Palu earthquake hazard risk assessment (EHRA) based on urban land use planning

Jossi Ewindy*, Bombom Rachmat Suganda, Chay Asdak & Mohamad Sapari

Department of Environmental Studies, Graduate School, University of Padjadjaran.
Jl. Dipati Ukur No 35 Bandung City, West Java, Indonesia, 40132
*Corresponding author : Email: jossi18001@mail.unpad.ac.id

AGEOS

Abstract: Assessment of hazard and disaster risk is critical for urban resilience. Given that earthquake hazard assessments will often have limitations and uncertainty, it is essential to understand the worst-case scenario of hazard possibility. Palu City is located in a disaster-prone area because it is traversed by the Palu-Koro fault, an active fault in Indonesia. In preparing the latest risk assessment for earthquakes as consideration for potential land use planning in Palu, an earthquake hazard risk assessment was carried out, including estimating earthquake hazard, vulnerability, risk, and the integration of disaster risk into land-use planning documents. This study employed the applied methods with quantitative and quantitative approaches, and the data were processed with ArcGIS tools; field observations supported primary and secondary data. The results showed that 70% of the Palu area is under high earthquake threat as located in an active tectonic area. The findings of the earthquake hazard and risk assessments were then integrated into a land-use planning document that can be used as a foundation for creating a community development plan document for the Palu City Government, known as the Palu City Spatial Plan. The spatial plan of Palu City will support the resilience of Palu in carrying out its functions as a city to eliminate impacts and risks of hazards occur. Thus, strict land-use implementation as means for disaster mitigation is urgently needed.

Keywords: hazard, vulnerability, disaster risk, spatial planning, land use, Palu

1. INTRODUCTION

Earthquakes are among the most potent natural phenomena that can cause considerable losses to humans and the community's economy, which is an unpredictable hazard (Glavovic et al., 2010; Burby et al., 2000). Population growth, unplanned rapid urbanization, and poor land management have been the underlying reason for disaster risk over the last few decades, leading to the accumulation of life and property assets in potentially earthquake-prone areas, thereby raising the risk of earthquakes (EM-DAT, 2020; UNDRR, 2015[a]). One of the best efforts to address an earthquake's impact in an area, especially in a densely populated urban area, is to conduct an earthquake hazard risk assessment. In this term, it is common practice to conceptually define earthquake risk as a simple convolution of three components: hazard, exposure, and vulnerability (UNDRR, 2015[b]).

Palu is a city in Indonesia's Central Sulawesi Province, which is vulnerable to earthquakes (IETC, 2019). This condition is inseparable from its physical characteristics because it is located at the T junction of 3 (three) plates: the Pacific, Indo-Australia, and Eurasia, which have a higher tectonic hazard potential. As a result of the three plates' collision and interaction, Sulawesi Island has several active faults, one of which is the Palu-Koro fault, which crosses Palu and is thought to be a reason triggering the significant earthquake. The Palu-Koro fault is the main fault on Sulawesi Island and is classified as an active fault. Sulawesi Island is an intricate tectonic collage separating the Eurasian, Indo-Australian, and Philippine Sea Plates. The Palu Koro fault extends approximately 240 km from the north (Palu City) to the south (Malili) to the Gulf of Bone (Bellier et al., 2001; Kadarusman et al., 2011; Pakpahan et al., 2015). This fault is a sinistral active fault with a displacement speed of about 25-30 mm/year (Kaharuddin et al., 2011). In this route, earthquakes with a magnitude of more than 4.5 and a depth of less than 30 km were mainly seen in Central Sulawesi and off the coast of North Sulawesi. The history of destructive earthquakes along the Palu-Koro fault zone has experienced at least 19 destructive earthquakes from 1910 to 2018. The Mw 7.4 earthquake on September 28, 2018, with its epicentre, was in the Palu Valley mainland (USGS, 2018).

Currently, Palu City continues to develop and plays a vital role in supporting regional and national developments. Based on the Indonesian National Spatial Plan (Government Regulation of the Republic Indonesia Number 26 the Year 2008), Palu is located in a strategic location, is equipped with facilities that support economic activity and further reinforces the vision of Palu City as a city based on trade, services, and industry based on the Palu City Spatial Plan 2010–2030 (Local Regulation Number 16 the Year 2010), with an area of 395.06 km^2 consisting of 8 (eight) districts, namely, West Palu District, Tatanga District, Ulujadi District, South Palu District, East District, Mantikulore District, North Palu District, and Tawaeli District, as shown in Figure 1.

