Ocean and Coastal Management 268 (2025) 107751

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Review

Methodological advances in sea level rise vulnerability assessment: implications for sustainable coastal management in a climate change scenario

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ARTICLE INFO

Keywords:
Sea level rise
Coastal vulnerability
Coastal risk
Mediterranean region

ABSTRACT

Sea level rise (SLR) is one of the most evident consequences of global warming. Low-lying coastal areas with mobile coastal systems are particularly exposed to sea level change (SLC), both transient (storm surges and tsunamis) and permanent (SLR), especially when coupled with vertical land movements (VLMs), determining local relative sea level rise (RSLR). In the last two decades, several studies have focused on the analysis of coastal processes linked with SLC, in particular regarding the expected SLR up to 2150 AD and beyond. In this study, starting from a critical analysis of methods exploited for the assessment of the vulnerability to RSLR and their suitability, a tailored approach for the impact assessment as an operative tool for the management of coastal areas in a changing climate is proposed.

Our analysis was carried out through the evaluation of 49 selected studies, which were included in a specifically implemented database by searching in Scopus. Special focus was given to the methodological aspects for evaluating RSLR impacts as the vulnerability of the coastal areas of the Mediterranean region published in the last five years. This insight shows that the static approach represents the most popular method for the analysis and visualization of the expected coastal modifications, followed by the model-based approach. Furthermore, the evaluation of the suitability level of each accounted method highlighted that topographic and index-based methods are significant for regional analyses, whilst model-based approaches are strongly exploited for site-specific analyses. Based on the outcomes of this analysis, a multi-step procedure for coastal zone management is proposed.

1. Introduction

One of the most evident consequences of the current global warming is the sea level rise (SLR), as shown in the latest Assessment Report (AR6), published by the Intergovernmental Panel on Climate Change (IPCC) in 2021. Several papers published after 1995 focus on past and current global sea level trends (Gornitz, 1995; Lambeck et al., 2014; 2010, 2011; Cazenave and Llovel, 2010; Meyssignac and Cazenave,

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https://doi.org/10.1016/j.ocecoaman.2025.107751
Received 8 March 2025; Received in revised form 6 May 2025; Accepted 11 May 2025
Available online 26 May 2025

2012; Chambers et al., 2017; Zerbini et al., 2017; Cazenave and Moreira, 2022; Pandžić et al., 2024; Forster et al., 2024).

Tide gauge data available since the late 19th century highlighted that in the period 1901–1990 the global mean sea level (GMSL) rose at a rate of around 1.7 mm/yr (Wenzel and Schroter, 2010; Church and White, 2011; Ray and Douglas, 2011; Spada and Galassi, 2012; Dangendorf et al., 2017). Since 1992, in situ observations integrated with satellite data have provided global sea level trends (Cipollini et al., 2017; Cazenave et al., 2018). The analysis of data from radar altimeters showed that contemporary GMSL is rising at a much higher rate with respect to the previous decades (Adebisi et al., 2021). Ablain et al. (2009) estimated a mean SLR of 3.3 ± 0.4 mm/year during 1993–2009. The WCRP Global Sea Level Budget Group (2018) estimated an average SLR of 3.1 ± 0.3 mm/yr over the period 1993–2018, with an acceleration of 0.1 mm/yr^2. Since 2016, the Copernicus Climate Change Service (C3S) provides free downloadable climate datasets for the European region. Data are dedicated to the monitoring of the long-term evolution of sea level using up-to-date altimeter standards, computed as sea level anomalies with respect to a twenty-year mean reference period (1993–2012) (https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-level-global?tab=overview). C3S also provides a user-friendly interface for the daily change in GMSL measured by satellite altimetry from January 1993 to June 2023, with an associated uncertainty of 90 % confidence level and the relative trend over the accounted period. Concerning sea level projections for the next decades, according to the IPCC (2021), GMSL could rise by up to 1.01 m by 2100 (relative to a baseline of 1995–2014) under the worst-case climate scenario (SSP5-8.5). To promote access to the most updated sea level projections for five different climatic scenarios, namely the Shared Socioeconomic Pathway (SSP) and their distribution, a dedicated web-tool has been released by NASA (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?type=global).

At the local scale, coastal areas can be affected by local vertical land movements (VLMs) - uplift or subsidence - including anthropogenic factors, that could locally exacerbate or reduce the local SLC (Vecchio et al., 2024). The magnitude of sea level change at a certain location (relative sea level rise = RSLR) is related to climatic variations but also to vertical movements of the topographic surface (VLMs) due to tectonic and isostatic causes, natural compaction of sediments and thermal expansion or contraction of oceans (steric contribution) (Lambeck et al., 2011; 2011; Anzidei et al., 2014). The various contributions can be summarized in the equation:

$$\Delta\zeta rsl = \Delta\zeta E + \Delta\zeta I + \Delta\zeta T + \Delta\zeta S + \Delta\zeta CN$$

The relative sea level ($\Delta\zeta rsl$) is determined by the sum of the eustatic ($\Delta\zeta E$), isostatic ($\Delta\zeta I$), tectonic ($\Delta\zeta T$), steric ($\Delta\zeta S$) and sediment compaction ($\Delta\zeta CN$) contributions. The contribution of anthropogenic activities must also be considered in SLR analysis. For example, in some areas, land subsidence can be triggered by fluid extraction (e.g. hydrocarbons and/or groundwater) or sediment compaction also due to the overload on the land surface by infrastructures or buildings. This implies that in the previous equation we need to consider the anthropic contribution $\Delta\zeta A$ and then, according to Mastronuzzi et al. (2013), it is further modified as:

$$\Delta\zeta rsl = \Delta\zeta E + \Delta\zeta I + \Delta\zeta T + \Delta\zeta S + \Delta\zeta CN + \Delta\zeta A$$

In particular, land subsidence has a crucial role in the future RSLR projections (Fig. 1). The rate and amount of VLMs can be estimated for long-term (geological) and short-term (instrumental) data. The first data are generally inferred from the Late Pleistocene and Holocene sea level indicators (e.g., Pirazzoli and Umgiesser, 2006, 2005; Fereshtehpour and Karamouz, 2018; Lambeck et al., 2011; Antonioli et al., 2020, 2015; Anzidei et al., 2014; Vacchi et al., 2016; Rovere et al., 2016), while the current rates of VLMs can be estimated by the up component of the time series of GNSS data from stations located near the coasts and by InSAR data (Bürgmann et al., 2000; Matano et al., 2018; Anzidei et al., 2021). In addition, to account for the isostatic contribution to the observed VLM, different GIA models are used in the analysis (Lambeck et al., 2011, 2014; Spada and Galassi, 2012; Argus et al., 2014; Roy and Peltier, 2015).

The combined effect of sea level rise and land subsidence poses a significant threat to low-lying areas, such as in large river deltas and coastal plains, but also along gently sloping rocky areas (Syvitski et al., 2009; López-Dóriga and Jiménez, 2020; Rodriguez-Lloveras et al., 2020; Nicholls et al., 2021; Vecchio et al., 2024).

In the Mediterranean basin, several coastal areas are affected by land subsidence, leading to high rates of RSLR. For instance, in the Venice Lagoon (Northern Italy), the projected SLR, combined with local land subsidence estimated from the analysis of Sentinel-1 images acquired between 2015 and 2019, is expected to result in a mean RSLR of 30 cm by 2050 (Tosi et al., 2020, 2024) and 82 cm by 2100 (Vecchio et al., 2024).

Fig. 2 presents sea level trends estimated for Genoa (Fig. 2a), Trieste (Fig. 2b), and Venice (Fig. 2c and d). These data, collected from in situ tide gauges, indicate that in the subsiding area of Venice, sea level has been rising at higher rates both historically and in the recent period (2000–2024). In contrast, the sea level trends for Genoa and Trieste appear relatively similar (see caption of Fig. 2).

Along the Nile Delta (Egypt), InSAR and GPS data indicate land subsidence rates ranging from 8 to 3 mm/year (Rateb and Abotalib, 2020). In Spain (Rodriguez-Lloveras et al., 2020), the land subsidence in the Ebro Delta has been estimated at 1.0–2.3 mm/yr from DInSAR data, with higher values along the distal area (Grases et al., 2020). Apart from the vulnerability due to the submergence of those areas considering SLR

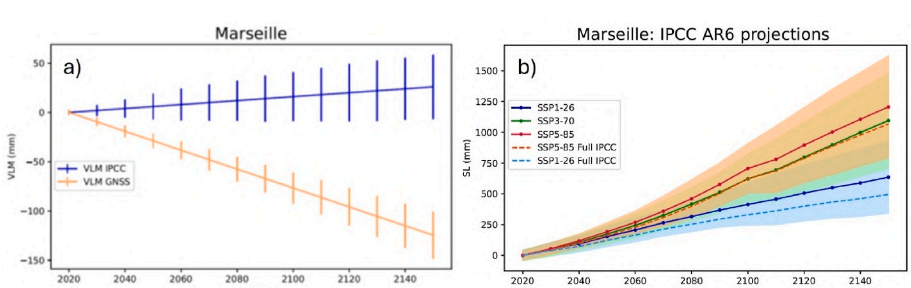

Fig. 1. Example of the relevance of VLM in the SLR projections for 2150 AD at Marseille (France). In a), the plot with the considered VLMs (in mm) by the IPCC models (in blue) and that estimated by the geodetic data (in orange) is shown. In b), the revised relative sea level projections to 2020 at the PSMSL tide gauge station of Marseille (France) for three SSP scenarios (full lines) and corresponding uncertainties (shadowed areas of the same tone as the lines) are presented. The original IPCC projections for the most optimistic and pessimistic scenarios are also shown (dashed lines, without uncertainties). Assuming the VLM will remain constant in time until 2150, the IPCC projections underestimate the projected SLR of about 15 cm (modified from Vecchio et al., 2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

