REVIEW ARTICLE

Indices of Coastal Vulnerability to Climate Change: a Review

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Abstract

The objective of this paper is to identify and analyze relevant research of index-based methods for the evaluation of climate change vulnerability and resilience of coastal areas. We searched, retrieved, classified and reviewed papers on climate-change hazards, impacts, vulnerability and resilience of coastal water systems and relevant infrastructure. For this, Scopus, Science Direct, Thompson-Reuters Web of Science, Google Scholar, PubMed and other relevant databases were used. The analysis of the state-of-the-art presented in this paper acknowledges that using vulnerability and resilience indices in climate vulnerability research is effective, providing a solid, efficient and user-friendly framework. However, selection of index variables should be part of a holistic as well as dynamic approach to identify not only areas in danger, but also the level of social vulnerability.

Keywords Climate change · Sea-level rise · Vulnerability Assessment · Vulnerability index · Coastal infrastructure resilience

1 Introduction

Climate change (CC), alongside with rapid population growth and natural and manmade disasters, require modern approaches to be addressed; forward-looking design can have a profound impact on safety and prosperity of individuals and communities as a whole (Rus et al. 2018). In everyday life, the term "vulnerability" is widely used. Comte et al. (2019) claim that a consistent definition of vulnerability is not available. It is difficult for a definition to include every assessment context, as it is used in different policies and systems exposed to diverse hazards (Nguyen et al. 2016). However, related to CC, the Intergovernmental Panel on Climate Change (IPCC 2014) definition of vulnerability has been acknowledged by researchers (e.g., Li et al. 2019; Gargiulo et al. 2020). It is defined *as "the propensity or predisposition to be adversely affected. Vulnerability encompasses a*

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variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt".

According to Gargiulo et al. (2020), coastal vulnerability can be considered as the integration of sensitivity and social vulnerability of coastal areas. For this purpose, physical, socio-environmental and socio-economic aspects of coastal areas are taken into consideration. The analysis of vulnerability is occasionally carried out using complex indices (Gargiulo et al. 2020). Vulnerability is also strictly linked with adaptation, as the adaptive capacity is described as the ability of systems, institutions, humans and other organisms to adjust and respond to potential damage, for example due to weather extremes (IPCC 2001, 2014).

In terms of social vulnerability, characteristics of communities as well as inequities indicate an important factor in the ability of groups to respond to natural hazards and climate challenges (Cutter et al. 2003). Especially in coastal areas, social inequities, income, race, ethnicity, and demographic data are key factors in people's vulnerability to environmental hazards (Li and Li 2011). Economic losses might be direct, affecting buildings, crucial infrastructure and their operations (Asariotis et al. 2017), or indirect, affecting local economy, causing issues in the supply chain, unemployment, investment decisions. The use of susceptibility functions (or damage functions) is the most frequently applied method (Meyer et al. 2013) to assess the direct costs related to natural hazards (e.g., Pistrika et al. 2014). Also, to assess indirect costs, economic models at local, regional or national level are used (Meyer et al. 2013). Financial costs vary from one place to another, as developed countries have higher property values and disaster insurance is affordable (Christian Aid 2021). However, it is rather difficult to define disaster cost, as it highly depends on the purpose of the assessment and the consequential uncertainties regarding the indirect cost (Hallegate and Przyluski 2010).

One question that needs to be addressed is "Why to use index-based approaches?" Indices are "measurable, observable quantities that serve as proxies for an aspect of a system that cannot itself be directly adequately measured" (McIntosh and Becker 2017). Abstract concepts like vulnerability and resilience can be visualized in spatial scales, using observable variables (McIntosh and Becker 2019). Within this approach, vague factors like "social factors" could be specified, and thus, quantified using multiple variables (e.g., age, education, unemployment) (Malone and Engle 2011).

In this study, a systematic review of assorted approaches applied globally is presented. In Sect. 2, the methodology followed in the literature review is analyzed. Section 3 discusses climate change vulnerability and resilience indices for coastal areas found in the literature. Section 4 briefly presents aggregation tools for the evaluation of the abovementioned indices. Finally, Sect. 5 presents the main conclusions and highlights gaps in the literature.

2 Review Methodology

The goal of the review was to identify and analyze relevant research of index-based methods for the evaluation of climate change vulnerability and resilience of coastal areas. Understanding and quantifying the risk is the main challenge that occurs, and is the first step in the development of an effective framework to address real-world cases. The PRISMA 2020 methodology by Page et al. (2021) was followed, as it includes both systematic reviews and meta-analyses. We searched, retrieved, classified and reviewed

papers on climate-change vulnerability and resilience indices related to coastal water systems and relevant infrastructure. For this, Scopus, Thompson-Reuters Web of Science, PubMed, ScienceDirect, Google Scholar and other relevant databases were used. The search strategy included free text terms such as "climate change vulnerability index", "coastal vulnerability indices", "resilience of coastal areas to climate change", "climate change resilience index", "climate change and socio-economic indicators", "coastal flood vulnerability", "climate change and coastal flooding". A summary of 1397 titles was revealed and screened by a single reviewer. The majority of the literature was in English. One hundred thirty-six (136) records were assessed for eligibility to be included in the study and 46 were finally included. The PRISMA flowchart is presented in Fig. 1.
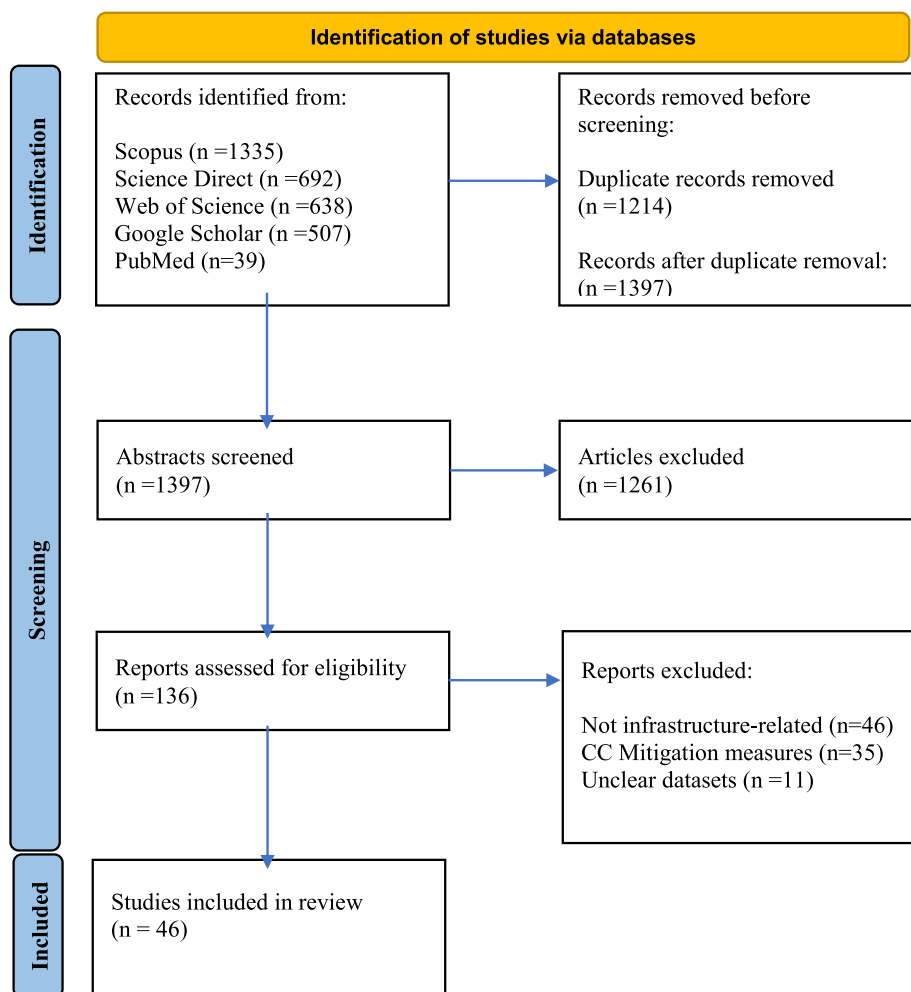

Identification of studies via databases

Identification

Records identified from:

Scopus (n =1335)
Science Direct (n =692)
Web of Science (n =638)
Google Scholar (n =507)
PubMed (n=39)

Records removed before screening:

Duplicate records removed (n =1214)

Records after duplicate removal: (n =1397)

Screening

Abstracts screened (n =1397)

Articles excluded (n =1261)

Reports assessed for eligibility (n =136)

Reports excluded:

Not infrastructure-related (n=46)
CC Mitigation measures (n=35)
Unclear datasets (n =11)

Included

Studies included in review (n = 46)

Fig. 1 PRISMA flowchart – Study methodology of excluded and included articles

3 Addressing Vulnerability and Resilience in a Changing Climate

It is widely believed that coastal zones are exposed to diverse natural hazards under a changing climate. Coastal areas and infrastructure should be designed to address these challenges (Malliouri et al. 2017). The exposure level is affected by the land use of coastal areas, the population and social factors, the shoreline type and the existing (and planned) infrastructure. Current and future socio-environmental and socio-economic data are used to develop different scenarios (Fig. 2). Also, there is a significant variety of presumed socio-economic impacts of climate change among key coastal sectors. The environment is described with hydrologic, atmospheric and geologic variables. As a result, vulnerability components could be identified in spatial scale (Bevacqua et al. 2019). Using different projections for future scenarios could also add a temporal scale to the vulnerability assessment.

