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Original Article

Adaptive Morphologies of Stilt Settlements in Flood Prone of Sempaja, Samarinda Indonesia

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Abstract *- This study investigates the morphological evolution and adaptation strategies of stilt-house settlements in the flood-prone of Sempaja, Samarinda, Indonesia. Combining spatial GIS analysis, field surveys, and socio-economic assessments, the study examines how these vernacular structures have changed in response to environmental pressures, urbanization, and policy interventions. Findings reveal that sedimentation (100-120 cm over 20 years) and increased flood frequency (1-2 events per year) have necessitated significant architectural adaptations, including raised stilts (from 60-130 to 170-270 cm) and a material transition from traditional ironwood to modern composites. The study identified distinct socio-economic stratifications in adaptive capacity, with middle/upper-income households (65.9%) adopting more durable modifications than low-income groups (28.6%) constrained by financial constraints. The impact of urbanization is evident through settlement expansion (331%) and densification (5 to 21 units/hectare). The Government's river normalization policy proved effective in reducing flooding events. This study contributes to the global discussion on climate-resilient vernacular architecture by proposing a framework for equitable adaptation that integrates environmental management, community participation, and policy support. These insights offer valuable lessons for flood-prone settlements in tropical wetland areas worldwide.*

Keywords *- Stilt-house settlements, Urban morphology, Flood resilience, Socio-economic disparity, River normalization.*

1. Introduction

The rapid pace of urban growth combined with the impacts of climate change has led to notable transformations in flood-prone settlements around the globe [1-3]. This is particularly pronounced in tropical delta regions, where traditional stilt-house architecture is under growing environmental stress [4-6]. These stilt-based dwellings, once seen as practical flood adaptation solutions, are now undergoing morphological transformations in response to natural and human-induced pressures [7-9]. In this context, Samarinda, Indonesia, an urban area along the Karang Mumus River, offers a valuable case due to its frequent flooding and sedimentation issues [10-13]. While ironwood (Eusideroxylon zwageri T. et. B) was historically favored for construction, material shortages and widening social disparities have resulted in varied adaptive responses [14, 15], raising concerns about fair access to resilience.

Although prior studies have assessed either vernacular flood responses [16, 17] or the urbanization impacts on settlements [18, 19], few have holistically examined how stilt-house morphologies change alongside socio-political and environmental dynamics [7, 20, 21]. Addressing this research gap is vital, particularly in light of the Intergovernmental Panel on Climate Change's recommendations [22, 23]. This study aims to close this gap by:

- Measuring physical adaptations, notably stilt height increases, in response to escalating sedimentation and flood risk over the 2002–2023 period through spatial-temporal analysis.
- Highlighting socio-economic differentiation in resilience strategies
- Analyzing the role of policy interventions like the 2021 river normalization project, effectively decreasing flood incidents but with unequal benefits across communities.

Utilizing morphological data spanning over 80 years (1941–2023), this research provides insights into long-term adaptation patterns in tropical alluvial urban settings.

These data illustrate the cumulative effect of sedimentation (100–120 cm in two decades), a factor often underestimated in short-term analyses [12]. The study draws on resilience theories by [4] and socio-hydrological models by [24] to frame its analysis.

Moreover, the study documents critical material transitions in vernacular housing practices, notably the shift from traditional ironwood structures to composite materials such as reinforced Concrete and GRC boards. This observation directly responds to [6] call for empirical studies addressing material scarcity and innovation in vernacular architecture. In terms of governance, the findings challenge conventional top-down resilience planning approaches (e.g.,), instead highlighting the importance of synergistic interactions between local communities and policy frameworks. This aligns with the inclusive governance paradigm advocated by [25], emphasizing participatory strategies for enhancing urban resilience in flood-prone environments.

By integrating urban morphology [26], climate adaptation and socio-economic analysis [24, 27], this research advances:

- Theoretical frameworks for vernacular architecture resilience, particularly in alluvial tropics.
- Policy debates on equitable flood-risk governance [28], 2023) emphasizing participatory approaches.
- Practical strategies for alluvial plain cities include adaptive stilt-height standards and subsidized material access for low-income households.

This study thus provides a replicable model for analyzing climate-resilient vernacular architecture in rapidly urbanizing floodplains while advocating for policies that address socio-environmental inequalities.

2. Materials and Methods

This study utilized a mixed-methods research design [29-31], integrating spatial quantitative techniques, direct field surveys, and qualitative socio-economic analysis. This integrative approach aimed to explore how stilt-house settlements in South Sempaja Village, Samarinda, have adapted morphologically in response to environmental and social dynamics. The methodology was structured to examine three interrelated aspects: (1) physical transformation of built forms, (2) socio-economic influences, and (3) policy interventions.

