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A FUZZY LOGIC APPROACH FOR ASSESSING THE ECOLOGICAL RISK OF COASTAL HABITATS IN THE SARDINIA REGION RELATED TO FLOOD HAZARD

UN APPROCCIO FUZZY LOGIC PER IL CALCOLO DEL RISCHIO ECOLOGICO DEGLI HABITAT COSTIERI DELLA REGIONE SARDEGNA RELATIVO ALLA PERICOLOSITA' DI INONDAZIONE

Abstract – *Coastal environments are increasingly threatened by the combined effects of sea-level rise, extreme waves, and storm surges, particularly in the Mediterranean, a recognized climate change hotspot. This study develops a habitat-based Ecological Risk Index for coastal flooding in southwestern Sardinia, employing a fuzzy logic approach to integrate hazard, exposure, and vulnerability indicators. Using ecological indicators from the "Carta della Natura" and flood data from the European Coastal Flood Awareness System, risk maps are produced under five flood scenarios. Results reveal a progressive increase in both the extent and intensity of risk across scenarios 1 to 5, with the beaches and dunes ecosystem exhibiting high sensibility, ranging from 0.65 to 0.68, respectively, of the mean Ecological Risk Index.* Caretta caretta *nesting sites exhibit the highest mean index value (0.74) under extreme scenario. The proposed approach provides a useful decision-support tool for coastal management and conservation in the context of climate change.*

Keywords: *Ecological Risk Index, Fuzzy logic, Coastal flooding, Sardinia,* Caretta caretta**.**

Introduction - Coastal areas are increasingly recognized as 'at-risk' environments, exposed to marine drivers, including Sea Level Rise (SLR), waves, and storm surges (Idier *et al.*, 2019). These stressors are intensifying pressures on coastal habitats, leading to the progressive degradation of ecosystems (e.g., wetlands, beaches and dunes, and Mediterranean scrubs) (EEA, 2010). SLR, a major consequence of climate change, intensifies the occurrence and severity of coastal flooding, which is typically driven by elevated water levels and wave action that can overtop flood defenses or inundate low-lying areas (Wolf, 2009). The Mediterranean basin is widely recognized as a climate change hotspot with the Sardinia region in Italy identified as one of its most vulnerable areas (Ivčević *et al.,* 2021). In particular, the island's western coast faces elevated risk, primarily due to the occurrence of extremely high waves (Satta *et al.,* 2017). The Coastal Risk Index integrates variables of exposure, vulnerability, and hazard to identify areas of higher susceptibility, linking theoretical risk concepts with practical decision-making and highlighting coastal "hotspots" for targeted risk reduction (Satta *et al.,* 2017).

This study develops a habitat-based Ecological Risk Index for coastal flooding, applied to the southwestern area of Sardinia. The approach employs fuzzy logic to account for

environmental gradients, thereby providing an assessment of the sensibility degree of beach and dune ecosystem within the study area This framework also allows the identification and evaluation of vulnerable *Caretta caretta* (Linnaeus, 1758) nesting sites, in line with the objectives of the LIFE Turtlenest project, co-funded by the LIFE Programme, which aims to protect nesting sites in Italy, Spain, and France.

Materials and methods – The habitat-based Ecological Risk Index was computed by integrating three main components: exposure, vulnerability, and hazard. Exposure and vulnerability were determined based on the ecological characteristics of each mapped ecotope. Ecological indicators were derived from the "Carta della Natura" of Sardinia (Camarda *et al.,* 2011), clipped to the coastal strip available from the Sardinia Geoportal. Exposure, representing the ecological value of habitats, was defined as the mean of seven indicators: endemic habitats, habitats of community interest, presence of vertebrates, presence of flora, ecotope extent, ecotope rarity, and the perimeter/area of ecotope. Vulnerability, representing the ecological sensitivity of habitats, was assessed using seven indicators: protected areas, N2000 priority habitat, vertebrates at risk, flora at risk, distance to the nearest ecotope, contiguity index, and proximity index. The latter two correspond to landscape metrics computed with FRAGSTATS. Hazard was constructed using a weighted additive model of water height, flow velocity, and storm duration. These variables were obtained from the European Coastal Flood Awareness System (ECFAS) project (Le Gal *et al.,* 2023) and were used to generate maps of five coastal flood hazard scenarios. The dataset was resampled to a 10 m spatial resolution and georeferenced to the WGS84/UTM zone 32N reference system.
Fuzzy logic was applied to all exposure, vulnerability, and hazard indicators by classifying the dataset into membership values within the [0–1] range through appropriate membership functions (e.g., linear, large, small). In this study, fuzzification followed the rule whereby maximum values (membership = 1) correspond to maximum contribution to the risk level, and minimum values (membership = 0) correspond to the minimum level. Exposure, vulnerability, and hazard were integrated through the Fuzzy Overlay tool in ArcMap 10.8 to produce ecological risk maps for the five coastal flooding scenarios. Zonal statistics were performed on the five Ecological Risk Index maps and on the beach and dune ecosystem (obtained by grouping habitat types) to provide a comprehensive assessment of potential impacts of coastal flooding, identifying the extent and the degree of risk while also accounting for *Caretta caretta* nesting sites. The overall workflow is shown in Fig. 1.

