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COMMUNITY-BASED ADAPTIVE SUSTAINABILITY AND FLOOD VULNERABILITY ZONING USING SOCIAL RESILIENCE INDICATORS IN KAMPAR REGENCY, INDONESIA

*Dedi Hermon[1] , Tengku Adeline Adura Tengku Hamzah[2], Febriandi[1], Risky Ramadhan[1], Rahadhatul Aisy[1]

[1]Department of Geography, Universitas Negeri Padang, Indonesia
[2]Department of Geography, University of Malaya, Malaysia

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ABSTRACT: Flood disasters are among the most frequent natural hazards in Indonesia, with Kampar Regency regularly affected due to its river basin and lowland setting. This study aims to delineate flood vulnerability zones and assess the sustainability of adaptation strategies using social resilience indicators, providing a practical framework for flood risk management. Vulnerability zoning was carried out with the Multi-Criteria Decision Analysis (MCDA)-Weighted Overlay method, based on Indonesia's National Disaster Management Agency (BNPB) Regulation No. 2/2012. Adaptive sustainability was examined using Multidimensional Scaling (MDS) with the Rapid Appraisal for Hazard (APHAZA) approach, supported by leverage (Root Mean Square or RMS change) analysis and Monte Carlo validation. The framework covered four dimensions, namely Population Adaptation (infrastructure and household preparedness), Health Adaptation (medical readiness and service), Flood Awareness Education (knowledge transfer and school functionality), and Social Capital Adaptation (community cooperation and networks). Results show that high flood vulnerability zones are concentrated in Tambang, Tapung Hilir, Tapung Hulu, and Kampar, while upland areas such as Kampar Kiri Hulu and XIII Koto Kampar remain flood-free. MDS analysis indicates that all dimensions are within a moderately sustainable range. Integrating physical vulnerability zoning with social resilience assessment offers methodological novelty and relevant insights for resilience-based flood risk management in hazard-prone regions

Keywords: Flood Vulnerability, Social Resilience, Adaptive Sustainability, MCDA, Kampar.

1. INTRODUCTION

Flooding occurs when water accumulates on the ground surface beyond the land's capacity to absorb or drain it, causing physical damage and socio-economic losses. It frequently affects coastal zones, river basins, and densely populated lowland areas with inadequate drainage systems [1, 2]. Climate change further increases flood risk by intensifying and prolonging heavy rainfall events [3-5]. Vulnerability also rises when environmental conditions limit soil infiltration. Key physical indicators contributing to flood risk include land use patterns, slope gradients, elevation, drainage capacity, and soil types [6-9].

Kampar Regency is among the areas frequently affected by flooding. Administratively located in Riau Province, Indonesia, it includes alluvial plains, mountains, and lowlands and is traversed by many rivers, lakes, and wetlands. The Kampar River, a major waterway, stretches about 413 km, with an average depth of 7.7 m and a mean width of 143 m [10]. Originating from the Barisan Mountains, it flows eastward through the Sub-districts of XIII Koto Kampar, Kuok, Salo, Bangkinang, Kampar, East Kampar, North Kampar, Rumbio Jaya, Tambang, and Siak Hulu. The Kampar Kiri River crosses Kampar Kiri, Gunung Sahilan, Central Kampar Kiri, and Lower Kampar Kiri. Kampar also forms part of the upstream region of the Siak River, which runs about 90 km with a depth of 8–12 m across the Tapung Sub-district. The Tapung River divides into Tapung Kanan, passing through Tapung and Tapung Hulu, and Tapung Kiri, which also flows through Tapung [11].

In 2024, severe flooding affected five villages in Kampar Kiri Sub-district—Kuntu, Padang Sawah, Sungai Paku, Teluk Paman, and Teluk Paman Timur in Kampar Kiri Hulu [10]. Previous flood vulnerability studies in Indonesia and elsewhere have largely focused on physical and environmental indicators such as slope, elevation, land cover, soil type, and drainage capacity [12-16]. While useful for spatial mapping, such approaches often overlook community-level indicators including adaptive behavior, health preparedness, education continuity, and social capital. Studies such as [9] noted that physical mapping alone offers limited insight without socio-ecological perspectives, while [13] argued that resilience-based frameworks better capture community dynamics. More recently, [10] emphasized that integrating spatial hazard models with local adaptive capacity provides stronger policy relevance for disaster risk reduction. This gap creates uncertainty regarding which social dimensions most influence adaptive sustainability and how they interact with physical vulnerability.