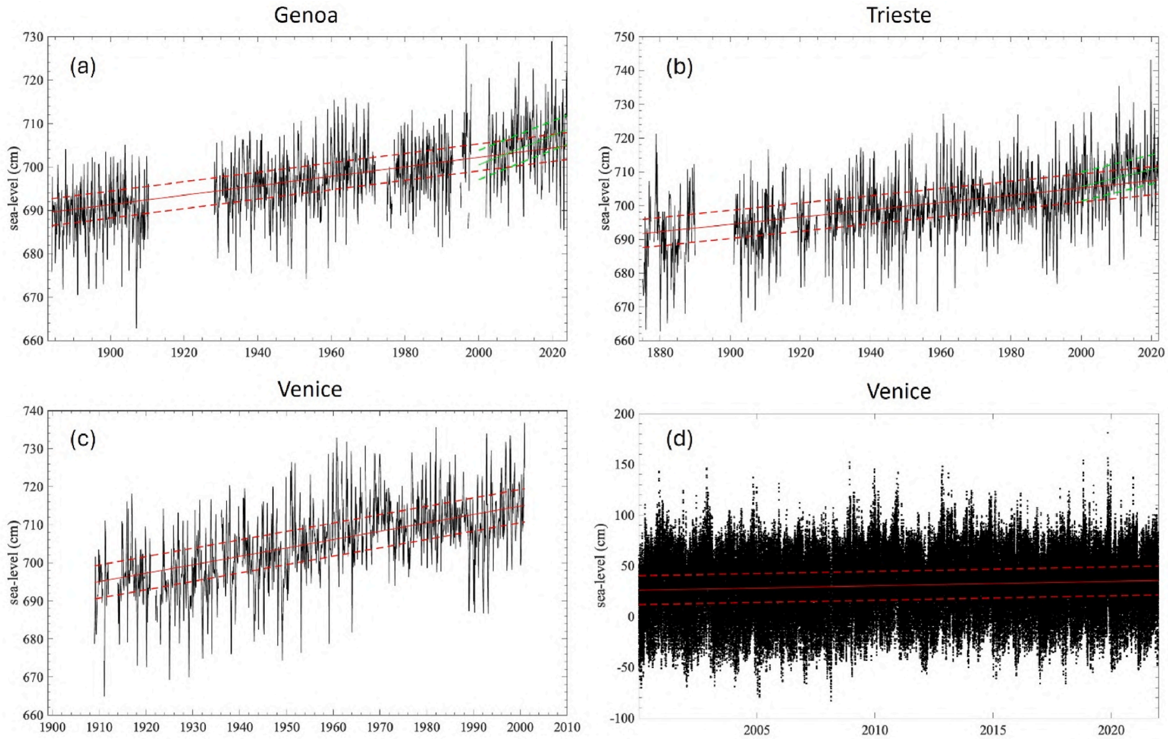

Fig. 2. Example of sea level trends estimated for three Italian sites with different VLMs. Data collected at a) Genoa and b) Trieste exhibit comparable trends, with rates of 1.09 ± 0.04 mm/yr and 1.08 ± 0.06 mm/yr for the historical period (Genoa: 1884–2024; Trieste: 1875–2022), and of 3.51 ± 0.29 mm/yr and 2.65 ± 0.41 mm/yr for about the last two decades (Genoa: 2000–2024; Trieste: 2000–2022). Conversely, data from Venice indicate significantly higher rates, reaching 2.23 ± 0.1 mm/yr for the period 1872–2000, and 4.4 ± 0.5 mm/yr for the period 2000–2024. Historical sea level data are available from the Permanent Service Mean Sea Level (https://psmsl.org/), while the Italian tide gauge network has been managed since 2000 by the Italian Institute for Environmental Protection and Research (ISPRA).

rates, higher water levels linked with SS and Ts are expected to have greater impacts on the coastal zones, in terms of temporary flooding, erosion and sinkhole generation (Pignatelli et al., 2009; Mastronuzzi et al., 2013; Hartmann et al., 2014; Parise et al., 2015; Vousdoukas et al., 2016; Liso and Parise, 2020; Olarinoye et al., 2020; Johnston et al., 2021; Anzidei et al., 2021; De Dominicis et al., 2020; Grezio et al., 2024; Anzidei et al., 2023; Grezio et al., 2025). Combined with projected variations of hydrological regimes, resulting in more severe and prolonged summer droughts, rising sea level can also intensify saltwater intrusion in coastal water bodies (Masciopinto and Liso, 2016; Bonaldo et al., 2023) with consequences on the availability of freshwater resources. Since the sea is the base level for the outflow of groundwater discharge, any upward movement in its mean position will reduce the hydraulic heads of inland water bodies (Bear, 1979). In coastal aquifers, such a reduction enhances the advancement of the saline intrusion wedge, with consequent pollution of groundwater and soil salinization (Werner and Simmons, 2009; Carretero et al., 2013; Lu et al., 2015).

In this context, the Mediterranean region, which hosts approximately 7 % of the world's population, has been classified as a "climate change hotspot" since it is warming 20 % faster than the global average (Giorgi, 2006; Cramer et al., 2020). In addition, the formation of large storms known as "medicanes" (Mediterranean hurricanes) is modified with respect to today's climate (Flaounas et al., 2022; Kushabaha et al., 2024). The combination of SLR and intense storm surges has severe implications on agriculture, freshwater availability, and human settlements in the urbanized areas (Fig. 3), like in the Nile Delta, the Ebro River Delta, and coastal cities such as Venice. In the latter, rising sea levels, coupled with intense weather events, have caused, in recent

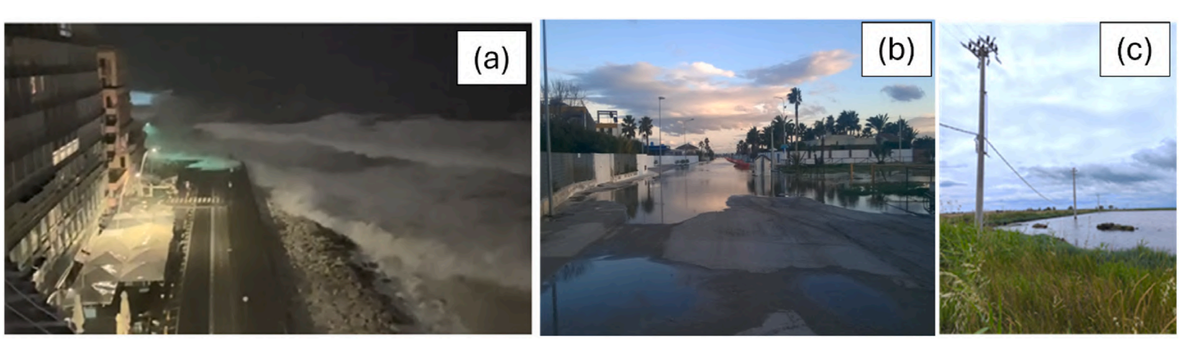

Fig. 3. Examples of storm surges and SLR impacts in southern Italy: a) flooding of an urban sector of Naples (Campania Region) during a marine storm in March 2021 (photo from Mattei et al., 2021); b) sea flooding in February/March 2009 at the Ippocampo residential area (Tavoliere delle Puglie, Foggia, Apulia region - photo taken in March 2009 by Prof. M. Caldara); c) area flooded as a consequence of current RSLR along the coastal plain of Tavoliere delle Puglie near the Carapelle river mouth (May 2024).

years, a significant increase in the frequency and severity of flood events (Stanley and Clemente, 2017; Lionello and Scarascia, 2018; Lionello et al., 2020; Ferrarin et al., 2021; Alberti et al., 2023; Faranda et al., 2023).

Due to the remarkable relevance that such a topic has in the context of risk assessment and climate change adaptation, several research projects have been funded by national and international programs. For example, the SAVEMEDCOASTS-1 (https://www.savemedcoasts.eu/index.php) and SAVEMEDCOASTS-2 projects (https://www.savemedcoasts2.eu/index.php/it/) focused on a rigorous methodology to map flooding scenarios due to SLR (Vecchio et al., 2024; Anzidei et al., 2021, 2023). Similarly, specific mapping and visualization tools have been developed in the framework of other international projects, such as EuroSea (https://eurosea.eu/outputs-reports/), the Connecticut Sea Level Rise and Storm Surge Viewer (https://circa.uconn.edu/sea-level-rise/tools/), and the CoCliCo service (https://coclicoservices.eu/).

Although several reviews have focused on the assessment of the potential impacts triggered by climate change in the Mediterranean area (Cramer et al., 2018; Sarkar et al., 2022; D'Ettorre et al., 2024) as well as the assessment of the coastal vulnerability and risk to geo-environmental processes (Roukounis and Tsihrintzis, 2022; Rizzo et al., 2022a, 2024; Zanin et al., 2024), this study focuses on the most common methods applied for addressing SLR impacts. Starting from the search of research articles dealing with global SLR and local RSLR, we examined recent publications for the last five years (2019–2024) to provide a critical overview of methodological approaches used in the various Mediterranean countries and an assessment of their suitability.

