Integrated Assessment of Urban Land Carrying Capacity (ULCC) for Reducing Earthquake Risk Risaster in Palu City

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Keywords: land carrying capacity, urban area, earthquake disaster, Palu City

Posted Date: August 24th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-764274/v1

Abstract

The land is a natural resource that has limitations to accommodate human activities. Rapid urban population growth, continuous expansion of urban scale, rapid socioeconomic development, and increased pressure on land resources between residents and urban land are monumental contradictions when urban planning does not match land carrying capacity. Assessing urban land carrying capacity is very important to evaluate and obtain an overview of the land capability level by classifying its capacity to be designed according to the area function; to get an overview of the potential and constraints of each land capability class, and to serve as a basis for future regional development. This research was conducted in Palu City, a national urban area in Indonesia. It has limited regional development because it is an area prone to high earthquake disasters. Developing the area requires assessing the land's carrying capacity, especially to minimize the risk of earthquake hazards. The assessment involves three stages of analysis, namely Mapping Earthquake-Prone Areas with Mapping of Earthquake-Prone Areas with seismic micro-zonation; Land Capability Assessment; and Comparative Analysis of Land Capability and City Planning of Palu 2030. This study's results indicate that 74.56% of Palu City is an earthquake-prone area, dominated by land capability classes type A to B, namely low to very low land capability classes (55.42%). Thus, there are physical limitations in urban development. However, suppose it is integrated with the spatial plan of Palu City until 2030. In that case, most (56.07%) are already in accordance with the carrying capacity of their land, especially in protected areas. However, land development still does not comply with their carrying capacity (35%) in cultivation areas with earthquakes. High and covering an area of 24% of the total area of Palu City requires special attention in the development of its area going forward. The requirement that land use plans that do not comply with their carrying capacity must be strictly controlled, especially in high disaster-prone areas.

Introduction

The land is one of the main abiotic components of the environment, the fundamental matrix of life (Xiao et al., 2021). The land has a limited carrying capacity. Therefore, its use must be maintained to prevent damage or degradation (Goodland, 1995). High pressure on population growth in various places has resulted in pressure on land through overuse. Degradation occurs on land used excessively beyond its natural capacity and carrying capacity (Goldshleger et al., 2009). Land degradation is the loss of a land's capacity to grow due to either physical or chemical processes. (Singer et al., 2002). Many studies show that land quality deteriorates due to misuse and exceeds its ability (Dougill et al., 2002; Boix and Zinck, 2008; Adamu et al., 2014). Incorrect land use will require high costs to repair; if the degradation reaches an irreversible stage, the damage will be irreparable (Gupta et al., 2010; Sudershan, 2003). As with other non-renewable natural resources, rational land use is an essential indicator of development (Chang et al., 2011) and economic growth (Pilvere et al., 2014). This is even related to the concept of sustainable development (Akinci et al., 2013). Sustainable development is defined as development that meets the current generation's needs without jeopardizing future generations' ability to meet their own (Anonim, 1987; Munasinghe, 1993; Feizizadeh dan Blaschke, 2012).

The fast population growth requires new areas to fulfill primary needs, especially in urban areas. In turn, this need causes natural resources such as forests, grasslands, wetlands and agricultural lands to be converted into settlements or industrial areas. It causes the land to be used in ways that are not suitable for its potential and exceed its carrying capacity (Symeonakis et al., 2007). Land use planning that allows a good legacy of land resources for future generations is essential. An integrated approach to sustainable land use planning is explicitly stated in Agenda 21 (Smardon, 2008). This can be done through planned and sustainable land use and in a way that is appropriate to its capabilities and potential through ULCC.

Urban Land Carrying Capacity (ULCC) is part of evaluating the environment's carrying capacity, which refers to its maximum carrying capacity (Costantini, 2009). Although the carrying capacity of an area is not constant, this suggests a kind of human-environmental lead-lag relationship. Carrying capacity is conceptualized as a full load or a load, an essential dimension of carrying capacity [20]. Projected economic, technological, and social growth rates and the material requirements needed decide the number of people a region can support with its land resources. To live on various time scales (Shi et al., 1991; Feng, 1994). consequently, the carrying capacity of urban land can be defined as the level of human activity, population growth, land use patterns and extent, and physical development that the urban environment can support without significant and irreversible damage (Sarma et al., 2012).

There are several ways to assess ULCC; one way is to evaluate the carrying capacity of the environment is a land capability-based evaluation (Singer, 2002). Land use planning can be guided based on this assessment. Land can be used according to its capabilities (Sharififar et al., 2013), and use can be directed based on its carrying ability. ULCC research has been the subject of several studies in the Palu Region, including the analysis of land carrying ability to monitor land use growth for buildings in residential areas and visitor accommodation facilities based on land characteristics. Based on the land capacity calculation, i.e., the amount of per capita land consumption and the level of population density per hectare, Palu City's land carrying capacity in 2010–2030 is still available and did not exceeded the threshold to support the area of land use for buildings and population growth (Amar, 2017). In addition, other research related to the carrying capacity of the land for settlements in Mantikulore District based on variables of the slope, groundwater potential and areas prone to flooding and landslides obtained results that there are conditional locations according to the allotment of settlements. Still, areas or zones that are unsuitable can be directed as gardens, forests, and green open spaces (Gerika, 2018). As with evaluating the carrying capacity of land in several other studies, the threat of natural disasters, especially earthquakes, has not become a significant consideration.

