SRSD
Spatial Review for Sustainable Development
SRSD 2(2): 111–128
ISSN 3062-8229

Mapping household physical vulnerability to tidal floods through indicator-based scoring analysis

Trida Ridho Fariz[1,*], Taufik Bahrul Rizky[1], Vera Angelina Holeng[1], Meilinda Damayanti[2], Andhina Putri Heriyanti[1]

[1] *Environmental Science Study Program, Faculty of Science, Universitas Negeri Semarang, Semarang, Central Java 50229, Indonesia;*

[2] *Environmental Science Study Program, School of Environmental Science and Management, University of the Philippines Los Baños, Los Baños, Laguna 4031, Philippines.*

*Correspondence: trida.ridho.fariz@mail.unnes.ac.id

Received Date: February 3, 2025 Revised Date: June 12, 2025 Accepted Date: August 31, 2025

ABSTRACT

Background: Tidal flooding is a significant problem in the coastal areas of Semarang City, due to climate change and environmental pollution issues. **Method:** The research method involved direct observation and interviews with homeowners to collect primary data, as well as scoring analysis based on four main indicators. This study used a structural indicator-based scoring analysis approach to assess the physical vulnerability of houses to tidal flooding. **Findings:** Tambakrejo area, which is a coastal area, also experiences periodic inundation due to sea level rise. The physical vulnerability of houses in this area is influenced by various factors, such as building materials, building age, floor height, and building height. The results show that most houses in Tambakrejo have a moderate level of vulnerability, with building materials and age as the main causes. Houses with wooden materials and more than 20 years old are more vulnerable to damage from inundation, while multi-storey houses and those with higher floors have better resilience. **Conclusion:** The study highlights that building materials and age are key factors affecting the physical vulnerability of houses to tidal flooding in Tambakrejo, Semarang City, and suggests consideration of structural indicators in flood risk mitigation. **Novelty/ originality of this article:** The novelty of this study lies in using a structural indicator-based scoring analysis to assess the physical vulnerability of houses to tidal flooding in Tambakrejo, highlighting building materials, age, and floor height as key factors.

KEYWORDS: physical vulnerability mapping; tidal flood; scoring analysis; household level, adaptation strategies.

1. Introduction

Coastal zones are among the most vital socio-ecological systems on Earth, functioning simultaneously as centers of human settlement, hubs of economic activity, and reservoirs of ecological richness. Globally, these areas support more than half of the world's population while contributing disproportionately to national and regional economies through fisheries, aquaculture, maritime trade, tourism, and a diverse array of ecosystem services (Peduzzi, 2019). Their ecological significance extends beyond human use, as mangroves, coral reefs, and seagrass beds provide coastal protection, carbon sequestration, and biodiversity habitats. Yet, despite this critical importance, coastal regions are increasingly under threat. A combination of climate change, unregulated urbanization, and unsustainable resource extraction has produced a perilous imbalance between economic growth and ecological

Cite This Article:
Fariz, T. R, Rizky, T. B., Holeng, V. A., Damayanti, M., & Heriyanti, A. P. (2025). Mapping household physical vulnerability to tidal floods through indicator-based scoring analysis. *Spatial Review for Sustainable Development, 2*(2), 111-128. https://doi.org/10.61511/srsd.v2i2.2025.1657

stability, intensifying the vulnerability of coastal populations to disaster risks (Young, 2014). Indonesia, as the world's largest archipelagic nation, represents both the immense promise and profound fragility of coastal development. Its more than 17,000 islands stretch across three major oceans, providing extraordinary marine biodiversity and serving as a foundation for the livelihoods of millions (Rahmawati & Setiawan, 2019). The fisheries sector, maritime industries, and coastal tourism offer enormous economic potential, yet these opportunities coexist with persistent social and economic challenges. Many coastal communities continue to grapple with poverty, underdeveloped infrastructure, and limited access to education and healthcare. This paradox, between ecological wealth and socio-economic marginalization, forms the backdrop against which the impacts of climate change, particularly tidal flooding, are becoming ever more acute.

The climate crisis has entered a new and alarming phase. What once was described as "global warming" is increasingly characterized in scholarly and policy discourse as "global boiling," reflecting both the intensification of temperature extremes and the cascading consequences of climate disruption. The Intergovernmental Panel on Climate Change (IPCC) warns that global mean sea level rise, driven by melting ice sheets and thermal expansion, is accelerating at an unprecedented rate (Calvin et al, 2023). For low-lying coastal regions such as northern Java, this trend is catastrophic. Higher mean sea levels amplify the frequency and intensity of tidal flooding events, transforming what were once seasonal or episodic floods into near-daily occurrences in some locations. At the same time, anthropogenic land subsidence in major Indonesian coastal cities compounds the effects of sea-level rise. Driven by excessive groundwater extraction, poorly regulated urban expansion, and inadequate drainage systems, land subsidence creates a "double exposure" scenario: while seas are rising globally, the land itself is sinking locally. Semarang, one of Indonesia's largest coastal cities, is emblematic of this phenomenon. Studies estimate that parts of the city are sinking by several centimeters per year (Naja & Mardiatno, 2018; Nurhadi et al., 2017). The convergence of these global and local processes means that tidal flooding (locally referred to as rob) has shifted from being an occasional hazard into a chronic disaster that disrupts daily life, undermines livelihoods, and erodes infrastructure resilience.

The global discourse on climate justice underscores that communities in the Global South, such as those in Semarang's coastal neighborhoods, bear the brunt of climate change despite contributing least to its causes. These areas embody the inequities of global boiling: while industrialized nations account for the vast majority of historical greenhouse gas emissions, it is marginalized, resource-constrained populations in developing countries who face the most severe and immediate impacts. Thus, studying the vulnerability of Semarang's households is not only a local or national concern but also a critical node in the global conversation on climate adaptation, resilience, and justice. Northern Java has long been recognized as one of Indonesia's most vulnerable coastlines. Its geographic exposure to the Java Sea, coupled with high population density and intensive economic activity, creates a setting where environmental stressors and human pressures collide. Semarang, the capital of Central Java, epitomizes these dynamics. As an industrial and commercial hub, the city's coastal districts accommodate warehouses, fishing ports, small industries, and densely populated settlements. However, this economic role is undermined by the recurring onslaught of tidal flooding (Juniarti et al., 2021).

Tidal floods occur when seawater, driven by high tides, overtops coastal defenses and inundates low-lying areas. In Semarang, this process is exacerbated by deteriorating drainage networks, blocked waterways, and increasingly erratic rainfall patterns (Syafitri & Rochani, 2022). Inundation damages residential structures, corrodes building materials, and disrupts public facilities, from schools to clinics, leaving communities in a state of recurrent disruption (Suherman et al., 2023). The persistence of rob floods means that households in areas such as Tambakrejo not only face immediate losses but also experience cumulative and long-term degradation of their living conditions. Vulnerability is commonly defined as the degree to which communities are susceptible to harm due to the interaction of physical, social, economic, and environmental factors. The Indonesian National Disaster

Management Agency (BNPB) adopts a fourfold classification, namely physical, social, economic, and environmental (Utomo & Marta, 2022). Within this framework, physical vulnerability refers specifically to the structural fragility of buildings and infrastructure when confronted with hazards such as flooding or earthquakes.