2.1. Study Area and Population

The selected research site is in RT31 and RT33 of South Sempaja Village, part of North Samarinda District in Samarinda City, Indonesia. This location was specifically chosen due to its high exposure to flooding and the presence of distinctive stilt-house typologies. The area remains a developing stilt-house settlement amidst modern residential zones along the floodplain of the Karang Mumus River. The population under study consists of 194 households, representing a microcosm of adaptation strategies in urban flood-prone environments.

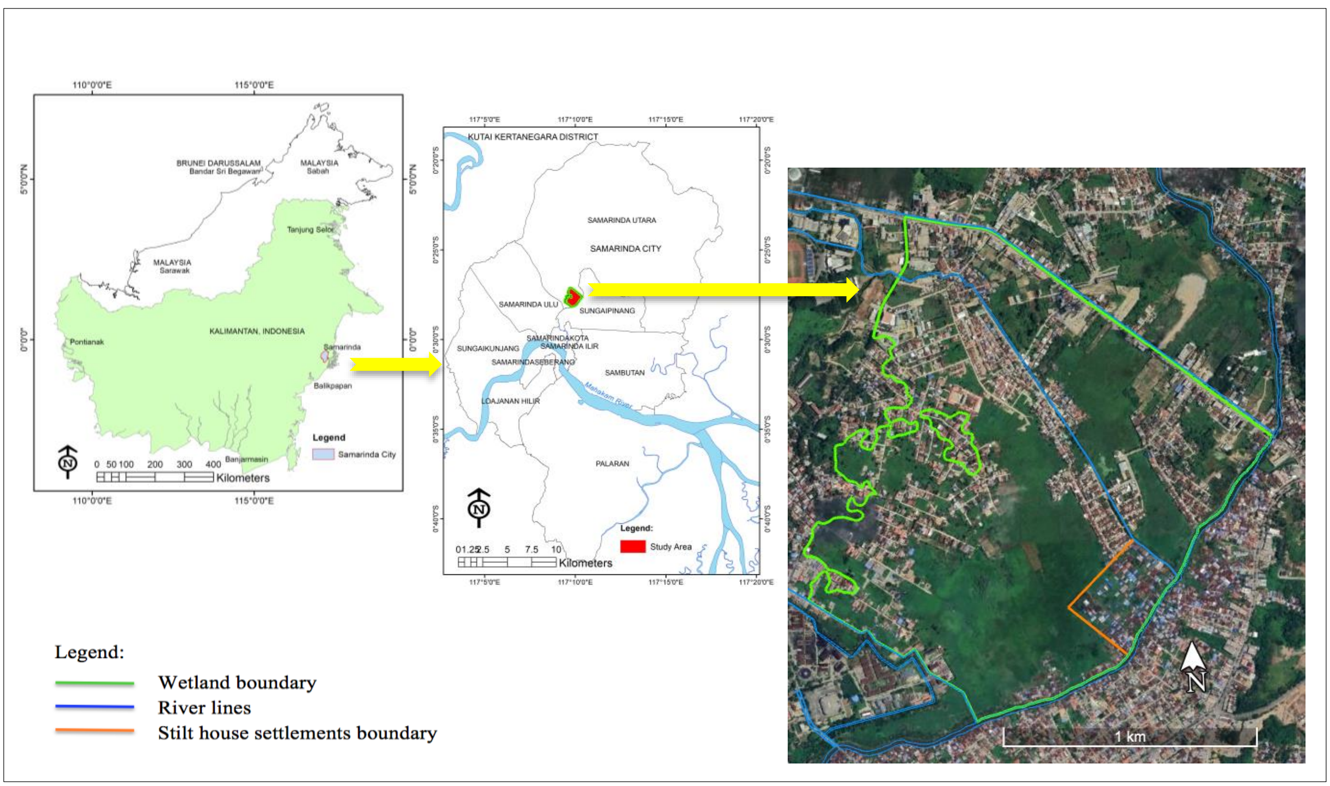


Fig. 1 Study area

2.2. Data Collection Methods

2.2.1. Spatial Data

This research incorporated temporally diverse spatial datasets to analyze land use transformation, the evolution of stilt-house morphology (from 1941 to 2023), and flood susceptibility. Historical maps were acquired from Universitaire Bibliotheken Leiden (1941) and Indonesia's Geospatial Information Agency (BIG) (1991). Satellite imagery with a resolution below 1 meter was collected for 2002, 2013, and 2023 via Google Earth [32-34]. Photogrammetric maps with ultra-high resolution (<5 cm) were also sourced from the Ministry of Agrarian Affairs and Spatial Planning/National Land Agency (ATR/BPN) in December 2023 [35]. All map and image files were digitally formatted and processed using Geographic Information System (GIS) tools for georeferencing and integration.

