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Marine coastal hazards for the eastern coasts of the Baltic Sea

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Abstract Major potential marine hazards affecting the coasts of the northern and eastern parts of the Baltic Sea are reviewed. While several classical hazards such as tsunamis are immaterial here, changes in sea level and its variability, wave regime, and wind-induced coastal flooding can significantly impact coastal environments. Recent advances in detecting, analysis, and quantification of the influence of the natural factors and their changes in different Baltic Sea regions are described. Promising technologies for the monitoring of changes in the coasts and ways of mitigation of marine hazards are discussed.

Keywords *Baltic Sea, sea level rise, flood risk, wave action, coastal protection.*

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INTRODUCTION

The Baltic Sea is a unique water body, the dynamics of which combines features of large lake, large estuary and small ocean (BACC 2008). The intricacy of its internal dynamics extends far beyond the typical features of basins of comparable size (Alenius *et al.* 1998, Soomere *et al.* 2008). The vulnerability of this water body has been legally recognized by declaring the Baltic Sea as a particularly sensitive sea area by the International Maritime Organization at the end of 2005. The combination of the relatively small size of the Baltic Sea and the vulnerability of its ecosystem and its relatively young coasts makes this region extremely susceptible with respect both to climate changes and anthropogenic pressure.

A substantial part of the energy and momentum submitted to the water masses by winds blowing over the sea surface is carried further in the form of surface waves. They bring to the coastline massive amounts of energy and thus form one of the generic sources of hazards in the coastal zone. Another basic hazard is the local, wave-induced change in sea level. These and similar hazards that may considerably affect the coasts are called marine coastal hazards below.

Numerous changes in the forcing conditions and of the reaction of the water masses of the Baltic Sea have been reported during the latter decade. A number of such observations can be related to a more frequent occurrence of marine hazards affecting the evolution of its coasts. Orviku *et al.* (2003) presented evidence that the apparently increasing storminess in the Baltic Sea (Alexandersson *et al.* 1998) has already caused extensive erosion of several depositional coasts. This opinion is supported by the analysis of Johansson *et al.* (2001) who showed that the probability of occurrence of high water levels has considerably increased within the last half-century.

There is ongoing debate on the consequences of the changes in the storminess. On the one hand, the wave climate changes in the adjacent North Sea have been found marginal, at least, until the mid-1990s

(WASA Group 1998). A decreasing tendency of the annual average wave heights has been recently found for the northern part of the Baltic Proper (Broman *et al.* 2006; Soomere & Zaitseva 2007). On the other hand, several cases of hazardous wave conditions that occurred at the turn of the millennium (Kahma *et al.* 2003). Ferocious winter storms in 2004/2005 (Suursaar *et al.* 2006; Soomere *et al*. 2008) have reinforced the discussion as whether the extreme wave conditions in the Baltic Sea have become rougher compared to the situation a few decades ago. In particular, windstorm *Gudrun*, the fourth most expensive natural disaster in the world in 2005 hit many areas in northern Europe on 7–9 January 2005, caused widespread property damage and exceptionally high coastal flooding on its way. The storm surge in the Estonian city of Pärnu (275 cm over the mean sea level) was the highest ever recorded (Suursaar *et al.* 2006). A combination of unusually high water levels and rough seas presents acute danger to depositional coasts.

The above suggests that the coasts of the Baltic Sea are under gradually increasing pressure. The marine coasts have a specific role not only as the interaction zone between water masses and dry land, but also as a zone of extremely intense energy and momentum conversion. It is well known that different coasts are vulnerable to different hazards (Gornitz 1991; Liu *et al.* 2000). For example, tsunami and storm surges affect very strongly coasts that have extensive relatively shallow shelf areas. On the other hand, the sea level rise is virtually insignificant for the functioning of many estuaries of large rivers in New Zealand, because the sedimentation rate at their mouths several times exceeds the effect of the sea level rise (T. Healy, personal communication).