Land use planning based on earthquake hazard and risk assessment (EHRA) provides an opportunity to plan a natural hazard assessment (i.e., the likelihood of events occurring) and structure the consequences of those events. Furthermore, earthquake hazard information and risk information are used to develop risk reduction measures and ultimately reduce earthquake side effects (Margottini et al., 2017). Therefore, this study aims to prepare a current earthquake risk assessment that includes the level of threat, vulnerability, and risk of earthquakes into land-use planning as input for mitigation planning for potential earthquake disasters in Palu.

Manuscript received 2021-02-01
Revised version accepted 2021-05-04

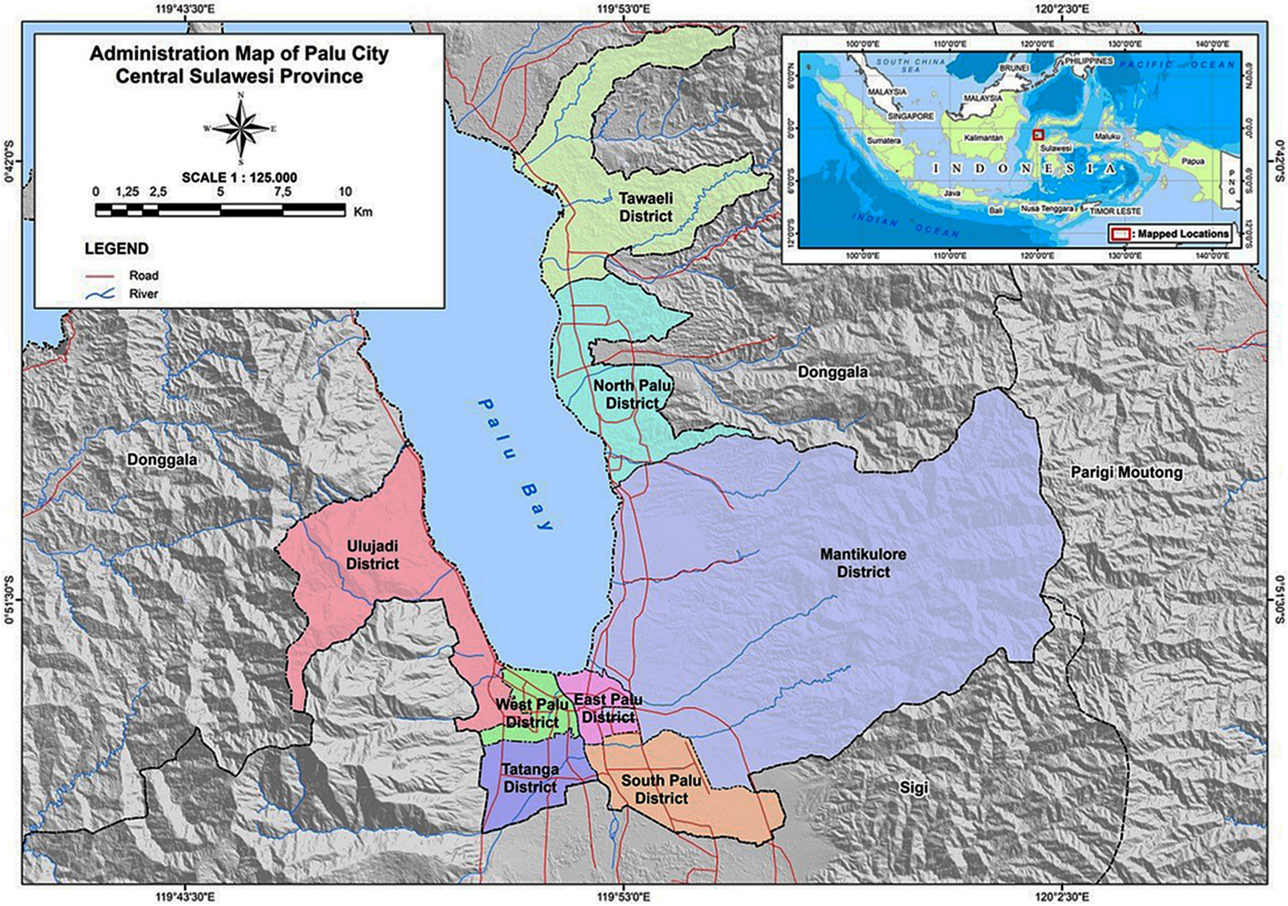

Figure 1. Administration map of Palu

2. METHODS

EHRA is used in land use planning, redevelopment planning, and development management. The assessment can create future land use; it also helps identify and avoid potential problems associated with developing hazard areas. Once the land has been proposed, a hazard assessment can be used to justify the imposition of existing development retrofit requirements, to determine areas where such control is required, and to assess the benefits of other means of reducing harm. Hazard assessment can provide a factual basis for decision-making at three levels of sophistication: hazard assessment, vulnerability assessment, and risk analysis (Sutanta et al., 2013).

2.1 Earthquake Hazard Assessment

Earthquake hazard analysis aims to determine specific earthquake intensity limits that apply in the study area based on a probability value that will occur or be exceeded in a certain period. The method used to determine this limit is the Probabilistic Seismic Hazard Analysis (PSHA) method, an earthquake risk analysis by explicitly considering the earthquake magnitude, location, uncertainty factors, and time occurrence. Peak Ground Acceleration (PGA) value in the bedrock as the PSHA results is used as the basis for determining the earthquake hazard index indicator. In this study, indicators were used in determining the earthquake hazard index, namely data on occurred earthquake disasters, maximum acceleration in bedrock (PGA), and the intensity of PGA shocks on the surface. Earthquake hazard classification was carried out through the scoring and weighting methods for each indicator based on the Analytic Hierarchy Process (AHP) principle and using the GIS map overlay technique to provide low, moderate, and high earthquake hazard levels.

