

DOI: 10.13137/978-88-5511-663-3/37551

Coastal vulnerability assessment and challenges for nature - based solutions (coastal dunes) in the Northern Adriatic sea

Annelore Bezzi¹, Saverio Fracaros¹, Carla Garcia Lozano², Cinzia Leccardi¹, Chiara Popesso¹

¹Department of Mathematics, Computer Science and Geosciences, University of Trieste, Italy;

² Departament de Geografia Universitat de Girona, Spain

$\Rightarrow$ ABSTRACT

As sea level rise and human activities increasingly affect both morphological and sedimentary dynamics, coastal risks are becoming more severe. As a result, assessing coastal vulnerability to storm events and identifying innovative, resilient, nature-based solutions to combat erosion have become essential components of modern coastal management strategies. This study presents an integrated assessment approach applied to 140 km of sandy coastline in the Northern Adriatic Sea (Italy), an area characterized by varying degrees of anthropogenic impact. An adapted version of the Coastal Vulnerability Index was employed to estimate the Potential Vulnerability (V_p), which reflects the morpho-evolutionary conditions of individual coastal cells under the assumption of no protective measures against sea storms. The subsequent classification and evaluation of both hard and soft coastal defences—including natural features such as dunes—enable the transition from Potential to Real Vulnerability (V_r). To more specifically assess the presence, functionality, and development potential of coastal dunes, the analysis incorporates two complementary dune indicators: ISand, which measures the system's potential for aeolian-driven transport of beach sediment towards the dune, and IDune, which evaluates the current eco-morphodynamic condition of the existing dune systems.

➤ INTRODUCTION

Natural and anthropogenic pressures have compromised the geological-physical and ecological qualities of coastal areas, leading to increased erosion and loss of coastal dunes. Climate change, including rising sea level and increased storm severity and frequency, is intensifying the need for coastal vulnerability assessments and the exploration of innovative coastal defence and resilience strategies. Although hard defences are necessary in certain instances, nature-based solutions (Morris et al., 2021), such as coastal dunes, are recognised as helpful in mitigating coastal risk (Nordstrom et al., 2000; Morris et al., 2021; Fernandez-Monblanc et al., 2020) and enhancing climate change resilience. Coastal dunes also serve as important natural habitats and valuable landscape features.

Hence, two alternative types of indicators were designed and applied to a sandy coastal region with varying levels of human impact. The aim was to assess the coastal vulnerability to sea storms and the presence and effectiveness of coastal dunes in relation to their development potential. The test area is the Northern Adriatic, which, according to Antonioli et al. (2017), is the Italian region most at danger of floods from relative sea level rise by 2100.

➤ STUDY AREA AND METHODS

The study area is a 140 km-long sector of sandy coasts located in the Northern Adriatic (Veneto and Friuli Venezia Giulia regions, Italy, Fig. 1). The coastal area is resulting from the Holocene evolution of an alluvial plain coasts in lagoons, barrier beaches, fluvial deltas, and spits. Today, several physiographic units are separated by river mouths or tidal inlets. Human activity has greatly influenced the evolution of the coast; since the 1950s, urbanization and tourism have destroyed most of the coastal dunes. The intense erosive processes were dealt in the 1960s and 1970s with the construction of hard defences (revetments, seawalls, and groynes), and since 1995, by beach nourishment with offshore sand. The coastal management is fragmented, coastal interventions are often promoted by municipalities, and beach monitoring is not updated or is quite sparse.



Figure 1
The study area in the Northern Adriatic Sea (Italy), the distinct physiographic units are represented in different colours

To this area we applied an assessment of sea storm vulnerability using an adaptation of the Coastal Vulnerability Index (Fontolan, 2011). The methodology includes the estimate of the *Potential Vulnerability* (V_p , indexed between 1 and 13.2) (Fig. 2): seven variables were analysed and weighted to define the physical and evolutionary conditions of beach – shoreface system, under the assumption that there is no defence against sea storms. Then, the classification and evaluation of coastal defences (hard and soft, including coastal dunes) allows the shift from *Potential* to *Real Vulnerability* (V_r).

