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Coastal Vulnerability Assessment in Urban Planning: A Comparative Tool-Based Selection Approach for the Egyptian Context

Aya A. Hemida[a], Marwa A. Khalifa[b], Morad Abdelsalheen[c] and Samy Afifi[d]
[a,b,d] Department of Urban Planning and Design, Faculty of Engineering, Ain Shams University, Cairo, Egypt.
[c] Irrigation and Hydraulics Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

aya_adelhemida@eng.asu.edu.eg , marwa_khalifa@eng.asu.edu.eg, Morad.Abdelsalheen@eng.asu.edu.eg, Samy.afifi@eng.asu.edu.eg

ABSTRACT

In the context of coastal cities facing Sea Level Rise (SLR) and climate extremes, this study seeks to provide Coastal Vulnerability Assessment (CVA) tools for improved urban planning in Egypt. Through a comparative analysis and systematic application of exclusion criteria, the researchers evaluated 16 tools to identify the most suitable options. The objective was to select tools that exhibit the greatest relevance and potential applicability to effectively address CVAs in the region. Among the analyzed tools, 37.5% appeared to align well with the context. Composite Vulnerability Index (CoVI) is notably recommended due to its comprehensive dimension consideration. This approach improves coastal vulnerability understanding and aids planners in decision-making for coastal areas.

Index-words: *climate change, CVA tools, physical vulnerability, SLR, socio-economic vulnerability, tool selection methodology, urban planning.*

I. INTRODUCTION

Cities face high vulnerability to disasters due to their concentrated populations, extensive infrastructure, and diverse activities in relatively small areas (UN-Habitat, 2014; Pregnolato, et al., 2016; Pregnolato, et al., 2017). Coastal cities are prone to vulnerabilities due to climate change impacts, especially Sea Level Rises (SLR) and storm surges. Urban centers in coastal regions, due to their susceptibility to disasters, have socio-economic and physical vulnerability (Celliers & Ntombela, 2016; Helderop & Grubesic, 2019). Although urban disasters primarily impact certain urban areas, their repercussions can extend to a national scale due to the significant physical, social, and economic importance of cities (UN-Habitat, 2014; Celliers & Ntombela, 2016; Mycoo, et al., 2021). Internationally, approximately 500 million people reside in delta areas (Woodroffe, et al., 2006). Deltas are characterized by diverse physical environments, rich ecosystems, and significant socio-economic benefits, but often have a low elevation and are prone to subsidence due to the intensive constructions that facilitate high population densities. According to Islam et al. (2016), Wolters & Kuenzer (2015), Ghosh & Mistri (2021), and Pramanik et al. (2016), coastal vulnerability assessment tools have been widely used in various vulnerable coastal areas, including river deltas.

Egypt is considered a highly vulnerable country, facing challenges such as shoreline erosion, SLR, and land subsidence. Ali et al. (2022) and Torresan et al. (2020) also indicated that the temperature of the sea water and the atmosphere in the Mediterranean Basin region have been increasing and the region is considered a Climate Change (CC) hotspot. Egypt is one of the most vulnerable countries to the potential effects of CC, with its northern coastal region being a particularly vulnerable area with a diverse ecosystem, extensive infrastructure and socio-economic activities. The region is particularly susceptible to the anticipated sea-level rise, given its substantial proportion of low-lying lands and sandy or muddy beaches (Hereher, 2015). With a specific focus on the Nile Delta, with its sandy coastlines and low-lying lands as shown in Figure 1, it becomes clear that it is at risk from SLR, land subsidence, shoreline erosion and flooding (Samra et al., 2021). According to SLR scenarios, coastal infrastructures in the Nile Delta, including roads, railways, harbors, etc., will be threatened due to expected storm surges and SLR (Doluschitz & El-Nahry, 2010).

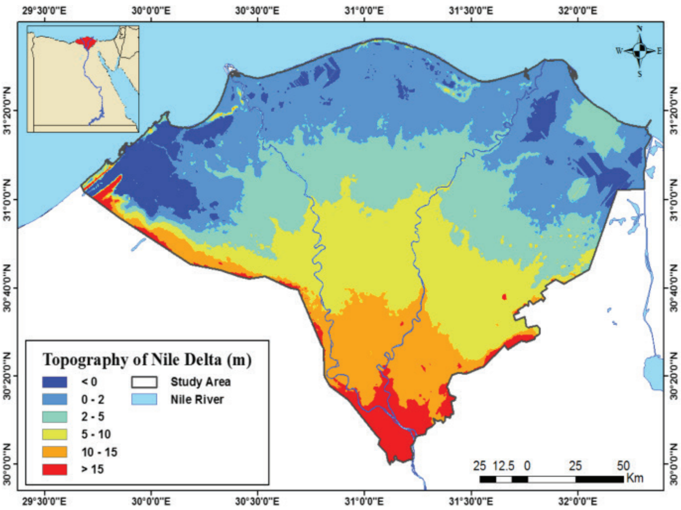


Fig. 1. Topography of Nile Delta region
Source: El-Quilish et al., 2023)

Urban mobility often relies on the road network as vital urban infrastructure, interconnecting major highways, commercial avenues, and residential streets essential for daily regional operations. Ensuring access to this network is significant for economic efficiency, personal and public transportation, and the provision of essential services like education, employment, and emergency services (Helderop & Grubesic, 2019). However, unexpected disruptions due to external factors like disasters can have serious consequences for communities relying on this infrastructure (Helderop & Grubesic, 2019; Pregnolo et al., 2016; Ji et al., 2022). Hence, understanding the impacts of extreme events on transportation systems is crucial, encompassing immediate disruptions, increased congestion, and isolated neighborhoods.