2.2 Vulnerability Assessment

Earthquake hazard risk depends not only on the earthquake (hazard) magnitude of the number of people exposed to the earthquake (exposure) but also on their susceptibility to damage and loss (vulnerability). The vulnerability index is based on population density data and population of vulnerable groups, US Dollar losses data based on housing density, buildings/public facilities, and critical facilities. The vulnerable groups were vulnerable age groups (aged 0–4 years and >65 years), sex ratio, poor people, and disabled people in the emergence of casualty residents exposed to disasters. The indicators used for physical vulnerability were house density (permanent, semi-permanent, and non-permanent), availability of public buildings/facilities, and critical facilities. House density was obtained by separating them into the village's built-up area, divided by region, and multiplied by each parameter's unit price. Vulnerability is the product of socio-cultural and environmental exposure, with different weighting factors for various threats. All weighting factors used for the vulnerability analysis were the result of the AHP process. Table 1 shows the determination of the vulnerability index.

2.3 Risk and Capacity Analysis

Disaster risk assessment was performed by calculating the value of risk factors, namely hazards and vulnerabilities, using the superimpose technique and scoring technique using the Arc GIS tools to produce maps containing vulnerability information. Assessment of the resilience of Palu to earthquake disasters can be seen in Figure 2.

After obtaining the disaster risk level, to find out the city resilience of Palu in facing disasters, it is needed to examine the land use plan that has been determined through the local regulation of Palu City of Spatial Plan 2010-2030. The city spatial plan is the land use planning process formulated through a participatory process; these capacity assessment results will provide evaluation and recommendations for current and future land-use planning.

3. RESULTS

3.1 Earthquake Hazard Level

The PGA value in Palu ranges from 0.59 to 0.875, which is divided into (1) < 0.60, indicates a low earthquake hazard level; (2) 0.61 - 0.70 is a moderate earthquake hazard level; and (3) > 0.7 indicates a high earthquake hazard level, as shown in Table 2.

