



Index based multi-criteria approach to coastal risk assesment

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Abstract

The present study focuses on the quantification of coastal risks associated with erosion and inundation accelerated by sea level rise and extreme storms events in the specific conditions of micro-tidal semi-enclosed seas. The main objective is to develop a measure that characterises climate-related external hazards, the exposure (of people and assets at risk of being damaged) and vulnerability of human and natural systems. This is accomplished by means of adaption of the concept of nondimensional coastal risk (or resilience) index (CRI), as a function of coastal vulnerability and exposure indices, to the conditions of sedimentary shores of the eastern Baltic Sea and testing its suitability for low-lying coastal zones considering their environmental and socio-economic characteristics. The study area is an about 45 km long coastal section of Lithuania in the south-eastern Baltic Sea. We introduce a set of locally relevant coastal vulnerability and exposure variables, apply an Analytical Hierarchy Process to calculate the criteria weights and GIS multi-criteria evaluation approach to calculate the CRI values. The coastal segments with high vulnerability often have low values of the exposure index. About 11% of the study area is under very high risk. The largest CRI values occur at a certain distance from the touristic or industrial spots near Klaipėda, around the Palanga pier and to the north of Šventoji. These coastal sectors are highly populated areas that suffer from sediments deficit due to coastal engineering structures.

Keywords Coastal vulnerability assessment · Coastal risk index · Climate change · GIS · Multi-criteria evaluation · AHP · Baltic Sea

Introduction

The coastal areas located in rapidly developing high-energy environments typically face high risks of disasters and vulnerability to natural and anthropogenic forcing. It is extremely

likely that coastal systems in low-lying areas will increasingly suffer from submerging, flooding and erosion throughout the twenty-first century (Hallegatte et al. 2013) and most possibly beyond, largely due to the reaction of seas and oceans to various aspects of climate change (IPCC 2014). It is already customary to build the estimates of the relevant economic losses in monetary terms (Darwin and RSJ 2011; Pycroft et al. 2016). The character and the patterns of use of the near-shore and the coastal zone are often such that classic (incl. monetary) concepts are not directly applicable and a more qualitative way of the description of severity and potential consequences of impacts is preferable. This viewpoint can be to some extent realised in terms of the quantities that depend not only on climate-related hazards but also on the exposure (of people and assets at risk of being damaged) and vulnerability (susceptibility to harm) of human and natural systems (IPCC 2014).

Recent projections of climate change indicate that by 2100, the water level will eventually rise by at least 28 cm and up to 98 cm in the World Ocean (IPCC 2014). The sea level rise in the southern and south-eastern Baltic Sea has been faster than in the neighbouring regions of the World Ocean over the last decades because of land subsidence (BACC II 2015). This applies to the shores of Lithuania where the relative sea level

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has been increasing by up to 2.9 mm/yr. (Dailidienė et al. 2006). The increase in water level extremes is apparently even faster: in the neighbouring sections of the Latvian nearshore this increase is 5–6 mm/yr. (Soomere and Pindsoo 2016). The budget of different projections of the future water level for the Baltic Sea region (BACC II 2015) leads to an estimate of the increase in the mean Baltic Sea level by 0.7 ± 0.3 m by the end of the twenty-first century. This means that the sea level rise can reach 1 m at the Lithuanian sea coast (BACC II 2015).

Rising sea levels will result in both temporary and permanent inundation. Even if coastal flooding only occurs during single storm events, it is likely that the magnitude of surges will increase on the eastern Baltic Sea shores (Soomere and Pindsoo 2016). An increase in its severity and frequency of high surges may cause damage to the property and may render the affected areas uninhabitable (Woodruff et al. 2018). The impact of this process on a particular coastal section depends on the morphology, lithological composition, and hydrodynamic regime of the affected region and also the extension of anthropogenic pressure (Žilinskas and Jarmalavičius 1996; Pranzini and Williams 2013).

The identification of the most vulnerable areas to sea level rise and other drivers supported by climate change is a key issue for nearshore communities (Ramieri et al. 2011). Different tools, such as an index or indicator-based methods, can be used to develop various approaches of coastal vulnerability assessment at various spatial and temporal scales. Such tools have an increasing demand to fulfil management purposes (Ramieri et al. 2011). Index-based approaches express the level of coastal vulnerability usually by a certain one-dimensional and generally dimensionless vulnerability index. This approach has been widely applied for tidal areas all over the world (Gornitz and White 1992; Gornitz et al. 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; Silva et al. 2017). A generalization of this approach to semi-enclosed sea areas is a non-trivial challenge (Bagdanavičiūtė et al. 2015; Benassai et al. 2015).

Even though in non-tidal or microtidal areas such as the Baltic Sea the main drivers of the coastal processes are wave impact and water level, their impact is substantially different from those on the open ocean shores. Firstly, high waves often approach the shores of semi-enclosed seas under a large angle (Soomere and Viška 2014). For this reason they cause unusually large alongshore sediment transport and associated erosion and accumulation. Secondly, high waves in the eastern Baltic Sea are usually accompanied with strongly elevated water levels (Pindsoo and Soomere 2015). As a consequence, the impact of virtually every wave storm is similar to the impact of storms in tidal areas that occur at a king tide. These two features create an environment that is quite

different from the one e.g. on the shores of the Gulf of Mexico (Bathi and Das 2016) and may substantially modify spatial patterns of classic risks associated with marine hazards in this water body (Valdmann et al. 2008).

Each of the eastern Baltic Sea countries has a multitude of planning, management and development documents (comprehensive plans, regional and tourism development strategies, adaptation plans for climate change, etc.) that fully or partially handle problems of coastal areas and seaside municipalities (Baltranaite et al. 2017). Virtually all these documents express a strong concern in increasing risk of coastal erosion and sea level rise related to the global climate change. This concern, however, is usually not accompanied by understanding the pressures affecting sustainability of the nearshore and coastal system in the broadest sense (Povilanskas et al. 2016). As ‘bending the rules’ has become a widespread practice of actors in the management and use of coastal landscape (Povilanskas et al. 2016), there is an acute need for a deeper specification of the boundaries of the currently prescribed management framework. Ernsteins et al. (2017) stress that main elements of integrated coastal zone management are well known and have been recognized in practice cases all around Baltic, but only to different degree as per different contexts and coastal issues studied. Stottrup et al. (2017) conclude that most of the integrated coastal zone management processes in eight Baltic Sea countries failed to include an integrated, cross-sectorial, ecological-socio-economic assessment. This extends from the lack of system thinking (Stottrup et al. 2017).

A feasible step forward would be to develop a meaningful joint quantification of the potential impact of external hazards, exposure to these hazards and susceptibility of the coastal community that would be able to indicate, at least qualitatively, the level of combined environmental and socio-economic risks for different coastal segments. Such quantities usually are dimensionless and do not follow the classic definition of risk as a product of the probability of an accident and its consequences. We still employ the common notion of the outcome of such a procedure as a coastal risk index (CRI) (e.g. Satta et al. 2016). In densely populated areas this quantity has the meaning of community resilience index (Qin et al. 2017). Even though this approach is not principally new, the application of this technique for coastal sections with different properties and external loads is nontrivial and requires careful consideration of the role of different indicators and forcing factors.