2. Materials and Methods

In order to obtain an adequate number of papers for the analysis of the methodological approaches exploited in studies on SLR impact, a preliminary bibliographic research was performed. Then, the collected papers were first analyzed from a bibliometric perspective to gain quantitative information on their temporal and geographic distribution, and, secondly, methodological aspects were explored to evaluate their suitability level.

2.1. Bibliographic search

A systematic literature review was conducted in March 2024 using the Scopus database, an authoritative source for scientific research that offers advanced search and filtering functionalities (Martín-Martín et al., 2021). It is worth noting that Scholar and Web of Science databases were not used in this study for the following reasons: i) to exclude from the evaluation unpublished works and grey literature that are contained in Scholar; ii) Scopus and WoS have considerable overlap in scientific documents, but Scopus covers many publications not included in WoS. The search was performed by applying a number of research queries to the "Article Title" field and limiting the search to "Article" and "Review" papers. Furthermore, it is worth noting that the words used for the selection of papers are joined by the Boolean operator "AND", and this means that the results of the search contain both or all the used words.

The methodological approach was aimed at collecting the most relevant peer-reviewed papers in a specific database. The conceptual model of the applied approach is based on a four-stage procedure (Fig. 4) that aims to reconstruct the state-of-the-art on sea level variations' impacts on the coasts from a global overview to a local analysis of the Mediterranean coasts.

In detail, in the first stage (Phase 1), the search was focused on peer-reviewed articles concerning either sea level rise (SLR), storm surge (SS), and tsunami (Ts), in order to identify pertinent studies available at the global level on the most-relevant marine-related processes impacting the coasts. In this case, the following research queries were applied: "Sea AND Level AND Rise", "Storm AND Surge", and "Tsunami".

The second stage of the analysis (Phase 2) was aimed at identifying studies at the global scale that integrate the SLR with weather-related (i.e., storm surges) and extreme events (i.e., tsunamis) and coastal

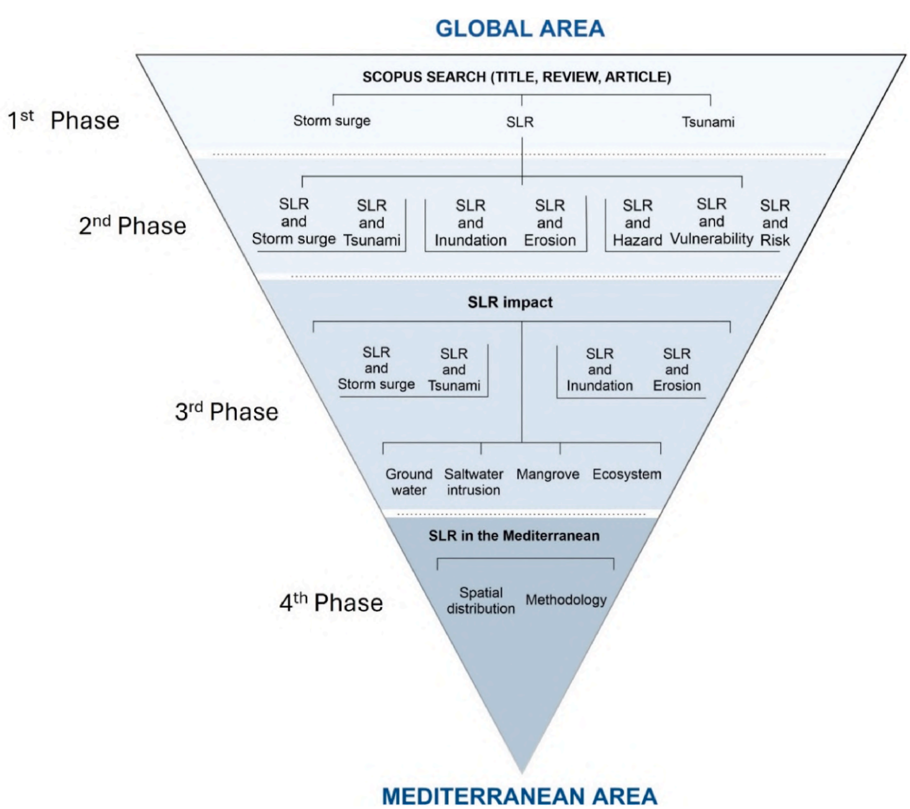

Fig. 4. Methodological approach applied to implement the database of peer-reviewed papers dealing with the SLR at the global and the Mediterranean scale.

processes, in terms of erosion and flooding (the latter searched by considering the terms "flooding", "inundation", and "submersion"). Furthermore, based on the general definition of the risk (IPCC, 2014), in this phase, the combination of "Sea Level Rise" and the terms "Hazard", "Vulnerability", and "Risk" was also investigated to select studies focused on procedures of analysis. The term "Exposure" is not accounted due to the finality of the study.

Subsequently, in the third stage (Phase 3), the search was further refined to focus specifically on studies examining the impact of SLR coupled with each of these phenomena individually, still at a global level. In this case, the first query was defined as "Sea AND Level AND Rise AND Impact", while in the further queries, the previous words related to coastal effects ("erosion", "flooding", "inundation", and "submersion") have been added. In this stage, we expanded our search to consider the connections between SLR and specific coastal elements through the following keywords: groundwater, saltwater intrusion, mangrove, and ecosystems.

Finally, the last phase of the analysis (Phase 4) entailed filtering the comprehensive dataset to identify studies conducted within the Mediterranean Basin and to assess both their spatial distribution and different methodological approaches applied for the evaluation of sea level variations' impact. This latter aspect was analyzed, focusing on studies published in the last five years (from January 2019 to March 2024) to highlight recent improvements and developments in the methods of analysis. Selected papers were evaluated through expert-based knowledge of the topics and, in the case of missing items, they were added.

In summary, the database was implemented by the following steps:

- Identification of documents meeting the selected queries in Scopus (Phases 1–3 in Fig. 4);
- Importing the identified papers into the costumed Zotero database by using the BibTex format;
- Automatic identification and removal of duplicate items;
- Selection of the papers dealing with the Mediterranean areas and exclusion of those documents not fitting the analysis criteria (Phase 4 in Fig. 4);
- Selection of the papers dealing with the Mediterranean areas, published in the period 2019–2024 (Phase 4 in Fig. 4).

2.2. Data analysis

Once the database was implemented, a bibliometric approach was employed to investigate research productivity in terms of globally published papers per year, focusing on the annual output of documents. Then, detailed analyses were performed on the subset of papers published in the Mediterranean countries selected in Phase 4 of the approach above described. In this case, as shown in Fig. 4 (Phase 4), the following aspects were explored: i) Analysis of the publishing trend, ii) Analysis of the geographic distribution, iii) Analysis of the methodological aspects for coastal impact evaluation.

Based on the assumption that the sea level issue can be investigated both in a qualitative and a quantitative way, the methodologies were classified as follows:

- index-based approaches (based on the integration of several variables into a single comprehensive index);
- model-based approaches (based on the application of numerical models for the simulation of dynamic scenarios);
- GIS-based approaches (based on the application of specific tools for the analysis of topographic data);
- geometric approaches (based on the application of specifically proposed formulas).

To this aim, the "Materials and Methods" section of each paper was consulted and details on the applied methods were collected.

3. Results

3.1. – Analysis of the scientific papers

The bibliographic search was carried out by applying several queries in the Scopus database, focusing on the documents' titles and limiting the search to "research articles" and "reviews". Based on the collected papers, a comprehensive database was implemented.

The results obtained from the analysis at the global scale highlighted that:

- Since (2008), the publishing rate of papers has strongly increased, from 148 papers published in the period 1989–2007 to 1066 papers published in the period 2008–2024.
- The number of papers including the word "tsunami" in their title is higher than those containing the words "sea level rise" and "storm surge" (respectively, 62 %, 24 %, and 14 % of the total papers resulting from the search queries);
- the number of papers containing in their title at the same time the words "sea level rise" and "storm surge" is higher than those including "sea level rise" and "tsunami" (113 and 19 papers, respectively);
- the number of papers containing in their title the words "SLR" coupled with Hazard, or Vulnerability, or Risk has a remarkable difference (51, 215, and 147, respectively).

The results obtained from the analysis for the Mediterranean area highlighted:

- The highest number of published papers identified for the year 2021 agrees with the analysis performed by Rousseau et al. (2023), who observed that the number of research articles and reviews published in 2021 in almost all scientific research fields has strongly increased, even more than expected;
- a higher percentage of papers (87 %) was published in the period 2008–2023 in Italy and Spain, which are the most productive countries, followed by Egypt;
- 13 out of the 43 investigated papers deal with the analysis of "SLR" impact coupled with the "storm surge" process.

3.2. – Analysis of the methodological approaches used to evaluate the impacts of sea level rise

Analysis of the methodologies applied for the evaluation of SLR impacts was carried out by considering the 49 papers included in the sub-dataset (i.e., papers published in the last 5 years dealing with the SLR in the Mediterranean area), comprising 45 research articles (91.8 %) and 4 reviews (8.2 %) which were categorized according to the method applied for the investigation (cf. section 2.2). This analysis highlighted that the majority of the papers (19 out of 49) use the GIS-based static method to evaluate the SLR impact. Modelling approaches have been applied in 11 out of the total analyzed papers. Finally, the number of studies that exploited the geometric approach and the index-based approach is quite similar (8 and 10 papers, respectively, for each method).

