



FLOOD HAZARD ANALYSIS AND POLICY PRIORITIZATION USING INTERPRETATIVE STRUCTURAL MODELING IN PADANG CITY, INDONESIA

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ABSTRACT: Flooding in tropical coastal urban areas is increasingly influenced by a combination of intensified extreme events and increased spatial exposure resulting from uncontrolled land use. Therefore, this study aimed to analyze flood prone areas using spatial based hazard mapping validated with an Cyclone Senyar extreme event, so that the hazard classification accurately reflects actual flooding conditions. Furthermore, the resulting hazard and exposure patterns serve as an empirical basis for determining and prioritizing risk-reduction policies using Interpretative Structural Modeling (ISM). The analysis showed that 6 percent of the city's area fell within the low hazard class, 42 percent within the moderate class, 25 percent within the high class, and 27 percent within the very high class, with a dominant concentration in river corridors and coastal lowlands. Spatial overlay identified 186,621 buildings within the hazard zone, including 15,674 buildings located in the riverbank area, which was regulated as a protected zone. The extreme event on November 28, 2025, had significant impacts on residential areas and infrastructure, further strengthening the relationship between spatial exposure and loss magnitude. Furthermore, the ISM results showed that Enforcement of Spatial Utilization and Control Regulations, as well as Disaster Mitigation-Based Spatial Planning, were the policy elements with the highest driving force and served as the foundation for other interventions. Therefore, long-term flood risk reduction depended not only on structural mitigation but primarily on controlling exposure through consistent spatial governance, accompanied by effective regulatory oversight and enforcement mechanisms.

Keywords: Disaster, Geographic Information System, ISM, Flood, Padang

1. INTRODUCTION

Flooding is one of the most frequent hydrometeorological disasters and has significant impacts on social, economic, and environmental life, particularly in coastal urban areas [1]. Based on global literature analysis, climate change plays a role in amplifying these extreme events, including the intensification of extreme rainfall and flooding, specifically recorded in recent decades across various climate regions [2,3]. Several studies have shown that the combination of climate change, urbanization, and population growth contributes to increasing exposure to flood risk [4]. Furthermore, limited land in urban centers encourages the expansion of settlements into marginal areas, including floodplains and riverbanks that naturally function as water retention and runoff areas [5].

A flash flood in Padang City on November 28, 2025, caused by Cyclone Senyar, affected 6 districts and 32 villages, resulting in 11 deaths and 2 missing persons. A total of 5,555 housing units were affected,

with estimated losses of IDR 394.4 billion, while infrastructure damage reached IDR 776.3 billion. Social and health impacts were also significant, including hundreds of cases of acute respiratory infections (ARI) and diarrhea, as well as a high number of affected vulnerable groups [6]. These impacts were exacerbated by the presence of 15,674 buildings in riverbank areas [7], a community resilience level that remained in the moderate category [8], and several watersheds characterized by short upstream-downstream distances [9].

One of the non-structural approaches to flood disaster mitigation is spatial analysis-based hazard mapping, which aims to identify areas potentially affected by flooding. The dominant methods for flood risk analysis still rely on physical parameter-based hazard mapping using GIS and multi-criteria flood decision analysis at the watershed and urban scales, integrating static physical parameters such as slope gradient, rainfall, and land cover type to generate hazard zonation [10–17]. However, these methods are generally static, rely heavily on

weighting [18], and are rarely validated using actual inundation data from extreme events.

Advances in remote sensing technology, particularly radar data such as Sentinel-1, enable more accurate identification of actual flooding, even under cloud cover. Event-based flood assessment methods have been used to analyze flood dynamics in various cities [12,19]. Lessons from Cyclone Senyar provide insights into flood impacts during extreme events.

Although spatially-based flood hazard mapping has been widely applied, in many studies its use is often limited to identifying vulnerable areas without being effectively translated into policy directions and decision-making processes [20–22]. To address these limitations, it is necessary to integrate hazard analysis with a structured approach to policy formulation.

One approach that can be applied is Interpretative Structural Modeling (ISM), which enables the identification of relationships among key factors and the prioritization of policies within complex systems [22,23]. ISM has been widely applied across various fields to structure decision-making processes and to identify the primary driving elements within policy systems. However, in the context of flood risk management, its application is often not explicitly linked to empirical spatial data, particularly flood inundation based on extreme events.