The effect of earthquakes in urban areas is a complicated issue exacerbated by multi-hazard and significant risk issues, a large inventory of vulnerable physical components, and socioeconomic issues. Because earthquakes are complex, they must be carefully considered. They were able to predict when and where it will happen. The foundation and vital rationale for practical risk reduction activities are rational urban risk predictions and projected losses from future significant earthquakes. Therefore, for urban centers affected by a powerful quake, specific emergency preparedness and procedures must be established during and before the earthquake, requiring calculating the earthquake's impact on the physical and social environment. Population, buildings, infrastructure, systems, and socioeconomic activities are all “Elements at Risk” in urban areas (Erdik, 2006), so possible earthquake hazards must be factored into the measurement of the land's carrying capacity for urban planning.

Palu City is one of the cities in Central Sulawesi Province with a high earthquake disaster index because it cannot be separated from its position located at the confluence of the Pacific, Indo-Australian Eurasian plates (NADM, 201). On the other hand, Palu City is one of the national urban areas designed by the Indonesia National Spatial Plan (Indonesia Government Regulation Number 26 the Year 2008, 2008) as the central hub for export-import activities or the gateway to the international area, the center of industrial activity. Moreover, services on a national scale or serving several provinces, the central node for national scale transportation or serving several regions and urban areas on the coast can become international hub ports and export gates for marine and fisheries activities. An area of 395.06 km2 consists of 8 (eight) districts, namely West Palu District, Tatanga District, Ulujadi District, South Palu District, East Palu District, and Mantikulore District North Palu District, and Tawaeli District, as shown in Fig. 1. The rapid development in Palu City has led to very dynamic land use changes, especially the increasing need for settlements inconsistent with their designation. The rapid development in Palu City has led to very dynamic land use changes, especially the increasing need for settlements that are not following their designation. Due to the physical limitations of the environment and the threat of a relatively large and recurring earthquake, Palu City requires urban development planning by considering aspects of urban land capacity to mitigate threatening earthquakes. This research aims to assess the land's carrying capacity to develop Palu City while minimizing earthquake disasters. This study will analyze the land's development capacity following the function of the area; get an overview of each land capability class, and consider the main aspects of earthquake disasters by using earthquake susceptibility micro-zonation.

Materials And Methods

In this study, the ULLCC was analyzed by three assessments, consisting of :

1. Mapping of Earthquake-Prone Areas with Seismic Micro-zonation;

2. Land Capability Assessment; and

3. Comparative Analysis of Land Capability and City Planning of Palu 2030.

Mapping of earthquake-prone areas with seismic micro-zonation

Palu City is on the Palu-Koro fault line, an active fault that spreads 170 kilometers along the mainland of Sulawesi Island, moving at a speed of 35 to 8 millimeters per year. Since the 19th century, earthquakes have occurred in Central Sulawesi. Some of them were of high magnitudes, such as in 1968 (6.7 SR), 1993 (5.8 SR), 2005 (6.2 SR), and 2008 (6.7 SR) (7.4 SR) (Bellier et al., 2001). On this route, earthquakes with a magnitude greater than 4.5 and a depth of fewer than 30 kilometers occurred mainly in Central Sulawesi and off the coast of North Sulawesi. The earthquake formed due to the tectonic process that occurred earlier. One of the mitigation efforts is through micro-zonation mapping of earthquake-prone areas to minimize damage in these areas. Micro-zonation is generally recognized as the most accepted tool in seismic hazard assessment and risk evaluation. Zoning concerning ground motion characteristics takes into account source and location conditions (TC4-ISSMGE, 1999). Micro-zonation is dividing an area into zones that have relatively similar exposure to the effects of earthquakes. Micro-zonation maps are very useful for earthquake-resistant infrastructure planning, land use management, estimating potential liquefaction, estimating damage to buildings, estimating casualties and estimating economic losses due to earthquakes in the future.

In general, seismic micro-zonation planning starts with a simple assessment based on current regional hazard forecasts, seismotectonic and macro-seismic studies. Several localized hazard factors are then assessed and mapped on a Geographical Information System (GIS) platform using a standardized and uniform geographic reference scheme. The four key sections of the general technique for seismic micro-zonation of a region are as follows: (1) Ground motion parameter estimation based on historical seismic data and seismic motion documents, which include the position of possible sources, magnitudes, mechanisms, and epicentral distance; (2) Characterization of the location using geological, geomorphological, geophysical, and geotechnical data; (3) Evaluation of local location effects, such as location amplification, main frequency, liquefaction hazard, landslides, and tsunamis; and (4) preparation of seismic micro-zonation maps.

In this study, seismic micro-zonation was carried out through microtremor analysis to determine the characteristics of the soil layer based on the parameters of the dominant period and the amplification factor. Microtremor micro-zonation divides an area based on certain parameters having considered characteristics, including ground vibration, amplification factor, and dominant period. The stages of analysis carried out are through (1) HVSR (Horizontal - Vertical Spectral Ratio) analysis, namely comparing the spectrum of the horizontal component to the vertical component of the microtremor wave; and (2) Analysis of dominant frequency and dominant period, namely the frequency value of rock layers in the area so that it can show the type and characteristics of the rock. The microtremor data used in this study were 36 data collection points in Palu City. The data is then processed using the HVSR method to obtain the dominant frequency value that will determine the level of earthquake vulnerability. The dominant frequency value will calculate the value of the wave velocity (amplification) up to a depth of 30 meters (Vs30) which will then be used to determine the level of disaster risk that occurs through the Peak Ground Acceleration (PGA) value. Furthermore, to obtain a micro-zonation map, data processing used the overlay technique and weighting of the GIS by providing the highest earthquake hazard values for each parameter of PGA, amplification (Vs30), and maximum period using the analytical hierarchy process (AHP). This earthquake micro-zonation map was then verified using field survey data that showed the location of the destroyed buildings and classified according to the Modified Mercalli Intensity (MMI) class.