In Fig. 5, the relative percentage of each method resulting from the analysis of the selected papers is shown. It is worth noting that the percentage values are evaluated taking into account that in five papers, a combination of two methods is applied. Based on our analysis, it emerged that i) 40 % of the analyzed papers exploit the static GIS-based method for the evaluation of coastal impact in terms of inundation, and, among those, 74 % (14 papers) are focused on the SLR issue; ii) high-resolution numerical models are used in approximately 20 % of the collected papers, with case studies carried out in Italy and Spain; and iii) despite its limitations and criticalities, the geometric approach is still used to assess the potential coastal retreat in studies mostly carried out

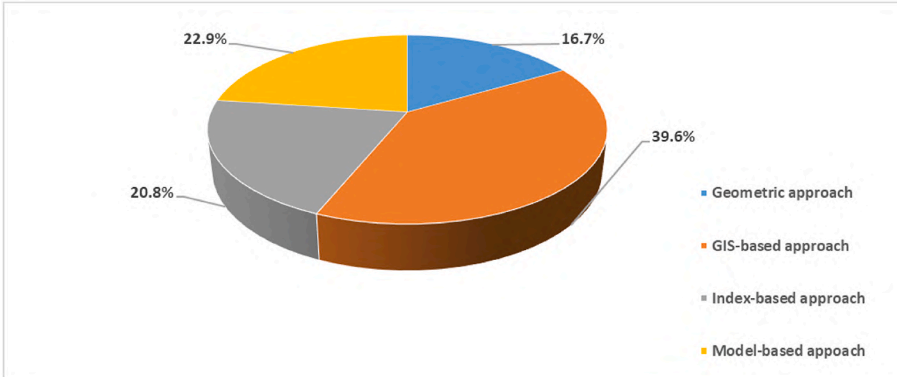

Fig. 5. Percentage of methodological approaches applied in the articles selected for this study.

in Spain and Egypt.

4. Discussion

4.1. GIS-based method

According to the analysis of this study, the GIS-based method was the most used methodological approach developed for the assessment of vulnerability due to the impact of SLR. Following this method, an area is deemed vulnerable to the effects of a temporary or permanent SLR if its topographic elevation is lower than the expected sea level. This kind of approach, commonly referred to as the "bathtub method" (NOAA, 2012), requires high-resolution Digital Elevation Models as a topographic base of the investigated areas (Kulp and Strauss, 2018; Marsico et al., 2017; Vernimmen and Hooijer, 2023). The output of this altimetric approach, which requires the definition of orthometric elevations, is usually a map of potential inundation, highly valuable for identifying hot-spot areas, i.e., areas that, due to their specific topographic characteristics, require more extensive investigation and priority management actions (Di Paola et al., 2021). The static method, on the other hand, does not allow for the analysis of any possible morpho-dynamic response of potential resilient environments, such as mobile coastal systems, in which the local sedimentary budget can thwart the SLR (Fig. 6), allowing the system to dynamically respond and adapt to the rising sea level (Passeri et al., 2015; Cooper, 2022). Similarly, the static method does not account for poor sediment supply and unfavorable sediment transport gradients that can lead to erosional hotspots. A schematic representation of the different morphodynamic responses between a resilient (in which the sediment input is higher than RSLR) and an inactive (in which the sediment input cannot balance the RSLR) coastal system is indicated in Fig. 6. In detail, the expected and the future MSL (MSLt1 and MSLt2 = t3, respectively) will result in a landward shift and co-adjustment of the coastal forms in the case of resilient system (in blue in Fig. 6) and in a predominant coastal erosion and consequent inundation of the low-lying areas in the case of inactive system (in red in Fig. 6).

A key input parameter for the application of the GIS-based static approach is represented by the resolution of the topographic information, in terms of vertical spatial accuracy and altimetric datum (Fereshtehpour and Karamouz, 2018; Gesch, 2018). Furthermore, it is necessary to harmonize the reference systems and altimetric datums to which the SL values and the topographic data are referred, as in Anzidei et al. (2023) and Ricciardi et al. (2024). The static approach is used for the analysis of both SLR and SS (Fig. 7). Based on the articles collected, this approach has been used extensively in Italy, accounting for 50 % of the papers that examined the coasts of the country. The first application to a vast area of the Italian territory was used in 1995 to analyze the risk of inundation for storm surges and SLR in the northern Adriatic (Bondesan et al., 1995). Later, Gambolati et al. (2002) re-examined the same area using a similar methodology. The GIS-based static method was then applied using more precise altimetric data to create SLR inundation maps for 33 Italian coastal plains by Lambeck et al. (2011). In Aucelli et al. (2017), inundation maps were obtained by coupling global sea level projections (IPCC, 2014) with local subsidence trends derived by multi-temporal interferometric processing of satellite Synthetic Aperture Radar (SAR) images, to classify the investigated territories in different classes of exposure, as in Aucelli et al. (2018) and Di Paola et al. (2018, 2021). In the works by Anzidei et al. (2017, 2020, 2023, 2024), maps of the SLR scenarios for the next decades were instead realized taking into account the VLMs rates, as estimated by GNSS stations located near the coastline and regional IPCC projections (RCP-2.6 and RCP-8.5 scenarios). Following this approach, maps of coastal submersion scenarios for the years 2100 and 2300 are proposed for four Italian coastal plains in Deiana et al. (2021). Antonioli et al. (2017) provided maps of SLR scenarios for 2100 combining global projections by IPCC (2014) and Rahmstorf (2007) models, considering long-term tectonic behavior without referring the obtained scenarios to the orthometric elevations and neglecting the contribution of VLMs through the analysis of geodetic data and any possible local resilience of the coastal systems, as similarly done in Marsico et al. (2017), Antonioli et al. (2020), and Lo Presti et al. (2022). In particular, the paper by Antonioli et al. (2020) focused on some sectors of the Mediterranean coasts where SLR could severely impact anthropic activities, due to the presence of strategic infrastructures.

A comprehensive analysis of the RSLR issue for the Northern Mediterranean area was performed by Vecchio et al. (2024), in which updated VLMs estimated from geodetic data were used to revise local SL projections up to 2150 AD. The results obtained from the static RSLR analysis indicate that about 19.000 km^2 of the investigated Mediterranean coasts will be potentially exposed to the risk of inundation during the next decades. Applications of the static approach for the analysis of the coastal sector of Egypt are also shown in Abou Samra et al. (2021) and Elshinnawy and Almaliki (2021), where Bruun's rule (Bruun, 1962) is applied for the analysis of the shoreline landward shift, as done also in López-Dóriga and Jiménez (2020).

It is worth noting that the static approach is mostly used for assessing permanent submersion due to SRL. Only in some cases, the SS process is also analyzed by the static method (Anzidei et al., 2020, 2023; Abou Samra et al., 2021; Falciano et al., 2023; Vandelli et al., 2023). As regards the latter aspect, Falciano et al. (2023) implemented an online web-GIS platform to assess present-day and projected RSLR up to 2100 along the coasts of France, Greece, Italy, and Spain. The web-platform has been designed to provide maps regarding storm surge scenarios, comparisons between mapped scenarios and risk indicators. In Rizzo et al. (2022b), the SLR inundation risk scenarios along Gozo Island in the Maltese archipelago are investigated. Detailed inundation maps are available in Vandelli et al. (2023), in which the potential storm surge impact is also mapped. Coastal risk analysis was carried out in Turkey

