

dr Igor Ružić / др Игор Ружић¹
dr Denis Ambruš / др Денис Амбруш²

COASTAL VULNERABILITY AND URBAN PLANNING UNDER SEA-LEVEL RISE: RIJEKA AND CRIKVENICA

ОБАЛНА РАЊИВОСТ И УРБАНИСТИЧКО ПЛАНИРАЊЕ У УСЛОВИМА ПОРАСТА НИВОА МОРА: ПРИМЕРИ РИЈЕКЕ И ЦРИКВЕНИЦЕ

ABSTRACT: The coastal zone of the Republic of Croatia is increasingly exposed to development pressures while representing a highly sensitive system influenced by coastal processes. This paper examines the relationship between urbanization and natural processes along the Adriatic coast, with a focus on geological conditions, coastal erosion, wave action, and sea-level rise. The analysis is based on selected case studies from the Kvarner region, including Rijeka and Crikvenica. In Rijeka, reclaimed areas such as the Central Market are increasingly exposed to flooding, while parts of the Pećine area show instability due to construction near erodible brecciated limestones. In contrast, historical development in Costabella demonstrates better adaptation to natural conditions, although recent interventions highlight less favorable planning practices. In Crikvenica, reclaimed coastal zones have largely been reserved for public use, allowing greater adaptability to future sea-level rise[1], while areas such as Havišće illustrate the consequences of construction too close to the shoreline. The results highlight significant differences in urban planning approaches and emphasize the importance of integrating geological and coastal process analyses into planning. Failure to do so increases long-term vulnerability, particularly in reclaimed and low-lying coastal areas under projected sea-level rise scenarios.

Keywords: urban planning, coastal vulnerability, geomorphology, Adriatic coast

РЕЗИМЕ: Обални простор Републике Хрватске изложен је све већим развојним притисцима, а истовремено представља изразито осетљив систем под утицајем обалних процеса. У раду се анализира однос урбанизације и природних процеса дуж јадранске обале, са посебним нагласком на геолошке карактеристике, обалну ерозију, деловање таласа и пораст нивоа мора. Анализа је заснована на одабраним примерима са подручја Кварнера, укључујући градове Ријеку и Цриквеницу. У Ријечи су насуте делови обале, попут зоне Централне тржнице, све чешће изложени плављењу, док подручје Пећина показује нестабилност услед изградње у близини еродибилних бречастих кречњака. Насупрот томе, историјска изградња на подручју Костабеле показује бољу прилагођеност природним условима, иако новије интервенције указују на мање повољне планерске приступе. У Цриквеници су насуте обални простори у великој мери сачувани за јавну употребу, што омогућава већу прилагодљивост будућем порасту нивоа мора, док подручја попут Хавишћа указују на последице изградње преблизу обали. Резултати указују на значајне разлике у приступима урбанистичком планирању и наглашавају потребу за интеграцијом геолошких и обалних процеса у планске процедуре. Њихово занемаривање доводи до повећане дугорочне рањивости, нарочито у насутим и нисколежећим обалним зонама у условима очекиваног пораста нивоа мора.

Кључне речи: урбанистичко планирање, обална рањивост, геоморфологија, Јадран

1. INTRODUCTION

Coastal zones are among the most valuable and most vulnerable areas of urban development. They are shaped by complex natural processes such as wave action, coastal erosion, and sea-level fluctuations, which are increasingly intensified by climate change. At the same time, these areas are exposed to growing development pressures, particularly along the Adriatic coast. The eastern Adriatic coastline, including Croatia, is predominantly formed in carbonate rocks that generally allow favorable construction conditions. However, local geological variations, such as fractured and brecciated limestones, significantly influence coastal stability and susceptibility to erosion. Low-lying and reclaimed coastal areas are particularly vulnerable, especially under storm surge conditions and projected sea-level rise[1]. Despite these constraints, coastal processes and geological conditions are

¹ prof. dr. sc. Igor Ružić, Sveučilište u Rijeci – Građevinski fakultet u Rijeci, e-mail: iruzic@uniri.hr, ORCID: 0000-0003-4964-790

