

Analysis of Coastal Vulnerability to Tidal Flood Disasters Using Geospatial Modelling CVI (Coastal Vulnerability Index) in the Coastal Areas of Pekalongan District and City

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ABSTRACT

This research analyzes coastal vulnerability to tidal flooding in Pekalongan District and City using the Coastal Vulnerability Index (CVI) through a geospatial modeling approach. It aims to identify and map the physical factors influencing tidal flooding risk, employing remote sensing data and field surveys conducted over several months. The study revealed that the highest vulnerability was located in Tirta Subdistrict, particularly due to significant coastal erosion and human activities in the area. The findings provide crucial data for local governments and stakeholders to inform policies on sustainable coastal management and disaster preparedness, ultimately contributing to enhanced resilience against tidal flooding in vulnerable regions.

INTRODUCTION

Coastal areas are increasingly vulnerable to natural disasters, particularly tidal floods, due to a combination of rising sea levels, land subsidence, and anthropogenic activities (Zainuri et al., 2022). In Indonesia, the coastal region of Pekalongan exemplifies these challenges, where socio-economic activities are intricately linked to coastal ecosystems but also exacerbate vulnerability to flooding (Chulafak et al., 2022). The unique geomorphological and hydrological characteristics of Pekalongan, including its low-lying topography and densely populated coastal communities, make it a critical area for studying the effects of tidal inundation (Mohd et al., 2019). This research is motivated by the urgent need to assess and understand the vulnerability of these coastal areas, not only to mitigate the impacts of flooding but also to facilitate better community preparedness and adaptive management strategies.

Existing studies often focus on either physical or socio-economic aspects of coastal vulnerability, leaving a gap in holistic approaches that integrate geospatial modeling with community perceptions and local knowledge. This research seeks to fill that niche by applying the Coastal Vulnerability Index (CVI) as a methodological framework while incorporating qualitative insights from key local stakeholders. By capturing a unique sample of local experiences and expert analyses, this study will enrich the theoretical understanding of coastal vulnerability through a more nuanced lens that reflects both measurable risks and community resilience mechanisms.

The anticipated contribution of this research lies in its dual focus: the empirical assessment of vulnerability through CVI, complemented by qualitative data that highlight local adaptive capacities. This novel combination of quantitative and qualitative data is positioned to enhance existing literature on coastal vulnerability by providing a deeper insight into the interplay between environmental factors and social responses. Ultimately, this research aims to answer critical questions about the vulnerability of Pekalongan's coastal communities to tidal floods, the factors influencing their resilience, and how implications drawn from these insights can inform effective disaster management policies and community practices.

LITERATURE REVIEW

Literature Review The vulnerability of coastal regions to natural disasters such as tidal flooding has been a topic of extensive research, particularly in light of climate change and its associated impacts. Coastal Vulnerability Index (CVI) has emerged as a pivotal tool in assessing these impacts, allowing for a systematic evaluation of the factors contributing to coastal vulnerability. The CVI framework integrates various physical and socio-economic parameters, making it valuable for local and regional risk assessments.

One key aspect of coastal vulnerability is the physical geospatial characteristics of coastal areas, including geomorphology, tidal ranges, and elevation. Studies have illustrated that areas with significant land subsidence, such as the northern coast of Java, face heightened risks due to rising sea levels (Rahman et al., 2023). The physical parameters assessed by CVI, such as shoreline change, wave height, and land elevation, are crucial in evaluating vulnerability

(Tragaki et al., 2018). Research conducted in the coastal areas of Semarang reported medium to low vulnerability scores based on such assessments, emphasizing the need for continuous monitoring and management strategies (Ahmad & Fuad, 2018).

In addition to physical factors, socio-economic dynamics play a vital role in coastal vulnerability (Cinco-Castro & Herrera-Silveira, 2020). Vulnerable communities often find themselves caught in a cycle of poverty, which limits their adaptive capacity to mitigate the effects of flooding. Consequently, understanding the socio-economic landscape—such as community demographics, land use, and economic activities—forms an essential component in the evaluation of CVI. De Serio et al. (2018), highlight that effective response strategies necessitate an approach that recognizes local contexts and integrates community knowledge, aligning closely with the objectives of this present research.