There are many options to develop a CRI depending on the predominant current and future hazards. The present study focuses on quantification of coastal risks associated with erosion and inundation in about 45 km long coastal section of Lithuania in the south-eastern Baltic Sea. It is natural to assume that these processes are accelerated by sea level rise and extreme storms events. This assumption is supported by extensive evidence about acceleration of the intensity of coastal

processes on Lithuanian shores (Žilinskas 2005; Jarmalavičius et al. 2016) and in adjacent sea areas (Orviku et al. 2003; Zhamoida et al. 2011; Lapinskis 2017) since the 1990s.

The main objective is to develop and test an adaptation of the concept of coastal risk index (CRI) that reflects the described specific features of the study area. To do so, we introduce a set of coastal vulnerability and exposure variables considering the basic governing characteristics of the study area. The level of coastal risk is derived from so-called coastal vulnerability (CVI) and exposure (CEI) indices by applying GIS-based multi-criteria evaluation (MCE) approach. We also make an attempt to investigate potential impact of climate change and sea level rise on the system. We believe that such an application still provides an important contribution towards developing more systemic approaches for spatial planning, risk evaluations and local developments of the coastal areas in the eastern Baltic Sea region as well as in areas with similar hydrometeorologic conditions. The core contribution is a simple way to prioritise different sections.

Study area

Most of the eastern Baltic Sea coast is a typical example of a sandy micro-tidal low lying area where sediment sources are scarce (and thus sediment deficit prevails) and sediment transport processes are mainly driven by wind induced waves and water level fluctuations (e.g., Zeidler 1997; Furmanczyk and Dudzinska-Nowak 2009). The Lithuanian part of this shore system is open to the predominant south-western, western and north-western (SW, W, NW) winds, has the longest fetch in these directions and hosts one of the severest wave climates of the Baltic Sea (Soomere and Räämet 2014; Björkqvist et al. 2018). This coastal area is exposed to significant and rapidly evolving pressures from both natural and anthropogenic drivers. During the last 100 years, the average water level in the study area has risen by about 15 cm (Dailidienė et al. 2004, 2006). It is likely that the water level extremes have increased by a much larger amount (cf. Soomere and Pindsoo 2016).

Simulations of wave-driven alongshore sediment transport indicate that the wave-driven sediment flux has mostly divergent character in the nearshore of Lithuania (Viška and Soomere 2013). Relatively weak convergence is only observed near the tip of the Curonian Spit and in the northernmost section of the Lithuanian Baltic Sea shore. This pattern basically determines the alongshore variation in the coastal erosion or accumulation rate. It is governed by the combination of the geographical position (orientation of the coastline) of the study area and the wave height and predominant propagation direction (Žilinskas 2005; Kelpšaitė and Dailidienė 2011; Bagdanavičiūtė et al. 2012). The simulated structure of sediment flux matches the observations of erosion and

accumulation on the coasts of Lithuania. The likely increase in storminess (Alexandersson et al. 2000) apparently will increase the impact of wave and water level rather than alter this pattern.

A natural conjecture from these features is that in the long-term run this area is expected to be highly vulnerable to climate change effects primarily associated with the sea level rise and enhanced sediment relocation and coastal erosion (Žilinskas and Jarmalavičius 2007; Hünicke et al. 2015). The area has already been subject to significant coastline changes in the recent past (Žilinskas 2005; Jarmalavičius et al. 2012; Bagdanavičiūtė et al. 2012). These changes have a different nature. For example, next to Šventoji the shoreline has moved seawards by 179 m in 50 yrs. (Bagdanavičiūtė et al. 2012). Coastal retreat is observed more frequently and particularly after strong storms. The waterline was relocated inland by 30 m during storm Anatolij in 1998 at Palanga (Žilinskas et al. 2000). Such rates of relocation are very large in the context of the Baltic Sea (Pranzini and Williams 2013) and indicate the possibility of instability of the coastline under the impact of high waves that approach the shore under large angles (Ashton et al., 2001). The described processes are strongly affected and modified by several kinds of anthropogenic interference such as intensive dredged spoil dumping, beach nourishment and building of hard coastal engineering structures. For example, significant modifications to the entrance of the Curonian lagoon have additionally affected the nearshore sediment transport in the vicinity of Klaipėda.

Our study area is located in the central part of the eastern Baltic Sea coast. It consists of approx. 45 km long coastal stretch from south to north along the Curonian Spit and the mainland (Fig. 1). Its landscape is formed of Quaternary deposits. The shore belongs to the accumulative-abrasive coastal type. The major sources of sediment are the nearshore bottom and the Sambian Peninsula (Gudelis 1998; Bitinas et al. 2005; Jarmalavičius et al. 2012). Sandy sediments (optionally containing a certain amount of gravel, pebble and boulders) that are usually numerous times reworked by waves prevail on the mainland coast, while glacial (moraine) deposits are exposed in abrasional cliffs in the central part (Bitinas et al. 2005; Jarmalavičius et al. 2012).

The amount of sediment is limited along most of the study area. Most of the underwater slope is covered by a moraine plateau that supplies only a small amount of sediments into the system. The overall continuity of the sandy coast is interrupted by several river outlets. Several sections of the mainland coast suffer from serious sediment deficit that occurs mainly due to hydrotechnical constructions intercepting the nearshore sediment transport. The largest amount of fine sediment is found on the Curonian Spit. This landform is included into the list of the UNESCO World Heritage sites and has considerable amounts of fine sediment (mostly sand) on the shore and in the nearshore. The predominant accumulation processes in the

Lithuanian section of the spit (at least in the past) are reflected via the presence of wide beaches, well developed foredunes and up to four sand bars on the active part of the underwater slope (Gudelis 1998).

The study area includes nine coastal settlements units within three municipalities. The mainland coast is highly populated (171,494 inhabitants, approx. 6% of the total population in Lithuania) compared with the Curonian Spit (3069 inhabitants). Coastal resorts Palanga and Šventoji are located at sandy beaches and account for 121 thousand beds in the official accommodation establishments (19.5% of country's total). Approx. 275.6 thousand of tourists (10% of country's total) were reported to use these accommodation establishments in 2016 (Lithuanian Census data 2017). As the above number only reflects those who have reported to the local tourist office and about 50–70% of the visitors typically stay in the private sector, the actual number of visitors to this part of the seashore apparently is at least by an order of magnitude larger (Žilinskas and Eidikonienė 2012). Lithuanian tourism sector creates around 5.3% GDP and Palanga resort is the most popular among others tourist destinations (Lithuanian Census data 2017). The seaport Klaipėda with population density of 1677 inhab./km² (Lithuanian Census data 2017) accounts for 6.2% of country's GDP due to port industry only.

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The Smiltynė district of Klaipėda located on the Curonian Spit meets over two million visitors annually (Lithuanian Census data 2017). Coastal municipalities have approx. 300 objects of archaeological, architectural and art heritage (most of them in Klaipėda). Seven objects of environmental heritage (springs, hills, moraine cliffs) serve as major attractions for tourists. Much of this massive business and recreational industry relies on the beauty and attractiveness of the highly vulnerable environmental heritage and beautiful seashore that is exposed to various anthropogenic pressures such as tourism, various types of pollution or construction of coastal engineering structures. It is therefore vital to adequately estimate and quantify the level of vulnerability of different sections of this coastal area with respect to the major impacts. An index-based multi-criteria approach apparently is a suitable tool for this purpose.