Land capacity assessment

To determine the land carrying capacity in Palu City, a land capability analysis obtained an overview of the land capability level to be developed as an urban area by determining the Land Capability Unit (LCU), which consists of LCU morphology, LCU of Slope Stability, LCU of Foundation Stability, and LCU of Water Availability. The method used in this analysis is a map overlay and data input to each LCU using a thematic map with a scale of 1: 25,000, as shown in Table 1.

Table 1
Evaluation of Land Capability Unit

LCU	Data	Classification of LCU	Score
1. Morphology	a. Topography	a. Very High Morphology	1
	b. Morphology	b. High Morphology	2
		c. Moderate Morphology	3
		d. Low Morphology	4
		e. Very Low Morphology	5
2. Slope Stability	a. Topography	a. High Slope stability	1
	b. Morphology	b. Moderate Slope stability	2
	c. Slope	c. Low Slope stability	3
	d. Geology	d. Very Low Slope stability	4
	e. Hydrogeology		
	f. Rainfall		
	g. Land Use		
	h. Disaster		
3. Foundation Stability	a. Geology	a. Low Foundation stability	1
	b. Hydrology	b. Moderate Foundation stability	2
	c. Land Use	c. High Foundation stability	3
	d. Geology Hazard		
	e. Land Use		
4. Water Availibility	a. Hydrology	a. Very Low Water Availability	1
	b. Climatology	b. Low Water Availability	2
	c. Morphology	c. Medium Water Availability	3
	d. Topography	d. High Water Availability	4
	e. Geology	e. Very High Water Availability	5
	f. Land Use Existing		

The total land capability was classified by overlaying each LCU by multiplying the final value (weighted one by one so that the resulting map of the total absolute value is multiplied by the overall cumulative weight using the principle of the AHP. The digital spatial analysis method using the GIS produces a land capability classification map as output.

Comparative analysis of land sustainability and spatial planning of Palu City 2030

Comparative analysis of land sustainability and spatial planning aims to determine land use capability between land capability analysis, earthquake hazard mapping, and spatial use plan 2030. This will help determine areas for which development is currently suitable and unsuitable so that further actions can be taken on appropriate and unsuitable to determine ways of improvement of Palu planning based on land carrying capacity.

The method overlays the land capability map and earthquake hazard risk map with the Palu City spatial use plan until 2030, as stated in Regional Regulation No. 16 of 2010 concerning the Palu City Regional Spatial Plan 2010–2030 results of land capability analysis. Furthermore, one of the considerations that must be considered when preparing the city's development is the earthquake disaster that risks Palu City.

Results

Earthquake hazard mapping with seismic micro-zonation

To assess the hazard, earthquake hazard mapping with seismic micro-zonation necessitates a thorough field investigation. It's very good at identifying seismic hazard variations across space. They're also helpful for assessing risk scenarios in the research field. Seismic micro-zonation maps are extremely useful in urban planning because they aid in the prediction of possible earthquakes. (EASSER, 1954). In this study, seismic micro-zonation was used at a map detail scale of 1: 25,000.

Based on the results of seismic micro-zonation analysis, three parameters can be obtained for further calculations by giving the highest class in earthquake-prone areas, with parameters and classification as shown in Table 2.

Table 2
Parameters for the Preparation of the Palu City Earthquake Micro-zonation Map

No	Parameter	Class Division	Score
1	Dominant Period	< 0.4 (Alluvial/Sediment)	1
		0.4–0.6 (Alluvial/Sediment)	2
		> 0.6 (Granit/Metamorf)	3
2	Amplification	1.01–2.69 (Alluvial/Sediment)	1
		2.69–4.86 (Alluvial/Sediment)	2
		4.86–7.56 (Granit/Metamorf)	3
3	Peak Ground Accelaration (PGA)	0.59–0.691 (Medium High)	1
		0.691–0.783 (High)	2
		0.783–0.875 (Very High)	3

The value of the dominant period is in the range of 0.4 to 0.6 seconds; by referring to the National Earthquake Hazard Reduction Program classification, the research area shows that the dominant geological layer is alluvial to granite and metamorphic sediments, especially along the fault line. The value of the dominant period of land indicates the level of vulnerability. The greater the value of the dominant period of land in a location, the more vulnerable the location is to earthquake shocks. Almost all study areas are in a thick layer of sediment with a very high risk of damage at the time of the earthquake (> 0.6 seconds), especially in most of Mantikulore and Tawaeli Districts, areas with a dominant period ranging from 0.4–0.6 seconds. A medium soil layer has a high risk of damage, especially in most of the Ulujadi District, Mantikulore District, and Tawaeli District. Areas with a dominant period of < 0.4 seconds indicate a hard soil layer with a fairly low risk of damage, especially in parts of South Palu District, West Palu District, North Palu District, and Ulujadi District.