Important components affecting coastal areas are the astronomical tide, the storm surge, the wave run-up, the weather extremes and the sea-level rise. CC affects the frequency of storm surge events and the magnitude of wave heights, having crucial impact on coastal and port infrastructure (Tsoukala et al. 2016; Afentoulis et al. 2017). The main impacts of
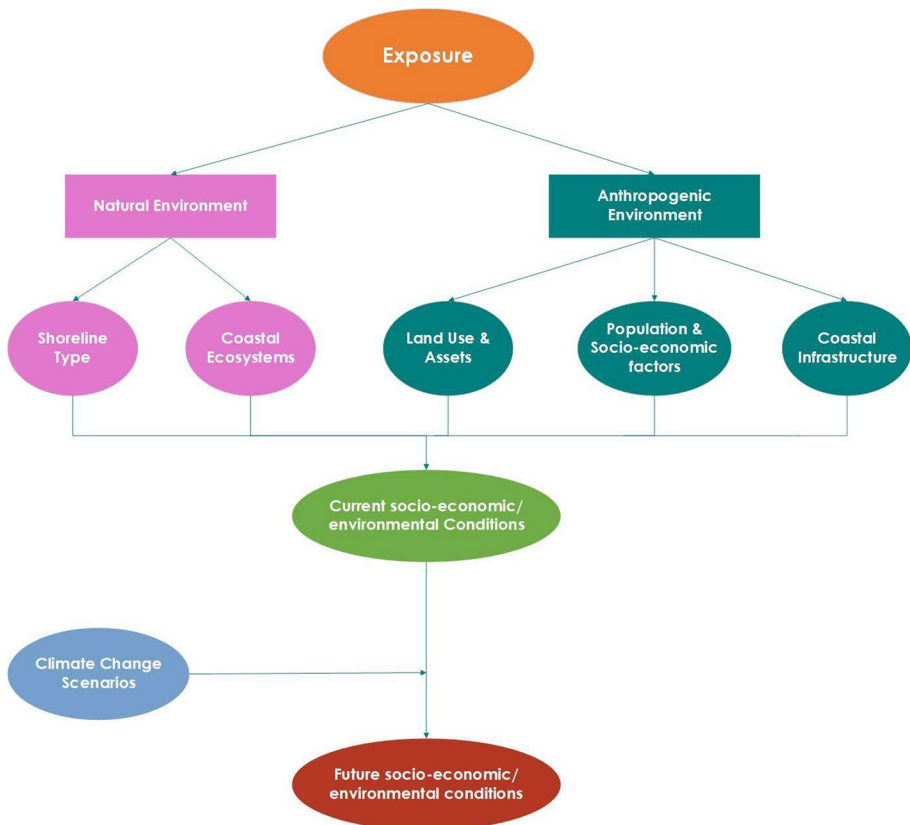
Fig. 2 Flowchart for the definition of exposure and socio-environmental scenarios (Modified from Toimil et al. 2017)

these phenomena are coastal erosion and coastal flooding. The majority of the literature analyzes risk caused by SLR and storm surges, while wave data have only been used by a few researchers (e.g., Gornitz et al. 1994; Dawson et al. 2009; Toimil et al. 2017). The use of historical weather data, as well as climate projections downscaled at the regional level have been used extensively in the literature to model the impacts of CC in various case studies (Fig. 3). However, climate projections and bias correction methods still have significant uncertainties (Kourtis and Tsihrintzis 2021).

Social variables include population, nationality, economic status, age, gender, household type, housing quality, and health. Coastal areas are particularly exposed to climate change and extreme weather events, and the dependence of many regions on touristic and recreation activities intensifies the vulnerability level (Bevacqua et al. 2019). This also creates an uncertain environment for touristic activities (Uyarra et al. 2005).

3.1 Tools for Aggregation/Evaluation of Variables

The majority of the approaches in the literature promote a static understanding of human–environment interactions. Ford et al. (2018) raised similar concerns. The recent crisis caused by the COVID-19 pandemic is an example of the importance of dynamic approaches when social indicators are used. Hinkel (2011) also supported that, as useful as they can get, vulnerability and resilience indices solely cannot direct decision makers and stakeholders to raise public awareness, propose adaptation measures and monitor adaptation policy and funds.

A holistic approach is necessary to overcome the abovementioned concerns. This creates the urge to aggregate the divergent aspects of geophysical and social vulnerability
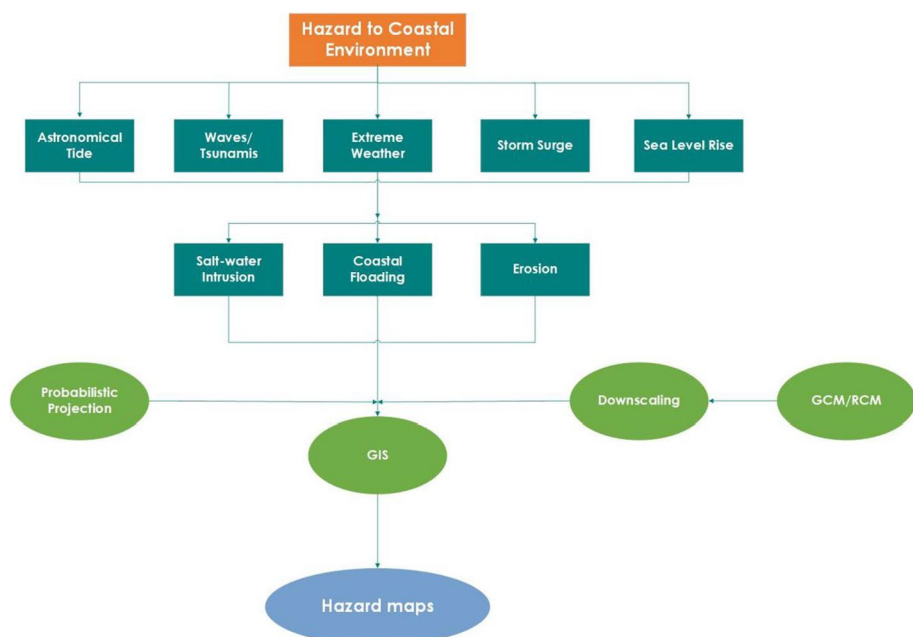
Fig. 3 Flowchart for the creation of hazard maps (Modified from Toimil et al. 2017)

into a sole index, or a limited group of indices. Integrating data from diverse sources is frequently necessary to understand potential relationships among them (Preston and Jones 2008). Aggregating variables reduces the amount of complexity, and the indices, often described as a "vulnerability score," visualize the climate change vulnerability (Nguyen et al. 2016).

Flood risk management and defense projects interact with various sectors (socio-economic, environmental, etc.) of an area wider than the affected one. Different stakeholder groups are involved and expected to have diverse opinions about the projects' magnitude and the alternatives which seem viable. Therefore, policy and decision-making on coastal flood defense and risk management at strategic level depend on many criteria and stakeholders (Maragoudaki and Tsakiris 2005).

Weighting and ranking methods are used to express the relative importance of different individual variables in a system. With Multi-Criteria Decision Analysis (MCDA), it is rather possible to overwhelm many of the disadvantages of conventional evaluation methods. It allows for factors that cannot easily be expressed in monetary terms or quantified, but nevertheless play a decisive role in shaping policies, such as environmental, spatial and social impacts of a project, social justice etc., which should always be taken into consideration (Roukounis et al. 2020; Roukouni 2016).

Especially the Analytic Hierarchy Process (AHP) by Saaty (1987) is frequently met in the literature. Ellen et al. (2016) suggested that in climate planning, multi-criteria analysis has the ability to perform more efficiently than cost–benefit analysis and working group approaches during the decision-making process, as they are more comprehensive and scenario-driven.

GIS can be used to produce different kinds of hazard and vulnerability maps, as researchers integrate indicators regarding various aspects of vulnerability. To locate 'hot spots' of vulnerability, measures of exposure, sensitivity and adaptive capacity are combined and mapped. On the other hand, uncertainties in the model could also be identified (Malone and Engle 2011).

3.2 Different Approaches to Coastal Vulnerability and Resilience Indexation

In order to establish new approaches in vulnerability and risk analysis, the development of solidly identified and quantified variables could be effective (Brooks 2003). Index-based methods offer a simple way for the classification of alternative options during decision making procedures (Giannakidou et al. 2020).

One major challenge in climate vulnerability research is to define the subject of interest. Initially, research was focused on the physical profile of climate change vulnerability (e.g., Gornitz 1991; Thieler and Hammar-Klose 1999), developing robust indices that estimate the exposure of coastal areas. However, the understanding that climate change is a concern of humankind globally (UN 2015) had raised the question "who is vulnerable" rather than "what". The assumption that people lacking wealth and resources are more susceptible to be damaged by climate change impacts has been common among researchers (Malone and Engle 2011). Indeed, Islam and Winkel (2017) illustrated how social inequality affects the ability of disadvantaged groups to respond to climate change hazards.

