Modelling of flows, sea level variations and bottom stresses in the coastal zone of West Estonia

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Abstract

Flow features and sea level variations were studied in the nearly tideless sub-basins of the Baltic Sea, the Gulf of Riga and the Väinameri, using a high-resolution (of order 1 km grid) shallow sea 2D hydrodynamic model. The model is forced by the wind stress calculated from single-point meteorological data, and the tide gauge sea level data applied along the open boundaries. The simulations based both on the realistic and idealistic forcing schemes were carried out. The aim of the study was to analyse circulation patterns during different meteorological conditions and to investigate the influence of currents, waves and sea level fluctuations on the littoral processes. In the Pärnu Bay the high flow velocities, participating (along with storm waves) in the coastal erosion events, act 1.5-2 m above the average waterline and about half of the year's summary work is done during the 2-3 most stormy days of the year. In the indented West Estonian coast infrequent storm surges flush the eutrophic ends of the narrow and shallow bays, e.g. the Matsalu Bay, but low wave activity and weak currents cannot either remove muddy deposits of the delta region or import sandy deposits from the nearby Väinameri region.

1 Introduction

Though nearly tideless (M_2 and K_1 amplitudes 1-3 cm), the coastal waters of West Estonia are hydrodynamically quite active. The historical range of sea level variations is up to 376 cm and the wind-driven currents in the straits can reach velocities up to 2 m/s. The conditions in the Väinameri sub-basin and in the NE part of the Gulf of Riga (Fig. 1a) are strongly influenced (1) by the excursions of the hydrophysical and hydrochemical front forced by the oscillatory currents in the system of semi-enclosed sub-basins and straits, (2) by the resuspension events during storms due to the currents or surface waves, and (3) by the storm surges in the shallow bays of the indented coast [1,2]. Among them, the Pärnu Bay has probably the highest measured storm surges (up to +253 cm) in the Baltic Sea except those near St.Petersburg and in the region of Schleswig [3]. In addition, the currents and waves cause the displacement of bottom sediments. Coastal erosion events and dune scarp retreat have been reported in the Pärnu beaches during storms. Considering the increasing trend of storminess above the Scandinavia (60% increase in the number of storm-days during the last 50 years), intensification of coastal destruction and changes in the established equilibrium of coastal processes can be expected in the future. Also, due to a relatively large freshwater input via the Pärnu and Kasari River, the mixing processes of the riverborne ingredients have a considerable ecological importance. The whole area is very shallow, the Väinameri sub-basin has an area of 2243 km^2 and an average depth of 5 m, including the eutrophied Matsalu Bay (area 67 km^2, volume 0.1 km^3). The inner Pärnu Bay is approximately 14 x 14 km^2 with a volume of 1 km^3 (Fig. 1bc).

The main aim of the paper is to model and to describe the flow regimes in the above-defined areas and to discuss their influence on the coastal environmental processes. The inferences drawn from the data of the numerical simulations are of statistical character: the study is not aimed at giving applicable calculations of sand transport, as we do not handle information about the sediment properties, etc. Our aim is to evaluate some general proportions between different hydrodynamic conditions and between different forcings.

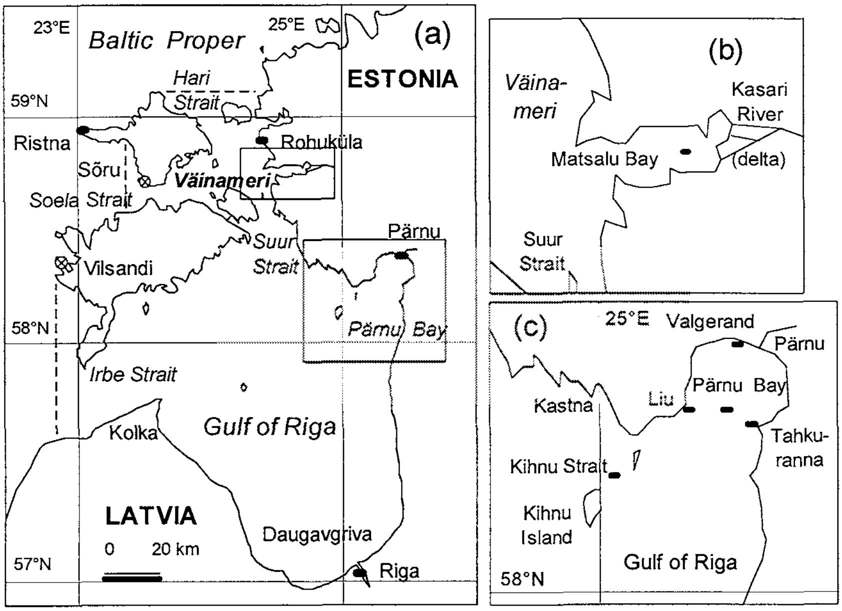

Figure 1: The map of the study area (a) and the case study locations (b,c).

