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Fuzzy-Based Spatial Analysis and Coastal Vulnerability Assessment of Balanga City, Bataan due to Sea-Level Rise

Maan F. Josue[a,*], John Melvin B. Petito[a], Nikki Hershey R. Dionisio[a], Rommel Glenn S. Mendova[b], Gil G. Cruz Jr.[c], Sam P. Olarte[a]

[a]Department of Civil Engineering, College of Engineering and Architecture, Bataan Peninsula State University, Capitol Compound, Tenejero, City of Balanga, Bataan 2100, Philippines
[b]Department of Civil Engineering, Gokongwei College of Engineering, De La Salle University, 2339 Taft Ave, Malate, Manila, Metro Manila, Philippines 1004
[c]Research and Innovation Center for Climate Change and Sustainability, Bataan Peninsula State University, Capitol Compound, Tenejero, Balanga, Bataan, Philippines 2100
mfjosue@bpsu.edu.ph

The coastal areas face imminent threats from rising sea levels, which are further exacerbated by storm surges, leading to the relocation of communities. This study aims to conduct a comprehensive assessment of the potential hazards posed by sea level rise in Balanga City, Bataan, Philippines. A physical vulnerability index was developed considering factors such as geomorphology, elevation, and projected sea level rise. The socioeconomic vulnerability index assessed variables such as household density, education, household monthly income, and housing materials. The study employed Geographic Information Systems (GIS), Fuzzy Logic, and Analytical Hierarchy Process (AHP) to evaluate socioeconomic, physical, and total vulnerability indices. The study used World Bank Group's projected sea level rise data for different scenarios, surveyed 321 households, obtained elevation data from the University of the Philippines-LiPad's Digital Terrain Model, and classified the area's geomorphology with Landsat 8-9 OLI/TIRS imagery. The PVI analysis indicated that in barangay Tortugas, around 20 % had very high vulnerability, and 19.9 % had very low vulnerability. In Puerto Rivas Ibaba, about 22 % displayed very high vulnerability, and approximately 34 % were classified as very low vulnerability. For SVI, Tortugas had roughly 20 % very high vulnerability and 20 % very low vulnerability. Puerto Rivas Ibaba showed about 20 % very high vulnerability and 19.9 % very low vulnerability. Regarding TVI, Tortugas had 20 % very high vulnerability and 19.9 % very low vulnerability, while Puerto Rivas Ibaba had 20 % very high vulnerability and 20% very low vulnerability. The analysis revealed varying levels of vulnerability in the barangays of Tortugas and Puerto Rivas Ibaba, ranging from very high vulnerability to very low vulnerability. This research serves as a valuable resource for informing and reforming future strategies and policies aimed at mitigating the impacts of sea level rise and safeguarding vulnerable coastal communities.

1. Introduction

The steadily rising ocean water levels pose a significant risk to the shore portions currently inhabited. The climate, seas, and ice sheets of our planet, in addition to the flow of water, are all undergoing transitions as a direct consequence of human-caused global warming. Today, Earth grapples with unavoidable outcomes from climate change. Urgent measures are needed to halt irreversible greenhouse gas buildup and escalating global warming (Eh et al., 2022). Driven chiefly by human-induced emissions like carbon dioxide, climate change is a critical concern demanding global scientific efforts for mitigation and adaptation (Tan and Foo, 2018).
The Philippines is the fifth in the world with the most extensive coastline, approximately 36,000 km. On a local scale, Bataan, a peninsula considered a vulnerable area in an isolated archipelago, is most susceptible to sea level rise. Sea level rise rates vary from area to area, and there is broad agreement that global warming leads to sea level rise worldwide. Sea level rise is a topic that has received significant attention because its effects

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are not uniform and depend on each coastal region's geomorphological and climatic features (Barbaro et al., 2022).

The forecasted increase in sea levels will have a significant effect on coastal areas. The Philippines has already seen sea levels rise at a pace of 5.7 to 7.0 mm per year in certain locations, exceeding the world average between 1951 and 2015. Regardless of the emission scenario, sea levels are expected to increase by one-fifth of a meter by 2100 (PAGASA, 2018). The study aims to provide information regarding the potential threats of sea level rise through vulnerability risk assessment, mapping, and projections. It can close the knowledge gap on sea level rise and provide a more accurate observation of its impacts. Research is urgently required to comprehend the impacts of SLR and enhance planning and adaptation possibilities (Nazarnia et al., 2020).