² doc. dr. sc. Denis Ambruš, Sveučilište u Rijeci – Građevinski fakultet u Rijeci, e-mail: denis.ambrus@gradri.uniri.hr, ORCID: 0000-0002-8721-3783

often insufficiently integrated into urban planning practice. Current regulatory frameworks do not consistently require the involvement of coastal engineering or geomorphological expertise, which can lead to increased long-term vulnerability. Recent advances, such as coastal vulnerability mapping and web-based GIS tools developed at the regional level [2–4], enable a more systematic assessment of coastal risk and provide valuable support for planning processes. The aim of this paper is to analyse the relationship between urban development and natural coastal processes through selected case studies from the Kvarner region, focusing on the resilience and vulnerability of coastal urban systems.

2. STUDY AREA

The study area covers the coastal zone of Primorje-Gorski Kotar County (PGŽ), located in the northern Adriatic. This region is characterized by a highly indented and heterogeneous coastline, with a total shoreline length of approximately 1,200 km, including numerous islands, bays, and urban coastal zones. The geological structure of the area is complex and dominated by carbonate rocks (limestones) of varying strength and degree of fracturing. In addition, locally significant occurrences of flysch deposits, marls, and unconsolidated sediments can be found, particularly in coastal zones and river mouths. Such variability strongly influences coastal stability, erosion processes, and suitability for construction. The coastal morphology ranges from steep rocky cliffs to low-lying and artificially reclaimed areas. Karst processes are highly developed, resulting in irregular terrain, coastal caves, and discontinuous sediment supply [5]. In areas composed of weaker materials, such as brecciated limestones and flysch formations, increased susceptibility to erosion and slope instability is observed. Wave conditions along the PGŽ coast are also spatially variable, depending on orientation and exposure. The dominant wave regime is associated with the sirocco (jugo) wind, generating long-period waves and elevated sea levels, which significantly contribute to coastal flooding and erosion, particularly in semi-enclosed bays. Bora-driven waves are typically shorter and steeper, affecting exposed coastal segments. The study focuses on selected urban coastal areas within PGŽ, specifically Rijeka and Crikvenica, which represent contrasting examples of coastal urban development and interaction with natural processes.

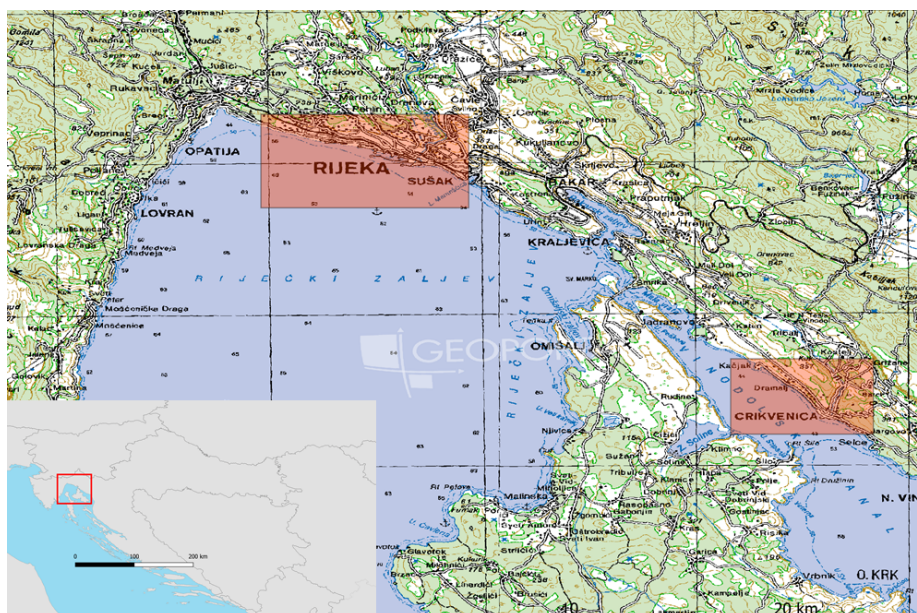


Figure 1. Location of the study area in Europe, with the position of Croatia and Primorje-Gorski Kotar County (PGŽ), and highlighted case study areas: Rijeka and Crikvenica.