2 The models, inputs, outputs and simulations

The Gulf of Riga–Väinameri (see Fig. 1a) 2D model is a shallow sea depth-averaged free-surface model with quadratic bottom friction:

$$\frac{DU}{Dt} - fV = -g(H+\xi)\frac{\partial \xi}{\partial x} + \frac{\tau_x}{\rho_w} - \frac{kU}{H^2}\left(U^2+V^2\right)^{1/2} , \tag{1}$$

$$\frac{DV}{Dt} + fU = -g(H+\xi)\frac{\partial \xi}{\partial y} + \frac{\tau_y}{\rho_w} - \frac{kV}{H^2}\left(U^2+V^2\right)^{1/2} , \tag{2}$$

$$\frac{\partial \xi}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 , \tag{3}$$

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \frac{1}{H}\left(U\frac{\partial}{\partial x} + V\frac{\partial}{\partial y}\right) , \tag{4}$$

where U and V are vertically integrated volume flows in x and y directions respectively, ξ is the sea surface elevation (from the equilibrium depth, H), f is Coriolis parameter, ρ_w is water density, k is the bottom stress coefficient, k= 0.0025 [4], τ_x and τ_y are wind stress components of $\vec{\tau}$ along x and y axis. Wind stress ($\vec{\tau}$) was computed using the formula by Smith and Banke [5].

Using a 1 km grid size, the model domain includes 18 964 marine points. Calibration was made in comparison with the currents from Helmholtz model [2], the latter has been calibrated and validated using the flow measurements in the straits from 1993-1995. Relying on the studies that proved the model`s ability in a successful simulation of the sea levels [3] and flows in the straits of the Väinameri [1], we can also expect a realistic performance of the model at least in relation to the general flow patterns in the NE part of the Gulf of Riga.

The simulations of the sea levels and currents were carried out with realistic year 1999 forcing data. The wind and sea level data at the open boundaries are the major forcings in such relatively small and semi-enclosed marine areas. Monthly average river inflow data (32 km^3/yr) were applied for keeping the long-term water budget. Wind stress could be calculated either from the HIRLAM (a North-European climate model) wind data, or from single-point measured data. In the present study the wind data of the Vilsandi meteorological station with a 6 h time step, were applied homogeneously over the modelled area. The hourly sea level time series obtained from the Sõru tide gauge were applied identically at the three cuts of the open boundaries near the Irbe, Soela and Hari Straits (Fig. 1a). The comparison of the output sea level data with the mareograph data from the Rohuküla and Pärnu showed good correlation and forecasting abilitites of the model [3]. In addition to year 1999 hindcast simulations, stationary flow patterns were calculated for different (steady state) wind directions.

Current induced bottom stresses were calculated, wave action was taken into account separately at a few selected points (Liu and Valgerand, depth 2m; Matsalu, depth 1 m), using a simple first generation wave model based on SMB method [6]. There are difficulties in the application of any wave model in such a narrow, indented and shallow coastal zone. Thus, only certain statistical proportions were studied. Significant wave heights, corresponding maximum orbital velocities and bottom stresses were calculated, fetch distances depending on the headwind distances from the land in relation to the wind directions.

3 Results and discussion: Flow patterns in the Pärnu Bay

A strong positive correlation between the Liu S-N velocity component and Valgerand W-E component (r=0.81), as well as between Liu and Tahkuranna S-N components (Figs. 1c, 2a) was found. There are two major flow patterns in the bay (Figs. 2d, 3ab), but the favoured one has inflows along the Liu and Tahkuranna coasts and outflow along the axis of the Pärnu Bay. The two quite well-defined flow regimes have switch wind directions at 90°-130° and 270°-310°. The pattern with a cyclonic and an anticyclonic circulation cells is quite wellknown in the small oval basins (bays, lakes) with the distribution of smaller depths near the coast and bigger ones in the central part of the area. One flow regime (Fig. 3b) prevails over another (Fig. 3a) due to corresponding local wind statistics. The winds and currents are stronger in the favoured case, firstly, due to the uneven (anisotropic) distribution of strong wind directions above the Baltic Sea [7], and secondly, due to the smaller influence of land shade.