The low earthquake hazard level in Palu City is equivalent to the MMI strength's magnitude on the X scale, which results in substantially damaged wooden buildings, large cracks in the ground, curved rails, and landslides. There is an 86.02 km^2 area with a low earthquake hazard level (or 21.77% of the total area of Palu City), which is in most of the eastern regions, namely the Mantikulore District. Based on field observations, no significant earthquake cracks were found in the East part of Palu, but many minor cracks were found in north-south and west-east directions. While the moderate earthquake hazard level is equivalent to the strength of MMI scale IX, that is, if an earthquake occurs, significant damage occurs to sturdy construction, ordinary building frames are detached from the foundation, considerable damage to a robust structure with part of the building collapsed, the foundation of the building shifted. The ground is cracked, the underground pipe is broken. The moderate earthquake hazard level that threatens 48.93% or approximately 193.29 km^2 of Palu City's total area is mostly located in the central part of Palu City, namely in Tawaeli District, West Palu District, Ulujadi District, North Palu District, and Tatanga District, as shown in Figure 3.

3.2 Earthquake Hazard Vulnerability

Based on the vulnerability assessment results, it was found that the vulnerability in Palu was classified as high both for popula-

Table 1. Components of the vulnerability index

Component	Indicators	Classification			Total Weight
		Low	Moderate	High	
Population Exposure	Population Density	< 500 people/km^2	500–1000 people/km^2	> 1000 people/km^2	0,6
	Vulnerable Ratio	< 20%	20–40 %	> 40 %	0,4
USD Losses (million)	House	< 40 mil	40–80 mil	> 80 mil	0,4
	Public Facilities	< 50 mil	50–100 mil	> 100 mil	0,3
	Critical Facilities	< 50 mil	50–100 mil	> 100 mil	0,3

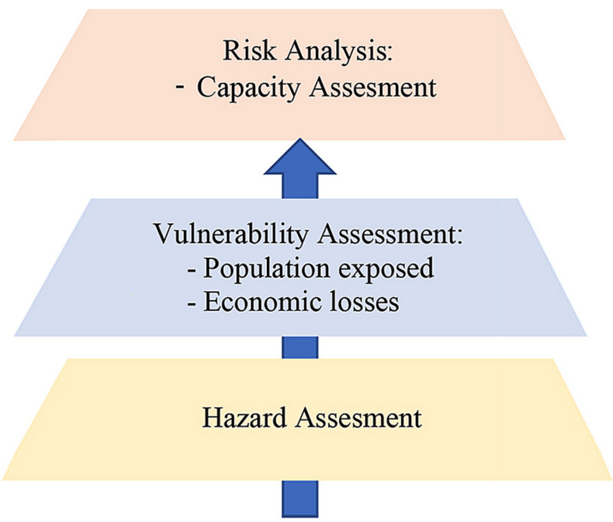

Figure 2. The method in creating a risk map

Table 2. The PGA value in Palu

PGA Value	Indicators	Area (km^2)	Districts
< 0.60	Low	86.02	Mantikulore
0.61–0.70	Moderate	193.29	Tawaeli, West Palu, Ulujadi, and North Palu
> 0.70	High	115.00	East Palu, South Palu, North Palu, Tatanga, and West Palu

tion exposure and losses arising from the disaster, as shown in

The estimated population exposed to Palu's earthquake is 390,331 people in East District, South Palu District, and West Palu District. The areas with the highest population in Palu are East Palu District (18.8%), followed by West Palu District (16.4%), and South Palu District (18.6%). In contrast, the highest population density per km^2 is in East District (9,267 km^2), West Palu District (7,523 per km^2), Tatanga District (2,675 per km^2), and South Palu District (2,577 per km^2). High vulnerability is dominated by urban activities, namely densely populated settlements, offices, trade, and services.

Besides, the potential loss of USD lost due to the disaster of approximately 86,504 million USD. Areas with a permanent condition for building construction are areas with a very vulnerable vulnerability due to permanent construction buildings potentially experiencing damage due to earthquakes. Of the eight districts, 80% are buildings with permanent construction, 15% are semi-permanent, and 5% are not permanent. Based on the research results, in general, the types of public buildings in Palu had a high vulnerability level. Based on the vulnerability assessment results, it was found that the vulnerability in Palu was classified as high, either for population exposure losses or arising from the hazard, as shown in Figure 4.

3.3 Risk Analysis

Based on the hazard and vulnerability assessment, the earthquake hazard risk level can be obtained (Thein et al., 2014), where almost all Districts in Palu have a high risk of hazard, especially South Palu District and East District, which require strenuous efforts to develop these areas as shown in Table 4.