Flood risk assessment [36-38] was performed by combining satellite-based stilt-house footprint data with drone imagery, field measurements of stilt elevations, and historical flood depth data sourced from local disaster management agencies (1998–2023). These were then classified into three risk levels: low (floodwater below floor level), medium (floodwater up to 40 cm above floor), and high (floodwater more than 40 cm above floor, with potential for severe damage).

Table 1. Description of spatial data

Type / Data name	Year of acquisition	Resolution / Scale	Source
Topographic map (Samarinda; Shelfmark:D B49,1)	1941	1:100.000	Batavia : Reproductiebedrijf Topografische Dienst, 1941
Topographic map (Sheet: 1915-41)	1991	1:50.000	Geospatial Information Agency (BIG) of Indonesia
High-resolution image	2002, 2013, 2023	< 1 m	Google Earth Pro
Digital Map Photos	Des,2023	< 5 cm	the Ministry of Agrarian Affairs and Spatial Planning of the Republic of Indonesia

2.2.2. Field Survey

The field component focused on capturing detailed morphological characteristics of the dwellings [57, 59, 60]. Platform heights were measured and categorized (≤90 cm, 91–130 cm, 131–170 cm, 171–210 cm, 211–250 cm, and 251–290 cm) [41, 42], while data on structural changes, construction age [44-46] (<10 years, 10–20 years, >20 years), and building materials were recorded.

Materials included both traditional types (e.g., ironwood "in") and modern alternatives (e.g., Concrete, ceramics, GRC boards). Sediment accumulation was evaluated using interviews with 15 respondents and direct field inspection of pillar base levels and underfloor clearances.

2.2.3. Socio-Economic Data

Socio-economic profiles were constructed from interviews with 98 residents using a semi-open format [27, 47-49]. The data encompassed income brackets (less than IDR 3.5 million/month, IDR 3.5–7 million/month, and over IDR 7 million/month), education level, and occupation. These variables were examined in relation to adaptation expenditures, building material preferences, and policy perception.

2.2.4. Government Policy

Government interventions, specifically the 2021 river dredging and widening along the Sempaja floodplain, were examined as part of the Karang Mumus River Normalization and Slum Settlement Upgrading Program. The intervention aimed to improve flood flow capacity.

Supporting data were obtained from field assessments and secondary sources, including social media. The spatial-temporal effects of the policy were analyzed through high-resolution imagery comparisons (2013 vs. 2023) and resident interviews focusing on flood risk perceptions post-intervention 48-50].

Table 2. Government programs and policies

Government Policy	Regulation /Years	Institution	Description
Locations of Slum Housing and Settlements	413.2/222 /HK.KS/ VI/2018	Mayor of Samarinda City	The location of Karang Mumus II as a residential and slum area (includes RT31 and RT32)
Normalization of Karang Mumus River	2021	*River Basin Center*/ BWS Kalimantan IV	Dredging and widening of the Karang Mumus River

2.3. Data Analysis

2.3.1. Spatial Analysis

Spatial interpretation in this study relied on visual-based techniques, where parameters such as dimension, form, distribution, color, texture, and spatial relationships were used to identify features of stilt-house settlements [51-53]. All datasets were analyzed using ArcGIS 10.8 [54, 55] and QGIS 3.34.2 [56].

Spatial analysis comprised three primary stages:

1. Georeferencing of High-Resolution Data: All satellite and photogrammetric images were spatially corrected and digitized in QGIS 3.34.2 for consistent geolocation accuracy.
2. Land Cover Change Detection: Supervised classification using the Random Forest algorithm (Liu et al., 2018) was implemented to assess settlement expansion, showing a 331% increase in the area of stilt houses across the observed timeline.
3. Flood Risk Mapping: A weighted overlay approach was employed to map flood vulnerability by combining mean platform height, field-observed flood depths, and rates of sediment accumulation (Ouma & Tateishi, 2014).

2.3.2. Ground Validation

Validation of remote sensing outputs was carried out through field surveys in 194 stilt-house units within RT31 and RT33.

Each unit was assessed for structural characteristics and photographed. Additionally, 30 residents (approximately 10%) were selected using stratified sampling to validate historical building data, materials used, and adaptive practices.

2.3.3. Statistical Analysis

Quantitative data from 98 households, representing 50.5% of the total population, were subjected to statistical testing. A Chi-square test with a 0.01 significance level was conducted to explore associations between income level and adaptation strategies, such as platform elevation and material change [57-59].

2.3.4. Content Analysis

Qualitative insights from interviews, field notes, and policy-related documents were examined using content analysis. This process helped identify recurring themes regarding the morphological adaptation strategies of the stilt settlements [28, 60-62].