The amplification value ranges from 1.01 m/s to 7.56 m/s. The amplification value is a parameter of the soil gain factor related to the contrast ratio between the impedance of the surface layer and the layer below it. The stronger the shock strengthening, the smaller the S wave velocity and the softer the formation of the soil material. The harder the soil is, the greater the shear wave speed and the smaller the shock amplification factor. Soils are getting softer, the shear wave velocity is getting smaller, and the shock amplification factor will be bigger. Most of the amplification values of Palu City are 2.69–4.86 (Alluvial / Sediment), especially in Ulujadi District, Tatanga District, South Palu District, North Palu District, and Tawaeli District.

The PGA value obtained is the value of the wave acceleration on the rock report that occurs due to an earthquake. The PGA value will be smaller as the distance from the site to the epicenter is caused by the absorption of earthquake energy by the soil media. The distribution of values consists of: (1) a value of 0.59–0.60, which indicates the magnitude of the MMI strength on the X scale, which results in damaged strong buildings of wood, part of wooden buildings and frames and damaged foundations. Locations in Palu City are in most of the eastern regions of Mantikulore and Ulujadi Districts, with large cracks in the ground, curved rails, and landslides. PGA values range from 0.691 to 0.783, equivalent to the strength of the XI scale MMI. Only a few wooden buildings are still standing; there are broken bridges and wide cracks in the ground, where most of the central area of Palu City is in this area. PGA values from 0.783 to 0.875 or the equivalent strength of the XII scale MMI, resulted in total damage, with visible waves on the ground. The view darkens and objects are thrown away, and the whole area of Palu's terrace, especially in the middle and eastern part of Palu, is included in this category.

Figure 2 shows a micro-zonation map, which referred to the three parameters mentioned above, namely the value of the dominant period, amplification, and PGA, using the GIS overlay technique with the results as shown.

Based on the map of earthquake-prone areas, 48.9%, or 193.29 km^2, of Palu City is dominated by areas with a moderate level of danger. Most of them are in Tawaeli District, West Palu District, Ulujadi District, North Palu District, Mantikulore District, and Tatanga District; and areas prone to high earthquake disasters 29.25% km2 or an area of 115.75 km, especially in most of Tawaeli District, East Palu District, South Palu, West Palu and Ulujadi Districts; while the low disaster-prone area of 21.77% or an area of 86.02 km2, spread across Mantikulore District, Tawaeli District and Ulujadi District.

Land capability assessment

One approach in land use planning is capability assessment (Singer, 2014). Subsequent assessments can be used as a guide toward optimizing land use. This assessment reveals the constraints that certain land has (Mokarram et al., 2010), guiding land use decisions based on its capabilities and potentials (Amiri et al., 2012). By analyzing land capability, classification of land capability will be obtained, which can be developed according to the function and carrying capacity of the area and the final land suitability for the development of urban areas. Based on the analysis of the physical aspects of land capability-based on the LCU, namely: Morphological LCU, Slope Stability LCU, Foundation Stability LCU, Water Availability LCU, to obtain an overview of the LCU in Palu City, as shown in Fig. 3, as follows:

a. LCU morphology: morphology is a landscape. LCU morphology is carried out to sort out the natural landscape in the area and/or planning area that can be developed according to its function. The land capability of high morphology means that the area's morphological conditions are complex. High morphology means the landscape is hilly and wavy. Low morphology is not complex; the land is relatively flat and easy to develop for settlements and cultivation activities. Most of the Palu City area has a high morphology; 43% is hilly areas in the western and eastern parts, with limited development potential. Meanwhile, the morphology is low, at 27%, and is generally located along the bay of Palu and spread over almost all districts.
b. LCU Slope Stability: if an area has low slope stability, then the condition of the area is unstable because it is prone to landslides, is easy to move, so it is not safe to develop it for buildings, settlements, especially the development of built-in cultivation activities. This area can be used for forest areas, plantations, and water absorption. Slope stability in Palu City is dominated by low (31%) and moderate (31%) slope stability. In general, it still has a good chance of development into an established cultivation area, especially in Mantikulore District.
c. LCU foundation stability: to determine the level of land capability to support heavy structures in urban development and the type of foundation suitable for each level of land capability. West Palu District has high foundation stability, while low foundation stability is in Mantikulore District. However, when viewed as a whole, 51% of Palu City is dominated by a low level of stability, and only 10% shows a high level of foundation stability.
d. Water Supply LCU: conducted to determine the level of water availability and water supply capacity for urban development. If water availability is very high, it means that the availability of deep and shallow groundwater is quite a lot. Meanwhile, moderate water availability means that there is insufficient shallow groundwater, but there is a lot of deep groundwater. The level of water availability in Palu City 39% has low availability, mostly in Mantikulore and West Palu Districts, while the high water availability of 24% is mostly in Tawaeli District.
Based on the analysis carried out in each LCU, through the stacking of maps and assigning values and weighting to each parameter, land capability in Palu City is divided into 5 classes, namely class A, class B, class C, class D, and class E, as shown in Table 3.