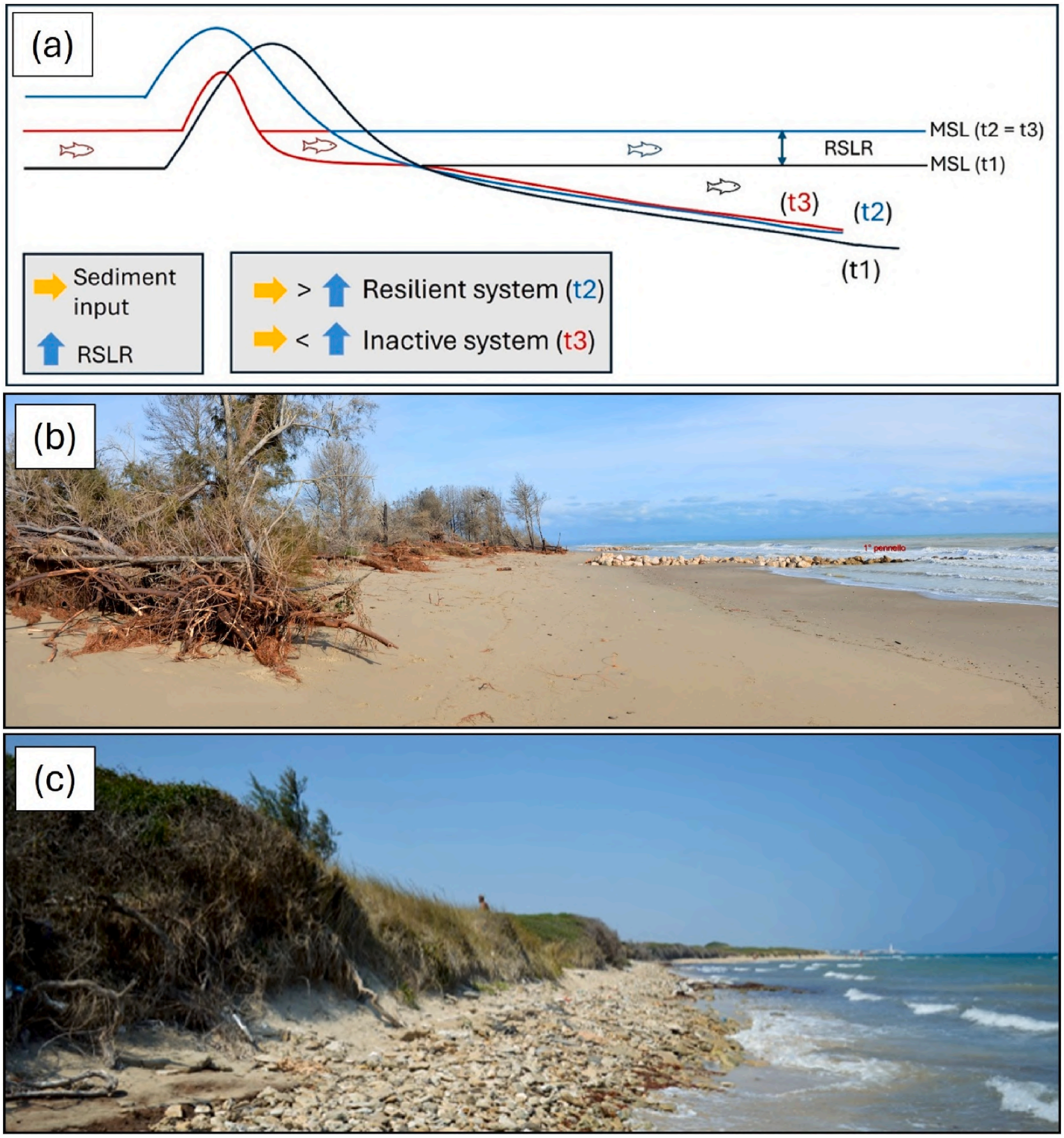

Fig. 6. a) Schematic representation of the potential coastal response to RSLR. The present (t1) coastal morphology and MSL are indicated in black. In the case of a resilient system (t2), future MSL will result in a landward migration of the coastal environments due to a natural coastal adaptation, whilst, in the case of an inactive system (t3), the erosion process will prevail with consequent coastal retreat and inundation of the low-lying areas. Panels b) and c) provide examples of inactive coastal systems in southern Italy. Photo in b) was taken by A. Trivisani at Metaponto beach (Matera), while photo in c) was taken by G. Mastronuzzi at Torre Canne beach (Brindisi). It is worth noting that, in the first case, the apparent beach advancing is due to the presence of the light breakwater structures. In addition, the evident dune demolition, due to both anthropogenic and wave action, can cause the inundation of inland areas during the occurrence of storm surges.

and Greece by Zengin (2023), which evaluated potential SLR impacts on 464 archaeological and historical sites.

Modelling approaches (Fig. 8) are based on numerical models that exploit high-resolution tools such as XBeach (Roelvink et al., 2009) to determine the wave propagation patterns, the expected run-up, and the potentially flooded beach area. Enríquez et al. (2019) calculated the shoreline changes in response to projected SLR by using a non-linear morpho-dynamic model for large-scale shoreline dynamics (Falqués et al., 2007) and simulated the impact of storm waves in terms of erosion by the XBeach model. Similarly, Sánchez-Artús et al. (2023) evaluated for the year 2100 beach erosion as a consequence of SLR through the XBeach numerical simulations, based on different combinations of waves and mean water level projections under different climate scenarios. Bergillos et al. (2019) applied the spectral wave model SWAN (Holthuijsen et al., 1993) to propagate the sea states during storm conditions from deep water to the nearshore region under three SLR scenarios. Furthermore, to quantify the total run-up under the storm conditions and SLR scenarios, the authors applied the XBeach-G modelling, which allows the reproduction of the storm hydro-dynamics and morpho-dynamics of gravel-dominated beaches (McCall et al., 2014, 2015). In Scardino et al. (2020, 2022) and Anzidei et al. (2021), a multi-temporal mathematical model implemented in MATLAB environment was developed for the analysis of SLR effects. In this case, VLMs and SLR trends were considered to assess the local evolution of the coastal trend, as well as the future marine submersion. In Ojeda-Zújar et al. (2021), the inundation hazard is assessed by

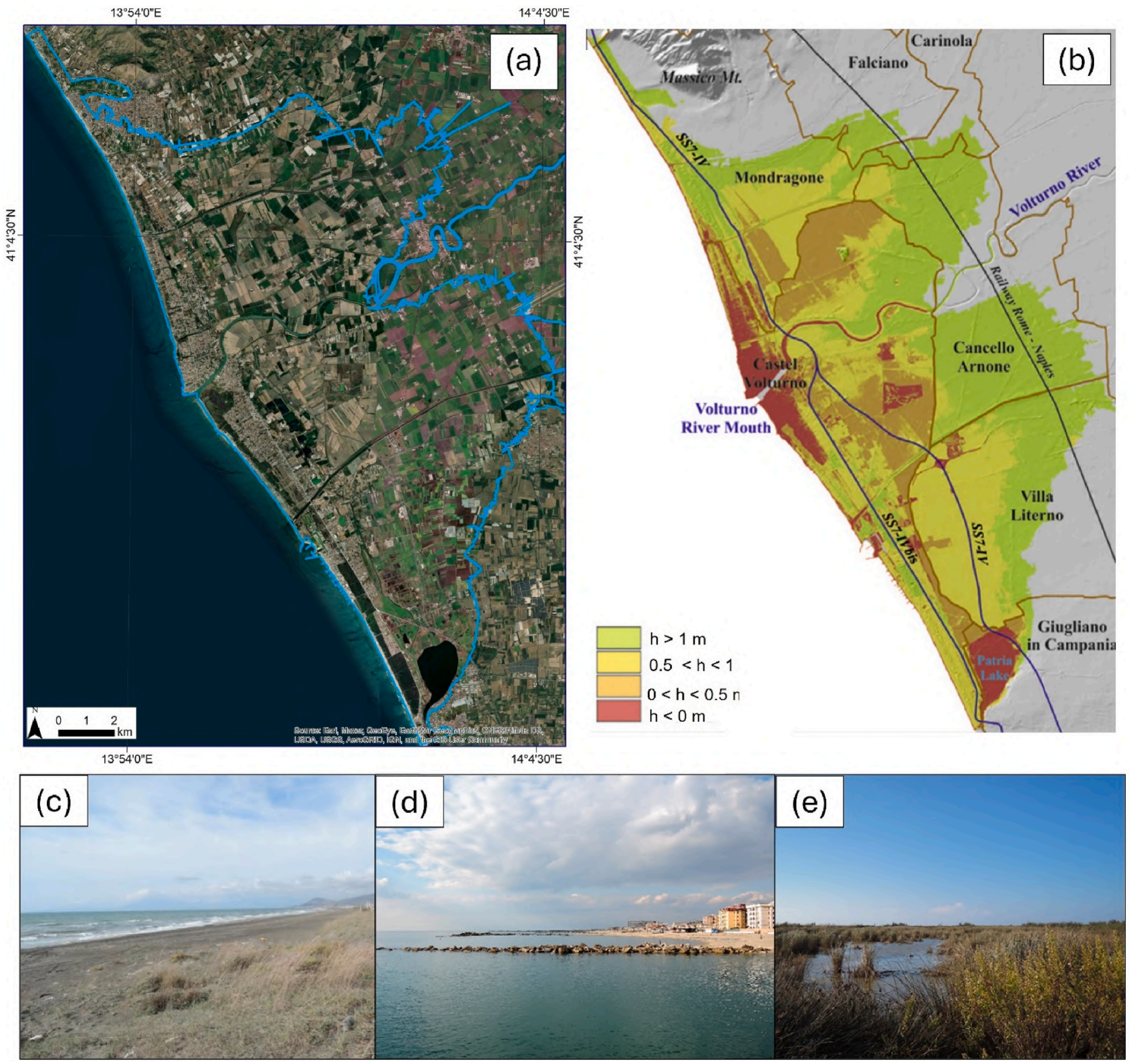

Fig. 7. An example of a GIS-based map. In panel a), the area within 5 m above mean sea level in the Volturno River coastal plain (Campania Region, southern Italy) is outlined by a blue line. In panel b), the investigated area is classified into different levels of vulnerability to projected relative sea-level rise (RSLR). This map is based on the IPCC worst-case sea level projection (RCP8.5) for 2100 and vertical land movements (VLMs) derived from InSAR data analysis (modified from Di Paola et al., 2018). Panels c), d), and e) show the present-day coastal landscape for the same area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

applying a statistical model of the normal distribution, where the highest cells have a lower probability of inundation, and the lower cells have a higher probability of inundation. Finally, in Koks et al. (2023), a 2D-Hydrodynamic model (Roberts et al., 2015) capable of simulating the free surface elevation of water flow over land areas is applied to estimate coastal flood maps.

It is worth noting that in the last five years, methodological approaches based on high-resolution numerical models have been exploited only in Italy and Spain. Among the many available numerical models, several offer predictive frameworks for understanding seawater intrusion dynamics under various climate and groundwater extraction scenarios and simulating density-dependent flow and solute transport (Kerrou and Renard, 2010; Pool et al., 2015; Sebben et al., 2015), capturing the complex interactions between freshwater and seawater in coastal aquifers (Langevin et al., 2024). These models integrate physical parameters, such as hydraulic conductivity and aquifer geometry, to predict future seawater intrusion trends and guide management practices. SEAWAT model is also used to predict how seawater intrusion will respond to changes in sea level, climate, and pumping rates, aiding in sustainable management strategies for freshwater resources (Werner and Simmons, 2009).

