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Evolution in Coastal Vulnerability Assessment Tools of the Small Island Developing States in the Atlantic, Indian Ocean and South China Sea Region: A Review

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ABSTRACT

Island nations around the world are vulnerable to natural coastal dynamics and the anticipated effects of climate change given their geographic locations and size. It is critical for such states to assess and quantify the probable consequences of coastal dangers in order to preserve their assets and protect their lives. Technological advancement these past years has changed the discipline of vulnerability assessment so much that today detailed and accurate results of impacts can be obtained and used for management practices. This study aimed at reviewing the literature on coastal vulnerability assessment methods used in the Atlantic, Indian Ocean and South China Sea Region and analyze the evolution in tools used over the years as a measure of island nations' resolution to adapt to future changes. Using a series of specific keywords such as 'coastal vulnerability assessment' + 'Maldives' to grab relevant materials in Google Scholar and Google search engine for the period 1987 to 2019, over 100 papers were analyzed and filtered for relevancy to the topic. The results revealed an evolution in coastal vulnerability assessment tools in the AIMS region from paper based CVI methods to more robust models like GIS. Despite the vulnerability of AIMS SIDS to coastal hazards, financial resources and technical expertise, they are engaging in assessing their vulnerability to external hazards. This review sheds light on the various coastal vulnerability assessment tools used in island nations thereby forming a knowledge base for policy and decision makers, researchers and scientists involved in coastal management.

1. Introduction

Vulnerability to natural hazards is a very important concept with research in this field ranging from asset management to national security [1]. With the right information on risks associated with hazards, natural disasters can be mitigated and catastrophes can be avoided [1]. Today, the coastal zone represents one of the most vulnerable environments to global climate change [2] with repercussions far beyond the shoreline. When it comes to the island states such as the Maldives, Seychelles and Mauritius, the coast represents almost all the entire habitable area where economic centers, agriculture and tourist amenities are located [3]. Thus, external impacts not only affect the ecological system but also the socio-economic spheres.

The AIMS Small Islands Developing States (SIDS) are a group of 9 small islands scattered in the Atlantic (Cape Verde, Guinea Bissau, Sao Tome and Principe), Indian Ocean (Mauritius, Comoros, Seychelles, Maldives, Bahrain) and South China Sea (Singapore) region. Though each island has its own characteristics, these small states also have many features in common. They face numerous challenges related to economic development, environmental preservation, and social justice [4]. Like other SIDS, their coastal zones are home to some of the world's most diverse and rich ecosystems [5]. Today, climate change and sea level rise have been identified as the main present and future threat for many of these small states to successfully address the Sustainable Development Goals (SDGs). Maldives can even be singled out as climate change induced sea level rise of 1 m threatens its very existence. In this respect, vulnerability assessments (VA) help to understand the risks associated with coastal hazards and provide information for identifying the most appropriate ways to deal with them. Globally, VAs show how some coastal regions may be unable to cope with the impacts of coastal hazards; on a local and national level, VAs help to identify the risk zones and to ponder on the best practices that would be needed in the future. Precisely estimating the risk zone is critical for any nation in order to prevent damage and loss of lives.

Despite the number of reviews on country-wise coastal vulnerability assessments such as the works by [6] in India, [7] in the EU or [8] on the Australian coast, no such initiative has been undertaken for the SIDS while they remain the most vulnerable to the current and future impacts of coastal hazards, including climate change. Thus, the goal of this paper was to perform an extensive review of literature to identify the coastal VAs undertaken in the SIDS of the AIMS region and analyze the evolution in tools used over the years as a measure of island nations' resolution to adapt to future changes. Since island specific cases are often missing in the academic literature, this is the first review on coastal vulnerability assessments in SIDS thus providing critical information to both internal and external policy and decision makers, researchers and scientists involved in coastal management.

1.1.Importance of the coastal zone

Many attempts have been made to define the coastal zone; while some authors describe it based on physiographic characteristics, others quantify it according to a fixed distance from the shoreline. [5] contend that for the SIDS, the coastal zone could represent the entire island and thus state that irrespective of their definitions, coastal zones have some distinct characteristics that make them unique: high biological productivity and diversity, high rate of dynamic changes in the natural environment, high rate of economic development and population growth, high exposure to natural hazards like storms and stringent management regimes that include both the terrestrial and marine ecosystems.