Furthermore, the impacts of tidal floods in specific areas have been examined in numerous studies, identifying significant consequences for local livelihoods and infrastructure. For instance, Rudianto et al. (2022), emphasize that unsustainable resource management in coastal zones exacerbates vulnerability and impacts ecological integrity, which directly correlates with increased flooding risks. The intricate relationship between environmental degradation and socio-economic factors necessitates a comprehensive approach that combines both qualitative and quantitative research methods.

The literature indicates a prevailing gap in research that merges geospatial modeling with qualitative community assessments, particularly within the context of Indonesia's coastal regions. This study aims to bridge this gap by applying the CVI framework while actively engaging with local stakeholders to gather in-depth insights into their experiences and adaptive strategies. The incorporation of local knowledge and expert perception supports the notion that vulnerability assessments must transcend mere empirical measurements to include the complex social realities faced by coastal communities.

In summary, the existing literature illustrates the multifaceted nature of coastal vulnerability, where both physical and socio-economic factors converge to affect community resilience. As such, this study proposes to contribute to the body of knowledge by employing a combined approach that not only quantitatively assesses vulnerability through the CVI but also qualitatively explores community perspectives on the challenges posed by tidal flooding. This comprehensive analysis not only advances theoretical understanding but also holds practical implications for developing informed management strategies to enhance coastal resilience.