This study addresses the gap by integrating flood vulnerability zoning using the Multi-Criteria Decision Analysis (MCDA) method with a community-based adaptive sustainability assessment using Multidimensional Scaling (MDS). This integration not only maps physical exposure but also identifies sensitive indicators such as household preparedness, medical and school infrastructure, and community collaboration, which enhance resilience. The novelty lies in combining Indonesia’s National Disaster Management Agency (BNPB) standardized flood vulnerability framework with social resilience dimensions, validated through leverage (RMS change) analysis and Monte Carlo simulation, producing actionable insights for local disaster risk reduction. This methodological contribution distinguishes the study from prior work that focused solely on physical hazards, by operationalizing resilience indices and identifying leverage attributes that support context-specific interventions.

To effectively manage flood risks, the people of Kampar must strengthen their adaptive capacity to cope with vulnerability, hazards, and disaster-related risks, and improve their response capabilities. This study aims to delineate flood vulnerability zones and assess the sustainability of adaptation strategies using social resilience indicators, offering a practical framework for flood risk management. Established resilience frameworks such as the Methods for the Improvement of Vulnerability Assessment in Europe (MOVE) provide conceptual structures for organizing exposure, susceptibility, and lack of resilience across physical, social, economic, institutional, and cultural domains [17]. However, these frameworks do not offer an operational technique for producing sustainability indices or identifying sensitive indicators. In this study, MOVE informed the conceptual grouping of indicators, while MDS–the Rapid Appraisal for Hazard (APHAZA) was used as the operational method to quantify adaptation sustainability (0–100) and identify the most sensitive attributes through leverage (RMS change) analysis [18]. This combination ensures both conceptual comprehensiveness and quantitative robustness in assessing community resilience.

2. RESEARCH SIGNIFICANCE

This study provides original contributions by integrating physical flood vulnerability zoning with adaptive social resilience assessment, a combination rarely applied in Indonesian flood research. The novelty lies in using the MCDA-Weighted Overlay method aligned with national disaster regulations, coupled with MDS-based APHAZA analysis, to evaluate sustainability across four dimensions: population, health, education, and social capital. Unlike conventional studies that focus solely on hazard mapping or socio-economic surveys, this framework simultaneously identifies spatial vulnerability zones and measures adaptive capacity. The approach delivers an innovative, practical tool for resilience-based flood risk management in Kampar and other hazard-prone regions.

3. MATERIAL AND METHODS

3.1 Flood Vulnerability Zoning

Flood vulnerability analysis in Kampar Regency was conducted using a spatial approach through the Multi-Criteria Decision Analysis (MCDA) method [9-16]. The weighting scheme follows the guidelines established in Indonesia's National Disaster Management Agency Regulation No. 2/2012 [10, 19]. We applied a GIS-based Multi-Criteria Decision Analysis using the Weighted Overlay (WO) technique in accordance with Indonesia’s BNPB Regulation No. 2/2012. Each indicator was normalized to 0–1 and multiplied by its weight before aggregation into sub-indices: SVI (Social Vulnerability Index), PVI (Physical Vulnerability Index), EVI_1 (Economic Vulnerability Index), and EVI_2 (Environmental Vulnerability Index). The Flood Vulnerability Index (FVI) for each sub-district was then computed as:

$$\begin{aligned} \boldsymbol{FVI} = (\boldsymbol{SVI} \times \mathbf{40}\%) + (\boldsymbol{PVI} \times \mathbf{2} \\ + (\boldsymbol{EVI}_1 \times \mathbf{25}\%) \\ + (\boldsymbol{EVI}_2 \times \mathbf{10}\%) \end{aligned}$$

Data sources and preprocessing comprised 1) Digital Elevation Model (DEM) 30 m for elevation/slope derivation; 2) land-use/land-cover maps; 3) rainfall and extreme-event climatology; 4) population and socio-economic statistics at sub-district/village levels; and 5) recorded flood-affected locations in 2024 from local disaster management agencies. All rasters were resampled to a common 30 m grid. Vector attributes were harmonized to sub-district boundaries before overlay.