In general, the coastal zone can be simply defined as the region where the land, ocean and atmosphere interact that is highly dynamic in nature [9]. Globally, coastal zones are valuable areas that comprise unique ecological, geological and biological elements that are crucial for terrestrial and marine life including humans [10]. The coastal zones of the SIDS are characterized by highly diverse ecosystems such as mangrove forests, coral reefs and seagrass meadows which in turn support various habitats that preserve an exquisite biodiversity. [10] further state that people have always been attracted to the coastal zones for economic reasons as they are among the most resource-rich areas that humans can exploit. Industries such as aquaculture, fishery and tourism are the economic backbone of thousands of coastal communities which at the same time ensure a large portion of the dietary needs of millions of people. Thus, achieving a balance between development and environmental protection is important [10]. As coastal development in small islands requires adaptation to climate and ecosystem changes, understanding the variability of coastal vulnerability along the entire coastline is essential for coastal planning and management at island-wise scale [11].

1.2.Integrating technological advancement into vulnerability assessments

Right on point with [12] 'A 2020 Vision for Ocean Science' and the powerful impact of technology on ocean science, these past 25 years have seen an impressive advance in technological application in coastal science from recording, measurement to information processing [13]. New technologies including, and not limited to, information technology, biotechnology, nanotechnology, imaging technologies, computational technologies and robotics [12] have helped tremendously in the way data is obtained from the oceans, processed and simulated for the future. Most of these technologies stem from the revolutionary discoveries of the 20th century such as the development of electronic computers in the 1940s, the launch of early satellites in the 1950s and the amplification of light to create laser in the 1960s [13]. Persistent research into these fields eventually led to the now revolution of big data storage, mapping using the GPS system and the precise spatial measurement in LiDAR. As the field of computer science branches even more, converging with ocean science in novel ways, it is unimaginable what technological application in ocean science coupled to vulnerability assessments will do in the future.

Modern vulnerability assessments are based on the use of these technological innovations in order to obtain more detailed results of probable vulnerability hotspots subsequently leading to better management practices. [1] propound that the application of technology in assessing coastal vulnerability can be in the form of data collection using aerial imagery and satellites, crowdsourcing local knowledge with GIS, (PGIS), to environmental simulation using system dynamics. Given the fragility of the small islands, applying technological innovation is the best way to get the right information which will form the basis of management practices.

2. Materials and Methods

To provide an in-depth assessment of the topic, a comprehensive search on coastal vulnerability assessment tools was undertaken on Google Scholar. Secondary data analysis was deemed suitable to meet the goal of the study as it provides details and in-depth information on the subject. The literature was reviewed from 1987 to 2019 to gain a thorough understanding of the evolution of tools since the Commonwealth Expert Group on Climate Change and Sea level Rise was created to assess the vulnerability of the Maldives to sea level rise. Also, Google Scholar was chosen as it a free, accessible web engine that indexes the full text of scholarly publications across a range of publishing formats and disciplines ([14]. Thus, to retrieve the required publications, a search query was initiated using the following keywords: 'coastal vulnerability assessment Cape Verde', 'coastal vulnerability assessment Guinea Bissau', 'coastal vulnerability assessment Sao Tome and Principe', 'coastal vulnerability assessment Mauritius', 'coastal vulnerability assessment Comoros', 'coastal vulnerability assessment Seychelles', 'coastal vulnerability assessment Maldives', 'coastal vulnerability assessment Bahrain' and 'coastal vulnerability assessment Singapore'. However, a screening process revealed that the majority of the papers that came up were not directly related to the topic in question and so an advanced search with keywords in title was conducted. In this case, the search did not match any articles, except for 1 article each for Bahrain, Mauritius and Maldives. Consequently, Google Search Engine tool was used to conduct the research using the same above mentioned keywords. While according to [13] the first page of Google mainly captures 71% of clicks, a detailed analysis of the pages on Google Search Engine was carried out till page 10 to ensure that all grey literature published on the topic was acquired. Data reliability was tested based on the sources of the scientific journals and reports retrieved while data validity was measured by the accuracy of the papers related to the topic and adequate content coverage as well as an evaluation of the researcher's/agency's expertise and familiarity on the topic.

3. Results and discussion

Using the above-mentioned keywords, no relevant studies were captured on Google Scholar for the period 1987-2019. The second analysis on Google Search Engine up to page 10 or through 100 results per searched keyword captured mainly national reports and documents as listed below.