Increasing climate change risks, particularly SLR, highlight the need to enhance infrastructure resilience and durability (Helderop & Grubesic, 2019). Assessing coastal vulnerability is vital for urban planning due to infrastructure's lasting nature. Advanced flood models enable innovative urban modeling with enhanced capabilities and high resolution (Pregnolato et al., 2017).. The urgency of prioritizing physical variables in Coastal Vulnerability Assessment (CVA) for urban mobility arises as few coastal regions proactively strengthen their infrastructure against such challenges (Helderop & Grubesic, 2019). Also, it is worth highlighting that internationally the existing CVA researches lack sufficient studies that focus on the impact of natural disaster events on physical dimensions such as urban mobility performance studies (Singh et al., 2018).. As stated above, the Nile Delta faces significant vulnerability to SLR, storm surge, and coastal erosion (Hereher, 2015; Torresan et al., 2020; Mohamed 2020).. The presence of infrastructure like roads and urban areas intensifies this vulnerability, posing a risk of inundation and erosion (Torresan et al., 2020).. Urgent and effective adaptation measures are essential to mitigate these risks (Frihy, 2017).

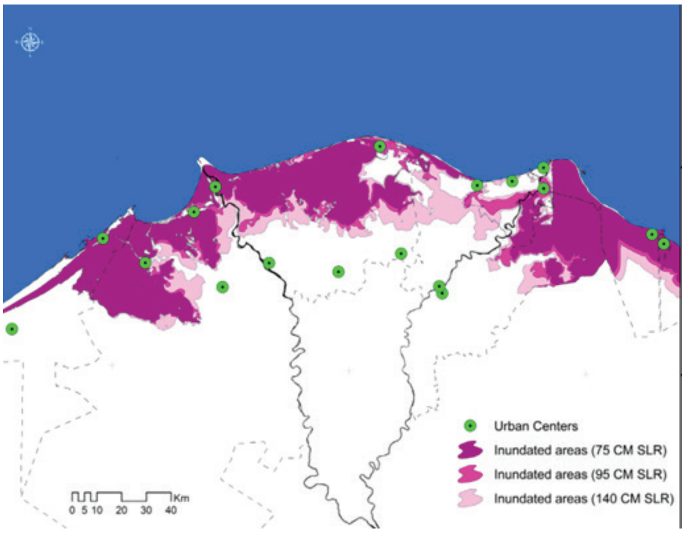


Fig. 2.Inundated areas based on SLR scenarios
Source: (M.A.Abdrabo & MahmoudA.Hassaan, 2015)

Despite extensive research on coastal vulnerability in Egypt, a notable gap exists in assessing the physical aspect of roads and infrastructure. Studies by Kantamaneni (2016), Hereher (2015), Frihy (2017), and El-Raey (1997) have primarily concentrated on the susceptibility of coastal areas to sea-level rise, particularly along the Nile Delta coast. However, these studies have not specifically addressed the physical vulnerability of roads and infrastructure, critical components of coastal areas. This **literature gap** underscores the necessity for further research to evaluate the physical vulnerability of roads and infrastructure in the Egyptian context, particularly in the context of climate change and sea-level rise. Hence, **the problem** is focused on the significant need for CVAs that comprehensively consider and incorporate variables related to the physical dimension.

McLeod et al. (2015), McFadden et al. (2007), and Royo et al. (2016) also emphasized the lack of a comprehensive and user-friendly method to guide and facilitate the selection of appropriate tools. According to Hemida et al. (2023), existing CVA studies consistently lack justification for the selection of the tools used in the assessment. These studies highlighted another **gap in literature** about the lack of existence of effective methods for evaluating existing coastal vulnerability assessment tools and stressed the significance of a systematic tool selection process that caters for the specific requirements of individual studies. Therefore, the **research problem** revolves around the necessity for a systematic method to select the most appropriate CVA tool for conducting assessments in a specific context. **Two research questions** have arisen from the highlighted gaps in the literature. The first question is, "What effective methods can be employed to evaluate existing CVA tools, and how can a systematic tool selection process be developed to cater for the diverse needs of different studies?" The second question is, "How can a CVA tool be selected to encourage and prioritize the inclusion of the physical dimension?"

The **research aims** to develop a method for the selection of CVA tools by analyzing the characteristics of well-known existing tools and evaluating their success. It also seeks to apply selection criteria that specifically focus on including the physical dimension in the chosen tool. The ultimate goal is to recommend tools for future CVA studies, addressing the gap in attention to the physical dimension. The **research design** utilized a comparative analysis and applied inclusion and exclusion criteria to underscore the importance of effectively incorporating the physical dimension of vulnerability. The study specifically concentrates on the escalating rates of SLR and their repercussions on infrastructure, aligning with the objectives of Sustainable Development Goal (SDG) 13, which pertains to "Climate Action." This aligns with the overarching aim of taking urgent action to combat climate change and its associated impacts and SDG 9, which pertains to "Industry, Innovation, & Infrastructure." This aligns with building of resilient infrastructure.

The research develops a new systematic process for selecting comprehensive CVA tools tailored to the Nile Delta context. The proposed method incorporates both socio-economic and physical dimensions in the assessment, aiming to provide decision-making guidance for planners. The research is structured into four main sections, with an introductory part providing background information. The sections include: (1) Methodology: Outlining the process for selecting CVA tools. (2) Results: Presenting findings based on the comparative analysis and applied criteria. (3) Discussion: Analyzing the success factors derived from the comparative analysis and the shortlisted tools. (4) Conclusion and Future Research: Summarizing the results and providing insights for future research endeavors.

