Coastal records of rapid changes in the eastern Baltic area

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Abstract

Rapid changes taking place in coastal areas are of fundamental importance for better understanding the natural and man-induced processes which should be recognized and managed. Technological developments and the ensuing progress in marine transport have been accompanied by a dramatic increase in human activity of which the Baltic Sea has experienced more than any other sea in the world. In recent years, intense traffic of high-speed passanger ships, especially in Tallinn Bay, has caused damage to objects located in the coastal area, has brought serious problems to the traffic of small ships and has endangered holidaymakers on the beach. The sea-level in the eastern Baltic region has been controlled by the unequal land uplift that has affected different areas in different ways. The present average rise of the world ocean level does not remarkably affect the evolution of the beaches in the northern part of the study area: in that area, due to crustal uplift (2-3 mm per year), the coast is rising more rapidly than the level of the world ocean (about 1.5 mm annually). However, the sinking southern part of the study area would be endangered, especially due to accelerated sea-level rise, which is the result of natural processes and the "greenhouse effect". Extensive erosion and alteration of depositional sandy shores appears to be largely due to the increased storm activity. Severe shore damage is usually caused by the combination of heavy storms, high sea-level, and absence of ice cover. The exceptional storm named Erwin/Gudrun of January 2005 motivated studies of the wave measurements and coastal protection. Substantial changes in coastal morphology have often been caused by the action of ice, when ridges of pressure ice up to 15 m high are generated by persistent undirectional winds. and are pushed forward against the shore with an enormous force, shaping the shore, breaking trees and damaging buildings.

1 Introduction

Research into topography and shoreline displacement of the Baltic Sea goes back well over a century. However, in spite of a great number of publications and serious improvement in investigation methods, many topical problems of the history of the Baltic Sea have still remained unsolved. It is well-known that the North, Central and South Baltic developed under sharply different tectonic conditions and their shorelines mirror this (Fig. 1). The connection between the lowering of shorelines and their seaward retreat, and the process of land uplift was obvious to scientists back to the nineteenth century; however, the present land uplift around the Baltic Sea, in which isobases denote the extent of uplift in relation to sea level, is still under discussion. It is clear that the land uplift in Fennoscandia is mainly glacio-isostatic in nature, but to calculate another inclusion in total uplift seems to be more than speculation. It is quite possible that in the basement and sedimentary cover there are neotectonically active lifting and sinking blocks, which influence the sedimentation and erosional processes in different ways.

Figure 1
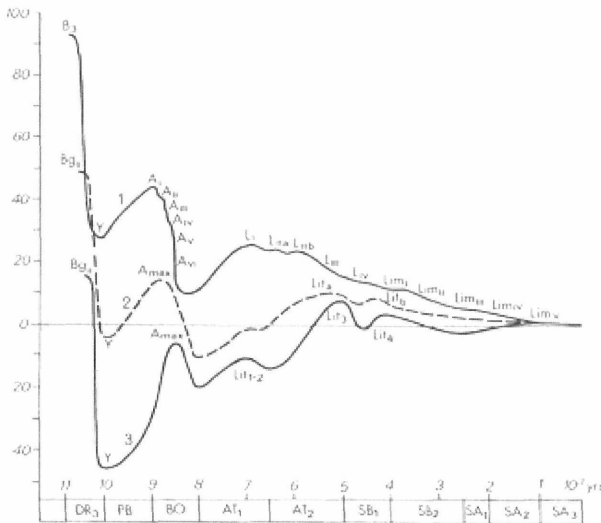
Structurally the study area, comprising Estonia, Latvia and Lithuania, and the St. Petersburg and Kaliningrad Districts of Russia, belongs to the north-western part of the East-European Platform. The boundary between the Fennoscandian Shield and the Platform is defined by the northern limit of sedimentary rocks and runs through the Gulf of Finland. Depending on tectonical pecularities, the bedrock of different ages crops out in the form of sublatitudinal belts, starting from Vendian and Cambrian rocks in the north (North Estonia) and ending with Mesozoic and Neogene rocks in the south (Lithuania). As a part of the vast East-European Plain, the study area is characterized by a flat surface topography with small absolute and relative heights. The sea-level history in the eastern Baltic region has been controlled by the unequal land uplift which has affected different areas in different ways. In the northern regions of the study area, the ancient coastal formations are located tens of metres above the water level; in the southern part of the area, correlative coastal formations lie at the depth of up to 60 metres below the sea level (Fig. 2). Several sinking and lifting blocks with anomalous heights are also encountered (Miidel 1994).