Table 3
Value and Class of Land Capability

Class of Land Capability	Total Area		Classification
	(km^2)	(%)	
A	124.48	31.51%	Capability Land of Very Low
B	94.48	23.92%	Capability Land of Low
C	37.11	9.39%	Capability Land of Medium
D	60.86	15.41%	Capability Land of High
E	78.13	19.78%	Capability Land of Very High

When viewed from the land capability map, most of Palu City is dominated by low (23.92%) to very low (31.51%) land capability, indicating that Palu City has the physical and environmental freedom to develop into an urban area, as shown in Fig. 4.

Integration of land sustainability and spatial planning of Palu City 2030

An integrated approach to sustainable land use planning is explicitly stated in Agenda 21 (Singer, 2014). It is very important to prepare land use planning that allows the legacy of good land resources for future generations. This can be done by integrating planned and sustainable land use and in a way that is appropriate to its capabilities and potential. The next study is integrating land suitability with the Palu City spatial plan by comparing an area's spatial plan with the land's ability to determine the suitability between the two. The results will show that the area currently under development can be classified as suitable, conditional, and unsuitable land, as shown in Table 4.

Table 4
Compatibility of the Palu Spatial Plan and ULCC in Palu City

Parameter	Area (%)	Classification
Class A with High Earthquake Prones with Protected Areas	9.12%	Suitable
Class B with Medium Earthquake Prones with Protected Areas	26.52%	Suitable
Class C with Low Earthquake Prones with Protected Areas	20.43%	Suitable
Class D with High Earthquake Prones with Built up Areas	21.21	Not Suitable
Class E with Medium Earthquake Prones with Built up Areas	21.57%	Conditional

Most (56.07%) of the 2030 Palu City's spatial use plan complied with the land's carrying capacity, which is dominated by spatial use plans for protected areas and is in class A in areas with a high-medium earthquake threat and cultivation area utilization plans, while only 1.15 percent of the built-up area is acceptable, notably those in Class F.. Cities in areas prone to earthquakes are low. Conditional land suitability is given to the spatial use plan in cultivation areas with the threat of an earthquake but is in class C land capability class covering 20.43% of the total area of Palu City. Land development is not suitable for urban development because it is in class C and is a high disaster-prone area covering 21.21% of the total area of Palu City. It requires special attention in the future development plan of Palu City. The quality of good city spatial planning avoids allocation of spatial use that is inconsistent with the capacity of the land. Figure 5 shows the land suitability distribution in Palu City.

Discussion

Studies of disasters in urban areas indicate a rapid increase in the number of disasters in urban areas and an increase in the geographic locations where they occur. Although the reasons for this differ, as does their relative significance, they are generally related to a rise in the urban population in settlements, an increase in runoff resulting from urban development, and poor land use (Shi, 1991; Feng, 1994). As a result, ULCC can be characterized as the level of human activity, population growth, land use patterns and extent, and physical development that the urban environment can support without significant deterioration and irreversible harm. Traditional hazard-oriented beliefs that interpret disasters as merely “natural” phenomena are being challenged by mounting evidence of this cumulative danger (Cannon, 2000).

Because of the qualitative nature of the data, only experienced experts can assess it. [63–64]. In its implementation in Indonesia, this approach can be quantified to make land evaluation more quantitative and make it easier to enforce. Several studies have mapped land capacity, most of which used GIS (Campos et al., 2010).

Conclusion

High and covering an area of 24% of the total area of Palu City requires special attention in the development of its area going forward. The requirement that land use plans that do not comply with their carrying capacity must be strictly controlled, especially in high disaster-prone areas.

Declarations

Availability of data and materials

Not applicable.

Competing interests

Authors declare that there is no competing interest.

Funding

Not applicable.

Authors' contributions

Jossi Ewindy did the conception and design, performed the experiment, wrote the original draft, and gave final approval. Chay Asdak did the conception and design, revised the paper and gave final approval. Bombom Rachmat Suganda performed the experiment and analysis, wrote the original draft, and gave final approval. Mohamad Sapari Dwi Hadian performed the analysis, revised the paper, and gave final approval.

Acknowledgements

Authors thank Department of Environmental Studies, Graduate School, University of Padjadjaran for the support.