In order to address the abovementioned challenges, indicators should be consistent and coherent, based on robust data, using multiple criteria in the selection process. A holistic approach is crucial in order to assess coastal vulnerability, as excluding features may lead to unrealistic results (Li and Li 2011). Furthermore, high spatial resolution is crucial for

the effectiveness of vulnerability indices (Gargiulo et al. 2020), taking into consideration factors that cannot be evaluated at large scales (Torresan et al. 2008).

The index-based approaches have been the most widely accepted methods to assess vulnerability (Debortoli et al. 2019; Blasiak et al. 2017; Nguyen et al. 2016; Balica 2012; Jun et al. 2011; Baker 2009). In complex human and other natural systems, more than one factors are present. The exposure and vulnerability of these environments is estimated by integrating multiple factors of every part of the system. As a result, these approaches are adopted more frequently than single-factor methodologies (Giri et al. 2020). In the present research various vulnerability indices were identified. The literature review showed that the majority of vulnerability indices were developed considering the geomorphological and socio-economic factors as main features.

In order to evaluate the geophysical characteristics of coastal areas and to allocate the future impacts of climate change among divergent coastal sections, the Coastal Vulnerability Index (CVI) was developed (Gornitz 1991). Different versions of the CVI were applied first on the coasts of the USA, Canada and Mexico (Gornitz et al. 1994; Thieler and Hammar-Klose 1999). This index was also applied, after modifications matching local preferences and data limitations in various other locations (Shaw et al. 1998; Doukakis 2005; Abuodha and Woodroffe 2006; Mendoza and Jiménez 2009; Gaki-Papanastassiou et al. 2010; Karymbalis et al. 2012; Yin et al. 2012; Kokkinos et al. 2014; Satta et al. 2015; Pantusa et al. 2018; Tragaki et al. 2018; Hawchar et al. 2020).

Pendleton et al. (2004) developed a weighted CVI method, based on Multi-Criteria Analysis, and more specifically, the AHP. Similar approaches to the CVI include those by: Bagdanavičiute et al. (2015); Devoy (2008); Mani Murali et al. (2013); Pendleton et al. (2004); Rao et al. (2008); Tibbetts and van Proosdij (2013); Addo (2013); Mani Murali et al. (2013); Bonetti et al. (2013). A summary of the studies implementing indices with geophysical characteristics is presented in Table 1.

A variety of physical characteristics have been included to these indices, in order to evaluate vulnerability levels of coastal areas to different climate change-related hazards. Geomorphological (slope, elevation, shoreline type, rock type, solid and drift geology, coastal erosion/accretion rate), sea (SLR, tidal range, storm surge), wave (wave height, wave run-up) and weather data, alongside with information regarding land cover, existing coastal flood protection measures and other environmental agents are used for this purpose. A summary of the physical variables used in the literature is presented in Table 2.

Climate change and socio-economic development are profoundly connected, as human activities have been the main driver of environmental harm. Socio-economic variables are used to determine the impacts of climate change on the society. These variables broaden physical indices to an inherent cultural bias (McLaughlin and Cooper 2010). About 10% of people who reside at low elevation coastal zones, located up to 10 m elevation of present-day mean sea level (MSL) (Wahl et al. 2018), face a great threat due to sea level rise (SLR) (McGranahan et al. 2007). Thus, identifying social vulnerability of coastal communities is crucial for planning resilience strategies (Tragaki et al. 2018). Social vulnerability may include characteristics of the communities and the built environment, such as the urbanization level, the growth rates, and the economic stability and development (Cutter et al. 2003). As it is believed that vulnerability depends on the sensitivity of both the natural and social components of a system (Heinz Center 2002), social inequities are key factors in natural hazard vulnerability assessment (Li and Li 2011). Characteristics of communities as well as social inequalities have also been taken into consideration. Socio-economic parameters such as demographic data, education level, population density and land use are constantly used in the literature to estimate social vulnerability. Cutter et al. (2003) used

Table 1 Geophysical Coastal Vulnerability Indices found in the literature

No	Index	Authors	Case Study Area	Variables
1	CVI (Coastal Vulnerability Index)	Gornitz (1991)	Canada	Relief, Geomorphology, Rock Type, Vertical Sea movement, shoreline displacement, tidal range, wave height
2	SI (Sensitivity Index)	Shaw et al. (1998)	Canada	Relief, Geomorphology, Rock Type, sea level tendency, shoreline displacement rate, mean tidal range, mean annual maximum significant wave height
3	CVI (Coastal Vulnerability Index)	Thieler and Hammar-Klose (1999)	Mexico	Geomorphology, coastal slope, relative SLR rate, shoreline erosion/acceleration rate, mean tidal range, mean wave height
4	Coastal Vulnerability Index	Pendleton et al. (2004)	USA	Geomorphology, coastal slope, relative SLR rate, shoreline erosion/acceleration rate, mean tidal range, mean wave height
5	Coastal Vulnerability Index	Doukakis (2005)	Greece	Geomorphology, coastal slope, relative SLR rate, shoreline erosion/acceleration rate, mean tidal range, mean wave height
6	CVI (Coastal Vulnerability Index)	Abuodha and Woodroffe (2006)	Australia	Elevation, barrier types, beach types, shoreline erosion/acceleration rate, SLR, mean tidal range, mean wave height
8	Coastal Vulnerability Index	Rao et al. (2008)	India	Coastal geomorphology, coastal slope, shoreline change, mean spring tide range, mean significant wave height
9	Flood/Erosion Vulnerability Index (FVI—EVI)	Mendoza and Jiménez (2009)	Spain	Storms, maximum elevation of flood water, storm surge wave run-up, shoreline type coastal erosion, sediment grain size, wave height, hinterland properties
10	Coastal Vulnerability Index	Gaki-Papanastassiou et al. (2010)	Greece	Geomorphology, coastal slope, relative SLR rate, shoreline erosion/acceleration rate, mean tidal range, mean significant wave height
11	CSI (Coastal Sensitivity Index)	Karymbalis et al. (2012)	Greece	Geomorphology, coastal slope, relative SLR rate, shoreline erosion/acceleration rate, mean tidal range, mean significant wave height
12	Coastal Vulnerability Index	Yin et al. (2012)	China	SLR, geomorphology, coastal elevation, coastal slope, shoreline erosion, coastal land use, mean tidal range, mean wave height
13	Coastal Vulnerability Index	Tibbetts and van Proosdij (2013)	Canada	Freeboard, relative coastline exposure, width of foreshore, coastal slope, observed erodibility, presence of vegetation, presence of anthropogenic or natural protection, morphological resilience

Table 1 (continued)

No	Index	Authors	Case Study Area	Variables
14	Coastal Vulnerability Index	Bonetti et al. (2013)	Brazil	Backshore landforms, backshore altitude, shoreline displacement, shoreline exposure to wave incidence, population and buildings at risk
15	Coastal Vulnerability Index	Addo (2013)	Ghana	Mean elevation, mean shoreline displacement, local subsidence trend, mean tidal range, maximum significant wave height
16	Flood/Erosion Vulnerability Index (FVI—EVI)	Kokkinos et al. (2014)	Greece	Storms, maximum elevation of flood water, storm surge wave run-up, shoreline type coastal erosion, sediment grain size, wave height, hinterland properties
17	Coastal Vulnerability Index	Bagdanavičiute et al. (2015)	Lithuania	Historical shoreline change rate, beach width, beach height, beach sediments, mean significant wave height
18	Coastal Vulnerability Index	Pantusa et al. (2018)	Italy	Geomorphology, coastal slope, coastal erosion, emerged beach width, dune width, relative SLR, mean significant wave height, mean tidal range, width of vegetation behind the beach, presence of *Posidonia Oceanica*
19	Coastal Vulnerability Index (CVI)	Tragaki et al. (2018)	Greece	Geomorphology, shoreline shifting rate, coastal slope, relative SLR rise rate, mean wave height, mean tidal range
20	Geospatial Risk Index for Critical Infrastructure	Hawchar et al. (2020)	Ireland	SLR, coastal erosion rate, heavy rainfall, long periods of precipitation, high river flow, high wind speed, temperature, landslides, infrastructure importance
21	Coastal Sensitivity Index (CSI)	Zampazas et al. (2022)	Greece	Geomorphology, geology, shoreline erosion/accretion rate, relative SLR change rate, mean wave height, mean tidal range

