A Multi-source Geospatial Framework for Assessing Coastal Risks and Cascading Processes into the COASTLINE Project

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Abstract. After the Second World War, the coastal areas have been subjected to a wide range of hazards, including human activities, geomorphological changes, and hydrodynamic forcing, which have molded their shapes and generated non-linear risk patterns. Nevertheless, most of the existing approaches assess hazards individually and do not explore the consequences of their interaction. To go beyond these constraints, this work introduces a novel geospatial pipeline for assessing risks in coastal environments, including cascading processes through the integration of heterogeneous data sources. The proposed framework is based on the integration of multi-source data (satellite observations, UAV surveys, in situ, and geophysical datasets), which are incorporated in a structured data fusion process, along with the evaluation of hazard dependency and propagation. This methodology is tested on three case studies in order to derive spatial indicators of hazard intensity and risk amplification. The results show that this approach allows for improving the detection of critical areas, elements at risk, exposure, and vulnerability. In contrast to conventional methods, this approach provides a more comprehensive representation of coastal zones. Additionally, the methodology is designed to be scalable and transferable, supporting the planning of adaptation and mitigation strategies.

Keywords: Cascading processes · probability analysis · risk analysis · vulnerability

1 Introduction

Coastal areas are widely acknowledged as among the most dynamic and vulnerable environments on Earth [1, 2]. In recent decades, there has been an increased number of threats from climate change, sea level rise, extreme weather conditions, and increasing anthropogenic impact on coasts [3, 4]. As a result, a gradual increase in the frequency of various coastal hazards, such as erosion, flooding, and deterioration of the coast, has been observed [5, 6]. The threat of coastal erosion is particularly acute, since it impacts the majority of sandy coasts, with an even greater threat posed by future sea level rise [7–9].

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 48–59, 2027.
https://doi.org/10.1007/978-3-032-30524-4_4

Coastal risk understanding has evolved considerably over the last decade, shifting from a mono-hazard perspective to a multi-hazard and systemic risk approach [10, 11]. Hazard processes are considered to be interdependent and are able to initiate cascade effects within the environment and socio-economic systems. Cascade effect can be defined as a chain of processes triggered by the first process and leading to a compounding of the impact through interaction of different processes in space and time [12, 13]. This approach appears highly relevant for coastal environments, where geomorphological, hydrodynamic, and human processes often create a non-linear pattern in the development of coastal risks [14, 15].

Even though great achievements have been made in the field of multi-risk or disaster risk assessment, there are still some challenges remaining when applying these methods to assess risks in coastal areas. First of all, most of the methods currently used don't fully utilize the capabilities of multi-scale and heterogeneous geospatial data. Secondly, the concept of cascade effects is rarely represented explicitly, including its temporal dimension, and finally, there is still a gap between the existing approaches to risk assessment and operational tools that could support decision-making in the field [14]. Though some frameworks have already been suggested describing the hazard interdependence, dynamic vulnerability, and probabilistic chains of events [13]. Nevertheless, practical application of these concepts for the analysis of coastal risk appears to be insufficiently developed at this point [16, 17].

However, research on coastal erosion and the functioning of coastal ecosystems has shown that primary risks, such as the increase in sea level, may cause a number of secondary effects, such as habitat loss, fragmentation of the coastal system, and disruption of its ecological processes [8]. These phenomena exemplify the fact that coastal risk is a cascading phenomenon, where physical changes in shoreline morphology translate into ecological and socio-economic processes, eventually affecting the resilience of coastal territories [18]. With technological advancements in Earth observation systems, monitoring of coastal processes has considerably increased. Remote sensing observations from satellites, UAV surveys, and GIS-supported techniques are some of the modern methods of monitoring coastline and coastal hazards, producing high-resolution multitemporal datasets [19–21]. Although integrating all these information sources in order to produce a risk assessment framework is quite challenging, especially considering the existence of cascading processes and multi-risk events.

It should be noted that in this context, this paper presents an innovative methodology framework for supporting coastal risk assessment, using geospatial multi-source datasets and analysis of cascading processes. In particular, the approach uses information from remote sensing systems and UAV surveys together with other geophysical and environmental data for assessing risks, exposures, and vulnerabilities to a particular hazard. Moreover, the approach uses a theoretical approach for representing cascading effects, which makes it possible to identify connections among different coastal processes and analyze the impact on important assets in line with cascading risk models [14].