Therefore, integrating extreme event based flood mapping with ISM offers an opportunity to bridge the gap between technical analysis and policy formulation. By linking spatial evidence of flooding and exposure with a structured policy framework, this approach enables the development of policy priorities that are not only systematic but also grounded in empirical data.

2. RESEARCH SIGNIFICANCE

This study aims to analyse flood-prone areas using spatial-based hazard mapping validated with an extreme event, specifically the Cyclone Senyar event, so that the hazard classification accurately reflects actual flooding conditions. Furthermore, this research explicitly links the spatial distribution of flooding and exposure levels to policy prioritization using Interpretative Structural Modeling (ISM). The research workflow is reproducible, meaning that the results of hazard and exposure analysis are not only used for technical analysis but also serve as an empirical basis for establishing a policy prioritization framework.

3. METHOD

3.1 Flood Inundation

The floods analysed in this study are river floods and flash floods in Padang City. The analysis was conducted by combining two methods: a flood hazard analysis prepared by Regulation No. 2 of 2012 of the National Disaster Management Agency of the Republic of Indonesia, and an analysis of actual inundation based on Sentinel-1 imagery. This combined method aims to obtain a spatial representation of flood hazards based on the geomorphological characteristics of the area and to validate actual inundation conditions during extreme flood events.

The data used in compiling the hazard map included a Digital Elevation Model (DEM) raster map, watershed boundaries, historical flood event data, and river networks (Figure 1). Additionally, this study utilized building and land-use data sourced from the 2024 Detailed Spatial Plan (RDTR) of Padang City to support the interpretation of the relationship between flood hazard distribution and land-use patterns. Although the RDTR data possesses a high level of detail, there are several limitations that must be considered, including the possibility of changes in building conditions on the ground after 2024.

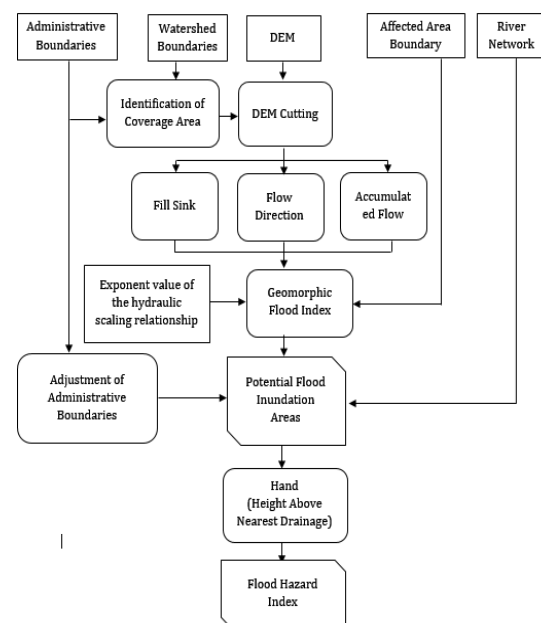


Fig. 1. Flood hazard map stages

These data processing produced an inundation map with an index value ranging from 0 to 1, depicting the spatial level of flood hazard.

Based on inundation height, low hazard was defined as inundation ≤ 0.75 meters, moderate hazard as $0.75\text{--}1.5$ meters, and high hazard as >1.5 meters. Meanwhile, based on the hazard index value, the low category was defined as ≤ 0.333 , the medium category as $0.333\text{--}0.666$, and the high category as > 0.666 [24,25].

Actual inundation analysis was also conducted based on Sentinel-1 imagery to identify areas that were inundated during the flood event. The images used consisted of pre-flood imagery and imagery captured during the peak flood event caused by Cyclone Senyar, which occurred on November 28, 2025. The use of radar-based Sentinel-1 (SAR) imagery was selected due to its ability to penetrate cloud cover and its effectiveness under extreme weather conditions [3]. The inundation analysis was conducted using a processing model developed from the Indonesian Natural Map mapping method [26] (Figure 2). The processing stages included intersect, erase, multipart to singlepart, and zonal statistics as a table.

In this study, the Synthetic Aperture Radar (SAR) data used were obtained from Sentinel-1 SAR, with acquisition dates of October 11, 2025 (prior to the flood event) and November 28, 2025 (during the flood event). The data were obtained through the Copernicus Data Space Ecosystem platform in the form of images that had undergone standard pre-processing, including radiometric calibration and geometric correction, making them ready for further analysis.

