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# Multi-criteria evaluation approach to coastal vulnerability index development in micro-tidal low-lying areas

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The coastal zones face much higher risks disasters and vulnerability to natural and anthropogenic forcing because of their location in extremely high-energy and rapidly developing environment. We develop and implement an updated set of indicators of coastal vulnerability that characterise relatively low-lying coastal segments with negligible tidal range but affected by substantial storm surges driven by atmospheric factors. The study area is about 90 km long coast of Lithuania in the south-eastern Baltic Sea. The classical methods for building the coastal vulnerability index (CVI) are combined with the outcome analytical hierarchical process (AHP) based approach for incorporating experts' judgements to specify the weights of used criteria. The CVI relies mostly on geological parameters (shoreline change rate, beach width/height, underwater slope, sand bars, and beach sediments) and involves only significant wave height as the representative of direct physical drivers. The selected criteria were integrated into CVI calculation using two options: (I) all criteria contribute equally, (II) each criteria may have a different contribution. Based on the weights and scores derived using AHP vulnerability maps are prepared to highlight areas with very low, low, medium, high and very high vulnerability. $CVI_w$ calculation based on option II highlighted 32% of the coast being of very high to high vulnerability, 22% of moderate vulnerability and 41% of low to very low vulnerability. Although these numbers vary to some extent depending on the viewpoint, in general about 10% of the coast in the study area is under very high risk, which calls for urgent planning and protective measures.



## 1. Introduction

Most coastal environments around the world are experiencing the effects of climate change (IPCC, 2007). Although coastal zones occupy only a very small part of the land used by society, they face particularly large pressure from these changes that are often realised through sea level rise and coastal erosion due to increased wave activity and high storm surges. Recent projections of climate change indicate that by 2100, the water level will eventually rise at least 18 cm and maximum 59 cm in the World Ocean (IPCC, 2007). The impact of this process on a particular coastal section depends on its morphology, lithological composition, hydrodynamic regime and the extension of anthropogenic pressure (Žilinskas and Jarmalavičius, 1996; Pranzini and Williams, 2013). For example, an increase in the water level can accelerate erosion at sedimentary coasts but usually does not have any considerable impact at a rocky coast; the intrusion of saline water into the groundwater may impact ecosystems (e.g. wetlands) even quite far inland but is unimportant if there is strong fresh water flux in the groundwater. The wave action may endanger cultural values, infrastructure and population in low-lying areas (Valdmann et al., 2008) but does not affect similar assets located at high cliffed coasts. Therefore, the reaction of individual sections of the coast to climate change should be evaluated separately whereas each section can be to a certain extent characterized in terms of its vulnerability with respect to potential changes to the forcing conditions, at least in qualitative terms.

Various methods have been proposed over the years for the prediction of shoreline changes induced by physical drivers, starting from simple estimates of inundation based on a static

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topography (which are valid, e.g., for rocky coasts of Finland or Sweden) and various implementations of Bruun's rule (Bruun, 1962) over extrapolation into the future of information about shoreline displacements extracted from historical charts (Deng et al., 2014) up to its generalisations and modern methods of coastline modelling (e.g., Roelvink and Reniers, 2011). These methods are usually based on several assumptions that are either difficult to validate or that oversimplify the complexity of processes driving the coastal changes. Therefore, the ability of these methods to quantify for instance the links between sea-level rise and shoreline changes has been questioned by various authors (Cooper and Pilkey, 2004, 2007; Alexandrakis et al., 2011; Pilkey et al., 2013).

A different, more qualitative, approach for the assessment of shoreline vulnerability due to effects of climate change consists in developing a version of the Coastal Vulnerability Index (CVI). The aim is to make use of the physical characteristic of the coastal system to at least qualitatively classify the potential impacts of climate change on different coastal sections. This approach is widely used in tidal areas all over the world (Gornitz and White, 1992, 1994; Pendleton et al., 2004; Boruff et al., 2005; Doukakis, 2005; Szlafsztein and Sterr, 2007; Devoy, 2008; Nageswara Rao et al., 2008; Mani Murali et al., 2013; Tibbetts and van Proosdij, 2013; Kunte et al., 2014) but hardly used on non-tidal or micro-tidal ones. The Baltic Sea, our study area, is one of the largest basins of this type and heavily impacted by climate change (BACC, 2008). The contribution from the diurnal tides to the water level of the Baltic Sea is usually a few cm. It may reach close to 10 cm in selected locations of the Gulf of Finland (Leppäranta and Myrberg, 2009) and to 17–19 cm in the easternmost region of this gulf, Neva Bay (Medvedev et al., 2013). Originally CVI methods take into account factors related to the local hydrodynamic regime (tidal amplitude, wave climate) and geomorphology (slope, sediment type), however some of the proposed factors are not relevant in micro-tidal low-lying areas. The resulting CVI provides a simple numerical basis for ranking sections of coastline in terms of their potential for change. Ideally, it can be used by managers to identify regions where risks may be relatively high.