The objective of this paper is to establish and illustrate the utility of an operational methodology that will improve the effectiveness of coastal risk assessment through the use of multiple and diverse data sources in a geospatial environment, taking into consideration the cumulative effects of coastal risks, and offering useful information

that will aid in risk-based decision making. The methodology employed is versatile and scalable enough for application in different coastal scenarios and valuable in both scientific inquiry and risk management [4, 16].

2 Methodology

The methodology has been developed within the COASTLINE project as an operational framework for coastal risk assessment, specifically designed to integrate multi-source geospatial data and analyze cascading processes. The approach builds upon established risk assessment paradigms, in which risk is conceptualized as a function of hazard, exposure, and vulnerability, while extending these models by explicitly considering hazard interdependencies and dynamic system responses [14, 17, 21]. Within this framework, coastal risk is interpreted as the result of interacting processes evolving in space and time, rather than as the outcome of isolated hazard events. This perspective is consistent with multi-risk approaches, which highlight the importance of hazard interdependencies and the role of cascading effects in amplifying overall impacts [10, 11]. Cascading processes are therefore treated as a central component of the methodology. They are defined as sequences of interconnected events triggered by an initial hazard, characterized by feedback mechanisms and cumulative impacts [13, 14].

The framework is structured as a modular and scalable workflow composed of six main analytical components:

(i) reference context definition;
(ii) multi-source data integration;
(iii) hazard characterization;
(iv) exposure and vulnerability assessment;
(v) cascading process analysis;
(vi) spatial risk evaluation and mapping;

These components are implemented within a geospatial environment, enabling the integration of heterogeneous datasets and the production of spatially explicit outputs to support decision-making. The overall workflow is illustrated in Fig. 1.

2.1 Reference Context

The methodology has been defined as a framework for coastal risk assessment, intended for application in different Mediterranean coastal environments. The first step, referred to as reference context definition, represents a key phase to ensure coherence and comparability among the collected multi-source data. This step includes:

i) the definition of the spatial reference system;
ii) the delineation of the analysis domain, and
iii) the specification of the temporal framework.

To ensure spatial consistency and interoperability, all datasets should be processed in the same geodetic reference system (e.g., WGS84 or equivalent projected coordinate systems). In parallel, to account for coastal processes across different spatial scales,

