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SUSTAINABLE DEVELOPMENT GUIDELINES FOR POST-DISASTER SETTLEMENTS IN PALU CITY: A SPATIAL PLANNING PERSPECTIVE

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Abstract: Post-natural disaster spatial planning requires an analysis of spatial carrying capacity and support to promote sustainable settlement development. This study aims to analyse the carrying capacity and spatial support of settlements and to formulate development guidelines for post-disaster settlements in Mantikulore District, Palu City. Using a sequential explanatory approach that combines quantitative and qualitative methods, data were gathered through observation, surveys, and documentation. The analysis reveals that the environmental carrying capacity and support for settlement zones could be more robust, with only the Lasoani and Poboya neighbourhoods demonstrating high capacity. The zoning guidelines for the district are categorised into allowed, conditionally allowed, limitedly allowed, and prohibited zones, with a priority on development in Lasoani and Poboya. This study contributes to the body of knowledge by offering a comprehensive framework for sustainable settlement planning in disaster-prone areas, highlighting the importance of robust zoning regulations and community engagement in enhancing urban resilience and sustainability.

Keywords: Settlement development, natural disasters, city zoning, sustainable development.

Introduction

Indonesia's cities face complex social, economic, and environmental challenges that affect urban life (Wandl *et al*., 2017; Panteleeva & Borozdina, 2022; Ouedraogo *et al*., 2023). The lack of effective city planning and management has contributed to a decline in urban environmental quality, leading to the proliferation of slums and natural disasters (Bathrellos & Skilodimou, 2019). Achieving better city management requires spatial planning, which involves designing and organising land use, infrastructure, and the environment to promote sustainable urban development (Turkelboom *et al*., 2018; Ouedraogo *et al*., 2023). Effective spatial planning can mitigate disaster risks by avoiding construction in disaster-prone areas (Puturuhu & Christianty, 2020; Yu *et al*., 2021; Hofmann, 2022). This involves zoning urban areas based on land-carrying capacity and environmental support to create safe, comfortable, and sustainable spaces (Liu *et al*., 2018; Kalfas *et al*., 2023). Specifically, proper spatial planning minimises risks by preventing development in vulnerable areas, such as earthquake- and flood-prone regions (Hofmann, 2022; Huang *et al*., 2023). The concepts of "absorption" and "carrying capacity" are also crucial in this context. "Absorption" refers to the intensity of unmet need relative to the effective supply, while "carrying capacity" relates to an area's ability to accommodate the number of properties without damaging the value of natural environmental elements (Foryś & Kazak, 2019). An in-depth understanding of these concepts is essential for sustainable spatial planning.

Spatial planning in Palu City involves recovering and reconstructing urban areas damaged by earthquakes. In 2018, the National Disaster Management Agency (NDMA) reported a 7.7 magnitude earthquake in Palu City, in which caused thousands of casualties, extensive infrastructure damage, and significant social and economic impacts on the community. Meanwhile, according to the Central Bureau of Statistics of Palu City, the city's the continued to grow at an average rate of 1.27% in 2022, leading to an increasing demand for residential land. As a result, Palu City requires well-structured spatial planning and an integration of social, economic, environmental, and infrastructural considerations (Teklemariam, 2022; Alipour & Dia, 2023). Directed spatial planning is crucial for sustainable urban growth (Naess, 2001; Lara *et al*., 2021; Kalfas *et al*., 2023). Proper zoning for residential areas and disaster-responsive zones must be the primary consideration in Palu City's planning (Akola *et al*., 2023; Dandoulaki *et al*., 2023). Therefore, effective spatial planning can help reduce disaster risks, including avoiding building settlements in disaster-prone areas (Mileu & Queirós, 2018; Rezvani *et al*., 2023).

The development of settlements in Palu City is integral for residential areas' post-earthquake recovery and reconstruction process. The selection of locations for these settlements must be based on a comprehensive risk assessment to ensure that they are safer, sustainable, and earthquake-resistant (Aman & Aytac, 2022; Hosseni *et al*., 2022; Alipour & Dia, 2023). Sustainable settlement development must consider environmental carrying capacity and land carrying capacity to balance urban growth with the environment's ability to maintain sustainability and quality. This approach ensures that development meets current needs without compromising the ability of future generations to meet their own (Luo *et al*., 2022; Pourebrahim *et al*., 2023). Key factors considered in the development of settlements in Palu City include protected zones, disaster-prone areas, land cover ratio, population size, potential area size, and the coefficient of built-up area requirement (Wang, 2018; Alipour and Dia, 2023). Sustainable settlement development not only provides safety and comfort for residents, but also contributes to long-term environmental resilience (Ibrahim *et al*., 2020; Harbiankova & Shcherbina, 2021). Therefore, the authors argue that a holistic approach, considering both ecological and social factors, is crucial in the planning of settlement development in disaster-prone areas like Palu City. This will help create a more resilient and sustainable environment for the community.