Table 2 Geophysical Variables used in the literature

Variables	Authors
Geomorphology (slope, elevation, shoreline type, rock type, beach type, solid and drift geology)	Gornitz (1991), Shaw et al. (1998), Thieler and Hammar-Klose (1999), Pendleton et al. (2004), Doukakis (2005), Boruff et al. (2005), Abuodha and Woodroffe (2006), Rao et al. (2008), Mendoza and Jiménez (2009), Gaki-Papanastassiou et al. (2010), McLaughlin and Cooper (2010), Karymbalis et al. (2012), Balica et al. (2012), Yin et al. (2012), Tibbetts and van Proosdij (2013), Addo (2013), Mani Murali et al. (2013), Alexandrakis et al. (2014), Kokkinos et al. (2014), Ahsan and Warner (2014), Satta (2014), Satta et al. (2015), Bagdanavičiute et al. (2015), Zanetti et al. (2016), Tragaki et al. (2018), Gargiulo et al. (2020), El-Zein et al. (2021), Zampazas et al. (2022)
Sea-level rise	Shaw et al. (1998), Pendleton et al. (2004), Doukakis (2005), Abuodha and Woodroffe (2006), Gaki-Papanastassiou et al. (2010), Karymbalis et al. (2012), Yin et al. (2012), Mani Murali et al. (2013), Ahsan and Warner (2014), Alexandrakis et al. (2014), Satta (2014), Satta et al. (2015), Kantamaneni (2016), Zanetti et al. (2016), Toimil et al. (2017), Tragaki et al. (2018), Pantusa et al. (2018), Hawchar et al. (2020), Zampazas et al. (2022)
Erosion and shoreline change	Gornitz (1991), Shaw et al. (1998), Thieler and Hammar-Klose (1999), Pendleton et al. (2004), Boruff et al. (2005), Abuodha and Woodroffe (2006), Mendoza and Jiménez (2009), Gaki-Papanastassiou et al. (2010), Karymbalis et al. (2012), Tibbetts and van Proosdij (2013), Addo (2013), Mani Murali et al. (2013), Alexandrakis et al. (2014), Kokkinos et al. (2014), Satta (2014), Satta et al. (2015), Bagdanavičiute et al. (2015), Zanetti et al. (2016), Tragaki et al. (2018), Pantusa et al. (2018), Zampazas et al. (2022)
Tidal range	Gornitz (1991), Shaw et al. (1998), Thieler and Hammar-Klose (1999), Pendleton et al. (2004), Doukakis (2005), Boruff et al. (2005), Abuodha and Woodroffe (2006), Rao et al. (2008), Gaki-Papanastassiou et al. (2010), McLaughlin and Cooper (2010), Karymbalis et al. (2012), Yin et al. (2012), Mani Murali et al. (2013), Tibbetts and van Proosdij (2013), Addo (2013), Alexandrakis et al. (2014), Zanetti et al. (2016), Toimil et al. (2017), Tragaki et al. (2018), Pantusa et al. (2018), Zampazas et al. (2022)
Wave height	Gornitz (1991), Shaw et al. (1998), Thieler and Hammar-Klose (1999), Pendleton et al. (2004), Doukakis (2005), Boruff et al. (2005), Abuodha and Woodroffe (2006), Rao et al. (2008), Gaki-Papanastassiou et al. (2010), McLaughlin and Cooper (2010), Li and Li (2011), Karymbalis et al. (2012), Mani Murali et al. (2013), Tibbetts and van Proosdij (2013), Yin et al. (2012), Alexandrakis et al. (2014), Addo (2013), Bagdanavičiute et al. (2015), Calil et al. (2017), Tragaki et al. (2018), Pantusa et al. (2018), Zampazas et al. (2022)

Table 2 (continued)

Variables	Authors
Storm surge	Mendoza and Jiménez (2009), Balica et al. (2012), Kokkinos et al. (2014), Calil et al. (2017), Toimil et al. (2017)
Number of extreme events	Balica et al. (2012), Tibbetts and van Proosdij (2013), Zanetti et al. (2016), Calil et al. (2017), Hawchar et al. (2020)
Coastline (km)	Balica et al. (2012)
Distance from shoreline	Tibbetts and van Proosdij (2013), Satta (2014), Satta et al. (2015), Zanetti et al. (2016), Gargiulo et al. (2020)
Elevation	Abuodha and Woodroffe (2006), Mendoza and Jiménez (2009), McLaughlin and Cooper (2010), Yin et al. (2012), Kokkinos et al. (2014), Satta (2014), Satta et al. (2015)
Land cover	Mani Murali et al. (2013), Balica et al. (2012), Satta (2014), Satta et al. (2015), Calil et al. (2017)
Hazard maps	Kleinosky et al. (2007), Tate et al. (2010), Balica et al. (2012), Satta (2014), Guillard-Gonçalves et al. (2015), Bagdanavičiute et al. (2015), Hawchar et al. (2020)
Coastal flood protection	Li and Li (2011), Balica et al. (2012), Satta (2014)
Groundwater level	Satta (2014)
Vegetation-*Posidonia oceanica*	Tibbetts and van Proosdij (2013), Satta (2014), Pantusa et al. (2018)

qualitative and quantitative data related to 42 variables (that were then reduced to 11 independent factors) to estimate the level of social vulnerability within American metropolitan coastal areas, creating the Social Vulnerability Index (SoVI). This index has been the baseline for the vast majority of the indices in the literature that take social factors into consideration. Alexandrakis et al. (2014) used the term socCVI, in an effort to combine the physical parameters of CVI with socio-economic factors. Guillard-Gonçalves et al. (2015) readapted SoVI to suit the social context of their case study in Lisbon, Portugal. Kleinosky et al. (2007) used a variety of socio-economic parameters within scenarios of sea-level rise to assess storm-surge flooding vulnerability level. In the approach of Tate et al. (2010), frequent hazards define a higher level of risk, as monetary losses are depicted via crucial infrastructure damage. A summary of the social coastal vulnerability indices used in the literature is presented in Table 3.

Composite indices composed of various index types, such as geophysical, social, economic (i.e., socio-economic, socio-enviromental) are also frequently used. From simpler (Wu et al. 2002; Boruff et al. 2005; Chakraborty et al. 2005; Kantamaneni 2016) to more complex indices (Li and Li 2011; Satta 2014; Zanetti et al. 2016), recent researches tend to consider multiple factors. More and more variables describing climate data, wave and wind, geomorphology, land use/land cover, education, unemployment, and crucial infrastructure in coastal areas are used, with the proper adjustments for each case study (Briguglio and Galea 2003; McLaughlin and Cooper 2010; Mackey and Russell 2011; Balica et al. 2012; Mani Murali et al. 2013; Satta 2014; Ahsan and Warner 2014; Kantamaneni 2016; Zanetti et al. 2016; Calil et al. 2017; Toimil et al. 2017; Debortoli et al. 2019; Gargiulo

Table 3 Social Coastal Vulnerability Indices found in the literature

No	Index	Authors	Case Study Area	Variables
1	SoVI (Social Vulnerability Index)	Cutter et al. (2003)	USA	Socio-economic status, gender, race and ethnicity, age, commercial and industrial development, employment loss, rural/urban, residential property, infrastructure and lifelines, renters, occupation, family structure, education, population growth, medical services, social dependence, special needs populations
2	No named-Social Vulnerability Index	Kleinosky et al. (2007)	USA	Flood risk maps, poverty, immigrants, old age/disabilities
3	No named-Social Vulnerability Index	Tate et al. (2010)	USA	Flood hazard maps, socio-economic status, age, race and ethnicity, gender, total population, population distribution
4	SoVI (Social Vulnerability Index)	Guillard-Gonçalves et al. (2015)	Portugal	Flood hazard maps, socio-economic status, gender, race and ethnicity, age, employment loss, rural/urban, renters, occupation, family structure, education level, population growth, medical services and access, social dependency, special needs population
5	Social Vulnerability Index (SVI)	Tragaki et al. (2018)	Greece	Population density, share of persons above 65 years in total population, share of children below 5 years in total population, share of foreign-born in total population, share of women in total population, share of low educated in total population

et al. 2020; Edmonds et al. 2020; El-Zein et al. 2021). Especially in urban coastal environments (e.g., Zanetti et al. 2016; Gargiulo et al. 2020), the combination of different variable types seems to provide a more dynamic approach to human–environment interactions. As index-based methods are believed by some authors (e.g., Ford et al. 2018) to consist a static approach, the use of combined indices is a step to fill this gap, since human–environment interactions in coastal urban environments are highly dynamic. Especially in coastal cities, natural systems are distorted by human actions and co-exist with the built environment (Malvarez et al. 2021) in a complex definition of resilience (Masselink and Lazarus 2019). However, some authors suggest that one single complex index is not representative and prefer the use of multiple single indices instead (e.g., Tragaki et al. 2018). A summary of composite indices found in the literature is presented in Table 4, and the socio-economic variables used for social and composite indices are presented in Table 5.

Questionnaire surveys have also been used to evaluate vulnerability and resilience, as in the case of the Port Resilience Index (Morris and Sempier 2016). Global indices such as the World Risk Index (World Risk Report 2019), the Index for Risk Management (INFORM; Messina et al. 2019), the Climate Risk Index (CRI; Eckstein et al. 2020) and the University of Notre Dame's Global Adaptation Index (ND-GAIN; Chen et al. 2015) have also been frequently used in order to validate custom indices, as they are designed to improve the common data basis for risk management so that the majority of governments and policy makers and other stakeholders can work consistently (Poljansek et al. 2020).