Flood detection was performed using a threshold-based classification approach based on backscatter values, utilizing VV (Vertical-Vertical) and VH (Vertical-Horizontal) polarizations. Initial classification was performed using a script on the Copernicus platform, where pixels with VH values < -15 dB were classified as water bodies, while values between -15 dB and -13 dB were interpreted as wetland areas [26]. This approach is based on radar characteristics, where water surfaces tend to have low backscatter values.

The next step involved integrating flood hazard map with the results of the Sentinel-1 inundation analysis using an overlay technique in a Geographic Information System (GIS). This integration aimed to assess the consistency between the hazard model and actual field conditions.

If the overlay results for a given area are classified as low or moderate risk on the flood hazard map based on physical parameters, but flooding is identified based on Sentinel-1 data during an extreme event (Cyclone Senyar), then the flood hazard class is reclassified as high risk to reflect

actual conditions. Remote sensing data is used as empirical evidence to correct the initial classification so that it better represents the flood potential in the field. [27].

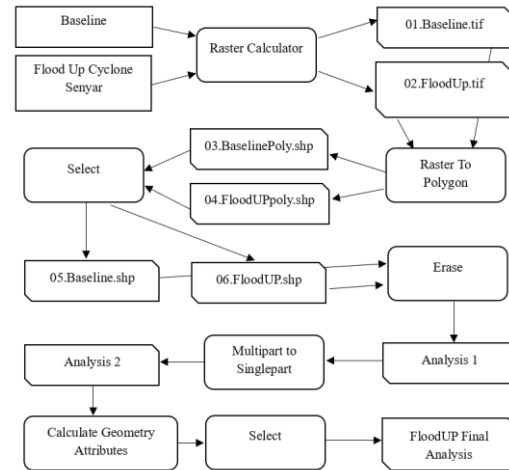


Fig. 2. Flood Inundation Model

A total of 100 sample points were randomly selected using ArcGIS software and classified into flood and non-flood categories. Field observations included information from local residents and evidence of flooding. Each sample point was then compared with the ground truth to evaluate accuracy, by calculating the proportion of correctly classified samples relative to the total number of samples [28].

3.2 Interpretative Structural Modeling (ISM)

To analyze policy directions for managing potential flood hazards in Padang City, ISM was applied. According to Umar & Triyatno (2023) [23] and Dewata & Umar (2019) [29], this model was designed to show complex aspects of a system through structured patterns using graphs and descriptive statements. Moreover, ISM was effective for structuring complex issues to define and clarify problems, as well as to assess and identify relationships among policies. The stages of ISM are as follows:

- 1) Break down each element into several sub-elements.
- 2) Determine the contextual relationships among the sub-elements of each element by conducting pairwise comparisons to determine whether these contextual relationships exist, based on expert judgment.
- 3) Construct a Structural Self-Interaction Matrix (SSIM) using the symbols V, A, X, and O.
- 4) Create a Reachability Matrix (RM) by replacing the symbols V, A, X, and O with 1 or

- 0.
- 5) Arrange the sub-elements within each element vertically or horizontally.
- 6) Construct a Driver Power Dependence (DPD) matrix for each sub-element. The element classification is divided quadrants I,II,III, IV.

4. RESULTS AND DISCUSSION

4.1 Flood Inundation

The distribution of hazard classes showed that the moderate category dominated, covering 8,341.34 ha, or approximately 42.4% of the total affected area (Table 1). The very high category was 5,258.79 ha (26.7%), followed by the high category at 4,892.76 ha (24.9%). Meanwhile, the low category covered 1,097 ha (5.6%), and the very low category was relatively insignificant spatially (0.4%). The accuracy assessment results indicate that 91 out of 100 validation points were correctly identified as flooded, resulting in an overall accuracy of 91%. This high level of agreement demonstrates that the flood hazard classification is consistent with observed inundation conditions.