Table 1. Classification of flood vulnerability levels

Vulnerability	Descriptions
Flood free	Flood events pose minimal threat to community socio-economic conditions
Low flood	Floods disrupt daily socio-economic routines
Moderate flood	Floods affect social activities and halt local economic operations for less than one month
High flood	Floods cause damage to housing, disrupt social order, and halt economic activity for more than one month

Source: Indonesia National Disaster Management Agency Regulation No. 2/2012 on General Guidelines for Disaster Risk Assessment.

3.2 Community-Based Adaptive Sustainability Model using Social Resilience

We assessed community-based adaptive sustainability across four dimensions using the MDS-APHAZA approach [18,19]. Primary data were collected through a structured survey of 210 respondents across 22 sub-districts during 2023–2024, applying stratified cluster sampling by exposure class (flood-free/low/moderate/high) to ensure representativeness. Responses were coded into ordinal scores and compiled into indicator sets P1–P8, H1–H5, E1–E5, and S1–S7. MDS ordinations were converted into 0–100 sustainability indices for each dimension through linear normalization [20]. Leverage (RMS change) analysis identified sensitive indicators by one-at-a-time deletion, with the RMS change in ordination results indicating the relative influence of each indicator [21]. Ordination robustness was tested using Monte Carlo permutation with 999 iterations [22, 23]. Stress values below 0.25, together with permutation-based p-values and 95% bootstrap confidence intervals for the indices, were used to confirm reliability [23].

The choice of MDS-APHAZA was motivated by the need for an operational technique that could handle heterogeneous ordinal data, generate sustainability indices (0–100) for each dimension, and identify sensitive indicators influencing adaptation outcomes. While the MOVE framework is widely used to structure vulnerability assessment conceptually, it does not prescribe a quantitative algorithm. In this study, the MOVE framework only serves as a reference for organizing indicators into population, health, education, and social capital dimensions, while MDS-APHAZA provides the numerical indices, leverage (RMS change) analysis, and Monte Carlo validation.

MDS-APHAZA produces a sustainability score from 0 to 100% by coordinating multidimensional indicator data and standardizing distances to produce a finite index. Scores closer to 100 indicate higher adaptive sustainability, while those near 0 reflect very low resilience [18]. Leverage (RMS change) analysis plays a critical role in this process by identifying which indicators exert the strongest influence on the ordination configuration, thereby highlighting the most sensitive attributes for targeted policy interventions.

4. RESULTS AND DISCUSSION

4.1 Results of Flood Vulnerability Zoning

Areas identified as highly vulnerable to flooding in Kampar Regency include Tambang (4,488.06 ha), Tapung Hilir (2,464.01 ha), Tapung Hulu (2,410.22 ha), and Kampar (2,046.14 ha). Flood-free zones are found in areas with hilly terrain where slopes exceed 25%, preventing water accumulation during heavy rainfall. These include Kampar Kiri Hulu (126,800.31 ha), XIII Koto Kampar (95,533.71 ha), Kampar Kiri (68,236.39 ha), and parts of Tapung (69,032.92 ha). Moderately vulnerable zones cover approximately 295,053.23 ha, primarily across Tapung, Tapung Hilir, and Tapung Hulu. Within Tapung, about 54,734.81 ha is categorized as moderately flood-prone. More details can be seen in Table 3 and Fig. 1 below.