The anisotropic nature of the Baltic Sea wind and wave fields (Soomere 2003; Jönsson *et al.* 2002, 2005) suggests that the eastern coast of the Baltic Sea is probably under the largest natural pressure among the variety of the coasts of this water body. This coast is to a large extent in active evolution and the potential changes in the forcing are expected to become evident relatively fast. These parts of the coast host several major ports and cities, a part of which are still under active development. The potential increase in the frequency and/or severity of marine coastal hazards may substantially affect the planning, operation, maintenance, and reconstructions of the relevant infrastructure.

The study starts from the identification of the potential large-scale marine coastal hazards along the eastern coast of the Baltic Sea. This part is followed by an overview of the experience in mitigation of the most devastating marine coastal hazards for similar coasts in other parts of the world. Finally, we discuss to some extent the gaps in the existing knowledge in selected areas and depict the needs for the further research necessary for building effective countermeasures to marine coastal hazards.

MATERIAL AND SITES

We depict the basic marine coastal hazards in the context of two sections in different parts of the Baltic Sea (Fig. 1). The analysis is mostly made based on existing international publications. Some latest achievements are depicted based on current research reports.

The coast of Lithuania represents a generic type of (1) more or less straight, high-energy, actively developing coasts that (2) contain a relatively large amount of finer, mobile sediments, (3) are open to predominating

Fig. 1. Location scheme of the Baltic Sea.

wind directions in this water body, and (4) are exposed to wave activity for a wide range of wave approach directions.

The coastline of the City of Tallinn is characteristic for the eastern and southern coasts of the Gulf of Finland. These coasts were formed and develop predominantly under the effect of wave action (Orviku & Granö 1992). The Estonian coast of this gulf hosts numerous peninsulas, islands, and bays cutting deep into the land. The beaches form a large erosional-accretional system, divided into compartments by rocky peninsulas and headlands. The volume of finer sediments and the magnitude of littoral drift are modest. The most common types of coasts here are the straightening, accumulation, and embayed coasts – type 20 according to Kaplin (1973). The distinguishing feature of such coasts is the high spatio-temporal variability of wind- and wave-induced coastal hazards. Such coasts are usually sheltered for most of the wind directions. Coastal hazards become evident relatively seldom here whereas the sections where they occur substantially depend on the local features of each hazardous (e.g. storm) event.

We intentionally leave aside a description of marine coastal hazards along the western and northern parts of the Baltic Sea. The coasts in these areas are mostly of the skären type and are generally uplifting; thus, they have largely different hazardous factors.

A more subtle issue is the problem of salinization of the groundwater and the soil in the coastal zone. There is an overall excess of precipitation in the Baltic Sea countries. The groundwater flux is generally from the mainland to the sea and the threat of salinization is fairly minor. Classical earthquake- or landslide-generated tsunamis also present no acute danger in the Baltic Sea region. A large tsunami may only occur in a highly improbable case when a large asteroid directly hits the Baltic Sea. For the listed reasons these phenomena are not analysed below.

MARINE COASTAL HAZARDS

Sea level changes

In the Baltic Sea both sea level increase and decrease may cause substantial problems (Johansson *et al.* 2004; Kont *et al.* 2003). The sea level rise has a number of potential effects on coastal urban infrastructures, including accelerated erosion and increased occurrence of the coastal flooding. While the coastal flooding and its consequences are a general issue in coastal studies, wind-induced low water levels and effects caused by the postglacial land uplift are not very frequent in other water bodies. Another factor of extensive potential influence is the change in the properties of the variability of the local sea level.

The state-of-art estimates for the rate of the global sea level rise for the 21st century range from about 1.7 mm/year to about 5 mm/year (IPCC 2007). As the land is currently experiencing even faster uplift in the northern part of the Baltic Sea, the global sea level change is not dangerous for Finland or for the northern part of Sweden. In Estonia, the expected net sea level rise is quite small because of a similar uplift. The global seal level change will apparently balance or weakly override the uplift there. Yet in the southern Baltic Sea, e.g. along the Polish (Zeidler 1997) and Lithuanian coasts (that both experience slow down-lift), this rise apparently will cause problems within the coming decades. These coasts are generally quite vulnerable in this respect.