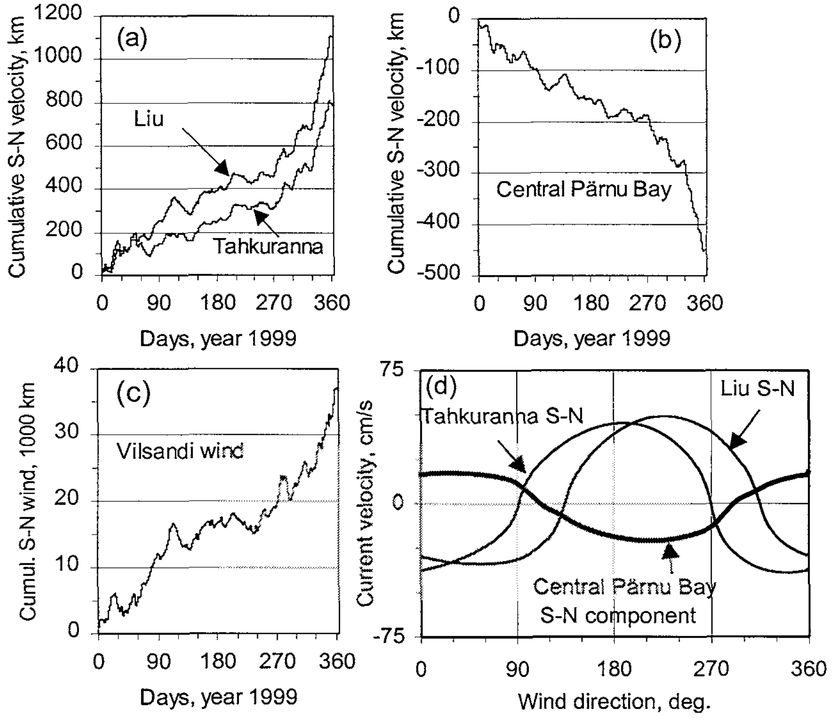

Figure 2: Annual cumulative (integral) curves of current velocity (a, b) and wind vector components (c). Modelled current velocity components depending on the direction of the 20 m/s stationary wind (d).

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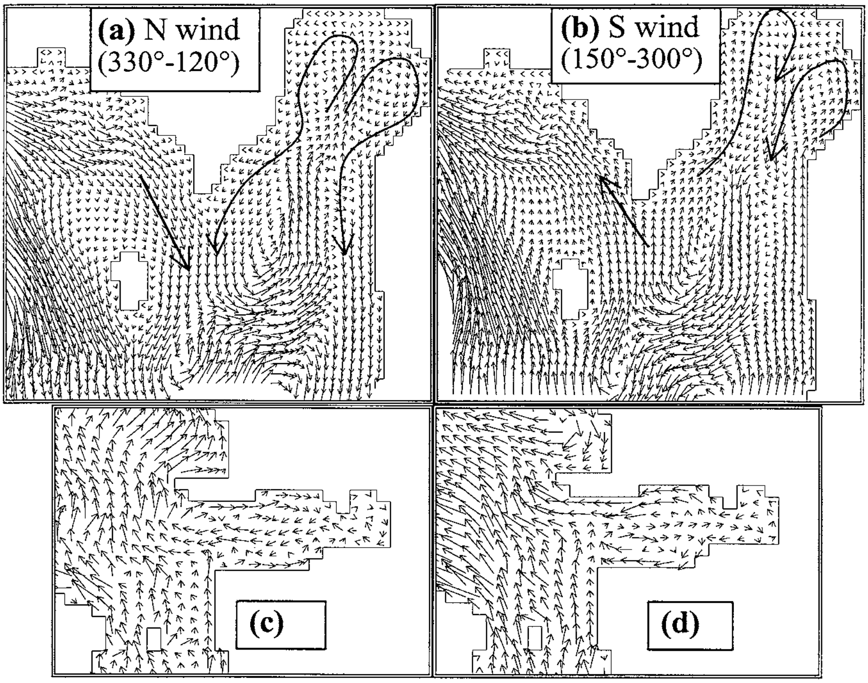

Figure 3: Flow patterns (volume fluxes) in the Pärnu Bay produced by the 20 m/s stationary wind from the north (a), and south (b). Current velocities in the Matsalu Bay with realistic SW (c) and E wind (d).

