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Coastal vulnerability assessment in complex geological and changing climate conditions

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Abstract

The paper provides an overview of the impact of geomorphological processes on coastal zones in the Kvarner area (channel part of the north-eastern Adriatic Sea), recent instability phenomena, and the effects of climate change on their occurrence. The study focused on the coastal area near the Stara Baška settlement on the southwestern coast of Krk Island. The delicate geodynamic balance, combined with a complex geological fabric and active coastal geomorphological processes, makes this area particularly prone to erosion induced by wave action. The consequences of these events are rockfalls, rock slumps, and active landslides, which represent a natural hazard while also serving as a source of beach-forming sediment.

The complexity of the geological fabric required an adaptation of the methodology for assessing coastal vulnerability. A novel coastal vulnerability analysis was carried out using existing data complemented by detailed field investigations. The Coastal Vulnerability Index was calculated at 5-m intervals along approximately 2 km of coastline, representing a newly developed high-resolution methodology enabled by precise 3D datasets obtained from UAV and LiDAR surveys. Geological fabric, coastal slope, beach width, significant wave height, and land use were taken into account. The results of the new high-resolution vulnerability assessment were validated through field investigations and comparison with ortho-photo maps, confirming the reliability of the proposed approach and highlighting the importance of detailed spatial data for accurate coastal vulnerability evaluation.

Keywords

Coastal processes, Slope instabilities, Coastal Vulnerability Index, Photogrammetry, Climate change.

1 Introduction

A comprehensive, clear, and effective strategy for mitigating and preventing risks associated with geohazard events is still lacking along the Croatian Adriatic coast. At present, interventions are largely reactive, focusing primarily on the repair of storm-induced damage to coastal buildings and artificial beaches. Marine geohazards affecting the coastal area around the Stara Baška settlement, located on the south-eastern coast of Krk Island (Fig. 1), have been described in several studies (Juračić et al., 2009; Benac et al., 2013; Ružić et al., 2014, 2015, 2021). The dominant issues in this area are coastal erosion and associated local instabilities, driven by sea-level rise and unfavourable wave and wind regimes.

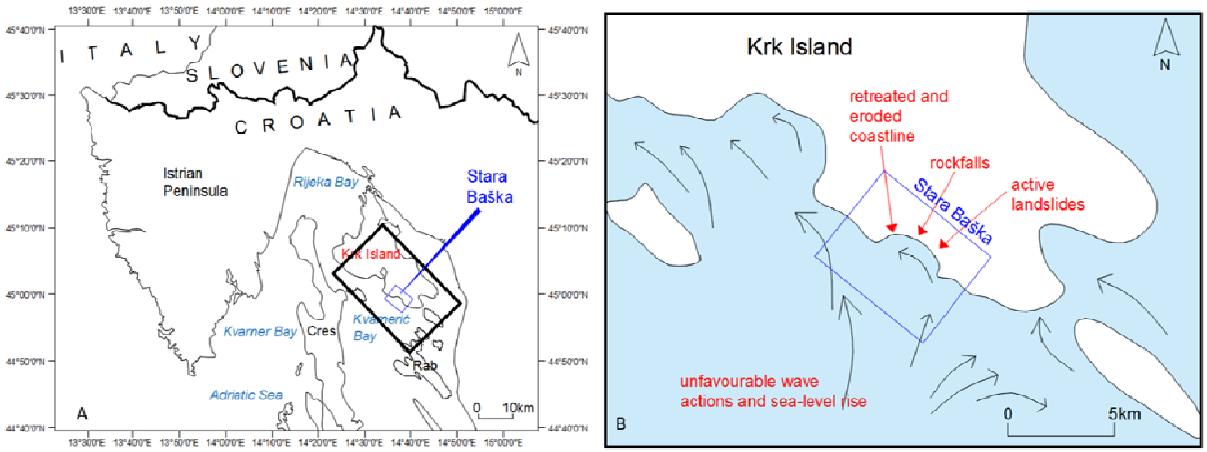


Fig. 1 Location of the study area Stara Baška on Krk Island (a) and the dominant geohazards in the investigated area (b).