3.1. Region wise vulnerability assessments and tools

[15] used the DIVA Model to estimate the physical and economic impacts of SLR on the coastal zones around Africa including the islands of Guinea-Bissau, Cape Verde, Comoros, Mauritius, Sao Tome and Principe, Seychelles as part of a quantitative assessment on the impacts of SLR in the African Region. Furthermore, [16] was entrusted by the IOC to monitor the vulnerability of Mauritius, Seychelles and Comoros using a Coastal Vulnerability Index by gathering oceanographic parameters in order to build a vulnerability map through the use of aerial imagery and GIS. [17] investigated the areas that would be flooded in the AOSIS member states based on a certain height of sea level rise using Spatial Analysis Methodology.

Island wise vulnerability assessments and tools

This section includes the coastal vulnerability assessments which have been carried out in individual islands of the AIMS region or as part of other global studies.

Table 1. Coastal vulnerability assessment method/tool used in the SIDS of AIMS region

Island/Remarks	Method/Tool used	Year, Reference
Bahrain (Information unavailable)	• Modified IPCC Common methodology, GIS, remote sensing • Coastal Vulnerability Assessment, GIS, remote sensing	2008, [18] 2012, [19]
Cape Verde (Coastal management initiated mostly by the tourism sector)	LEG Methodology	2007, [20]
Comoros (Systematic assessment per se do not exist)	• Interviews and ecological surveys, Redundancy Analysis • CAMPA	2014, [21] 2018, [22]
Guinea Bissau (No coastal vulnerability assessment per se.)	Spatial Vulnerability Assessment, CVI, DIVA, Social Vulnerability Index, Economic Systems Index	2014, [23]
Maldives (Detailed reports on the impacts of sea level rise on Maldives has been produced since 1989)	• Coral Bleaching and Mortality Assessment, bias corrected satellite derived SST data using the Advanced Very High Resolution Radiometer (AVHRR) • SLR Vulnerability Assessment, Least Square Method • SLR Vulnerability Assessment,	2001, [24] 2001, [25]

	• Trend Analysis • Coastal Flooding Assessment, Existing literature, T-Tide Harmonic Analysis software, WAVEWATCH 111 Model, Tidal Inversion Software • Alongshore Sediment Transport Assessment, Satellite imagery, Simulating Waves Nearshore (SWAN) model • Human-driven Undermining Assessment, Human footprint, Satellite Imagery	2002, [26] 2017, [27] 2019, [28] 2019, [29]
Mauritius	• GIS, COSMOS, CASI Reef classification • IPCC Common Methodology, Vulnerability Index • Survey • GIS • Shoreline change and coastal risk assessment, GIS-DSAS • Climate Change Vulnerability Assessment, Vulnerability and Adaptation Assessment based on the COSMO-CLM	2003, [30] 2009, [31] 2009, [32] 2013, [33] 2016, [34] 2016, [35]
	• Climate Change Vulnerability Assessment, Vulnerability and Adaptation Assessment • SLR VA, Trend Analysis • Beach erosion monitoring, Coastal Vulnerability Index Map	2016, [36] 2017, [37] 2018, [38]
Sao Tome and Principe	• Climate Change Vulnerability Assessment, Satellite Imagery • Coastal Vulnerability Assessment, Satellite imagery using drones • Climate Change Vulnerability Assessment, Delft3D, XBeach, WFlow, interviews • Coastal Vulnerability Assessment, IOC-UNESCO Methodological Guide to ICZM	2016, [39] 2017, [40] 2018, [41] 2019, [42]
Seychelles (Coastal VAs carried out as part of three main studies: the preparation of the first national communication, the AIACC project and the	• Beach Vulnerability Index • Coastal and marine environment Vulnerability Assessment, GIWA Methodology • Climate Change VA,	2001, [43] 2002, [44]

preliminary outcome of the Second National Communication)	MAGICC/SCENGEN • Survey • GIS, satellite imagery • Coastal Vulnerability Assessment, Geomorphic assessments, GIS • SLR VA, Interviews, data-driven and process-based models, Multi-criteria analysis using GIS	2006, [45] 2009, [32] 2014, [46] 2015, [47] 2019, [48]
Singapore (Coastal VAs carried out by the government; unavailable to the public)	• SLR VA, Cost benefit analysis, spot elevation measurements • SLR VA, Travel cost method, contingent valuation method and GIS • Coastal Vulnerability Assessment, DIVA, LOICZ-DISCO (Deluxe Integrated System for Clustering Operations)	2005, [49] 2006, [50] 2008, [51]

A Pareto chart was also constructed using the same data to analyze the evolution in coastal vulnerability assessment tools over the years.