The studies supporting this research include: (1) Lara *et al*. (2021), who found that non-integrated city planning between the city centre and other sub-centres leads to urban issues in terms of economic, social, and environmental aspects; (2) Atmaca *et al*. (2023), who stated that the lack of resources for post-disaster temporary evacuation plans resulted in significant physical, economic, and social losses for the community; (3) Hofmann (2022), who mentioned that effective governance supports faster and better post-disaster recovery and resettlement; and, (4) Kalfas *et al*. (2023), who found that weak institutions in managing urban activities lead to social, economic, and environmental problems. These four studies emphasise that non-integrated city planning, a lack of resources for post-disaster temporary evacuation plans, and effective governance are crucial factors influencing rapid and successful recovery and reconstruction in Palu City. The difference between this study and previous research lies in the dimensions and aspects examined. This study not only considers the economic, social, and environmental aspects of city planning, but also emphasises the importance of coordination between the city centre and other sub-centres, as well as the need for strong governance and adequate resources to support post-disaster temporary evacuation plans. Furthermore, this study focuses on assessing the environmental carrying capacity and support as determining factors for the sustainability of post-earthquake settlement development in Palu City.

The long-term benefits to be obtained are as follows: (1) the availability of settlement land zoning that is not prone to natural disasters; (2) the provision of housing to support the social and economic activities of the community; and, (3) the establishment of sustainable spatial planning for settlements in Palu City. These three benefits will foster the creation of a balanced settlement environment, facilitating the effective utilisation of natural resources and the restoration of Palu City's environmental quality (Wardhani *et al*., 2021; Wang *et al*., 2022). Consequently, settlement development will ensure the safety and security of residents, enabling them to engage in economic activities and promote the sustainability of urban development (Purnamawati *et al*., 2023; Wei *et al*., 2023).

The development dynamics of Palu City, as the capital of Central Sulawesi Province, have led to an increase in settlement development, contributing to changes in land use and a decline in environmental quality (Surya *et al*., 2020). The urgency of this research is contextualised in several key aspects: (1) the recovery and reconstruction of residential areas after the earthquake; (2) spatial planning and settlement zoning based on an assessment of environmental carrying capacity and support; and, (3) the realisation of settlement development that ensures both human quality of life and environmental sustainability (Mumford, 2021). The research questions in this study are designed to address both critical and practical aspects of post-disaster settlement development in Palu City.

The study aims to determine the land carrying capacity and environmental support available for new settlements in Mantikulore District. It also seeks to identify guidelines for developing new settlements in the aftermath of natural disasters. Furthermore, the study explores ways to improve coordination between the city centre and sub-centres to enhance urban planning and disaster management. Additionally, it examines the importance of effective governance for the sustainability and resilience of post-disaster settlements. Finally, the research investigates how integrating social, economic, and environmental aspects can contribute to the overall success of settlement development in Palu City. Through these inquiries, the study aims to provide a comprehensive framework for sustainable and resilient urban development in disaster-prone areas.