Material and methods

In this study, the coastal risk assessment consists of an index-based multi-criteria approach dealing with qualitative and quantitative spatial attributes. Elements of the assessment represent both environmental (incl. Physical properties) and

socio-economic variables of the coastal system. The assessment developed in this study does not take into account the vulnerability of coastal communities because the risk of a collapse of an entire community or its strategic infrastructure (e.g. via a major hurricane) is very low in the present hydro-meteorological conditions.

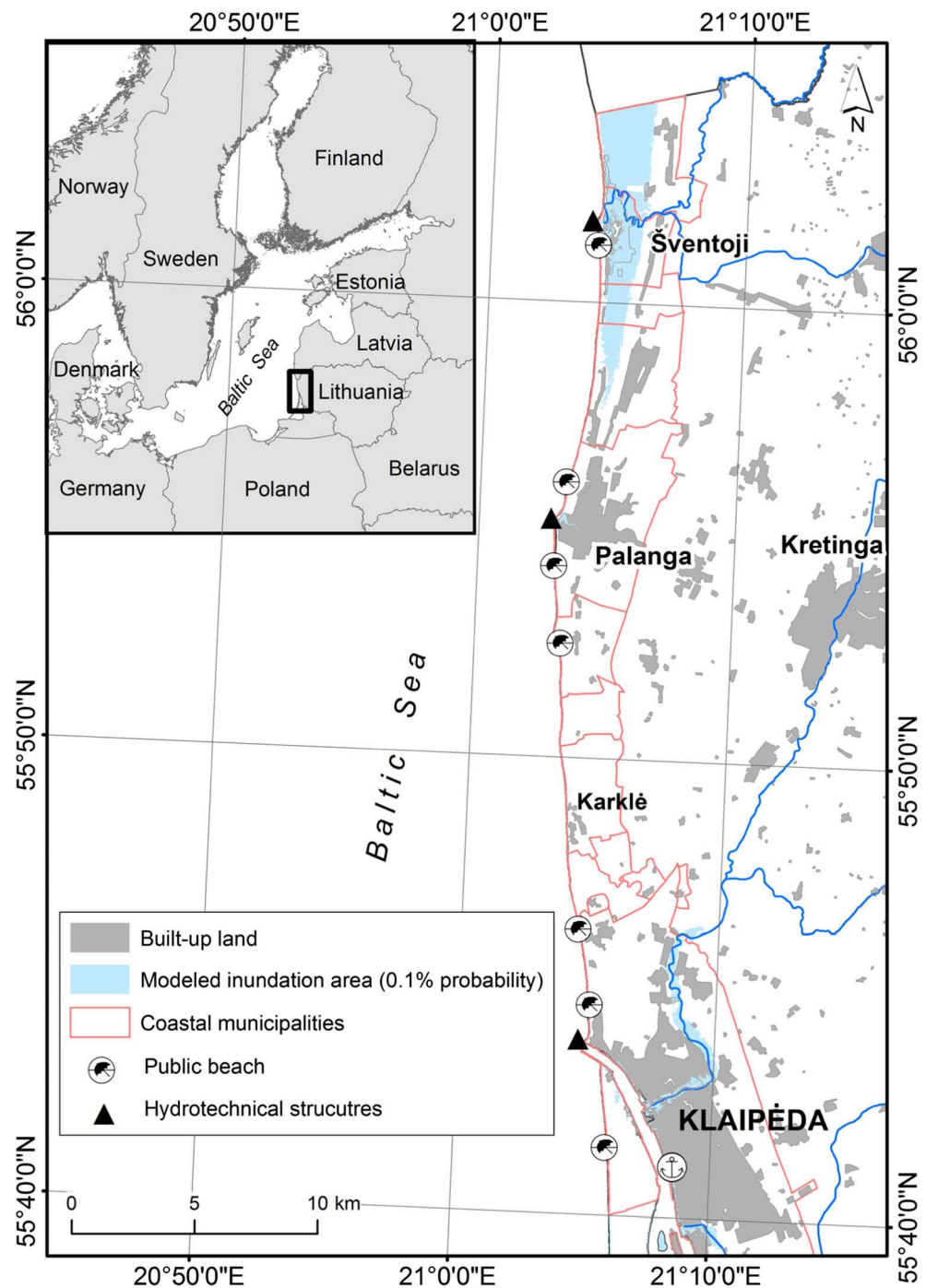
The coastal risk index (CRI) integrating the multi-criteria evaluation approach is used as a basis for the risk assessment of micro-tidal low-lying Lithuanian coast. The CRI provides a simple numerical basis for ranking coastline sections in terms of their potential alteration under climate change and helps managers to identify and display regions of higher risks (Satta et al. 2017). The CRI is considered as a function of two measures: coastal vulnerability (CVI) and exposure (CEI) (Figs. 1 and 2). A multi-criteria CRI assessment consists of the following major steps: (1) the identification of the environmental criteria representing coastal characteristics and significant driving processes that influence the coastal vulnerability and the coastal evolution; (2) the identification of socio-economic criteria exposed to impacts of climate change; (3) the ranking and reclassification of criteria to compile criteria maps; (4) an application of an Analytic Hierarchy Process (AHP, Saaty 1980) to assess the relative importance (weights) of the criteria; (6) the calculation of CVI, CEI, and CRI; (7) the compilation of vulnerability, exposure and risk maps and hotspot analysis.

Coastal vulnerability index (CVI)

The level of coastal vulnerability was evaluated by modifying the coastal vulnerability index (CVI) (Gornitz and White 1992; Gornitz et al. 1994; Pendleton et al. 2004). The original geologic and physical criteria of the CVI for tidal ocean coasts were revised considering specific litho-morphodynamic features of the micro-tidal low-lying study area (see Bagdanavičiūtė et al. 2015 for details). The CVI assessment relied on the main characteristics of the coast. In essence, it describes coastal susceptibility to erosion and includes the historical shoreline change rate (HSC), beach width (BW), beach height (BH), beach sediment (BS), inclination of the underwater slope (US), number of sand bars (SB) and significant wave height (SWH) as the climate forcing criteria (Table 1).

Data for each vulnerability criteria were gridded into 500 × 500 m resolution cells along the coastline and analysed using the ArcGIS 10.3 software. The HSC was assessed using the Digital Shoreline Analysis System (DSAS) (ver. 4.2) software (Thieler et al. 2009; Fletcher et al. 2012). The average rate of shoreline change (m/yr) within the selected time period was described by the End-point rate (EPR) statistical parameter. It was calculated for each transect spaced 500 m apart, by dividing the distance of shoreline relocation by the time elapsed between the instants of scanning of the earliest and the most recent shoreline.