Results – The Ecological Risk Index (ranging from 0 to 1) displays spatial variations across the five simulated coastal flooding scenarios (shown in Fig. 2). The extent and degree of ecological risk increase progressively with the severity of the flooding scenarios. Overall, the total area exposed to risk increases from 33.5 km² in Scenario 1 to 37.5 km² in Scenario 5, while the proportion of areas classified as 'very high risk' rises by 4%, from 54% in Scenario 1 (Fig. 2a) to 58% in Scenario 5 (Fig. 2e).
Within the beaches and dunes ecosystem, the proportion of area exposed to coastal flooding risk ranges between 14% (Scenario 1) and 19% (Scenario 5) across the considered scenarios (Fig. 3). The average ecological risk index shows a progressive increase from 0.65 in Scenario 1 to 0.68 in Scenario 5, indicating a gradual but consistent rise in ecosystem sensibility under more severe flooding conditions. *Caretta caretta* nesting site is particularly critical (Fig. 2f), with Scenario 5 showing a mean

ecological risk of 0.74, the highest value when compared to the mean indices of the beaches and dunes ecosystem across all scenarios

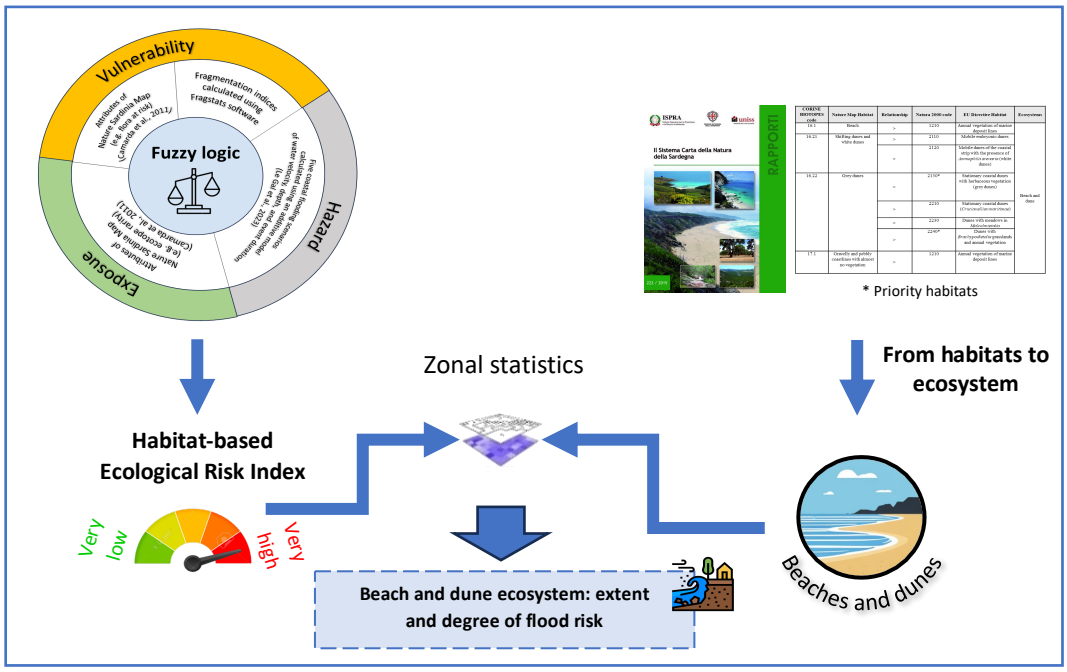

Fig. 1 - Workflow of the habitat-based Ecological Risk Index: fuzzy logic integrates hazard, exposure, and vulnerability indicators to assess flood risk in beach and dune ecosystems.
Workflow dell'Indice di Rischio Ecologico basato sugli habitat: la logica fuzzy integra gli indicatori di pericolosità, esposizione e vulnerabilità per valutare il rischio di inondazione negli ecosistemi di spiagge e dune.