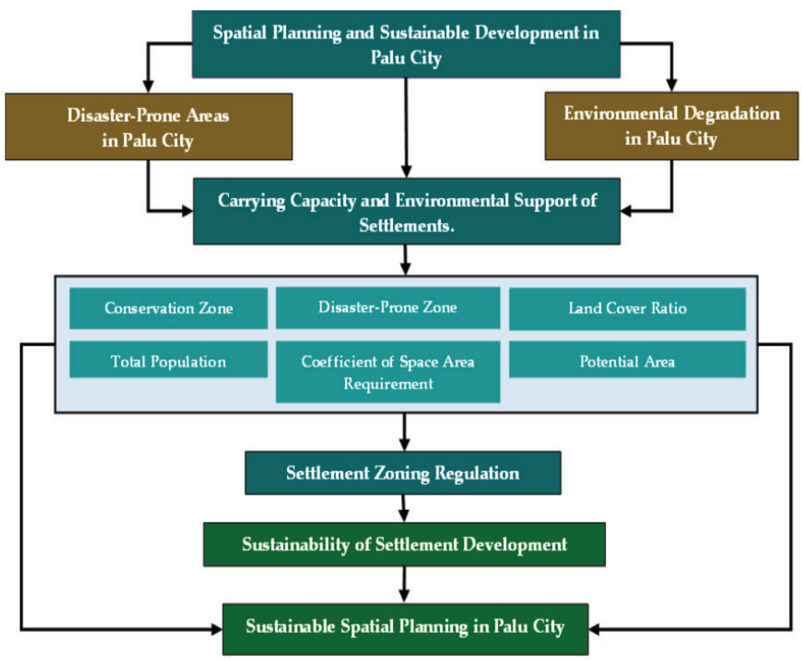

Figure 1: Conceptual Framework for Sustainable Spatial Planning and Development of Post-Disaster Settlements in Palu City, Central Sulawesi, Indonesia. Source: Author Elaborator

Materials and Methods

Type of Research

This study employs a mixed-methods approach, combining both quantitative and qualitative techniques (Creswell & Creswell, 2017). Quantitative data were gathered through surveys and documentation, while qualitative data were collected through observations and in-depth interviews.

Study Area

The study was conducted in Mantikulore District, Palu City, Central Sulawesi, covering an area of 206.80 km². The location of the research is illustrated in Figure 2.

Data Collection

The data in this study are categorised into two groups: (1) primary data, obtained through direct observation and fieldwork and (2) secondary data, gathered from existing studies related to the settlement areas of Palu City. The data collected through observation include (1) land use; (2) activity systems; (3) spatial utilisation patterns; and, (4) environmental characteristics. The instruments used for observation are (1) field notes, (2) periodic notes, and (3) checklists. Furthermore, the documentation data used in this study include administrative data, spatial planning policies, land types, rainfall, topography, slope, hydrology, and land use.

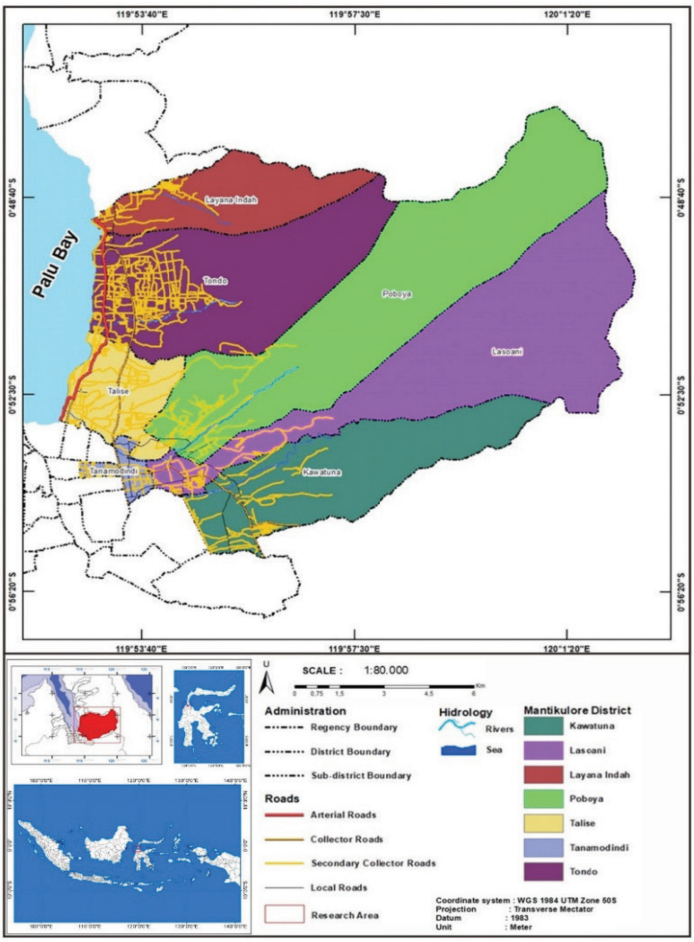

Figure 2: Research location post-disaster settlements in Palu City
Source: Geospatial Information Agency Indonesia (GIA)

