Housing Conditions and Site Planning for Flood Vulnerability at the Bingai River Border

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Abstract

The Bingai River border in Binjai City shows an increase in the frequency and depth of inundation which exacerbates the vulnerability of riverside settlements. This study examines how residential conditions and site arrangement (setback, floor elevation, land permeability, drainage, riparian vegetation, and evacuation access) contribute to flood vulnerability, as well as formulate improvement strategies based on SWOT analysis.

Descriptive research was conducted on several border segments with a combination of structured field observations, brief interviews with residents, and inundation maps/drainage networks. Audit indicators include residential typology, floor elevation to ground level, distance of buildings from the river bank, channel type and depth, surface cover/permeability, continuity of riparian vegetation, and availability of evacuation routes. Data were tabulated, mapped simply, and assessed against a matrix of vulnerability (exposure–sensitivity–adaptive capacity). Key findings are then mapped to internal (strengths-weaknesses) and external (opportunities-threats) factors to formulate a TOWS strategy.

The highest vulnerability is concentrated on dense banks with building distances near riverbanks, low floor elevations, shallow/dysfunctional channels, impermeable land surfaces, and disconnected riparian vegetation. A stage or raised floor residence shows better performance than a single-story residence without elevation. The adaptive capacity of communities is relatively aided by social networks and repeated flood experiences, but has not been offset by adequate site planning standards and microinfrastructure.

Flood vulnerability at the border is strongly influenced by micro-decisions at the site scale. Strategic priorities include: (1) rearrangement of setbacks according to border regulations along with riparian green corridors, (2) elevation of floors/stilts and protection of water entry points, (3) rehabilitation of environmental drainage and improvement of permeability (infiltration wells, porous pavement), (4) continuity of riparian vegetation as a buffer of surface flow, and (5) arrangement of evacuation routes and community-based early warnings. The integration of physical-footprint interventions with strengthening the capacity of residents is the key to reducing the risk of flooding in the Bingai River.

Keywords: *River Borders, Flood Vulnerability, Housing, Site Planning, SWOT, Binjai*

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Introduction

The frequency and intensity of heavy rains in Southeast Asia are projected to increase in the middle of the 21st century, increasing the risk of urban flooding – including in Indonesia. The climate risk framework also emphasizes that the impact of flooding is determined by a combination of hazard, exposure, and vulnerability (exposure–sensitivity–adaptive capacity) [1]. Locally, Binjai City has repeatedly experienced floods; on September 9, 2024, hundreds of houses were submerged, and on January 13, 2025, floods occurred again as the discharge of several rivers in Binjai, including the Bingai River, increased. Official disaster records confirm the scale of household/life impact and significant inundation heights [2], [3]. In terms of spatial planning, Indonesia has a regulatory umbrella regarding rivers and boundary lines to maintain the natural function of flows, but the implementation of its determination/control in urban areas is often weak [4], [5]. At the site scale, microdesign decisions—finished floor elevation, distance of buildings from riverbanks, impermeable surface proportions, environmental drainage performance, and sustainability of riparian vegetation—greatly affect the amount of runoff and vulnerability of habitation. Technical evidence suggests porous pavement is able to meaningfully lower runoff peaks, while strategic planting of riparian vegetation can dampen stream energy and lower the risk of flooding [6], [7].

In the context of residential-based adaptation, the typology of stilt houses—both in local wisdom and the application of contemporary adaptive design—has proven to be relevant for reducing damage during floods through floor/basement elevation and opening protection [8], [9]. Residential segments along the Bingai River border show typical symptoms of vulnerability: some buildings are near the riverbank (minimal setback), low floor elevation, high impermeable surface area, shallow/clogged environmental drainage, and disconnected riparian vegetation—leading to recurrent inundation during extreme rains. This condition is exacerbated by the increase in flooding incidents in the city of Binjai in the last two years [2], [3], [1]. On the institutional side, IoT-based flood early warning system initiatives have been studied/piloted for Binjai, but operational readiness—including digital infrastructure and human resources—remains a challenge, so structural adaptation at the site level remains crucial [10], [11]. In addition, the implementation and enforcement of boundary lines as riparian protected corridors—which are normatively mandatory—has not been consistent in congested areas, even though these corridors are important for absorption space, maintenance access, and safety [5], [4]. This study aims to: (1) Diagnose the relationship between residential conditions and site arrangement (setback, floor elevation, surface permeability, drainage performance, riparian vegetation, evacuation access) with the level of flood vulnerability at the Bingai River border. (2) Assess vulnerability with exposure–sensitivity–adaptive capacity lenses based on field indicator audits and simple mapping [1]. (3) Formulate a priority strategy based on SWOT Analysis that is in line with border regulations and green engineering practices (porous pavement, riparian vegetation, floor elevation/stilt house) to reduce the risk of residential flooding on the banks of the Bingai River [5]–[9].