3.2.Evolution in VA tools in the AIMS SIDS: Shift from literature analyses to computer models

The IPCC CM was the first methodology proposed to assess the vulnerability of the coastal zone in 1991. It takes into account the physical characteristics and socio-economic components of the system being analyzed. In the early 1990s, the IPCC CM was the main tool used to carry out coastal vulnerability assessments. Yet, it lacks the flexibility to consider factors that matter on the small islands and in many cases require quantitative data that is unavailable. From the data obtained, it can be seen that throughout the study period, the IPCC CM was used twice (2008, Bahrain; 2009, Mauritius) mainly to provide background data on the vulnerability of coastal regions [18, 31]. Several indices followed like the coastal vulnerability indices, socio-economic indices and adapted forms that consider different parameters. Such indices are generally relatively easy to use and provide simple numerical basis for ranking sections of the coastline related to change. A number of indices are represented here such as the social vulnerability index (ScVI) and economic system index (ESI) used in Guinea Bissau [23], coastal vulnerability index (CVI) in Mauritius [38] and beach vulnerability index in Seychelles [43]. However, indices are often opinion biased based on the organization carrying out the survey and the final score represents a relative measure not an absolute measure. With technological advancement in ocean science, the inclusion of software and hardware for coastal studies has revolutionized the field [1]. The most common technological tools like GIS (Geographic Information Systems), remote sensing and satellite images have been used since 2001 in many states like the Maldives [24] and Mauritius [30] to assess the vulnerability of coastal regions. While technological tools like expert software are indeed excellent to assess coastal vulnerability revealing critical information like exposure and allowing simulations to visualize impacts, small island nations often lack the human resource expertise to run such models. At the same time, certain of these models are quite expensive requiring developing organizations to train local staff for implementation such as the DELFT3D software developed by Deltares. But as internet became more accessible to communities on small islands, the use of technological software also increased. GIS for instance is now widely used as online documents and tutorials become more accessible. In a number of cases, robust models like COSMOS [30], Delft3D, XBeach, WFlow [41], and SWAN [28] have been used to provide valuable information on coastal vulnerability in the AIMS SIDS. Such software, with their various suites and add-ons, permit different external and local parameters to be considered and eventual effects visualized. In this way, risks are better understood thus acting as catalysts for stakeholders to successfully pursue the right adaptation policies and options.

It is worth to note that while the technological evolution trend has been increasing over the years in the AIMS SIDS, it is mainly experts from external agencies who have been using them not locals per se. Despite their immediate vulnerability to coastal hazards, many island nations still lack the capacity to assess just how vulnerable their coastal areas are. For some countries like Cape Verde, Guinea Bissau and Comoros which are amongst the poorest nations of the world [4] there are only sparse assessments. Conversely, the coastal zone of well -known touristic island states like Mauritius, Seychelles and the