Figure 2

2 Rapid changes in the past.

The Baltic Sea was formed about 12,000 years ago after the readvance of the ice margin from the northern slope of the Pandivere Upland in northern Estonia (Kvasov & Raukas 1970). Consequently, the isolated big ice-dammed basins west and east of the elevation joined up. Basically, the Holocene and Late-glacial stages are intervals of either open or closed connection with the ocean, with consequent changes in the mode of sedimentation, shore displacement and salinity in the Baltic basin, which are, in turn, reflected in the biology of the basin. The Late-glacial drop of the Baltic Ice Lake (the first stage in the history of the Baltic Sea) to ocean (Yoldia) level, the rapid transgression of the following Ancylus Lake about 9500 yr BP (Haila & Raukas 1992) and its regression in late Ancylus time were rather catastrophic and are clearly traceable on the shore displacement curves. In Estonia the lowering of the Baltic Ice Lake level was estimated at about 25-30 m.

The Ancylus transgression culminated in the different regions of the Baltic Sea at different times. In the area of the Gulf of Finland it reached its maximum somewhere between 9200-9000 years BP. If the water level in the Ancylus Lake rose 15-20 m above the ocean level over 300 years, then its annual rate of rise must have been 5-6 cm (Eronen & Ristaniemi, 1992). The velocity and amplitude of the rapid Ancylus regression are well established on the Island of Hiiumaa in Estonia. On the Kõpu Peninsula, the Ancylus transgression level has been fixed at the height of 42-45 m, and the lowest Ancylus regression level at Partsi at the height of 8.7 m. This yields some 30-35 m for the regression amplitude and 3.0-3.5 cm for the annual regression rate between 9000 and 8000 yearrs BP (Raukas et al. 1996).

Such rapid events were important both from the geological and social point of view, because the inhabitants had to adapt themselves to the rapidly changing shoreline. For example, a Stone Age human settlement at Pulli (SW Estonia) was highly controlled by the evolution of the Baltic Sea and related changes in the local hydrology (Raukas et al. 1995). In the first half of the Pre-Boreral, during the low standing of the Yoldia Sea, when the regression of the Baltic basin was most pronounced in the entire history of the Baltic, Mesolithic hunters and fishers settled here about 9600 years ago, but were soon forced to abandon the settlement of Pulli due to the rise of Ancylus Lake water level. During the Ancylus regression, the shoreline again retreated a long distance towards its present-day position and the early inhabitants had to adapt themselves again to the changing shoreline and the new drainage system. A new water level rise took place during the following Litorina Stage.

3   Contemporary shore changes and influencing factors.

In general, the epicontinental character of the Baltic Sea is reflected in all processes that have influenced the coastal morphology and sedimentation. Isolation, modest size and small depth are the factors limiting the development of significant currents. Tidal changes of the water level are small. The principal coastal agent is the wave action induced by heavy storms with wind velocity 40-45 m/s. In the autumn-winter period, when the water level is relatively high, great water masses are piled up. Under such high-water conditions, the surge can reach several metres and cause severe damage to the coast (Fig. 3). Wave observations in the Baltic sea area extend back more than 200 years. These data, however, represent only wave properties in the near-shore regions and often reflect open-sea wave fields inadequately. Contemporary wave measurements in the northern Baltic Sea were launched about three decades ago when semi-autonomous measurement devices were deployed in different parts of the sea. Unfortunately, hardly any by wave data measured instruments are available from the coastal areas of Estonia, Latvia and Lithuania, except for visual observations from the coast and for sporadic measurements made with pressure-based sensors (Soomere 2005). During exceptional storm named Erwin/Gudrun of January 2005, extreme wave conditions existed and according to Soomere in the late evening of 13th January the largest wave height reached 7.82 m in the open sea. But on 25 th December 1996 an extremely high single wave 12.79 m high was measured. Although devastating tsunamis in Eastern Baltic are virtually impossible, the occurrence of such high waves should be taken into account in strategic planning, as the appearance and the results of these hazards are fairly similar.

Figure 3

Ice-push (Fig. 4) is at its greatest on sandy beaches; where under the compressing and ploughing influence of the ice, deep furrows are often formed on the beach and coastal slope. On till shores big erratics are moved by expanding ice. Occasionally, tens-of-metres-long stone walls are encountered in

front of scarps which they defend from further erosion. Cornics, wave-cut notches and vertical tectonic joints in the bedrock contribute to the downfall of huge blocks on the shore, modifying the erscarpments, but on the other hand, they protect the cliff from erosion (Fig. 5) and affect longshore drift of sediments over decades.