In Semarang, physical vulnerability is amplified by factors such as poor construction quality, use of materials prone to water damage, and inadequate elevation of floors relative to tidal water levels (Fitria et al., 2019). Land subsidence further weakens foundations, producing structural cracks, tilted buildings, and sunken roads. In many cases, recurrent flooding renders houses partially or completely uninhabitable, forcing families into cycles of repair, displacement, or unsafe habitation. The United Nations Office for Disaster Risk Reduction (UNISDR, 2015) emphasizes that such cumulative structural degradation not only increases direct disaster risk but also undermines community resilience by eroding household assets and adaptive capacity. Disaster risk is rarely uniform. Even within a single neighborhood, households may exhibit vastly different levels of vulnerability due to variations in building material, structural design, economic resources, and access to information. Fariz et al. (2023a) argue that a household-scale approach is crucial because aggregated or sample-based analyses can mask critical intra-community differences. For instance, while two adjacent households may face similar tidal inundation levels, their actual capacity to withstand and recover may diverge significantly depending on whether the dwelling is brick or wooden, one-story or multi-story, new or old. Household-scale studies thus provide the granularity needed to design targeted mitigation strategies (Fariz et al., 2022; Pamekas & Poli, 2019). This micro-level perspective is particularly valuable in contexts like Semarang, where socio-economic inequality intersects with environmental vulnerability. Low-income households are disproportionately exposed, as they often occupy the most flood-prone locations and inhabit structures of substandard quality. Danianti & Sariffuddin (2015) highlight that in Semarang's coastal areas, it is precisely these marginalized groups who bear the greatest burden of tidal flooding, suffering losses that extend beyond physical damage to include income disruption, increased health risks, and reduced educational opportunities for children. While previous studies of vulnerability analysis in Indonesia have advanced knowledge, many have relied on aggregated indices or macro-level assessments (Esariti et al., 2024; Yuliastuti, 2023). These approaches, while useful for broad policy formulation, risk overlooking household-specific dynamics that ultimately determine the lived reality of disaster impacts. The methodological limitation of aggregation underscores the need for more granular research at the level of individual households (Fariz et al., 2023a). Recent scholarship emphasizes this shift, with Macusi et al. (2025) and others calling for detailed household-level studies that capture not only physical attributes but also the socio-economic diversity of households.

The impacts of tidal flooding extend far beyond physical structures. Affected households experience a complex interplay of social, economic, and psychological stressors. Physical damage to homes often coincides with interruptions to daily life, such as the inability to commute to work, loss of small business income, and compromised access to education when schools are inundated (Ullah et al., 2025). The health risks associated with stagnant floodwaters, ranging from waterborne diseases to increased vector populations, compound the challenges of survival in flood-prone neighborhoods. Households invest significant portions of their limited income into repeated repairs, reducing resources available for food, education, and healthcare. Community cohesion, once a source of resilience, can become strained as prolonged exposure to flooding forces some families to relocate or abandon their homes entirely. The ripple effects of tidal floods thus extend into the very fabric of social relations, altering community structures and threatening long-term development trajectories (Danianti & Sariffuddin, 2015; Suherman et al., 2023).

Against this backdrop, the present study aims to map physical vulnerability to tidal floods at the household scale in Semarang Utara, focusing on identifying specific structural weaknesses and informing the design of localized adaptation strategies. By foregrounding household-level diversity, the study addresses the methodological limitations of aggregated analyses and provides a nuanced picture of vulnerability that reflects both structural fragility and adaptive responses. In addition, this research integrates an analysis of community adaptation strategies, recognizing that vulnerability is not solely a product of exposure but also of agency. By documenting social, economic, environmental, and infrastructural adaptations, the study highlights how households navigate the recurring challenge of rob flooding. This dual focus on vulnerability and adaptation ensures that the findings are not only diagnostic but also prescriptive, offering a basis for tailored risk reduction strategies.

The broader significance of this study lies in its potential contributions to global debates on climate adaptation and resilience. As coastal communities worldwide grapple with the realities of global boiling, localized analyses such as this one serve as critical case studies. They demonstrate how vulnerability manifests in specific socio-ecological contexts and how community-level adaptations can inform larger policy frameworks. Furthermore, the findings of this research are expected to support climate-resilient development pathways aligned with the United Nations Sustainable Development Goals (SDGs). In particular, the study contributes to SDG 9 (industry, innovation, and resilient infrastructure), SDG 11 (sustainable cities and communities), SDG 13 (climate action), and SDG 14 (life below water). By aligning household-scale insights with global development frameworks, this research bridges the gap between local realities and international agendas, offering knowledge that is both context-sensitive and globally relevant.

2. Methods

This study examines the physical vulnerability of residential buildings to tidal flooding in the Tambakrejo area (RT 1–RT 4, RW 16) of Tanjung Mas Village, Semarang Utara District, Semarang City, Central Java (Figure 1). The methodological design integrates field-based data collection, qualitative inquiry, and spatial analysis, with the aim of systematically assessing vulnerability factors at the household scale. The research design is grounded in both quantitative and qualitative traditions, allowing for the development of a holistic understanding of vulnerability that not only identifies structural weaknesses but also situates them within the broader context of community adaptation and resilience.

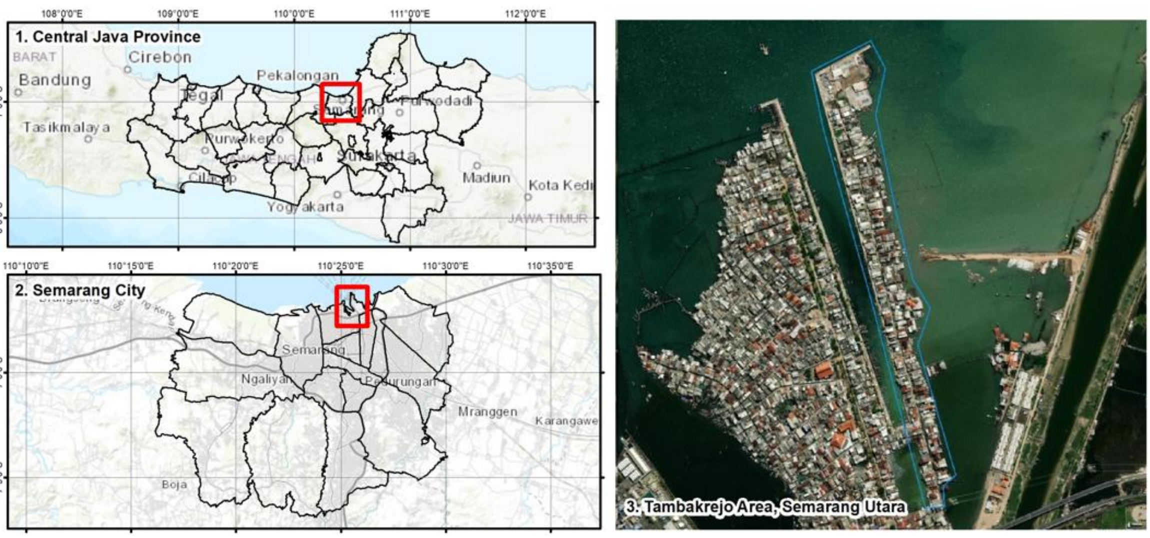

Fig. 1. Study location

2.1. Data collection approach

The research employs both primary and secondary data sources to ensure analytical robustness. Primary data was collected through field-based surveys, direct observation of residential buildings, and structured interviews with community leaders and residents. These field interactions were designed to capture a high level of accuracy regarding housing characteristics such as wall materials, floor elevation, and number of stories, which are often absent from official cadastral datasets. By prioritizing ground-truthing, the study reduces the risk of misclassification of household conditions. The structured interviews, conducted with purposively selected respondents, captured local knowledge regarding building history, age, and recurrent structural damages associated with tidal flooding. Particular attention was paid to subtle construction details, such as the porosity of building materials and retrofitting practices, that have implications for long-term flood resilience. Interview protocols were semi-standardized, combining closed-ended items for comparability with open-ended prompts that encouraged respondents to elaborate on their experiences.