Unplanned settlement expansion, intensive construction of tourism infrastructure, and the lack of an adequate drainage system have significantly increased the vulnerability of the area. Analysis of historical aerial imagery indicates rapid cliff retreat in breccia, along with evidence of past localized rockfalls (Ružić et al., 2014). Depending on local geological conditions, coastal cliffs are highly susceptible to failure, and detached rock blocks are frequently found on adjacent beaches, posing a hazard to the tourist camp located northwest of Stara Baška. In recent decades, tourism-driven development has led to the expansion of Stara Baška without corresponding infrastructure improvements. Consequently, some residential structures have been constructed in potentially unstable, landslide-prone areas (Ružić et al., 2021).

The Coastal Vulnerability Index (CVI) for this area was recently calculated by Ružić et al. (2019), incorporating parameters such as geological setting, coastal slope, beach width, significant wave height, and land use. The CVI is defined as the square root of the product of ranked variables divided by the number of parameters (Gornitz, 1990). However, the methodology was adapted to local conditions, and the present study examines how these modifications influence the resulting CVI assessment.

2 Factors influencing geohazards

2.1 Oceanographic conditions

Kvarnerić Bay (Fig. 1a) is a relatively enclosed channel part of the Adriatic Sea, and due to the limited, relatively short wind fetch, waves in this marine basin are smaller than in the western open zone. Weak to moderate winds prevail, while storm winds (speed > 30 m/s) are relatively rare. North-eastern wind (bora or bura) has the highest frequency and reaches maximum speeds, but waves are moderate due to small fetches. The south-eastern wind (jugo or sirocco) generates the highest waves. The study area is exposed to wind-driven waves from southeast to southwest directions, with the largest significant wave height being 3 m (Ružić et al. 2019).

The entire Kvarner area is a micro tidal area with a tidal range between 30 and 35 cm. The highest waves from the southeast direction are usually accompanied by storm surges. In recent decades, storm surges high tides were measured at a mareograph in Bakar Bay: 1.17 m CVD on 1 December 2008, 1.22 m CVD on 1 November 2012, and 1.27 m CVD on 29 October 2018 (Ružić et al. 2021).

2.2 Geological fabric

The slopes surrounding Stara Baška are developed in Upper Cretaceous limestones, dolomitic limestones, dolomitic breccias, and Paleogene foraminiferal limestones. Paleogene siliciclastic rocks (flysch) occur within a relatively narrow lower coastal zone. Both carbonate and siliciclastic rock masses are strongly tectonically deformed and squeezed. The fault contact between these units is masked by younger deposits (Benac et al., 2013). The terrain developed in carbonate rocks exhibits typical bare karst morphology. Despite the surrounding karst relief, most of the flysch rock mass is covered by talus breccias and colluvial deposits (Fig. 2). As a result, siliciclastic outcrops are only sporadically exposed along the narrow coastal belt (Ružić et al., 2021) and locally visible both along the coast and on the seabed, which is otherwise covered by a thin layer of sand. In the western part of the coastal area, proluvial sediments occur as friable deltaic deposits accumulated at the slope toe due to episodic torrential transport of fragmented material.