The CVI (Gornitz 1991) has been the ground for many indices with a geophysical approach developed later in the literature, and the SoVI (Cutter et al. 2003) for indices with a socio-economic approach. Past researches included simpler indices and variables were one-dimensional. As years advanced, more and more papers combining physical and socio-economic approaches have been published. Despite having similarities in variable selection, it was not possible to find consistency between different approaches, especially for complex indices. Also, even though the majority of the variables are quantitative, the evaluation process highly depends on the personal opinion of the researchers. Variable ranking and categorization may differ, taking into consideration specific aspects of each study area. There are even different approaches for the same variable. For example, some researchers suggest that low values for the variable "tidal range" indicate high vulnerability (e.g., Tragaki et al. 2018; Zampazas et al. 2022), while others suggest the opposite (e.g., Pantusa et al. 2018). Furthermore, vulnerability assessment using indices seems to be a static approach while human–environment interactions are highly dynamic. The approaches of Zanetti et al. (2016), Toimil et al. (2017) and Gargiulo et al. (2020) tried to fill this gap with indices matching diverse socio-economic issues; however, there is still room for improvement in this direction. The MHCRI by Satta (2014) included diverse variables that are implemented in both urban and rural environments.

4 Summary and Conclusions

A total of 46 studies that generate a vulnerability index for climate change related hazards in coastal areas has been reviewed. There are studies that focus on physical variables and others that focus on both physical and social factors. An interesting fact is the diversity of the approaches that have been developed. Authors have used different scales of analysis, criteria for variable selection and natural phenomena as main hazards for their research. Especially among social indicators, it is possible that limitations in data availability have

Table 4 Composite Coastal Vulnerability Indices found in the literature

No	Index	Authors	Case Study Area	Variables
1	No-named Socio-Environmental Vulnerability Index	Wu et al. (2002)	USA	Total population, Total housing units, Number of females, Number of non-white residents, Number of people U18, Number of people O60, Number of female-headed single parent households, Number of renter-occupied housing units, Median House Value, Flooding Risk Zones
2	Composite Vulnerability Index	Briguglio and Galea (2003)	Malta, Singapore	Economic Openness, dependence on narrow range imports, dependence strategic imports, peripherality, economic vulnerability and resilience
3	PVI (Place Vulnerability Index)	Boruff et al. (2005)	USA	Geomorphology, coastal slope, relative SLR rate, shoreline erosion/acceleration rate, mean tidal range, mean wave height, socio-economic status, gender, race and ethnicity, age, commercial and industrial development, employment loss, rural/urban, residential property, infrastructure and lifelines, renters, occupation, family structure, education, population growth, medical services, social dependence, special needs populations
4	No-named Socio-Environmental Vulnerability Index	Chakraborty et al. (2005)	USA	Flooding Risk, Population and structure, Differential access to resources, Population with special evacuation needs
5	CVI (Coastal Vulnerability Index)	McLaughlin and Cooper (2010)	Ireland	Shoreline type, rivers, solid geology drift geology, elevation, orientation, inland buffer, landform, coastal elevation, inland buffer, significant wave height, tidal range, difference in modal and storm waves, frequency of onshore storms, storm probability, morpho-dynamic state, settlement, cultural heritage, roads, railways, land use, conservation designation

Table 4 (continued)

No	Index	Authors	Case Study Area	Variables
6	No-named Socio-Environmental Vulnerability Index	Li and Li (2011)	China	Total population, population density, age, educational level, road density, road grade, industrial output value, agricultural output value, per-capita output value, residential land area, ratio of urban residential land, farming land area, aquaculture land area, ratio of low-lying arable land, beaches and wetlands area, ratio of beaches, mangroves area, rivers density, harbors and wharfs, tide-prevention engineering, ratio of coastal highways, coastal building density, seawalls completion rate, ratio of seawalls, ratio of labor population, gross income
7	No-named Vulnerability index	Mackey and Russell (2011)	China	SLR, extreme weather events, storm surge, inundation, salinity, population, population density, average family size, number of households, population at working age, average natural population growth rate, annual average income per capita, number of poor households, percentage of poor households, number of teachers, number of doctors, agricultural land per person, percentage of ethnic households, number of rural households, number of livelihood streams, streams employing > 10,000 or producing > 250billion VND, average annual GDP per household, rice crop land per person, households reliant on industry, average annual GDP per household contributed by industry, households connected to national grid, length of high/medium voltage powerlines, number of power plants, percentage of off-farm income, number of factories, number of different industries, urban population, urban households, urban area, sewer/septic tank, water supply, major waterways, major roads, district roads, transport hubs

Table 4 (continued)

No	Index	Authors	Case Study Area	Variables
8	CCFVI (Coastal City Flood Vulnerability Index)	Balica et al. (2012)	Cities worldwide	SLR, storm surge, number of cyclones, river discharge, foreshore slope, soil subsidence, coastline length, percentile of disabled people, shelters, cultural heritage, awareness/preparedness, length of drainage, growing coastal population, recovery time, uncontrolled planning zones, flood hazard maps, institutional organizations, flood protection measures
9	Coastal Vulnerability Index	Mani Murali et al. (2013)	India	SLR, geomorphology, regional elevation, shoreline change, sea level changes, significant wave height, tidal range, population, land use, land cover, road network, cultural heritage
10	Social Coastal Vulnerability Index (SocCVI)	Alexandrakis et al. (2014)	Greece	Geomorphology, coastal slope, relative SLR rate, shoreline erosion/accretion rate, mean tidal range, mean wave height, presence of settlements, sites of cultural heritage, transport network, land use, economic activities in the coast
11	MHCRI (Multi-Hazard Risk Index)	Satta (2014)	Mediteranean	SLR, storms, urban development, tourist development, coastal erosion, artificial frontage, coastal slope, elevation, distance from the shoreline, river flow regulation, groundwater occurrence, aquifer thickness, hydraulic conductivity, height of groundwater level, groundwater consumption, distance from the shoreline, impact of existing status of riverflow regulation, ecosystems health, hazard maps, coastal protection structures, drainage density, freshwater barrier wells, water management, education level, age, awareness/preparedness, people and livelihoods, infrastructures, land use, socio-cultural assets, livestock density index, tourism structures density, presence of aquifers

Table 4 (continued)

No	Index	Authors	Case Study Area	Variables
12	Socio-Economic Vulnerability Index	Ahsan and Warner (2014)	Bangladesh	Population density, age, gender, population growth rate, percentage of migrated households, percentage of illiterate households, percentage of households not having brick-built house, percentage of households participated in the last local-election, percentage of households contributed free-labor to embankment construction or similar activity, percentage of households depending on natural source for their income, percentage of unemployed households, percentage of households below poverty line, percentage of households lost land in last 5 years due to disasters, percentage of households not getting electricity, percentage of households not getting sanitary latrine, percentage of households using pond, river and well water for drinking and cooking, percentage of households with family member with chronic illness, percentage of not-paved roads, percentage of households not willing to go to cyclone shelter, percentage of households not having shelter in cyclone shelter, percentage of households do not understand National Warning System, provision of local early warning system, number of cyclones in the last 5 years, number of floods in the last 5 years
13	MS-CRI (Multi-Scale Coastal Risk Index)	Satta et al. (2015)	Mediterranean	SLR, storms, drought, landform, coastal elevation, population over 65 years, education level, population growth, tourist arrivals, land cover, population density

Table 4 (continued)

No	Index	Authors	Case Study Area	Variables
14	CIVI (Coastal Infrastructure Vulnerability Index)	Kantamaneni (2016)	Wales	Population in coastal vulnerability zones, infrastructure, land use, rainfall, flood/storm impact, fiscal value of the place, coastal erosion, high growth of population alongside coasts, drainage system, warning system, marine industry growth, politics and policies
15	Socio-Environmental Vulnerability Index for Coastal Areas (SEVICA)	Zanetti et al. (2016)	Brazil	Geomorphology, SLR, tide height, relief, distance from the coast, coastal slope, number of extreme events, water body proximity, geotechnical classification of soil, education level, income, population density, age
16	CCRI (Comparative Coastal Risk Index)	Calil et al. (2017)	Latin America-Caribbean	Wave energy, storm surge, El Nino, significant wave height, cumulated tropical cyclone winds, urban coverage percentage, crop coverage percentage, beach area, coastal forests area, wetlands area, GDP per capita, Gini coefficient, child malnutrition rate, child mortality rate, population
17	No named socio-economic index	Toimil et al. (2017)	Spain	Wave height, storm surge, SLR, astronomical tide, land use, assets (housing, industry), population, assets (capital stock), activity flows
18	Climate Change Vulnerability Index for aviation and marine sectors	Debortoli et al. (2019)	Canada (Arctic)	SLR, rain, snow, winter-summer temperatures, airport sensitivity, marine sensitivity, disaster search and rescue rates, emergency volunteers, education, housing conditions, local language knowledge, immigration ratio, population growth
19	CORI (Coastal Resilience Index)	Gargiulo et al. (2020)	USA, Netherlands, Denmark	Coastal slope, water body proximity, distance from coastline, urban permeable surface, raised buildings, conservation of buildings, transport network proximity, ground floor activities, presence of public facilities

Table 4 (continued)

No	Index	Authors	Case Study Area	Variables
20	Composite Climate Change Vulnerability Index (CCCVI)	Edmonds et al. (2020)	Australia	Ecosystem services, food, human habitat, health, infrastructure, water
21	Flood-Social Vulnerability Index	El-Zein et al. (2021)	Australia	Extent of flooding, average maximum flood depth, average maximum velocity, average flood duration, household structure, English proficiency and schooling, immigration status and income, property rental/ownership, unemployment, age, education