Secondary data was obtained from government publications, municipal planning reports, non-governmental organizations, and academic literature. These sources were used to contextualize the field observations within broader patterns of flood exposure in Semarang, where land subsidence, sea-level rise, and coastal development converge to exacerbate risk (Afifah & Hizbaron, 2020; Subasinghe & Kawasaki, 2021). Historical data on past flooding events, government housing classifications, and socio-economic profiles of the Tambakrejo community were triangulated with field data to strengthen the reliability of the analysis. In addition to capturing physical conditions, the study also sought to document adaptation strategies practiced by residents in response to recurrent tidal inundation. Data on adaptation was obtained through in-depth interviews with household representatives and validated through participant observation. Adaptation strategies were categorized across four domains (social, economic, environmental, and physical/infrastructural) enabling a systematic understanding of how households adjust their daily routines, financial decisions, and building practices in the face of chronic flooding. This dual focus on vulnerability and adaptation reflects an integrated disaster risk reduction framework that not only diagnoses problems but also identifies community-driven solutions.

2.2 Vulnerability assessment framework

To operationalize household vulnerability, the study employed a composite index approach, adapted from the Social Vulnerability Index (SoVI) methodology (Cutter et al., 2003; Dunning & Durden, 2013). The SoVI framework is widely recognized in disaster research for its flexibility in integrating multiple indicators into a single metric of vulnerability, while also allowing for weighting schemes that reflect the relative importance of each factor. In this study, the SoVI principles were adapted specifically to the physical dimension of building vulnerability, focusing on four critical variables: building material, building age, floor height, and building height.

Table 1. Variable and score

Variable	Operational definition	Scoring parameters (1,2,3)	Theoretical basis
Building material (W1 = 0.3)	Resistance of wall materials to water penetration and saltwater corrosion.	1: Brick 2: Concrete block 3: Wood	Afifah & Hizbaron (2020)
Building age (W2 = 0.2)	Older buildings are more vulnerable due to outdated construction standards.	1: <10 years 2: 10–20 years 3: >20 years	Subasinghe & Kawasaki (2021)
Floor height (W3 = 0.25)	Height of the main floor above ground level; higher floors reduce flood risk.	1: >1 m 2: 0.5–1 m 3: <0.5 m	Pradika (2012)
Building height (W4 = 0.25)	Multi-story buildings are less vulnerable as floodwater is less likely to reach upper floors.	1: 3 floors 2: 2 floors 3: 1 floor	Arif et al. (2017)

Each variable was assigned both scoring parameters and weights, as summarized in Table 1. The weighting scheme reflects the theoretical and empirical importance of each factor. For instance, wall material was assigned the highest weight (0.3), recognizing its fundamental role in resisting water penetration and saltwater corrosion (Afifah & Hizbaron, 2020). Floor height and building height each received weights of 0.25, reflecting their combined role in determining whether floodwaters are able to directly impact household interiors. Building age was weighted at 0.2, capturing the notion that older structures, often built under less stringent construction standards, are more susceptible to cumulative damage (Subasinghe & Kawasaki, 2021).

2.3. Data collecting and analytical process

To maximize validity, the study adopted a triangulated data collection strategy. Physical surveys were conducted by field teams who systematically documented housing characteristics across RT 1–RT 4. These observations were supported by the use of Google Street View, which offered supplementary verification and visual documentation, particularly in areas where physical access was constrained by flooding, construction barriers, or restricted property access. The digital imagery proved useful for cross-referencing reported data, enhancing reliability, and filling observational gaps.

Furthermore, semi-structured interviews with residents added a qualitative layer to the analysis. Respondents were asked about recent flood events, damage histories, household repair costs, and informal adaptation measures such as raising floors, constructing makeshift dikes, or relocating belongings to upper floors. This qualitative evidence captured nuances that are often invisible in quantitative scoring systems, including the emotional stress of living in chronically flooded environments, informal networks of mutual aid, and localized knowledge of water pathways. For analytical rigor, vulnerability scores were calculated using a weighted composite scoring system:

$$\textit{Total vulnerability score} = (S1 \times 0.3) + (S2 \times 0.2) + (S3 \times 0.25) + (S4 \times 0.25) \qquad \text{(Eq.1)}$$

Where S represents the variable scores (1–3) and W denotes the predetermined weights. The resulting index classifies households into three categories: 1.0–1.5 = Low vulnerability, 1.6–2.5 = Moderate vulnerability, and 2.6–3.0 = High vulnerability. This scoring matrix enabled a transparent transformation of qualitative observations into numerical data, producing actionable metrics for policy and planning. In recognition of ongoing debates in vulnerability science regarding the subjectivity of weighting schemes, an alternative, non-weighted scoring approach was also applied. Under this method, each of the four indicators was treated with equal importance, avoiding potential bias introduced by predetermined weights. This non-weighted scoring facilitated direct comparisons across households and provided a robustness check against the weighted results.

The non-weighted scores were visualized spatially using ArcMap, allowing for fine-grained, household-level mapping. A choropleth map design was employed, with a three-color gradient to represent vulnerability levels: red for high, yellow for moderate, and green for low. This visual representation not only improved communication of findings but also highlighted spatial clustering of vulnerable households. Identifying clusters of high vulnerability is particularly useful for municipal planners, as it enables prioritization of intervention zones where risk is concentrated. In sum, this study's methodology integrates quantitative scoring with qualitative analysis to produce a comprehensive understanding of household-scale vulnerability to tidal flooding. The triangulation of field surveys, Google Street View, and interviews enhanced data reliability, while the dual weighted and non-weighted scoring systems ensured robustness and comparability. By combining vulnerability mapping with community-level adaptation practices across social, economic, environmental, and infrastructural domains, the approach bridges structural assessments with lived experiences, generating insights that are both diagnostic and prescriptive. Despite limitations such as temporal gaps in imagery, subjective weighting, and potential respondent bias, the mixed-methods design offers a replicable framework that not only identifies where risks are concentrated but also reveals how households cope, thereby providing a more holistic evidence base for disaster risk reduction and climate-resilient policy interventions.