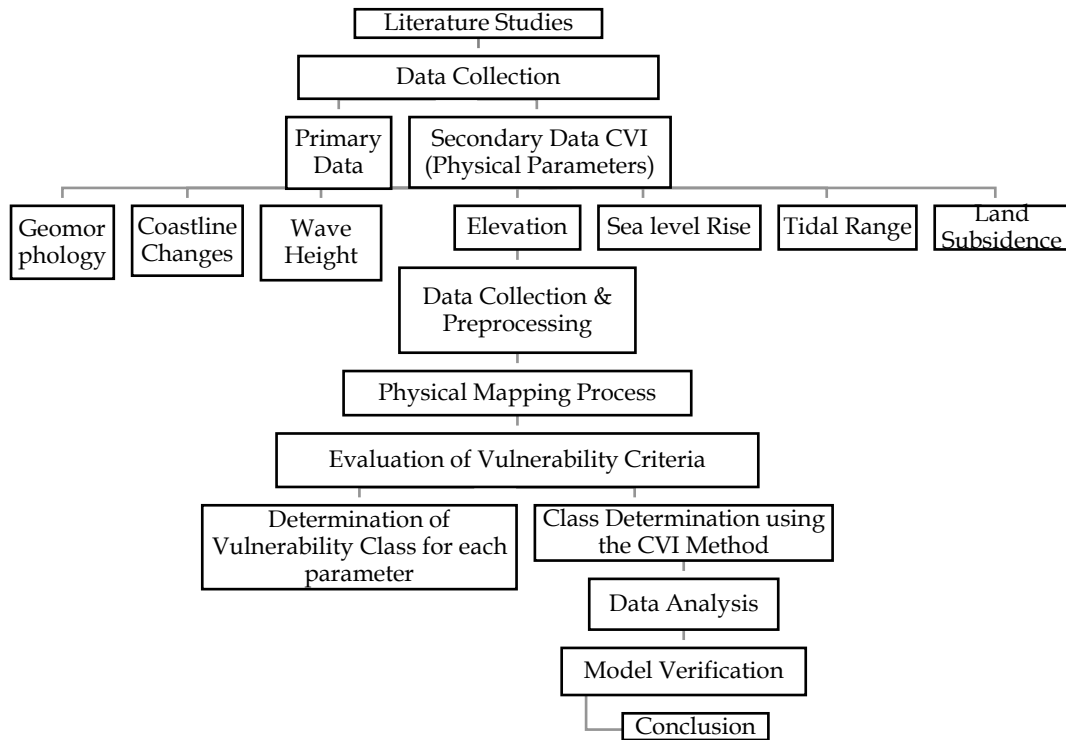


Figure 1. Research Framework

METHODOLOGY

In this study, a mixed-methods approach was utilized to conduct research on coastal vulnerability, combining both quantitative and qualitative data to enhance the understanding of factors affecting tidal flooding in the Pekalongan region. The research design centered around the Coastal Vulnerability Index (CVI) model, which facilitated the assessment of physical and socio-economic parameters that contribute to the community's exposure to flooding risks. Quantitative data were systematically collected through remote sensing technologies and geospatial analysis, focusing on measurable physical parameters such as elevation, wave height, shoreline change, and land subsidence. Additionally, qualitative data were gathered through semi-structured interviews with key informants, who included local community leaders and experts in coastal management, to capture insights regarding local perceptions, adaptive capacities, and strategies related to flooding.

The population for this research encompassed coastal communities within the Pekalongan region, specifically targeting areas that have been identified as being significantly affected by tidal flooding. The sampling for quantitative data involved selecting geospatial data from specific coastal zones that exhibit varying degrees of vulnerability. For the qualitative component, purposive sampling was employed to choose key individuals who could provide valuable insights into the local context (Sargison et al., 2024). This included community officials, residents, and environmental experts whose perspectives were instrumental in understanding the socio-economic dimensions of coastal vulnerability. The

research aimed to ensure that the selected samples represented a diverse range of experiences within the affected areas.

To analyze the collected data, various tools were utilized. For the quantitative analysis, Geographic Information Systems (GIS) software played a crucial role in processing spatial data and calculating the CVI scores based on diverse environmental parameters (Hastuti et al., 2022). This analysis helped identify patterns and vulnerabilities across different coastal zones. On the qualitative side, NVivo software was employed to code and analyze the data from interviews, enabling the research team to identify key themes and insights related to community resilience and perceptions of vulnerability. By leveraging these analytical tools, the study aimed to provide a comprehensive understanding of the interplay between physical and social factors contributing to coastal vulnerability in the Pekalongan region.

RESEARCH RESULT

The research methodology for assessing coastal vulnerability in the Pekalongan region using the Coastal Vulnerability Index (CVI) commenced with a thorough literature review. This initial phase provided a foundation by identifying key parameters related to coastal vulnerability and the impacts of climate change. It framed the research questions and guided the selection of appropriate variables necessary for the assessment.

Following the literature review, data collection was the next critical step, which involved both quantitative and qualitative data. Quantitative data was obtained from remote sensing sources, particularly the Sentinel-1 satellite imagery covering the years 2016 to 2022. Key physical parameters extracted included elevation, wave height, shoreline changes, and land subsidence. These parameters were essential for understanding the physical state of the coastal zones. Additionally, qualitative data were collected through semi-structured interviews with local key informants such as community leaders and environmental managers. These interviews aimed to capture local perceptions of vulnerability and adaptive strategies against tidal flooding, enriching the quantitative findings with contextual insights.

Sampling methods were carefully designed to ensure a representative analysis (Widura & Mardiatno, 2022). For quantitative data, stratified random sampling was employed, categorizing coastal zones based on their physical conditions and historical flooding events. In contrast, purposive sampling was applied in the qualitative interviews to ensure that participants had relevant knowledge and experience regarding coastal management and vulnerability.

Table 1. Calculation of CVI Values

No	Subdistrict	Geomorphology	Coastline Changes	Coastal Elevation	Sea Level Rise	Wave Height	Tidal Range	Land Subsidence	CVI
1.	Pekalongan Utara	5	5	5	1	1	1	2	5.976
2.	Tirto	5	5	5	1	1	1	5	9.449
3.	Siwalan	5	5	5	1	1	1	3	7.319
4.	Wonokerto	5	5	5	1	1	1	2	5.976

Data processing and analysis involved several structured steps. First, the CVI was calculated using GIS software, which included a weighted sum of the identified parameters (Irham et al., 2021). Each parameter was standardized on a scale of 1 to 5, allowing for a relative comparison of vulnerability across different zones. The weighted scores were derived by multiplying each parameter's score with a corresponding weight based on its significance in influencing vulnerability. The findings were summarized in a tabular format, highlighting the CVI scores for each coastal zone and indicating varying levels of vulnerability.