Table 5 Socio-Economic Variables used in the literature

Variables	Authors
Age of inhabitants	Cutter et al. (2003), Boruff et al. (2005), Kleinosky et al. (2007), Tate et al. (2010), Li and Li (2011), Satta (2014), Guillard-Gonçalves et al. (2015), Zanetti et al. (2016), Tragaki et al. (2018), Gargiulo et al. (2020), El-Zein et al. (2021)
Income (inhabitants' annual income)	Cutter et al. (2003), Boruff et al. (2005), Mackey and Russell (2011), Ahsan and Warner (2014), Zanetti et al. (2016), El-Zein et al. (2021)
Employment	Cutter et al. (2003), Boruff et al. (2005), Guillard-Gonçalves et al. (2015), Gargiulo et al. (2020), El-Zein et al. (2021)
Population (total numbers and population density)	Wu et al. (2002), Cutter et al. (2003), Boruff et al. (2005), Chakraborty et al. (2005), Tate et al. (2010), McLaughlin and Cooper (2010), Li and Li (2011), Mackey and Russell (2011), Balica et al. (2012), Mani Murali et al. (2013), Satta (2014), Satta et al. (2015), Guillard-Gonçalves et al. (2015), Kantamaneni (2016), Zanetti et al. (2016), Calil et al. (2017), Toimil et al. (2017), Tragaki et al. (2018)
Housing units	Wu et al. (2002), Cutter et al. (2003), Toimil et al. (2017)
Conservation of buildings	Gargiulo et al. (2020)
Race	Cutter et al. (2003), Boruff et al. (2005), Tate et al. (2010), Guillard-Gonçalves et al. (2015)
Access to resources	Cutter et al. (2003), Boruff et al. (2005), Chakraborty et al. (2005), Guillard-Gonçalves et al. (2015)
Land use	Li and Li (2011), McLaughlin and Cooper (2010), Mani Murali et al. (2013), Alexandrakis et al. (2014), Satta (2014), Zanetti et al. (2016), Gargiulo et al. (2020), Toimil et al. (2017), Yin et al. (2012), El-Zein et al. (2021)
Cultural heritage	McLaughlin and Cooper (2010), Li and Li (2011), Balica et al. (2012), Mani Murali et al. (2013), Alexandrakis et al. (2014), Satta (2014)
Infrastructure dependence	Cutter et al. (2003), Boruff et al. (2005), Mani Murali et al. (2013), Alexandrakis et al. (2014), Satta (2014), Hawchar et al. (2020), Debortoli et al. (2019)
Tourism	Satta (2014), Satta et al. (2015)
Awareness	Balica et al. (2012), Satta (2014)
Economic openness/dependence	Cutter et al. (2003), Boruff et al. (2005), Li and Li (2011), Briguglio and Galea (2003), Alexandrakis et al. (2014), Ahsan and Warner (2014)

led to many different approaches worldwide. Furthermore, the lack of consistency in the selection of variables and indicators (especially socio-economic) is observed, whereas the selection of geophysical indicators is rather standardized. Outcomes of models based on geophysical approaches seem to be more consistent as well. This research demonstrates that a broad range of variables have been used in this context, considering different types of time and space scales for coastal process operation, categorizing into different intervals and ranking each variable result in a large spectrum of vulnerability levels. However, in terms of suitability for vulnerability classification, variable ranking is often controversial, as the evaluation process highly depends on the personal opinion of the researchers.

The objective of this review paper was to provide a valid description of the key dimensions of heterogeneity within research on climate change vulnerability. Through this

review, researchers and policy-makers can determine the gaps in knowledge on climate change vulnerability of coastal areas, and the challenges that need to be addressed in future research.

The absence of a specific framework for the selection of indicators was identified, especially regarding social vulnerability. In most of the case studies, indicators have been selected taking into consideration data availability and researchers' aspirations. Moreover, researchers do not acknowledge concerns regarding static understanding of the human environment in index-based vulnerability research. A holistic approach in the selection of variables would be able to overcome these concerns, in order to identify not only areas in danger, but also the level of vulnerability of people and communities at local scales, as damage on crucial infrastructure will affect directly their livelihood.

Authors contribution CNR: Conceptualization, Investigation, Methodology, Writing—original draft; VAT: Conceptualization, Methodology, Project administration, Resources, Supervision, Validation, Writing—Review & Editing. Both authors approved the final paper.

Declarations

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References

Abuodha PA, Woodroffe CD (2006) Assessing vulnerability of coasts to climate change: A review of approaches and their application to the Australian coast. GIS for the Coastal Zone: A Selection of Papers from CoastGIS 2006, 458. 2006

Addo KA (2013) Assessing coastal vulnerability index to climate change: the Case of Accra – Ghana. J Coastal Res 165:1892–1897. https://doi.org/10.2112/si65-320.1

Afentoulis V, Kragiopoulou E, Skarlatou E, Moschos E, Lykou A, Makropoulos C, Tsoukala V (2017) Coastal processes assessment under extreme storm events using numerical modelling approaches. Environ Process 4:731–747. https://doi.org/10.1007/s40710-017-0253-8

Ahsan MN, Warner J (2014) The socioeconomic vulnerability index: A pragmatic approach for assessing climate change led risks—A case study in the south-western coastal Bangladesh. Int J Disaster Risk Reduct 8:32–49. https://doi.org/10.1016/j.ijdrr.2013.12.009

Alexandrakis G, Petrakis S, Ghionis G, Kampanis N, Poulos SE (2014) Natural and human indicators in coastal vulnerability and risk assessment. In: 10th International Congress of the Hellenic Geographical Society: pp. 644–655. https://doi.org/10.13140/2.1.4033.5363

Asariotis R, Benamara H, Mohos-Naray V (2017) Port Industry Survey on Climate Impacts and Adaptation, UNCTAD Research Paper No. 18, United Nations, December 2017

Bagdanavičiute I, Kelpšaite L, Soomere T (2015) Multi-criteria evaluation approach to coastal vulnerability index development in micro-tidal low-lying areas. Ocean Coast Manag 104:124–135. https://doi.org/10.1016/j.ocecoaman.2014.12.011

Baker SM (2009) Vulnerability and resilience in natural disasters: a marketing and public policy perspective. J Public Policy Mark 28(1):114–123. https://doi.org/10.1509/jppm.28.1.114

Balica SF, Wright NG, van der Meulen F (2012) A flood vulnerability index for coastal cities and its use in assessing climate change impacts. Nat Hazards 64(1):73–105. https://doi.org/10.1007/s11069-012-0234-1

Bevacqua E, Maraun D, Vousdoukas MI, Voukouvalas E, Vrac M, Mentaschi L, Widmann M (2019) Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change. Sci Adv 5(9):1–7. https://doi.org/10.1126/sciadv.aaw5531

Blasiak R, Spijkers J, Tokunaga K, Pittman J, Nobuyuki Y, Österblom H (2017) Climate change and marine fisheries: Least developed countries top global index of vulnerability. PLoS ONE 12(6):e0179632. https://doi.org/10.1371/journal.pone.0179632

Bonetti J, Klein AHF, Muler M, De Luca CB, Silva GV, Toldo EE Jr, Gonzalez M (2013) Spatial and numerical methodologies on coastal erosion and flooding risk assessment. In: Finkl C (ed) Coastal Hazards. Chapter 16. Coastal Research Library Series, pp. 423–442. Dordrecht, Springer

Boruff BJ, Emrich C, Cutter SL (2005) Erosion hazard vulnerability of us coastal counties. J Coastal Res 215:932–942. https://doi.org/10.2112/04-0172.1

Briguglio L, Galea W (2003) Updating and augmenting the economic vulnerability index. Occasional paper, Islands and Small States Institute of the University of Malta 4:1–15 https://www.um.edu.mt/library/oar/handle/123456789/18371. Accessed 01/12/2020

Brooks N (2003) Vulnerability, risk and adaptation: A conceptual framework. Tyndall Centre for Climate Change Research. Working paper 38. School of Environmental Sciences, University of East Anglia, Norwich, UK. https://gsdrc.org/document-library/vulnerability-risk-and-adaptation-a-conceptual-framework/ (Accessed on 20/05/2021)

Calil J, Reguero BG, Zamora AR, Losada IJ, Méndez FJ (2017) Comparative coastal risk index (CCRI): A multidisciplinary risk index for Latin America and the Caribbean. PLoS ONE 12(11):1–24. https://doi.org/10.1371/journal.pone.0187011

Chakraborty J, Tobin G, Montz B (2005) Population evacuation: assessing spatial variability in geophysical risk and social vulnerability to natural hazards. Nat Hazards Rev 6(1):23–33. https://doi.org/10.1061/(ASCE)1527-6988(2005)6:1(23)

Chen C, Noble I, Hellmann J, Coffee J, Murillo M, Chawkla N (2015) University of Notre Dame global adaptation index country index technical report. ND-GAIN, South Bend, IN, USA. https://gain.nd.edu/assets/254377/nd_gain_technical_document_2015.pdf. Accessed 02/10/2021