4.2. The geometric method

The application of the geometric method (Bruun's rule) assumes that, under SLR conditions, the beach profile adapts through an upward and landward migration of the active profile, maintaining the shoreline shape and relative elevation to the new water level (Bruun, 1962, Fig. 9). Since its preliminary implementation, the geometric approach has been widely used worldwide for the analysis of the shoreline response to sea level variation mainly due to its simplicity, notwithstanding the multiple weaknesses pointed out by the scientific community (Cooper and Pilkey, 2004). As in the case of the static approach, the application of the geometric method does not account for the potential resilience induced by the sedimentary processes acting along the mobile coastal systems. To try to overcome the limitations of this approach, several modifications have been suggested. For instance, in Ranasinghe et al. (2012), a probabilistic estimate of SLR-driven coastal recession based on physical processes is proposed; in Rosati et al. (2013) an extended version of the model is applied to evaluate beach landward transport. As concerns the

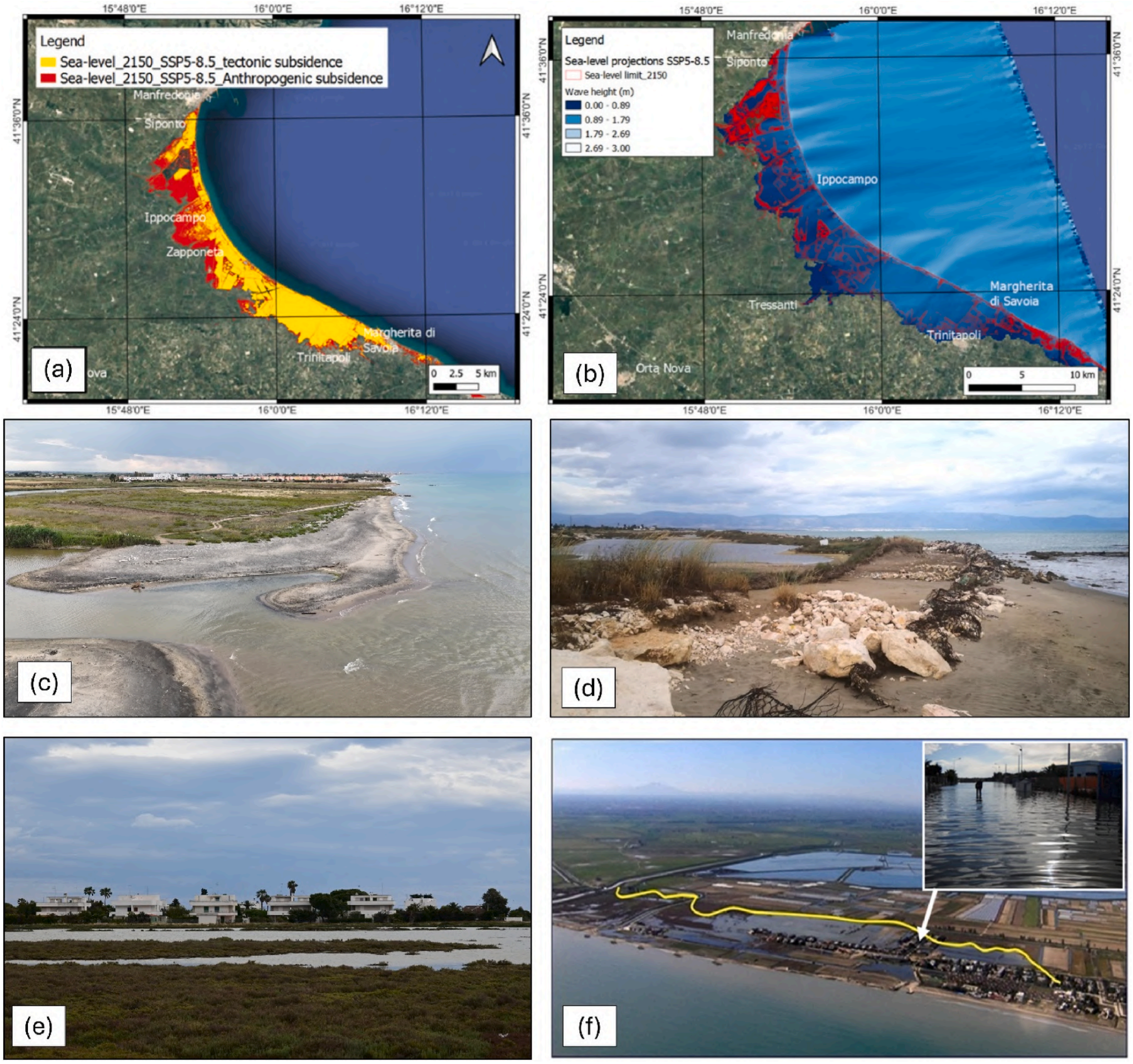

Fig. 8. Maps generated using the model-based approach. In panel a), the areas exposed to RSLR in the Tavoliere delle Puglie coastal plain (Apulia Region, southern Italy) are shown. The scenario, which includes the contribution of land subsidence from geodetic data, is based on the IPCC et al. (2021) sea level projection under the SSP5.8.5 scenario for 2150 AD. Panel b) shows the potential impact of RSLR in combination with storm surge (after Scardino et al., 2022). Panels c), d), e), and f) indicate the present-day coastal landscape of the investigated area. In particular: in panel c), the mouth of the Ofanto River; in panel d) the area of the Ippocampo Village (Tavoliere delle Puglie) was sheltered by adherent artificial breakwaters, at present destroyed by wave action and by-passed by the SLR (photo taken in December 2024); in panel e), the present day coastal landscape of the Ippocampo Village; in panel f), yellow line indicate the maximum sea ingression up to about 300 from the shoreline, during the flooding of February/March 2009, between the Carapelle river mouth and the Ippocampo Village (photos taken by prof. M. Caldara in March 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

application of Bruun's rule in the Mediterranean countries over the last five years, the bibliometric analysis has shown that no paper has been published since 2022. In 2019, Thiéblemont et al. (2019) used Bruun's rule for a first-level evaluation of the effects of regional SLR on the shoreline evolution along sandy coasts in Greece, Cyprus, France, Italy, Malta, Slovenia, and Spain, considering three SLR scenarios. López-Dóriga and Jiménez (2020) applied a pseudo-dynamic method coupling equilibrium-based coastal response and classical "bathtub" approach. In Sharaan and Udo (2020), the impacts of SLR in terms of future shoreline recession and corresponding beach loss in Egypt are assessed by using the standard Bruun rule. The exploitation of the geometric model has also supported the analysis of the economic impact due to the decrease in the beach carrying capacity induced by SLR (López-Dóriga et al., 2019; Garola et al., 2022), providing an indicative estimate of expected shoreline retreat at the regional scale following the approach proposed by Jiménez et al. (2017), who used the Bruun model. Another application of a geometric-based approach is illustrated in Sierra (2019). In this case, the impact of SLR in terms of overtopping port breakwaters is analyzed at a regional scale by applying the empirical equations proposed by the European Overtopping Manual. Numerical models were not applicable due to the huge number of analyzed sites. Nevertheless, to estimate wind-wave and long-wave propagation from offshore to the inner part of the ports, the SWAN model is adopted (Booij et al., 1999). The analysis also showed that all the applications exploiting the geometrical method were focused on the SLR impact, excluding the potential SS effect.

4.3. The index-based approach

Considering the application of the index-based approach (Fig. 10), it is worth noting that since the introduction of the Coastal Vulnerability Index in the early 1990s (Gornitz, 1990; Gornitz et al., 1992, 1994), a very large number of studies have been conducted worldwide through the evaluation of tailored indicators. The first version of the proposed

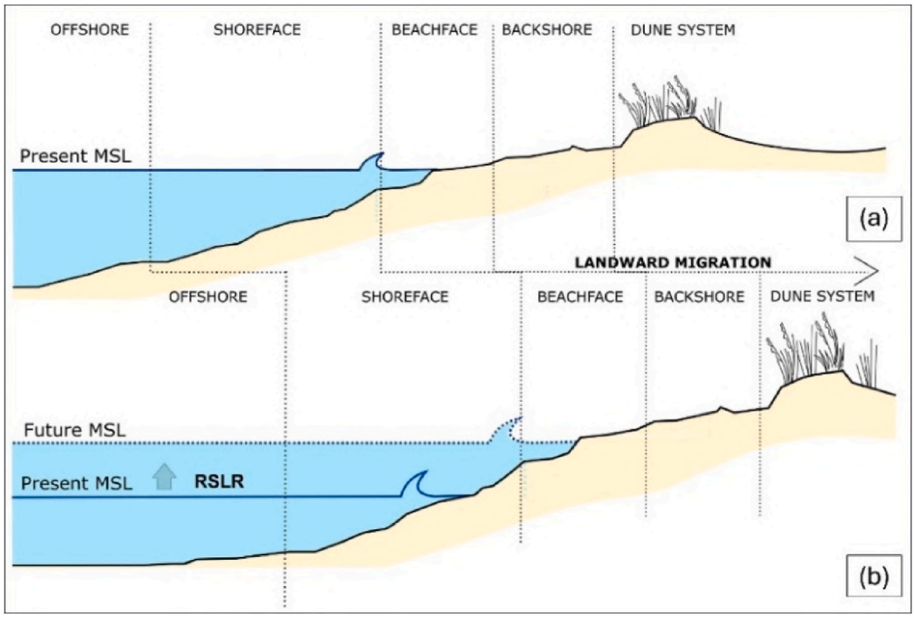

Fig. 9. Expected landward migration of the active beach profile in consequence of RSLR according to the geometric approach. Panel a) shows an example of a beach profile under MSL. In panel b), the beach profile adapts to the new MSL by maintaining the shoreline shape and the relative elevation of the main morphological elements.