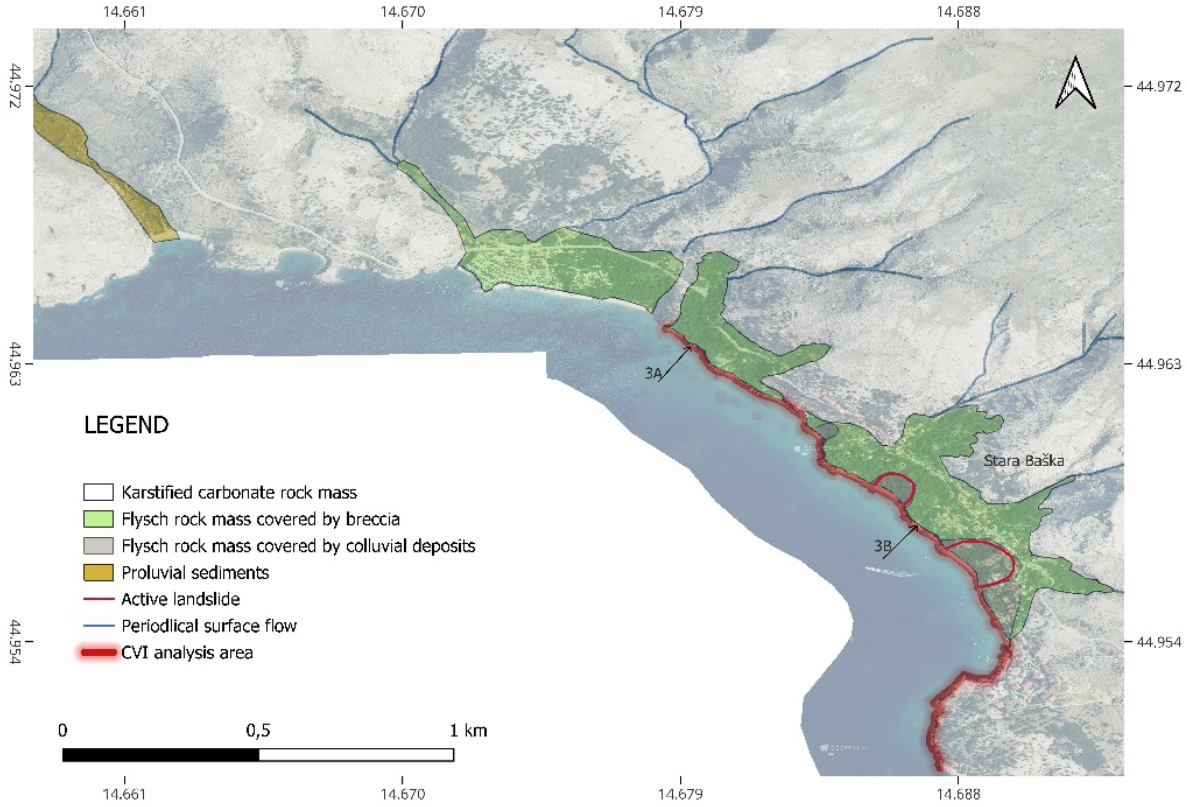


Fig. 2 Geological fabric of the study area.

Talus breccia predominates in the north-western part, whereas colluvium deposits are found in the south-eastern part of the study area. The talus breccia exhibits pronounced sub-horizontal stratification, with no clearly visible jointing. The layers consist of limestone fragments ranging from a few millimetres to blocks exceeding 50 cm in size, with fragments between 1 and 4 cm being dominant. The matrix is composed of a reddish, silty-sandy material (20–50% silt and clay) with variable degrees of calcification. The uppermost subsurface layer, approximately 1 m thick, is completely weathered and displays characteristics of residual soil (Ružić et al., 2015). Colluvial deposits have a soil-like character and consist of silty clay containing 30–50% carbonate rock fragments. The narrow coastal zone is predominantly covered by well-rounded gravel and pebbles forming beach deposits, while occasional larger rocky blocks derived from talus breccia are also present (Ružić et al., 2021).

2.3 Geomorphological processes

Stagnation of sea level occurred in the last 5000 years, after the rapid Late Pleistocene–Holocene rise in the Adriatic Sea (Surić 2009). During this period marine erosion/abrasion increased, and gravelly alluvial fans formed along the coast (Juračić et al. 2009). The combined influence of these geomorphological processes facilitated the development of a relatively wide marine terrace in the investigated area.Subsequent erosion of the adjacent slopes contributed to the formation of gravelly beaches (Ružić et al., 2021). However, these beaches are generally narrow, with mean grain sizes

ranging from 2 to 20 mm, and are therefore unable to develop a stable winter profile capable of effectively dissipating wave energy during storm events. As a result, waves frequently overtop the beaches and directly erode the base of coastal slopes. This process promotes cliff retreat, rockfalls, slumping, and the downslope movement of sliding masses (Fig. 3).



Fig. 3 Rock falls of talus breccia and marine erosion on flysch rocks and colluvium (a) and marine erosion of flysch rocks (b) (photos: Č. Benac).

Coastal cliffs formed in talus breccias and have an average height of 5 to 6 meters. The top layer at the subsurface, of about 1 m thickness, is completely weathered and has characteristics of residual soil. Due to high permeability,a great part of precipitation can penetrate in karstic aquifer during rainfall events. Surface runoff is generally absent but may occur episodically in dry valleys during intense precipitation (Fig. 2). In contrast, the siliciclastic (flysch) rock mass is relatively impermeable, promoting the development of subsurface (hypodermic) flow within the overlying permeable talus breccia and colluvial deposits, which drain toward the sea.