Fig. 1 Location of the study area



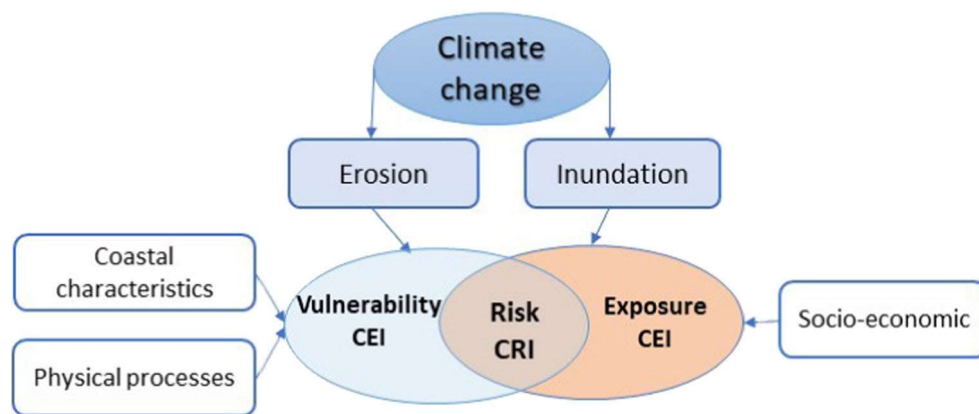
The properties of wind waves for the typical and extreme meteorological conditions were modelled using the SWAN model (Delft University of Technology, www.swan.tudelft.nl). The wind parameters from 2006 to 2009 were used as the model input. The model bathymetry with a 500 m horizontal resolution was created from the so-called Warnemünde topography (Seifert et al. 2001) of the offshore area by augmenting it with a more recent description of the nearshore bathymetry (Bitinas et al. 2005) and in situ

measurements from 2012 (unpublished data). The 90 and 95 percentiles of the mean and maximum significant wave height at a depth of 10 m were used for each transect.

Coastal exposure index (CEI)

The coastal exposure was assessed considering socio-economic criteria, describing targets potentially at risk by flood hazard (McLaughlin et al. 2002; McLaughlin and

Fig. 2 Workflow scheme



Cooper 2010; Satta et al. 2016, 2017). The CEI relied on population density (PD), built-up land (BL), cultural heritage (CH), tourist spots (TS) and beach facilities (BF). Flood hazard maps (1 × 1 m resolution grid) were developed by hydrodynamic models using water level, detailed bathymetry and LIDAR elevation data, and delivered in ESRI GRID format (Environmental Protection Agency 2014).

The created flood hazard maps, in essence, provide information about land level in the context of probabilities of different high water levels or their return periods. They included potentially flooded areas for the low probability flood (0.1%) scenario. The uncertainty of the modelled water level in coastal flood maps exceeds 10 cm. The exposure criteria BL, CH, TS and BF were assessed for the low probability flood (0.1%) scenario.

To define the most attractive and the most visited tourist spots on the coast, we downloaded 6443 geolocated photographs covering the coastal municipalities of the study area from the Google Earth (by 12/01/2017). The geographical coordinates of each photograph were used to create a point layer. The PD, BL and TS data sets were merged for coastal municipalities and approximated to single coastal sectors.

Criteria ranking and weighting

The quantitative and qualitative values of each criteria were standardized according to the vulnerability/exposure levels in the range from 1 to 5 (from very low to very high vulnerability/exposure, respectively) (Table 2). Since environmental and socio-economic criteria may have different contributions to the overall vulnerability and exposure, the multi-criteria evaluation (MCE) approach was employed to calculate the relative importance (weights) of single criteria. The MCE was performed using the Super Decisions software (Creative Decisions Foundation) based on the Analytic Hierarchy Process (AHP) (Saaty 1980).

Four experts, all internationally renowned scientists with the background in the coastal processes and familiar with the situation in the entire study area, were involved into a comparative judgment. Their role was limited to the identification of the criteria used in the analysis and to the estimates of the relative importance of single criteria. A pairwise comparison was performed following Saaty (1980) approach, where criteria are rated against each other using a scale of relative importance (from equal (1) to extreme preference (9)). The weights were determined by normalizing the eigenvector associated with the maximum eigenvalue of the reciprocal ratio matrix (Malczewski 1999). The consistency ratio (CR) (Saaty 1980, 1996) was used to assess consistency of expert judgements. The values $CR \geq 0.1$ indicate an adequate evaluation of the criteria and acceptable results whereas $CR < 0.1$ denotes an inconsistent judgment of a matrix. In cases of inconsistency, the original values in the pairwise comparison matrix were revised.

Calculation of CVI, CEI and CRI

The assessment of the CVI and CEI was based on the aggregation of the weighted criteria. We used the Weighted Linear Combination (WLC) (Malczewski 2000) method to estimate the CVI and CEI indices according to the expression:

$$CVI_i = \sum_{j=1}^n w_j \cdot v_{ij} \quad (1)$$

where CVI is the vulnerability/exposure index for a given area, w_j is the weight of criterion j , v_{ij} is the vulnerability score of area i under criterion j and n is the total number of criteria.

The aggregated CRI was calculated as follows:

$$CRI = \frac{(CVI + CEI)}{2}. \quad (2)$$

Table 1 Criteria descriptions and data sources used for the coastal risk assessment

Criteria	Description	Data source
Historical shoreline change rate (HSC)	HSC represents rearrangement of beaches over time and highlight the most heavily impacted coastal sectors ¹	Aerial photos ² , orthophotos and topographic maps ³ (1984–2013)
Beach width (BW) and beach height (BH)	A wide beach acts as a buffer, dissipating wave energy and serving a temporary source of mobile sediments to be redistributed across the coastal zone during storms. The wider beach has greater capacity to dissipate wave energy and reduce the impacts of extreme weather events ⁴	Beach profiling 2011–2012 ⁵
Underwater slope (US) and sand bars (SB)	SB defend the coastline and prevent from sediment loss by absorbing and dissipating wave energy as well as gradually supplying beach with sediment. Flat US supports it higher capacity to dissipate wave energy and reduce the wave impacts to the shoreline.	Bathymetry map (scale 1:5000) ⁶
Beach sediments (BS)	BS are directly affected by physical processes. As waves break the swash sweeps sediment up on to the beach, while backwash tends to carry it back. Permeable gravel and coarse sand beaches retain backwashed sediment and diminish backwash rates more efficiently compared to fine sand beaches ⁴	In situ sediments sampling 2011–2012 ⁵ , Geological map (scale 1:5000) ⁶
Mean significant wave height (MWH)	MWH is used as a proxy for wave energy, which drives the coastal sediment budget.	SWAN model (2006–2009)
Population density (PD)	Densely populated areas are generally associated with an increased economic value and higher antropogenic pressure on the coast than low population density areas.	Lithuanian Census data (2017)
Built-up area (BU)	BU shows the level of social and economic population activity in the area. BU is used to derive urban areas and settlements at risk by flood within coastal municipality boundaries	Orthophotos (2013), Georeferential database GDR10LT (1: 10,000) (2013)
Cultural heritage (CH)	CH includes archaeological and historical monuments, which form part of the cultural resource and are irreplaceable. ⁷ CH is used to derive heritage areas at risk by flood.	Cultural heritage register (2017)
Tourist spots (TS)	The records of geolocated photographs were used as a proxy for sightseeing spots and spatial patterns of tourist flows ⁸	Google Earth (2017)
Recreational facilities (RF)	RF support tourism, recreation and residential developments and reflect the level of social-economic activity at the coast. The greatest concentration of visitors arises along the main roads towards the sea, but also where the objects of recreational infrastructure are concentrated: car parking, catering and sanitary facilities, children's playgrounds, rescue stations and etc. ^{9,10}	Georeferential database GDR10LT (1:10,000) (2013)

¹ Hapke et al. 2010; ² Lithuanian Geological Survey; ³ National Land Service of Lithuania 2010; ⁴ Davidson-Arnott 2010; ⁵ Bagdanavičiūtė et al. 2015; ⁶ Bitinas et al. 2005; ⁷ McLaughlin et al. 2002; McLaughlin and Cooper 2010; ⁸ Salas-Olmedo et al. 2018; ⁹ Peña-Alonso et al. 2017; ¹⁰ Žilinskas and Eidikonienė 2012

Compilation of vulnerability, exposure and risk maps

The calculated values of CVI, CEI and CRI were ranked into five categories according to the ArcGIS equal intervals classification. The maps of CVI, CEI and CRI values were compiled as the final output.