Among the world's coastlines, the largest losses are expected to occur around the Mediterranean and Baltic Seas and to a lesser extent on the Atlantic Ocean coast of Central and North America and the smaller islands of the Caribbean Sea. The most vulnerable with respect to the sea level rise are low-lying coastal areas where even a relatively small global rise in sea level could have significant adverse impacts if there is no adaptive response. The relevant analysis for one subclass of coastal environment – coastal wetlands – suggests that the sea-level rise could cause a substantial loss of the world's coastal wetlands. As these wetlands are also under very strong anthropogenic pressure, Nicholls *et al.* (1999) conclude that, combined with other losses due to direct human action, up to 70% of the world's coastal wetlands could be lost by the 2080s.

A relatively rare threat, important in the northern parts of the Baltic Sea, is the postglacial net uplift of land with respect to the mean water level. This process governs the long-term evolution of the mean sea level in most of Finland and around the Sea of Bothnia (Fig. 2). In the north-western part of Estonia, the land uplift rate is up to 3 mm/year (Zhelnin 1966) and thus faster than the expected sea level rise according to a large part of the future scenarios. The land uplift leads to the necessity of more frequent dredging of harbours and waterways, or even to the relocation of the coastal infrastructure to meet the need for a free access to the

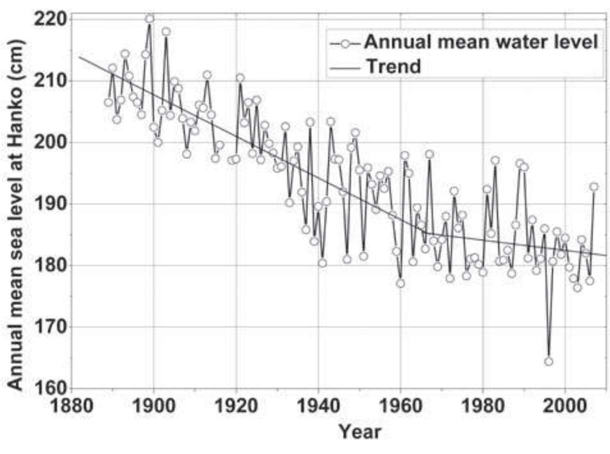

Fig. 2. Annual mean (solid line and circles) and fitted mean sea level (dashed line) at Hanko. Based on Fig. 9 of Johansson *et al.* (2004). Data for 2003–2007 presented by Milla Johansson (Finnish Marine Research Institute).

open sea. The economic estimates made in similar conditions in other parts of the ocean suggest that the countermeasures may be quite costly for the local community. For example, the costs of harbour and marina dredging are estimated as much as 7.6 million USD for Goderich Harbour and adjacent marinas only (Schwartz *et al.* 2004).

While around the Hanko Peninsula the water level for the last 100 years has decreased by 30 cm, the similar dropdown for the northern part of the Gulf of Bothnia exceeds 1 m (Johansson *et al.* 2001). An interesting feature is that the relative magnitude of the land uplift along the northern coast of the Gulf of Finland apparently has changed around year 1960 (see Fig. 1). The relative uplift was about 3.3 mm/year until 1960 and about 1.6 mm/year since then (Johansson *et al.* 2004). This large shift in the uplift rate apparently is jointly caused by the global sea level rise and the increase in the local sea level owing to the overall intensification of westerly winds.

The situation is completely different for the Lithuanian coast. The entire coast of the southern part of the Baltic Sea generally experiences a certain downlift. Combined with the increase in the global sea level, this process may result in large-scale adverse effects and the loss of considerable amount of land in low-lying coastal sections. In particular, for the Lithuanian coasts the relative coast downlift rate is as large as about 2 mm/year (Dailidienė *et al.* 2004, 2006). During the latter 100 years, the water level in Klaipėda Strait has risen by about 15 cm (Fig. 3). Much of this rise is