3. METHODOLOGY

The methodological approach is based on the analysis of coastal topography, historical shoreline development, and spatial distribution of low-lying areas using geographic information system (GIS) tools. A high-resolution digital elevation model (DEM) with a spatial resolution of 1×1 m was derived from the Croatian national multi-sensor LiDAR dataset [6], ensuring high vertical and spatial accuracy for coastal terrain analysis. DEM was used to identify low-elevation coastal zones. The DEM datasets for the study areas were merged and processed in QGIS. Based on elevation values, three classes were defined to represent present and future coastal flood-prone conditions:

- 0–1.2 m above sea level – present-day conditions (extreme sea levels)
- 1.2–1.8 m – sea-level rise scenario (+0.60 m)
- 1.8–2.4 m – sea-level rise scenario (+1.20 m)

The classification was performed using raster-based analysis (Raster Calculator), and resulting zones were visualized and analyzed as flood-prone areas.

Surface areas of each elevation class were calculated based on raster cell counts, where each cell represents 1 m². The results were further processed and statistically analyzed to obtain total areas and relative shares of each zone.

In addition, historical shoreline positions were reconstructed and compared with the present coastline to identify areas of land reclamation and coastal transformation. This enabled the assessment of spatial relationships between artificially formed coastal zones and present-day flood vulnerability.

The analysis was complemented by the use of regional coastal vulnerability data and GIS-based tools, providing additional context for interpreting coastal processes and urban development patterns.

4. RESULTS

The paper focuses on selected case studies from the Kvarner region, highlighting different interactions between urban development and coastal processes. In Rijeka and Crikvenica, flooding of low-lying central coastal areas is analyzed in relation to elevation and land reclamation. In addition, the Pećine area in Rijeka is examined as an example of shoreline change in brecciated limestones, where buildings have been constructed too close to an unstable coastal cliff. The Costabella area provides a contrasting example, including both historically well-adapted development and recent interventions such as the construction of an artificial beach under unfavorable geological and morphodynamic conditions.

4.1. Flood-prone zones – Rijeka

The analysis of low-elevation coastal areas in Rijeka shows a pronounced spatial concentration of flood-prone zones within reclaimed and heavily urbanized coastal areas (Figure 2). The analysis was performed for areas located below 2.4 m above sea level, representing zones potentially exposed to coastal flooding under present and future sea-level conditions. The total analyzed area amounts to 80.15 ha



Figure 2. Elevation-based flood-prone zones in Rijeka (0–2.4 m above sea level), indicating present-day conditions and future sea-level rise scenarios. The most vulnerable areas correspond to reclaimed and highly urbanized coastal zones, where flooding events are becoming increasingly frequent.

Approximately 13.6% of this area (10.90 ha) is already vulnerable under present-day conditions (0–1.2 m), primarily corresponding to reclaimed zones such as the Central Market area and port infrastructure. Under a sea-level rise scenario of +0.60 m, the affected area increases to 34.3% (27.53 ha), while under a +1.20 m scenario, more than half of the area (52.1%, 41.72 ha) becomes exposed to coastal flooding.

The spatial distribution of these zones shows a strong correlation with artificially formed land, indicating that reclaimed coastal areas represent the most vulnerable parts of the urban system.

This is consistent with observed conditions (Fig 3), where flooding events in these areas have become increasingly frequent, particularly during storm surge events associated with the sirocco wind



Figure 3. Coastal flooding in Rijeka recorded on 5 November 2023, illustrating inundation of low-lying urban areas during a storm surge event.

4.2. Flood-prone zones – Crikvenica

The analysis of low-elevation coastal areas in Crikvenica was conducted for areas located below 2.4 m above sea level, representing zones potentially exposed to coastal flooding under present and future sea-level conditions. The total analyzed area amounts to 25.06 ha (Figure 4).

Approximately 30.6% of this area (7.67 ha) is already vulnerable under present-day conditions (0–1.2 m), indicating that a relatively large portion of the coastal zone is currently exposed to flooding. Under a sea-level rise scenario of +0.60 m, the affected area increases to 44.7% (11.20 ha), while under a +1.20 m scenario, the share of flood-prone areas reaches 24.7% (6.19 ha).