Table 1. Flood Hazards in Padang City

District	Flood (ha)				
	Very Low	Low	Mode rate	High	Very High
Bungus					
Teluk Kabung	3.79	38.46	694.48	583.98	967.14
Koto Tangah	11.52	270.94	2,600.22	1,793.10	1,905.47
Kuranji	5.07	184.25	1,123.80	595.39	611.18
Lubuk Begalung	4.27	47.09	662.66	293.65	298.68
Lubuk Kilangan	10.50	16.42	481.27	354.04	455.81
Nanggalo	22.77	66.22	349.73	179.24	169.17
Padang Barat	0.32	68.64	226.84	126.73	13.44
Padang Selatan	0.83	34.07	175.67	199.21	137.17
Padang Timur	9.69	165.20	414.28	91.38	30.39
Padang Utara	2.76	175.71	436.15	125.45	22.92
Pauh	14.52	30.01	1,176.24	550.58	647.43
Total Area (ha)	86.04	1,097	8,341.34	4,892.76	5,258.79

In general, districts with a significant combination of very high and high flood areas tend to be located along major river systems and within transition zones between hilly areas and coastal lowlands. Conversely, districts such as Padang Barat

and Padang Selatan showed relatively smaller flood-prone areas, although concentrations in the moderate to high categories remained evident (Figure 3).

To further interpret the results, an overlay analysis was conducted between the flood hazard map and the land-use map (Figure 4). The overlay results show that built-up areas occupy a significant portion of the high- to very-high-hazard zones, covering 1,233.83 ha and 737.40 ha, respectively (Table 2). This indicates a high level of exposure of urban areas to flood hazards. The high concentration of built-up land in these hazard zones implies a potential increase in casualties and significant economic losses.

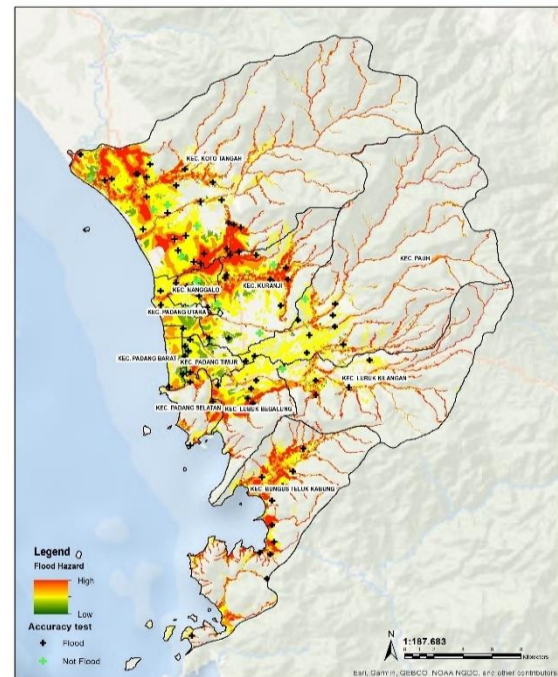


Fig. 3. Flood Hazard Map of Padang City

Additionally, the use of rice fields also shows a significant distribution across the moderate-risk (2,327.13 ha), high-risk (968.21 ha), and very high-risk (1,125.71 ha) categories. This reflects the vulnerability of the agricultural sector to flood events, particularly in the form of potential crop failures and economic losses within the agricultural subsector, which are currently being felt. This condition aligns with the characteristics of rice fields, which are generally located in low-lying areas and adjacent to river systems.

Other land uses, such as shrubland and mixed-use land, also contribute significantly to the high to very high hazard classes. Shrubland covers 133.28 ha (high) and 523.02 ha (very high). Mixed-use land also shows a fairly extensive distribution, namely 365.14 ha (high) and 292.37 ha (very high). There is concern that this will increase the risk of flooding in the future

because shrubland has the potential to be converted into developed land in the future.

Table 2. Land use in Flood Hazard Area

Landuse	Flood (ha)				
	Very Low	Low	Moderate	High	Very High
Built-up Land	46.38	629.29	2,567.06	1,233.83	737.40
Forest	6.54	35.17	947.74	933.49	1,665.84
Mangrove	-	0.87	9.37	5.97	27.53
Road	4.14	60.14	297.67	158.43	92.89
Railway	0.04	4.05	5.13	1.54	0.21
Rice Field	5.47	93.86	2,327.13	968.21	1,125.72
Shrubland	3.68	86.05	689.20	533.28	523.02
Farmland	6.56	29.45	326.96	280.56	237.02
Mixed-Use Land	7.17	73.97	600.23	365.14	292.37
Lake	-	0.00	1.02	0.28	0.38
Sports Field	0.17	4.68	70.92	7.53	1.45
Cemetery	0.02	0.08	4.31	6.57	1.81
Grassland	5.56	64.56	337.20	136.02	94.45
Other land uses	0.31	14.82	157.4	261.92	458.69
Total Area	86.04	1,097	8,341.34	4,892.76	5,258.79