Scardino et al. (2022) highlight the significance of multidisciplinary research to better comprehend the impacts of climate change on urban areas and populations residing in coastal zones worldwide. Multi-dimensional metrics can be employed to evaluate risk and decide on the most suitable course of action by collecting diverse risk information across various criteria (Da Silva et al., 2022). Markphol et al. (2021) stress the importance of science-based and socially inclusive solutions, including participatory and comprehensive sea level rise adaptation, to effectively mitigate the risks faced by coastal communities.

The coastal areas in Balanga City, Bataan Philippines, are particularly susceptible to the effects of SLR due to their proximity to the ocean. The population residing in these areas heavily relies on the bodies of water for their livelihoods, further exacerbating the potential impact. This study aims to assess the coastal vulnerability of Balanga City, Bataan due to sea level rise. The study involves four steps: collecting satellite and community data, normalizing through Fuzzy Logic for uncertainty, determining criteria weights using Analytic Hierarchy Process (AHP), and mapping vulnerability via Quantum Geographic Information System (QGIS).

2. Methods

To assess the coastal vulnerability of the study area, a technique integrating Geographic Information System (GIS), Fuzzy Logic, and Analytic Hierarchy Process (AHP) was employed. Physical characteristics were gathered from various reputable organizations, while socioeconomic parameters were obtained through community surveys and barangay profiles utilizing a stratified random sampling approach and Slovin's formula. Specifically, a total of 163 and 158 respondents were computed from Barangay Tortugas and Puerto Rivas Ibaba, respectively.

2.1 Data Preparation

To accurately assess and visualize the potential impacts of future sea level rise, extensive data preparation was conducted using climate models, specifically focusing on the parameter of projected sea level rise from the World Bank Group (2021) model. This data was then integrated into a Geographic Information System (GIS) to create comprehensive maps illustrating the potential inundation areas resulting from sea level rise, based on validated model projections.

To assess the vulnerability of coastal areas, the Coastal Vulnerability Index (CVI) proposed by Gornitz et al. (1991) was utilized, with a specific focus on the geomorphology parameter. Additionally, another approach incorporated the minimum and maximum values for elevation and projected sea level rise to accurately represent the potential range of vulnerability. For the socioeconomic parameters, Inverse Distance Weighting (IDW) was employed to assign appropriate values and integrate them into the Socioeconomic Vulnerability Index (SVI) calculation. This comprehensive approach allowed for the evaluation of coastal vulnerability by considering both physical and socioeconomic factors. The modified equation used in the study, which integrates these components, was adapted from Diez et al. (2007) and Mani Murali et al. (2013) and is presented as Eq(1) and (2):

$$PVI = W_1X_1 + W_2X_2 + W_3X_3 \tag{1}$$

$$SVI = W_1X_1 + W_2X_2 + W_3X_3 + W_4X_4 \tag{2}$$

The Eq(1) defines a measure for assessing physical vulnerability based on specific physical factors. Here, W_n stands for the weight attributed to each variable, and X_n represents the fuzzified layer associated with the variable. The Eq(2) defines a measure for assessing socioeconomic vulnerability based on specific socioeconomic factors. Here, W_n stands for the weight attributed to each variable, and X_n represents the fuzzified layer associated with the variable. This allows for the calculation of the Total Vulnerability Index (TVI), considering the individual weights assigned to each primary parameter.

2.2 Data Processing

The process of standardization is crucial in the analysis to ensure consistency and comparability. In this study, the gathered maps exhibit variations in terms of range, units, and values, necessitating the conversion to a common unit. To achieve this, fuzzy logic is employed as a standardization technique. Fuzzy theory suggests that data can be categorized on a continuum from 1 to 0, where 1 indicates membership in a particular set and 0 signifies non-membership. Fuzzification methods are applied to each criterion, employing assigned methods based on the existing knowledge and understanding of values associated with a specific criterion. This study utilized a linear fuzzy membership approach with an ascending function type to fuzzify the criteria, determining the maximum and minimum values as shown in Table 1.