3. Results and Discussion

Tambakrejo, located within Tanjungmas Sub-district of North Semarang, is one of the most flood-prone coastal settlements in the city. Geographically, Tanjungmas lies at an elevation of only 0.5 meters above sea level and covers a total area of 323.738 hectares (Subekti et al., 2023). It is bordered by Kemijen to the east, Bandarharjo to the west, Purwodinatan to the south, and the Java Sea to the north. This sub-district also hosts the only major seaport in Semarang, making it a vital hub for economic activity. According to the Central Bureau of Statistics (BPS, 2024), Tanjungmas is home to 27,479 residents, comprising 13,790 males and 13,707 females, distributed across 9,338 households. The area is administratively divided into 16 neighborhood units (RW) and 29 smaller community units (RT). The tidal flood dynamics in Tambakrejo are strongly influenced by lunar cycles, with severe inundations often occurring during full or new moon phases (Jabbar et al., 2023). However, these natural tidal patterns are aggravated by inadequate drainage systems that slow down the recession of floodwaters. As a result, roads and houses are frequently submerged, while stagnant pools of water increase the risk of vector-borne diseases and other health problems. The vulnerability of the settlement is further exacerbated by its low elevation and the dominance of housing structures that are not designed to withstand recurring tidal floods.

Beyond physical exposure, the socio-economic fabric of the community amplifies the adverse impacts of flooding. Many residents depend on informal livelihoods such as fisheries, small-scale trading, and daily wage labor, sectors that are highly sensitive to disruptions caused by coastal inundation. This economic fragility means that every episode of tidal flooding not only damages infrastructure and disrupts mobility but also undermines household income and community resilience. Consequently, the recurring tidal floods in Tambakrejo highlight the urgent need for targeted adaptation strategies, improved infrastructure, and community-based resilience measures to safeguard both livelihoods and living environments in this vulnerable coastal area.

Fig. 2. Building with concrete block and brick

Our household-level analysis advances the understanding of physical vulnerability by systematically evaluating four key parameters: building material, building age, floor elevation, and building height. Brick houses, which constitute 73.7% of sampled structures (n=145), demonstrate superior flood resilience due to their water-resistant properties and, when combined with elevated foundations and protective coatings, show 62% less flood damage compared to other materials (Figure 2). In contrast, concrete block homes (n=46, 23.4%) absorb water more readily and exhibit moderate vulnerability, while wooden structures (n= 6.3%) are most at risk due to rapid deterioration from saltwater exposure (Subasinghe & Kawasaki, 2021). These findings highlight the critical role of material selection in flood risk reduction and align with recent research emphasizing the need for material-specific retrofits in vulnerable coastal communities.

Fig. 3. Building with > 20 years and building with 10-20 years

Building age further compounds vulnerability, with 70.6% of homes (n=139) over 20 years old showing advanced material degradation, a condition accelerated by saltwater corrosion that leads to structural decay rates approximately 3.2 times higher than in newer buildings (Figure 3). Homes aged 10–20 years (n=54, 27.4%) display moderate vulnerability with emerging cracks and wear, while only a small fraction (n=4, 2%) under 10 years old remain in relatively good condition, although their resilience is contingent upon initial construction quality. This evidence suggests that aging infrastructure is a significant risk factor, a finding that is consistent with broader literature on urban flood vulnerability in rapidly developing coastal cities.

Fig. 4. Building with flor heigh >1m and <0,5m

Floor elevation and building height are equally critical in determining flood resilience. Only 44.1% of homes (n=87) have floors elevated more than one meter above ground level, providing optimal flood protection (Figure 4). Moderate vulnerability is observed in 37% of homes (n=73) with floor elevations between 0.5 and 1 meter, while 18.8% (n=37) with floors below 0.5 meters are at severe risk of inundation. Vertical development patterns further stratify vulnerability: single-story homes (n=135, 68.5%) face the highest risk, lacking elevated refuge during floods, whereas two-story (n=51, 25.9%) and three-story (n=11, 5.6%) structures offer increasing levels of protection (Figure 5). This stratification reflects the economic constraints that limit most residents' ability to invest in multi-level construction, reinforcing the link between socio-economic status and flood vulnerability.

Composite vulnerability mapping reveals that 87.3% of homes (n=172) fall into the moderate vulnerability category, with only 7.6% (n=15) classified as low and 5.1% (n=10) as high vulnerability. Spatial analysis demonstrates a clear gradient, with higher vulnerability clustered along the coastline and decreasing inland, a pattern that correlates strongly with both elevation and building quality (Figure 6). This spatial distribution confirms the compound nature of flood risks in Tambakrejo, where natural, structural, and socio-economic factors intersect to shape community vulnerability. Community adaptation efforts in Tambakrejo are both innovative and indicative of the challenges faced by coastal residents. Most households practice incremental elevation, raising their floors by approximately 50 cm every five years to keep pace with land subsidence and rising flood levels.

Fig. 5. Building with 3 floor and 2 floor

This practice has become normalized over the past two decades, creating a cycle of continuous construction and financial pressure for residents. Public facilities such as mosques and schools have also adopted similar strategies, albeit on a larger scale, while government-installed pump systems have reduced the average flood duration from 120 to 72 hours. The construction of seawalls along the coastline, extending from Tambaklorok, has contributed to a perceived reduction in flood hazard (Fig 7). However, despite these interventions, ongoing physical vulnerability and disaster risk assessments remain essential to ensure long-term resilience in these communities.