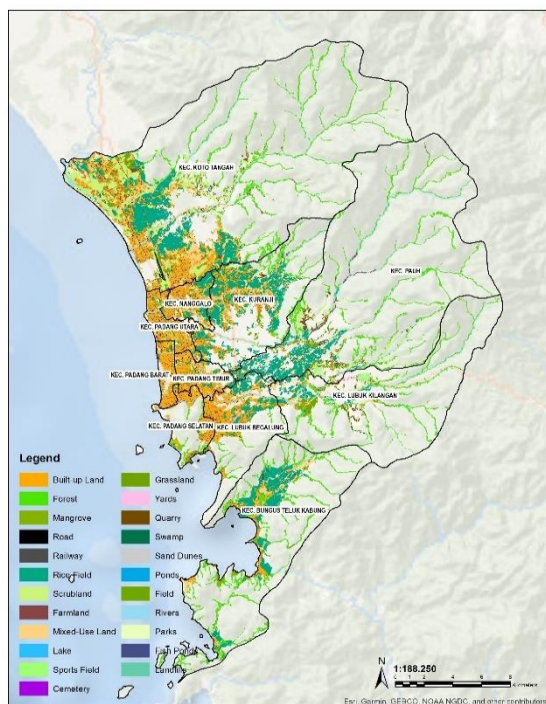


Fig. 4. Landuse in Flood Hazard Area

Although other land uses, cover relatively smaller areas, their presence within hazard zones remains significant because they can disrupt infrastructure and public services.

4.2 Buildings in Flood Hazard Areas

The overlay of flood hazard maps and building data confirmed that a total of 186,621 buildings fell into various hazard classes. Out of these, the moderate category dominated with 89,576 units, followed by the high category with 45,892 units and the very high category with 26,411 units. Meanwhile, 21,828 units fell into the low category, and 2,914 units fell into the very low category.

Sectorally, residential buildings constituted the most impacted category, totaling 181,243 units, the majority of which fell into the moderate (86,667 units), high (44,826 units), and very high (25,964 units) classes. Significant exposure was also observed in educational buildings (1,247 units), places of worship (1,110 units), commercial and service buildings (1,141 units), as well as offices (835 units). Healthcare buildings (223 units), tourism and entertainment (344 units), and industrial (126 units). Meanwhile, other categories such as defense and security (149 units), social (101 units), transportation (62 units), sports (38 units), and utilities (2 units) were also identified across various hazard classes, albeit in smaller numbers.

In general, the high number of buildings within the moderate to very high hazard classes confirmed that flood risk in Padang City was not only physical and spatial but also had broad social and economic implications, particularly for the residential and public service sectors. These conditions can disrupt urban activities, including housing functions, public services, economic activities, and access to critical infrastructure during flood events.

This risk is particularly critical for essential facilities such as primary schools and hospitals, where evacuation processes are more complex due to the presence of vulnerable groups, including children, patients, and individuals with limited mobility. The exposure of these facilities within flood-prone areas may therefore increase the potential for service disruption and complicate emergency response and evacuation operations during extreme flood events [30,31].

4.3 Interpretative Structural Modeling (ISM)

The experts involved in determining the policy directions for flood hazard management in Padang City were participants in the Doctoral Program in Environmental Science, where structured academic

discussions were conducted as part of the coursework. These participants represented various stakeholder institutions, including the Provincial Government of West Sumatra, the Padang City Government, academics from various universities, and community representatives.

The ISM analysis showed that among the 7 policy elements analyzed, E1 (Enforcement of Spatial Utilization and Control Regulations) and E2 (Disaster Mitigation-Based Spatial Planning) represented the top policy priorities (Level 4), with high driving power and relatively lower dependence compared to the other elements. Therefore, strengthening spatial planning policies and regulatory enforcement constituted the primary foundation influencing the success of other policies, including disaster training and simulations (E5 and E6), incentives and disincentives for spatial utilization (E3), structural mitigation (E4), and palapa metropolitan (E7) (Figures 5 and 6).

The policy recommendations in this study are based on empirical findings from the hazard and exposure analysis, which indicate that 186,621 buildings are exposed to various flood hazard classes. Additionally, there are 15,674 building units located in riverbank areas legally designated as protected zones [7], reflecting a high level of land-use violations in high-risk areas. These conditions empirically support element E1 (enforcement of land use control and management) as a top priority, as the data indicate significant land use non-compliance in high-risk areas.