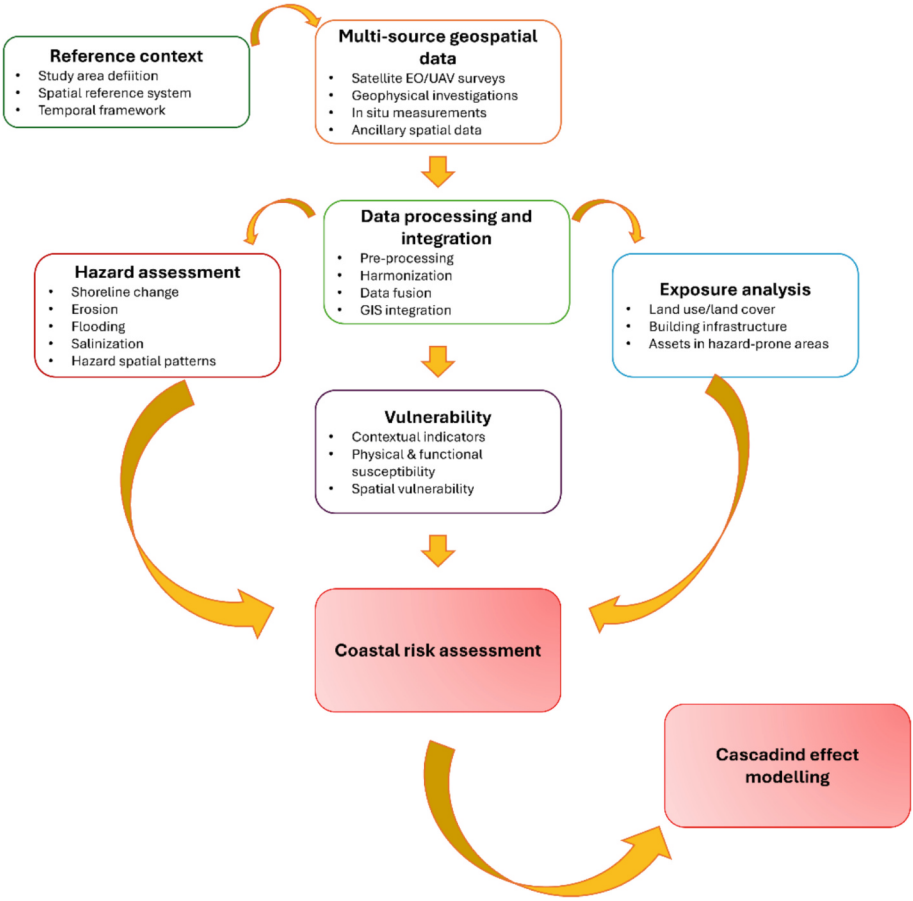

Fig. 1. Conceptual workflow of the methodology.

the spatial domain for each pilot site is defined on the basis of coastal boundaries, geomorphological units, and administrative limits. Lastly, to ensure time consistency, the temporal framework is defined to capture both long-term trends and short-term dynamics. Long-term processes are linked with phenomena evolving over extended periods and are described with multi-decadal datasets (e.g., shoreline evolution and relative sea-level changes); in contrast, short-term dynamics are associated with episodic events such as storms, extreme wave conditions, and coastal flooding. Thus, three pilot sites were selected to represent different Mediterranean coastal conditions: Elounda (Crete, Greece), the Paphos district (Cyprus), and Margherita di Savoia (Puglia Region, Southern Italy) (Fig. 2). This selection is aimed at capturing variability in geomorphological settings, environmental characteristics, and levels of anthropogenic pressure.

Elounda, located in northeastern Crete, is characterized by a complex tectonic setting associated with the subduction of the African plate beneath the Aegean microplate, with carbonate and karst formations and active fault systems influencing coastal dynamics.