II. Methodology

This research follows an inductive approach to compare and evaluate existing CVA tools in order to select the most relevant tools for application in Egypt. The study aims to provide insights into the strengths and weaknesses of each tool, particularly with regard to their capacity to accommodate local scales and incorporate socioeconomic and physical dimensions. This analysis is designed to enhance the researchers' comprehension of how these tools can adeptly tackle the distinct challenges associated with coastal vulnerability as well as their influence on infrastructure and urban mobility. The **first part** of the research involved a desktop review of various sources to assemble a set of CVA tools. These tools were gathered according to the four methods, which are: index-based methods, indicator-based methods, GIS-based methods, and dynamic models. The research included 16 CVA tools, which were not exhaustive. However, the tools where selected based on being the mostly found to be used tools among the reviewed literature.

The **second part** is a comparative analysis conducted to analyze and highlight the differences between the selected CVA tools. The analysis encompassed several criteria such as coastal typology, spatial scale, dimensions included, main driver and impact targeted, inclusion of adaptive measures, as well as data inputs and outputs. The data pertaining to the selected tools was collected and organized into a binary matrix and to aid in visualizing the relationships between the multiple criteria used and the associated CVA tools, a heat map was generated using Microsoft Excel.

In the **third part**, the collected data, comparative matrix, and exclusion criteria were utilized across multiple phases of analysis. Some of the aforementioned characteristics and criteria served as exclusion criteria during the tool screening and selection process, such as coastal areas' types, spatial scale, included dimensions, and the existence of adaptive capacity. The four inclusion criteria were identified based on literature and previously identified gaps in the Egyptian context by Hemida et al. (2023). Ten assessment tools were excluded, and six were shortlisted due to better alignment with the contextual needs of the Egyptian coastal environment, and one was selected for including the physical dimension.

The **fourth part** of this study conducts a success factor analysis to systematically assess the usability of the six chosen CVA tools. This analysis aims to offer valuable guidance for the selection of the most suitable tools for implementing CVA in the specific context of Egypt. It also aims to identify tools that exhibit flexibility, allowing for the integration of additional dimensions and improvements, particularly in terms of incorporating physical data inputs. The assessment is structured around three key dimensions: user friendliness, applicability, and maturity.

III. Results

A comparative analysis of the non-exhaustive list of CVA tools gathered from a literature review was conducted. Assessment tools were categorized according to the four existing methods. Methods include indicator-based approach, index-based approach, Geographic Information Systems (GIS)-based methods, and dynamic models for coastal vulnerability assessment (Oloyede et al., 2021). Indicator and index-based methods depend on variables quantification using numerical assessments to rank coastal areas by vulnerability and rate of vulnerability increase. These rankings enable coastal managers to identify regions with higher vulnerability levels. The resulting index values are used as input data to create vulnerability maps that visually highlight areas of elevated vulnerability (Oloyede et al., 2021 & 2022). However, indicator-based methods aggregate measurements of indices or variables to create a consolidated summary indicator, representing aspects not easily measurable directly (Oloyede et al., 2022). Seven tools were analyzed with regard to indicator and index-based approaches that include the Coastal Vulnerability Index (CVI), CVI-SLR, Social Vulnerability Index (SoVI), Composite Vulnerability Index (CoVI), Multi-Scale CVI (MS-CVI), Coastal Risk Index (CoRI), and Eurosion. GIS-based methods utilize computer tools for processing and visualizing data through interactive maps, relying on shoreline attributes, digital land elevation, vegetation, and land use data. This method is notably user-friendly, allowing non-experts to use it easily, and it boasts a straightforward construction process. In the context of GIS-based decision support systems (DSS) methods, the study included two tools, which are the Decision Support System for Coastal Climate Change Impact Assessment (DESYCO DSS) and the THESEUS DSS (Serio et al., 2018; Oloyede et al., 2021; Ramieri et al., 2011). Dynamic models are categorized into two types: sector models, which analyze specific climate change impacts on coastal processes, and integrated assessment models (IAMs), capable of comprehensively studying multiple climate change impacts. IAMs explore diverse research approaches to complex climate change. Their effectiveness stems from addressing climate change's multidimensional nature through interdisciplinary methods, offering insight into its impact on complex systems. However, expertise related to the usage of the software might be necessary. The study analyzes seven dynamic model tools: RACE, SLAMM, FUND, SimCLIM, DIVA, RegIS, and Delft 3D. All tools were collectively evaluated based on set criteria (Oloyede et al., 2021; Gold, 1999).

The comparative analysis included the 16 previously mentioned tools from the above-illustrated methods. As shown in Table A1 in Appendix 1, the comparative analysis was represented in the form of a heat map for a matrix of binary data based on the criteria stated in the methodology part. Regarding the first criterion, coastal typology, the heat map indicated that 75% of the analyzed tools addressed various coastal types, with each type represented by at least one tool from each method. The second criterion, spatial scale, revealed that 71% of index-based and dynamic model tools focused on smaller scales, while only one GIS-based tool considered the local scale, where local scale here considers the neighborhood and city scales. The third criterion, included dimensions, indicated that nearly all tools encompassed the biophysical dimension except SoVI. Only 18% (from index-based and dynamic model tools) included the physical dimension, while 75% covered the socio-economic dimension. Additionally, 56% of the tools considered the ecological dimension in their study. The fourth criterion elucidates the main assessment drivers, predominantly tied to biophysical issues like SLR. Some tools integrated biophysical issues with socioeconomic or physical drivers, although this was less common. The fifth criterion assessed inclusion of study area's adaptive capacity in tools, with 62.5% of analyzed tools incorporating this aspect.