Research Variables

The research variables in this study are derived from the theoretical framework proposed by Muta'Ali *et al*. (2012). The study focuses on determining the land carrying capacity and land absorption capacity of settlements in the Mantikulore District of Palu City. Key variables include the land area available for settlement, conservation zones, disaster-prone zones, land cover ratio, total population, total potential area, and the coefficient of space area requirement. Additionally, the study seeks to identify guidelines for developing new settlements following natural disasters in the same district, focusing on variables such as settlement capacity and the disaster-prone zones outlined in the spatial plan of Palu City. These variables collectively provide a comprehensive understanding and framework for sustainable urban planning and effective disaster management in Palu City.

Technical Analysis

Concept of Absorption and Carrying Capacity

In the context of real estate, the concept of "absorption" refers to the intensity of unmet need relative to effective supply or demand. Essentially, absorption falls between market capacity and effective supply (Foryś & Kazak, 2019). On the other hand, "carrying capacity" pertains to an area's ability to accommodate a certain number of properties without compromising the natural environment's value or the benefits to property users. In planning, carrying capacity refers to the maximum number of properties that can be separated from the space and can perform certain functions without damaging the value of the natural environment (Foryś & Kazak, 2019). Considering both concepts together provides a more complete picture of the real estate market dynamics.

Settlement Carrying Capacity

Carrying capacity refers to an area's ability to support human life and activities. This analysis uses quantitative methods to evaluate an area's capability to provide sufficient settlement land for a specific population. Key data include available land for settlements, population size, and land requirement standards per individual (Asefa *et al*., 2021; Tang *et al*., 2022). For settlement development, a land cover ratio of 60% of the potential area is considered (Muta'Ali *et al*., 2012).

The formulas for calculating the developable land area and potential area are:

$$LPm = LWP \text{ x } 60\% \qquad (1)$$

where

LPm = Area of land available for settlement development (ha)
= Potential area (ha)
= Land cover ratio

To find LWP, use:

$$LWP = LW - (LKL + LKRB) \qquad (2)$$

where

LWP = Potential area size (ha)
LW = Total area size (ha)
LKL = Protected area size (ha)
LKRB = Disaster-prone area size (ha)

After determining the developable land area, the next step is to calculate the carrying capacity index, which compares the potential area with standard per capita space requirements, taking into account geographic location and latest population data. This evaluation assesses the area's ability to optimally accommodate the population (Muta'Ali *et al*., 2012).

$$DDPm = \frac{LPm/JP}{a} \qquad (3)$$

where

DDPm = Residential Carrying Capacity
LPm = Land Area Available for Settlement (ha)
JP = Population (Individuals)
a = Coefficient of Space Requirement (ha/capita)

The carrying capacity index values for settlements are:

- *DDPm* > 1 : High carrying capacity can accommodate more population.

- *DDPm* = 1 : Optimal carrying capacity, balance between population and available area.
- *DDPm* < 1 : Low carrying capacity, cannot accommodate additional population.

Residential Absorption Capacity

Carrying capacity also pertains to a region's ability to accommodate an optimal population (Sunkar *et al*., 2022; Van Der Meer *et al*., 2023). This analysis considers population growth dynamics, which lead to increased housing density (Ali *et al*., 2021; Strobl *et al*., 2022). Required data include the settlement carrying capacity (DDPm) and the latest population size. The formula for calculating the optimal population capacity is:

$$DT = DDPm \times JP \quad (4)$$

where
DT = Residential absorption capacity
DDPm = Residential carrying capacity
DDPm = Population size

Zoning guidance

Zoning guidance controls development through zone regulations based on the city's carrying capacity. This qualitative analysis (Wang & Cao, 2022) uses settlement carrying capacity and disaster characteristics in the Mantikulore District of Palu City. The guidelines are informed by the National Disaster Management Agency's Technical Guidelines for Regional Disaster Management Plans. Zoning classifications facilitate appropriate actions during disasters, as shown in Figure 3.

Results and Discussion

Settlement Carrying Capacity Analysis

The analysis of settlement carrying capacity involves calculating the index value for potential areas, taking into account the per capita space requirements based on geographical location (rural and urban) and the most recent population data. For this analysis, it is important to distinguish between "absorption" and "carrying capacity". Absorption measures the intensity of population demand on available land, while carrying capacity assesses an area's ability to support a certain amount of population without harming the environment.