Based on the earthquake risk assessment, it can be seen how much resilience is based on the capacity component reflected in policies and plans related to land use, namely the Palu City of Spatial Plan. This resilience study focuses on the development plan for promoted areas, especially those with a high hazard risk level. On the other hand, protected areas function must be maintained, considering that Palu is a disaster-prone area.

The level of resilience to earthquake risk for land use plans shows that Palu's development plan has shown a high resilience level, meaning that 67% of the use plan follows the EHRA results. Especially in Mantikulore District, Ulujadi District, Tawaeli District, Tatanga District, and North Palu District, there is still a low level of resilience (32%) in West Palu District, South Palu District, and East Palu District, as shown in Figure 5.

The three districts with low resilience levels are located in the middle of the city with high activity load and a large area of built-up land. The activities carried out are dominated by the settlement, trade and services, governance, and other economic support activities, as shown in Figure 6. As a result, strict land-use planning is required to organize land use, especially in cultivated areas with a high-risk level. Protected areas, on the other hand, must preserve their function as conservation areas.

Table 3. Population exposure and USD losses in Palu City

District	Exposed Population (people)	Classification of the Exposed Population	USD Losses (million)	Classification of USD losses
Mantikulore	66,085	High	12,244	High
West Palu	65,773	High	3,322	High
South Palu	74,176	High	4,025	High
East Palu	74,717	High	47,478	High
North Palu	20,520	High	7,881	High
Tatanga	42,137	High	2,962	High
Tawaeli	17,836	High	5,204	High
Ulujadi	29,087	High	3,388	High
Total	390,331	High	86504	High

Table 4. The matrix for determining the level of earthquake risk in Palu City

Level of Hazard Risk		Vulnerability Index		
		Low	Moderate	High
Threat Index	Low			Mantikulore
	Moderate			Tawaeli West Palu North Palu Tatanga Ulujadi
	High			South Palu East Palu

4. CONCLUSION

Land use planning in earthquake-prone areas such as Palu can be done through a risk level approach to minimize high risk and consider earthquakes' level of alertness. Land use plans prepared for the EHRA are integrated into the revised land-use planning document known as the 2030 Spatial Plan of Palu City to support the city's resilience based on earthquake disaster mitigation.