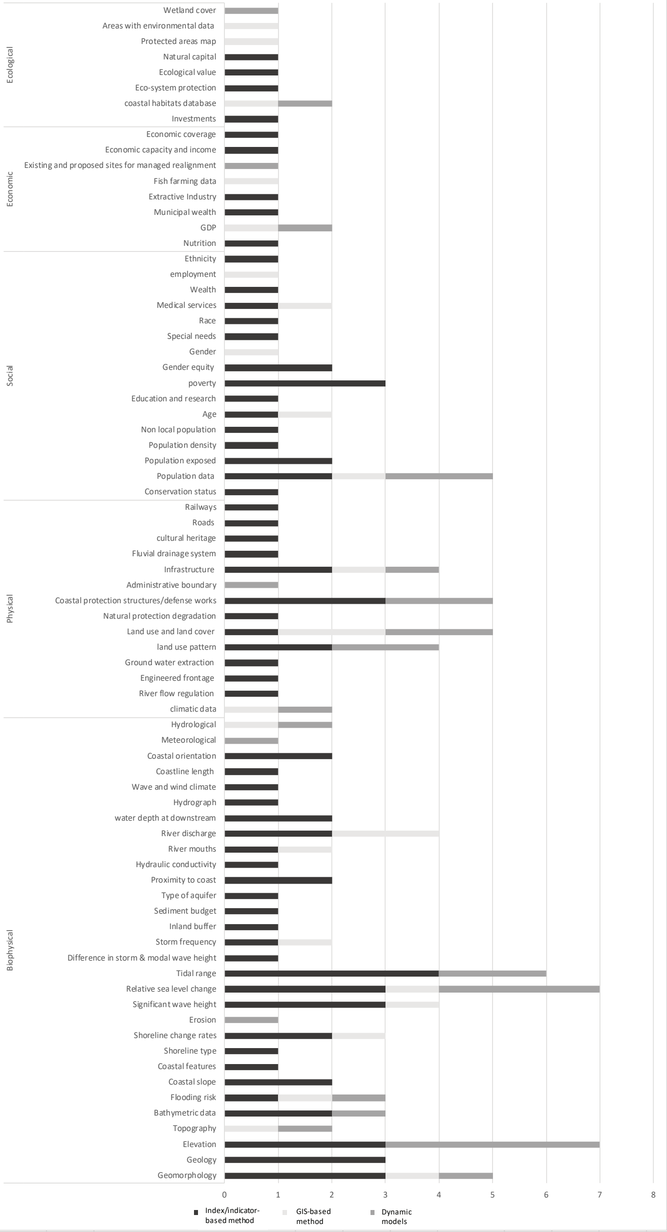


Fig. 3. Number of tools in each method using the variable
Source: Authors

The sixth criterion analyzed data input variables, revealing in Figure 3 that biophysical and physical variables were most prevalent, with the latter primarily linked to coastal protection measures and land use patterns. Few tools emphasize economic or ecological variables. Index/indicator tools generally encompass more variables, especially common ones, compared to other tools. The researchers also noticed that GIS tools exhibit various dimensions but with limited variables each, while dynamic model tools prioritize biophysical and physical variables, offering fewer variables than index/indicator tools. They include minimal social, economic, and ecological variables. The seventh criterion indicates the study results that are mostly presented as maps and can also be in statistical or index form.

Following the application of successive layers of exclusion criteria to select tools for the Nile Delta, Table I illustrates the outcomes of the initial exclusion criteria, based on relevant local coastal classifications. The table also presents tools for assessing vulnerability across various coastal types. The Egyptian northern coastal region features diverse types, such as the low-lying Nile Delta with upper lagoons and rich wetlands. Furthermore, a significant portion of existing agricultural land is situated in proximity to the shorelines (Fishar, 2016). The diverse nature of the Nile Delta region prevented the exclusion of any tools based on this criterion.

TABLE I
CVA TOOLS FOR DIFFERENT COASTAL AREAS' TYPES

Coastal areas	Tools			Reference
	Index/ Indicator- Based	GIS-Based	Dynamic Model-Based	
Delta regions	CVI, CVI (SLR), SoVI, CoVI, CoRI, Eurosion	THESEUS-DSS,	RACE, SLAMM, FUND, SimCLIM, DIVA, Delft 3D	(Anderson, et al., 2019; Zanuttigh, et al., 2014; Moura, 2015; Ramieri, et al., 2011; Tobey, et al., 2014)
Coastal lagoons	CVI, CVI (SLR), SoVI, CoVI, CoRI, Eurosion	THESEUS-DSS,	RACE, FUND, SimCLIM, DIVA, Delft 3D	(Anderson, et al., 2019; Zanuttigh, et al., 2014; Moura, 2015; Ramieri, et al., 2011; Tobey, et al., 2014)
Coastal wetlands	CVI, CVI (SLR), SoVI, CoVI, CoRI, Eurosion	THESEUS-DSS,	RACE, SLAMM, FUND, SimCLIM, DIVA, Delft 3D	(Anderson, et al., 2019; Zanuttigh, et al., 2014; Moura, 2015; Ramieri, et al., 2011; Tobey, et al., 2014)
Coastal agricultural lands	CVI, CVI (SLR), SoVI, CoVI, CoRI, Eurosion	THESEUS-DSS,	RACE, FUND, SimCLIM, RegIS, DIVA, Delft 3D	(Anderson, et al., 2019; Zanuttigh, et al., 2014; Moura, 2015; Ramieri, et al., 2011; Tobey, et al., 2014)
Different coastline typologies (sandy, cliff, etc.)	CVI, CVI (SLR), SoVI, CoVI, MS-CVI, CoRI, Eurosion	DESYCO-DSS, THESEUS-DSS,	RACE, FUND, SimCLIM, DIVA, Delft 3D	(Mclaughlin & Cooper, 2010; Anderson, et al., 2019; Zanuttigh, et al., 2014; Moura, 2015; Ramieri, et al., 2011)

Source: Authors

Table I also highlights that the majority of the reviewed tools included in the comparative study were index- and indicator-based methods. The data also indicate that index- and indicator-based methods are applicable to various coastal areas, while MS-CVI exclusively assesses coastlines with diverse typologies. Concerning the GIS-based methods, only two tools were included: DESYCO and THESEUS and they are considered among the recent DSS tools used in the literature (Zanuttigh et al., 2014). Also, the Theseus tool only works on the coastlines with their different typologies. Concerning the dynamic models, seven tools were included in the comparative analysis, and most of the work focused on the different types of coastal areas. However, SimCLIM does not work on coastal lagoons, SLAMM only works on delta regions and coastal wetlands, and RegIS only works on coastal agricultural lands.