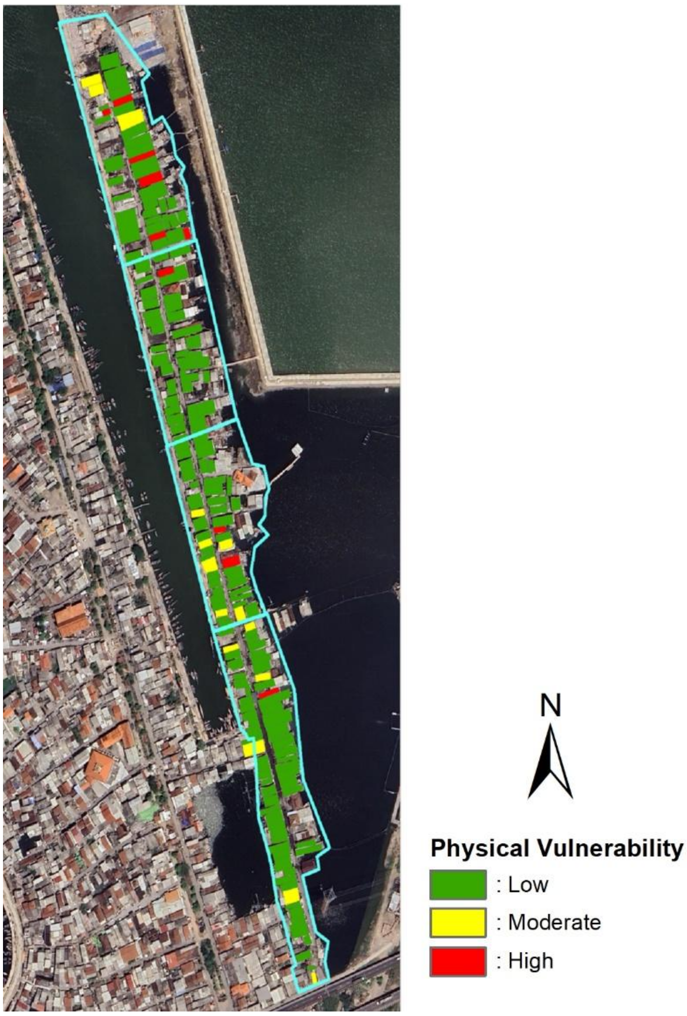

Fig. 6. Physical vulnerability map to tidal flood

Recent studies provide valuable benchmarks for interpreting these findings. Aprijanto et al. (2025) underscore the importance of an integrated approach to flood management, combining structural measures such as seawalls and storm surge barriers with non-structural strategies like early warning systems and public education. While structural solutions offer effective protection, their high installation and maintenance costs, as well as potential environmental impacts, necessitate careful planning. Non-structural approaches, including community-based early warning systems and green infrastructure, are not only cost-effective but also enhance community resilience and biodiversity. The involvement of local communities in flood management is crucial, as it ensures that solutions are tailored to local needs and fosters sustained engagement (Aprijanto et al., 2025). These insights are highly relevant to Tambakrejo, where community-driven adaptation and government support are both present but require greater coordination and integration.

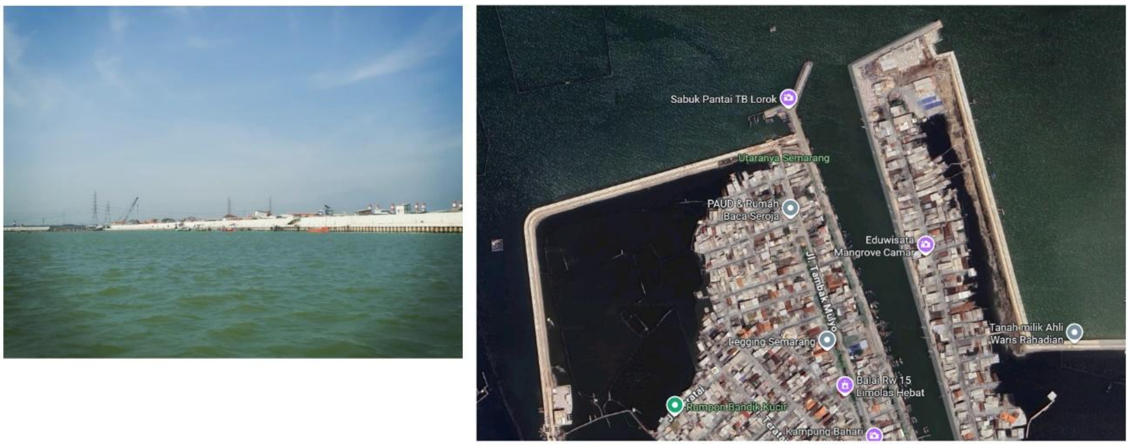

Fig. 7. Seawall at the study site

Huda et al. (2024) further elucidate the policy challenges facing Semarang City, particularly in managing land subsidence and environmental degradation. Their research highlights significant inefficiencies in policy implementation, bureaucratic structures, and stakeholder communication, all of which are exacerbated by the tension between urban development and environmental management (Huda et al., 2024; Saputri & Linda, 2023; Moloney & Fünfgeld, 2015). Weak government oversight of industrial groundwater use and unclear institutional frameworks at the local level further complicate efforts to address land subsidence. These findings underscore the need for a comprehensive, multi-stakeholder approach to policy formulation and implementation, with clear roles and responsibilities for all actors involved. Such an approach is essential for aligning long-term development goals with environmental sustainability and disaster risk reduction.

While the broader adaptation strategies in Tambakrejo demonstrate community resilience and government engagement, closer examination of the most affected neighborhoods, specifically RT 03 and RT 04 reveals the highly localized, context-specific dimensions of tidal flood adaptation. These two RTs are regularly exposed to the most severe tidal flooding, and yet they display different levels of preparedness and adaptive capacity. RT 03 is comparatively better positioned due to the presence of an online early warning system, implemented through WhatsApp group communication. This system allows residents to receive real-time updates on tidal conditions and potential flood threats, often sourced from BMKG (Meteorological, Climatological, and Geophysical Agency) or local port authorities. In contrast, RT 04 lacks both traditional and modern early warning systems. Residents there tend to normalize tidal floods as part of daily life, relying instead on personal observation or community gossip to anticipate high tides. This divergence highlights how even small differences in institutional or technological infrastructure can significantly influence resilience at the micro-community level.

3.1 Social adaptation

From a social perspective, residents in both RT 03 and RT 04 exhibit strong traditions of collective action (*gotong royong*) in response to tidal flooding. Community fund-raising to finance road elevation, with each household contributing approximately 200,000 IDR, exemplifies how solidarity remains a cornerstone of coastal resilience. This echoes findings from Danianti & Sariffuddin (2015), who argued that collective practices in Semarang's coastal villages are vital stopgaps in the absence of sustained government support. Mutual aid allows communities to mobilize resources for infrastructural improvements that would otherwise be unattainable. Yet the findings also highlight persistent ambivalence toward government intervention. While occasional aid has come in the form of BLT (direct cash transfers), *sembako* (staple food packages), and sporadic infrastructure programs, these initiatives are often viewed as insufficient or inconsistent. The frequent stalling of projects, such as seawall expansions and drainage upgrades, creates a perception of state neglect. Similar patterns are documented in other Global South contexts, where inconsistent state presence has driven communities toward self-reliance but simultaneously fostered distrust in formal institutions (Hung et al., 2024).

This tension reveals the dual nature of social adaptation: it strengthens community solidarity but risks entrenching inequities if state institutions continue to abdicate responsibility. Without consistent government involvement, collective action, though effective in the short term, cannot substitute for systemic interventions. Overreliance on communal resources places disproportionate burdens on the poorest households, who may struggle to meet communal financial contributions. Thus, while gotong royong demonstrates resilience, it also underscores the limits of social capital as a standalone adaptation strategy.

3.2 Economic adaptation

Economic adaptations manifest in households' incremental investments in housing elevation and repair. The study found that residents often elevate their houses earlier than the typical 10–12 year cycle, in response to worsening floods. This decision reflects a calculated trade-off between urgent repairs and long-term adaptation investments. Families continually juggle between immediate needs, such as replacing flood-damaged walls and structural elevation, resulting in heterogeneous housing profiles where some dwellings tower above others while adjacent homes remain low-lying. This pattern illustrates the "hidden cost of adaptation." Unlike state-led infrastructure projects, which benefit from economies of scale, household-level adaptations are piecemeal and costly. The result is a patchwork urban landscape where wealthier families achieve relative safety while poorer households remain trapped in cycles of loss. This unevenness parallels findings in Bangladesh and the Philippines, where wealthier families can afford protective measures such as house elevation or migration, while poorer households rely on temporary repairs (Ullah et al., 2025; Macusi et al., 2025). From a resilience perspective, incremental adaptation is both a strength and a weakness. It demonstrates agency and foresight, but its fragmented nature risks widening socio-economic disparities. Over time, inequality becomes spatially embedded, as better-off households create elevated enclaves while others remain increasingly exposed. Such dynamics resonate with Cutter et al. (2003) notion of "differential vulnerability," where hazards affect communities unevenly, mediated by socio-economic capacity. Unless supported by redistributive policies, such as targeted subsidies for housing retrofits, incremental adaptation may exacerbate vulnerability rather than reduce it at the community scale.