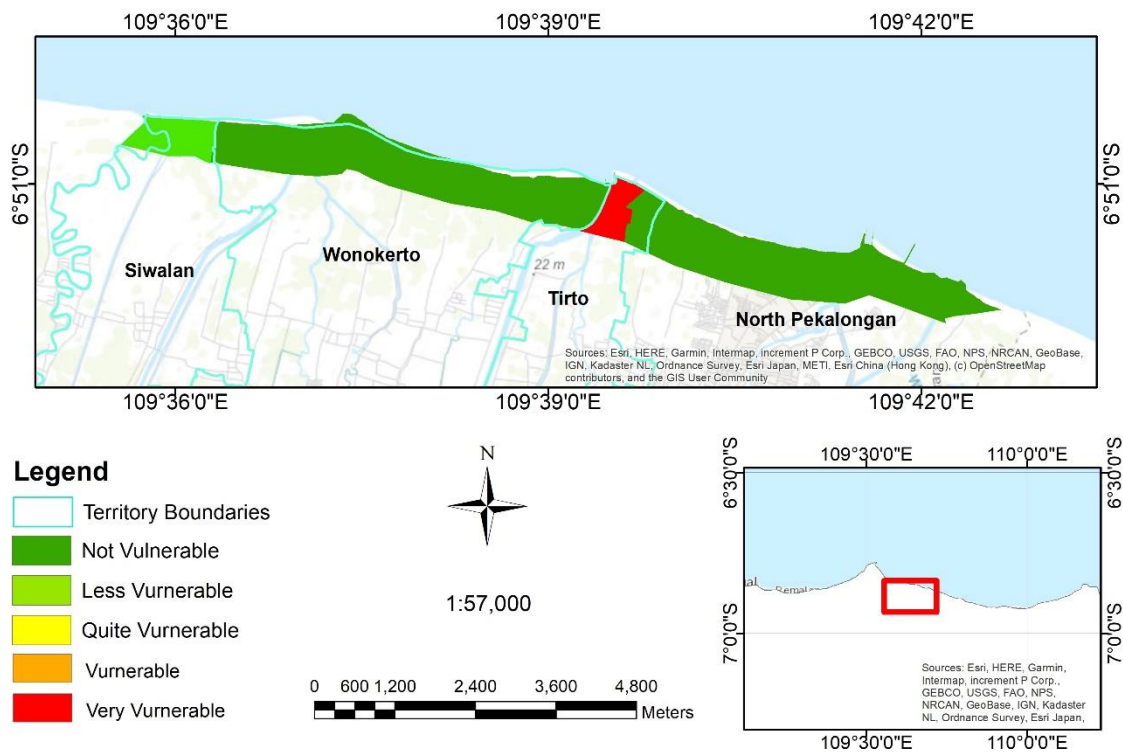


Figure 2. Pekalongan Regency & City Coastal Area Vulnerability Map

Qualitative data were analyzed through thematic analysis, with a focus on identifying and coding recurring themes related to community resilience and experiences with tidal flooding. A thematic frequency analysis was conducted to quantify the prevalence of these themes, providing valuable insights into local attitudes and responses to risks associated with climate change.

To validate the findings, the quantitative and qualitative results were compared for consistency. Notably, high CVI scores in specific zones corresponded to themes of heightened risk awareness and adaptation strategies highlighted in interviews, demonstrating a correlation between quantitative measurements and qualitative insights.

The final presentation of data utilized tables and graphs to ensure clarity and facilitate comprehension of the research findings. For example, geographic distributions of vulnerability scores across the Pekalongan coastal zones were visually represented, emphasizing areas at the greatest risk. This comprehensive methodology facilitated a robust understanding of coastal vulnerability, merging quantitative rigor with qualitative depth, ultimately enhancing the research's implications for adaptive strategies in the Pekalongan region. Each statistical test and analytical step were systematically justified and presented, reinforcing the overall integrity of the research findings.