The spatial distribution of flood-prone zones indicates that low-lying areas are predominantly located on reclaimed coastal surfaces. However, unlike in Rijeka, these areas in Crikvenica are largely unbuilt and used for public functions such as promenades, beaches, and open spaces. As a result, flooding primarily affects non-built areas, significantly reducing direct damage to urban structures and allowing adaptability to future sea-level rise.

This spatial arrangement reflects a more pragmatic urban planning approach, where reclaimed coastal zones have been intentionally preserved as flexible and multifunctional spaces. Consequently, although flood-prone areas are present, their impact on the urban system is considerably lower compared to more intensively built-up coastal environments.

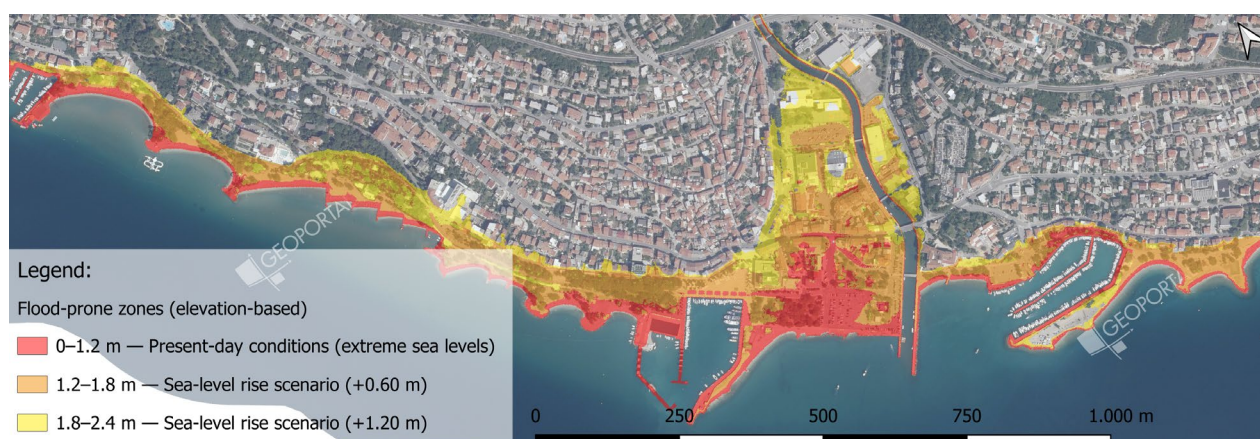


Figure 4. Flood-prone zones in Crikvenica (0–2.4 m above sea level), showing that low-elevation areas are primarily located on unbuilt reclaimed coastal surfaces used for public spaces.

4.3. Coastal erosion and beach reduction – Pećine (Rijeka)

The coastal zone of Pećine in Rijeka is formed in brecciated limestones, which are highly susceptible to erosion and slope instability. Historical shoreline analysis indicates ongoing coastal retreat and active geomorphological processes. Due to the construction of buildings too close to the coastline, natural erosion processes have been treated as a hazard, leading to the implementation of various geotechnical stabilization measures, including retaining structures and shoreline reinforcement. While these interventions reduce immediate risk to infrastructure, they simultaneously interrupt natural sediment supply from cliff erosion. As a result, a gradual reduction in beach area has been observed (Fig 5), as the natural replenishment of sediment is no longer

maintained. This has led to increased dependence on artificial interventions to preserve beach functionality. In the long term, a transition toward more adaptive approaches will be required, including the application of soft engineering measures such as beach nourishment and the construction of coastal promenades and artificial beaches designed to replicate natural conditions. The Pećine example demonstrates that inadequate consideration of coastal processes in urban planning—particularly construction too close to the shoreline—can lead to shoreline instability, loss of beach area, and increased need for engineering intervention.



Figure 5. Comparison of beach areas in the Pećine coastal zone (Rijeka) between historical conditions (1968 – left) and present-day conditions (2023 - right), showing a significant reduction in beach surface due to decreased sediment supply following coastal stabilization.