3.3 Environmental adaptation

Environmental adaptation in Tambakrejo is most visible in water access systems. Households in RT 03 and RT 04 rely primarily on small-scale, privately managed artesian wells, as PDAM water services are unreliable and prone to interruptions. Residents pay weekly fees to neighborhood entrepreneurs who maintain pumps and distribute water. This informal arrangement reflects both resilience and fragility. On the one hand, it provides households with greater autonomy over water access, reducing dependence on weak formal utilities. On the other, it creates systemic vulnerabilities: should private operators face financial instability or infrastructural damage from floods, entire neighborhoods could be left without water.

In Indonesian coastal communities, informal service provision often substitutes for failing state systems. While functional in the short term, reliance on small-scale providers can lock communities into fragile arrangements, exposing them to cascading risks during extreme climate events. Moreover, environmental adaptation in Tambakrejo extends to behavioral responses during flood events, such as relocating electronic devices to higher shelves or suspending daily mobility when roads are submerged. Residents report that morning floods are especially disruptive, delaying school attendance and work commutes. This disruption to mobility illustrates how tidal flooding extends beyond physical structures to reshape social rhythms and economic productivity.

Fig. 8. Flood in evening

Incremental environmental adaptation demonstrates community ingenuity but also underscores systemic vulnerability. Without institutional reforms in water governance and urban drainage, household-scale coping strategies remain precarious stopgaps rather than sustainable solutions.

3.4 Physical and infrastructure adaptation

Physical adaptation is the most visible form of resilience in Tambakrejo. Households elevate their homes every 10 years, but worsening flood conditions and government-driven road elevation projects often accelerate this cycle. Residents describe this as a “race” between road elevation and house elevation: once streets are raised, households must immediately follow suit to avoid being left at a lower level where water intrusion becomes inevitable. This dynamic reflects what Effiong et al. (2024) term “reactive adaptation,” where households continuously adjust to shifting baselines rather than achieving long-term stability. The process is costly, stressful, and unsustainable, particularly for low-income families. Moreover, community-led road elevation may temporarily mitigate flooding but can inadvertently exacerbate risks by creating new low points in adjacent areas, illustrating the complex feedback loops between adaptation and vulnerability.

Early warning systems also highlight disparities between RT 03 and RT 04. In RT 03, WhatsApp groups have replaced sirens, allowing residents to receive real-time alerts. However, this digital system excludes elderly residents who lack smartphone literacy, creating gaps in preparedness. RT 04 lacks such systems altogether, leaving households more exposed. These findings emphasize the need for inclusive adaptation measures that bridge technological divides, ensuring that vulnerable groups are not marginalized in the transition to digital resilience tools. Theoretical discussions of physical vulnerability emphasize its dynamic nature, shaped by the interplay between natural hazards, built environment characteristics, and socio-economic conditions. Vulnerability is not a fixed state but evolves with shifts in climate, land use, and adaptive capacity (Effiong et al., 2024;

Hung et al., 2024). This study contributes to this evolving discourse by combining granular household-level data from RT 03 and RT 04 with broader community-wide observations in Tambakrejo. The results illustrate that vulnerability is context-specific and heterogeneous, even between adjacent neighborhoods, as adaptive practices vary according to resources, social capital, and exposure levels. Such micro-level variations underscore the need for localized analyses that capture diversity within communities, rather than relying solely on aggregated or city-wide indicators.

The policy implications of these findings are both immediate and long-term. In the short term, targeted material-specific retrofit programs could significantly enhance resilience. Homes constructed with wood or non-durable concrete blocks are particularly vulnerable to saltwater corrosion and require priority attention. Incentivizing the use of more resilient construction materials and techniques would reduce structural fragility, while subsidies for vertical construction could lessen vulnerability among single-story households. In the medium to long term, such strategies would not only enhance flood resilience but also reduce the need for costly and frequent household-level retrofits. Equally urgent is the establishment of community-based early warning systems synchronized with tidal cycles. As shown in Tambakrejo, digital tools such as WhatsApp groups are already in use but are not universally accessible, particularly for elderly residents or those without smartphones. To be effective, early warning systems must therefore adopt inclusive, multi-channel approaches that combine digital and traditional communication methods (Tarchiani et al., 2020). This would ensure that preparedness is extended to all community members, including vulnerable groups that are often overlooked in resilience planning. Complementary non-structural measures, such as public education campaigns, participatory monitoring of tidal patterns, and integration of green infrastructure like mangrove restoration, provide low-cost and sustainable avenues for strengthening adaptive capacity while generating co-benefits for local ecosystems.

At the governance level, one of the most pressing challenges is bridging the gap between community initiatives and government programs. The persistence of stalled or incomplete projects, such as seawall extensions and drainage improvements, highlights institutional weaknesses that erode public trust. This fragmentation reflects deeper structural issues in governance, where bureaucratic inertia, limited resources, and poor inter-agency coordination undermine the effectiveness of planned interventions. Strengthening collaboration between municipal governments, NGOs, private stakeholders, and local community organizations is therefore essential. Such coordination would foster more comprehensive and equitable flood management strategies, ensuring that grassroots initiatives are complemented, rather than substituted, by formal interventions. Despite its contributions, this study acknowledges several limitations. The reliance on surveys and interviews, while yielding rich qualitative detail, is labor-intensive and challenging to scale. Household registry data in RT 03 and RT 04 had not been fully updated in three years, producing potential gaps in socio-economic profiling. Moreover, the vulnerability assessment conducted here remains largely static, capturing conditions at a single point in time rather than reflecting dynamic processes such as seasonal tidal variability, progressive land subsidence, or projected climate change impacts.

Future research should therefore move beyond vulnerability to address comprehensive risk, defined as the interaction of hazard, exposure, and vulnerability. In North Semarang, this would require the integration of UAV (unmanned aerial vehicle) technologies, remote sensing, and advanced spatial-statistical modeling (Fariz et al., 2023b; Albano et al., 2024; Yu et al, 2024). These methods allow researchers to capture the temporal and spatial variability of hazards with greater precision, extending coverage while maintaining household-scale detail. Such approaches would also facilitate scenario modeling, enabling policymakers to anticipate future risks under different climate and development pathways.

Ultimately, the findings from Tambakrejo highlight the complex interplay of tidal dynamics, aging infrastructure, economic constraints, and community-led adaptation. Incremental measures, such as house and road elevation, reliance on informal water systems, and digital early warning mechanisms, have helped reduce risks but remain inadequate in the face of persistent land subsidence and climate change. Building long-term resilience in Semarang Utara requires a comprehensive and multidisciplinary approach. This includes integrating structural and non-structural strategies, strengthening collaboration between governments and communities, and adopting adaptive management frameworks that are flexible to evolving climatic and socio-economic conditions. Only through such proactive and cohesive interventions can tidal flood resilience in coastal Semarang be secured, preventing fragmented, short-term responses from perpetuating cycles of vulnerability.