The spatial statistic tool Hot Spot Analysis (ArcGIS) which uses the Getis-Ord Gi* algorithm (Getis and Ord 1992) was applied to determine statistically significant hot-spots according to the obtained set of CRI values. The hot spot analysis allows the calculation of the so-called Z score to identify statistically significant hot spots (i.e. clusters of cells with high vulnerability values) and cold spots (i.e. clusters of cells with low vulnerability values) (Mitchell 2005). To become identified as a statistically significant hot spot, a cell should have a high level of vulnerability and be surrounded by other cells with similarly high values of vulnerability. The *p*-values <0.01 (that is, the formal statistical significance at a 99% level) and Z-score values outside the range ± 2.58 (Mitchell 2005) were

used to identify significant hotspots and coldspots from the CRI analysis. The spatial relation called “zone of indifference” was selected for Hot Spot Analysis.

Results

Due to the different spatial resolutions of coastal vulnerability (500 m) and exposure indices (based on data aggregated for administrative units), the final output largely serves for regional scale decision-making rather than detailed local interpretations.

Coastal vulnerability index (CVI)

In the CVI assessment, the highest relative weights were assigned to the SB and HSC criteria (Table 3). As discussed above, we divided the calculated CVI values (1.72–4.41) into five vulnerability classes (Table 4). Approximately

Table 2 Ranking of vulnerability and exposure criteria for assessment of coastal vulnerability index (CVI) and coastal exposure index (CEI)

Criteria	Units	Rank				
		Very Low 1	Low 2	Moderate 3	High 4	Very High 5
CVI						
Historical shoreline change rate	m/year	> 1	0.3–1	–0.3–0.3	–0.3––1	< –1.0
Beach width	m	>60	40–60	30–40	20–30	<20
Beach height	m	>4	3–4	2–3	1–2	<1
Beach sediments	type	Sand/pebble/morainic loam/boulders	Sand/gravelly sand/gravel/pebble	Sand/gravelly sand/sand with gravel	Sand	Sand/ peat/ sapropel
Underwater slope	tan α	>0.0005	0.0005–0.001	0.001–0.008	0.008–0.01	>0.01
Sand bars	number	>4	3	2	1	0
Mean significant wave height	m	<0.5	0.5–0.6	0.6–0.7	0.7–0.8	>0.8
CEI						
Population density	inhab./km ²	0–10	10–25	25–100	100–250	>250
Built-up area	km ²	0	0–0.001	0.001–0.01	0.01–0.1	>0.1
Cultural heritage	–	absence				presence
Tourist spots	number of photos	0–25	26–100	101–250	251–700	>700
Recreational facilities	–	Access by bike, on foots >1 km from roads, no parking	Access by private transport, parking at distance >500 m, no services and amenities	Access by private transport, parking at distance <500 m, limited services and amenities	Accessible by public transport, parking, safety and rescue service, limited service and amenities, semi-urban area	Accessible by public transport, parking, safety and rescue, service and amenities, urban area

Table 3 Significance weighting of the criteria

CVI	Weight	Rank	CEI	Weight	Rank
Historical shoreline change rate	0.277	2	Population density	0.335	1
Underwater slope	0.052	5	Built-up area	0.304	2
Beach width	0.112	4	Cultural heritage	0.131	3
Beach height	0.046	6	Tourist spots	0.116	4
Sand bars	0.297	1	Recreational facilities	0.114	5
Beach sediments	0.036	7			
Wave height	0.179	3			
CR	0.04		CR	0.00	

50% of the coast was assigned to the high and very high vulnerability class, 39% was of moderate and 12% of low or very low vulnerability (Fig. 3). Coastal sectors with a low vulnerability are located mostly in the southern part of the study area (Fig. 4). The relevant coastal sections have considerable amounts of fine sediment on the shore and in the nearshore and/or often host convergence areas of the wave-driven alongshore sediment transport (Soomere and Viška 2014).

In contrast, sectors with high vulnerability mostly occur in the mainland part of Lithuania where the coastal system often suffers from sediment deficit. Unexpectedly, a relatively long section next to the Latvian border belongs to this category. This section appears in the analysis of Viška and Soomere (2013) as a frequent location of convergence of sediment flux. Potential reasons for this outcome are that the underwater slope of this sector is covered by a moraine plateau that supplies only a small amount of sediments into the system and the impact of coastal engineering structures at Šventoji that block the overall sediment transport to the north. Another longer highly vulnerable coastal section according to the CVI values near Karkle and between Giruliai and Melnragė evidently reflects an almost permanent region of divergence of simulated wave-driven alongshore sediment flux to the north of Klaipėda (Viška and Soomere 2013; Soomere and Viška 2014). A hot-spot of high vulnerability according to CVI immediately to the north of the pier at Palanga is evidently caused by the presence of this pier and groins nearby.

The CVI assessment revealed that none of the coastal sections was characterized exclusively by very high or very low vulnerability according to all seven criteria. The highest CVI values were obtained for coastal sectors that were highly vulnerable according to at least three criteria. Such a situation, when different criteria provide contradicting information about a single coastal section, occurs frequently in the environmental multi-criteria assessments (e.g., Mosadeghi et al. 2009).

Coastal exposure index (CEI)

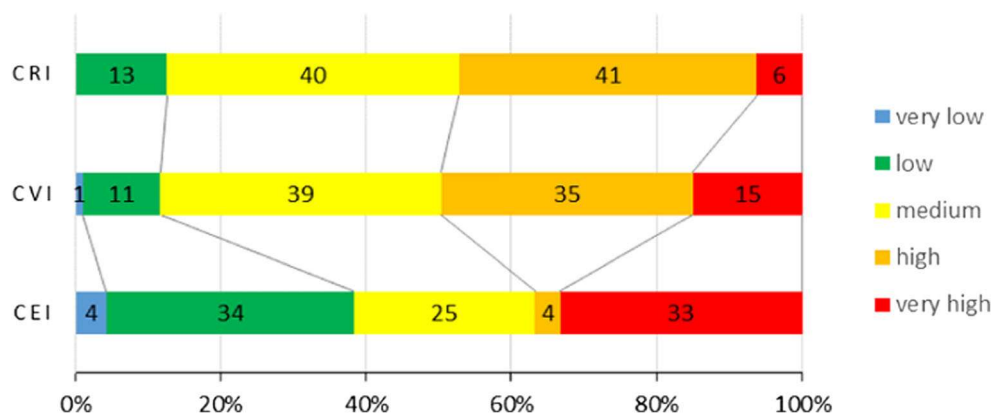
The highest relative significance among the socio-economic criteria was obtained for population density and built-up land (Table 3). The calculated CEI values ranged from 1 to 4.7. The results indicate a relatively even distribution of different exposure levels. About one-third of the coast (37%) has very high and high exposure values. The remaining 38 and 25% of the coast correspond to very low/low and moderate risk classes, respectively (Table 4, Fig. 3).