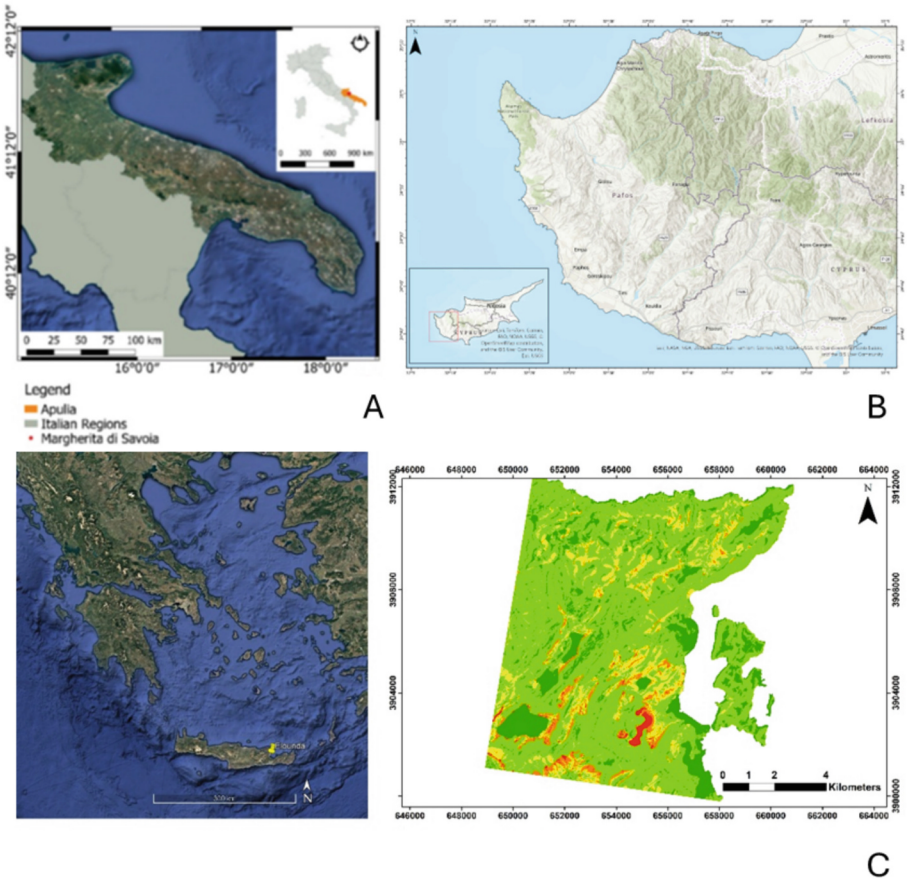

Fig. 2. COASTLINE pilot sites: (a) Margherita di Savoia (Italy); (b) Paphos (Cyprus); (c) Elounda (Crete, Greece).

The Paphos district, in western Cyprus, represents a coastal system of high ecological and cultural value, including protected ecosystems and archaeological heritage. Margherita di Savoia, along the Adriatic coast of southern Italy, is characterized by low-lying sandy shorelines, salt marshes, and pronounced morphological variability, with increasing exposure to coastal hazards.

2.2 Multi-source Geospatial Data

Following the definition of the reference context (Sect. 2.1), the methodology focuses on the acquisition, preprocessing, and integration of heterogeneous geospatial datasets describing both coastal dynamics and elements at risk. The objective is to combine data sources characterized by different spatial resolutions, temporal frequencies, and acquisition techniques in order to obtain a coherent and comprehensive representation

of coastal systems. The datasets considered include: (i) satellite imagery for exploring long-term processes; (ii) UAV-based surveys providing high-resolution topographic and geomorphological information; (iii) environmental and geophysical data, such as bathymetry, sediment characteristics, wave climate, and meteorological forcing; and (iv) socio-economic and infrastructural datasets describing exposed assets and human activities. Given their heterogeneity, these datasets require a harmonization process to ensure spatial and temporal consistency. This process includes georeferencing, spatial resampling, and normalization within a common coordinate reference system, as well as the alignment of datasets with different temporal resolutions. The integration of multi-temporal data allows for investigating coastal dynamics over time, supporting the identification of both long-term trends and short-term variability [20–22]. Hence, the combination of remote sensing and in situ observations improves the robustness and reliability of hazard assessment [23, 24]. This step provides the necessary substratum for all subsequent analyses.

2.3 Hazard Characterization in the Coastal System

Hazard characterization focuses on identifying, quantifying, and depicting coastal processes that pose risks. Contrary to classical methodology, which treats each hazard as an independent variable, coastal hazards are regarded as part of an interacting system in which more than one hazard may occur at the same place and time [25, 26]. This perspective reflects recent developments in multi-hazard and multi-risk assessment, which emphasize process interactions and systemic behavior in complex environments [10, 11]. This approach aligns with current multi-hazard and multi-risk assessment research, which focuses on interactions between processes and their systemic behavior in complex environments [24, 27].

Spatial indicators, which describe processes occurring in time and space, are used for hazard characterization, e.g., rates of shoreline changes, degree of inundation, frequency of extreme event exposure. Indicators of this type allow quantifying hazards in terms of their magnitude and spatial variability, thus providing the possibility to identify areas where risks may potentially be higher than elsewhere. A multi-temporal indicator-based approach has been widely applied in coastal risk analysis as it allows considering processes' evolution over time [21, 22]. The temporal element is essential for depicting the dynamic aspect of coastal risks, both long-term, like sea-level rise, and short-term processes linked to extreme events like storm surges. Both factors acquire significance in relation to coastal hazards, which are dependent on the interaction of gradual and episodic phenomena [3, 18]. In general, the study of hazards involves establishing the spatiotemporal characteristics of coastal phenomena, which serve as the foundation for their synthesis with exposure, vulnerability, and cascade effects.

2.4 Exposure and Vulnerability Assessment

In accordance with EU guidelines, exposure and vulnerability are considered as distinct components of coastal risk, although they are closely interconnected. Both concepts are based on the definition of elements at risk, understood as assets potentially affected

by coastal hazards (e.g., population, infrastructure, economic assets, and environmental resources). Hence, exposure refers to the spatial distribution of these elements at risk, typically categorized into homogeneous groups, including, for instance, built-up areas, critical infrastructure, land use classes, and environmental assets, using geospatial datasets [17, 27]. This classification enables the detection of concentrations of elements at risk in areas prone to hazards' impacts, providing a structured representation of the spatial dimension of risk.