4. Conclusions

This study reveals critical insights into the physical vulnerability of households to tidal flooding in Tambakrejo, Semarang Utara. The findings demonstrate that while brick structures dominate the area and exhibit lower vulnerability due to their water-resistant properties, the majority of homes remain at moderate risk due to compounding factors such as aging infrastructure, insufficient floor elevation, and single-story designs. Notably, older buildings (over 20 years) suffer accelerated deterioration from saltwater exposure, exacerbating their susceptibility to flood damage. The research highlights that floor height and building elevation are decisive factors in mitigating flood impacts, yet economic constraints limit most residents from implementing optimal adaptations. A key contribution of this study is its household-scale vulnerability assessment, which uncovers micro-level risk patterns often overlooked in broader analyses. The concentration of high-vulnerability homes in low-lying coastal zones underscores the urgent need for targeted interventions, particularly for economically disadvantaged households reliant on flood-prone informal sectors. While community-driven adaptations, such as incremental floor elevation, demonstrate local resilience, systemic solutions integrating material upgrades, multi-story housing incentives, and improved drainage infrastructure are essential for long-term risk reduction. These findings provide a scientific foundation for policymakers to prioritize context-specific flood mitigation strategies in vulnerable coastal settlements.

Adaptation practices observed in Tambakrejo, particularly in RT 03 and RT 04, reflect how communities have normalized tidal flooding as a routine challenge. Although residents perceive flooding as “common,” it nevertheless disrupts daily activities, mobility, and livelihoods. Collective strategies such as community-led road elevation, carried out through kerja bakti and supported by communal financial contributions, highlight the role of local solidarity in managing risks. At the household level, incremental house elevation serves as an individual adaptation measure, though it often requires substantial financial resources that many families struggle to afford. These community and individual adaptations illustrate a layered resilience, yet they remain temporary and unevenly distributed. Without broader structural support, households with limited economic capacity will remain trapped in cycles of vulnerability. Thus, long-term resilience in Semarang Utara requires an integrated approach that bridges grassroots adaptation with formal urban planning and policy interventions.

Acknowledgement
The authors would like to thank the IASSSF team for supporting the writing of this research.

Author Contribution
All contributed fully to the writing of this article.

Funding
This research received no external funding.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

Not available.

Conflicts of Interest

The authors declare no conflict of interest.

Open Access

References

Afifah, S., & Hizbaron, D. (2020). Vulnerability assessment of residential buildings to tidal flood hazards in Sriwulan Village, Sayung District, Demak Regency. *E3S Web of Conferences, 200,* 01008. https://doi.org/10.1051/e3sconf/202020001008

Albano, R., Limongi, C., Dal Sasso, S. F., Mancusi, L., & Adamowski, J. (2024). Flood scenario spatio-temporal mapping via hydrological and hydrodynamic modelling and a remote sensing dataset: A case study of the Basento river (Southern Italy). *International Journal of Disaster Risk Reduction, 111,* 104758. https://doi.org/10.1016/j.ijdrr.2024.104758

Aprijanto, Prijambodo, T., Wibawa, B., Fithor, A., Santoso, M. A., Irfani, M., ... & Sukmana, C. I. (2025). Innovative strategies for tidal flood protection: A systematic literature review on spatial management in coastal city (case study: Semarang City, Central Java, Indonesia). *Marine Systems & Ocean Technology, 20*(1), 9. https://doi.org/10.1007/s40868-024-00158-5

Arif, D. A., Mardiatno, D., & Giyarsih, S. R. (2017). Kerentanan masyarakat perkotaan terhadap bahaya banjir di Kelurahan Legok Kecamatan Telanipura Kota Jambi. *Majalah Geografi Indonesia, 31*(2), 139–148. https://doi.org/10.22146/mgi.29779

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., ... & Hauser, M. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6).* IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647

Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003). Social vulnerability to environmental hazards. *Social Science Quarterly, 84*(2), 242–261. https://doi.org/10.1111/1540-6237.8402002

Danianti, R. P., & Sariffuddin. (2015). Tingkat kerentanan masyarakat terhadap bencana banjir di Perumnas Tlogosari, Kota Semarang. *Jurnal Pengembangan Kota*, 3(2), 90–99. https://doi.org/10.14710/jpk.3.2.90-99

Dunning, M. C., & Durden, S. (2013). *Social vulnerability analysis: A comparison of tools.* IWR White Paper. U.S. Army Corps of Engineers. http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/Social_Vulnerability_Analysis_Tools.pdf

Effiong, C., Ngang, E., & Ekott, I. (2024). Land use planning and climate change adaptation in river-dependent communities in Nigeria. *Environmental Development, 49,* 100970. https://doi.org/10.1016/j.envdev.2024.100970

Esariti, L., Handayani, W., & Purnomo, M. S. (2024). Vulnerability assessment of tidal flood prone disaster settlement of Muarareja Tegal. *IOP Conference Series: Earth and Environmental Science, 1394*(1), 012036. https://doi.org/10.1088/1755-1315/1394/1/012036

Fariz, T. R., Jatmiko, R. H., & Mei, E. T. W. (2023a). Pemanfaatan foto udara UAV untuk pemetaan kerentanan fisik rumah terhadap longsor di Sub-DAS Bompon. *Jurnal Ilmu Lingkungan, 21*(4), 819–829. https://doi.org/10.14710/jil.21.4.819-829

Fariz, T. R., Jatmiko, R. H., Mei, E. T. W., & Lutfiananda, F. (2023b). Interpretation on aerial photography for house identification on landslide area at Bompon sub-watershed. *AIP Conference Proceedings, 2683*(1), 050004. https://doi.org/10.1063/5.0125382

Fariz, T. R., Nugraha, F. A., Putra, G. A. Y., Nugroho, A. A., Salima, D. R., Pradiny, L. E., & Mubarizi, E. F. (2022). Kajian kapasitas masyarakat berbasis aset penghidupan terhadap bencana kekeringan. *LaGeografia, 21*(1), 31–43. https://doi.org/10.35580/lageografia.v21i1.37174

Fitria, L. M., Ni'mah, N. M., & Danu, L. K. (2019). Kerentanan fisik terhadap bencana banjir di kawasan perkotaan Yogyakarta. *Reka Ruang, 2*(1), 1–9. https://doi.org/10.33579/rkr.v2i1.1048

Huda, M. N., Nirmala, R. J., & Yusuf, I. M. (2024). Policy incoherence and reactive approaches: Barriers to effective management of land subsidence in Semarang City, Indonesia. *Jurnal Ilmu Sosial, 23*(1), 1–16. https://doi.org/10.14710/jssis.2024.39228

Hung, C. H., Hung, H. C., & Hsu, M. C. (2024). Linking the interplay of resilience, vulnerability, and adaptation to long-term changes in metropolitan spaces for climate-related disaster risk management. *Climate Risk Management, 44,* 100618. https://doi.org/10.1016/j.crm.2024.100618