This index value helps in evaluating a region's potential to optimally accommodate

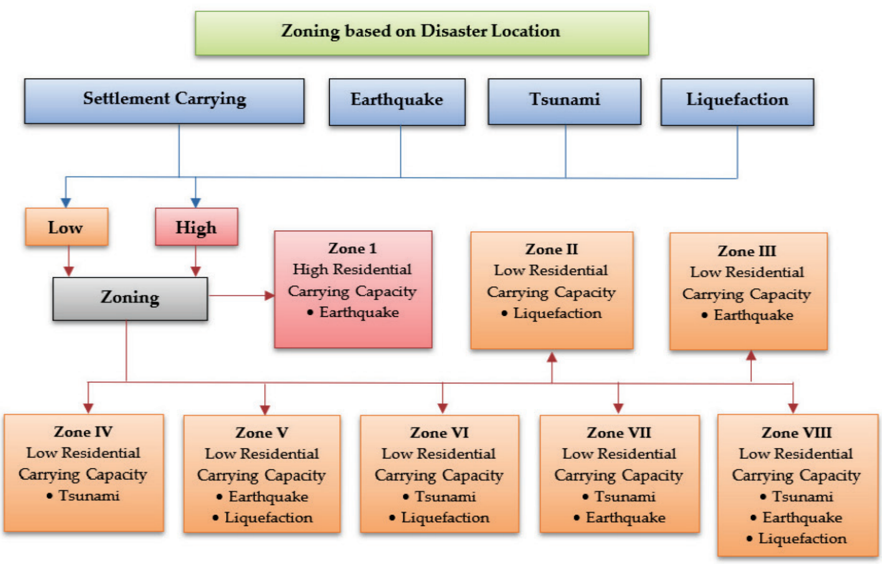

Figure 3: The concept of determining the zoning of disaster-prone post-disaster settlements in Palu City.
Source: The National Disaster Management Agency of Palu City

its population. The analysis results, presented in Table 1, indicate that the settlement carrying capacity in Mantikulore District varies significantly, with high settlement carrying capacities observed in Lasoani and Poboya sub-districts, while low settlement carrying capacities are noted in Kawatuna, Layana Indah, Talise, Tanamodindi, and Tondo sub-districts. This variation is primarily due to the limited potential areas available in these sub-districts.

Settlement Absorption Capacity Analysis

The capacity of a particular area to accommodate and support an optimal population is crucial for sustainable urban planning (Pellicano *et al*., 2022; Karami *et al*., 2023). This capacity analysis addresses the dynamics of population growth, which often lead to increased housing density and land use (Ehrlich *et al*., 2021; Xu *et al*., 2022). The analysis uses data from the settlement carrying capacity analysis (DDPm)

Table 1: Results of settlement carrying capacity analysis in Mantikulore District

No.	Sub-districts	Total Population	LWp (ha)	DDPm Index	DDPm
1	Kawatuna	5529	-365.58	-0.61	Low Residential Carrying Capacity
2	Lasoani	11435	845.16	1.42	High Residential Carrying Capacity
3	Layana Indah	4400	-376.74	-0.63	Low Residential Carrying Capacity
4	Poboya	3528	1041.52	1.74	High Residential Carrying Capacity
5	Talise	21883	-261.69	-0.44	Low Residential Carrying Capacity
6	Tanamodindi	13242	-18.34	-0.03	Low Residential Carrying Capacity
7	Tondo	14461	-485.08	-0.81	Low Residential Carrying Capacity

Source: Analysis Results (2023)

Table 2: Results of settlement capacity analysis in Mantikulore District

No.	Sub-districts	DDPm	Total Population	DT (Capacity)	Information
1	Kawatuna	-0.61	5529	-2,268	The areas cannot accommodate and support settlements
2	Lasoani	1.42	11435	9,981	The areas can accommodate and support settlements
3	Layana Indah	-0.63	4400	-1,852	The areas cannot accommodate and support settlements
4	Poboya	1.74	3528	2,976	The areas can accommodate and support settlements
5	Talise	-0.44	21883	-5,516	The areas cannot accommodate and support settlements
6	Tanamodindi	-0.03	13242	-435	The areas cannot accommodate and support settlements
7	Tondo	-0.81	14461	-10,426	The areas cannot accommodate and support settlements

Source: Analysis Results (2023)

and the most recent population figures. Table 2 shows that Mantikulore District needs to improve its capacity to accommodate its population. Among the areas evaluated, Lasoani Village exhibits the most significant settlement capacity, able to support 9,981 people.