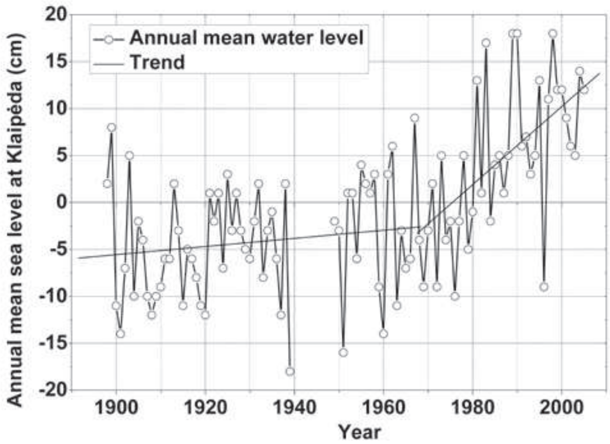

Fig. 3. Annual mean water level in Klaipėda Strait. Based on data from Dailidienė *et al*. (2006).

storm season, the combination of a high waver level and rough seas may considerably accelerate the coastal erosion (Jarmalavičius & Žilinskas 1996).

Increased risk of coastal flooding

Another major long-term hazard accompanied with the gradual increase in the water level is the increased risk of coastal flooding. This risk is already high in several low-lying areas along the southern, eastern, and northeastern coasts of the Baltic Proper, and for certain sections of the coasts of the Gulf of Riga and Gulf of Finland. An important feature that apparently has not been properly understood yet is that most of the increase in the flood risk is connected with a substantial change in the probability distribution of different sea levels within the latter half-century. The above-mentioned considerable increase in the probability of the occurrence of high sea levels, first detected for the Finnish coasts by Johansson *et al.* (2001) means that the coastal flooding becomes more frequent and generally more devastating. A similar effect of the increase in the variability of sea level and a frequent occurrence of high sea levels has been recognized also for Estonian and Lithuanian coastlines. This tendency apparently is a generic source for coastal hazards for the entire eastern part of the Baltic Sea.

The most dramatic event in the area in question was windstorm *Gudrun*, during which the all-time highest sea levels were measured at all sea level measurement sites along the Finnish southern coast and at many sites along the Estonian western and northern coasts (Suursaar *et al.* 2006). A high variability of sea levels and extreme single events has also been observed at Lithuanian sites (Dailidienė *et al.* 2006). The highest water level in Klaipėda Strait (186 cm over the long-term mean value) was registered on 17 October 1967. The maximum wind speeds in hurricanes *Anatol* (4 December 1999) and *Gudrun* (9 January 2005) occurred far from Lithuanian coasts; for that reason the highest water level (165 and 154 cm over the mean level, respectively) remained moderate. An overall increase in the typical annual maximum sea level was observed during the last decades of the 20th century. This feature means that the probability of an extensive coastal flooding has also considerably increased. An additional risk factor is the relatively fast water level rise during strong storms: sea level may rise with the rate of 20 cm an hour. The maximum water level is usually reached within 6–7 hours (Dailidienė *et al.* 2004).

Mitigation of risks of sea level rise and coastal flooding

A number of local studies of long-term hazards associated with the water level rise (Gornitz 1991; Zeidler 1997; Thumerer *et al.* 2000; Kont *et al.* 2003; Dailidienė *et al.* 2006; Dinesh Kumar 2006; Jarmalavičius *et al.* 2007) confirm the significant increase in the estimated damage costs of flood events. The relevant activities towards the mitigation of the consequences consist of two major aspects. First, the knowledge of the physical parameters of hazardous events and their adequate forecast obtains gradually an even larger role. Second, planning and organization of reasonable countermeasures (both active and passive) to a particular event and creating strategy for an overall reduction of the related costs for the whole community have become crucial.

Usually, these aspects have been studied individually. The first relevant joint studies have been published only in recent years. The value of a community approach to improved prediction and characterization of coastal storm hazards is extensively discussed in relation of the activities of the US Army Corps of Engineers (Ebersole *et al.* 2006). This approach embraces simultaneous modelling of the physical parameters (e.g. hurricane-induced water levels and wave conditions) and validation of the data through field measurements, historical data analysis, and, if possible, assimilation of real-time data into the models. Such studies were triggered by the unsatisfactory performance of the hurricane protection system in the southeastern part of Louisiana and by the lack of adequate response to hurricane *Katrina*. The preparedness and the quality of the reaction of the local community were obviously insufficient in this part of the world (Ebersole *et al.* 2006). Similar aspects of low preparedness became evident during an extensive flooding in Estonia in January 2005 (Suursaar *et al.* 2006). Ebersole *et al.* (2006) underline that the attempts to create an adequate reaction to marine coastal hazards will only be successful if the efforts at all levels are synchronized.

