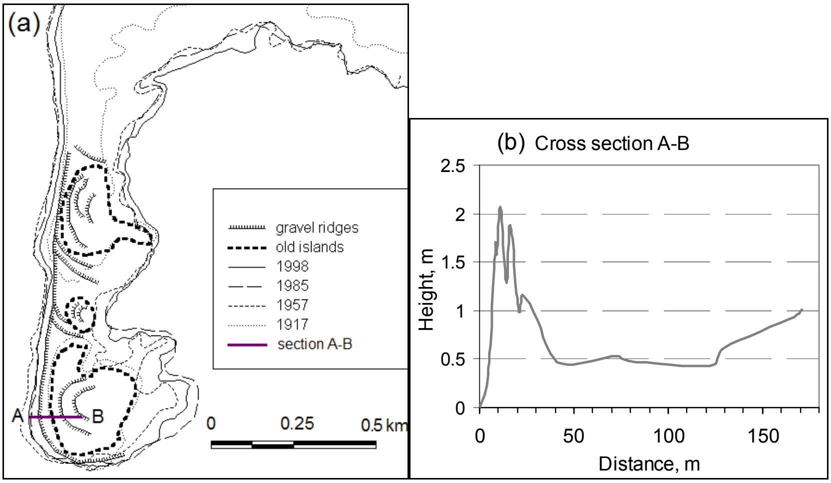

Figure 5: Map of shoreline changes on Küdema spit (a). Cross-section through the beach ridges (b) is shown with “section A-B” on (a).

Analysis of hydrodynamic conditions showed that in annual course the predominant share of hydrodynamical forces is directed southwards. While the SW wind with its highest occurrence in Estonia is sheltered by the land, the secondary frequent westerlies and north-westerlies have the longest fetch for the Panga location. Induced by westerlies and north-westerlies the maximum wave height 1 km off the cliff (depth 15 m) was up to 3 m in 1999 (Fig. 4g). These waves significantly yield cliff erosion and southward transport of matter, while the waves yielding northward sediment movements are only up to 0.5 m high.

Comparing different sections with equal extensions in Fig. 4b,h, it appeared that while in December the average wind speed (9.5 m/s) was only two times larger than in July (4.4 m/s), the total sum of wind and wave generated stresses is roughly 10 times bigger. As bottom stress is proportional to the second power of flow speed, and wave energy density is proportional to the second power of wave amplitude as well, the major share of annual work aggressing the coast is concentrated to stormy periods. Severe coastal damage therefore results from a combination of strong storms, high sea level and absence of protective ice cover in winter: storms mainly occur during the cold half-year. Estonia lies close to the average Baltic Sea winter freezing line, and the ice conditions near the Estonian coast are highly sensitive to the decreasing Baltic ice extent trends [5]. It is also easy to notice, that as strong storms are becoming more and more frequent [6,11], vitalization of shore development is anticipated in the future.

5 Conclusions

Hydrodynamic modelling of waves, sea levels and currents can provide the explanatory link between the changes in meteorological forcing conditions and coastal geomorphic processes. It appeared that while the wind-induced currents show roughly equal north- and southward motions near the Küdema spit, the wave energy is much stronger and predominantly directed southwards. The spit of gravel and pebble has gradually formed as a result of along- and onshore transport of sediments eroded mainly from the Panga cliff. The spit elongates (with the present rate of 14 m per year) due to the exposure against the waves induced by the longest possible fetch for the location. Major changes take place during strong storms and further vitalization of shore processes could be expected in the future due to anticipated increasing storminess.

Acknowledgements

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