Table 2. Dimensions and indicators of community-based adaptive sustainability

Resilience dimensions	Indicators	Code
Population Adaptation (P)	– Elevated house structure	P1
	– Adequate drainage system in settlement areas	P2
	– Use of flood-prone land for economic activities with mitigation considerations	P3
	– Water dikes for flood prevention	P4
	– Drainage infrastructure in vulnerable zones	P5
	– Public understanding of flood risk	P6
	– Evacuation training for community members	P7
	– Households with flood disaster preparedness plans	P8
Health Adaptation (H)	– Availability of safety equipment	H1
	– Emergency response capacity	H2
	– Operational condition of health facilities post-flood	H3
	– Pre-disaster health service preparedness	H4
	– Flood-time health service readiness	H5
FloodAwarenessEducation (E)	– Educational programs focused on flood disaster awareness	E1
	– Number of residents aware of flood risks	E2
	– Skills in managing flood disasters	E3
	– Public training and awareness initiatives	E4
	– Ability of schools to resume function post-flood	E5
SocialCapital Adaptation (S)	– Community knowledge on flood vulnerability	S1
	– Participation in flood-related community organizations	S2
	– Involvement in social activities for flood response	S3
	– Active communication among community members in disaster contexts	S4
	– Integrated community social networks for flood disaster management	S5
	– Mutual cooperation during all flood phases (before, during, after)	S6
	– Social cohesion in managing flood disasters	S7

Source: Indonesia National Disaster Management Agency Regulation No. 2/2012 on General Guidelines for Disaster Risk Assessment.

Table 3. Area affected by flood vulnerability in Kampar Regency

Sub-district	Free Zone (ha)	Low (ha)	Moderate (ha)	High (ha)	Total (ha)
Bangkinang	11,412.58	261.68	2,585.51	1,147.86	15,407.62
Bangkinang Kota	6,083.56	232.89	1,352.67	347.21	8,016.32
GunungSahilan	23,602.08	789.49	9,206.28	4.89	33,602.74
Kampa	10,462.26	235.45	5,219.68	1,146.94	17,064.34
Kampar	16,057.54	232.72	2,921.78	2,046.14	21,258.18
Kampar Kiri	68,236.39	1,355.22	15,938.58	1,323.64	86,853.84
Kampar Kiri Hilir	35,477.64	10,368.77	21,944.25	1.62	67,792.28
Kampar Kiri Hulu	126,800.31	355.40	1,088.80	243.43	128,487.94
Kampar Kiri Tengah	23,474.35	1,622.93	5,498.18	513.34	31,108.81
Kampar Utara	4,231.56	260.01	3,710.96	1,090.76	9,293.29
Koto Kampar Hulu	35,789.35	110.27	3,671.97	201.76	39,773.34
Kuok	20,214.05	199.04	4,790.42	1,210.42	26,413.93
Minas	4,882.41	32.97	830.02	0.00	5,745.40
Perhentian Raja	3,723.17	455.52	5,225.75	1,120.42	10,524.80
Rumbio Jaya	2,855.53	200.97	3,107.76	832.71	6,996.96
Salo	17,225.25	341.13	2,901.99	692.21	21,160.57
Siak Hulu	12,473.45	3,917.55	22,624.91	2,295.97	41,311.88
Tambang	10,774.60	1,314.18	21,941.12	4,488.06	38,517.96
Tapung	69,039.92	5,647.36	54,734.81	12.60	129,434.69
TapungHilir	34,696.18	3,895.33	45,012.85	2,464.01	86,068.36
Tapung Hulu	45,502.66	2,261.66	55,521.59	2,410.22	105,696.14
XIII Koto Kampar	95,533.71	1,828.07	5,223.35	573.89	103,159.02
Total	678,548.53	35,918.60	295,053.23	24,168.03	1,033,688.39

Source: Results of data analysis, 2025.