Table 1: Primary and Secondary Criteria Weights

				Tortugas		Puerto Rivas Ibaba	
Primary Criteria	Value	Secondary Criteria	Value	a (Min)	b (Max)	a (Min)	b (Max)
Physical	0.68	Projected SLR	0.23	0.00	6.00	0.00	6.00
		Geomorphology	0.55	0.00	5.00	0.00	5.00
		Elevation	0.22	0.00	81.10	-0.96	13.65
Socioeconomic	0.32	Household Density	0.25	0.00	0.01	0.00	0.02
		Household Monthly Income	0.08	2407.56	33890.71	2510.17	39714.88
		Housing Material	0.45	1.00	5.00	1.00	5.00
		Education	0.21	1.00	5.00	1.00	5.00

For this study, a panel of nine experts from both academia and industry specializing in coastal and environmental areas was invited to participate in the assessment. They were asked to complete the pairwise comparison matrix, evaluating the importance of primary and secondary indicators. The pairwise comparisons were conducted using a scale ranging from 1 to 9 (Saaty, 1977). The collected data were subsequently processed using Microsoft Excel and SuperDecisions software to derive the weights of the criteria. The resulting AHP table presents the outcome of this analysis. To ensure the validity of the comparisons, a consistency ratio threshold of 0.1 or lower was set. If the inconsistency ratio exceeded this threshold, the corresponding criterion was considered inappropriate for further analysis.

2.3 Coastal Vulnerability Mapping

The Integrated Coastal Vulnerability Index (ICVI) maps were generated using the Raster Calculator in QGIS. The calculation involved multiplying fuzzified socioeconomic and physical parameters by their weights determined through the AHP. The sub-criterion results were then summed together. The Total Vulnerability Index was obtained by averaging the parameters, multiplying them by primary criteria weights, and combining them through addition.

The indices (PVI, SVI, TVI) were categorized into quantiles and ranges, indicating different vulnerability levels. Lower values represented very low to low vulnerability, while higher values indicated moderate to very high vulnerability. This quantile classification method, employed by previous researchers, proved effective in identifying high-risk area (Hastuti et al., 2022). It's important to note that this method doesn't provide detailed information about specific physical effects and processes related to vulnerabilities. The study's vulnerability maps provided valuable insights into spatial risk patterns, helping prioritize areas for mitigation and adaptation strategies.

The evaluation of available data underscored the need to address certain issues before analysis to ensure reliable results. Particularly, the land classification from Balanga City's local government stood out. This classification covered 2012-2020, with delineations too small for accurate georeferencing. Leveraging Landsat 8-9 OLI/TIRS and the Semi-Automatic Classification Plugin (SCP) improved accuracy and currency. Neglecting updates could have compromised classification quality. Adjustments also enhanced precision of point data from community surveys, aligning with exact house locations.

3. Results

The analysis involved utilizing fuzzy layers, where the linear ascending fuzzy membership technique was employed to calculate their values, as shown in Table 1. The Physical Vulnerability Index (PVI), Socioeconomic Vulnerability Index (SVI), and Total Vulnerability Index (TVI) were derived using the weights obtained from the Analytic Hierarchy Process (AHP) (Saaty, 1977) . The equations used to calculate PVI and SVI were adapted from the works Diez et al. (2007) and Mani Murali et al. (2013), incorporating the assigned weights and normalized parameters.

By employing quantile classification, the data were categorized into five levels of vulnerability: "very low vulnerability" (blue), "low vulnerability" (green), "moderate vulnerability" (yellow), "high vulnerability" (orange), and "very high vulnerability" (red) as shown in Figure 1. According to Hastuti et al. (2022), this method serves as a useful tool for identifying areas most susceptible to the risks posed by sea level rise. It should be noted that while this approach provides valuable insights into vulnerability levels, it may not fully capture the precise physical effects and underlying processes involved.

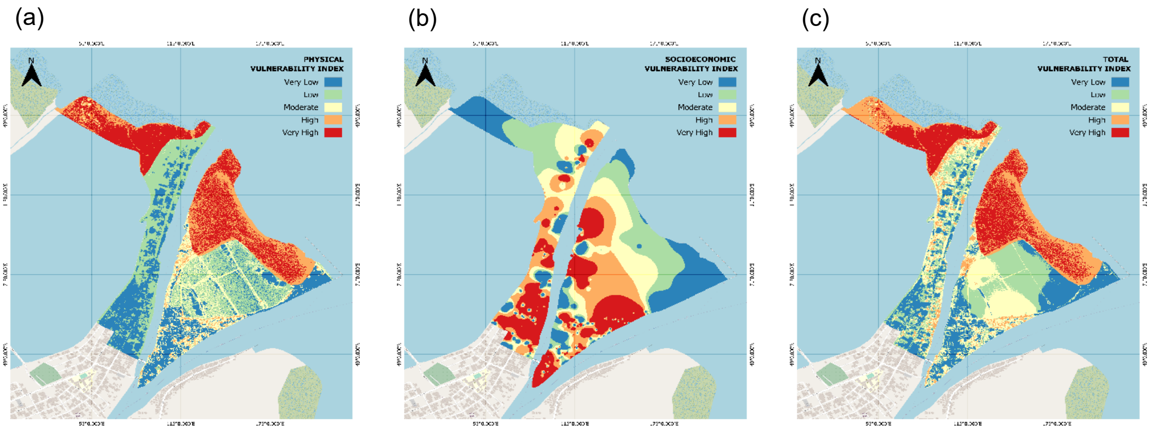

Figure 1: Vulnerability Index Map for (a) Physical, (b) Socioeconomic, (c) Overall