In reality, such strong (20 m/s as shown in Fig. 3a) N and E winds have never been registered in Pärnu, whereas SW winds could distinctly exceed 20 m/s. The length of the cumulated S-N velocity components reached about 1000 km in Liu and Tahkuranna points in 1999 and the resultant flow was directed northwards (Fig. 2a), whereas the cumulative velocity was directed southward in the central bay. Being synchronous to the Vilsandi cumulative wind component`s curves (Fig. 2c), the progressive current component curves exhibit seasonality: the steep sections during autumn and winter mark the predominance of one regime over another and the relatively level sections correspond to nearly equal occurrence of different wind regimes in spring and summer.

4 Influence on coastal processes: the Pärnu Bay

In the Pärnu Bay the maximum velocities reached 90 cm/s during the December 18 storm, which according to the Pärnu tide gauge data raised the sea level up to 146 cm above the Kronstadt zero benchmark. The distribution of the modelled velocities in the Liu and Valgerand show a vast predominance of small velocities regardless of direction (Fig. 4a) and only 0.9% of the velocity readings were bigger than 45 cm/s in 1999. However, when trying to identify the role of different directions and velocities on the coastal environment, a

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crucial role of those rare but large velocities could be stated. As bottom stress is proportional to the second power of the velocity, the asymmetry between the two tails of the distribution (Fig. 4a) dramatically increases when taking into account the bottom stresses caused by the corresponding velocities. Physical entity which is proportional to work (or energy), which includes velocity in the third power, is shown in Fig. 4b. Account of the sums below the different sections of the "work" curve reveals that the mentioned 0.9% of the velocities yield about 26% of the total annual bottom stress and 49% of the annual "work". Moreover, small velocities below a certain threshold value, e.g. 15 or 20 cm/s, produce "wasted" stresses which are not able to erode, suspend and transport sediments at all. This further increases the role of those infrequent but high velocities. As a result, the ratio between the tails of the Fig. 4b becomes 90% vs 10%. Thus, the current-induced bottom stresses at the Valgerand were predominantly directed to the east (or north at Liu) and about half of the annual work aggressing the coast was probably done during the 2-3 most stormy days of the year.