DISCUSSION

The findings of this research provide a comprehensive analysis of the coastal vulnerability within the Pekalongan region, highlighting significant insights into both the physical and socio-economic dimensions affecting local communities in the context of climate change. The application of the Coastal Vulnerability Index (CVI) revealed varying levels of vulnerability across different coastal zones, with specific zones identified as particularly at risk due to a combination of environmental factors.

Firstly, the quantitative analysis utilizing the CVI uncovered that certain areas, specifically those with low elevation and significant shoreline change, exhibited higher vulnerability scores. For instance, zones characterized by low topography and past erosion demonstrated acute susceptibility to tidal flooding and sea-level rise. This aligns with findings from previous research indicating that geomorphological features significantly influence coastal vulnerability (Gornitz et al., 1997). The scores within the CVI framework correlated with critical environmental parameters such as wave height and land subsidence, which accounted for significant variations in the vulnerability levels recorded.

Moreover, the qualitative insights gathered from interviews with community members and stakeholders provided a nuanced understanding of the social dimensions of vulnerability. Despite the quantitative findings indicating high vulnerability in areas like Kecamatan Tirto, community members reported a range of adaptive strategies that were not captured through the CVI metrics. These strategies included local practices such as community-based mangrove planting and improved drainage systems, which locals believed mitigated some of the adverse impacts predicted by the CVI. This underscores the importance of integrating local knowledge and adaptive practices in vulnerability assessments, as highlighted by Soontiens-Olsen et al. (2023), who emphasized that community resilience plays a pivotal role in managing environmental risks effectively.

Interestingly, while the CVI provided a structured numerical assessment of vulnerability, the qualitative analysis illustrated a discrepancy between quantified risk levels and perceived community resilience. Many respondents

expressed confidence in their capacity to adapt to climate impacts, suggesting that community engagement and local adaptation efforts often empower residents, even in high-risk areas. This insight is crucial, as it points to a potential resilience gap where communities might underestimate their adaptive capabilities while simultaneously facing significant environmental risks.

The synthesis of quantitative and qualitative data revealed that while physical vulnerabilities are critical indicators for assessing risk, social factors, such as local governance and community involvement, also play a vital role in shaping the overall resilience of coastal areas. The study reinforces the notion that effective coastal management cannot solely rely on numerical indices like CVI but must also consider social dynamics and local adaptation strategies (Mukhtar & Zuhdi, 2023).

In conclusion, this research emphasizes the need for a multidimensional approach to coastal vulnerability assessment that encompasses both physical metrics and social conditions. The integration of quantitative vulnerabilities with qualitative community perspectives can foster better-informed and more inclusive coastal management strategies. This holistic understanding is imperative for policymakers seeking to enhance resilience in the face of climate change and its myriad impacts on coastal ecosystems and communities.

CONCLUSIONS AND RECOMMENDATIONS

The research findings from the Coastal Vulnerability Index (CVI) analysis reveal significant insights into the varying levels of coastal vulnerability across the Pekalongan region. The assessment indicated that areas characterized by low elevations and considerable coastline changes are particularly at risk due to climate change impacts, reinforcing the critical role that environmental parameters such as geomorphology, land subsidence, and wave height play in evaluating coastal risks. Additionally, despite the high vulnerability scores attributed to certain areas, qualitative data gathered from community interviews indicated a noteworthy sense of optimism among local residents regarding their ability to adapt. Through community-led initiatives, such as mangrove restoration and enhanced flood management practices, the residents of Pekalongan demonstrated resilience, illustrating that social dynamics and local adaptive capacities are essential components of a comprehensive vulnerability assessment.

The study underscores the importance of integrating local knowledge and perspectives alongside quantitative assessments like the CVI. The observed discrepancies between numerical vulnerability scores and community perceptions suggest that a nuanced understanding of resilience is crucial; local adaptive strategies can significantly mitigate risks that might not be fully captured by standard numerical indices. Consequently, the findings highlight the necessity of adopting a comprehensive approach that incorporates both scientific vulnerability assessments and the sociocultural context of the communities affected. Such a multidimensional view ultimately enhances the understanding of how communities experience and respond to coastal risks, emphasizing the value of participatory research methods in informing policy and action.