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Figures

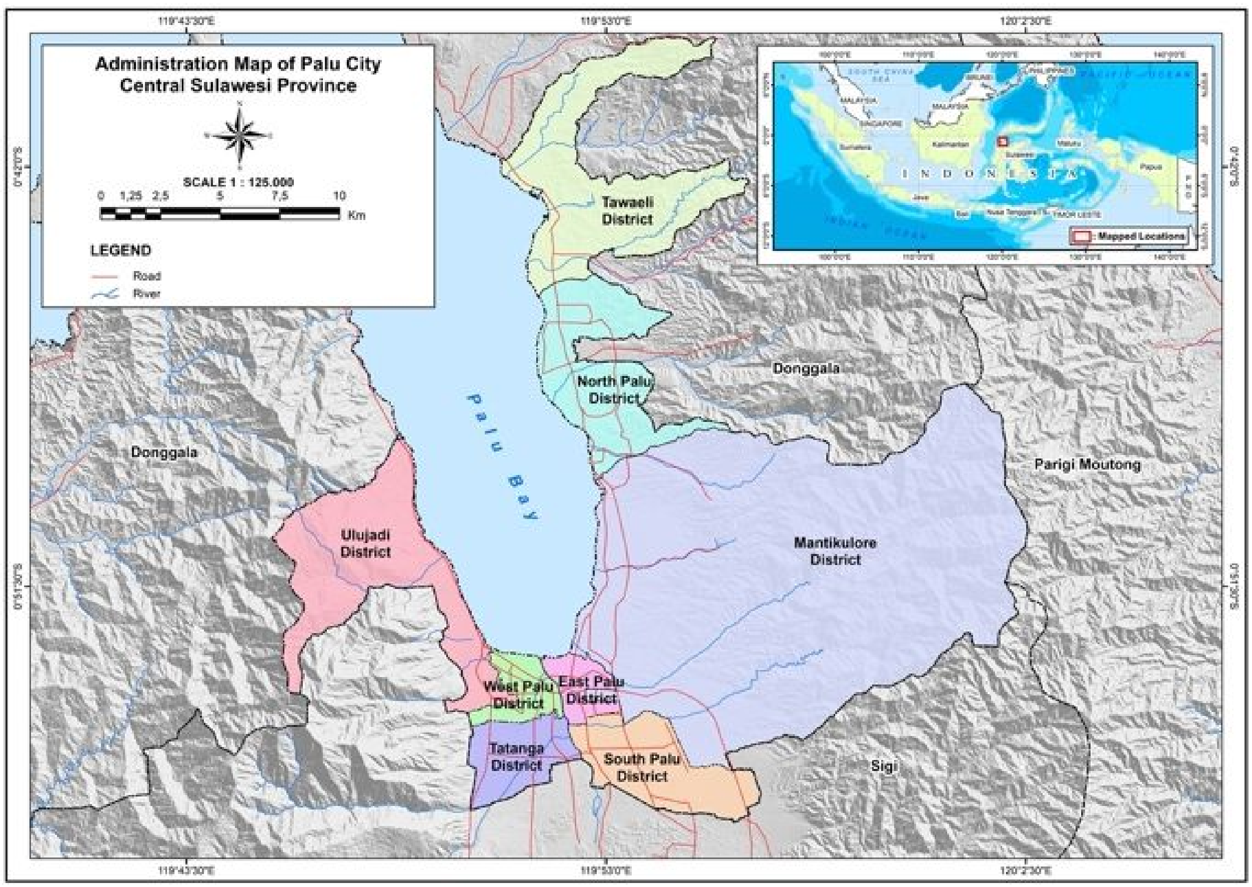

Figure 1

Map of Palu City

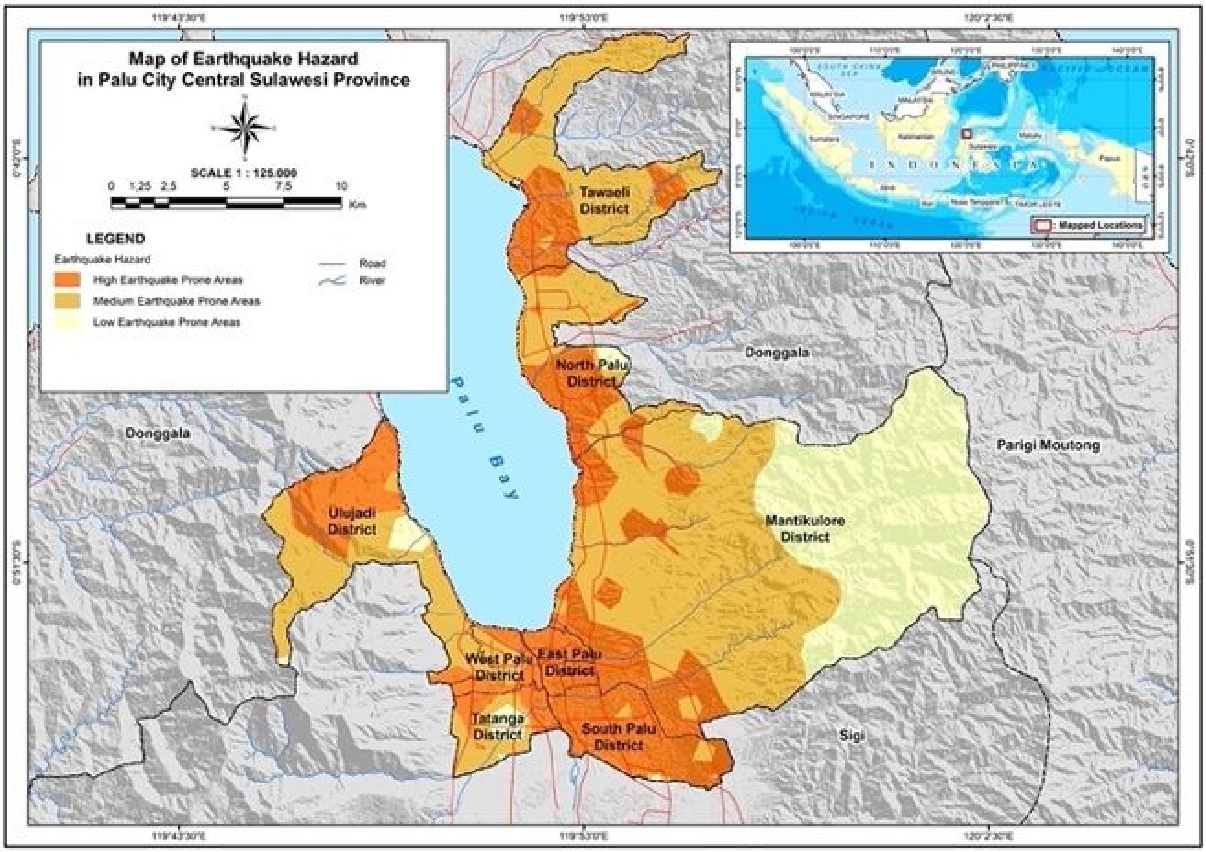