In contrast, vulnerability describes the degree to which exposed elements are susceptible to damage under specific hazard conditions. It is determined by considering the physical characteristics of assets, the environmental sensitivity and adaptive capacity, as well as the socioeconomic factors. These indicators are combined to derive spatially distributed vulnerability levels, in accordance with established approaches to vulnerability analysis [29]. To ensure comparability across spatial units, indicators are normalized when necessary. In this context, vulnerability is recognized as a dynamic property that may evolve in response to repeated or interacting hazard events [28]. This dynamic perspective is particularly relevant in coastal environments, where sequential hazard impacts and process interactions can progressively increase system fragility. As a result, vulnerability is considered inherently linked to the temporal evolution of coastal processes and their cumulative effects.

The explicit distinction between exposure and vulnerability is essential to ensure conceptual clarity in risk assessment, as it separates the spatial distribution of assets from their susceptibility to damage. Their integration enables the identification of areas where high exposure coincides with high vulnerability, which are typically associated with elevated risk levels. Once exposure and vulnerability layers are calculated, they are integrated into hazard characterization and cascading process analysis in order to quantify the amplification of spatial risk patterns and supporting risk-informed decision-making.

2.5 Cascading Hazard Modelling

To explicitly represent cascading coastal hazards, hazard interactions are modeled as a directed weighted graph $G = (V,E)$, where nodes $H_i \in V$ correspond to hazard states derived from multi-source geospatial data, and edges $e_{ij} \in E$ encode dependency relationships between interacting processes. This formulation is in line with recent multi-hazard methodology based on modelling the interconnection among various hazards and the corresponding cascading effects, which are often neglected in conventional approaches. Each hazard is quantified through a data fusion process F based on the integration of multi-source heterogeneous datasets (satellite imagery, UAV surveys, and geophysical measurements):

$$H_i = F\left(D_i^{sat}, D_i^{UAV}, D_i^{geo}\right) \tag{1}$$

where D_i^{sat} represents satellite-derived indicators (i.e., shoreline change rates, spectral indices, and digital elevation models), D_i^{UAV} provides high-resolution topographic and morphological information (e.g., DSMs and orthophotos), and D_i^{geo} captures subsurface

characteristics relevant to sediment dynamics. To ensure cross-scale consistency, the data fusion process includes the co-registration, normalization, and spatial aggregation.

Instead, cascading dynamics are modeled by associating each edge e_{ij} with a weight $w_{ij} \in [0,1]$, representing the strength of interaction, and a conditional probability $P(H_j \mid H_i)$, expressing the likelihood of hazard propagation. This probabilistic interpretation is consistent with Bayesian and multi-risk approaches to compound hazards. The propagation of hazard intensity through the network is expressed as:

$$I(H_j) = \sum_{i \in N(j)} w_{ij} * P(H_j|H_i) * I(H_i) \tag{2}$$

where $I(H_i)$ denotes the normalized intensity of hazard H_i, and $\mathcal{N}(j)$ represents the set of hazards influencing H_j. Edge weights are estimated through spatial correlation between hazard layers:

$$w_{ij} = \frac{Cov(H_i, H_j)}{\sigma_{H_i}\sigma_{H_j}} \tag{3}$$

while conditional probabilities are computed from spatial co-occurrence patterns:

$$P(H_j|H_i) = \frac{N(H_i \cap H_j)}{N(H_i)} \tag{4}$$

where $N(\cdot)$ denotes the number of spatial units satisfying a given condition. This data-driven parameterization allows the framework to capture observed dependencies rather than relying on purely conceptual assumptions. Finally, cascading-aware risk is quantified by integrating the propagated hazard intensity with exposure and vulnerability components:

$$R = H * E * V \tag{5}$$

where H represents the aggregated hazard intensity resulting from graph propagation, E denotes exposure (e.g., infrastructure distribution), and V represents vulnerability factors. This formulation extends traditional risk models by explicitly incorporating hazard interdependencies, enabling a more realistic and dynamic representation of coastal risk processes.