The aim of this study is to develop a CVI index suitable for micro-tidal low-lying coastal environment considering geological and physical factors and apply it to case study area. South-eastern Baltic Sea coasts, as typical example of a micro-tidal low lying area, are predominantly sandy and mostly affected by water level and wind (e.g., Zeidler, 1997; Furmańczyk and Dudzińska-Nowak, 2009) thus are particularly vulnerable with respect to various effects of climate change such as possible sea level rise and enhanced coastal erosion due to likely increase in storminess in this region (Alexandersson et al., 2000; Žilinskas and Jarmalavičius, 2007; BACC, 2008).

The following article introduces a set of coastal vulnerability indicators that characterise low-lying coastal segments with negligible tidal range affected by substantial storm surges. Evaluation of coastal vulnerability index is based on two methods: the original CVI method (Gornitz and White, 1992, 1994; Pendelton et al., 2004) fitted to micro-tidal low-lying areas and weighted CVI method (developed in this study) based on multi-criteria evaluation. Analytical Hierarchy Process (AHP, Zahedi, 1986; Vaidya and Kumar, 2006) was integrated into this method to calculate the criteria weights. Coastal vulnerability maps for the entire study area were produced using both variations of the CVI method and advantages, limitations and applicability of derived coastal vulnerability estimates are discussed.

## 2. Study area

Although Lithuania has the shortest coastline (90.6 km) among the Baltic Sea countries (Žilinskas, 1997), its coast is still geologically and geomorphologically diverse (Fig. 1). The Lithuanian coast, a typical example of micro-tidal low-lying coast, is located in the south-eastern part of the Baltic Sea. It is formed of Quaternary deposits and belongs to the accumulative-abrasive coastal type supplied by sediments from the nearshore bottom and the Sambian Peninsula (Gudelis, 1998; Bitinas et al., 2005; Jarmalavičius et al., 2011). It is open to the predominant south-western, western and north-western (SW, W, NW) wind directions, and is exposed to wave activity for a wide range of wave approach directions (Valdmann et al., 2008). A large part of the Lithuanian coast forms the Curonian Spit, the most unique and fascinating coastal landform of the south-eastern Baltic Sea that has been shown to be the most vulnerable with respect to even such minor changes as a rotation of the approaching waves (Viška and Soomere, 2012).

The Klaipėda Strait divides this coast into two sections, a 51.03 km long compartment on the Curonian Spit and a 38.49 km long mainland section (Žilinskas, 1997). The Klaipėda Strait partially disconnects the sediment drift along the Curonian Spit further to the North. The Curonian Spit is an accumulative structure, included into the UNESCO World Heritage list, formed during intensive sand drift from the Sambian Peninsula to the North (Gudelis, 1998). The upper part of the Quaternary deposits of the spit is composed of sediment formed in the basins of various Baltic Sea development stages starting from the Baltic Ice Lake and ending with recent marine sediments (Bitinas et al., 2005). The coast of this spit has considerable amounts of fine sediment (mostly sand) on the shore and in the nearshore. This abundance is expressed as wide beaches, well developed foredunes and the presence of 1–4 sand bars in its underwater slope (Gudelis, 1998).

The mainland coast is geologically more diverse and highly affected by anthropogenic pressure. Generally sandy sediments predominate along the Lithuanian coast: from fine to coarse grained sand with appearance of gravel, pebble and boulders (Bitinas et al., 2005; Jarmalavičius et al., 2011). Consequently the offshore area of the Lithuanian coast is covered by three main lithological facies: boulders with gravel, coarse and medium sand, and fine sand. Sandy sediments prevail in the northern part of the coast while the southern part is covered by glacial (moraine) deposits that often become evident in abrasional cliffs (Bitinas et al., 2005). The mainland coast suffers from sediment deficit that is largely of anthropogenic origin and occurs mainly due to hydrotechnical constructions which intercept the nearshore sediment transport. Also, most of the underwater slope is covered by a moraine plateau that supplies only a small amount of sediments into the system.

The basic morphological features and morphometric characteristics of the Lithuanian nearshore have been comprehensively described in a number of recent studies (Janukonis, 2000; Gelumbauskaitė, 2003, 2009; Žilinskas and Jarmalavičius, 2007; Žaromskis and Gulbinskas, 2010). Regular monitoring of coastal processes and beach characteristics have been performed during several decades since the mid-1950s (Žilinskas and Jarmalavičius, 2003; Žilinskas, 2005; Jarmalavičius et al., 2011). Short-term dynamics of coastal stretches were also investigated in detail (Žilinskas et al., 1994, 2000, 2008; Mėžinė et al., 2013). All these results were generalised in a context of the entire Lithuanian Baltic Sea coast (Kirlys, 1990; Žilinskas and Jarmalavičius, 1996, 2003; Žilinskas, 2005; Jarmalavičius et al., 2011). This knowledge was complemented by several studies of physical processes driving the coastal evolution such as sea level rise (Dailidienė et al., 2006) and wave regime (Kelpšaite et al., 2008, 2011; Kriaučiūnienė et al., 2006). Long-term changes have been studied to a much lesser extent (Gudelis et al., 1990; Žilinskas, 2005; Dubra, 2006) and coastal vulnerability assessments have been performed considering