Coastal sectors with a low vulnerability are fragmented along the entire study area (Fig. 5). They are associated with lower than 25 inhab./km² population density and are characterized by a complicated access to beach. These aspects greatly diminish the relevant fluxes of tourists in these spots. The characteristic sections are located in the northernmost section of the study area (that was the hot spot according to the CVI assessment) and in the Giruliai–Karkle region. In contrast, sectors with very high exposure mostly occur in the highly

Table 4 Coastal vulnerability index for levels of vulnerability, exposure and risk

Vulnerability/ exposure/risk class	Index range	CVI		CEI		CRI		Hot spot	
		Length (km)	%	Length (km)	%	Length (km)	%	Length (km)	%
Very low	1.00–1.74	0.5	1.1	2.0	4.3	–	–		
Low	1.74–2.48	4.8	10.6	15.3	34	5.7	12.6		
Moderate	2.48–3.22	17.6	38.7	11.3	24.9	18.2	40.2		
High	3.22–3.96	15.7	34.6	1.6	3.5	18.5	40.9		
Very high	3.96–4.7	6.8	15.0	15.0	33.3	2.8	6.3	5.17	11.4

Fig. 3 Histogram of the percentage of shoreline in each vulnerability (CVI), exposure (CEI) and risk (CRI) category



populated zones and areas of high recreational importance next to major cultural heritage sites such as Palanga, Šventoji and the coastal segment immediately to the north of Klaipėda.

Not unexpectedly, the coastal segments with high values of CVI often have low values of CEI. This feature simply reflects the difference in the associated viewpoints to the properties and functioning of the coastal area. Only the shores of the Curonian Spit have low values of both CVI and CEI. In contrast with the above, the CEI assessment revealed more consistent behaviour of the criteria. A wider interval of CEI values (1–4.7) indicated the presence of “very low” exposed coastal sectors under all five criteria. Similarly, the highest CEI values were obtained by the aggregation of four criteria having “very high” exposure level.

Coastal risk index (CRI) and hot spots

The performed analysis resulted in an amalgamated map of coastal risks (Fig. 6). This map first of all shows the areas at risk of coastal erosion and coastal flooding. A combination of the CVI and CEI estimates resulted in a narrower interval of CRI values compared to its constituents. The nondimensional risk values (in the scale from 1 to 5) for single sectors of the study area range from 2.1 to 4.4. The larger minimum evaluated levels of the CRI values compared to similar CVI values reflect a systematic (albeit fully natural) mismatch of environmental and socio-economic criteria. As a result, none of the coastal segments belongs into a very low risk class in the final output (Table 4, Fig. 3). In other words, even the smallest CRI values (around 2.1) express relatively high risk level. Therefore there are evidently no coastal segments of the study area that have very low risk. Consequently, only four risk classes were defined in the final map.

Nearly half of the coastal sectors are represented by very high and high risk levels (47% in total), while low risk values comprised only 13% of the coast (Fig. 3). Coastal sectors with a low risk are located mostly in the southern part of the study area (on the shore of the Curonian Spit) where both coastal

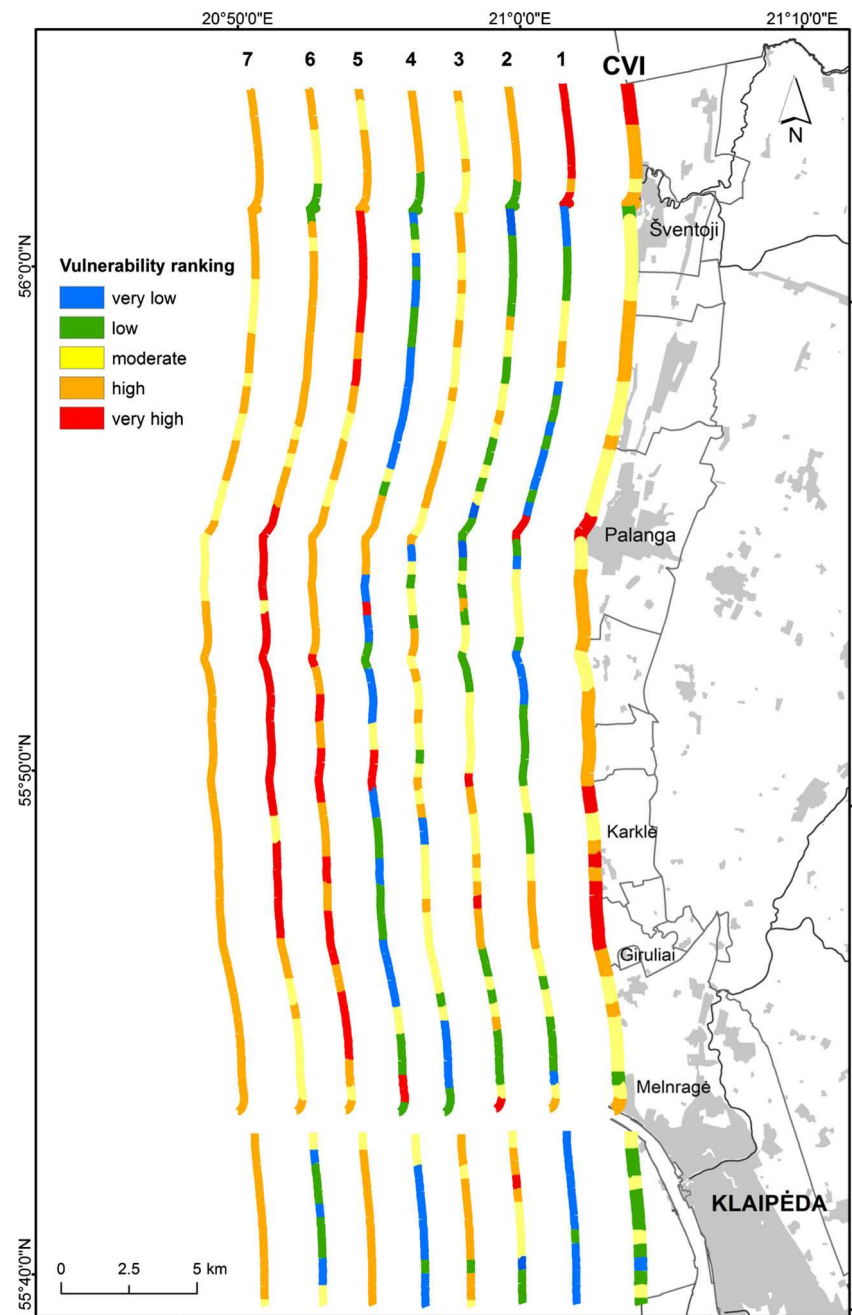
vulnerability and exposure levels are low or moderate (Fig. 6). Another segment of low risk is located between Karkle and Palanga. Zones of very high risk (6% of the entire length of the study area) are associated with spots of high anthropogenic pressure (dense population, tourist flows and close proximity of hydrotechnical structures). The maximum values of CRI appear for a short section next to the northern breakwater of the Klaipėda Strait (where the coastal engineering structures block the sediment transport), to the north and south of the Palanga pier (where the impact of this pier on sediment transport is combined with high population density) and to the north of Šventoji because of similar reasons. These coastal sectors are characterized by a high erosion rate, narrow beaches, and absence of sand bars and overall scarcity of sediment supply.