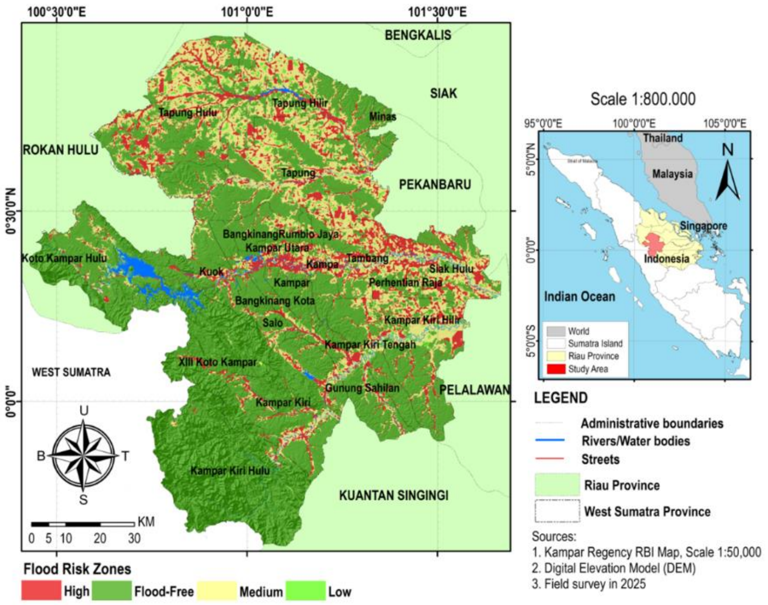

Fig. 1. Map of flood hazard, Kampar Regency

Flood vulnerability in Kampar Regency demonstrates significant spatial variation, influenced by physical features, population density, and economic activities. Low-lying areas near major rivers are more vulnerable due to surface runoff accumulation and limited drainage, as seen in Tambang, Tapung Hilir, Tapung Hulu, and Kampar, classified as high flood vulnerability zones. Upland regions with slopes over 25% resist water accumulation, making Kampar Kiri Hulu and XIII Koto Kampar flood-free due to elevation and river distance. Unplanned urban expansion in peri-urban zones reduces infiltration and overwhelms drainage [26–30]. Deforestation has weakened natural buffers, while rapid agricultural expansion without drainage has enlarged vulnerable zones [31–33]. The spatial pattern of high-vulnerability zones identified in Tambang, Tapung Hilir, Tapung Hulu, and Kampar shows a strong correlation with the 2024 flood-affected areas, particularly in Kuntu, Padang Sawah, Sungai Paku, Teluk Paman, Teluk Paman Timur, and Gema villages. This consistency supports the reliability of the vulnerability zoning results. The spatial resolution of the mapping was based on a 30 × 30 m DEM and land use data, which were overlaid with administrative boundaries at the sub-district level to ensure spatial detail suitable for local planning. Accuracy was assessed by cross-checking high-vulnerability outputs with recorded flood-affected locations in 2024, yielding a high degree of correspondence. This triangulation with observed events provides empirical validation, strengthening the robustness of the flood vulnerability assessment. Unlike many previous studies that relied primarily on coarse-scale hazard models (e.g., 12, 13), this research demonstrates how DEM integration with social resilience data enhances both accuracy and policy relevance. By explicitly connecting hazard zones with empirical flood records, the study addresses the common limitation of predictive-only models and grounds the mapping in observed impacts. This approach aligns with [10], who emphasized the need for empirically validated spatial assessments that capture both exposure and adaptive capacity, ensuring that vulnerability mapping translates effectively into actionable disaster risk reduction strategies.

4.2 Community-Based Adaptive Sustainability Model using Social Resilience

4.2.1 Population Adaptation

Fig. 2 consists of two parts that display the sustainability analysis results for the Population Adaptation dimension. In Fig. 2a, the x-axis is labeled "Dimension 1" and the y-axis is labeled "Dimension 2". The sustainability scale extends from "BAD" (low resilience) on the left to "GOOD" (high resilience) on the right. The blue shows Kampar Regency's position (53.05), which falls in the moderate sustainability range. "UP" and "DOWN" markers indicate directions of increasing or decreasing sustainability, while triangles represent anchor points used for calibration. This visualization helps clarify whether population adaptation tends closer to sustainable or unsustainable conditions. Fig. 2b presents the leverage (RMS change) values of individual adaptation indicators. These values were calculated by sequentially removing each indicator from the MDS analysis and measuring the resulting change in the configuration. Indicators with higher leverage values (P1 = 1.24; P8 = 0.58; P7 = 0.53) exert stronger influence on the sustainability outcome, while indicators with lower values (P6 = 0.44; P4 = 0.40; P3 = 0.15) contribute less sensitivity.

As shown in Fig. 2a, the sustainability index for the population adaptation dimension is 53.05, indicating moderate sustainability. This shows that while adaptive measures exist, more efforts are needed to enhance resilience against flood risks. The leverage (RMS change) analysis (Fig. 2b) identifies P1 as the most influential indicator (1.24), highlighting its critical role in adaptive capacity. P8 (0.58) and P7 (0.53) follow, supporting the need for strong physical infrastructure and community readiness. Although P6 (0.44) and P4 (0.40) are less sensitive, they still contribute to resilience. Household preparedness, like P8, directly improves individual and collective response [32–34]. Infrastructure must be combined with behavioral and institutional readiness to build lasting resilience [35].