3.1 Physical Vulnerability Index

Referring to Figure 1a, the barangay of Tortugas spanning approximately 400,000 m^2, approximately 20 % of the mapped area, equivalent to 80,146 m^2, is classified as very high vulnerability. An additional 19.9 % (80,140 m^2) falls under the high vulnerability category. Moreover, 20 % (80,228 m^2) of the barangay exhibits a moderate vulnerability level. The residual land area is distributed, comprising 19.9 % (80,109 m^2) designated as having low vulnerability, and an equal 19.9 % (80,091 m^2) classified as very low vulnerability.

Similarly, in the barangay of Puerto Rivas Ibaba covering approximately 250,000 m^2, approximately 22 % (51,666 m^2) of the mapped area exhibits a very high vulnerability, accompanied by 3.6 % (8,497 m^2) falling under the high vulnerability category. The moderate vulnerability category encompasses a small portion, specifically 0.09 % (216 m^2), of the barangay. The remaining area of the barangay is divided into 39 % (90,839 m^2) and 34 % (79,684 m^2), representing the low and very low vulnerability categories.

3.2 Socioeconomic Vulnerability Index

As depicted in Figure 1b, the barangay of Tortugas, spanning approximately 400,000 m^2, demonstrates that approximately 20 % of the mapped area (80,504 m^2) was classified as very high vulnerability, with an additional 20 % (80,675 m^2) falling under the high vulnerability category. The moderate vulnerability classification encompasses 19.7 % (79,212 m^2) of the barangay, while 19.9 % (79,896 m^2) and 20 % (80,775 m^2) were categorized as low and very low vulnerability.

Likewise, within barangay Puerto Rivas Ibaba, which covers about 250,000 m^2, around 20 % (51,361 m^2) of the surveyed area was labeled as having very high vulnerability. Additionally, approximately 19.9 % (51,359 m^2) fell into the high vulnerability category. The moderate vulnerability category encompasses 20 % (51,361 m^2) of the barangay. The remaining area consists of 19.9 % (51,357 m^2) and 19.9 % (51,359 m^2) in the low and very low vulnerability categories.

3.3 Total Vulnerability Index

As shown in Figure 1c, Tortugas demonstrates that approximately 80,054 m^2 (20 %) of the mapped barangay are classified as very highly vulnerable, with an additional 80,052 m^2 (19.9 %) falling into the category of high vulnerability. The moderate vulnerability category encompasses 80,053 m^2 (19.9 %) of the barangay. The remaining area comprises 80,054 m^2 (20 %) and 80,053 m^2 (19.9 %) in the low and very low vulnerability categories.

Similarly, in Puerto Rivas Ibaba, approximately 51,145 m^2 (20 %) of the mapped barangay are classified as very highly vulnerable, with another 51,143 m^2 (19.9 %) falling under the high vulnerability category. The moderate vulnerability category encompasses 51,147 m^2 (20 %) of the barangay. The remaining area consists of 51,142 m^2 (19.9 %) and 51,145 m^2 (20 %) in the low and very low vulnerability categories.

3.4 Projected Sea Level Rise Using RCP Scenarios

The sea level rises data from the World Bank Group (2021) for the Philippines were analyzed, focusing on the 50th percentile values of the Representative Concentration Pathways (RCP) 2.6 (0.08 m), 4.5 (0.22 m), and 8.5 (0.45 m) scenarios projected for 2100. The visual representations (Figure 2) illustrate the sea level rise patterns in the studied barangays.

In the barangay Tortugas, the susceptibility to sea level rise (SLR) is evident. At 0.08 meters of SLR as shown in Figure 2a, approximately 312,700 m^2, which accounts for 77.78 % of Tortugas, are prone to the projected rise in sea levels. As the SLR increases to 0.22 meters as shown in Figure 2b, the area of susceptibility expands to 335,400 m^2, representing 83.43 % of Tortugas. At the highest projected SLR of 0.45 meters as shown in Figure 2c, the vulnerable area further extends to 374,600 m^2, which corresponds to 93.17 % of the total area of barangay Tortugas.