Literature Review

This literature review outlines theoretical foundations, policies, and empirical findings that are relevant in understanding urban flood risk, river boundary policies, as well as residential site determinants and vulnerability assessment approaches. In addition, this section also reviews the use of open spatial data in the analysis of riverbank areas in Indonesia.

2.1 Theoretical figures for urban flooding and climate risk

Flooding in urban areas is the result of a complex interaction between hydrometeorological hazards, asset exposure, and socio-ecological vulnerability. The IPCC AR6 (WGII, Chapter 10) shows an increase in the incidence of heavy rainfall in parts of Asia, as well as a projected intensification of extreme rainfall in Southeast Asia in the middle of the 21st century [12]. This increase has implications for the increasing frequency of flooding in cities with high density and vulnerable infrastructure. Modern climate risk frameworks link hazard–exposure–vulnerability/adaptive capacity elements, so that risk reduction efforts include not only technical-hydrological interventions, but also strengthening social capacity and spatial planning at the site level and riparian corridors [1], [12].

2.2 River boundary Policy in Indonesia

Regulatively, river management in Indonesia is based on Government Regulation No. 38 of 2011 concerning Rivers and Regulation of the Minister of PUPR No. 28/PRT/M/2015 which requires the determination of boundary lines as protected corridors and maintenance service spaces [4], [5]. This provision aims to maintain ecological, hydraulic, and safety functions along the river channel. However, in practice, implementation in densely populated urban areas is often constrained by limited land and weak enforcement, so that riparian protection functions are often not optimal [5].

2.3 Site Determinants and Adaptation of Residential Scalen

Micro footprint design plays an important role in determining the level of flood risk in riverbank dwellings. Factors such as the distance of buildings from the riverbank (setback), floor elevation, proportion of porous vs watertight surfaces, environmental drainage performance, and sustainability of riparian vegetation contribute directly to the size of runoff and inundation depth [6], [7].

International guidelines such as ASCE 24-14 and FEMA P-312 emphasize the importance of minimum floor elevation, flood openings, as well as the use of waterproof materials for buildings in vulnerable zones [13], [14]. The Sustainable Drainage Systems (SuDS)-based approach encourages the application of green technologies such as porous pavement and continuous riparian vegetation that are able to improve hydraulic roughness and retain flow energy [7], [15].

2.4 Vulnerability Index and Assessment Approach

The assessment of residential flood vulnerability draws heavily on the study of integrated socio-ecological systems by Turner et al. [16] and the development of social vulnerability indices by Cutter et al. [17], which are the basis of various studies of environmental disasters. In practical contexts, physical, environmental, and social indicators are often combined in the Analytic Hierarchy Process (AHP) model to produce a composite index with consistency control ($CR \leq 0.10$) [18].

The results of this assessment are then associated with a SWOT analysis to formulate adaptation strategies based on internal and external factors, so that each field finding can be translated into applicable adaptive actions [19].

2.5 Open Spatial Mapping and Data for Shoreline Studies

In the context of mapping riverside settlements, OpenStreetMap (OSM) and Humanitarian OpenStreetMap Team (HOT) data have been widely used to assess setback distances and building density [20]. However, the completeness of this dataset varies between regions, so field validation is needed to ensure accuracy.

The Indonesian OSM building datasets available on the Humanitarian Data Exchange (HDX) and LP-DAAC (USGS) can be combined with elevation data (DEM) to map inundation-prone areas spatially [20], [21].

Research Methodology

This study uses a descriptive-evaluative design focused on residential segments on the border of Sungai Bingai, Binjai City, which have experienced repeated floods. This approach aims to describe the actual condition of the site and habitation while evaluating the factors that cause vulnerability to flooding. The analytical framework of the study follows the paradigm of risk = hazard × exposure × vulnerability/capacity as used by the IPCC and UNDRR [1], [12], [22], which links the physical attributes of the site and residential characteristics with the level of flood vulnerability at the micro (site/house) and meso (riparian area) scales. The research data consists of primary data and secondary data. Primary data was obtained through a structured residential site audit, including observations of facades, yards, floor elevation, riparian vegetation, and environmental drainage conditions. In addition, a short interview lasting less than ten minutes was conducted with household representatives to obtain information related to the history of inundation, flood frequency, and evacuation routes. The selection of field audit indicators refers to the literature on vulnerability and adaptation of flooded settlements [16], [17], [14], which emphasizes three main dimensions of vulnerability, namely exposure, sensitivity, and adaptive capacity. Meanwhile, secondary data includes rainfall data and climatological analysis from BMKG which are used to understand the context of flood events [23]; surface elevation data or Digital Elevation Model (DEM) SRTM 30 m from USGS LP-DAAC as the basis for regional topographic analysis [21]; and spatial data in the form of building footprints from OpenStreetMap (OSM/HOT-OSM) for mapping building density, setback distance, and relationship between riverbanks and buildings [20]. In addition, the study also uses regulatory documents and spatial planning plans as a reference for river boundary management policies [4], [5].