Furthermore, since foredunes play a crucial role in protecting coastlines from sea-level rise and storm impacts, two indicators were developed and applied to the study case, in order to assess the current eco-morphodynamic state of the dune system in relationship with the potential of dune development. *ISand* evaluates the potential for wind-driven sand transport on beaches to form new dunes (Fig. 2). The indicator includes beach width and orientation, sediment density and mean grain size, wind regime (direction and velocity). *IDune* is developed to understand the current state of the dune system (overall health and conservation status) and incorporates: foredune evolution, dune width, dune length, dune height, dune fragmentation, vegetation cover in foredune, vegetation cover in backdune and in stabilized dune (Fig. 2).

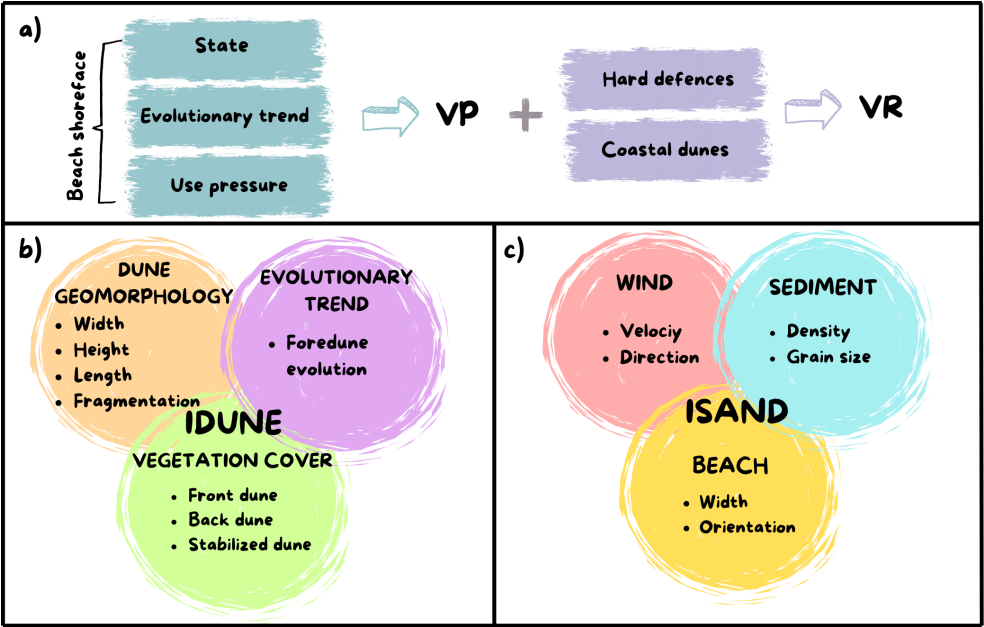


Figure 2
The assessment applied in the North Adriatic test area (a) Potential and Real Vulnerability, (b) IDune, (c) ISand.

➔ RESULTS

The results of the applied vulnerability assessment show varying grades of *Potential Vulnerability* (V_p) depending on distinct morpho-evolutive conditions of the coastal cells (Fig. 3). Low values of V_p (28 km) are typical of coastal cells acting as sedimentary traps in proximity to jettied or unjettied tidal inlets. Beaches with moderate V_p are the most common (77 km); many benefits from the widespread distribution of hard coastal defences and the presence of coastal dunes, which mitigate vulnerability, leading only 16 km to maintain a moderate V_p . Finally, littoral portions with a high V_p (22 km) are mostly affected by a persistent sedimentary deficit, which results in absent or nar-

row beaches with a steep shoreface. Overall, the significant presence of hard defences or coastal dunes ensures that V_p is reduced to safe levels, with contrasting effects on the resilience of the morpho-sedimentary system. Only 3.6 km without defences hold high V_p values.

