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# Delineating suitable site for settlement in potential earthquake vulnerable areas using spatial multi-criteria decision analysis in the Sukabumi regency, Indonesia

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**Abstract:** Land suitability assessment is an important stage in land use planning that guides the direction of optimal land use. The objective of this study was to select a suitable location for settlements in earthquake-prone areas using the integration of the Analytical Hierarchy Process (AHP) and Geographical Information System (GIS). In total, six maps were considered to determine a suitable location for settlements, namely topography, soil, geology, land cover/land use, a regional spatial planning pattern map, and an earthquake vulnerability map. The results showed that in medium earthquake-prone areas, the suitable land area which are available for settlement was 90.25 $km^2$ (46.36% of the total land area available – 194.68 $km^2$). Whereas in highly earthquake-prone areas, the suitable and available land area was 528.11 $km^2$ (70.25% of the total land area in the high vulnerability zone – 751.81 $km^2$). The research proved that AHP and GIS integration is very effective and robust for mapping land suitability in earthquake-prone areas. The results of the analysis can be used by planners to prioritize settlement development in the Sukabumi regency. The methodology developed is recommended to be applied in selecting locations for settlements in other parts of Indonesia.

**Keywords:** Analytical Hierarchy Process (AHP), earthquake vulnerable areas, Geographical Information System (GIS), land availability, regional planning

## INTRODUCTION

Indonesia is the fourth most populous country in the world and is also a country prone to natural disasters. USGS [2015] stated that Indonesia experiences earthquakes more frequently than any other country in the world. In Indonesia, an average 14 earthquakes and five volcanic disasters occur each year, resulting in death and damage to infrastructures [World Bank 2019]. It has been estimated that 60 cities in Indonesia and around 42% of Indonesia's population (110 mln) had been exposed to natural disasters [Gunawan *et al.* 2015]. Its position, which is at the confluence of three tectonic plates, namely Eurasia, Indo-Australian, and the Pacific plates, makes Indonesia prone to earthquakes. The meeting of the three plates forms a highly active zone, with the presence of a fault that stretches from Sumatra to Papua with volcanoes along it [Verstappen 2010]. Putra *et al.* [2012] reported that during the period from 1799 to 2010 in Indonesia there were more than 48,000 earthquake disasters with a magnitude of M ≥ 4 on the Richter scale. The largest earthquake in the last 15 years with a magnitude of 9.3 on the Richter scale occurred in Aceh on 26 December 2004 and caused a tsunami that affected 15 countries and left 130,000 people dead, alongside destroying 250,000 houses in Aceh [World Bank 2011].

The Indonesian government has made various efforts to reduce the risk of earthquake disasters, including the creation of a national earthquake hazard map and establishing the InaSAFE [InaSAFE 2015] which is a software used for analysing the impact of natural disasters. This software was established by the National

Disaster Management Agency (Ind. Badan Nasional Penanggulangan Bencana – BNPB). BNPB has also built an Indonesian Disaster Information Data application [DIBI 2020] which can be used as a reference for disaster data in Indonesia. The selection of a suitable location for settlements in earthquake-prone areas also plays an important role in mitigating earthquake disasters. This information is not yet available in Indonesia so this study was conducted to fill this gap.

A good and detailed selection of locations for settlements in earthquake-prone areas can become a complex process involving physical, economic, social, and political factors. Such a complexity requires the simultaneous use of multiple decision support tools such as remote sensing data (RS), Geographical Information Systems (GIS), and Multi Criteria Decision Analysis (MCDA). GIS is a tool capable of analysing large and complex spatial data and has been widely used in land evaluation based on various criteria [Hamerlinck, Lieske 2015]. Land suitability evaluation involves assessing land potency for a use using various criteria. In land evaluation, consideration should include various factors such as data availability, the evaluation of data accuracy, and the environmental characteristics of the study area [Karimi *et al.* 2018]. Selecting the right algorithm for assessing land suitability is an important stage for current and future land use planning [Zhang *et al.* 2015]. Kavurmaci [2016] has discussed the use of GIS to assess the suitability for settlements.