Figure 2

Map of earthquake-prone areas in Palu City

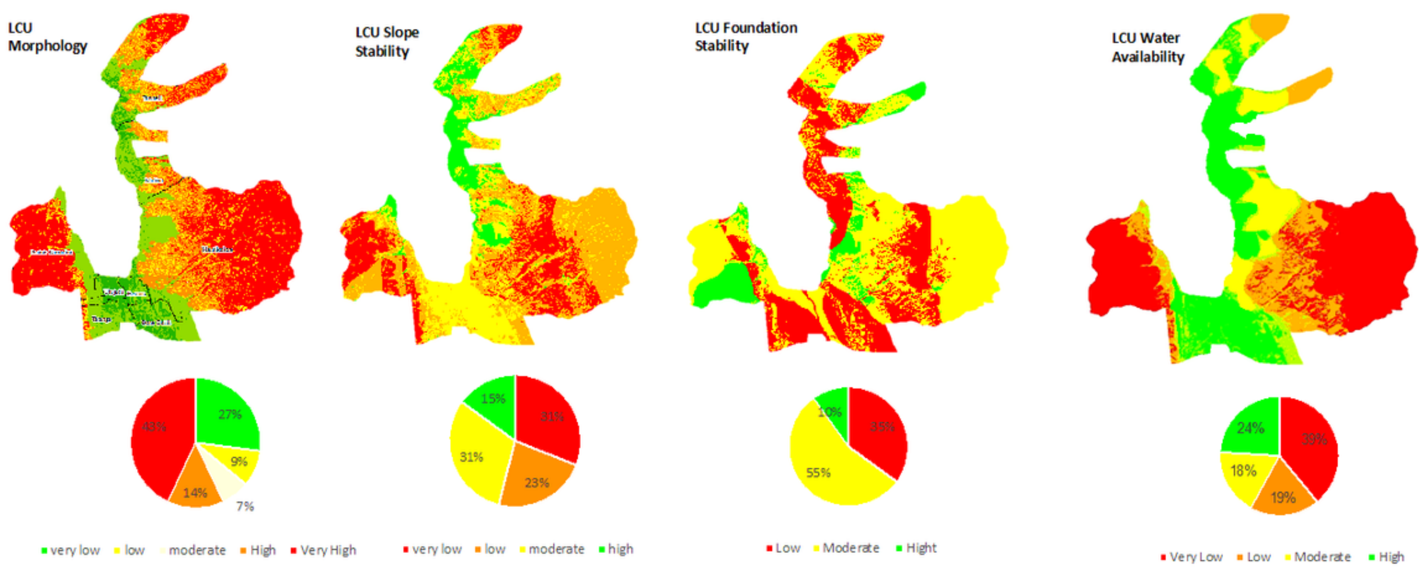

Figure 3

Land Capability Unit Calculation Results

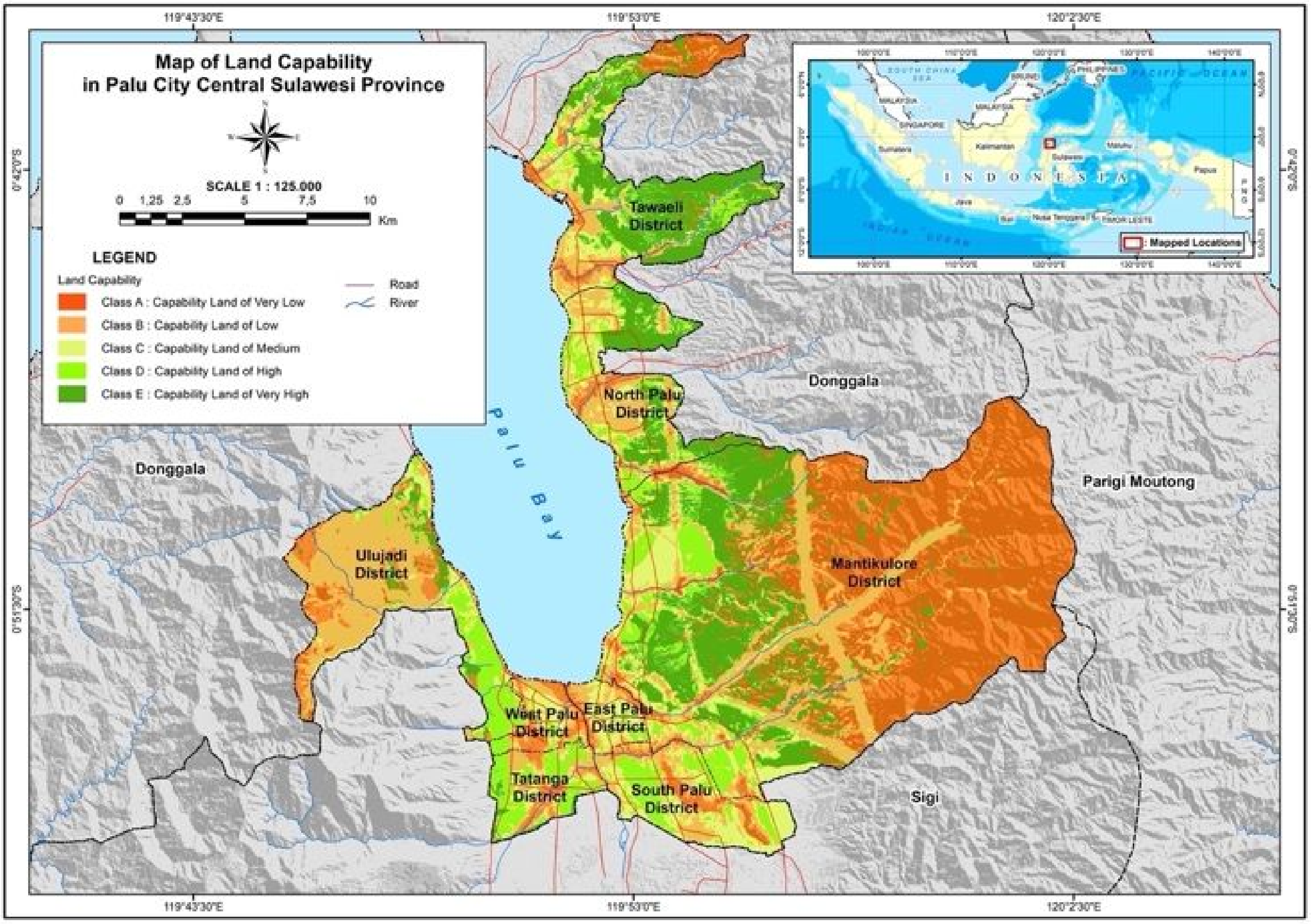