The second part of our assessment intended to evaluate the current eco-morphodynamic state of the dune system in relationship with the potential of dune development by the application of the two indicators (Fig. 4): *ISand* and *IDune*. According to our findings, the beaches of the study area provide general favourable conditions for the growth of coastal dunes, in terms of wind regime and the available sediment grain size (0.2 – 0.4 mm), although they differ in terms of beach width and shoreline orientation. The dominant wind is the Bora, blowing from ENE, reaching gust velocities over 100 km/h (Fig. 4a) and playing a fundamental role in dune formation, as sand can be transported, trapped and anchored by vegetation.

The integration of the *ISand* and *IDune* indicators offers valuable insights into both the potential for dune formation and the status of dune conservation. Based on the analysis of the physiographic units (Fig. 4), it becomes evident that even in sectors where the prevailing wind direction is long-shore, as in Bibione, the *ISand* values remain relatively high in areas characterized by wide beaches. This occurs because *ISand* reflects both the potential aeolian transport and the beach width, this last variable indicating whether sufficient space is available for dune development. So even where the wind transport potential is low ($< 8 \text{ m}^3/\text{my}$), we can have a moderate *ISand* and *IDune* thanks to the presence of wide beaches. However, in some locations such as in Valle Vecchia and Pellestrina, the *IDune* is quite high (>3) and the *ISand* is low (<2); this indicates that the dune systems have reached their maximum spatial expansion, typically resulting in narrow beaches.

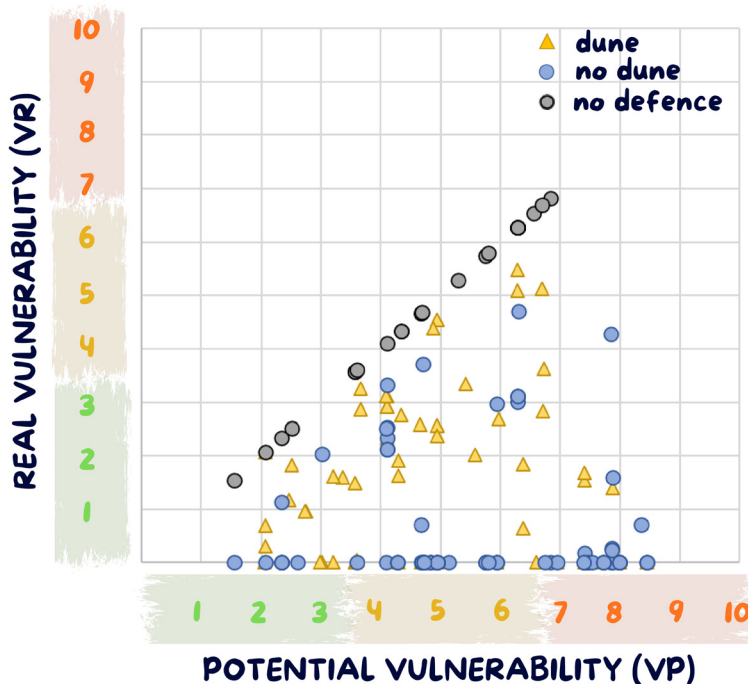


Figure 3
Potential and Real Vulnerability for Veneto and Friuli Venezia Giulia beaches: low (green), moderate (yellow) and high (orange). Coastal cells are differentiated according to the type of coastal defences



Figure 4

(a) Wind roses for some location in Veneto. (b) ISand for every cell of the different physiographic units in Veneto and IDune for every different physiographic unit. Aeolian potential increases particularly when the cross-shore wind direction is higher, as in Albarella and Rosolina.

Moderate to high *ISand* values reflect a sufficient sediment supply and favourable wind conditions, which tend to support better dune development. An exception is found in Sottomarina, where dunes are either absent or highly degraded due to inadequate management practices. In the best circumstances, dunes have considerable height and width, low levels of fragmentation, and dense vegetation cover features that contribute significantly to their stability. Overall, our results imply that dune formation and condition are influenced by factors other than wind regime and beach width. Instead, effective coastal management appears to play a critical role.