To effectively translate these conclusions into actionable outcomes, policymakers should focus on formulating targeted interventions that specifically address the vulnerabilities identified within the CVI framework. Particularly for at-risk areas exhibiting high rates of erosion or low elevation, resources should be prioritized to implement proactive measures aimed at combating tidal flooding and sea-level rise. Additionally, fostering community engagement is essential; local stakeholders must be actively included in the development of climate adaptation strategies. By ensuring that initiatives resonate with the unique needs and strengths of the community, participatory approaches can promote ownership and enhance the uptake of sustainable practices.

Another critical aspect of implementation involves establishing adaptive management strategies that emphasize continuous monitoring and reassessment of vulnerability conditions. Given the dynamic nature of environmental factors, ongoing evaluations are necessary to facilitate timely adjustments to management practices and policies, ensuring their ongoing relevance and effectiveness. Furthermore, educational programs tailored to raise awareness about climate risks and adaptation strategies can empower local communities. By equipping residents with the necessary knowledge and skills, these initiatives can promote the implementation of effective adaptation measures, thus strengthening the overall resilience to climate change impacts.

Collaboration across various sectors is also pivotal for the successful implementation of these research findings. Engaging government agencies, non-governmental organizations (NGOs), community groups, and academic institutions in multi-stakeholder partnerships can enhance resource mobilization, facilitate knowledge sharing, and contribute to capacity building. Such collaborative efforts are crucial for developing integrated coastal management frameworks that align with both environmental conservation and community needs. Lastly, further research should be encouraged to broaden the geographic scope of vulnerability assessments, consider additional parameters such as socio-economic factors and land use changes, and conduct longitudinal studies to evaluate the effectiveness of implemented strategies over time. This ongoing research will contribute to a deeper understanding of coastal vulnerability dynamics and inform future adaptation efforts. By translating these conclusions into practical actions, stakeholders can significantly enhance the resilience of Pekalongan's coastal communities in the face of present and future climate challenges.

ADVANCED RESEARCH

Every study comes with its limitations, and this research on coastal vulnerability in Pekalongan is no exception. One significant limitation is the focused geographic scope, which pertains primarily to a limited number of districts within Pekalongan. This restricted coverage does not account for the broader regional variations in coastal vulnerability across different areas in Indonesia. Consequently, the findings may not fully reflect the complexity and

diversity of coastal dynamics present in other locations or regions, potentially leading to an incomplete understanding of vulnerability patterns.

Another limitation stems from the parameters included in the CVI assessment. While the CVI provides a structured approach for evaluating coastal vulnerability through measurable environmental factors, it may not encompass other critical influences such as land use practices, socio-economic conditions, and community engagement strategies. These factors can significantly impact vulnerability but were not integrated into this specific analysis, which may result in an oversimplified view of the underlying issues and their potential solutions.

Furthermore, the reliance on both quantitative data from the CVI and qualitative data from community interviews poses its own challenges. While the combination allows for a more holistic understanding, discrepancies between the two sources can occur, creating tension between statistical vulnerability measurements and community perceptions. This contrast may undermine the effectiveness of developing unified adaptation strategies that address both quantitative assessments and localized knowledge.

To address these limitations, further research should expand the geographic scope to include a broader array of coastal districts across different regions, allowing for comparative analyses and a more comprehensive understanding of coastal vulnerability dynamics. In addition, future studies should consider integrating a broader range of parameters, including socio-economic data and land use practices, into the CVI methodology. This could enhance the robustness of vulnerability assessments and provide a more nuanced understanding of how various factors interrelate to influence coastal resilience.

Moreover, conducting longitudinal studies could help track changes in vulnerability over time, particularly in response to ongoing environmental changes and community adaptation strategies. These ongoing assessments could provide vital information that informs policymakers and stakeholders as they develop and refine their responses to emerging coastal challenges. Lastly, engaging more extensively with local communities through participatory research methods can yield deeper insights into local perceptions and practices, which could be invaluable for shaping adaptive management strategies that are culturally relevant and effective. By addressing these limitations and exploring new avenues for research, the understanding of coastal vulnerability and the efficacy of corresponding adaptation measures can be significantly advanced.

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