Indices of Coastal Vulnerability to Climate Change: a Review

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Received: 2 February 2022 / Accepted: 4 April 2022 / Published online: 3 May 2022
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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
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 (Hallelagate 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.

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**Identification of studies via databases**

- 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)

- 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)

- Studies included in review (n = 46)

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*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

![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.

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![Fig. 3 Flowchart for the creation of hazard maps (Modified from Toimil et al. 2017)](image-url)
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; Douakakis 2005; Abuodha and Woodroffe 2006; Mendoza and Jiménez 2009; Gaki-Papanastassiou et al. 2010; Karymbalis et al. 2012; Yin et al. 2012; Kokkins 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
| 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, wave height |
| 4  | Coastal Vulnerability Index        | Pendleton et al. (2004)        | USA             | Geomorphology, coastal slope, relative SLR rate, shoreline erosion/acceleration rate, mean tidal range, wave height |
| 5  | Coastal Vulnerability Index        | Doukakis (2005)                | Greece          | Geomorphology, coastal slope, relative SLR rate, shoreline erosion/acceleration rate, mean tidal range, 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, 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, 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 |
| 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     | Gornitz (1991), Shaw et al. (1998), Thieler and Hammar-Klose (1999), Pendleton et al. (2004),    |
| type, rock type, beach type, solid and drift   | Doukakis (2005), Boruff et al. (2005), Abuodha and Woodruff (2006), Rao et al. (2008), Mendoza    |
| geology)                                       | 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 Woodruff (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 Woodruff (2006), Mendoza and Jiménez (2009), Gaki-Papanastas-|
|                                                | siou 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),    |
|                                                | Boruff et al. (2005), Abuodha and Woodruff (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    |
|                                                | (2022)                                                                                            |
| Wave height                                    | Gornitz (1991), Shaw et al. (1998), Thieler and Hammar-Klose (1999), Pendleton et al. (2004),    |
|                                                | Boruff et al. (2005), Abuodha and Woodruff (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)                                                               |
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-Goncąlves 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-environmental) 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 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                         | Abuooha 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-Goncąlves 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)   |
| 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

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| 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 |
| 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 > 250 billion 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 |
| 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)                  | Mediterranean   | 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 |
| 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                                                                 |
| 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 |
| 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 |
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

| Table 5 | Socio-Economic Variables used in the literature |
|---------|-----------------------------------------------|
| Variables | Authors |
| Age of inhabitants | Cutter et al. (2003), Boruff et al. (2005), Kléinosky 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), Deblortoli 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) |
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.

**Acknowledgements**  A graduate scholarship to C.N. Roukounis by the Research Committee of the National Technical University of Athens is greatly appreciated.

**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**

**Competing interest**  There is no conflict of interest with regard to this work.

**Availability of data and materials**  Not applicable.

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