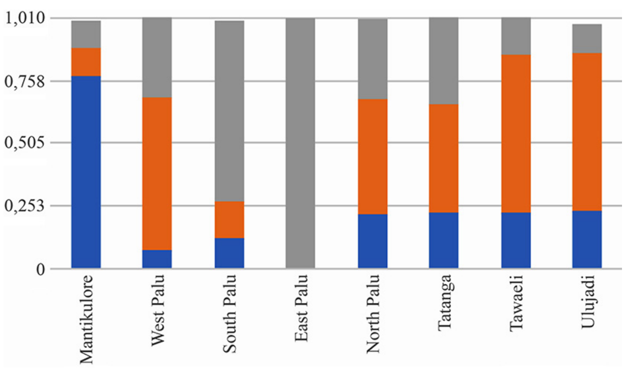

Figure 3. The level of earthquake hazard threats in Palu

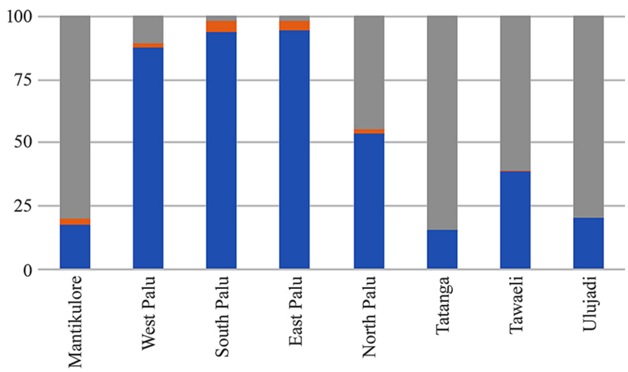

Figure 5. Palu City resilience based on EHRA

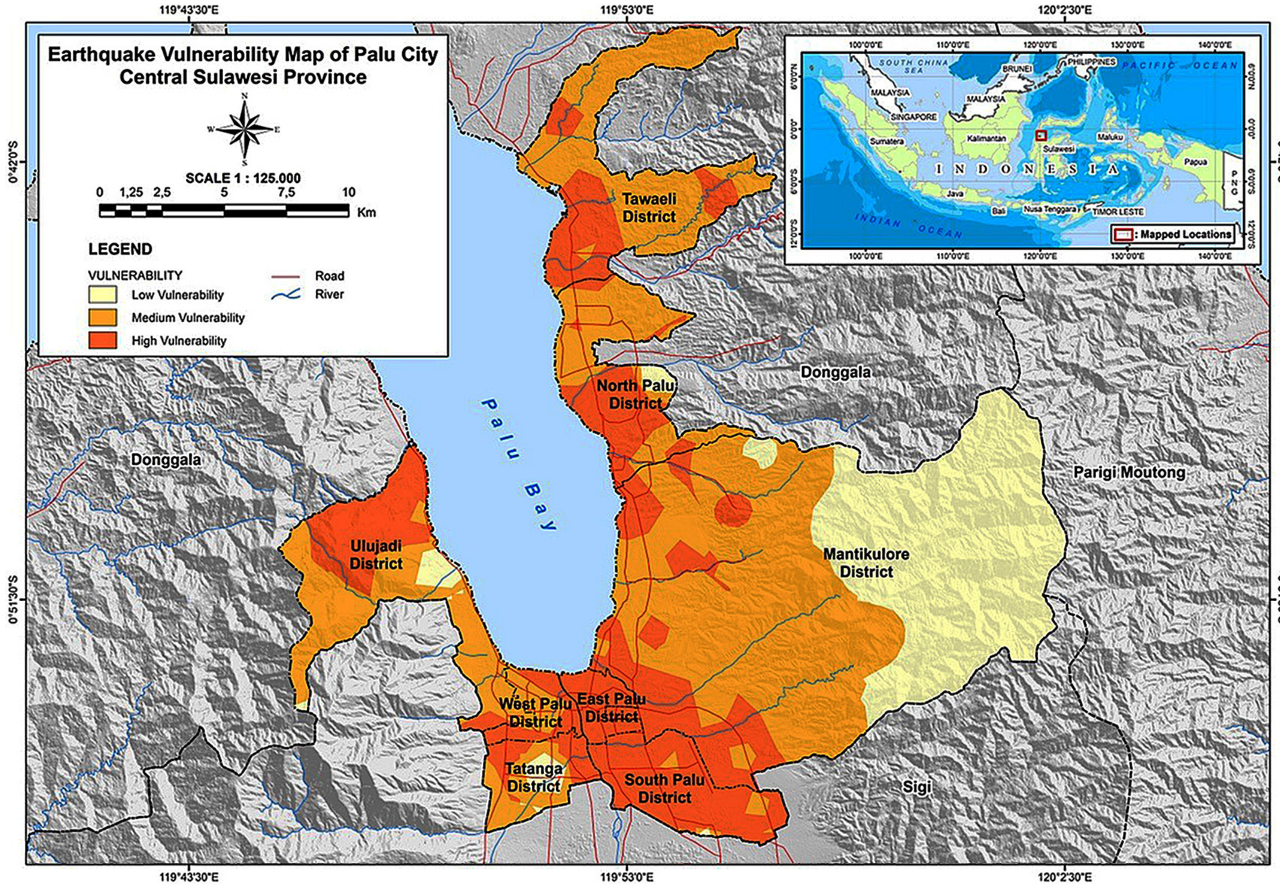

Figure 4. Analysis of vulnerability of Palu City

The limitation of this study is only considering earthquakes as a disaster that may happen in Palu. Given the several disasters that may occur as an aftereffect of the earthquake, such as tsunamis, liquefaction, and landslides, it is necessary to conduct multi-hazard research to plan comprehensive land use. This study's results can be used as a basis for consideration for local governments to plan land use based on the disaster risks faced by an area, which will be determined according to its spatial functions. The spatial mitigation for earthquake-prone areas will be effectively implemented through detail spatial planning and zoning regulation, which regulates activities, level of density, type of developments, and a technical solution and for the desired area to reach a certain level of performance.