3 Methodology of the CVI index analysis

Vulnerability analysis was performed in the narrow coastal area of about 2km (Fig. 2), considering 5 parameters. The Coastal Vulnerability Index (CVI) presents a combined result of these parameters on the coastal change due to their impact. Index-based approaches express coastal vulnerability by means of a one-dimensional CVI index (1), originally proposed by Gornitz (1990), and based on a segmentation of a coastline and the assignment of vulnerability values to each coastal segment.

$$CVI = \sqrt{(a \cdot b \cdot c \cdot d \cdot e)/5} \tag{1}$$

The resulting error using this original methodology has motivated the authors to adopt the methodology to present complex conditions (Ružić et al. 2019) and to modify the equation as shown in (2).

$$CVI = \sqrt{(a\text{^}2 \cdot b \cdot c \cdot d \cdot e)/6} \tag{2}$$

Geological fabric is squared to emphasise its importance and complexity, and to leave the possibility to split factor “a” in two vulnerability factors (e.g. cliff and slope stability conditioned with the mechanical parameters of the rock and shoreline erosion/accretion rates). Factors considered in the CVI analysis with respect to different vulnerability grades (very low to very high) are shown in Table 1.

Table 1. Physical and anthropogenic parameters considered in the vulnerability analysis around Stara Baška (Ružić et al. 2019)

Parameter	**Vulnerability grade**				
	Very low (1)	**Low (2)**	**Moderate (3)**	**High (4)**	**Very high (5)**
a-Geologic fabric	Proluvial sediments	Resistant carbonate rocks	Crushed carbonate rocks	Talus breccia	Flysch rocks and colluvium
b- Coastal slope (°)	< 5	5 - 12	12 - 20	20 - 32	> 32
c- Beach width (m)	> 15	10 - 15	5 - 10	2.5 - 5	< 2.5 m
d- Significant wave height - Hs (m)	< 0.35	0.35 - 0.70	0.70 - 1.05	1.05 - 1.40	> 1.40
e- Land use	Bare karst	Mediterranean vegetation cover	Beach	Touristic zone	Settlement

The CVI assessment results' reliability was verified in the field and from the photographs of specific locations surveyed with the Unmanned Aerial Vehicle (UAV). The total CVI values are classified into five vulnerability categories: 'very low' (blue), 'low' (green), 'moderate' (yellow), 'high' (orange), and 'very high' (red).

4 Results

The calculation was made using original CVI (1) and modified methodology CVI (2), and the differences are noticeable. The CVI class ranges have been determined on the basis of the field investigations and statistical parameters (Table 2). The minimum calculated CVI value for the investigated area is 1.41, the maximum is 31.62, the mean is 11.48, and the median is 8.22. Detailed comparison of the CVI calculated using equations 1 and 2 is presented on the most vulnerable part of the Stara Baška coastline (Fig. 1), including urban area (Ružić et al. 2019).

Table 2.Vulnerability categories.

CVI	colour	value (Eq. 1)	value (Eq. 2)
very low		CVI < 8	CVI < 4.4
low		8 ≤ CVI < 12	4.4≤ CVI < 6.6
moderate		12 ≤ CVI < 16	6.6 ≤ CVI < 8.8
high		16 ≤ CVI < 20	8.8 ≤ CVI < 11
very high		20 ≤ CVI	11 ≤ CVI

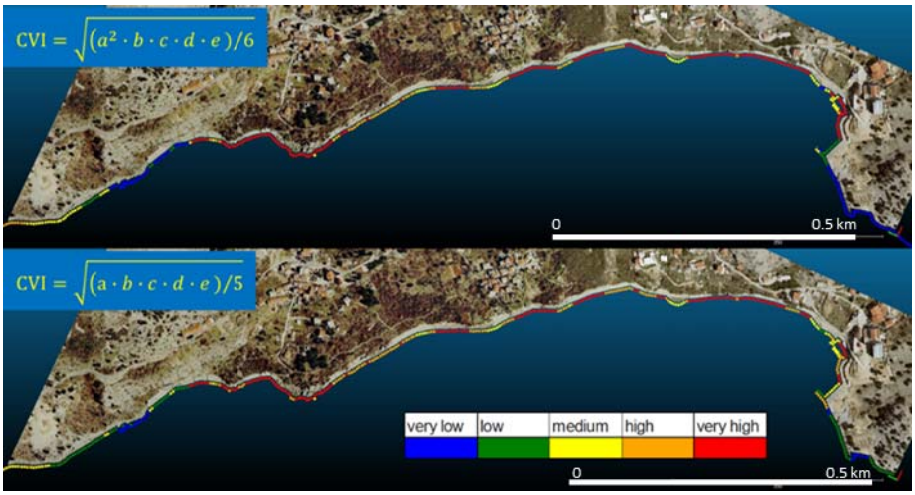


Fig. 4 Coastal Vulnerability Index (CVI) values comparison.