The study segment was selected by purposive sampling based on three main criteria, namely having experienced significant flooding, being close to the riverbank, and having adequate field access. Within each segment, observations of houses or kaplings were carried out by systematic sampling using constant intervals from random starting points to maintain spatial representation and avoid location bias [24], [25]. The analysis was carried out quantitatively-descriptively by arranging field findings into internal and external factors. Internal factors include strengths and weaknesses related to the condition of sites and buildings, while external factors include opportunities and threats stemming from boundary policies, hydrological dynamics, and urban infrastructure programs. The results of the two groups of factors were then analyzed using a SWOT matrix to formulate adaptation strategies which were categorized into four strategy groups, namely strength-opportunity (SO), weakness-opportunity (WO), strength-threat (ST), and weakness-threat (WT) [19]. The results of the final analysis are presented in the form of thematic maps and narrative descriptions that illustrate the relationship between the characteristics of residential sites and the level of flood vulnerability in the Bingai River area as well as the direction of adaptation strategies that can be applied to reduce risks in the future.

Results

The results of this study explain the actual condition of the Bingai River border area in Binjai City based on site-dwelling audits, spatial analysis, and flood vulnerability index calculations. This analysis was then followed up by the preparation of an adaptation strategy through a SWOT matrix based on empirical findings in the field.

Based on a structured visual audit and preliminary mapping, a number of relatively consistent vulnerability patterns were obtained between segments. In dense segments such as [A] and [B], the majority of buildings have a setback of less than 10 meters from the river bank, and some clusters are even below 5 meters away. This condition indicates the limitation of border space that should function as a protected corridor. Meanwhile, in segment [C], there are some units with higher floor elevations (stilt houses or multi-storey floors), which have been shown to have a lower level of damage after the last flood. These findings are in line with the recommendations of flood-resistant construction guidelines issued by ASCE and FEMA, which emphasize the elevation of flood-free floors and the use of waterproof materials [13], [14].

The proportion of watertight surfaces such as hard pavements and permanent buildings is relatively high in most access roads and front yards. Areas with porous surfaces are still very limited, so rainwater runoff tends to flow directly into the environmental channels without an infiltration process. The condition is exacerbated by shallow and sedimented drainage systems, with many obstacles at the mouth of the culvert. Backflow often occurs during intense rain, especially on sections with small slopes. Riparian vegetation shows a fragmented pattern at a range of 40–120 meters, with open river banks and clear erosion trails. On the other hand, evacuation access in most RTs only has one to two lanes with several obstacles in the form of parking or utility installations. Evacuation signage is still inconsistent between neighborhoods.

The results of the vulnerability index (V) calculation using two weighting scenarios—equivalent and the Analytic Hierarchy Process (AHP)—show a consistent distribution between subjective and objective approaches. Segment [A] was categorized as having high vulnerability ($V = 0.71$ equivalent; 0.73 AHP), which was caused by minimal setback, low floor elevation, poorly functioning drainage channels, and a very large proportion of impermeable surfaces. Segment [B] is in the medium category ($V = 0.59$ equivalent; 0.56 AHP), with major weaknesses in the drainage and fragmentation aspects of riparian vegetation. Meanwhile, the [C] segment has low–medium susceptibility ($V = 0.38$ equivalent; 0.41 AHP), supported by the presence of more continuous riparian vegetation and some stilt houses that function as natural mitigation. The difference in values between scenarios was relatively small (median ΔV 0.02–0.05), which indicates the consistency and stability of the assessment between methods.

The field analysis also reveals a number of strengths, weaknesses, opportunities, and threats factors that are then synthesized in a SWOT framework. The main strengths identified include a strong social network of citizens, the presence of several pockets of riparian vegetation, as well as the slightly higher local topography of the segment [C]. In contrast, the dominant weaknesses include very minimal setbacks, low floor elevations, shallow or clogged drainage systems, high proportion of impermeable surfaces, and obstructed evacuation routes. In terms of opportunities, there is policy support through the Minister of Public Works and Public Works Regulation No. 28/PRT/M/2015 which opens up space for river boundary rearrangement, opportunities for the implementation of site-scale Sustainable Drainage Systems (SuDS) such as infiltration wells and porous pavement [15], as well as riparian rehabilitation and environmental drainage programs from local governments. The main threats stem from the projected increase in short-duration intense rainfall as reported by the IPCC [1], the potential for repeated overflows from the Bingai River, and the increasing pressure on development in the coastal areas.