Feasible ways towards mitigation of the (sequence of the) marine hazards consist in developing open-source, community-based computer software for coastal storm wave and surge predictions. A large threat identified by Ebersole *et al.* (2006) is the today's over-reliance on proprietary software. This is a particularly important issue for the Baltic States (Estonia, Latvia, and Lithuania) where the software predicting the sea state is actually run out of the country (currently in Sweden) and the results have quite a large bias for the eastern Baltic Sea coasts. The sea level forecasts are given with the use of certain approximations based on statistics of the past events. This *modus operandi* combined with an outdated information about critical water levels (in the Tallinn area for Estonia, and Klaipėda area for Lithuania) and the inappropriate knowledge of the realistic consequences of slight overshooting of these levels has led, for example, to a sequence of false warnings in the Tallinn area in winter 2006/2007. The situation is currently being improved. The first step towards more adequate reaction of the community is a dynamical description of the dangerous water levels in different sections of the City of Klaipėda and along the coasts of the City of Tallinn (Stonevičius & Rimkus 2007; Soomere 2007).

Monitoring of changes

Several recently developed tools are available to monitor the behaviour of wave fields, the position of the waterline, near-coastal dynamics in the breaker zone, and the reaction of the coast have become available during the recent years. The most promising tool to monitor the changes in the coastal zone is the Geographic Information Systems (GIS) technology. The GIS technologies allow developing various types of data and databases in which geographical, oceanographic, meteorological, and remote sensing data is associated into a unified system. Doing so opens new perspectives towards decreasing the risk of loss of highly priced land sections and key infrastructure by the natural hazards through the use of preventive measures. Combined with the classical model estimates, the GIS-based technologies and modelling systems serve as the generic basis of prototypes of the Decision Support System for the coastal area (Zeidler 1997; Thumerer *et al.* 2000).

Another promising technology is the video-based automated monitoring of coastal processes. This approach usually presumes a relatively large amount of involvement of experts; for this reason it is only use in the most exposed coast sections. The major benefit of such systems is their large temporal and spatial coverage. Video-based monitoring may require quite expensive software and, in general, considerable financial investment. The physical protection of video equipment may be problematic at the coasts of the Baltic Sea; however, this is a generic problem of the use of mainland-based equipment.

Such systems have shown good performance at the Australian coasts to monitor and quantify the regional-scale coastal response to sand nourishment and constructions in the near shore (Turner *et al.* 2004). An automated monitoring system of four cameras provides continuous coverage of a few kilometres of the coast. It enables (1) the mapping of changing shoreline position, (2) the measurement of three-dimensional dry beach morphology and resulting changes in the sediment volume; and (3) the estimates of wave breaking frequency and position.

The results of the last four years of the use of such equipment at the Lithuanian seacoast are promising. The situation at the coast is currently observed along an about 500 m long section of the beach near the Palanga wharf. The video image is broadcast live in the Internet (www.zebra.lt). The primary user of the system is the Palanga municipality, but there are no restrictions for the use of the images for commercial purposes. Valdmann and Käärd (2006) suggest using this method for the Kakumäe area, in the region where the most intense coastal erosion occurs in the City of Tallinn.

The GIS- or video-based technologies may be simply combined with the relevant satellite information. The latter has a somewhat lower resolution but allows much richer information of changes in larger regions. This approach has been used, for example, to study the land cover change within the Grand Bay National Estuarine Research Reserve in 1974–2001 (Hilbert 2006). Modifications of this approach can be very useful for the Baltic Sea conditions, in particular, for bays that are protected from the full force of waves, winds, and storms. The particular reason of such protection is immaterial. While Grand Bay is protected from open sea processes by reefs and barrier islands, numerous shallow areas at its entrances offer analogous protection for Tallinn Bay (Soomere 2005a). Such semi-sheltered bays have usually very rich but vulnerable ecosystem as they provide reasonable habitats for a large number of plant and animal species.