Figure 4

Figure 5

Earthquakes have also played a certain role in the shaping of shorelines, causing slides and remarkable changes in coastal escarpments up to 56 meters high, cut into Ordovician and Silurian limestones. The 4.7 magnitude Osmussaare earthquake on 25 th October 1976 affected an area of 191,000 sq km. Its epicentre was suposedly related to a fault zone running from the central Baltic via the Island of Hiiumaa to the coast of Finland. Because of this earthquake, particularly large masses of limestone blocks fell in front of the steep escarpments on the Island of Osmussaar.

Our recent investigations of mass movements at the North Estonian klint (Miidel & Raukas 2005) demonstrated the importance of joints and lithology in gravity erosion. The following types of mass movements were distinguished: rock falls, rock slides (or block glides), rotational slips and talus creeps. Rock falls are mentioned in the areas where the klint is exposed immediately at the sea or only a little away from the waterfront. Rock falls are the main factors related to the formation of the broad and thick talus in front of the escarpment. The material ranges from angular debris of variable size up to huge blocks. The size of the material depends on the spatial distribution of tectonic joints. The length of the blocks that have fallen down due to the sea erosion and earthquakes may reach 50-70 m (Fig. 5). As an example, in December 2003 during a heavy storm, an arch-like block, 9.4 m wide and 27 m long, and weighing about 1,500 – 2,000 tonnes, was involved in a rock fall in Pakri Cliff. Recent rock falls in the same place occurred in March 2008.

Rock slides are confined to the places where steep vertical walls consist of carbonate rocks and form the upper part of the escarpment. The slip surface is commonly formed by joint planes and is mostly associated with the terrigenous rocks in the lower part of the escarpment. In the case of rock slides, the rock block remains relatively monolithic and is not crushed. Often the downsliding beds face the sea. Rotational slips are related to the specific talus from Cambrian "blue clays". Such landslides may be triggered by heavy storms or rainfalls when the toe of the talus slope is eroded away. A great landslide took place at Toila in May 2001. The landslide was about 180 m long and formed a transverse ridge. In this process, sea erosion during the high-water stand plays a significant role, changing the equilibrium of the talus. The equilibrium can be disturbed also by the root systems of large trees. When the trees move back and forth in strong wind, their crowns act as wind-catching sails. Talus creeps occur in Cambrian clay areas, serving as a drainage pathway of groundwater percolating through the bedrock and discharging at the foot of the escarpment. As a result of talus creep, large blocks of Ordovician carbonate and Cambrian and Ordovician terrigenous rocks are found at the shore, 50-100 m away from the escarpment. Differences in mass movement depend on the geological structure. Talus is lacking in the western part of the klint and therefore rock falls prevail. Here in the eastern part of the klint, where the talus zone overlies Cambrian clays, rotational slips and talus creeps occur. In some places, due to slope processes, the edge of the escarpment reaches the old Tallinn – St. Petersburg highway and several houses, built on the klint edge, are in danger of falling down.

4 Influence of ship wave action

In recent years the staff of the Estonian Maritime Academy has intensively studyied the influence of stern waves in Tallinn Bay (Levald & Valdmann 2007 a. o.) Ships plying the Bay of Tallinn can be divided into two groups. One group comprises classical ferry boats and hydrofoil ships, the other group

consists of high speed catamarans and SuperSeaCat IVs. Intense traffic of high-speed passenger ships causes damage to objects located in the coastal area, creates problems in small ship traffic, and could be dangerous to holidaymakers on the beach. Hydrofoil ships and classical ferry boats do not cause dangerous waves to a large extent due to the fact that their stern waves do not exceed the reach of wind waves and they practically do not influence the coastal processes. Yet, the altitude of the stern waves of high-speed ships exceeds the altitude of wind waves highly many times a day (Käärd & Valdmann 2007, Soomere, 2005).