According to the identified gaps by Moreira et al., (2021), few CVAs are carried out on national and local scales. Also, Hemida et al. (2023) highlighted that in the Egyptian context, the smaller scales, such as the city and neighborhood scales, were mostly recommended for future research. Therefore, filtering the tools according to the recommended study scale was considered as the second exclusion criterion. Therefore, only tools working on regional and local spatial scales were selected for consideration, and tools working only on larger scales were excluded: CoRI, Eurosion, and DIVA as shown in Table II (spatial scale part). The third exclusion criterion is based on the dimensions included in each tool. Socio-economic and physical dimensions significantly influence a community's vulnerability to natural disasters as well as its readiness for disasters (Lima & Bonetti, 2020; Kantamaneni, 2016). There is a pressing necessity to deepen one's comprehension of coastal infrastructure susceptibility due to increasing coastal stresses. Coastal infrastructure is considered an asset of paramount importance to the nation's economy (Kantamaneni, 2016). Therefore, physical and economic variables play a crucial role in determining social vulnerability and can directly affect disaster preparedness efforts. Therefore, vulnerability assessments should incorporate physical and socio-economic variables together to mitigate potential future risks (Lima & Bonetti, 2020). The selected tools were the ones that included physical, social, and economic dimensions and the rest were excluded. As shown in Table II (that included dimensions part), CVI (SLR), SoVI, CoVI, MS-CVI, DESYCO-DSS, THESEUS-DSS, SimCLIM, and RegIS were selected for the fourth exclusion criterion; however, only CoVI included the physical dimension to be evaluated with the tool. Also, if any of the above tools has the flexibility of modification, they can be used with the inclusion of the physical aspect within the tool.

The fourth exclusion criterion was the existence of adaptive capacity variables in the tools. According to the IPCC, vulnerability encompasses susceptibility, exposure, and coping as the main input variables for vulnerability assessment (Romieu et al., 2010). The absence of high-quality infrastructure can directly impact the vulnerability level of a coastal community, thus impacting the degree of the community's coping capacity. Furthermore, the presence of adaptive infrastructure is crucial for enhancing the adaptive capacity of coastal areas (Groot et al., 2020; Mycoo et al., 2021). Therefore, coping capacity variables are crucial in such assessments, but their application is infrequent due to the extensive time and effort required for data collection (Moreira et al., 2021). Two more tools were excluded according to this layer of exclusion, which are multi-scale CVI and DESYCO-DSS in Table II (adaptive capacity part).

TABLE II
TOOLS EXCLUSION ACCORDING TO SELECTED CREITEIA

Tool/ Criteria	Spatial scale						Included dimensions				Adaptive capacity
	International	Supra-regional	National	Regional	Local	Biophysical	Physical	Social	Economic	Ecological	
CVI	0.5	1	0.5	1	1	1	0	0	0	0	0
CVI (SLR)	0	0	0	1	1	1	0	1	1	1	1
SoVI	0	0	0	1	1	0	0	1	1	0	1
CoVI	0	0	0	1	0	1	1	1	1	0	1
MS-CVI	0	1	1	1	1	1	0	1	1	0	0
CoRI	1	1	1	0	0	1	0	1	1	1	1

Eurosion	0	1	0	0	0	1	1	1	1	1	1
DESY-CO-DSS	0	0	1	1	0	1	0	1	1	1	0
THESEUS-DSS	1	1	1	1	1	1	0	1	1	1	1
RACE	0	0	1	1	1	1	1	0	0	0	0
SLAMM	0	0	0	1	1	1	0	0	0	1	0
FUND	1	1	1	1	0	1	0	0	1	0	1
SimCLIM	1	1	1	1	1	1	0	1	1	1	1
DIVA	1	1	1	0	0	1	0	1	1	1	1
RegIS	0	0	0	1	1	1	0	1	1	1	0.5
Delft3D	0	0	0	1	1	1	0	0	0	0	0

1 → Can be applied
0.5 → Can be applied theoretically
0 → Cannot be applied

▒ Exclusion by spatial scale
░ Exclusion by included dimensions
▓ Exclusion by adaptive capacity

Source: Authors

According to the previous analysis, a set of tools has been identified and considered most relevant for application in CVAs in the Egyptian context based on their main characteristics. These tools are: CVI (SLR), SoVI, and CoVI from the index-based methods; THESEUS-DSS from the GIS-based methods; and SimCLIM and RegIS from the dynamic models and the CoVI is the most recommended due to its inclusiveness concerning the dimensions, however it does not work on local scale.

IV. Discussion

Based on the previous comparative analysis, which highlighted the characteristics of the included CVA tools, and considering the applied exclusion and inclusion criteria, six tools representing 37.5% of the selected tools were shortlisted. Only one of these tools directly includes the physical dimension. To select the most fitting tool for CVA, with a focus on the physical dimension in the Egyptian context, or with high modification potential to accept the inclusion of physical variables, an additional layer of analysis was added based on the results to assess the success of each tool.