Wave action and its changes

Wave action is the principal driving force of the coastal processes. The largest wave activity can be observed along ocean coasts where wave heights over 10 m may occur regularly. As many beaches are vulnerable with respect to the joint occurrence of a high waver level and large waves, even short-lived but ferocious storms can cause rapid erosion and accretion. The most extensive damage in vulnerable areas (such as low-lying atolls and on the coastal fringes of high islands) usually occurs during short wave events created by strong cyclones indeed. Even infrastructure perched on 20 m high cliffs may not be immune during severe storms (Solomon & Forbes 1999). On the other hand, the role of even small waves may be very large under unfortunate conditions (f. e. see Dean & Dalrymple 2002).

Wave activity drives coastal processes along the eastern coast of the Baltic Sea and in many sections of its sub-basins. Here, the patterns of coastal changes are frequently modified by transient decadal and sub-decadal water level changes. Owing to specific features of the Baltic Sea wind fields (Mietus 1998; Soomere & Keevallik 2001, 2003), even relatively sheltered bays are at times subject to extensive wave loads (Soomere 2005a). For example, almost entire coastal area of the City of Tallinn is completely sheltered from waves excited by predominating southern winds. As a result, the local wave climate is at places very mild compared to that in the open part of the Gulf of Finland. The annual mean significant wave height varies from 0.29 m to 0.32 m in different sections of Pirita Beach in the City of Tallinn (Soomere *et al.* 2007). Western winds, however, may bring to this area wave energy stemming from the northern sector of the Baltic Proper. North and north-western winds may excite waves in this bay that are almost as high as the highest waves in the Gulf of Finland. The significant wave height exceeds 2 m each year and may reach 4 m in NNW storms in the central part of Tallinn Bay (Soomere 2005a). This feature well explains why most of the coasts of Tallinn Bay show features of intense erosion (Lutt & Tammik 1992; Kask *et al.* 2003).

The properties of storm waves at the Klaipėda Seaport gate are estimated by Kriaučiūnienė *et al.* (2006) who calculated extreme values of short waves propagating into Klaipėda Strait for strong winds blowing from the western to the northwestern directions and for wind speeds of 15, 20 and 25 m/s. At the wind speed of 15 m/s, the height of the waves at the port entrance reaches about 3 m. For even stronger storms (wind speeds of 20 and 25 m/s), the wave height is expected to exceed 4 or 5 m, respectively.

These estimates basically match visually observed wave data collected in the Centre of Marine Research, Klaipėda. Yet even larger waves may occur in this area. Historically, the roughest wave conditions were observed at the Lithuanian coast on 23 January 1962 when the wave height of 6 m was registered at Klaipėda. Such conditions were unexpectedly rough, because the SW wind speed was only about 20 m/s. During windstorm *Gudrun* in January 2005 the northwestern wind reached 20 m/s in Palanga, but the observed wave height was only 4 m.

Although the role of the wave action and its long-term changes in the coastal processes at the Lithuanian coast have not been properly quantified, in light of analogous studies performed for Estonia it is safe to say that the wave impact to the coastal processes at the open Lithuanian sea coast is significant, and can be largely amplified when it occurs in combination with the overall sea level rise or with the local coastal flooding.

The possible effects of the changes in the wave regime in the entire Baltic Sea area are also poorly understood. In the Baltic Sea conditions, the knowledge of the wave height only is not enough in the coastal management. A variety of wave-induced processes, in particular, the transport of sediments in the surf zone, largely depend on wave height, length or period, and propagation direction. The experience from the Baltic Sea basin is that even the quantification of the role of the ferry-induced waves requested extensive efforts from a large team of scientists (Soomere *et al.* 2003) and lead to quite a large uncertainty of the role of different wave parameters.