In the last few decades, almost all of land suitability evaluation studies have used GIS integration and MCDA methods such as for housing and industry location selection [Zeydan *et al.* 2018]. In the site selection process, the integration of MCDA and GIS is very efficient because it can reduce the time and costs required [Phua, Minowa 2005]. In such methods, GIS plays a role as a decision support system in spatial data analysis [Wang, Du 2016] while MCDA serves in setting decision problems and determining decision levels [Monprapussorn *et al.* 2011]. MCDA is a model used to predict the suitability of land to produce a decision using the weight of the criteria determined by the appropriate method. Several MCDA methods can be used to determine the weight of each criterion in the land evaluation process. Examples include the Analytical Hierarchy Process (AHP) method [Saaty 1980], average ordered weight [Mokarram, Aminzadeh 2010], fuzzy membership approach [Bostanci *et al.* 2017], and grey relational analysis [Li *et al.* 2012].

The AHP model was introduced by Saaty [1980], which involves solving complex multi-criteria problems into a hierarchy. This model is very useful for decision-making with different focuses and preferences to be included in the planning process and determination of appropriate areas for certain uses [Tzeng, Huang 2011]. This model was chosen in this study because AHP provides a strong and flexible decision-making process to help prioritise and make the best decisions when the quantitative and qualitative aspects of a decision element need to be considered at once [Weerakoon 2014]. The integration of GIS and AHP has been used in various fields of study such as agriculture [Bozdağ *et al.* 2016; Widiatmaka *et al.* 2016], as well as settlements [Değerliyurt 2014; Omar, Raheem 2016].

Java island is one of large islands in Indonesia, covering an area of approximately 126,700 km$^2$ or 7% of the total area of Indonesia. The population of Java island in 2020 was 151.6 mln people or 56.1% of Indonesia's population [SetKab 2020]. This figure causes the island of Java to be the most populous island in Indonesia. There are about 38 active and passive volcanoes and about seven faults on the island of Java, stretching from the west to the east [Nguyen *et al.* 2015]. This geological condition makes Java vulnerable to natural disasters including earthquakes. Sukabumi is one of the regencies in Java that is prone to earthquakes because it has a complex tectonic structure that is influenced by a subduction zone and the Java fault. The Indo-Australian Plate subducted under the Eurasian Plate along the island of Java has produced three active faults in West Java, namely the Cimandiri, Lembang, and Baribis faults, and around seven volcanoes [Supendi *et al.* 2018]. The central part of the Sukabumi regency has a large enough potential for seismicity because the area is traversed by the active Cimandiri fault. From the earthquake hazard map, it can be seen that no area in Sukabumi is completely safe. Most of the Sukabumi regency is dominated by a low percentage of permanent buildings. This condition causes an earthquake to have a high impact on damage.

Based on the description above, the main objective of this study was to develop a model for selecting suitable locations for settlements in earthquake-prone areas using AHP and GIS integration. The findings of this study can be used to select the appropriate location for certain types of earthquake-resistant building constructions to ensure safety in the study area.

## MATERIALS AND METHODS

### STUDY SITE

The research was conducted in the Sukabumi regency, West Java Province, Indonesia (Fig. 1).