The synthesis of the four components is summarized in the following SWOT Matrix which is the basis for the formulation of structural and non-structural adaptation strategies in the Bingai River border area.

Table 1. SWOT Matrix for Housing and Site Adaptation at the Bingai River Border

Internal/External Factors	*Opportunities (O) Policy, Rehabilitation Programs, Implementation Of Suds, Community Support*	*Threats (T) Extreme Rain, River Overflow, Development Pressure*
Strengths(S) ***Strong Social Networks, Residual Riparian Vegetation, Relatively High Topography***	**SO Strategy**: Restore riparian green corridors in a sustainable manner by utilizing existing vegetation pockets and combining them with the application of porous pavement in residential access.	**ST Strategy**: Protect the riverbank with bioengineering techniques through vegetative revetment of sections with active erosion and prepare clear and safe evacuation routes.
Weaknesses (W) ***Minimal Setback, Low Elevation, Clogged Drainage, High Sealing Surface***	**WO Strategy**: Selectively rearrange setbacks in the most congested areas, increase floor elevation with a stilt house system, and normalize micro channels for optimal hydraulic function.	**WT Strategy**: Implement a moratorium on new construction in areas with minimal setbacks and implement a phased retrofit program on existing dwellings using waterproof materials and adaptive flood openings.

Source : Summary of Results by the author, 2025

Based on these results, the proposed priority adaptation strategy is to increase the ecological capacity of riparian corridors and rehabilitate environmental drainage as the main step to reduce flood risk. The implementation of porous pavements and adaptive stilt houses in priority areas can reduce the potential for inundation, while social interventions such as the provision of evacuation routes and preparedness education can strengthen community capacity in dealing with extreme events. This approach is in line with the *ecosystem-based adaptation* framework recommended by the IPCC and UNDRR [1], [22], and can be a model for the implementation of community-based adaptation in high-risk urban areas.

Determination of vulnerability at the footprint scale suggests that the pattern of high vulnerability in Segment [A] is consistent with the literature confirming the role of micro-decisions—such as setback, floor elevation, impermeable surface proportion, drainage conditions, and riparian vegetation continuity—as the primary controller of flood outcomes at the residential level [14], [13], [15]. FEMA Guideline P-312 recommends *freeboarding* and flood opening to reduce structural damage and building contents, especially in the event of rapid runoff [14]. The ASCE 24-14 standard also emphasizes the importance of elevation and flood-resistant materials in vulnerable zones, which is particularly relevant for *ground-level residential units* on the banks of the Bingai River [13].

Findings related to the effectiveness of permeability and vegetation interventions show that a high proportion of impermeable surfaces correlates with lawn inundation and increased channel load. This is in line with empirical evidence that porous pavement is able to reduce the peak of runoff and inundation depth in intense rainfall [6]. On the riparian corridor side, vegetation continuity plays a role in increasing hydraulic roughness and dampening *out-of-bank* flows while reducing riverbank erosion [7]. Thus, Sustainable Drainage Systems (SuDS) strategies at the site scale—such as infiltration wells, porous pavement, and *bed infiltration*—combined with sustainable riparian vegetation restoration, have been proven effective in reducing sensitivity and *exposure* components to flood risk [15], [6], [7].

In terms of the conformity of the border policy, the main weakness is in the form of minimal setback in dealing with the obligation to determine the boundary line as stipulated in Government Regulation No. 38/2011 and the Minister of Public Works and Public Works Regulation No. 28/PRT/M/2015 [4], [5]. Consistent implementation of these provisions opens up opportunities for building repositioning, the establishment of maintenance green corridors, and increased safety access—an important component of dense shoreline areas. In the urban context, the scenario of selective rearrangement through *micro-readjustment*, limited release, or *co-design* of shared spaces is considered more realistic than total relocation.

From a climate risk perspective, the short-duration intensity of extreme rainfall projected in AR6 has the potential to increase the frequency of urban flooding in Southeast Asia [1]. Therefore, the adaptation of the footprint scale is an urgent need that must run in parallel with increasing macro drainage capacity. In the *framework of hazard–exposure–vulnerability*, interventions such as floor elevation, increased permeability, restoration of riparian vegetation, drainage improvement, and setback management play a direct role in reducing *exposure* and *sensitivity* while strengthening *adaptive capacity* [1], [22].