A detailed comparison of individual beach segments (P1–P8) shows a substantial reduction in beach area between 1968 and 2023 (Figure 5). The total beach surface decreased from 5377.52 m² to 1324.45 m², representing a reduction of approximately 75%. This significant loss confirms the impact of interrupted sediment supply following coastal stabilization measures and highlights the long-term consequences of limiting natural coastal processes.

4.4. Coastal interventions and vulnerability – Costabella (Rijeka)

The Costabella coastal zone in Rijeka represents a contrasting example of both well-adapted historical development and recent interventions that do not fully account for local coastal processes. While older structures were typically built at a greater distance from the shoreline and on more stable terrain, recent developments include the construction of an artificial beach and coastal infrastructure in a morphodynamically exposed area.

According to the regional coastal vulnerability assessment, available through the Primorje-Gorski Kotar County GIS portal, this section of the coastline is characterized by increased exposure to wave action and coastal processes. The area is influenced by strong wave conditions, particularly during sirocco (jugo) events, which generate elevated sea levels and wave overtopping.

The constructed beach and adjacent promenade are therefore exposed to conditions that exceed typical design expectations, resulting in frequent wave impact, overtopping, and maintenance issues. This suggests that not all relevant coastal engineering parameters and site-specific conditions were fully considered during the planning and design phase.

The example highlights the importance of integrating coastal vulnerability assessments and process-based understanding into urban planning and design. Failure to do so can lead to technically inadequate solutions, increased maintenance requirements, and reduced long-term resilience of coastal infrastructure.

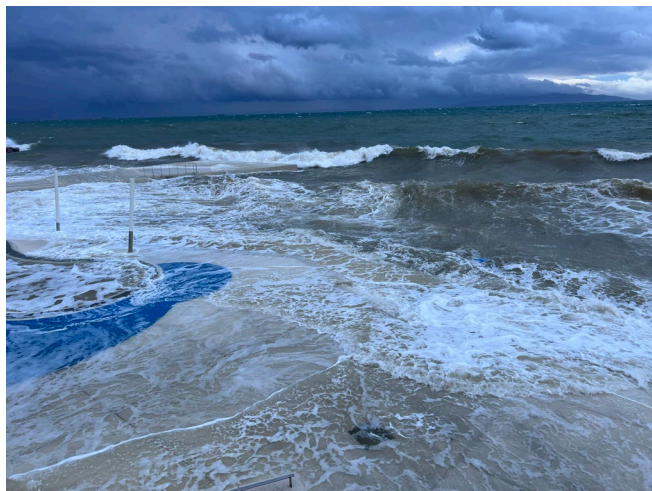


Figure 6. Wave overtopping and coastal flooding at Costabella (Rijeka), illustrating exposure of the artificial beach and promenade to high-energy wave conditions during storm events.

5. DISCUSSION

The analysis of urban development in Rijeka and Crikvenica confirms that coastal areas are strongly influenced by natural and geological conditions, which is consistent with theoretical frameworks of urban resilience [7,8]. Historical planning approaches, such as the development of villas in Costabella and the central coastal zone of Crikvenica, demonstrate a higher level of adaptation to natural conditions. In contrast, recent interventions in areas such as Pećine illustrate the consequences of neglecting geological and morphodynamic constraints, leading to increased coastal vulnerability.

The results indicate that coastal urbanization is not solely a technical issue related to construction, but also involves functional and social dimensions of spatial sustainability. Reclaimed coastal areas, although enabling short-term expansion of urban and tourism-related functions, often lead to long-term challenges, including periodic flooding, settlement of fill material, and infrastructural limitations.

Conversely, planning strategies that preserve reclaimed coastal zones as public spaces—such as parks, promenades, and flexible-use areas—demonstrate greater adaptive capacity and resilience to sea-level rise.

The analysis further shows that urban planning without interdisciplinary integration of geological, engineering, and climate-related data can result in spatial fragmentation and progressive degradation of coastal environments. Approaches that combine traditional planning knowledge with modern tools, including GIS-based analyses and digital planning instruments, offer significant potential for more sustainable coastal development.