Analysis of Settlement Development Directions in Mantikulore District

The direction of settlement development in Mantikulore District is determined using a qualitative descriptive analysis. It takes into

Table 3: Formulation of settlement development guidelines in Mantikulore District

Zone	DDPm	Natural Disasters	Area (Ha)	Development Direction of Settlements
Zone I	High Residential Carrying Capacity	Earthquake	1883.43	• Zoning earthquake-prone areas and regulating land use. • Implementing earthquake-safe building standards. • Applying land use regulations and building permits based on earthquake risk assessment. • Socialising disaster threats to the community, schools, and media.
Zone II	Low Residential Carrying Capacity	Liquefaction	4.26	• Relocating settlements affected by liquefaction to high-capacity areas in Zone I. • Developing city-level evacuation plans for priority disaster zones.
Zone III	Low Residential Carrying Capacity	Earthquake	16895.14	• Developing settlement placement plans to reduce housing density in earthquake-prone areas. • Establishing emergency response facilities and infrastructure. • Public awareness campaigns on disaster threats.
Zone IV	Low Residential Carrying Capacity	Tsunami	3.16	• Establishing land use regulations and building permits. • Developing buffer zones and disaster mitigation areas. • Public awareness campaigns on disaster threats.
Zone V	Low Residential Carrying Capacity	Earthquake Liquefaction	781.05	• Developing settlement placement plans to reduce housing density in earthquake-prone areas. • Public awareness campaigns on disaster threats. • Relocating settlements affected by liquefaction to Zone I (Lasoani and Poboya).
Zone VI	Low Residential Carrying Capacity	Tsunami Liquefaction	0.14	• Establishing land use regulations and building permits. • Developing buffer zones and disaster mitigation areas. • Public awareness campaigns on disaster threats. • Relocating settlements affected by liquefaction to Zone I (Lasoani and Poboya).
Zone VII	Low Residential Carrying Capacity	Tsunami Earthquake	118.39	• Prohibited for further development. • Creating settlement placement plans to reduce housing density. • Prioritising land use for protected areas and green spaces. • Public awareness campaigns on disaster threats.
Zone VIII	Low Residential Carrying Capacity	Tsunami Earthquake Liquefaction	25.03	• Prohibited for further development. • Prioritising space for protected areas and green spaces. • Public awareness campaigns on disaster threats. • Relocating settlements affected by liquefaction to Zone I (Lasoani and Poboya).

Source: Analysis Results (2023)

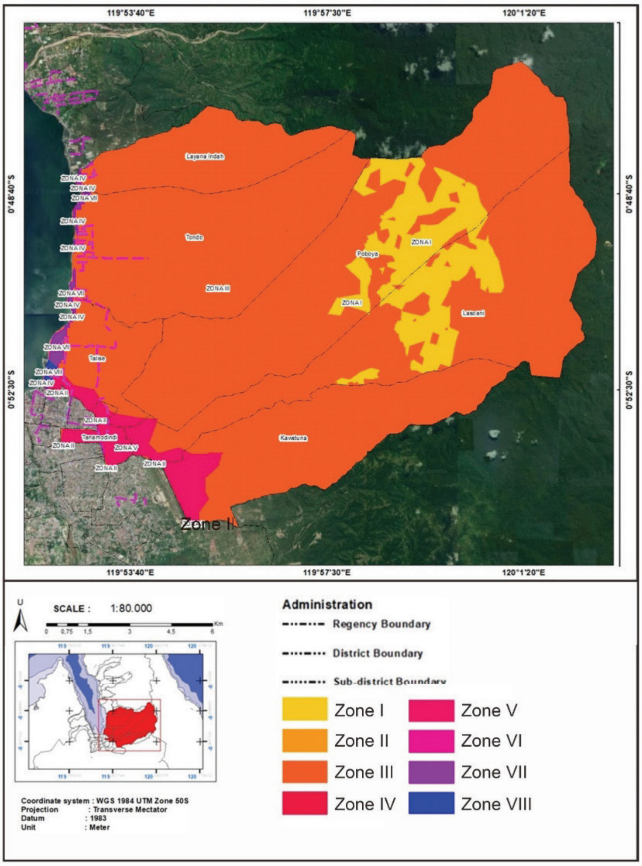

Figure 4. Map of natural disaster vulnerability zones in Mantikulore District.
Source: Analysis Result

account the results from the settlement carrying capacity analysis, population capacity, and natural disasters in the area.