Christian Aid (2021) Counting the cost 2021: A year of climate breakdown. Edited by Kramer K., Ware J. Report, Christian Aid, London, UK. No of pages: 25 https://www.christianaid.org.uk/sites/default/files/2021-12/Counting%20the%20cost%202021%20-%20A%20year%20of%20climate%20breakdown.pdf (Accessed on 18/03/2022)

Comte A, Pendleton L, Bailly D, Quillérou E (2019) Conceptual advances on global scale assessments of vulnerability: Informing investments for coastal populations at risk of climate change. Mar Policy 99:391–399. https://doi.org/10.1016/j.marpol.2018.10.038

Cutter SL, Boruff BJ, Shirley WL (2003) Social vulnerability to environmental hazards. Soc Sci Q 84(2):242–261. https://doi.org/10.1111/1540-6237.8402002

Dawson RJ, Dickson ME, Nicholls RJ, Hall JW, Walkden MJA, Mokrech M, Richards J, Zhou J, Miligan J, Jordan A, Pearson S, Rees J, Bates PD, Koukoulas S, Watkinson AR (2009) Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change. Clim Change 95:249–288. https://doi.org/10.1007/s10584-008-9532-8

Debortoli NS, Clark DG, Ford JD, Sayles JS, Diaconescu EP (2019) An integrative climate change vulnerability index for Arctic aviation and marine transportation. Nat Commun 10(1):2596. https://doi.org/10.1038/s41467-019-10347-1

Devoy RJN (2008) Coastal vulnerability and the implications of sea-level rise for Ireland. J Coastal Res 242:325–341. https://doi.org/10.2112/07a-0007.1

Doukakis E (2005) Coastal vulnerability and risk parameters. European Water 11(12):3–7

Eckstein D, Winges M, Künzel V, Schäfer L(2020) Global Climate Risk Index 2020 - Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2018 and 1999 to 2018. Germanwatch e.V., Bonn, Germany. https://germanwatch.org/sites/germanwatch.org/files/20-2-01e%20Global%20Climate%20Risk%20Index%202020_10.pdf (Accessed on 01/09/2021)

Edmonds HK, Lovell JE, Lovell CAK (2020) A new composite climate change vulnerability index. Ecol Indic 117 (106259). https://doi.org/10.1016/j.ecolind.2020.106529

Ellen IG, Yager J, Hanson M, Bosher L (2016) Planning for an uncertain future: can multicriteria analysis support better decision making in climate planning? J Plan Educ Res 36(3):349–362. https://doi.org/10.1177/0739456X16659911

El-Zein A, Ahmed T, Tonmoy F (2021) Geophysical and social vulnerability to floods at municipal scale under climate change: The cage of an inner-city suburb of Sydney. Ecol Indic 121:106988

Ford JD, Pearce T, McDowell G, Berrang-Ford L, Sayles JS, Belfer E (2018) Vulnerability and its discontents: The past, present and future of climate change vulnerability research. Clim Change 151:189–203

Gaki-Papanastassiou K, Karymbalis E, Poulos S, Zouva C (2010) Coastal vulnerability assessment to sea-level rise based on geomorphological and oceanographical parameters: the case of Argolikos Gulf. https://www.researchgate.net/publication/235960304

Gargiulo C, Battarra R, Tremiterra MR (2020) Coastal areas and climate change: A decision support tool for implementing adaptation measures. Land Use Policy 91:104413. https://doi.org/10.1016/j.landusepol.2019.104413

Giannakidou C, Diakoulaki D, Memos C (2020) Vulnerability to coastal flooding of industrial urban areas in Greece. Environ Process 7:749–766. https://doi.org/10.1007/s40710-020-00442-7

Giri S, Lathrop RG, Obropta CG (2020) Climate change vulnerability assessment and adaptation strategies through best management practices. J Hydrol 580:124311

Gornitz V (1991) Global coastal hazards from future sea level rise. Palaeogeogr Palaeoclimatol Palaeoecol 89(4):379–398. https://doi.org/10.1016/0031-0182(91)90173-O

Gornitz VM, Daniels RC, White TW, Birdwell KR (1994) The development of a coastal risk assessment database: vulnerability to sea-level rise in the U.S. Southeast. J Coastal Res 12:327–338. http://www.jstor.org/stable/25735608

Guillard-Gonçalves C, Cutter SL, Emrich CT, Zêzere JL (2015) Application of social vulnerability index (SoVI) and delineation of natural risk zones in Greater Lisbon, Portugal. J Risk Res 18(5):651–674. https://doi.org/10.1080/13669877.2014.910689

Hallegate S, Przyluski V (2010) The economics of natural disasters: concepts and methods. Policy research working paper 5507, The World Bank, Sustainable Development Network, December 2010. https://openknowledge.worldbank.org/handle/10986/3991 (Accessed on 04/10/2021)

Hawchar L, Naughton O, Nolan P, Stewart MG, Ryan PC (2020) A GIS-based framework for high-level climate change risk assessment of critical infrastructure. Clim Risk Manag 29:100235. https://doi.org/10.1016/j.crm.2020.100235

Heinz Center (2002) Human Links to Coastal Disasters. The H. John Heinz III Center for Science, Economics and the Environment. Washington D.C., U.S.A., ISBN-10: 0971759227

Hinkel J (2011) Indicators of vulnerability and adaptive capacity: Towards a clarification of the science-policy interface. Glob Environ Chang 21:198–208. https://doi.org/10.1016/j.gloenvcha.2010.08.002

IPCC (2001) Climate Change 2001: Impacts, Adaptation And Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. JJ McCarthy, OF Canziani, NA Leary, DJ Dokken, KS White (eds) Cambridge University Press, Cambridge, UK, and New York, USA, 1032p

IPCC (2014) Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–32

Islam N, Winkel J (2017) Climate Change and Social Inequality. UN Department of Economic and Social Affairs (DESA) Working Papers, No. 152, UN, New York, https://doi.org/10.18356/2c62335d-en

Jun KS, Chung ES, Sung JY (2011) Development of spatial water resources vulnerability index considering climate change impacts. Sci Total Environ 409(24):5228–5242. https://doi.org/10.1016/j.scitotenv.2011.08.027

Kantamaneni K (2016) Coastal infrastructure vulnerability: an integrated assessment model. Nat Hazards 84(1):139–154. https://doi.org/10.1007/s11069-016-2413-y

Karymbalis E, Chalkias C, Chalkias G, Grigoropoulou E, Manthos G, Ferentinou M (2012) Assessment of the sensitivity of the southern coast of the Gulf of Corinth (Peloponnese, Greece) to sea-level rise. Central Eur J Geosci 4(4):561–577. https://doi.org/10.2478/s13533-012-0101-3

Kleinosky LR, Yarnal B, Fisher A (2007) Vulnerability of Hampton roads, Virginia to storm-surge flooding and sea-level rise. Nat Hazards 40(1):43–70. https://doi.org/10.1007/s11069-006-0004-z

Kokkinos D, Prinos P, Galiatsatou P (2014) Assessment of coastal vulnerability for present and future climate conditions in coastal areas of the Aegean Sea. 11th International Conference on Hydroscience & Engineering, Hamburg, Germany, 28 September-2 October 2014. https://www.researchgate.net/publication/266561166_Assessment_of_coastal_vulnerability_for_present_and_future_climate_conditions_in_coastal_areas_of_the_Aegean_Sea (Accessed on 22/06/2021)

Kourtis IM, Tsihrintzis VA (2021) Adaptation of urban drainage networks to climate change: A review. Sci Total Environ 771:145431. https://doi.org/10.1016/j.scitotenv.2021.145431

Li K, Li GS (2011) Vulnerability assessment of storm surges in the coastal area of Guangdong Province. Nat Haz Earth Syst Sci 11(7):2003–2010. https://doi.org/10.5194/nhess-11-2003-2011

Li L, Cao R, Wei K, Wang W, Chen L (2019) Adapting climate change challenge: A new vulnerability assessment framework from the global perspective. J Clean Prod 217:216–224

Malone EL, Engle NL (2011) Evaluating regional vulnerability to climate change: purposes and methods. Wires Clim Change 2(3):462–474. https://doi.org/10.1002/wcc.116

Malliouri D, Afentoulis V, Bonaros V, Memos C, Tsoukala V (2017) Integrated design of coastal structures and adaptation to climate change hazards. 15th International Conference on Environmental Science and Technology, Rhodes, Greece, 31 August – 2 September 2017. https://cest2017.gnest.org/sites/default/files/presentation_file_list/cest2017_00880_oral_paper.pdf (accessed on 08/11/2021)

Malvarez G, Ferreira O, Navas F, Cooper JAG, Gracia-Prieto FJ, Talavera L (2021) Storm impacts on a coupled human-natural coastal system: Resilience of developed coasts. Sci Total Environ 768:144987. https://doi.org/10.1016/j.scitotenv.2021.144987

Mani Murali R, Ankita M, Amrita S, Vethamony P (2013) Coastal vulnerability assessment of Puducherry coast, India, using the analytical hierarchical process. Nat Hazard 13(12):3291–3311. https://doi.org/10.5194/nhess-13-3291-2013

Maragoudaki R, Tsakiris G (2005) Flood mitigation planning using Promethee. Eur Water 9–10:51–58