The methodological limitation of this study lies in its dependence on open spatial data. Initial mapping uses OpenStreetMap (OSM/HOT) to trace the footprint of buildings, but the level of completeness of the data varies between regions so that the interpretation of setback and density needs to be validated by field surveys [20], [27]. In addition, the 30 m SRTM DEM has a medium resolution, so microstream analysis and river-channel interactions require more detailed topographic data or additional elevation surveys [21]. Nonetheless, the consistency of priority rankings between weighting scenarios (equivalent vs. AHP) indicates adequate initial assessment robustness to compile the SWOT matrix as well as its implementation stages.

The practical implications of the results of the SWOT analysis can be described as follows. Priority zones that have a setback of less than 5–10 m with low floor elevation and shallow drainage require retrofit strategies in the form of flood openings, floor elevation, application of SuDS (porous pavement or infiltration wells), and cleaning and deepening of channels. Riparian corridors need to be strengthened through the extension of riparian canopy and shrubs to improve flow suppression and stabilization of river banks [7]. In terms of policy, it is important to synergize physical intervention packages at the site level with the enforcement of boundary lines as stipulated in the Minister of Public Works and Public Works Regulation No. 28/2015, as well as educate the public about adaptive housing techniques [14], [13]. In the context of climate adaptation, taking into account AR6 projections, it is necessary to design *adaptive freeboards* and minimum permeability standards on the RT/RW scale to anticipate increased rainfall intensity [26], [15].

Conclusion

Flood vulnerability in the Sungai Bingai border area It is mainly determined by design decisions at the scale of the site. The highest risk is found on dense banks with a distance of less than 5–10 meters from buildings to the riverbank, low ground floor elevations, high impermeable surfaces, shallow or clogged drainage, and fragmented riparian vegetation. These conditions increase exposure, slow down infiltration, and weaken the natural protective function of rivers. In contrast, stage dwellings with higher floor elevations and more continuous riparian vegetation showed lower damage during flooding. The calculation of the vulnerability index showed stable results between equivalent weighting and AHP ($\Delta V \approx 0.02$–0.05), confirming that the inter-segment priority pattern was consistent and valid. Border governance is a key factor: weak enforcement of border lines limits the functioning of green corridors and safety spaces. Even so, there is a "no-regret" intervention package that can be implemented immediately, namely floor elevation, the implementation of simple SuDS (porous pavement and infiltration wells), drainage normalization, and restoration of riparian vegetation to reduce exposure and sensitivity while strengthening adaptive capacity. Although the spatial data still have limitations (moderate DEM resolution and OSM completeness vary), the results of the analysis still show a consistent direction of intervention. Local validation through rapid surveys and participatory mapping can refine technical details without changing top priorities.

Suggestions and recommendations for improvement directions at the research site are directed first to improvement efforts that need to be focused on the highest risk pockets—particularly residences with a setback of less than 10 meters, low ground floors, and critical drainage in Segment [A]. The physical arrangement of the site must go hand in hand with strengthening community capacity, through the establishment of evacuation routes, periodic exercises, and community-based early warning systems.

Each unit is recommended to have a freeboard of at least 50–100 cm from the reference flood water level, with flood openings in the building plinth and waterproof materials to a safe height. Permeable surfaces are increased to a minimum of 40% per cabin, while RT/RW access roads apply porous pavement of at least 20–30%. Environmental drainage is normalized through cleaning, deepening, and installation of check valves at backflow prone points, with a regular operation and maintenance schedule.

The riparian corridor is reinforced with locally rooted vegetation in a 10–20 meter wide green zone, using bioengineering approaches such as vegetative revetment to stabilize the cliffs. A permanent evacuation route is provided at least two per RT, free of obstacles, with a simple early warning system and regular exercises.

Local governance strengthens all of the above efforts through border enforcement, RT rules on permeable quotas, prohibitions on construction in minimum border zones, and small financing (permeable material grants, light microfinance) for home retrofits. Implementation is carried out in stages—starting from normalization of drainage and socialization in 0–6 months, expansion of retrofits and formation of green corridors in 6–18 months, to consolidation and monitoring of performance indicators at 18–36 months.

Success indicators include increasing the proportion of dwellings with freeboards ≥50 cm, permeable surface area ≥40%, length of connected riparian corridors, compliance with maintenance schedules, and the number of functional evacuation routes. For further research, it is recommended to use high-resolution topographic data, hydrological–hydraulic 2D modeling, and evaluation of the effectiveness of social-based adaptation to make aid priorities more equitable and efficient.

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