2.4. Limitations

Despite offering a comprehensive framework, this study presents certain limitations. First, its geographic scope is restricted to specific settlements in Samarinda City, which may limit its broader applicability across other stilt housing contexts in Southeast Asia. Second, while analytically sufficient, the sample size may not capture the full diversity of household adaptation responses.

Furthermore, the reliance on self-reported data from interviews and surveys introduces the possibility of response bias, where participants may overstate or understate their adaptation experiences. Nevertheless, the methodological triangulation adopted in this study strengthens the overall validity of the findings and provides a foundational reference for future studies on flood-prone urban morphologies.

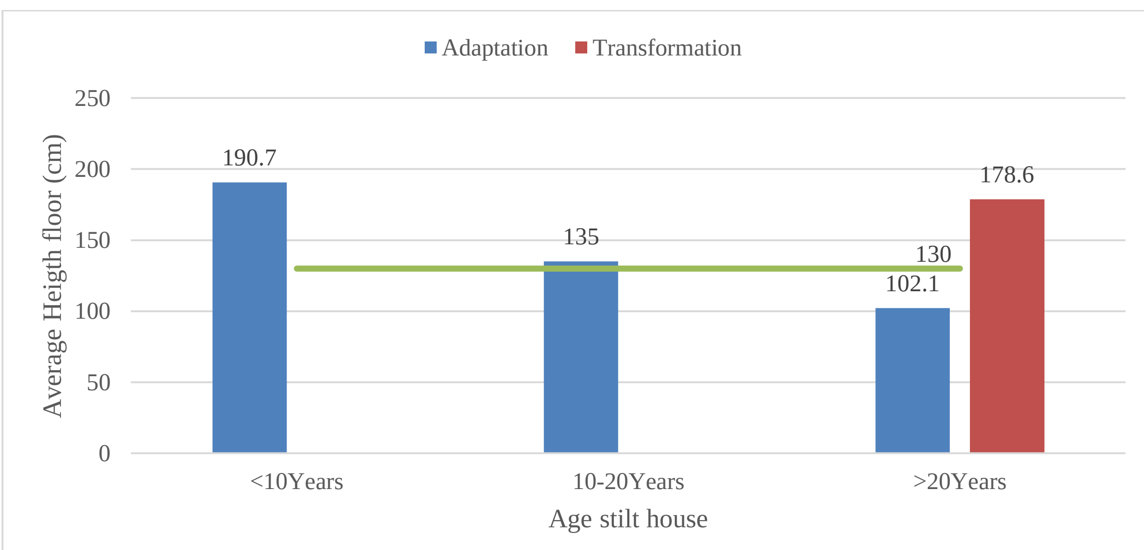


Fig. 2 Average floor height of stilt houses according to building age and flood level (1990s-2024)

3. Results and Discussion

3.1. Morphological and Socio-Economic Stratification

3.1.1. Morphological Transformation and Adaptation of Stilt House Settlements

The development of stilt house settlements in the flood-prone South Sempaja area began on former wet rice fields from the Dutch colonial period (circa 1940s) and continued into the 1990s. These plots were subdivided into residential lots measuring 200–250 m² (typically 10x20 m or 10x25 m), arranged in grid-like blocks delineated by roadways aligned with historical field boundaries. Initial constructions emerged along the banks of the Karang Mumus River before extending inland to occupy the full extent of the subdivision.

The morphological evolution of these settlements has been largely shaped by wetland environmental processes and socio-economic transitions. Key indicators include fluctuations in platform height, and the adoption of various construction materials. Houses built from the early 1990s to 2002 had platform heights of 150–200 cm, but by 2024 these had declined to between 60–130 cm (average 100.2 cm) due to sedimentation of around 100–120 cm over two decades. Dwellings constructed during 2003–2013 began at similar elevations (150–200 cm), yet by 2024 had reduced to 90–150 cm (average 135 cm), indicating sediment accumulation of 40–60 cm. In contrast, post-2014 houses were elevated significantly, reaching heights between 170–270 cm, with a mean of 190.7 cm (Figure 2 and Figure 3)

Fig. 3 Adaptation of stilt houses: a) less than 10 years and floor height 210 cm b) 10-20 years and floor height 100 cm c) Flood height more than 40 cm above the floor

A notable shift in material usage has also occurred. Traditionally, Kalimantan homes used ironwood ("Ulin" *Eusideroxylon zwageri*) for core structural components. Due to scarcity, regulatory restrictions, and escalating costs, households, especially those from lower income brackets, have adopted modern, more affordable materials.

While Ulin remains in use for vertical supports, newer constructions often utilize Concrete, ceramic tiles, GRC boards, and metal cladding (Spandek) for floors and walls.