Jabbar, A., Fariz, T. R., Putri, S. D., Rahmawati, D., Prahmani, Y. S., Putri, R. A., ... & Chasanah, A. N. (2023). Tidal flood susceptibility mapping and community adaptation assessment in Semarang Utara District. *Journal of Environmental and Science Education, 3*(1), 56–62. https://doi.org/10.15294/jese.v3i1.64910

Juniarti, T., Hendarso, Y., & Soraida, S. (2021). Peran pembimbing kemasyarakatan dalam pembimbingan dan pengawasan klien selama menjalani masa integrasi di BAPAS Kelas 1 Palembang. *Jurnal Media Sosiologi, 24*(1), 12–20. https://doi.org/10.47753/jms.v24i1.74

Macusi, E. D., Diampon, D. O., & Macusi, E. S. (2025). Understanding vulnerability and building resilience in small-scale fisheries: The case of Davao Gulf, Philippines. *Climate Policy, 25*(1), 1–14. https://doi.org/10.1080/14693062.2023.2261889

Moloney, S., & Fünfgeld, H. (2015). Emergent processes of adaptive capacity building: Local government climate change alliances and networks in Melbourne. *Urban Climate, 14,* 30–40. https://doi.org/10.1016/j.uclim.2015.06.009

Naja, D. A., & Mardiatno, D. (2017). Analisis kerentanan fisik permukiman di kawasan rawan bencana tsunami wilayah Parangtritis, Yogyakarta. *Jurnal Bumi Indonesia, 7*(1), 1–12. https://doi.org/10.31227/osf.io/228864

Pamekas, E. B. Z., & Poli, J. O. W. H. (2019). Adaptasi masyarakat bantaran sungai terhadap banjir di Kelurahan Pakowa Kota Manado. *Spasial, 6*(2), 482–492. https://ejournal.unsrat.ac.id/v3/index.php/spasial/article/view/25330

Peduzzi, P. (2019). The disaster risk, global change, and sustainability nexus. *Sustainability, 11*(4), 957. https://doi.org/10.3390/su11040957

Pradika, M. I. (2012). Kajian risiko tsunami terhadap bangunan gedung non-hunian dengan aplikasi PJ dan SIG di Kota Pacitan. *Jurnal Bumi Indonesia, 1*(3), 1–12.

Rahmawati, L., & Setiawan, D. (2019). Dinamika sosial ekonomi masyarakat perkotaan: Studi kasus Kelurahan Tambak Rejo, Semarang. *Jurnal Ilmu Sosial dan Humaniora, 8*(1), 75–90.

Saputri, A. D., & Linda, A. M. (2023). Government policies in addressing land subsidence dynamics in Tambakrejo Semarang. *Riwayat: Educational Journal of History and Humanities, 6*(1), 133–143. https://doi.org/10.56370/jhlg.v4i3.356

Subasinghe, C., & Kawasaki, A. (2021). Assessment of physical vulnerability of buildings and socio-economic vulnerability of residents to rainfall induced cut slope failures: A case study in central highlands, Sri Lanka. *International Journal of Disaster Risk Reduction, 65,* 102550. https://doi.org/10.1016/j.ijdrr.2021.102550

Suherman, H., Setianingsih, A., & Toha, R. (2023). Analysis of social vulnerability to rob floods in North Semarang District. *Jurnal Pendidikan Geografi Undiksha, 11,* 179–187. https://doi.org/10.23887/jjpg.v11i2.59398

Syafitri, A. W., & Rochani, A. (2022). Analisis penyebab banjir rob di kawasan pesisir (Jakarta Utara, Semarang Timur, Kabupaten Brebes, Pekalongan). *Jurnal Kajian Ruang, 1*(1), 16–24. https://doi.org/10.30659/jkr.v1i1.19975

Tarchiani, V., Massazza, G., Rosso, M., Tiepolo, M., Pezzoli, A., Ibrahim, M. H., ... & Rapisardi, E. (2020). Community and impact based early warning system for flood risk preparedness: The experience of the Sirba River in Niger. *Sustainability, 12*(5), 1802. https://doi.org/10.3390/su12051802

Utomo, D. D., & Marta, F. Y. D. (2022). Dampak bencana alam terhadap perekonomian masyarakat di Kabupaten Tanah Datar. *Jurnal Terapan Pemerintahan Minangkabau, 2*(1), 92–97. https://doi.org/10.33701/jtpm.v2i1.2395

Ullah, W., Dong, H., Shah, A. A., Xu, C., & Alotaibi, B. A. (2025). Unveiling the multi-dimensional vulnerabilities of flood-affected communities in Khyber Pakhtunkhwa, Pakistan. *Water, 17*(2), 198. https://doi.org/10.3390/w17020198

UNISDR. (2015). *Global assessment report on disaster risk reduction 2015.* United Nations Office for Disaster Risk Reduction. https://www.preventionweb.net/gar

Young, A. F. (2014). Coastal megacities, environmental hazards and global environmental change. In M. Pelling & S. Blackburn (Eds.), *Megacities and the coast* (pp. 70–99). Routledge. https://doi.org/10.4324/9780203066423-14

Yu, L., Qin, H., Huang, S., Wei, W., Jiang, H., & Mu, L. (2024). Quantitative study of storm surge risk assessment in an undeveloped coastal area of China based on deep learning and GIS: A case study of Double Moon Bay. *Natural Hazards and Earth System Sciences, 24*(6), 2003–2024. https://doi.org/10.5194/nhess-24-2003-2024

Yuliastuti, N. (2023). Social vulnerability level appraisal at tidal flood areas: The case of a coastal settlement in Indonesia. *International Review for Spatial Planning and Sustainable Development, 11*(2), 99–113. https://doi.org/10.14246/irspsd.11.2_99

Biographies of Authors

Trida Ridho Fariz, Environmental Science Study Program, Faculty of Science, Universitas Negeri Semarang, Semarang, Central Java 50229, Indonesia.

- Email: trida.ridho.fariz@mail.unnes.ac.id
- ORCID: 0000-0002-3943-0089
- Web of Science ResearcherID: N/A
- Scopus Author ID: 57576594500
- Homepage: https://scholar.google.com/citations?user= 25XaPcAAAAJ&hl=id

Taufik Bahrul Rizky, Environmental Science Study Program, Faculty of Science, Universitas Negeri Semarang, Semarang, Central Java 50229, Indonesia.

- Email: taufikbr13@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: https://id.linkedin.com/in/taufikbahrulr

Vera Angelina Holeng, Environmental Science Study Program, Faculty of Science, Universitas Negeri Semarang, Semarang, Central Java 50229, Indonesia.

- Email: verangelina7@students.unnes.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Meilinda Damayanti, Environmental Science Study Program, School of Environmental Science and Management, University of the Philippines Los Baños, Los Baños, Laguna 4031, Philippines.

- Email: mdamayanti@up.edu.ph
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Andhina Putri Heriyanti, Environmental Science Study Program, Faculty of Science, Universitas Negeri Semarang, Semarang, Central Java 50229, Indonesia.

- Email: andhinaputri@mail.unnes.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: 57211884217
- Homepage: https://scholar.google.com/citations?user=uLLWem4AAAAJ&hl=en