Masselink G, Lazarus E (2019) Defining coastal resilience. Water 11(12):2587. https://doi.org/10.3390/w11122587

McGranahan G, Balk D, Anderson B (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environ Urban 19:17–37

McIntosh RD, Becker A (2019) Expert evaluation of open-data indicators of seaport vulnerability to climate and extreme weather impacts for U.S. North Atlantic ports. Ocean Coast Manag 180:104911

McLaughlin S, Cooper JAG (2010) A multi-scale coastal vulnerability index: A tool for coastal managers? Environ Hazards 9(3):233–248. https://doi.org/10.3763/ehaz.2010.0052

Mendoza ET, Jiménez JA (2009) Regional geomorphic vulnerability analysis to storms for Catalan beaches. Proc Inst Civ Eng Marit Eng 162(3):127–135. https://doi.org/10.1680/maen.2009.162.3.127

Messina L, Poljansek K, Vernaccini L (2019) Usage of INFORM GRI in Humanitarian Aid and Development Assistance Initiatives: Results of the INFORM GRI's Impact Survey. EUR 29894 EN, Publications Office of the European Union, Luxembourg, ISBN 978–92–76–12302–6 (pdf), https://doi.org/10.2760/591043 (Access date 28–03–2022)

Meyer V, Becker N, Markantonis V, Schwarze R, van den Bergh JCJM, Bouwer LM, Bubeck P, Ciavola P, Genovese E, Green C, Hallegatte S, Kreibich H, Lequeux Q, Logar I, Papyrakis E, Pfurtscheller C, Poussin J, Przyluski V, Thieken AH, Viavattene C (2013) Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps. Nat Hazards Earth Syst Sci 13(5):1351–1373. https://doi.org/10.5194/nhess-13-1351-2013

Morris LL, Sempier T (2016) Ports resilience expert committee (2016) ports resilience index: a port management self-assessment 28. https://masgc.org/assets/images/Ports_resilience_index.pdf. Accessed on 28/03/2022

Nguyen T, Bonetti J, Rogers K, Woodroffe CD (2016) Indicator-based assessment of climate change impacts on coasts: A review of concepts, methodological approaches and vulnerability indices. Ocean Coast Manag 123:18–43

Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD et al (2021) (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372:n71. https://doi.org/10.1136/bmj.n71

Pantusa D, D'Alessandro F, Riefolo L, Principato F, Tomasicchio GR (2018) Application of coastal vu 0lnerability index. a case study along the Apulian Coastline, Italy. Water 10(9):1208

Pendleton EA, Thieler ER, Williams SJ, Beavers R (2004) Coastal Vulnerability Assessment of Cumberland Island National Seashore (CUIS) to sea-level rise. https://pubs.usgs.gov/of/2004/1196/ofr20041196.pdf (Accessed on 16/10/2020)

Pistrika A, Tsakiris G, Nalbantis I (2014) Flood depth-damage functions for built environment. Environ Process 1(4):553–572. https://doi.org/10.1007/s40710-014-0038-2

Poljansek K, Vernaccini L, Nweke E, Marin Ferrer M (2020) Imputation of missing values in the INFORM Global Risk Index, EUR 30037 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-14657-5. https://doi.org/10.2760/97910JRC119496

Preston BL, Jones R (2008) A national assessment of the sensitivity of Australian runoff to climate change. Atmos Sci Lett 9(4):202–208. https://doi.org/10.1002/asl.188

Rao KN, Subraelu P, Rao TV, Malini BH, Ratheesh R, Bhattacharya S, Rajawat AS, Ajai (2008) Sea-level rise and coastal vulnerability: An assessment of Andhra Pradesh coast, India through remote sensing and GIS. J Coast Conserv 12(4):195–207. https://doi.org/10.1007/s11852-009-0042-2

Roukouni A (2016) Investigation of innovative financing schemes for transportation projects. PhD Thesis, Department of Rural and Surveying Engineering, Faculty of Engineering, Aristotle University of Thessaloniki, Greece, October 2016 (in Greek)

Roukounis CN, Aretoulis G, Karambas T (2020) A combination of PROMETHEE and Goal-Programming methods for the evaluation of water airport connections. Int J Decis Support Syst Technol 12(2):50–66. https://doi.org/10.4018/IJDSST.2020040103

Rus K, Kilar V, Koren D (2018) Resilience assessment of complex urban systems to natural disasters: A new literature review. Int J Disaster Risk Reduct 31:311–330. https://doi.org/10.1016/j.ijdrr.2018.05.015

Saaty RW (1987) The Analytic Hierarchy Process-what it is and how it is used. Math Model 9:161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Satta A (2014) An index-based method to assess vulnerabilities and risks of Mediterranean coastal zones to multiple hazards - Un Indice per la valutazione delle vulnerabilità e dei rischi generati da multiple pericolosità sulle zone costiere del Mediterraneo. Doctoral dissertation submitted in October 2014 to the Department of Economics Ca'Foscari University of Venice, Italy. https://doi.org/10.13140/RG.2.1.4825.4969

Satta A, Venturini S, Puddu M, Firth J, Lafitte A (2015) Strengthening the Knowledge Base on Regional Climate Variability and Change: Application of a Multi-Scale Coastal Risk Index at Regional and Local Scale in the Mediterranean. Plan Bleu Technical Report-September 2015. https://planbleu.org/wp-content/uploads/2020/04/multi-scale_coastal_risk_index_compressed.pdf (accessed on 10/01/2021)

Tate E, Cutter SL, Berry M (2010) Integrated multihazard mapping. Environ Plann B Plann Des 37(4):646–663. https://doi.org/10.1068/b35157

Thieler ER, Hammar-Klose ES (1999) National Assessment of Coastal Vulnerability to Sea-Level Rise. Open-File Report 0–179, 1. https://pubs.usgs.gov/dds/dds68/reports/gulfrep.pdf (accessed 19/11/2020)

Tibbetts JR, van Proosdij D (2013) Development of a relative coastal vulnerability index in a macro-tidal environment for climate change adaptation. J Coast Conserv 17(4):775–797. https://doi.org/10.1007/s11852-013-0277-9

Toimil A, Losada IJ, Díaz-Simal P, Izaguirre C, Camus P (2017) Multi-sectoral, high-resolution assessment of climate change consequences of coastal flooding. Clim Change 145(3–4):431–444. https://doi.org/10.1007/s10584-017-2104-z

Torresan S, Critto A, Dalla Valle M, Harvey N, Marcomini A (2008) Assessing coastal vulnerability to climate change: Comparing segmentation at global and regional scales. Sustain Sci 3(1):45–65. https://doi.org/10.1007/s11625-008-0045-1

Tragaki A, Gallousi C, Karymbalis E (2018) Coastal hazard vulnerability assessment based on geomorphic, oceanographic and demographic parameters. Land 7(2):56. https://doi.org/10.3390/land7020056

Tsoukala V, Chondros M, Kapelonis Z, Martzikos N, Lykou A, Belibassakis K, Makropoulos C (2016) An integrated wave modelling framework for extreme and rare events for climate change in coastal areas - The case of Rethymno, Crete. Oceanologia 58:71–79. https://doi.org/10.1016/j.oceano.2016.01.002

United Nations (2015) The Paris Agreement. Conference of the Parties, United Nations Framework Convention on Climate Change, Paris, November-December 2015. https://unfccc.int/sites/default/files/english_paris_agreement.pdf. Accessed 21/09/2020

Uyarra M, Côté I, Gill JA, Tinch RRT, Viner D, Watkinson AR (2005) Island-specific preferences of tourists for environmental features: implications of climate change for tourism-dependent states. Environ Conserv 32(1):11–19. https://doi.org/10.1017/S0376892904001808

Wahl T, Brown S, Haigh I, Nilsen JEØ (2018) Coastal sea levels, impacts and adaptation. J Marine Sci Eng 6(1):19. https://doi.org/10.3390/jmse6010019

World Risk Report (2019) Focus: water supply. Day JS, Forster T, Himmelsbach J, Korte L, Mucke P, Radke K, Thielborger P, Weller D. Bündnis Entwicklung Hilft and Ruhr University Bochum – Institute for International Law of Peace and Armed Conflict (IFHV), Berlin, Germany. https://reliefweb.int/sites/reliefweb.int/files/resources/WorldRiskReport-2019_Online_english.pdf. Accessed 20/12/2020

Wu SY, Yarnal B, Fisher A (2002) Vulnerability of coastal communities to sea-level rise: A case study of Cape May County, New Jersey, USA. Climate Res 22(3):255–270. https://doi.org/10.3354/cr022255

Yin J, Yin Z, Wang J, Xu S (2012) National assessment of coastal vulnerability to sea-level rise for the Chinese coast. J Coast Conserv 16:123–133

Zampazas G, Karymbalis E, Chalkias C (2022) Assessment of the sensitivity of Zakynthos Island (Ionian Sea, Western Greece) to climate change-induced coastal hazards. Zeitschrift Fur Geomorphol 63(2–3):183–200. https://doi.org/10.1127/zfg/2021/0730

Zanetti VB, de Sousa WC Jr, de Freitas DM (2016) A climate change vulnerability index and case study in a Brazilian Coastal City. Sustainability 8(8):1–12. https://doi.org/10.3390/su8080811