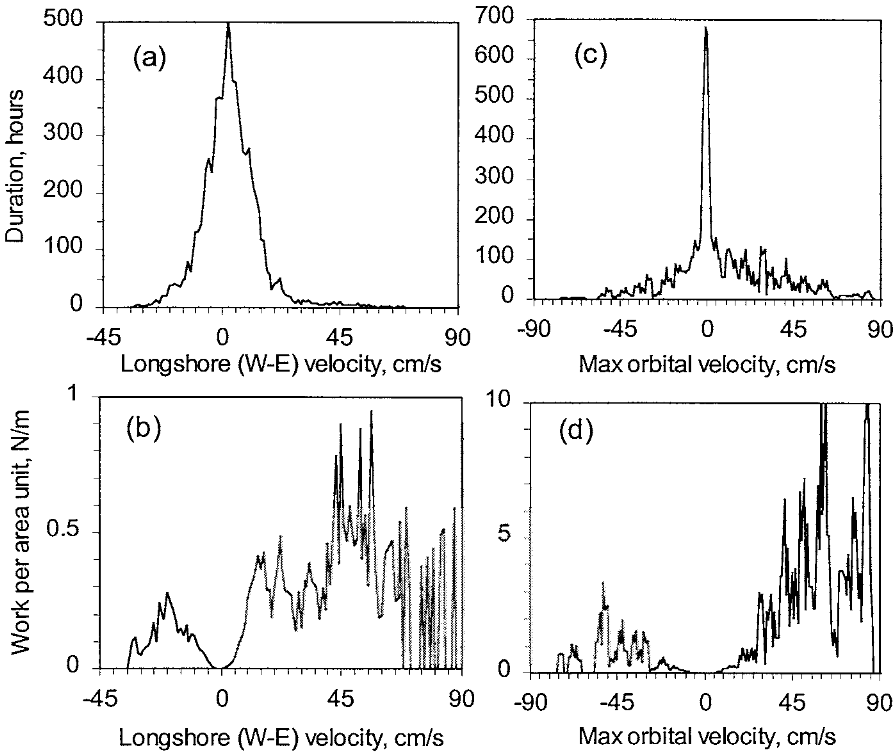

Figure 4: Distribution of modelled current velocities (with 1 cm/s increment) in the Valgerand (a), and corresponding works within the same intervals (b) in 1999. Similar presentations of wave-generated velocities (c) and possible works (d) at the Liu point in 1999. See also Fig. 5.

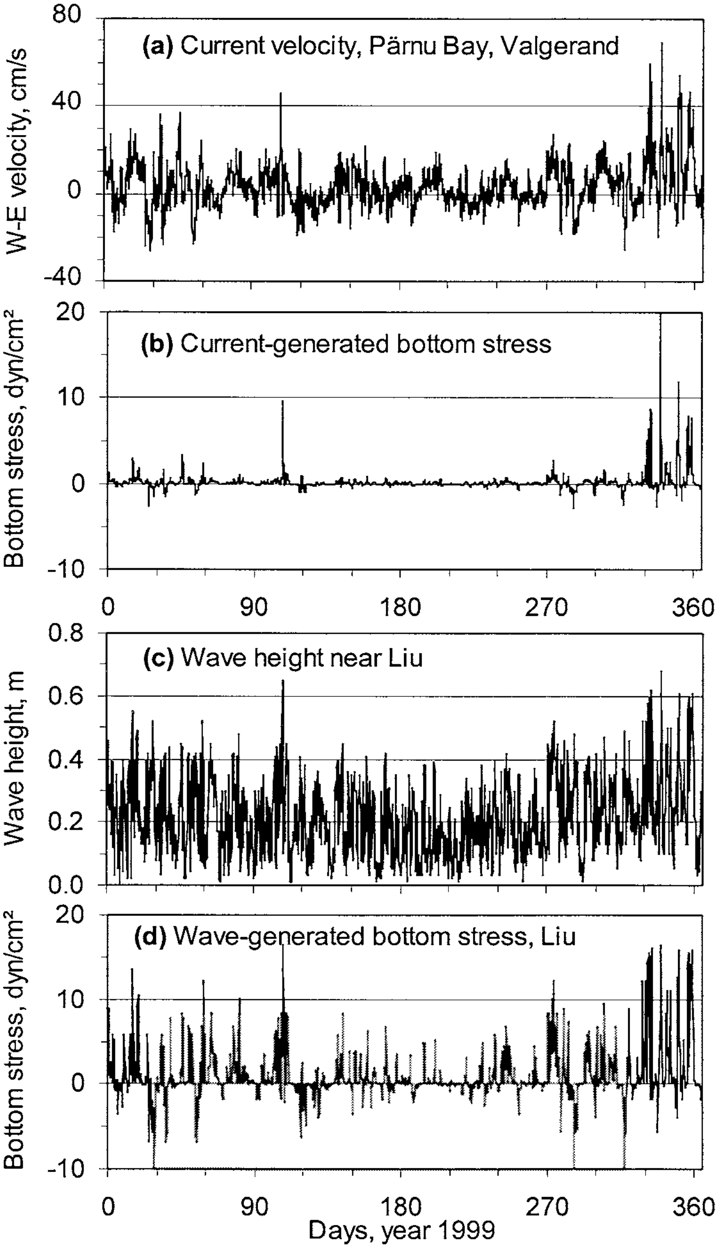

Figure 5: Time series of a current velocity component (a), corresponding bottom stresses (b); wave heights (c), corresponding near bed stresses (d) in the Pärnu Bay, 1 km off the coast. Positive direction in (d) was chosen if the waves were entering the bay, negative when departing.