A large part of this uncertainty forms the shortage of the information about the factual local wave regime. The relevant knowledge of long-term wave climate can be to some extent constructed from the long-term statistics of wave properties at the few existing measurement sites in the Baltic Proper. An attempt in this direction is made with the use of the longest available instrumentally measured time series of wave properties at Almagrundet (Broman *et al.* 2006). The results of both numerical studies (Soomere 2005a) and the analysis of historical wave data (Broman *et al.* 2006) confirm that the wave periods in the entire Baltic Sea are relatively small. This is the key reason why waves from fast ferries form an appreciable portion of the total wave activity in Tallinn Bay since 1997. Their annual mean energy and its flux (wave power) are about 5–7 % and 20–25 % from that of the total wave activity, respectively. The daily highest ship waves belong to the highest 5 % of wind waves in this area (Soomere 2005b).

The intense traffic of fast ferries, accompanied by high and long waves, at times approaching from direction not common for wind waves, may stimulate sediment transport in the opposite direction to the natural littoral drift or current-induced transport of suspended matter during a relatively calm season (Elken & Soomere 2004). The role of fast ferries waves in coastal processes, which may be potentially substantial under certain circumstances (Soomere & Kask 2003; Levald & Valdmann 2005; Erm & Soomere 2006), has been poorly understood yet and needs further investigation. The research into this field may reveal some processes and effects associated with potential changes in wave properties (such as wave period and direction) in changing climate conditions.

Coastal protection measures

The majority of sandy beaches in the Baltic Sea region develop under clear deficit of sand. The southern sections of the seacoast experience a relative rise of sea level and are very susceptible to coastal erosion. Orviku *et al.* (2003) claimed that the seemingly increasing storminess (which is expressed as a statistically significant increasing trend of the number of storm days over the last 50 years) has already caused an extensive erosion of many depositional coasts in the northern part of the Baltic Sea. They expressed the opinion that destructions of beaches due to more frequent occurrence of high water level and intense waves, and lengthening of the ice-free time (Sooäär & Jaagus 2007) has overridden the stable development of the many sections of the Estonian coast. Even bay head beaches of the Gulf of Finland that are in a nearly equilibrium stage and experience postglacial uplift suffer from storm damages at times (Orviku 1974; Orviku & Granö 1992).

The Lithuanian coast mostly consists of sandy beaches, with fine sand (Bitinas *et al.* 2005; Trimonis *et al.* 2005; Žilinskas 2005). The comparably short coast suffers from the sand deficit and more than a half of Lithuanian beaches are described as being intensively eroded. During the last 20 years, the length of the accumulative coastal sectors has been reduced by the factor of four (Žilinskas 2005).

The best protection measures for eroding coasts can obviously be found based on extensive knowledge of the vulnerable areas. The traditional starting point is a general classification of the vulnerable areas. For example, in Poland, three basic vulnerable area types according to their geographic and socio-economic background have been specified. After that the threat of land loss and the risk of its temporary or partial inundation were analysed in connection with the assessment of the material and social costs and losses (Pruszak & Zawadzka 2005). The greatest threat of a partial or full land loss and the associated material and social costs are expected to occur in the heavily urbanized agglomeration of Gdansk and the Zulawy polders, and less urbanized low-lying areas around the Szczecin Lagoon and the vicinity of the Odra river mouth.

A sea level rise by 1 m (which is somewhat larger than the maximum increase by 2100 according to scenarios of the IPCC (2007) but still not totally excluded) will have a dramatic effect not only upon low-lying beaches, but also for the City of Klaipėda. Stonevičius and Rimkus (2007) suggest that the Danes river district in Klaipėda will be mostly inundated. Although this rise has not lead to substantial enlargement of regularly flooded areas at the Lithuanian coast yet, the beach erosion has considerably accelerated within the last 20 years (Jarmalavičius *et al.* 2007). The loss of several sections of the low-lying beach at Palanga is probable. Already an increase in the sea level by 30 cm will apparently cause the shoreline retreat by up to 17 m.