4.2.2 Health Adaptation

Fig. 3 consists of two parts that display the sustainability analysis results for the Health Adaptation dimension. In Fig. 3a, the x-axis is labeled "Dimension 1" and the y-axis is labeled "Dimension 2". Kampar Regency's MDS score is 51.05, which lies near the middle between "BAD" and "GOOD", indicating moderate sustainability. The blue represents Kampar Regency's position, while "UP" and "DOWN" markers indicate direction of change, and triangles denote anchors for calibration.

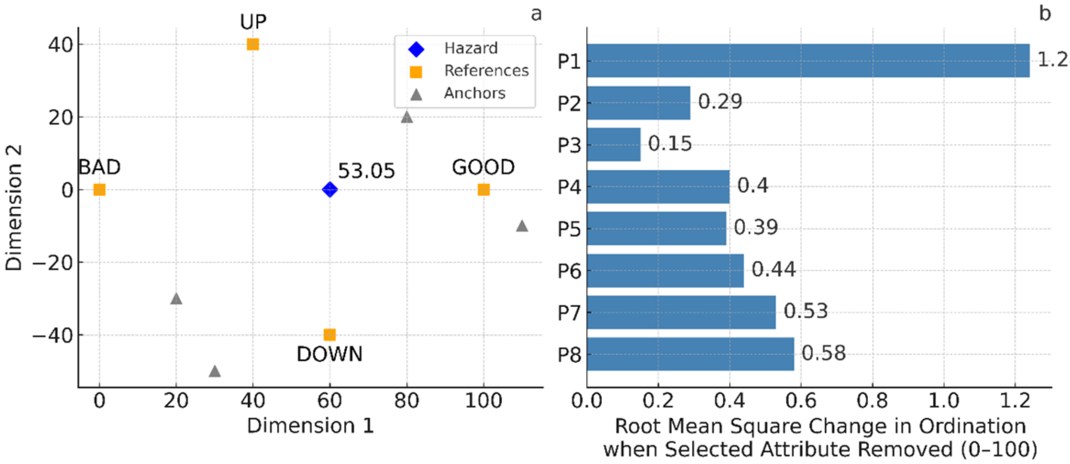

Fig. 2. a) MDS result for Population Adaptation; and b) Sensitive indicators based on Population.

Figure 3b shows the leverage (RMS change) values of the health-related indicators. Indicators with higher values (H1 = 3.29; H5 = 2.32) are the main drivers of health resilience, while H4 = 1.66 and H3 = 1.59 have moderate effects. H2 (0.88) contributes the least. As shown in Fig. 3a, the sustainability index for the health adaptation dimension is 51.05, placing it in the moderately sustainable category. The leverage (RMS change) analysis (Fig. 3b) confirms the dominant role of medical preparedness (H1) and emergency response capacity (H5) in shaping health adaptation outcomes. Well-equipped communities are less vulnerable to casualties and post-flood disease outbreaks [38–40].

4.2.3 Flood Awareness Education Adaptation

Fig. 4 consists of two parts that display the sustainability analysis results for the Flood Awareness Education Adaptation dimension. In Fig. 4a, the x-axis is labeled "Dimension 1" and the y-axis is labeled "Dimension 2". Kampar Regency's MDS score is 51.54, which lies in the moderately sustainable range. The blue indicates Kampar Regency's position, while "UP" and "DOWN" markers show directions of increasing or decreasing sustainability, and triangles denote anchors. Fig. 4b presents the leverage (RMS change) values of the education-related indicators. Higher values (E1 = 3.09; E5 = 2.52) significantly influence the ordination and are crucial for educational resilience. E4 (1.89) and E3 (1.65) contribute moderately, while E2 (0.88) has the weakest influence.