Statistical categorization of house types in RT31 and RT33, based on stilt height and materials, yields 14 typological variations, as summarized in Table 3.

Table 3. Typology of stilt houses settlements in RT31, RT33

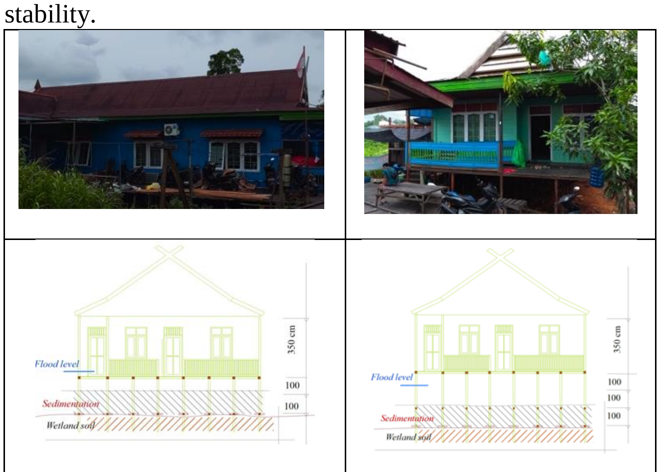
Type	Photograph	Stilt height (cm)	House of Materials		
			Struc true	Wall	Floor
A		<= 90	Ulin	Ulin	Ulin
B		91-130	Ulin	Ulin	Ulin
C1		131-170	ulin	ulin	ulin
C2		131-170	Ulin	Hebel	Ulin, Concrete
D1		171-210	Ulin	GRC board	Ulin, Concrete
D2		171-210	Ulin	GRC board	Ulin
D3		171-210; 2 storey	Ulin	GRC board	Ulin
D4		171-210;	Ulin	GRC board, spandek (zink)	Ulin
D5		171-210;	Ulin	Concrete	Ulin, ceramic

E1		211-250	Ulin	Ulin	Ulin
E2		211-250; 2 storey	Ulin	Ulin	Ulin
E3		211-250;	Ulin	Concrete	Ulin, Ceramic
E4		211-250;	Ulin	GRC board, Concrete	Ulin, Ceramic
F		251-290	Ulin	Hebel	Ulin

Source: Survey 2023-2024

3.1.2. Transformation Processes in Stilt House Settlements

Among stilt houses built before 2002, 53.8% of households have raised their floor platforms from under 90 cm to between 150 and 235 cm. The remaining 46.2% retained their original height, resulting in higher flood vulnerability. Elevation is achieved through manual lifting, employing eighteen 2-ton jacks in a sequential process. Each pillar is raised in 5 cm increments, beginning at the Front and continuing row by row until the target height of about 2 meters is reached. This involves dovetail joint extensions (30–40 cm) to connect new and existing pillars and supplementary crossbars for enhanced structural stability.



a. 2023 | b. 2024

Fig. 4 Stilt house Transformation (Source: survey 2023-2024)

Fig. 5 Method of raising the height of the stilt house pillars using the dovetail joint technique

3.1.3. Socio-Economic Stratification in Morphological Adaptation

Socioeconomic class significantly influences material choices and morphological adaptations. Middle-income households (IDR 3.5–7 million, 65.9%) and upper-middle-income groups (IDR 7–15 million, 5.5%) typically employ high-quality materials, such as ceramic tiles and cement-plastered walls. Meanwhile, lower-income households (below IDR 3.5 million, 28.6%) favor budget-friendly options like GRC wall panels. Structural adaptations such as elevating platforms or adding second stories are predominantly executed by the middle and upper strata. At the same time, 83.33% of non-adaptive households belong to the lowest income group, a statistically significant disparity ($p < 0.01$, chi-square test). These findings underscore the inequities in adaptive capacity and the increased flood vulnerability of economically disadvantaged residents.

3.2. Intersection of Urbanization, Climate Change, and Policy in Stilt House Morphology

3.2.1. Urbanization and Its Influence on Morphology

The urban expansion of Samarinda is reflected in its population growth from 521,471 in 2000 to 861,878 in 2023 (65.3% increase). This transformation turned South Sempaja from a rural village into a suburban settlement, with a local population rise of 216.3% (from 22,557 to 71,341). GIS-based temporal mapping illustrates that stilt houses multiplied by 331%—from 43 units in 1990–2002 to 194 units in 2013–2023. Residential density rose accordingly, from 5 to 21 units per hectare.

This densification was more prominent near major roads and arterial routes, indicating infrastructure as a spatial determinant of settlement growth. Internal connectivity also evolved; wooden walkways ("titian") extended from 616 meters (1990–2002) to 2,405 meters (2013–2023), a 290% increase Indicating physical and social integration within denser neighbourhoods.