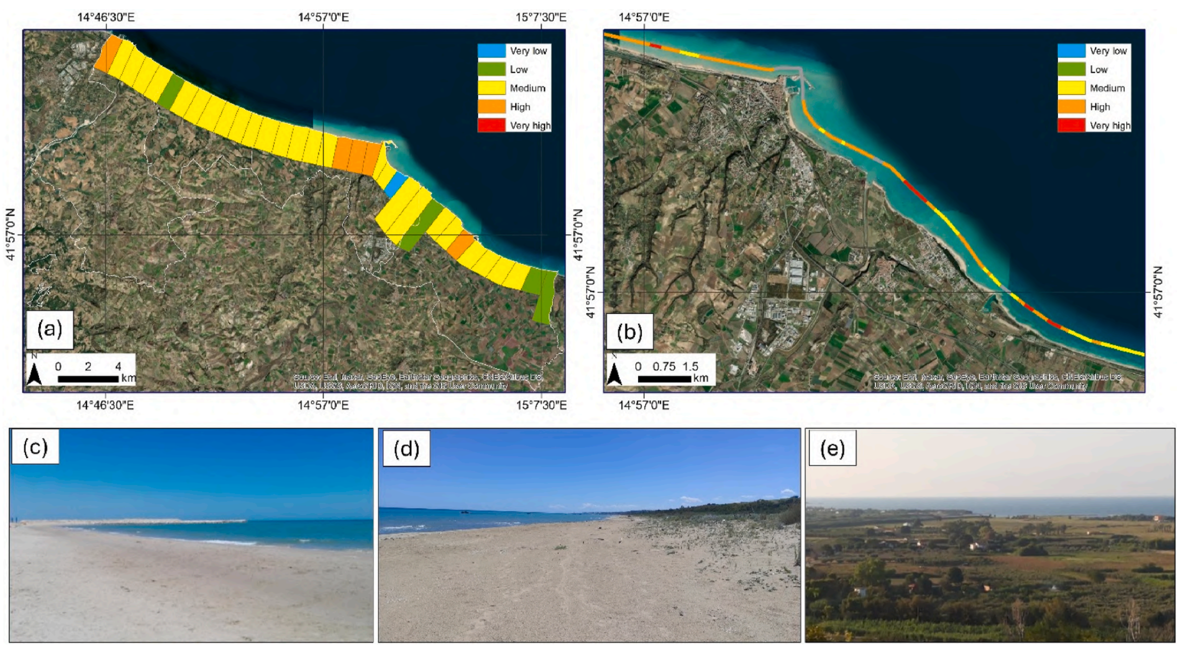

Fig. 10. Maps generated using the index-based approach. In panel a), the coast of the Molise Region (southern Italy) is classified according to the coastal vulnerability index developed within the framework of the RISKIT Project. In panel b), the investigated area is classified into various levels of coastal susceptibility to erosion, based on the methodology proposed by Rizzo et al. (2018). Modified from Aucelli et al. (2018). Panels c), d), and e) show the present-day coastal landscapes of the investigated area.

index was aimed at evaluating the coastal vulnerability to SLR, and seven variables were proposed and ranked in five vulnerability classes (from very low to very high).

The extensive use of the index-based approach for the coastal vulnerability analysis was also related to the definition of the vulnerability concept by the climate community up to 2014. In fact, the vulnerability to climate change was meant as "*the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. It was considered as a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, the sensitivity and adaptive capacity of that system*" (IPCC, 2007; Parry, 2007). Nevertheless, with the publication of the Fifth Assessment Report (AR5) by the IPCC in 2014, the climate community adapted to the definition of the vulnerability concept proposed by the disaster risk reduction community (IPCC, 2014). The latter considered vulnerability as a key element for risk analysis, being the risk defined as a combination of hazard, exposure, and vulnerability (IPCC, 2014). This led to a reformulation of the concepts of exposure and vulnerability (Schneiderbauer et al., 2017). The shift in the paradigm was also reflected in the methodological approach for coastal vulnerability and risk analysis. In fact, by searching in the Scopus database for published papers dealing with coastal vulnerability index to SLR, their number is quite constant before and after the IPCC AR5 release. On the contrary, in the case of coastal risk index to SLR, the number of published papers has increased significantly from 2015, passing from 10 before 2015 to 54 from 2015 to 2024 (last updated October 2024). Analyzing the papers in which the index-based approach is exploited, it resulted that some authors still referred to the original coastal vulnerability index developed by Gornitz et al. (1994), as in the case of Emam (2019) that have investigated the Egyptian coastal vulnerability by collecting data from satellite images. Then, Torresan et al. (2020) defined a Climate-improved Coastal Vulnerability Index (CCVI) to assess the vulnerability to climate-related processes (i.e., SLR, SS, and coastal erosion) of the Mediterranean shoreline of Egypt. Furlan et al. (2021) developed a multi-dimensional coastal vulnerability index (Mdim-CVI) for ranking the Italian coasts according to the relative vulnerability to extreme sea level scenarios in 2050 as a combination of SLR, SS, tidal range, and wave height modeled for the entire Italian coast by Vousdoukas et al. (2017). In Furlan et al. (2022), the proposed index-based approach has been exploited to evaluate the potential risk of loss or degradation of ecosystem services as a consequence of future inundation scenarios due to projected extreme sea levels. Giving a remarkable emphasis on the high spatial resolution and vertical accuracy of subsidence rates (obtained through the combination of L- and X-band SAR-based interferometric data), Da Lio and Tosi (2019) used several indicators to assess the vulnerability to RSLR along the Po delta (Northern Italy). As previously commented, in Rizzo et al. (2022b), a combination of approaches for risk evaluation in Gozo Island was applied. In this case, SLR susceptibility maps for years 2050 and 2100, obtained from the static GIS-based analysis, were joined to the site-specific exposure and vulnerability maps. Finally, three papers were analyzed dealing with case studies in Greece (Vandarakis et al., 2021; Komi et al., 2022). Ramnalis et al. (2023) applied both the CVI proposed by Thieler and Hammar-Klose (1999), in which the accounted variables had equal relative importance, and a second index in which to each variable a relative weight was assigned by using the Analytic Hierarchic Process (AHP), as similarly done in Sekovski et al. (2020). In Bonaldo et al. (2019), an overview of recent achievements obtained in the different scientific fields on coastal vulnerability to erosion and SLR is provided. Various approaches suitable for the assessment of coastal vulnerability to SLR, including index-based, indicator-based, and model-based methods are illustrated and discussed to support the implementation of services and infrastructures (e.g., the development of Decision Support Systems for coastal protection and management).

4.4. Suitability analysis and proposal of a roadmap for the multi-scale management of the coastal areas

The analysis performed on the selected papers has allowed an integrated/critical evaluation of a number of aspects related to each accounted methodological approach. In detail, the following aspects have been taken into account:

- extent of the area to be analyzed, expressed as regional/national or site-specific analysis;
- type of VLMs dataset, defined as data derived from geological/geomorphological/archaeological and biological markers (for long-term data) or instrumental observations (for short-term data);
- computational effort, evaluated in terms of required high-performing technological tools and high-resolution spatial data;
- mapping details, expressed as type of outcomes, i.e., linear or areal zonation of the investigated territory.

Each methodological approach has been evaluated in terms of suitable (green traffic light) or not suitable (red traffic light) in relation to each accounted aspect, as summarized in Table 1. A high level of suitability (green traffic light) is assigned when the accounted methodological approach achieves high performance with respect to the considered aspect; on the contrary, a low level of suitability (unsuitability – red traffic light) is assigned when the accounted methodological approach does not fit the aspect under consideration. A medium level of suitability (orange traffic light) is associated when the accounted methodological approach could fit the considered aspect but with low performance, or when the methodological approach is considered partially suitable in relation to the considered aspect. The "traffic light" approach represents an easy tool for qualitative analysis, which inherently contains a certain level of approximation due to the lack of quantitative data to support such evaluation. Nevertheless, this approach is highly exploited for spatial planning purposes and for the identification of tailored intervention actions (e.g., Rizzo et al., 2024). The proposed evaluation does not account for future methodological improvements due to the promising ongoing research frontiers. By way of example, the high exploitation of the Machine Learning/Deep learning tools could improve the computational effort for coastal model applications (e.g., Mlakar et al., 2024; Sabato et al., 2024).

Based on the above evaluation, the following two-phase methodological process is recommended for the analysis and mapping of the influence of sea level and related processes along the coastal sectors (Fig. 11):

- **Regional/national analysis:** application of index-based procedures for the identification of highly vulnerable coastal sectors (hot-spots) for which more accurate analyses are required. This analysis can be supported by the exploitation of physical data (DSM, SL) already available at the national scale in dedicated data repositories;
- **Site-specific/local analysis:** application of model-based approaches for the detailed analysis of the hot-spot areas. This analysis is carried out based on the exploitation of site-specific and high-

Table 1
Level of suitability (high, low, medium) associated with the available methods of analysis in relation to each accounted aspect. The evaluation was made on the vertical models without considering the potential coastal dynamic horizontal response that could invalidate the validity of the methods at the site-specific scale.