The wind wave contribution to erosion is also the strongest during the stormy periods. Due to shallowness the wave height is below 0.8 m at the Pärnu Bay points (Fig. 5c), but the maximum near-bed orbital velocities (up to 90 cm/s) are comparable with the current velocities (Fig. 4ac). The larger proportion of medium and higher velocities seems to produce much more "work" (Fig. 4d). However, the "works" of currents and waves are not strictly comparable here (Fig. 4b vs. 4d), as the waves orbital velocities involve to-and-fro movements. They can bring sediments into suspension, but not transport them. The waves mainly contribute to the cross-shore sediment movements and changes in the beach profile, whereas longshore fluxes are largely produced by the wind driven currents. Longshore currents are also formed in the surfzone due to the waves approaching the coast under an angle, but based on the grid step and technique used here, we cannot quantify how much of these cross-shore movements convert into energy of longshore movements. The complex of wave-current interaction processes and its relation to morphodynamics is rather complicated [4,8] and should be studied in detail in the future.

Due to the bay`s exposition in relation to the prevailing winds (and storms) the two above processes evoking longshore currents are usually not contradictory. They both favour the inflows along the coasts and the compensatory outflow in the bay`s trunk zone. They also provide a similar asymmetric geomorphological outcome: the processes favouring the import and accumulation of soft sediments are much more frequent and stronger than the processes of export. In addition to the influence of the regional wind statistics [7], the local wind is largely shielded by the land in the north. Also, the incoming waves are always higher than those that just depart from the coast. The ratio of corresponding "works" is 85/15 (%) at the Liu point (Fig. 4d), more at the Valgerand and less near the Kihnu Strait (see Fig. 1c). Accumulation of sand in the region of the famous Pärnu and Valgerand beaches is a result of such asymmetry (Fig. 4bd) in wave and currents action.

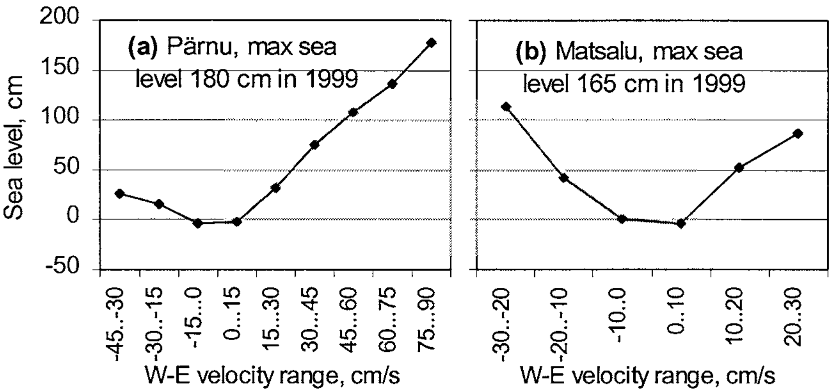

Figure 6: Dependence of the sea levels on the current velocities averaged over the velocity range with 15 cm/s increment in the Pärnu Bay (a) and 10 cm/s in the Matsalu Bay (b). Maximum sea levels as modelled in 1999.

As SW and W storms are associated with the sea level rise near Pärnu, the high flow velocities and strong wave action decisive in coastal erosion events act 1-2 m higher than the usual waterline (Fig. 6), thus explaining the strong bulldozing effect of storms on the sand dunes well away from the coastal line. The sea level and velocities have somewhat different relationships in the Matsalu Bay.

5 Matsalu Bay

While the maximum velocities in the straits of the Väinameri could reach 2 m/s [1], the velocities in the very shallow and relatively small Matsalu Bay do not exceed 30 cm/s due to large friction (Figs. 6b, 7b). The wave action is also weak due to its shallowness and short fetch. Waves up to only 0.3 m can bring muddy bottom sediments into suspension, but the flushing of the bay only occurs during storm surges (Fig. 7), when the Kasari River delta region and up to 110 km^2 of floodplains are flooded. While the inflow from the Kasari River yields less than 0.1 cm/s average outflow through the Matsalu Bay cross-section, the 20-30 cm/s surge velocities can transport nutrient- and organic matter rich waters into the Väinameri Proper. Such events occur infrequently and mainly in autumn. However, contrary to the Pärnu Bay, the bay`s currents cannot effectively either remove muddy bottom deposits or import sand from the nearby regions.