As shown in Fig. 4a, the sustainability index for the education adaptation dimension is 51.54, indicating moderate sustainability. The leverage (RMS change) analysis (Fig. 4b) identifies E1 as the most influential attribute, highlighting the critical role of formal and informal education in preparedness. E5 emphasizes the importance of educational continuity post-disaster. E4 and E3 enhance knowledge and social cohesion, while E2 shows that awareness without action-oriented capacity provides limited resilience [41–43].

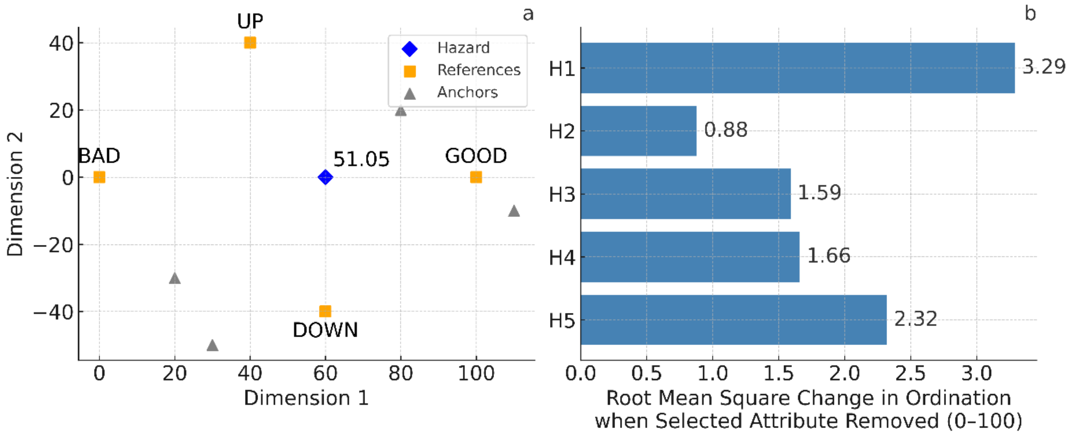

Fig.3. a) MDS result for Health Adaptation, and b) Sensitive indicators based on Health.

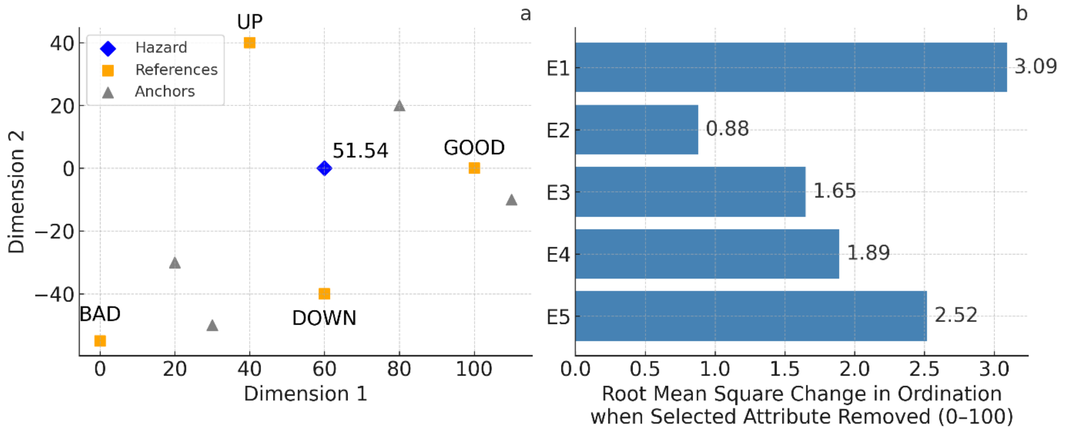

Fig.4. a) MDS result for Education Adaptation (E), and b) Sensitive indicators based on Education.

4.2.4 Social Capital Adaptation

Figure 5 consists of two parts that display the results of the Social Capital Adaptation dimension. In Fig. 5a, the x-axis is labeled "Dimension 1" and the y-axis is labeled "Dimension 2". Kampar Regency’s social capital score is 56.64, the highest among the four dimensions, plotted closer to the "GOOD" anchor. The blue shows Kampar Regency’s position, while "UP" and "DOWN" markers indicate direction, and triangles denote anchors. Fig. 5b presents the leverage (RMS change) values of social capital-related indicators. Indicators with high leverage values (S6 = 3.44; S4 = 2.86) demonstrate that mutual cooperation and communication networks are decisive. Moderate contributors include S3 = 2.02; S2 = 1.85; S1 = 1.51, while S5 = 1.47 has slightly less influence. S7 (0.02) shows negligible impact.