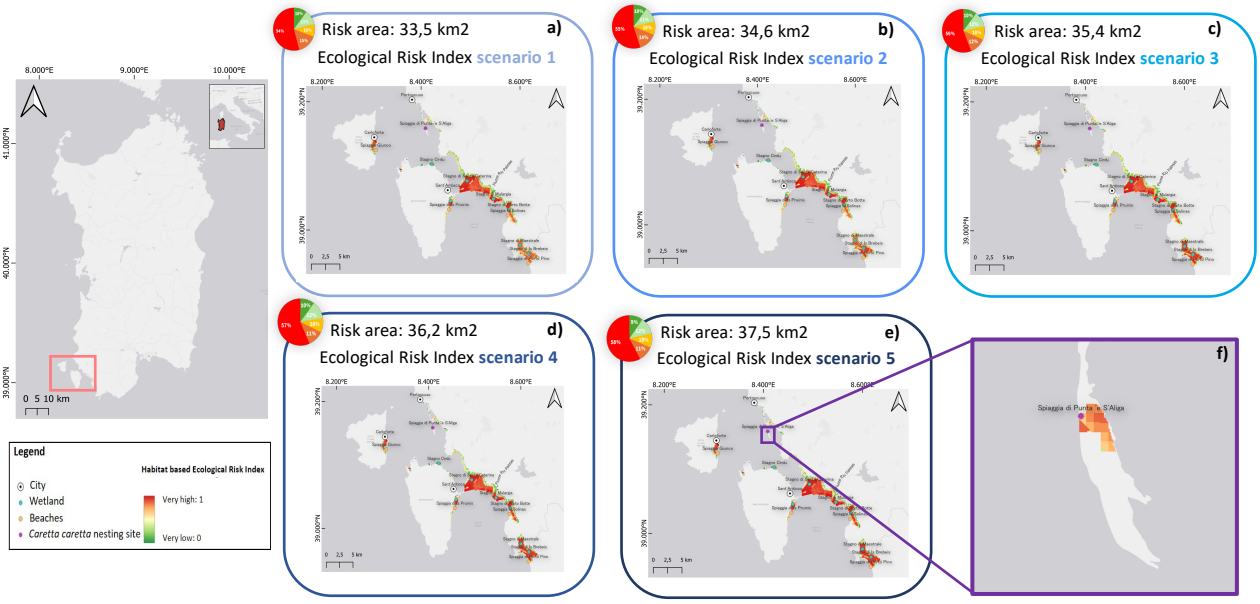

Fig. 2 - (a-e) Ecological Risk Index (0–1) for coastal habitats in the southwestern area of Sardinia under five coastal flooding scenarios from 1 to 5. (f) Zoom on the *Caretta caretta* nesting site.
(a-e) Indice di Rischio Ecologico (0–1) per gli habitat costieri nell'area sud-occidentale della Sardegna in cinque scenari di inondazione costiera da 1 a 5. (f) Zoom sul sito di nidificazione di Caretta caretta.

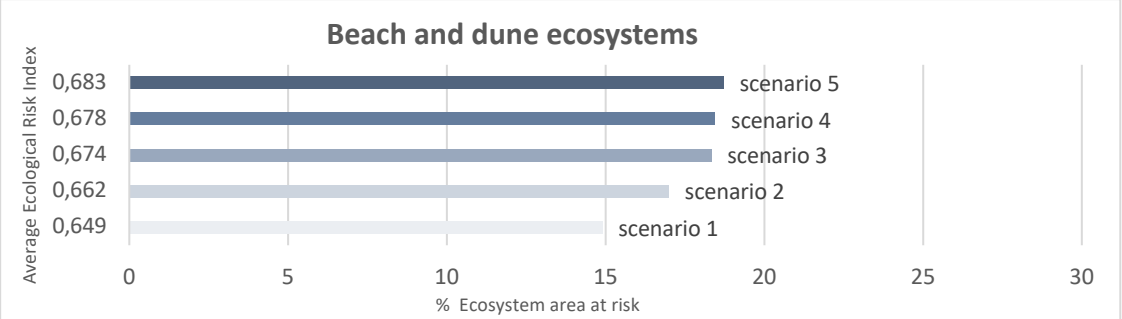

Fig. 3 - The percentage of the beach and dune ecosystem area that is at risk of coastal flooding, alongside the corresponding average Ecological Risk Index, across the five scenarios.
Percentuale dell'area dell'ecosistema spiagge e dune a rischio di inondazione costiera e corrispondente valore medio dell'Indice di Rischio Ecologico nei cinque scenari.

Conclusions - This study demonstrates, through the application of a fuzzy logic method to the habitat-based Ecological Risk Index assessment, that the beach and dune ecosystem of southwestern Sardinia is particularly vulnerable to coastal flooding. The results clearly indicate that both the spatial extent of the impacted area and the degree of ecological risk increase progressively with the severity of flooding scenarios, highlighting a consistent amplification of ecosystem sensibility under more extreme flooding conditions. The proposed approach provides a valuable decision-support tool for coastal zone and ecosystem management, enabling the identification of priority areas for risk reduction and conservation measures. In particular, this framework contributes to the protection of *Caretta caretta* nesting sites, which are increasingly threatened under climate change and simultaneously expanding their nesting range across the western Mediterranean (Hochscheid *et al.,* 2022).

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