A success factor analysis was done to evaluate the suitability and usability of six selected CVA tools for adoption in coastal vulnerability assessment within the Egyptian context. This analysis is based on previous work by Meex and Verbeeck (2014), Krans *et al.* (2022), Quernheim *et al.* (2023) and Marchand *et al.* (2014). The researchers have categorized the success factor analysis into three main aspects: user friendliness, applicability, and maturity as shown in Table 3. User friendliness encompasses six criteria; (1) Expertise, that evaluates the level of knowledge required prior to utilizing the tools and (2) Guidance, that assesses the presence of guidance resources associated with the tools. This includes the availability of manuals, tutorials, open-access publications, or built-in guidance within the tool itself. (3) Ease of use (+ and – scores), that describes its ease or difficulty of use. (4) Accessibility to tool, that checks whether the tool is freely accessible, published in a journal, open-source software, or if a subscription is required for its usage. (5) Time investment (low and high), that shows the time required to use the tool and obtain results. (6) Flexibility to modification (+ and – scores), that evaluates whether the tool allows for suggested improvements, the import of different datasets, or the alteration of assessed indicators. In the applicability section, the assessment focuses on the tool's breadth of applicability and identifies any usage limitations. The degree of maturity (+ and – scores) of the tool showed if the tool was still under development. Following the success factor analysis and referring to Table III, the results revealed that expertise is crucial for tool usage, with most tools requiring experience, except for index or indicator-based tools. Regarding the availability of guidance, it was found that most tools provide a guide to facilitate tool usage.

In terms of ease of use, most tools were deemed user-friendly except for the THESEUS-DSS tool. Regarding accessibility, RegIS and THESEUS-DSS were theoretically available, but they no longer function due to the end of their respective research projects. However, all tools were found to be positively suited for time investment and flexibility for modification. Based on the applicability criteria, all tools were deemed applicable to any spatial scale and coastal area given the availability of data. Additionally, all tools scored positively in terms of maturity, having been tested previously. However, it is worth noting that none of the shortlisted GIS or dynamic models tools have been tested in the Egyptian context before, as per the literature. Based on the results of the success factor analysis, the researchers recommend considering the utilization of one of the following tools: CoVI or SimCLIM.

Limitations of this study pertain to the quantity of tools considered in the analysis. The constrained timeframe prompted a focus on a concise selection of tools that were pertinent and frequently referenced in recent research. The field of CVA encompasses a wide array of tools developed both locally and internationally (Rangel-Buitrrago et al., 2020). However, many of these tools are often the outcome of research projects and may not be readily accessible or widely available (Woodruff et al., 2018). The sheer volume and variety of existing tools in coastal vulnerability assessment make it impractical to collect them all, and many may have become obsolete or ceased to function over time. Furthermore, the study did not assess the practical validation of these tools in the context of Egypt, which is crucial for determining their suitability and effectiveness in real-world applications. This aspect is essential as it can impact the outcomes, considering that the tools may perform differently when adapted to the specific data requirements concerning the infrastructure and urban mobility in the coastal cities of the Egyptian context.