Figure 4

Land Capability in Palu City

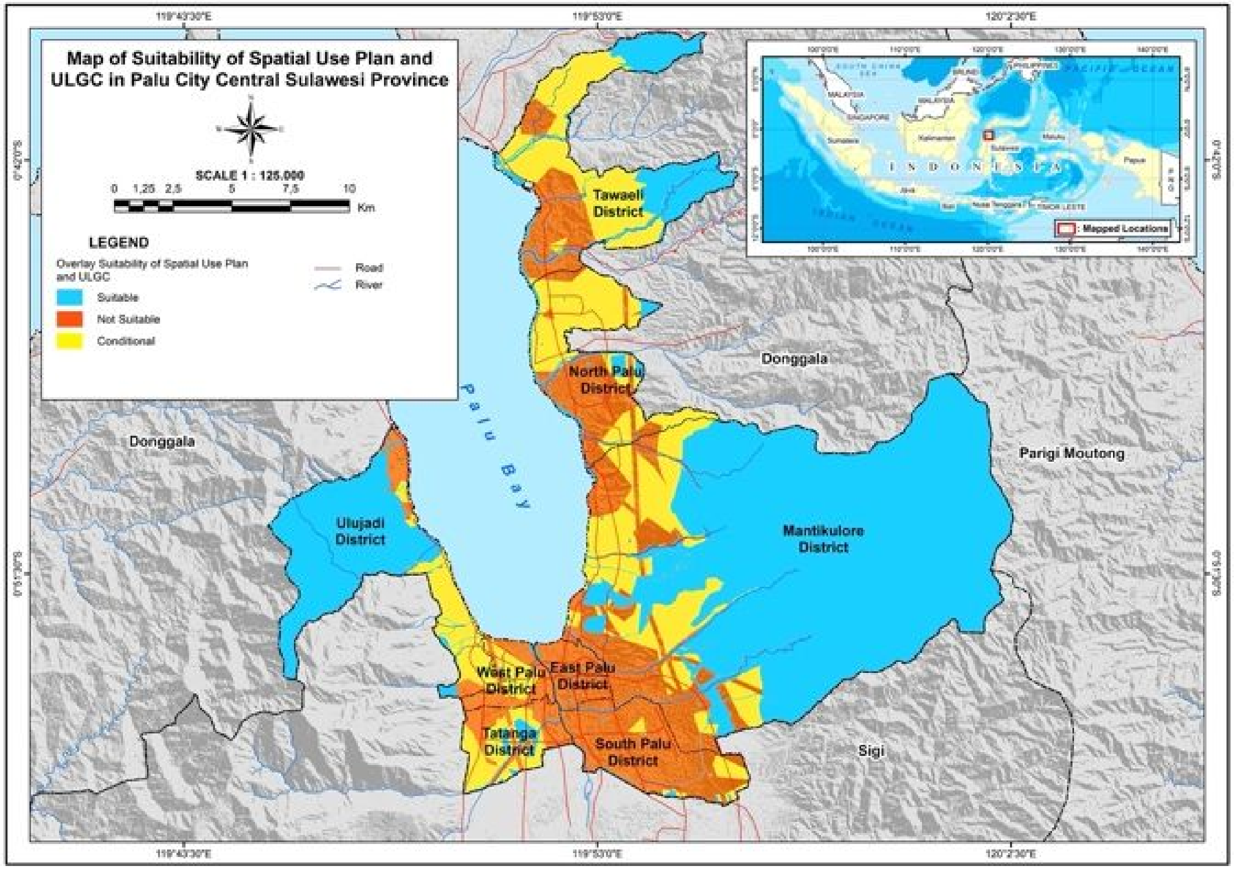

Figure 5

Map of Suitability of Spatial Use Plan and ULCC in Palu City