5   Conclusion

Some environmental changes in the Baltic Sea reflect global trends, the others reflect local and regional trends only. Nevetrtheless, it is important to compare them with global scale processes. In this paper potential marine, natural and anthropogenic hazards affecting the coasts in the Eastern Baltic area, were reviewed. In the long run the most important hazard for coastal communities is the rise in sea level. This problem is actual for the slowly sinking areas in the southern Baltic Sea (Poland and Germany), and also includes Lithuania and Kaliningrad District, where three potential adaption strategies (retreat, limited protection and full protection, Zeidler 1997) can be used. In the northern Baltic Sea the neotectonic uplift of the Earth`s Crust is faster than the rise of the sea level and this problem is not actual. Another major long-term hazard accompanied by the gradual increase of the water level, is the increased flood risk, which is already high even in several low-lying areas of south-west Estonia, where they may reduce the quality of coastal forests and damage low-lying buildings. Coastal hazards related to large wind waves (up to 4 m) and associated management issues are usually regarded to high water stand in autumn period. Rapid erosion and accretion can be the result of both short-lived storms and longer (sub-decadal) water-level changes. The results of both numerical studies and the analyses of historical wave data confirm that waves in the Gulf of Finland are relatively small and this is the reason why waves from the fast ferries form an appreciable portion of the total wave activity in Tallinn Bay. The daily highest ship waves belong to the highest 5% of wind waves in the area (Soomere 2005). Hummocky ice may also cause extensive damage to the coast. At the same time sea ice can reduce the wave loads during the ice season and protect the coasts.

Acknowledgements

References

[1]   Eronen, M. & Ristaniemi, O. 1992. Late Quaternary crustal deformation and coastal changes in Finland. – Quaternary International 11/12, 175-184.

[2]   Haila, H. & Raukas, A. 1992. Ancylus Lake. -   In: Raukas, A., Hyvärinen, H. (Eds.). Geology of the Gulf of Finland (in Russian, with English summary). Estonian Academy of Sciences, Tallinn, 283-296.

[3]   Kvasov, D. & Raukas, A. 1970. On the late-glacial history of the Gulf of Finland (in Russian). – Izvestiya Vsesoyuznogo Geographitseskogo Obshchestva 102, 432-438.

[4]   Käärd, A. & Valdmann, A. 2007. Laevalainete mõjust Tallinna lahes. (Influence of wave action in the Tallinn Bay). - Proceedings of Estonian Maritime Academy, 5. Tallinn, 23-35.

[5]   Levald, H. & Valdmann, A. 2007. Aegna sadama arendamine (Development of Aegna port). - Proceedings of Estonian Maritime Academy, 5, 36-44.

[6]   Miidel, A. 1994. Geological background of the present regional uplift anomaly in Estonia. – Proceedings of the Estonian Academy of Sciences. Geology, 43, 69-80.

[7]   Miidel, A. & Raukas, A. 2005. Slope processes at the Northestonian klint. – Proceedings of the Estonian Academy of Sciences. Geology, 54, 209-224.

[8]   Raukas, A., Moora, T. & Karukäpp, R. 1995. About the history of the Baltic Sea and early inhabitants in the Pärnu area. - In: Meidla, T., Jõeleht, A., Kalm, V., Kirs, J. (Eds.). Geology of Livonia (in Estonian with English summary). University of Tartu, Estonian Geological Society, Tartu, 119-124.

[9]   Raukas, A., Tavast, E. & Molodkov, A. 1996. Partsi – a new promising area for the investigation of Late Boreal and Early Atlantic water level changes of the Baltic Sea. – Proceedings of the Estonian Academy of Sciences. Geology, 45, 92-101.

[10]   Soomere, T. 2005. Fast ferry traffic as a qualitatively new forcing factor of environmental processes in non-tidal sea areas: a case study in Tallinn Bay. - Environmental Fluid Mechanics, 5, 293-323.

[12]   Zeidler, R. B. 1997. Climate change vulnerability and response strategies for the coastal zone of Poland. – Climatic Change 36 (1-2), 151-173.

Text to figures

Figure 1. Water level changes at Kõpu, Island of Hiiumaa, Estonia (1), in western Latvia (2) and western Lithuania (3) with clear regressions of the Baltic Ice Lake and the Ancylus Lake.

Figure 2. Ancylus Lake shoreline about 9200 yr BP and main localities, mentioned in the text.

Figure 3. Under high-water conditions heavy storms cause severe damage on the coast. Island of Ruhnu, October 2001. Photo by K. Orviku.

Figure 4. Every year in some places ridges of pressure ice shape the shore. Photo by K. Orviku.

Figure 5. Rock fall on the Island of Väike-Pakri in May 2004. Big limestone blocks will defend the shore from further erosion. Photo by G. Baranov.