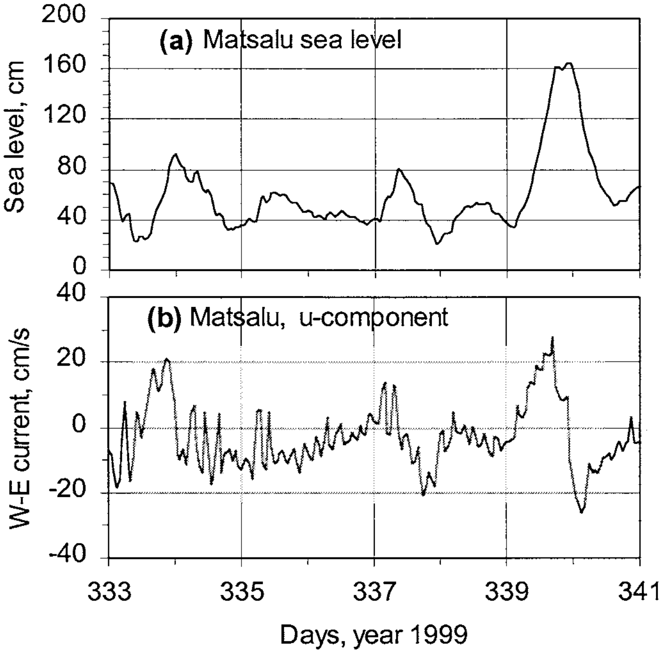

Figure 7: Sea level variations (a) and current velocities (b) in the Matsalu Bay during December 1999 storm surges. 150 cm surges occur roughly once a year and 200 cm surges once in 10 years in the Matsalu Bay.

6 Conclusions and future prospects

Two flow patterns alternate in the Pärnu Bay. The more frequent one has inflows along the Liu and Tahkuranna coasts and outflows along the axis of the Bay with velocities up to 90 cm/s. The smaller and shallower Matsalu Bay often has similar patterns, but the velocities can reach 30 cm/s only during infrequent storm surges (sea level rise 1.5-2 m). Such velocities may flush the water column, coastal plains and upper layers of the bottom sediments, but cannot prevent the eutrophication and siltation of the bay. In the coastal regions of the Pärnu Bay the current-induced bottom stresses are predominantly directed to the bay`s end (90% work against 10%) and the same applies to the waves action. Roughly half of the annual work aggressing the coast is done during the 2-3 most stormy days of the year. Decisive factors in coastal erosion and longshore sand displacement events, the high velocities and waves action, operate 1-2 m above the average waterline. At present the separate role of the wind-driven currents and waves could not be distinguished. Currents, waves and sea level fluctuations should be jointly modelled in the future, using a smaller grid size.

Acknowledgements

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References

[1] Suursaar, Ü., Kullas, T. & Otsmann, M., The influence of currents and waves on ecological conditions of the Väinameri. *Proc. Estonian Acad. Sci., Biol. Ecol.*, **50** (4), pp. 231-247, 2001.

[2] Otsmann, M., Suursaar, Ü. & Kullas, T., The oscillatory nature of the flows in the system of straits and small semienclosed basins of the Baltic Sea. *Continental Shelf Research,* **21** (15), pp. 1577-1603, 2001.

[3] Suursaar, Ü., Kullas, T. & Otsmann, M., A model study of the sea level variations in the Gulf of Riga and the Väinameri Sea. *Continental Shelf Research*, **22** (14), pp. 2001-2019, 2002.

[4] Jones, J.E. & Davies, A.M., Influence of wave-current interaction, and high frequency forcing upon storm induced currents and elevations. *Estuarine, Coastal and Shelf Science,* **53**, pp. 397-413, 2001.

[5] Smith, S.D. & Banke, E.G., Variation of the sea surface drag coefficient with wind speed. *Quarterly Journal of the Royal Meteorological Society*, **101**, pp. 665-673, 1975.

[6] Huttula, T., *Modelling the transport of suspended sediment in shallow lakes. Academic dissertation*, University of Helsinki: Helsinki, 1994.

[7] Soomere, T. & Keevallik, S., Anisotropy of moderate and strong winds in the Baltic Proper. *Proc. Estonian Acad. Sci. Eng.*, **7** (1), pp. 35-49, 2001.

[8] Whitford, D.J. & Thornton, E.B., Comparison of wind and wave forcing of longshore currents, *Continental Shelf Research*, **13**, pp. 1205-1218, 1993.