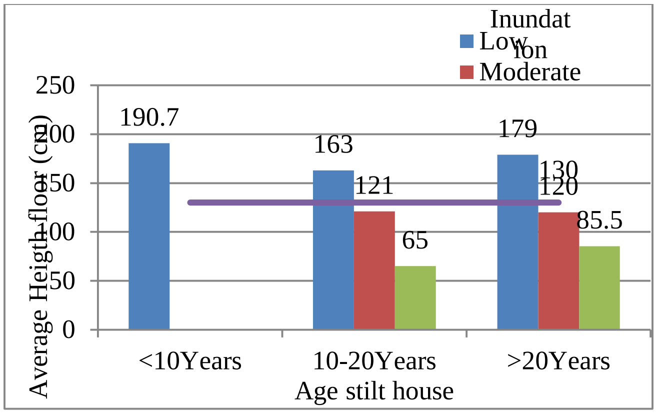
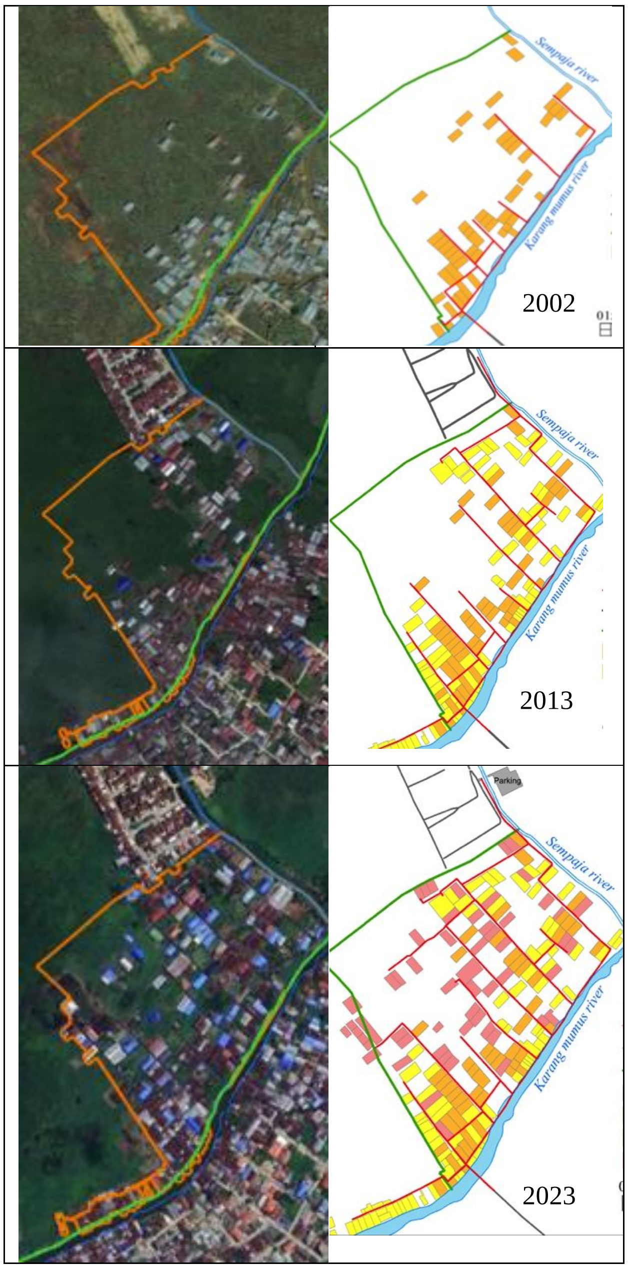


Fig. 6 Morphological adaptation of stage height 1990s-202



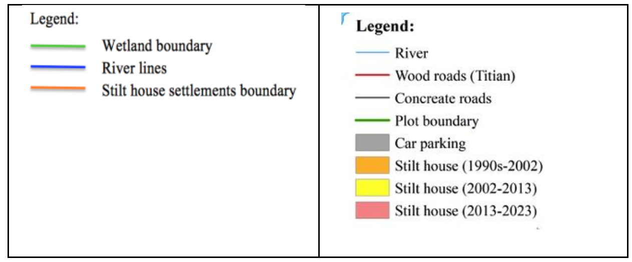


Fig. 7 High-resolution images and GIS (2002,2013,2023)

3.2.2. Impact of Climate Change on Morphological Patterns

Increased flood frequencies and intensities compounded by accelerated sedimentation have reshaped settlement structures. From 1998 to 2021, significant flood events with depths of 150–200 cm and prolonged inundations (3–5 days) became more frequent. Stilt houses from 1990–2002, typically under 90 cm in platform height, were severely impacted. In contrast, recent houses feature raised floors (up to 270 cm) and multi-story construction, signalling an adaptive architectural shift to counteract climate-induced risks. Spatial analysis further confirms vulnerability gradients, with older buildings closer to rivers experiencing deeper and more consistent flooding, regardless of distance from the riverbanks.