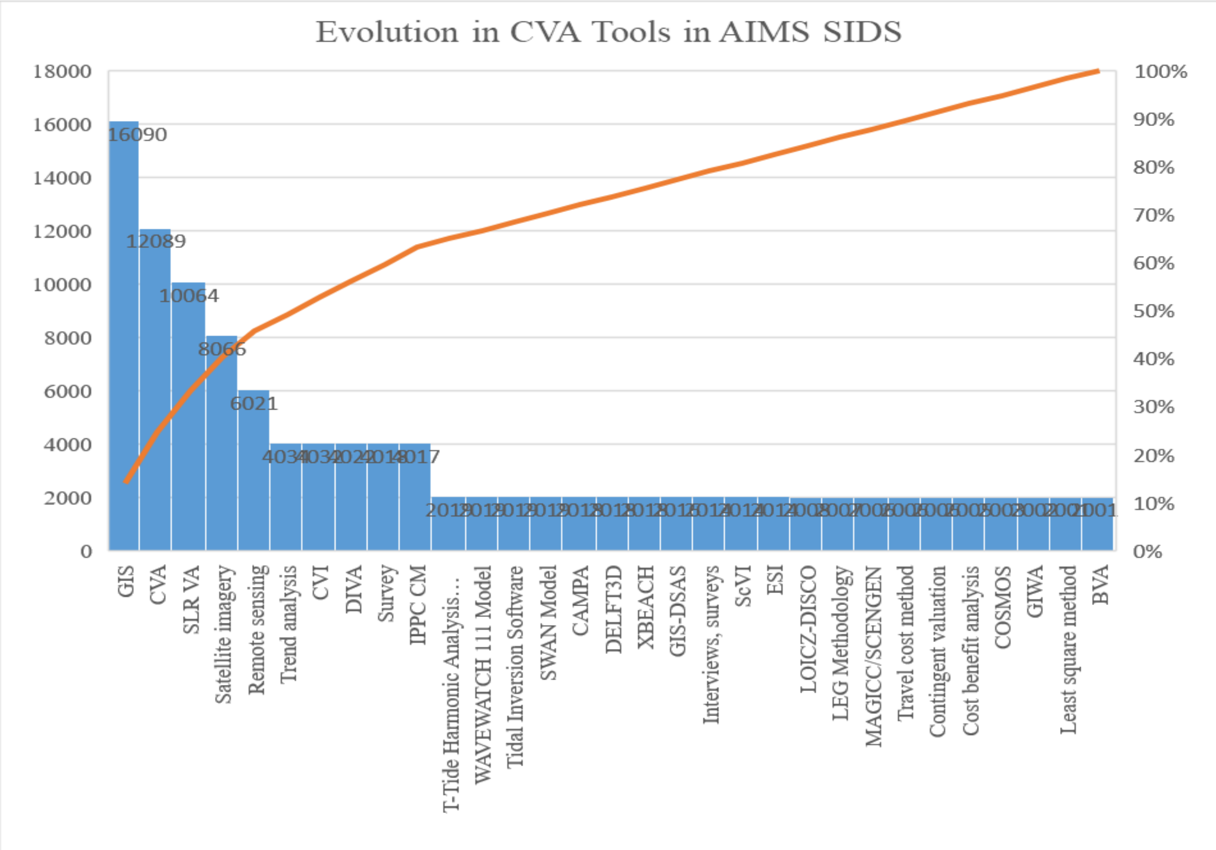

Figure 1. Evolution in coastal vulnerability assessment tools from 1987-2019 in the AIMS SIDS (where x-axis represents the coastal vulnerability assessment tools and y-axis the cumulative number of years from 2001 to 2019)

Maldives have been thoroughly studied. Given these states' dependency on the tourism sector, proactive approaches to adaptation planning are crucial both at the governmental level and individual stakeholders' level to minimize the effects of climate change and sea level rise.

3.3.Undertaking VAs in SIDS

Coastal vulnerability assessments are undertaken by first assessing and defining the coast itself. Since the definition of the coast varies from region to region and is not homogenous in nature such as beaches versus ports, it is imperative to carry out preliminary assessments of the area before choosing the appropriate approach for a VA. Thus, in certain cases, Sharple's methodology [52] may be more appropriate. This approach provides a general overview of the coastal region in the first phase, identifies the impacts in the second phase and includes a detailed assessment and proposal of adaptation measures in the third phase. Additionally, coastal vulnerability assessments imply the evaluation of both the landward and seaward regions as these two are constantly interacting. Sometimes, the latest tools to assess impacts on land may not be useful to the SIDS as there may be a lack of data on the seaward side. For example, while XBeach may be an excellent model to assess coastal vulnerability to sea level rise, bathymetry data is compulsory to run the model. The availability of such long-term, high quality data like Digital Elevation Models (DEMs) is of paramount importance to carry out coastal vulnerability assessments in SIDS. Also, researchers have used global models like DIVA and downscaled to national levels as part of their coastal vulnerability assessments in SIDS. However, such assessments are not always accurate and do not reflect the actual scenarios since data for many parameters is unavailable and consequently default values are used. Thus, the output of any model or assessment will be based on the quality of the data being fed in and used.

4. Conclusions

This paper examines the coastal vulnerability assessment methods and tools used in the SIDS of the Atlantic, Indian Ocean and South China Sea Region from 1987 to 2019 and also highlights the evolution in coastal vulnerability tools over the past years. It reflects how technological advancement has taken coastal vulnerability assessment to a higher level especially now, in the face of climate change and its associated impacts, on the most vulnerable nations. Throughout this extensive synthesis, it can be seen that technological tools now form an integral part of the vulnerability assessment procedure of the coastal zone. As the more recent publications reveal, advances in methodology, data collection, computational power and software design have made enormous leaps in progress such that researchers and stakeholders can now have a better understanding of coastal vulnerability. Similarly, if communities are to identify their weak spots, they need information and knowledge to be better prepared. As the research continues in coastal vulnerability, technology and the integration of these two concepts, undoubtedly the research scope and application will enlarge. This synthesis, aggregation and review of coastal vulnerability assessment methods and tools is to ensure that this information becomes more accessible to fellow researchers, academicians and the public especially when choosing the most convenient tool for small island nations.

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