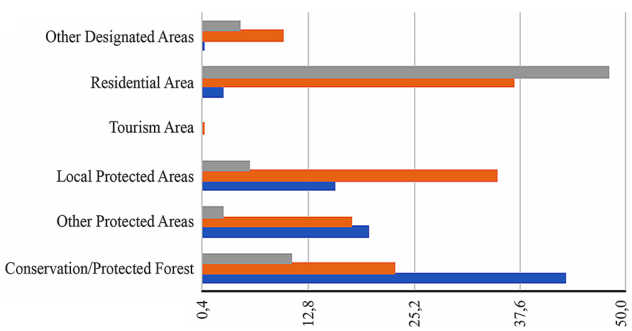

Figure 6. Land use in low resilience areas in Palu City 2019 (West Palu District, South Palu District and East Palu District)

References

Anonym, 2008: Government Regulation of the Republic of Indonesia Number 26 the Year 2008 about Indonesia National of Spatial Planning 2008-2028.

Anonym, 2010: Local Regulation of the Palu City Number 16 the Year 2010 about Palu City Spatial Plan 2010 – 2030.

Bellier O., Sébrier M., Beaudouin T., Villeneuve M., Braucher R., BourlèsD., Siayme L., Putranto E. & Pratomo I., 2001 : High slip rate for a low seismicity along the Palu-Koro active fault in Central Sulawesi (Indonesia). *Terra Nova*, *13*, 463–470. https://doi.org/10.1046/j.1365-3121.2001.00382.x

Burby R.J., Deyle R.E., Godschalk D.R. & Olshanksy R.B., 2000: Creating Hazard Resilient Communities Through Land Use Planning, *Nat. Hazards Rev.* 1., 99–106.

EM-DAT, 2020: *Centre for Research on the Epidemiology of Disasters (CRED)*. The International Disaster Database. www.emdat.be/

Glavovic B., Saunders W. & Becker J., 2010: Realising the potential of land use planning to reduce hazard risks in New Zealand. *The Australasian Journal of Disaster and Trauma Studies*. Australia, 54, 679-706

Indonesia Earthquake and Tsunami Center (IETC), 2019: Catalog of Significant and Destructive Earthquakes in Indonesia 1821-2018. Meteorological and Geophysical Agencies on. 32-233 [in Indonesian with English Summary].

Kadarusman A., Van Leeuwen T. & Sopaheluwakan J., 2011: Eclogite, Peridotite, Granulite, and Associated High-Grade Rocks from The Palu Region, Central Sulawesi, Indonesia: An Example of Mantle and Crust Interaction in A Young Orogenic Belt. *EOS Transactions*, American Geophysical Union, 83, 48, 1182.

Kaharuddin M., Hutagalung R. & Nurhamdan N., 2011: Tectonic Developments and The Implications for Earthquakes and Tsunamis Potential in The Sulawesi Island Region. *Proceeding The 36th HAGI JCM,* 1-10. [in Indonesian with English Summary].

Margottini C., Menoni S., Delmonaco G. & Galderisi A., 2017: Land use planning and management in hazardous areas : findings and perspectives for the future proposed by the Armonia project. Politecnico di Milano, 10-17.

Pakpahan S., Drajat N. & Masturyono M., 2015 : Seismic analysis in the Palu Koro fault zone, Central Sulawesi. Environmental and Geological Disasters, 6(3), 253–264. [in Indonesian with English Summary].

Sutanta H., Rajabifard A. & Bishop I. D., 2013: Disaster risk reduction using acceptable risk measures for spatial planning. *Journal of Environmental Planning and Management*, *56*(6), 761–785. https://doi.org/10.1080/09640568.2012.702314

Thein P., Pramumijoyo S., Brotopuspito K., Kiyono J., Wilopo W., Furukawa A. & Setianto A., 2014: Estimation of Seismic Ground Motion and Shaking Parameters Based On Microtremor Measurements at Palu City, Central Sulawesi Province, Indonesia. *International Journal of Geological and Environmental Engineering*, *8*(5), 308–319. https://doi.org/10.5281/zenodo.1092938

The United States Geological Survey (USGS), 2018: *Earthquake Hazards Program*. The United States Geological Survey. www.earthquake.usgs.gov/earthquakes/eventpage/us1000h3p4/executive

UNDRR, 2015[a]: *Sendai Framework for Disaster Risk Reduction 2015–2030*. United Nations Office for Disaster Risk Reduction (UNDRR).

UNDRR, 2015[b]: *Proposed Updated Terminology on Disaster Risk Reduction: A Technical Review*. The United Nations Office for Disaster Risk Reduction (UNDRR).