	Investigated area		VLMs		Computational effort		Mapping outcomes	
Method of Analysis	Regional	Site	Long-term	Short-term	Tools	Data	Linear	Areal
Geometric approach	orange	orange	green	orange	red	green	green	red
GIS-based approach	orange	orange	orange	green	orange	green	red	green
Index-based approach	green	orange	red	orange	orange	orange	green	red
Model-based approach	red	green	red	green	green	green	red	green

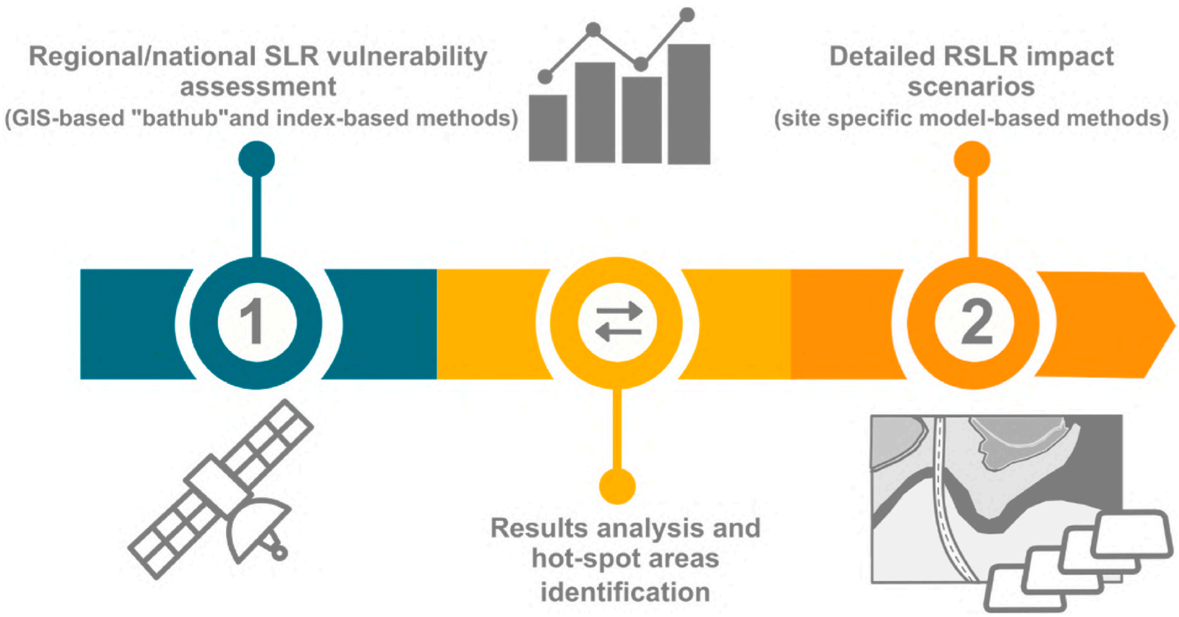

Fig. 11. Simplified roadmap for the multi-scale analysis of the SLR impacts along the coastal areas at the national/regional level and site-specific level (hot-spot areas).

resolution data acquired following tailored procedures specifically designed for this purpose.

Finally, to identify papers dealing with extreme events (SS and Ts) that may have been excluded from the above-discussed evaluations due to the absence of the word “Sea level rise” in their title, additional research in Scopus has been performed. To this end, the queries included the following terms: Storm Surge and Vulnerability (48 papers), Storm Surge and Inundation (102 papers), Storm Surge and Flooding (86 papers), Tsunami and Vulnerability (153 papers), Tsunami and Inundation (269 papers), and Tsunami and Flooding (27 papers). By removing the duplicates, 228 and 444 additional papers have been collected for the SS and Ts issues, respectively. Among those, 8 for SS and 43 for Ts deal with case studies in the Mediterranean countries, with 4 and 18 of these published in the 2019–2024 period (e.g., Androulidakis et al., 2023; Makris et al., 2023). The reference list of these papers is provided as Annex 1 for the SS and Annex 2 for the Ts.

The research further emphasizes that recent studies leverage freely available, high-resolution data, predominantly sourced from satellite information. For example, VLMs rates can be obtained from the European Ground Motion Service, which provides millimeter-level precision using Synthetic Aperture Radar Interferometry (InSAR) data from Sentinel-1. Additionally, climate-related data (datasets and indicators), including re-analysis and future projections, are accessible at the European level through the Copernicus web platform. Tools like the NASA Sea Level Rise projection web platform, the SAVEMEDCOASTS-2 website for inundation scenarios, and the Archimede web platform for tsunami modeling, along with the use of automated systems for monitoring key marine and coastal variables (Adebisi and Balogun, 2022; Sabato et al., 2024; Sozio et al., 2024), are the main strengths in developing integrated systems that generate more reliable results. These advancements will provide more detailed data to support the definition of tailored coastal management actions and the implementation of sustainable adaptation strategies.

5. Conclusions

This study presents a bibliographic analysis of peer-reviewed papers addressing vulnerability due to sea level rise (SLR), storm surges (SS), and tsunamis (Ts) at both global and regional scale. Furthermore, based on the assumption that the management of coastal areas in a changing climate context cannot disregard a thorough understanding of the expected impact of SLR and related vulnerability of the coastal system, this review proposes an evaluation of the most used approaches available in the literature for such purpose.

The bibliographic analysis reveals that, while a large volume of research has been published on the tsunami process, the scientific literature predominantly focuses on the geological triggers of tsunamis, such as earthquakes and landslides, and their impacts. In contrast, studies specifically addressing the relationship between tsunamis and induced SLR processes remain limited. Conversely, marine-related processes, such as storm surges and meteo-tsunamis, and their potential impacts on coastal areas have been extensively studied in the context of climate change and SLR scenarios (Pattiaratchi and Wijeratne, 2015; Kirezci et al., 2020). Another noteworthy finding is the persistence of the term “vulnerability” in the climate science literature, especially when associated with SLR, despite a shift in the scientific community towards a risk-based perspective. The term “vulnerability” joined with “sea level rise” continues to be more widely used than "risk" or "hazard" in discussions related to climate impacts.

The analysis of the methodological approaches applied in research articles published in the period 2019–2024 at the Mediterranean scale reveals that, despite the ongoing advancement of numerical models, the GIS-based approach, in which areas below a user-specified sea level elevation are considered as inundated, remain extensively used for mapping flooding and inundation areas due to SLR across different climate scenarios. Even recent regional studies, such as that by Cappucci et al. (2024), continue to rely on a static approach (the bathtub method) to map flood-prone areas, without accounting for the morphodynamic processes induced by waves and currents during the inundation event. However, compared to earlier studies assessing coastal inundation, the accuracy of recent investigations has improved due to the availability of more detailed sea level projections from high-resolution models, enhanced resolution of digital terrain models, and advanced satellite-derived data to accurately assess recent and contemporaneous VLMs without neglecting the detailed reconstruction of vertical behavior on a long-time scale. Although a clear methodological shift has not yet occurred, recent studies benefit from the use of more precise and accurate input data. To ensure robust and high-resolution analyses, it is of paramount importance that such data derive from standard acquisition, are comparable in terms of accuracy, and refer to the same vertical datum. Regarding modeling approaches, they remain most effective for smaller areas due to the significant computational resources and efforts required for analysis.

In conclusion, the study points out the need for a comprehensive vulnerability assessment as a tool for defying the path towards sustainable coastal management in a changing climate, whose definition provides for different typologies of outputs depending on the spatial and temporal resolution of the exploited data.

CRediT authorship contribution statement

Angela Rizzo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gaia Mattei:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Léa Dumon Steenssens:** Writing – original draft, Investigation, Formal analysis, Data curation. **Marco Anzidei:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Pietro P.C. Aucelli:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Tommaso Alberti:** Writing – review & editing, Validation. **Fabrizio Antonioli:** Writing – review & editing, Validation. **Annelore Bezzi:** Writing – review & editing, Validation. **Davide Bonaldo:** Writing – review & editing, Validation. **Giorgio Fontolan:** Writing – review & editing, Validation. **Stefano Furlani:** Writing – review & editing, Validation. **Isabella Serena Liso:** Writing – review & editing, Validation. **Mario Parise:** Writing – review & editing, Validation. **Paolo Sansò:** Writing – review & editing, Validation. **Giovanni Scicchitano:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Daniele Trippanera:** Writing – review & editing, Validation. **Antonio Vecchio:** Writing – review & editing, Validation. **Giuseppe Mastronuzzi:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was carried out in the framework of the "GAIA Project", funded by the Italian Ministry of the University and Research under the umbrella of the National Recovery and Resilience Plan (NRRP), contract n. PRIN2022_PE10_2022ZSMRXJ02. Scientific responsible: G. Mastronuzzi (University of Bari Aldo Moro, Bari, Italy. Responsibles of Partner Institutions: M. Anzidei (INGV, Italy) and P.P.C. Aucelli (University Parthenope, Naples, Italy). The research was also supported by the RETURN Enlarged Partnerships under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.3 funded by the European Union—NextGenerationEU (RETURN project "Multi-risk science for resilient communities under a changing climate", no. PE00000005, CUP B53C22004020002, Authors contribution: G. Mastronuzzi, I.S. Liso, M. Parise, A. Rizzo).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.107751.

Data availability

Data will be made available on request.

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