The results of the hot spot analysis identified fragments of statistically significant hot-spots along the entire mainland coast. These results were highly consistent with the spatial pattern of CRI values (Fig. 6). The identified hot spots occupy 11.4% of the coast. They correspond to very high risk zones assessed by the CRI, although the total coverage of the CRI-based high risk zones is about half of the above (6.3%, Table 4).

Discussion

This study is partly based on recently established coastal vulnerability assessment methodology (Bagdanavičiūtė et al. 2015). The core idea is to aggregate the cumulative CVI scores to identify highly vulnerable coastal sites. However, in contrast to the earlier study, the integration of socio-economic criteria into the calculation of the coastal exposure considerably extends the scope of the coastal risk assessment and creates an option of systematically involving the impact of possible climate change impacts on community assets. The effects driven by climate change (and included into this study) are still mainly attributed to the sea level rise and include increased beach erosion, inundation of low-lying areas, increased flooding and storm damage (IPCC 2014; Nicholls et al. 2014).

Fig. 4 Relative coastal vulnerability in respect of (1) historical shoreline change, (2) beach width, (3) beach height, (4) beach sediments, (5) underwater slope, (6) sand bars, (7) significant wave height and overall CVI



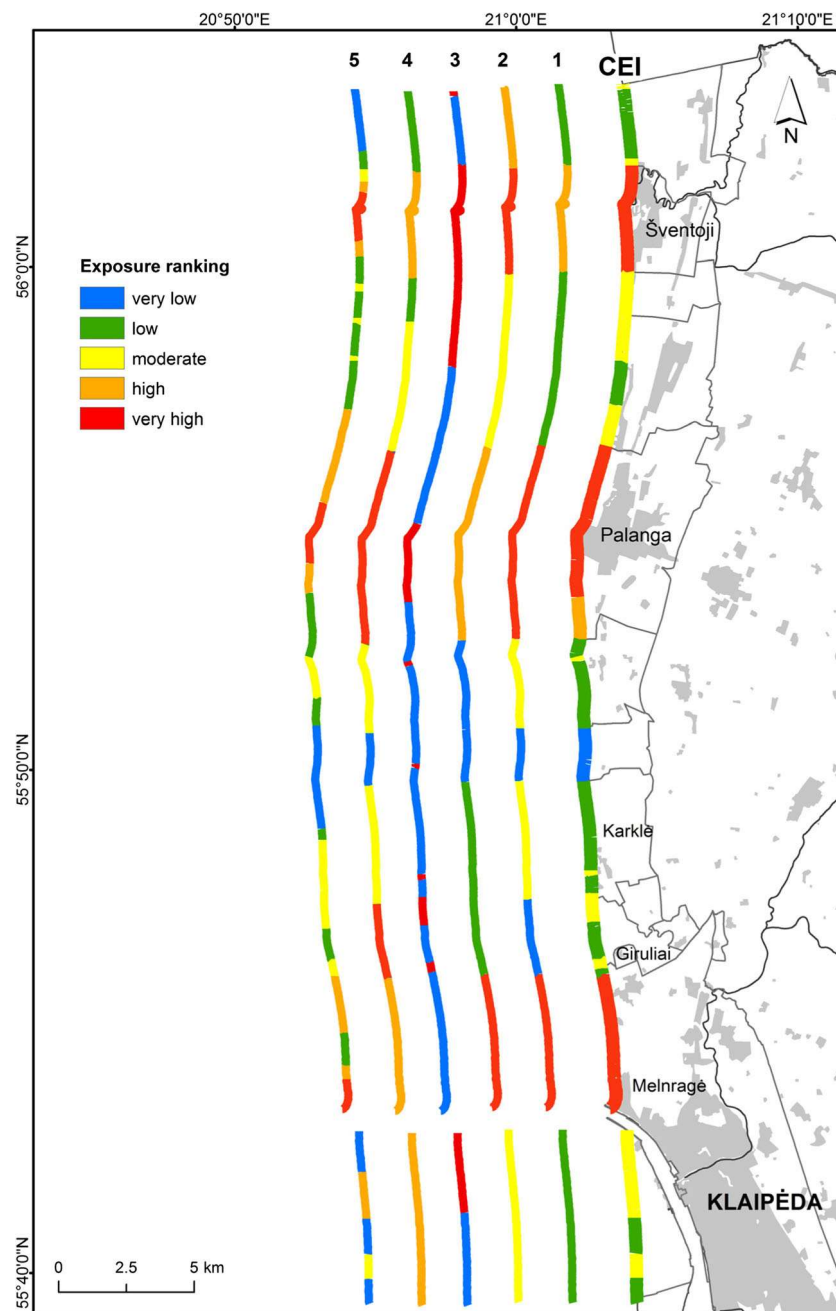
The potential impact of higher water tables and saltwater intrusion into aquifers later is less important for the brackish central Baltic Sea (in particular, in the conditions of excess of precipitation over evaporation in the entire region) and was not addressed in this study.

The MCE relative weights were integrated into the assessment in order to boost the contribution of the most important criteria and reduce the contribution of others. Doing so also makes it possible to reduce the inconsistency of contradicting characteristics. The MCE method makes weighting and the entire decision-making process more clear and transparent. The ability of the MCE to integrate independent and partially

contradicting expert opinions as well as to convert qualitative information into quantitative weights makes it beneficial for coastal vulnerability studies.

Even though the outcome of the performed CVI analysis for micro-tidal semi-enclosed areas is mainly based on simple and directly measurable geological criteria, it still largely matches the recommendations of much more detailed and resource-demanding studies (Mėžinė et al. 2013; Soomere and Viška 2014). These studies focused on the properties of wave-driven processes. They ignored several important features of the coast that may substantially alter the vulnerability of single coastal sections such as the supply of sediment from

Fig. 5 Relative coastal exposure in respect of (1) population density, (2) built-up land, (3) cultural heritage, (4) tourist spots, (5) recreational facilities, and overall CEI



ivers, the impact of contemporary coastal engineering structures, cliff erosion, beach nourishment activities and along-shore variations in the properties and availability of fine sediment.

Importantly, our results indicate that the hottest spots of vulnerability do not necessarily follow the structural features of wave-driven sediment transport or the locations of the largest anthropogenic loads. Many hydrotechnical constructions in this area generate additional anthropogenic pressure on single coastal segments (Žilinskas and Jarmalavičius 1996; Žilinskas 2008). Similarly to many other areas of the World Ocean their impact is asymmetric and becomes evident in the

context of the direction of wave-driven sediment flux. The coastal sectors at a highest risk are highly populated and attractive to tourists, but permanently suffer from sediments deficit mainly due to hydrotechnical constructions which intercept the nearshore sediment transport (Žilinskas and Jarmalavičius 1996; Dubra 2006; Dubra et al. 2011; Žilinskas 2008; Eidikonienė and Žilinskas 2011a, 2011b; Žilinskas and Eidikonienė 2012).