Figure 5, focusing on Rosolina beach, shows how combining the *Vulnerability* and *ISand* indicators can guide better coastal management. In Sector A, the absence of natural or artificial defences leads to high Real and Potential Vulnerability. In contrast, Sector B, protected by sand dunes, shows reduced vulnerability, proving their effectiveness. Since both sectors have the same *ISand*, the hypothesis of restoring dunes in Sector A could lower its vulnerability to levels similar to Sector B. The example highlights the value of natural defences and integrated indicators in planning sustainable coastal protection.

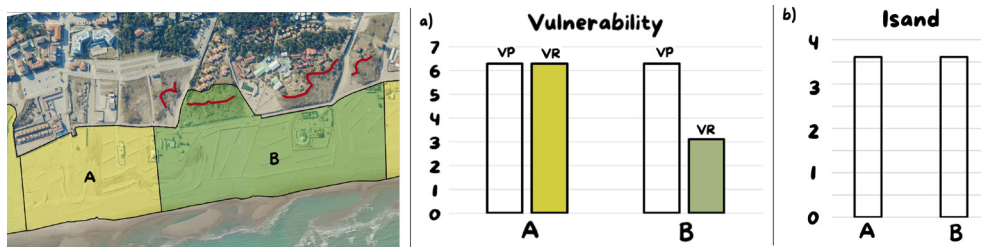


Figure 5

Vulnerability Index and ISand application - Rosolina example: a) Vulnerability b) ISand.

➤ CONCLUSIONS

A vulnerability assessment was conducted to evaluate the overall capacity of sandy beaches to withstand sea storm events (V_r), starting from their existing morpho-evolutionary conditions (V_p) and accounting for the mitigating effects of hard engineering structures and coastal dunes.

To complement this analysis, the *IDune* indicator offers a detailed characterization of dune systems by focusing on key eco-morphodynamic features. These features serve as a foundation for assessing future dune resilience under projected sea level rise scenarios. Additionally, the *ISand* indicator identifies areas with potential for dune development, particularly where dunes are currently absent, thereby highlighting opportunities for reducing actual vulnerability (V_r). Together, these indicators represent a valuable tool to sustain nature-based coastal management strategies, especially in regions experiencing varying levels of human impact.

➤ ACKNOWLEDGMENTS

This study was carried out within the PNRR research activities of the consortium iNEST Interconnected North-East Innovation Ecosystem - funded by the European Union Next GenerationEU - Piano Nazionale di Ripresa e Resilienza PNRR - Missione 4 Componente 2, Investimento 1.5 - D.D. 1058 23/06/2022, ECS_00000043 - CUP J43C22000320006; the European Commission (Horizon 2020) - IMPETUS project (101037084); and MCIN/AEI/10.13039/501100011033 and NextGenerationEU/PRTR - CoastSpace project (TED2021-130001B-C22).

➤ REFERENCES

- Antonioli, F., Anzidei, M., Amorosi, A., Lo Presti, V., et al. 2017. Sea-level rise and potential drowning of the Italian coastal plains: Flooding risk scenarios for 2100, *Quat Sci Rev*, 158, 29–43
- Fernández-Montblanc T., Duo E., Ciavola P., 2020. Dune reconstruction and revegetation as a potential measure to decrease coastal erosion and flooding under extreme storm conditions. *Ocean Coast Manage*, 188, 105075
- Fontolan, G., Bezzi, A., Pillon, S., 2011. Rischio da mareggiata. In: Vitturi, A. (Ed.), *Atlante Geologico della Provincia di Venezia. Cartografie e Note illustrative*. Provincia di Venezia, pp. 581-600.
- Morris R.L., Bishop M.J., Boon P., Browne N.K., et al., 2021. Australian guide to nature-based methods. NESP Earth Systems and Climate Change Hub, Australia, Report 26, 160 pp.
- Nordstrom K.F., Lampe R., Vandemark L.M., 2000. Re-establishing naturally functioning dunes on developed Coast *Environ Manage*, 25 (1), 37–51.
- Valls, J.F., Rucabado, J., Sardá, R., Parera, A. 2017). The beach as a strategic element of governance for Spanish coastal towns. *J Sustain Tour*, 25(9), 1338 1352.