Table 4. Flood vulnerability based on the age of stilt houses (1990s-2024)

Stilt House Age / Priod	Low Impact (below the floor)		Moderate (Inundation above the floor<40 cm)		High (Inundation above the floor > 40 cm)	
	Unit	%	Unit	%	Unit	%
<10 Years	51	52				
10-20 Years	10	10.2	10	10.2	2	2.04
20 Years >			1	1.02	11	11.2
Transfer mation	13	13.26				
Total	73	75.5	11	11.2	13	13.2

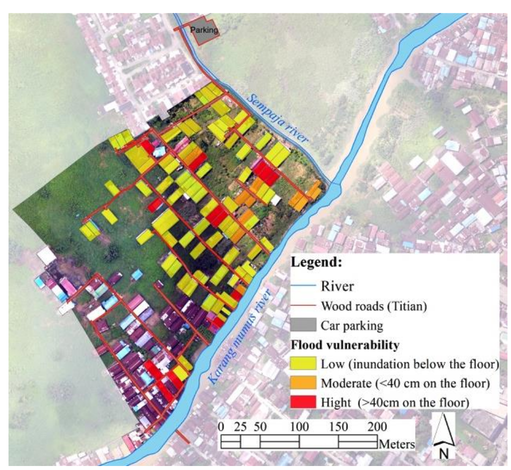


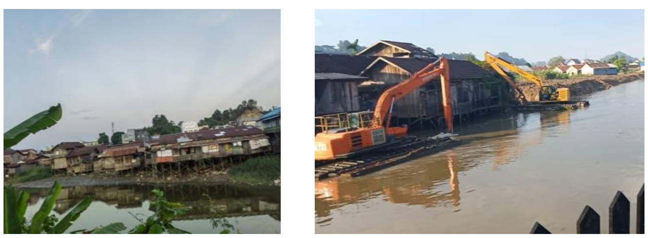
Fig. 8 Spatial distribution of flood vulnerability in RT31, RT33

3.2.3. Government Policy and Morphological Adjustments

River normalization initiated in 2021 has markedly influenced settlement form and resilience. Dredging riverbeds (1–2 meters) and widening river channels (10 meters for Karang Mumus and 2–5 meters for Sempaja) increased flow capacity and reduced sedimentation.

Post-project interviews revealed a notable drop in flooding incidence. Many households, previously categorized under moderate-to-high flood risk, were reclassified as low-risk, reflecting the policy's efficacy. These infrastructural interventions triggered not only physical improvements but also social empowerment, particularly among low-income communities, who began adopting more resilient construction methods.

Urbanization, climatic shifts, and targeted policies have coalesced to reshape traditional stilt housing into more compact, elevated, and durable configurations—highlighting the importance of integrated, inclusive planning in managing flood-prone urban transitions.



(a) before **(b) underway**

Fig. 9 Normalization of the Karang Mumus River carried out by the Government in 2021

(a) before **(b) after**

Fig. 10 Normalization of the Sempaja River carried out by the Government in 2021

(a) Image 2013 **(b) Image 2023**

Fig. 11 Change in Karang Mumus river width from 10-20 m (2013) to 20-30 m (2023)

3.3. Discussion

The findings of this study underscore the complex interplay between environmental, socio-economic, and policy factors in shaping the morphological adaptation of stilt house settlements in flood-prone alluvial plains. Several critical insights and innovations emerge from the integrated analyses of spatial transformation, socio-hydrological dynamics, and material transitions.

First, the quantitative analysis reveals a strong correlation between sedimentation rates and increased stilt height over time ($R^2 = 0.62$, $p < 0.001$). This statistically significant result indicates that vertical morphological adaptations in these settlements are not merely sporadic responses but reflect a systematic and measurable reaction to long-term sediment buildup and flood pressures. This finding aligns with the socio-hydrological feedback theory [63], which emphasizes that human adaptation is closely linked to environmental variability over time.

Second, the spatial clustering of high-vulnerability households, as identified through Moran's I ($p < 0.05$), demonstrates the non-random nature of flood risk exposure. Vulnerability concentrates in specific zones with lower adaptive capacity, particularly among older homes located closer to riverbanks, which validates the urban risk accumulation framework proposed by [64]. This highlights the compounded vulnerabilities stemming from spatial, social, and infrastructural inequalities.