CVI differences between the two approaches are shown in Fig. 4. Those differences are locally expressed, and they are within one vulnerability index class. The greatest differences are on the most and least vulnerable coastal parts. Fig. 5ashows the CVI difference at the coastal stretch where flysch rock mass (very high vulnerability) prevails in combination with unfavourable anthropological influence. The unmodified CVI analysis underestimates the vulnerability index compared to field verification. Field UAV has shown expressed toe erosion and installed remediation works, suggesting a potentially dangerous situation, which was not recognized by unmodified CVI, and has defined the CVI as high instead of very high. The main reason for such an underestimation is the coastal orientation and partial protection from the SE waves. Because of that, the significant wave height parameter is slightly lower than in the surrounding coastline. Fig. 5b shows CVI differences on the resistant carbonate rock mass, corresponding to the low vulnerability grade (Table 2). Unmodified CVI overestimates vulnerability in the marked coastal part. Coastal parts where relatively resistant sedimentary carbonate rocks prevail have very low coastal vulnerability, what is not recognized in unmodified CVI calculation.

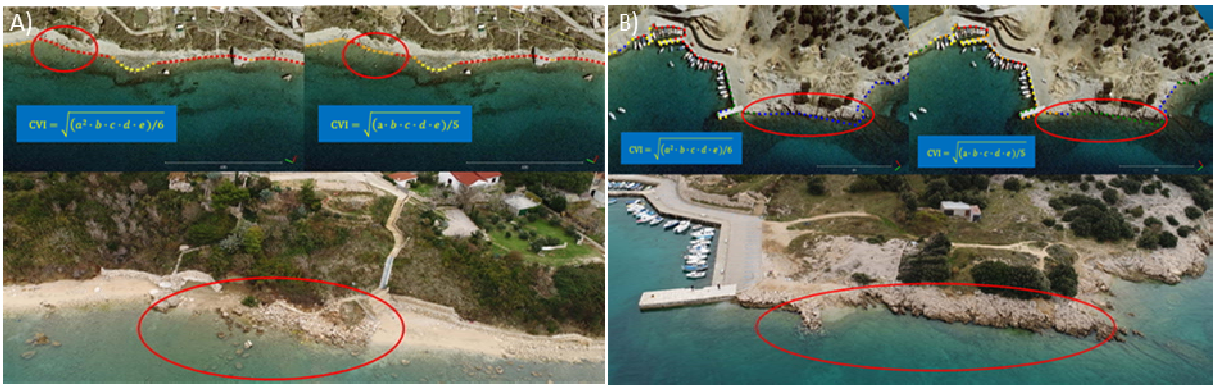


Fig. 5 Coastal Vulnerability Index (CVI) comparison – unfavourable geologic fabric (a), favourable geologic fabric (b).

5 Conclusions

Differences between the two CVI approaches are negligible at the regional scale but become significant at the local scale, where they provide more accurate and meaningful results. The original methodology tends to underestimate vulnerability in highly exposed coastal segments and overestimate it in more stable areas. Geologic fabric is identified as the dominant controlling parameter in CVI assessment, highlighting the necessity of its enhanced weighting in complex geological settings. The proposed methodology successfully identifies the most vulnerable coastal segments, providing a reliable basis for coastal management and land-use planning. Coastal vulnerability analysis is not currently required within Croatian land-use and urban planning legislation. However, the results obtained for the Stara Baška area clearly demonstrate the need to integrate such approaches into future regulatory frameworks. Effective coastal risk mitigation under climate change conditions should be structured into three key phases: coastal mapping, coastal engineering, and coastal management. Furthermore, the results indicate the need for systematic monitoring of the urbanized coastal zone of Stara Baška. Projected sea-level rise in the Adriatic Sea (19–33 cm by 2046–2065 and 32–65 cm by 2081–2100) further emphasizes the urgency of implementing these measures.

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