Conclusions and Limitations

The analysis of carrying capacity and residential zone capacity in the Mantikulore District of Palu City reveals a general deficiency in both environmental carrying capacity and residential zone capacity. However, the Lasoani and Poboya sub-districts exhibit robust levels in both areas. To address the gaps in other sub-districts, further efforts are needed to enhance their environmental carrying capacity and meet residential development needs. Therefore, it is imperative to implement stringent governmental regulations on spatial utilisation and land use, particularly in disaster-prone areas, to avoid regions vulnerable to tsunamis, liquefaction, and earthquakes.

To foster sustainable settlement development in Mantikolore's sub-districts, implementing spatial zoning regulations is imperative. Zoning activities in the Lasoani and Poboya sub-districts should adhere strictly to relevant guidelines. Similarly, conditional zoning in Kawatuna, Layana Indah, Talise, Tanamodindi, and Tondo sub-districts must strictly follow the prescribed regulations. These zoning initiatives extend to the aforementioned villages, highlighting the critical importance of ecosystem resilience and disaster mitigation-oriented settlement management in these areas. Sustainable development for residential zones in the Mantikulore area of Palu City embodies three fundamental principles: (1) environmental sustainability, aimed at ensuring environmental stability; (2) economic sustainability, which involves promoting community economic activities that do not harm the environment; and, (3) social sustainability, focused on fostering community trust within the inhabited spaces.

The establishment of environmental education within the community goes beyond participation; instead, it involves reinforcing sustainability principles by integrating local values, within the context of understanding potential disaster threats. Complementing this effort, the community should actively prepare disaster infrastructure and provide evacuation and mitigation facilities to ensure comprehensive disaster management. Additionally, fostering synergy among stakeholders enhances the monitoring mechanism. This approach helps the community gain insights into its vulnerable locations and the necessary regulations, particularly in high-risk disaster areas. Evaluation ensures that settlement development avoids negative areas, thus safeguarding ecosystem stability and environmental sustainability. The evaluation mechanism operates within a timeframe agreed upon by stakeholders, involving both governmental entities and the community.

The necessary policies include several crucial actions: Firstly, the rigorous enforcement of spatial zoning regulations; secondly, the prioritisation of sustainable development principles to bolster resilience against natural disasters; and, thirdly, the preservation of ecosystem stability through meticulous development practices, including the refinement of spatial areas or zones according to the spatial plan. Additionally, robust monitoring mechanisms must be established to ensure compliance with these regulations and principles. Public engagement and education initiatives are essential to foster community understanding and support for sustainable development goals. Lastly, ongoing evaluation and adaptation of policies based on emerging challenges and insights are imperative to ensure their effectiveness in achieving long-term urban sustainability.

While the study offers significant insights into the spatial planning and development of post-disaster settlements in Palu City, several limitations must be acknowledged: (1) The availability and accuracy of data related to land use, population density, and environmental conditions were restricted. Some data relied on secondary sources, which may not reflect the most current conditions; (2) The research focused solely on Mantikulore District in Palu City, limiting the generalisability of the findings to other districts or cities with different geographical and socio-economic contexts; (3) The time frame of the study was confined to the immediate aftermath of the 2018 earthquake, and long-term changes and the evolution of settlement patterns post-recovery were not covered within the scope of this research; (4) Although the sequential explanatory approach combining quantitative and qualitative methods was comprehensive, it may not capture all nuances and dynamic factors influencing settlement development in post-disaster contexts; (5) The recommendations, including strict zoning regulations and enhanced community engagement, may face practical challenges during implementation due to political, economic, and social barriers; and, (6) The study did not extensively account for climate change and its potential impact on future natural disaster frequency and severity, which could significantly alter settlement planning and development strategies. Future research should address these limitations by incorporating more comprehensive data sets, expanding the geographical scope, and considering long-term and climate-related variables to enhance the robustness and applicability of the findings.

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Conflict of Interest Statement

The authors declare that they have no conflicts of interest.

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