The shores of the Baltic Sea are shaped by the combination of the intermittent wave climate and occasionally occurring high surges (Hünicke et al. 2015). Their joint impact results in a step-like evolution of many beaches. The beaches evolve

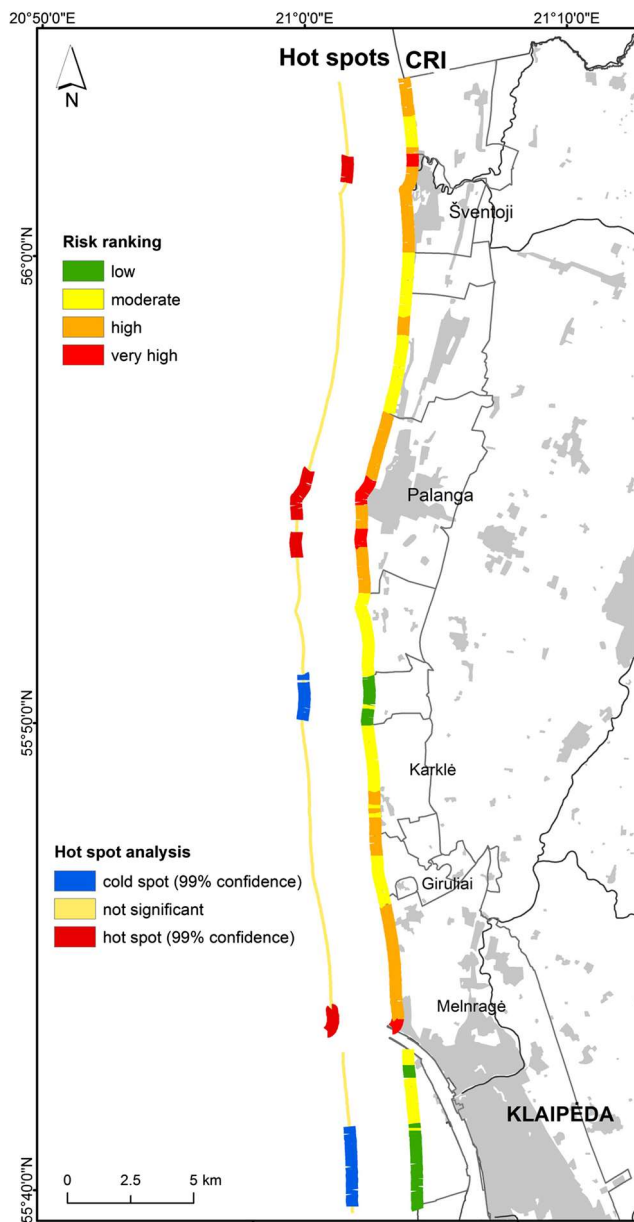


Fig. 6 Coastal risk index and hot spot analysis map

rapidly during infrequent events when high waves occur simultaneously with high storm surge. These cases occur usually less than once in several years. The evolution during rest of the time is very slow (Kartau et al. 2011) and beaches are in almost equilibrium during quite long time intervals (Soomere and Healy 2011).

The geological and geomorphic criteria used in our approach describe relatively well the “health” of such beaches during these long time intervals. During the last 100 years, the water level in the study area has risen by about 15 cm (Dailidienė et al. 2004, 2006). A rough estimate of the shoreline retreat for a sandy beach owing to the water level rise can be obtained using Bruun’s rule (Dean and Dalrymple 2002). The average slope of the active beach profiles (down to the

20 m isobath) is about 1:120 in the study area (Gudelis 1998). The expected shoreline retreat should thus have been about 15–20 m on average in natural conditions. This definitely has not happened (Jarmalavičius et al. 2013).

Apart from the stabilising impact of various coastal engineering structures and implementation of beach nourishment techniques, this mismatch suggests that there still is a significant sediment flow into the Lithuanian nearshore from adjacent coastal areas of the Baltic Sea. Hence, potential threat of straightforward inundation caused by sea level rise on the Lithuanian coast is negligible, but erosion processes accelerated by an elevated water line (and possibly under very high water levels, Soomere and Pindsoo 2016) can still have a significant negative impact.

The number of people in important tourist destinations exposed to the aforementioned physical vulnerabilities is much higher than just the count of the residents (Lins-de-Barros 2017). In turn, intense tourism brings more pressure on the surrounding environment and natural resources. It is thus not surprising that the most populated tourist destinations and well developed coastal areas in the study area are the sites of high exposure and elevated risk at the same time. This feature makes the issues of coastal adaptation in touristic regions to climate change an extremely complicated subject that requires the attention of the government, coastal municipalities and authorities, coastal dwellers and other stakeholders (Boateng 2012).

The interpretation of the risk level partly depends on the classification method of the data set in use and can affect the appearance of risk distribution in the final output maps. This drawback is, however, not particularly important as first of all the relative *variations* in the values of the indices between different coastal sections contain the core information about which sections are more at risk than others. Our results suggest, however, that the hot spots of the coastal risk index are located at a certain distance from the centre of the touristic or industrial spots. This feature leads to an important message in terms of management and planning: the coastal segments immediately adjacent to tourist or industrial centres may need even more attention than the centres themselves. This calls for associated changes in the coastal management and planning of protective measures to cope with the demonstrated spatial structure of the coastal risk index. It is likely that part of this structure is caused by the use of “hard” coastal protection measures to prevent loss of land and that the use of soft beach replenishment methods might avoid such a structure (Pupienis et al. 2014).

Finally, the results of this study are generally consistent with the outcome of other similar studies (Mosadeghi et al. 2009; Oropeza-Orozco et al. 2011; Le Cozannet et al. 2013; Sahin and Mohamed 2013; Wang et al. 2014, among many others). Even though the vulnerability and exposure ranking and weights of different criteria are chosen or developed in

different ways, the combined use of CVI and CEI approaches into an amalgamated CRI leads to a fresh view of the functioning and potential problematic hot spots of various coastal segments.

Conclusions

This research demonstrates an application of the multi-criteria framework to construct a meaningful coastal risk index that integrates physical, socio-economic and environmental data related to climate change for semi-sheltered water bodies. By applying the multi-criteria evaluation approach, we defined a set of coastal vulnerability and exposure indicators that characterise coastal segments with a negligible tidal range but often affected by storm surges. The method relies on easily measurable geological and geomorphological parameters of the beaches and socio-economic properties (based on local population and tourist activities) of coastal administrative units.

The presence and number of sand bars, the historical shoreline change rate and population at risk were considered as criteria of major importance. The relative coastal vulnerability and exposure is quantified for the Baltic Sea shores of Lithuania with a resolution of 500 m. The coastal segments with high vulnerability often have low values of the exposure index. About 15% of the study area is highly vulnerable. Zones of very high risk form 6% of the study area. The locations of the largest values of the coastal risk index are associated with high anthropogenic pressure but are located at a certain distance from the centres of the touristic or industrial spots.

Very large values of the coastal risk index appear in a short section next to the northern breakwater of the Klaipėda Strait, to the north and south of the Palanga pier and to the north of Šventoji. These coastal sectors are highly populated and attractive to tourists, but permanently suffer from sediments deficit mainly due to coastal engineering structures that intercept the nearshore sediment transport. The output maps are useful to identify areas where physical changes are most likely to occur at sea level rise as well as a planning tool for coastal management and protection.

In essence, we demonstrate that the integration of the GIS and multi-criteria evaluation methods is appropriate and relevant for tasks of spatial planning and environmental protection that require an adequate estimate of risk levels in the low-lying and erosion-prone nearshore area. The resulting concept of the coastal risk index can be applied to virtually any other microtidal and optionally semi-enclosed sea with low-lying coasts. Nevertheless, the vulnerability and exposure ranking and criteria weighting should be modified regarding to the specific lithomorphogenetic composition, hydrodynamic regime and socio-economic environment of the application area.

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