TABLE III
SUCCESS FACTOR ANALYSIS FOR THE SIX SELECTED CVA TOOLS

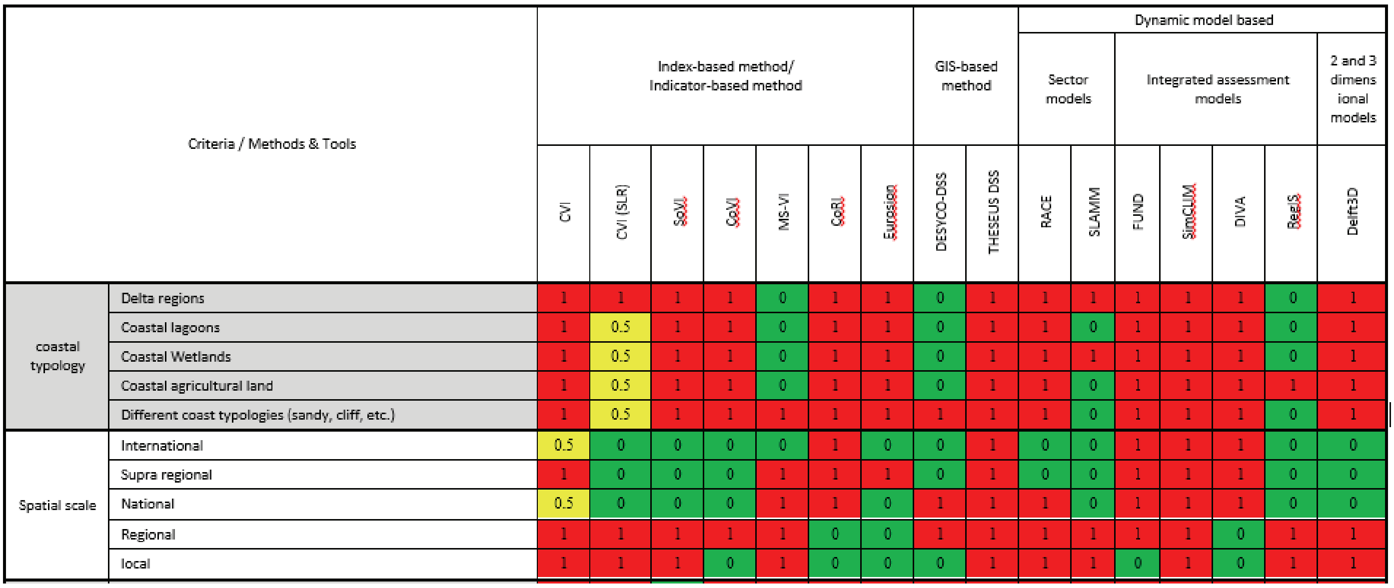
Criteria/ Selected Tools	User-friendliness						Applicability	Degree of maturity	Link to tool
	Expertise	Guidance	Ease of use	Accessibility to tool/cost	Time investment	Flexibility to modification			
CVI (SLR)	No specific experience required (Ozyurt & Ergin, 2009).	Journal publication (Ozyurt & Ergin, 2009).	+ (Ozyurt & Ergin, 2009; Ramieri, et al., 2011)	Open access publication (Ozyurt & Ergin, 2009).	N.A.	+ (Ramieri, et al., 2011)	Depends on data availability (Ramieri, et al., 2011)	+ (Ozyurt & Ergin, 2009; Ramieri, et al., 2011)	https://etd.lib.metu.edu.tr/upload/12608146/index.pdf
SoVI	No specific experience required (Cutter, et al., 2003).	Journal publication (Cutter, et al., 2003).	+ (Cutter, et al., 2003)	Open access publication (Cutter, et al., 2003).	N.A.	- (Cutter, et al., 2003; Anderson, et al., 2019)	Depends on data availability (Cutter, et al., 2003).	+ (Cutter, et al., 2003)	https://doi.org/10.1111/1540-6237.8402002
CoVI	Requires experience in GIS and remote sensing. (Szlafsztein & Sterr, 2007)	Journal publication (Szlafsztein & Sterr, 2007).	+ (Szlafsztein & Sterr, 2007)	Open access publication (Szlafsztein & Sterr, 2007).	Low (Szlafsztein & Sterr, 2007)	+ (Szlafsztein & Sterr, 2007; Ramieri, et al., 2011)	Depends on data availability (Szlafsztein & Sterr, 2007; Ramieri, et al., 2011).	+ (Szlafsztein & Sterr, 2007)	https://doi.org/10.1007/s11852-007-0003-6
THESEUS-DSS	Requires experience (Zanuttigh, et al., 2014).	Guidance built in tool (Zanuttigh, et al., 2014).	- (Zanuttigh, et al., 2014)	Open source tool to maximize availability and uptake of the tool (Zanuttigh, et al., 2014).	Low (Zanuttigh, et al., 2014)	+ (Zanuttigh, et al., 2014)	Can be applied to any coastal area and spatial scale. And depends on data availability (Zanuttigh, et al., 2014).	+ (Zanuttigh, et al., 2014)	https://www.vliz.be/projects/theseusproject/index.php
SimCLIM	Training and Knowledge of computer is required (Abuodha & Woodroffe, 2006). However, the expertise of CLIMsystems staff are available to assist (CLIMsystems, 1993).	Manual and introductory tutorials (https://www.climsystems.com/Downloads/SimCLIMAR6/DataManual.pdf).	+ (Ramieri, et al., 2011)	There is a cost to the use of the software (Abuodha & Woodroffe, 2006).	Low (Ramieri, et al., 2011)	+ (Iyalomhe, et al., 2013)	Offers potential but requires further testing and validation. Can be applied to different spatial scales. And depends on data availability (Moura, 2015)	+ (CLIMsystems, 1993)	https://www.climsystems.com/
RegIS	Needs significant expertise (Ramieri, et al., 2011). However, the tool accommodates "*predefined scenarios screen*" that allows users with less knowledge to run the model (Holman & Harman, 2008).	Guidance built in tool and help tutorials (Holman & Harman, 2008).	+ (Ramieri, et al., 2011)	Locally feasible (Ramieri, et al., 2011)	Low (Ramieri, et al., 2011)	+ (Iyalomhe, et al., 2013).	Multiple models were being developed. So, the object-oriented approach was valuable in allowing software modularity, and therefore the ability for different research groups to iteratively develop their models autonomously, yet at the same time (Holman & Harman, 2008).	+ (Holman & Harman, 2008).	N.A.

V. Conclusion

Based on the comprehensive analysis conducted in this research, which encompassed an examination of the existing literature, a comparative analysis of various CVA tools from index-based, indicator-based, GIS-based, and dynamic model methods, and a thorough success factor analysis, several key conclusions can be drawn. Firstly, it is evident from the literature review and comparative analysis that coastal cities, especially those in delta regions like the Nile Delta, face significant vulnerability to various natural hazards. The concentration of population and infrastructure in these areas exacerbates the socio-economic and physical vulnerability, making them highly susceptible to disasters. Secondly, the methodology employed in this research, which developed a systematic method to selecting CVA tools tailored to the Egyptian context, has provided valuable insights into the strengths and weaknesses of different tools. By applying specific inclusion and exclusion criteria, six tools were shortlisted, with one tool, CoVI, being highlighted as particularly promising due to its comprehensive inclusion of physical dimension together with social and economic dimensions. Thirdly, the success factor analysis conducted further emphasized the importance of user-friendliness, applicability, and maturity of the selected tools. While all tools showed strengths in certain aspects, such as ease of use and flexibility for modification, limitations were also identified, particularly regarding the accessibility and availability of some tools like RegIS and THESEUS-DSS.

Based on these findings, it is recommended that future CVA studies in the Egyptian context prioritize the utilization of tools like CoVI or SimCLIM, with a focus on and inclusion of the physical dimension, to address the existing gap in the literature. These tools have demonstrated suitability and effectiveness in addressing the complexities of coastal vulnerability, including the physical dimension. In conclusion, this research has contributed valuable insights into developing a systematic selection method of CVA tools for assessing coastal vulnerability in the Egyptian context or in other contexts. By addressing existing gaps in the literature and providing recommendations for future research and practical applications, this study aims to support informed decision-making and enhance resilience to climate-related hazards in vulnerable coastal regions. However, it is essential to acknowledge the limitations of this study, including the constrained timeframe and the focus on a limited number of tools. Future research should aim to address these limitations by considering a broader range of tools, especially if the adopted context has locally developed tools, and conducting practical validations in the specific context of Egypt. Additionally, ongoing monitoring and updates to the selected tools are crucial to ensure their continued relevance and effectiveness in guiding adaptation measures and resilience-building efforts in coastal cities facing the impacts of climate change.