This finding is reinforced by land-use analysis results indicating that built-up land occupies a significant area within the moderate-hazard class (3,048.71 ha) and high-hazard class (1,233.83 ha), accompanied by a high concentration of residential buildings and public facilities in high-risk zones. This situation indicates that the development of built-up areas tends to occur in high-hazard zones without adequate control. Therefore, element E2 (disaster-mitigation-based spatial planning) is crucial to ensure that disaster risk considerations are integrated into spatial planning.

In practice, spatial planning policies often stop at the planning stage without being followed by consistent implementation and enforcement of regulations. This highlights a gap between normative planning and actual conditions on the ground. Therefore, spatial planning priorities in the context of flood risk reduction must be accompanied by strengthened mechanisms for control, monitoring, and law enforcement.

This becomes increasingly important in the future, given the trend of land-use conversion, particularly from agricultural land such as rice fields

into residential areas. Such changes in land use have the potential to increase exposure in flood-prone areas if not balanced by strict oversight.

Moving forward, policies must ensure that no further building permits are issued for areas classified as high- or very-high-risk. Given the large number of buildings already located in high-risk areas, policies should also focus on enhancing community capacity through training (E5) and disaster drills (E6).

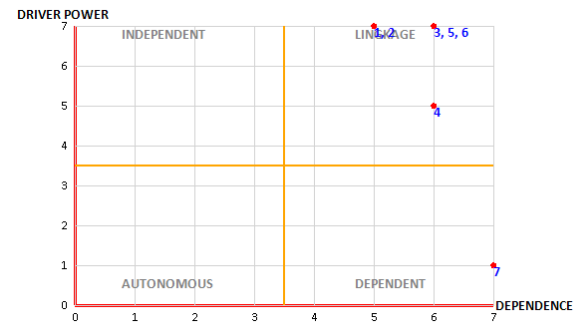


Fig. 5. Graph of the relationship between Power drivers and dependence relationships:

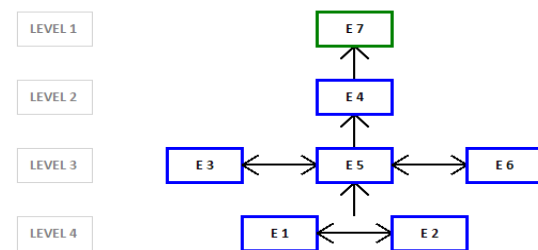


Fig. 6. Structure of Padang City's flood policy directives

Additionally, economic instruments in the form of incentive and disincentive systems are needed to encourage the relocation or adaptation of buildings that do not comply with land-use zoning, thereby serving as a deterrent against spatial planning violations. In practice, this approach may include restrictions on social assistance or sanctions for households that intentionally occupy prohibited zones such as riverbanks or floodplains. Incentive mechanisms can encourage appropriate land use, while disincentives or sanctions can limit development in flood-prone areas. This aligns with the findings of Egbalaki et al. (2017) [32], which indicate that compliance with policies increases when rewards and sanctions are in place.

Given the limited land availability in the city of Padang, this study advocates for the accelerated implementation of the PALAPA Metropolitan

Agglomeration. Under this framework, Padang will continue to serve as the center of economic activity, while the surrounding regencies and municipalities which have a lower risk profile are encouraged to support the residential land needs of the population.

5. CONCLUSION

This study examines flood hazard in Padang City using event based hazard mapping by the Cyclone Senyar event and integrated with policy prioritization through ISM. Padang City was characterized by areas with moderate to very high flood hazard levels. Based on analysis, 42 percent of the area fell into the moderate hazard class, 25 percent into the high hazard class, and 27 percent into the very high hazard class, with primary concentrations in river corridors and coastal lowlands. This high spatial exposure was evidenced by the 186,621 buildings located within the hazard zone.

Flood risk reduction policy directions based on the ISM results included enforcement of spatial planning regulations and control, implementation of disaster mitigation-based spatial planning, incentives and disincentives for spatial use, structural mitigation, disaster training, disaster simulations, and the Palapa Metropolitan. The hierarchical structure of the ISM confirmed that the primary policy priorities lay in the enforcement of spatial planning regulations and control, and the implementation of disaster mitigation-based spatial planning as a foundation.

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