3 Results

The introduced pipeline was applied to quantify the spatial distribution of hazards, as well as their associated vulnerability and exposure, cascading effects, and the resulting risks. Hazards layers are typically derived from satellite, UAV, and geophysical data. Following the data collection phase, these layers are processed and normalized to generate intensity maps $I(H_i)$, which are subsequently integrated into a graph-based model to simulate cascading effects. This approach allows the analysis of interdependencies among coastal processes and the propagation of consequences of hazard conditions in such environments. For instance, Fig. 3 illustrates the interconnection among coastal

erosion *(H_1)*, dune degradation *(H_2)*, flooding susceptibility *(H_3)*, and infrastructure damage *(H_4)*. Indeed, H_1 influences and increases the dune degradation, which, in return, enhances flooding susceptibility, specifically in low-elevation zones, characterized by weak natural protective barriers. The graph underlines both direct and indirect pathways by emphasizing the accumulation of hazard intensity along interconnected processes.

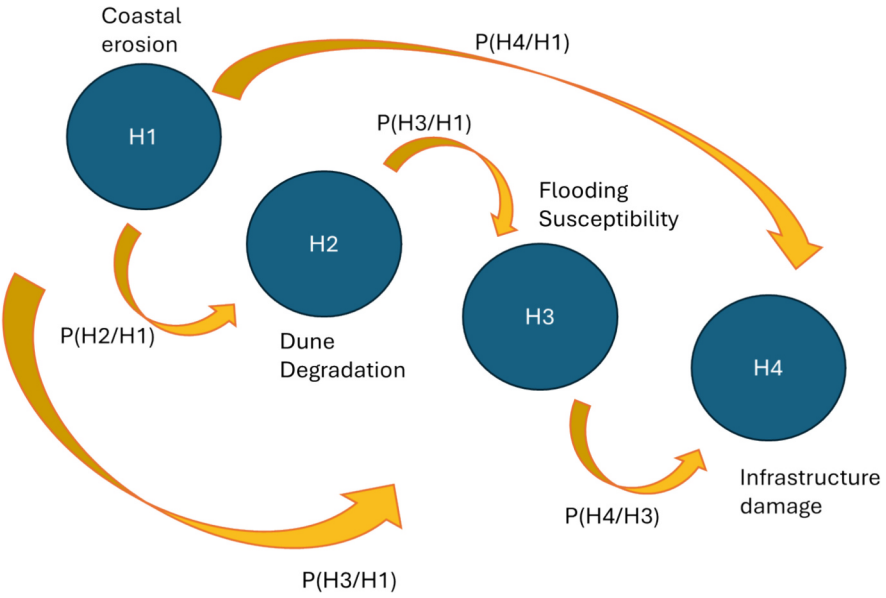

Fig. 3. Example of cascading processes in a coastal environment.

The resultant risk map R, computed by multiplying hazard, exposure, and vulnerability, identifies critical hotspots. Beyond the single-hazard assessment, the inclusion of cascading processes leads to an increased spatial extent and intensity of risk, providing a more comprehensive representation of its spatial distribution. This approach highlights areas that would not be detected when considering hazards independently, thereby enabling a more coherent understanding of complex coastal dynamics.

4 Discussion

The suggested framework provides evidence that the use of multi-source data analysis in the graph-based modeling of interrelated processes improves comprehension of coastal threats. In contrast to the conventional approach focusing on individual threats, the suggested method accounts for interrelationships among different types of coastal risk, allowing for obtaining an overall image of how geological and hydrological processes interact, thus increasing exposure to the hazard. This factor becomes crucial in the case of coastal territories, as any insignificant shift in the landscape, such as a shifting coastline,

leads to enhanced threats and consequences for coastal infrastructures. Nevertheless, there are also some drawbacks to the suggested framework, which should be considered. First, the relationships among different types of coastal risks are based on their concurrent manifestation, and, therefore, do not provide sufficient information regarding causal interactions or temporal dynamics. In addition, as coastal ecosystems possess inherent complexity, they include feedback loops that cannot be completely accounted for in the framework.