The study's novelty lies in two main contributions. The first is a comprehensive documentation of material transitions in stilt house construction. Unlike prior studies such as [6], which briefly noted changes from Ulin to modern materials, this research provides detailed typologies, cost-benefit evaluations, and adaptive implications of GRC boards, Hebel, ceramic tiles and spandex. Integrating traditional and modern materials reflects a transitional vernacular, a hybrid architecture uniquely suited to urbanizing, flood-prone environments.

The second major contribution is the measurable impact of the post-2021 river normalization policy, which resulted in a 100% reduction in major flooding for dwellings with a height equal to or above the wooden bridge (average height of 125 cm from the surface) in the surveyed areas over the past three years. This finding supports the argument that structural interventions can substantially improve urban resilience when implemented strategically and integrated with community-based adaptation.

Furthermore, the study introduces the concept of adaptive morphological layering, wherein platform height adjustments, material upgrades, and functional expansions (e.g., two-story configurations) co-evolve in response to cumulative hydrological stressors. This layered adaptation model complements concepts in adaptive urbanism [65], emphasizing resilience through flexible, iterative design.

Interview data further support this framework. The expressed preference of 73% of respondents for participatory policy mechanisms reflects a demand for inclusive governance in climate adaptation. This contrasts sharply with top-down models, such as in Manila [66], where centralized planning often neglects localized adaptive practices. The alignment between community agency and policy effectiveness highlights the potential of bottom-up planning approaches in socio-ecohydrological systems. Compared to studies in Jakarta [67], which often focus on displacement and relocation, this research emphasizes in-situ adaptation and vertical transformation as viable resilience strategies. By retaining socio-cultural ties and reducing disruption, these measures offer sustainable alternatives to forced relocation.

This study expands the discourse on flood-resilient housing by offering a multi-scalar framework that links morphological adaptation with environmental metrics, socio-economic strata, and governance structures. The integrative approach bridges theoretical perspectives from socio-hydrology, urban resilience, and vernacular architecture, providing empirical evidence for policy and planning frameworks tailored to Southeast Asia's flood-affected urban margins.

4. Conclusion

This study underscores the dynamic and multifaceted nature of morphological adaptation in stilt house settlements within flood-prone alluvial environments of South Sempaja, Samarinda. The interplay between socio-economic stratification, environmental processes, and policy interventions produces spatial configurations that are simultaneously vernacular and innovative. The findings demonstrate that residents' morphological responses, such as increasing stilt height, transitioning construction materials, and expanding vertically, are deeply influenced by sedimentation patterns, flood exposure, income levels, and access to infrastructural support.

Quantitative evidence, such as the predictive relationship between sedimentation and stilt elevation (R^2 = 0.62) and spatial analyses identifying vulnerability clustering, reinforce the theoretical frameworks of socio-hydrology and urban resilience. The documented material shift from Ulin to GRC and other contemporary materials reveals a hybridization of vernacular practice, offering a practical adaptation pathway amid resource constraints. Moreover, policy-driven interventions, particularly the 2021 normalization of the Karang Mumus and Sempaja Rivers, have proven effective, as shown by eliminating major floods in affected areas.

The study contributes significant insights by promoting an in-situ, layered adaptation model emphasising incremental, localized, and participatory strategies over wholesale relocation. This framework aligns with global urban resilience agendas and respects cultural continuity and social embeddedness, which are critical to the Sustainability of interventions in Southeast Asia's deltaic urban fringes.

4.1. Limitation and Future Work

Despite its contributions, the research is not without limitations. First, the geographic specificity of the case study centred on the floodplain settlements of RT31 and RT33 in South Sempaja limits the generalizability of its conclusions. The findings may not directly apply to upland or coastal communities with differing geomorphological or socio-economic contexts. Future studies should consider comparative analyses across diverse flood-prone geographies, such as the Mekong Delta or the Ciliwung River Basin, to validate and broaden the applicability of the adaptation model.

Second, while the research integrates spatial and qualitative data, the reliance on historical maps and resident memory for pre-1990 conditions introduces potential inaccuracies. Advanced spatial reconstructions using remote sensing or historical satellite data could enhance temporal depth and reliability.

Third, socio-economic data were categorized broadly; future investigations should adopt finer-grained analyses incorporating variables such as tenure security, household size, and access to insurance or social protection. This would yield deeper insights into the adaptive capacity gradient across communities.

For methodological advancement, incorporating machine learning or agent-based models could refine morphological and behavioral responses to sedimentation and flood recurrence predictions. Additionally, participatory GIS approaches may improve the integration of community knowledge in spatial planning. Finally, future research should engage directly with governance mechanisms. Longitudinal policy tracking, institutional mapping, and stakeholder analysis would clarify how administrative actions facilitate or hinder grassroots adaptation. Through these extensions, a more holistic understanding of adaptive morphology can be developed, bridging gaps between empirical observation, theoretical innovation, and policy relevance.

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