Conversely, in the barangay of Puerto Rivas Ibaba, the vulnerability to SLR is also evident. At 0.08 meters of SLR, approximately 144,900 m^2, accounting for 56.31 % of Puerto Rivas Ibaba, are prone to the projected rise in sea levels. As the SLR increases to 0.22 meters, the susceptible area increases to 173,100 m^2, representing 67.28 % of Puerto Rivas Ibaba. The SLR continues to rise to 0.45 meters, the vulnerable area expands once again to 217,700 m^2, which constitutes 81.68 % of Puerto Rivas Ibaba.

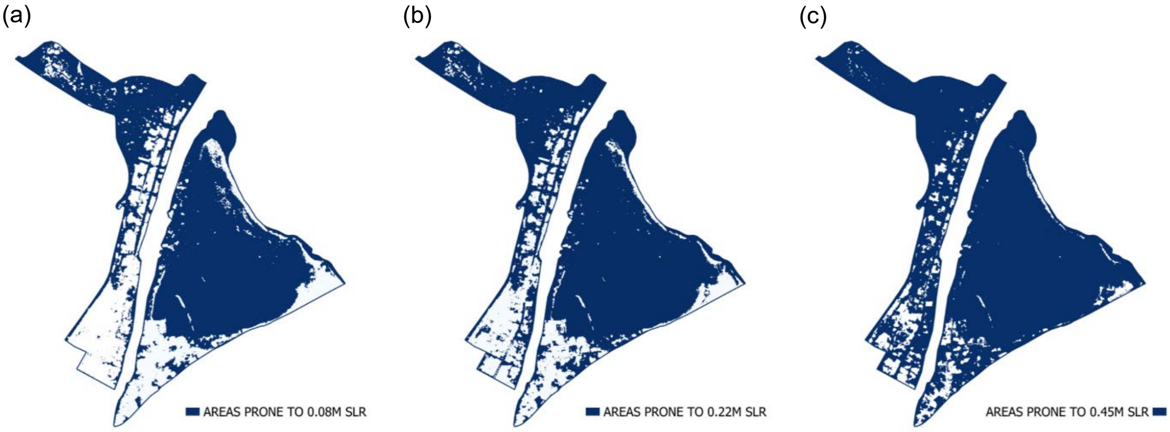

Figure 2: Inundation Maps Based on RCP Scenarios for Areas Vulnerable to Sea Level Rise of (a) 0.08 m, (b) 0.22 m, (c) 0.45 m.

4. Conclusions

In conclusion, the comprehensive analysis using fuzzy layers and vulnerability indices highlighted the vulnerability of Tortugas and Puerto Rivas Ibaba barangays to both socioeconomic and physical risks. The evaluation based on Socioeconomic Vulnerability Index (SVI) and Physical Vulnerability Index (PVI) values demonstrated varying levels of vulnerability across different areas within the barangays.

The analysis of PVI revealed that in the barangay of Tortugas, approximately 20 % of the mapped area exhibited very high vulnerability, while 19.9 % fell into the very low vulnerability category. Similarly, in barangay Puerto Rivas Ibaba, around 22 % displayed very high vulnerability, accompanied by approximately 34 % classified as very low vulnerability. The analysis of SVI revealed that in the barangay of Tortugas, approximately 20 % of the mapped area exhibited very high vulnerability, and another 20 % fell into the very low vulnerability category. Similarly, in barangay Puerto Rivas Ibaba, around 20 % displayed very high vulnerability, accompanied by approximately 19.9 % classified as very low vulnerability. In terms of TVI, Tortugas has 20% in very high vulnerability and 19.9 % in very low vulnerability. Puerto Rivas Ibaba also has 20 % in very high vulnerability and 20 % in very low vulnerability.

Additionally, the projected sea level rise analysis using Representative Concentration Pathways (RCP) scenarios showcased potential risks faced by these barangays. The findings revealed expanding areas prone to rising sea levels as the scenarios progressed, indicating the urgency of implementing adaptive measures. These results underscore the importance of implementing targeted adaptation strategies and resilience-building initiatives to mitigate the impacts of vulnerabilities in Tortugas and Puerto Rivas Ibaba. Adapting to sea-level rise is crucial for coastal communities. Strategies include reducing exposure and sensitivity to hazards, enhancing resilience, implementing integrated coastal zone management plans, raising awareness, and promoting strategic relocation and land use planning. Collaboration among researchers, policymakers, and local communities is vital. These proactive measures foster resilience, sustainability, and a prosperous future for coastal communities.

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