The quality of the information being used also proves essential in the analysis. The combination of various sources, including satellite imagery, UAV information, and geophysical measurements, leads to uncertainty caused by varying resolutions, accuracies, and acquisition methods. Even though much work was done towards aligning the datasets, some inconsistencies might still arise, affecting model predictions. Furthermore, the use of the simplified model that focuses only on several interactions between different parameters limits how realistic the analysis is. It is recommended that further improvements in the application include using more sophisticated models, such as dynamic and probabilistic ones, to improve the representation of nonlinear processes. Nevertheless, the framework gives substantial information when it comes to evaluating and mitigating risks. First of all, accounting for the cascading effects of various disasters provides a more comprehensive approach to risk assessment. For example, rising sea levels contribute to coastal erosion, which results in increased flood risks.

The methodology is also adaptable for application in various coastal settings, as long as the appropriate data can be obtained. In addition, it can help with spatial planning, infrastructure design, emergency planning, and the promotion of awareness about coastal hazards and preventive measures.

Future research needs to include temporal aspects in the model, refine the estimate of interaction coefficients using statistical and machine learning methods, and define uncertainty explicitly. Linking the model with scenarios will increase its capacity for decision support in coastal hazard management.

5 Conclusion

This study introduced the integrated geospatial pipeline developed within the COASTLINE project to assess the impact of multi-hazards on areas prone to coastal risk. Indeed, by integrating satellite, UAV, and geophysical data, this approach enables:

i) the identification of elements at risk and hazards occurred in specific coastal areas in Mediterranean regions;
ii) the delineation of coastal zones vulnerable to hazards defined in the previous step;
iii) the assessment of exposure, and, lastly
iv) the quantification of risk, including the combined risks raised from cascading processes.

The results demonstrate that the multi-risk approach facilitates the detection of hotspots caused by the amplification of the impacts of multi-hazards occurring in coastal vulnerable areas. In this way, this scalable and flexible approach provides an effective solution for capturing and describing complex hazard dynamics. Thus, in addition to its

methodological contribution, the developed framework supports coastal management and climate adaptation, fostering more informed and evidence-based decision-making.

Acknowledgments. This research has been supported by the European Union's Horizon Europe Framework Programme (COASTLINE Project - Grant Agreement N. 101130576 – CUP: D93C23000960006) under the grant agreement No 101130576. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

References

1. Boccia, L., Capolupo, A., Rigillo, M., Russo, V.: Terrace abandonment hazards in a Mediterranean cultural landscape. J. Hazardous Toxic Radioact. Waste **24**(1), 04019034 (2020)
2. Capolupo, A., Saponaro, M., Fratino, U., Tarantino, E.: Detection of spatio-temporal changes of vegetation in coastal areas subjected to soil erosion issue. Aquat. Ecosyst. Health Manag. **23**(4), 491–499 (2020)
3. Nicholls, R.J., Cazenave, A.: Sea-level rise and its impact on coastal zones. Science **328**(5985), 1517–1520 (2010). https://doi.org/10.1126/science.1185782
4. IPCC. Climate change 2021: The physical science basis. Cambridge University Press (2021). https://doi.org/10.1017/9781009157896
5. Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J.: Future coastal population growth and exposure to sea-level rise. Nat. Clim. Chang. **5**(3), 197–201 (2015). https://doi.org/10.1038/nclimate2462
6. Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., et al.: Sandy coastlines under sea-level rise. Nat. Clim. Chang. **10**, 260–263 (2020). https://doi.org/10.1038/s41558-020-0697-0
7. Leatherman, S.P., Zhang, K., Douglas, B.C.: Sea level rise shown to drive coastal erosion. EOS Trans. Am. Geophys. Union **81**(6), 55–57 (2000). https://doi.org/10.1029/00EO00034
8. Feagin, R.A., Sherman, D.J., Grant, W.E.: Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. Front. Ecol. Environ. **3**(7), 359–364 (2005)
9. Zhang, K., Douglas, B.C., Leatherman, S.P.: Global warming and coastal erosion. Clim. Change **64**(1–2), 41–58 (2004). https://doi.org/10.1023/B:CLIM.0000024690.32682.48
10. Kappes, M.S., Keiler, M., von Elverfeldt, K., Glade, T.: Challenges of analyzing multi-hazard risk: a review. Nat. Hazards **64**(2), 1925–1958 (2012). https://doi.org/10.1007/s11069-012-0294-2
11. Gill, J.C., Malamud, B.D.: Reviewing and visualizing the interactions of natural hazards. Rev. Geophys. **52**(4), 680–722 (2014). https://doi.org/10.1002/2013RG000445
12. Capolupo, A., Papadopoulos, N., Varitimiadis, S., Mancini, F., Sotiropoulos, P., Papakonstantinou, A.: The COASTLINE project: integrating advanced geospatial technologies for coastal monitoring and management. In: Italian Conference on Geomatics and Geospatial Technologies, pp. 322–332. Springer, Cham (2024)
13. Pescaroli, G., Alexander, D.: A definition of cascading disasters and cascading effects: going beyond the 'toppling dominos' metaphor, Global Risk Forum, GRF Davos Planet@Risk **3**(1), Special Issue on the 5th IDRC Davos 2014, March 2015 (2015)
14. Zuccaro, G., De Gregorio, D., Leone, M.F.: Theoretical model for cascading effects analyses. Int. J. Disaster Risk Reduct. **30**, 199–215 (2018)
15. Hallegatte, S., Green, C., Nicholls, R.J., Corfee-Morlot, J.: Future flood losses in major coastal cities. Nat. Clim. Chang. **3**(9), 802–806 (2013). https://doi.org/10.1038/nclimate1979