An analogous study by Kont *et al.* (2003) showed that both low-lying areas and heavily urbanized spots maybe under extensive pressure along the Estonian coast. The relative water level rise by 1 m would cause serious consequences in certain areas. The land loss in the northern Estonia area would probably be insignificant. In the easternmost part of Estonia, an important recreation site adjacent to Narva-Jõesuu with excellent sandy beaches would be under large pressure. Another site of great risk is the Sillamäe dumping site of the former uranium enrichment plant. Although it is currently protected by the new harbour constructions and their access road, possible damages of this site are one of the greatest threats to the environment of the Gulf of Finland. The spatial resolution of the analysis of Kont *et al.* (2003), however, is insufficient to locate smaller vulnerable spots, which may require both intensive care and protection efforts.

A specific feature of the Baltic Sea is the relatively small age of its coasts and vulnerability of near-coastal accumulation features. For that reason, the changes in the sea level and/or hydrodynamic conditions may result in extensive motion of fine sediments at medium depths. This may cause massive sedimentation in harbours and fairways. To the knowledge of the authors, this scenario has not been analysed for the Baltic Sea conditions.

DISCUSSION

The increase in wave heights is a widely studied issue for the North Atlantic (WASA Group 1998; see also references in Broman *et al.* 2006). Equally important for the functioning of the coasts are the changes in wave periods (that may lead e.g. to changes in the depth of closure) or in predominating wave directions. While sea ice attacks may become less frequent owing to the climate warming, the decrease in the length of the ice season (Sooäär & Jaagus 2007) evidently will lead to a considerable increase in the wave-induced loads on the coasts, because the winter season is the most windy one in the Baltic Sea (Mietus 1998).

Changes in wind regime are frequently considered only in the context of increasing storminess. Yet the change in the wind direction or the translation speed of low-pressure systems, or modifications of the overall wind patters in strong storms are at times even more serious issues (Soomere *et al.* 2008). In some cases, the anthropogenic pressure may also become evident in the form marine-induced coastal hazards. Wind farms potentially affecting wind patterns and changing sea water mixing properties (Burchard *et al.* 2005) and wakes from fast ferries (Soomere 2005a) are classical examples of this type.

The relative magnitude of a large part of the listed issues may considerably change when the local climate will be changed. As the coasts receive a large part of the energy of (changing) winds, changes in the coasts serve as a convenient "device" for early detecting the changes and shifts in the local climate. The relevant analysis therefore has an extremely important role in foresight studies and long-term planning of coastal areas.

The cost of the land loss and an increased level of marine coastal hazards, and the cost of the counter-measures have been estimated for the Polish coast by Zeidler (1997). The total cost of land losses is estimated at nearly 30 billion USD. Another loss (about 18 billion USD) is expected to occur owing to the increased occurrence and extension of coastal flooding. The cost of full protection is estimated as 6 billion USD. Thus, the strategy of full protection is generally preferable. This conclusion substantially relies on the fact that the Polish coastline is mostly straight and the necessary coastal engineering activities will be concentrated along this line only. This is not the case in Germany where abandoning of a part of the low-lying coastal areas and islands is under discussion. The above estimates are given in the prices of the mid-1990s. Since the prices for land and for coastal protection measures change more or less synchronously, the ratio of the losses and the costs of the full protection are expected not to vary considerably.

CONCLUSIONS

The complexity of the potential effects of marine coastal hazards on the near shore, evolution of the coastline, and functioning of the infrastructure at and in the vicinity of the coast suggests that any action planned in the coastal zone of the eastern Baltic Sea should be extensively scrutinised from the viewpoint of potential adverse scenarios. This conjecture is in line with the overall understanding of experts that the planning of long-term coastal protection measures is a multi-faced problem, adequate and successful handling of which needs a lot of time, substantial material resources, extended knowledge of specific features of marine and coastal environment, and an art of unifying different views to the whole process. However, this is the only way to effectively handle many of problems of coastal zone management.

In conclusion, it is safe to say that, generally, extensive amounts of high-resolution information about functioning of the beaches, dynamics and physics of marine hazards combined with detailed cost-benefit analysis form the prerequisite for sustainable development of the coasts of any region. The most promising are the technologies that combine the detailed knowledge of small sections of the coast with the large-scale patterns of changes. They can provide resource managers with information regarding the local changes and spatial distributions of changing patterns that cannot be extracted from point measurements. Consequently, they allow for more informed decisions also with regard to preserving biodiversity and planning restoration efforts.

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