In the context of climate change, sea-level rise, and increasing frequency of extreme events, neglecting these principles may lead to long-term degradation of urban environments, reduced quality of life, and increased socio-economic vulnerability. Therefore, sustainable coastal urban planning requires an interdisciplinary approach that integrates spatial planning instruments, geological and geomorphological knowledge, climate adaptation strategies, infrastructure innovation, and active involvement of local communities.

6. CONCLUSIONS

This paper highlights the importance of integrating coastal processes, geological conditions, and long-term sea-level rise considerations into urban planning of coastal areas. The analysis of selected case studies from the Kvarner region demonstrates that coastal vulnerability is strongly influenced not only by natural conditions, but also by planning decisions and the way coastal space is used.

The case of Rijeka shows that extensive land reclamation and construction in low-lying areas significantly increase exposure to coastal flooding, particularly under future sea-level rise scenarios. In addition, construction too close to unstable coastal slopes, as observed in the Pećine area, leads to the need for continuous stabilization measures, which disrupt natural sediment processes and result in beach loss.

In contrast, Crikvenica demonstrates a more adaptable approach, where reclaimed coastal areas are predominantly used as public open spaces, reducing direct damage and allowing greater flexibility in response to future sea-level rise. The comparison indicates that the key factor is not the presence of reclaimed land, but how it is planned and utilized.

The Costabella example further emphasizes the importance of understanding local coastal dynamics, as recent interventions in morphodynamically exposed areas have resulted in increased vulnerability and maintenance challenges.

Overall, the results confirm that insufficient consideration of coastal processes in urban planning leads to increased long-term risk, higher maintenance costs, and reduced resilience of coastal urban systems. The integration of geological, geomorphological, and coastal engineering analyses, supported by GIS-based tools and vulnerability assessments, is essential for sustainable and resilient coastal development.

7. ACKNOWLEDGMENT

This work has been supported by the Interreg Italy–Croatia Programme project “RESONANCE – Climate Resilient Coastal Systems in the Adriatic Region”, co-funded by the European Regional Development Fund (ERDF).

REFERENCES

- Intergovernmental Panel on Climate Change (IPCC) (2021): *Climate Change 2021: The Physical Science Basis*. Cambridge University Press.
- Ružić, I.; Benac, Č.; Tadić, A.; Krvavica, N.; Petrović, V.; Ljubičić, G.; Jakupović, D. (2022): *Vulnerability Analysis of the Coastal Zone of the Primorje-Gorski Kotar County Due to Sea Level Rise*. Public Institution for Spatial Planning of Primorje-Gorski Kotar County

- Tadić, A.; Krvavica, N.; Benac, Č.; Ružić, I. (2024): Coastal Vulnerability Index for the Indented Coastline of Primorje-Gorski Kotar County, Croatia. *Regional Studies in Marine Science*, 80, 103862. <https://doi.org/10.1016/j.rsma.2024.103862>
- Primorje-Gorski Kotar County (2023): Coastal Vulnerability GIS Viewer for Sea-Level Rise in Primorje-Gorski Kotar County. Available at: <https://gisportal.pgz.hr/portal/apps/experiencebuilder/experience/?id=8b96f9ed8bb24595bb1aab7d1603e16b>
- Benac, Č.; Juračić, M.; Matičec, D.; Ružić, I.; Pikelj, K. (2013): Fluviokarst and Classical Karst: Examples from the Dinarics (Krk Island, Northern Adriatic, Croatia). *Geomorphology*, 184, 64–173. <https://doi.org/10.1016/j.geomorph.2012.11.016>
- State Geodetic Administration (2020): Multisensor Aerial Survey of the Republic of Croatia (Project Code: KK.05.2.1.10.0001).
- Meerow, S.; Newell, J. P.; Stults, M. (2016): Defining Urban Resilience: A Review. *Landscape and Urban Planning*, 147, 38–49. <https://doi.org/10.1016/j.landurbplan.2015.11.011>
- Davoudi, S.; Shaw, K.; Haider, L. J.; Quinlan, A. E.; Peterson, G. D.; Wilkinson, C.; Fünfgeld, H.; McEvoy, D.; Porter, L. (2012): Resilience: A Bridging Concept or a Dead End? *Planning Theory & Practice*, 13(2), 299–333. <https://doi.org/10.1080/14649357.2012.677124>