Table IV: Comparative analysis of selected CVA tools"



Criteria / Methods & Tools		Index-based method/ Indicator-based method							GIS-based method		Dynamic model based						
											Sector models		Integrated assessment models				2 and 3 dimensional models
		CVI	CVI (SLR)	SoVI	CoVI	MS-VI	CoRI	Eurosion	DESYCO-DSS	THESEUS DSS	RACE	SLAMM	FUND	SimCLIM	DIVA	RegIS	Delft3D
coastal typology	Delta regions	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0	1
	Coastal lagoons	1	0.5	1	1	0	1	1	0	1	1	0	1	1	1	0	1
	Coastal Wetlands	1	0.5	1	1	0	1	1	0	1	1	1	1	1	1	0	1
	Coastal agricultural land	1	0.5	1	1	0	1	1	0	1	1	0	1	1	1	1	1
	Different coast typologies (sandy, cliff, etc.)	1	0.5	1	1	1	1	1	1	1	1	0	1	1	1	0	1
Spatial scale	International	0.5	0	0	0	0	1	0	0	1	0	0	1	1	1	0	0
	Supra regional	1	0	0	0	1	1	1	0	1	0	0	1	1	1	0	0
	National	0.5	0	0	0	1	1	0	1	1	1	0	1	1	1	0	0
	Regional	1	1	1	1	1	0	0	1	1	1	1	1	1	0	1	1
	local	1	1	1	0	1	0	0	0	1	1	1	0	1	0	1	1

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Included dimensions	Biophysical		1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
	Physical		0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0
	Social		0	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0
	Economic		0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0
	Ecological		0	1	0	0	0	1	1	1	1	0	1	0	1	1	1	0
Main driver	Biophysical drivers	SLR	1	1	1	0	0	1	1	1	1	0	1	1	1	1	1	1
		Sediment budget	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1
		Shoreline evolution	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
	Biophysical drivers	Salinity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Cyclones	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
		Storm surge	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	1
		Flooding	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0
		Wind	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
		Wave	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
		Drought	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		Tsunami	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
		Hurricanes	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
		Tide	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
		Erosion	0	0	1	0	1	0	0	0	1	1	0	0	0	0	0	0
	Physical drivers	Failure of sea defenses	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Socio-economic drivers	Land use change	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
		GDP growth	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0
		Population growth	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0
Adaptation measures considered			0	1	1	1	0	1	1	0	1	0	0	1	1	1	0.5	0
Data input	Biophysical variables	Geomorphology	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0
		Geology	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
		Elevation	1	0	0	0	1	0	1	0	0	0	1	0	1	1	1	0
		Topography	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
		Bathymetric data	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
		Flooding risk	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0
		Coastal slope	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Coastal features	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		Shoreline type	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		Shoreline change rates	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
		Erosion	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
		Significant wave height	1	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0
		Relative sea level change	1	1	0	0	0	0	1	0	1	0	1	1	1	0	0	0
		Tidal range	1	1	0	0	1	0	1	0	0	0	1	0	0	0	1	0
		Difference in storm & modal wave height	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		Storm frequency	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
		Inland buffer	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		Sediment budget	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Type of aquifer	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Proximity to coast	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		Hydraulic conductivity	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		River mouths	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
		River discharge	0	1	0	0	0	0	1	1	1	0	0	0	0	0	0	0
		water depth at downstream	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		Hydrograph	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		Wave and wind climate	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		Coastline length	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		Coastal orientation	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
		Meteorological	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		Hydrological	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
		climatic data	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
	Physical	River flow regulation	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Engineered frontage	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Ground water extraction	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		land use pattern	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	1
		Land use and land cover	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1	1
		Natural protection degradation	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Coastal protection structures/defense works	0	1	0	1	0	0	1	0	0	1	0	0	0	0	1	0
		Administrative boundary	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
		Infrastructure	0	0	0	0	0	1	1	0	1	0	1	0	0	0	0	0
		Fluvial drainage system	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		cultural heritage	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		Roads	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0

		Railways	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		Conservation status	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	Social	Population data	0	0	0	1	1	0	0	0	1	0	0	1	0	1	0	0
		Population exposed	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
		Population density	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		Non local population	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		Age	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0
		Education and research	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
		poverty	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0
		Gender equity	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
		Gender	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
		Special needs	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		Race	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		Medical services	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0
		Wealth	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		employment	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
		Ethnicity	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		Nutrition	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	Economic	GDP	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0
		Municipal wealth	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		Extractive Industry	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		Fish farming data	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
		Existing and proposed sites for managed realignment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
		Economic capacity and income	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
		Economic coverage	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
		Investments	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	Ecological	coastal habitats database	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0
		Eco-system protection	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
		Ecological value	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		Natural capital	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
		Protected areas map	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
		Areas with environmental data	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
		Wetland cover	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	Government and authority		0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Data output form	Tables		1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1
	graphs		0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1
	Maps		1	0	0	1	1	1	0	1	1	1	1	0	1	0	1	1
	Time series projections		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	Scores, rates and statistics		0	0	1	0	0	0	1	0	0	0	0	1	0	1	0	0
	Final vulnerability index		0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0
Used in Egyptian context in the last 10 years (Hemida, *et al.*, 2023)			1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0

1	→ Can be applied	0.5	→ Can be applied theoretically	0	→ Cannot be applied

Table is based on (Anderson, et al., 2019; Zanuttigh, et al., 2014; Mclaughlin & Cooper, 2010; Torresan, et al., 2010; Park, et al., 2003; Ltd, 2007; Narita, et al., 2009; Moura, 2015; Ramieri, et al., 2011; Tobey, et al., 2014) (Hinkel, et al., 2010)

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