16. Aerts, J.C.J.H., Botzen, W.J.W., Emanuel, K., Lin, N., de Moel, H., Michel-Kerjan, E.O.: Evaluating flood resilience strategies for coastal megacities. Science **344**(6183), 473–475 (2014). https://doi.org/10.1126/science.1248222
17. Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M.L., Di Ruocco, A.: Basic principles of multi-risk assessment. Nat. Hazards **62**(2), 551–573 (2012). https://doi.org/10.1007/s11069-012-0092-2
18. Vitousek, S., Barnard, P.L., Fletcher, C.H., Frazer, N., Erikson, L., Storlazzi, C.D.: Doubling of coastal flooding frequency. Nat. Clim. Chang. **7**(9), 681–686 (2017). https://doi.org/10.1038/nclimate3323
19. Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R.: The value of estuarine and coastal ecosystem services. Ecol. Monogr. **81**(2), 169–193 (2011). https://doi.org/10.1890/10-1510.1
20. Casella, E., et al.: Study of wave runup using UAV photogrammetry. Remote Sens. **8**(7), 549 (2016). https://doi.org/10.3390/rs8070549
21. Turner, I.L., Harley, M.D., Drummond, C.D.: UAVs for coastal monitoring. Earth Surf. Proc. Land. **41**(1), 157–165 (2016). https://doi.org/10.1002/esp.3786
22. Vos, K., Splinter, K.D., Harley, M.D., Simmons, J.A., Turner, I.L.: CoastSat: satellite-derived shoreline monitoring. Coast. Eng. **150**, 160–174 (2019). https://doi.org/10.1016/j.coastaleng.2019.04.011
23. Bird, E.C.F.: Coastline changes. A global review. United States: web (1985)
24. Mentaschi, L., Vousdoukas, M.I., Pekel, J.F., Voukouvalas, E., Feyen, L.: Global long-term observations of coastal erosion and accretion. Sci. Rep. **8**(1), 12876 (2018)
25. Capolupo, A., et al.: An interactive WebGIS framework for coastal erosion risk management. J. Mar. Sci. Eng. **9**(6), 567 (2021)
26. Montanino, A., Sotomayor, M.M., Franci, A.: One-way coupled Eulerian-Lagrangian strategy for wave propagation and impact on coastal areas. Commun. Nonlinear Sci. Numer. Simul. **147**, 108845 (2025)
27. Vousdoukas, M.I., et al.: Sandy coastlines under threat of erosion. Nat. Clim. Chang. **10**(3), 260–263 (2020). https://doi.org/10.1038/s41558-020-0697-0
28. Capolupo, A., Tarantino, E.: Multivariate geospatial modelling of drought exposure using multi-year remote sensing data. Procedia Comput. Sci. **277**, 928–947 (2026)
29. Capolupo, A., Boccia, L.: Innovative method for linking anthropisation process to vulnerability. World Rev. Sci. Technol. Sustain. Dev. **17**(1), 4–22 (2021)