As shown in Fig. 5a, the sustainability index for this dimension is 56.64, the highest among the four, placing it in the moderately sustainable category. The leverage (RMS change) analysis (Fig. 5b) highlights that practical, collective actions (S6, S4) matter more than symbolic or individual factors in strengthening social resilience.

5. CONCLUSION

Based on the leverage (RMS change) analysis, several concrete policy recommendations can be proposed to translate findings into practice. For population adaptation (P1, P8), local governments should subsidize the construction of elevated houses and implement household-level preparedness plans through training and evacuation drills. For health adaptation (H1, H5), ensuring continuous medical supplies and requiring contingency protocols for health facilities are crucial. For flood awareness education (E1, E5), disaster risk reduction modules should be integrated into school curricula and mechanisms established for the rapid resumption of classes after floods. For social capital (S6, S4), institutionalizing community-based mutual cooperation and creating local communication networks, early warning systems, and village resilience committees are essential. These practical measures directly address the most sensitive indicators and provide actionable strategies for policymakers. Importantly, this study integrates physical flood vulnerability zoning with community-based social resilience assessment. The overlay of high-vulnerability sub-districts with moderate sustainability indices across the four resilience dimensions demonstrates that spatial exposure cannot be understood in isolation from adaptive capacity. By linking zoning outputs with resilience indices, the findings highlight priority areas where both structural mitigation and social-strengthening interventions are urgently needed. This integration ensures that the zoning approach truly reflects "zoning using social resilience". Overall, this study makes a methodological contribution by demonstrating how MCDA-based flood zoning can be combined with MDS-based social resilience assessment to generate quantitative indices and leverage (RMS change) analysis. The application in Kampar Regency highlights the potential for replication in other flood-prone regions in Indonesia and worldwide. Future studies should employ high-resolution spatial data, dynamic climate scenarios, and longitudinal monitoring of community adaptation. This study paves the way for advancing socio-ecological resilience studies and evidence-based disaster risk reduction policies.

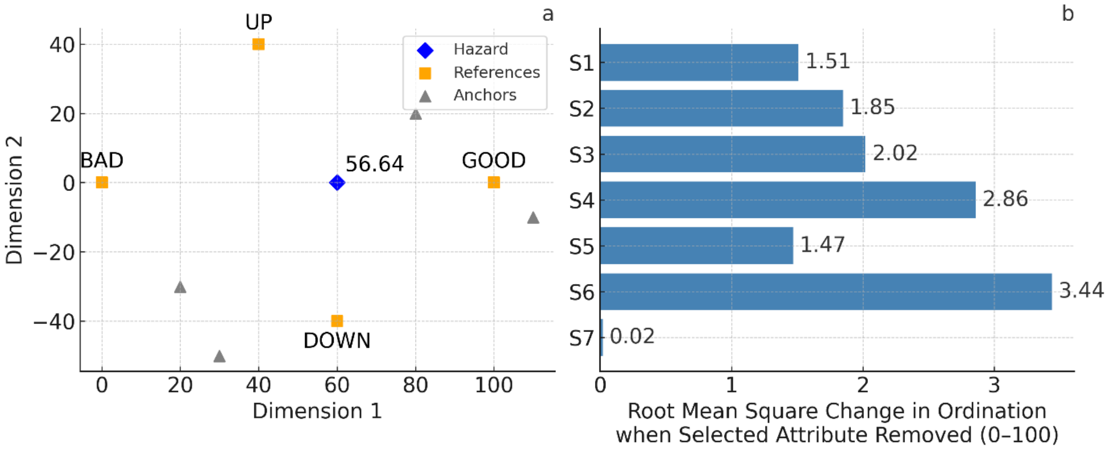

Fig. 5a) MDS result for Social Capital Adaptation (S), and b) Sensitive indicators based on Social Capital.

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