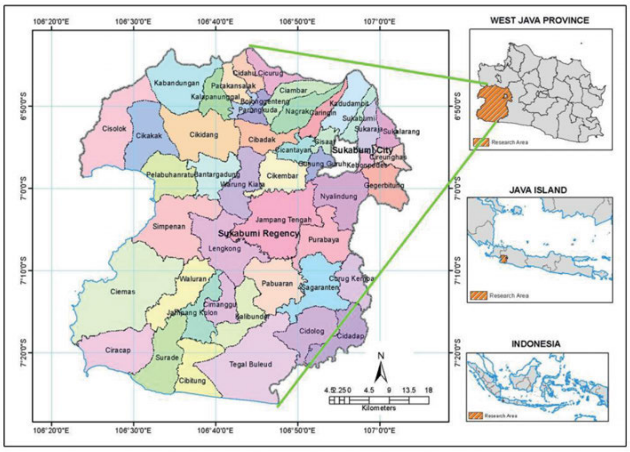



**Fig. 1.** Research area: Sukabumi regency, West Java, Indonesia; source: own elaboration

Geographically, this regency stretches between the latitudes 6°42'55.228" and 7°26'14.914" S and longitudes 106°22'14.351" and 107°3'50,346" E. Sukabumi is the second largest regency on the island of Java with an area of approximately 4,129.94 km$^2$ or 11% of the total area of West Java. Its total population is 2,460,693 [BPS Provinsi Jawa Barat 2021] which is spread across 47 subdistricts. The district has a B1-type climate (Oldeman) with an average wet month of 8–9 months, and an average annual rainfall of 2,805 mm. Sukabumi is dominated by an undulating to mountainous morphology (43%) in its northern and central parts, while flat areas (29%) are predominantly distributed around the city of Sukabumi and in its southern part. There are two volcanoes located in this district: Mount Salak and Mount Gede. Geologically, according to SUPARTOYO [2006], Sukabumi is dominated by sedimentary deposits in the form of alluvial plains, coastal sediments, volcanic sediments, and tertiary sediments which are unconsolidated rocks that are very susceptible to earthquake shocks.

## DATASET

Six datasets were used in this study, namely topographic maps at a scale of 1:25,000 [BIG 2014], soil maps at a scale of 1:50,000 [BBPPSDLP – Badan Litbang Pertanian 2017], geological maps at a scale of 1:100,000 [KUSNAMA, HERMANTO 1998], Land Use/Land Cover (LULC) maps at a scale of 1:50,000, regional spatial planning pattern (RSPP) maps [Peraturan … Nomor 22], and earthquake vulnerability maps [PVMBG 2014]. From these datasets, 13 thematic maps were produced which were used for further analysis.

## ANALYSIS

The study was divided into four stages, namely: (i) determining the weight using the AHP, (ii) applying weights to evaluate land suitability for settlements, (iii) evaluating land availability for settlements, and (iv) selecting settlement locations on available land in earthquake-prone areas. The process is illustrated in Figure 2.

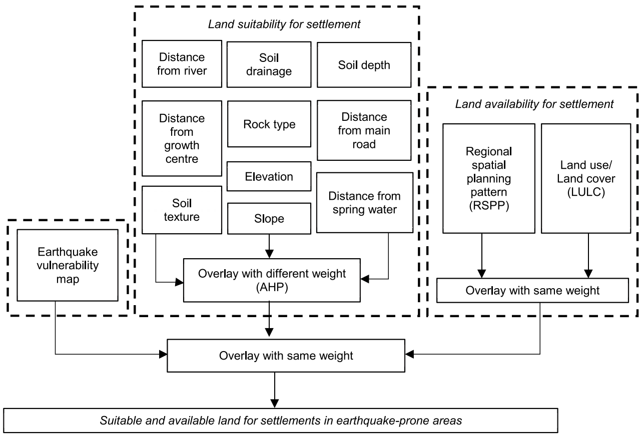



**Fig. 2.** Research flow diagram; source own elaboration

### Assigning the weights of criteria using AHP methods

The success of this research was largely determined by the success of the identification of the criteria, the quality of the data, and the conditions of the area. In this study, ten criteria were used to determine the location of settlements in earthquake-prone areas, which were slope, elevation, rock type, distance from main roads, distance from rivers, distance from springs, distance from growth centers, soil texture, soil depth, and soil drainage. The earthquake criteria itself did not become a factor in the calculation of land suitability maps, because all study areas were located in areas prone to earthquakes. The earthquake criteria were used in the determination of the area being considered for settlement in each class of earthquake vulnerability.

An important step after specifying the criteria was to determine the weights of the criteria and the sub-criteria scores. Both weights and scores were classified based on their contribution to the selection of suitable sites for settlements, judged by experts. Weights were assigned to each of the main criteria using the AHP approach. Comparisons were made by assessing the relative importance of the two criteria involved in determining suitability [SAATY 1980]. The AHP structure for site suitability analysis for settlements is shown in Figure 3. Five experts were involved in determining the weights in this study to compare the criteria in the pairwise comparison matrix. A scale of 1–9 was used for land suitability parameters. If the criteria were equally important, they were given a weight of 1, while a weight of 9 indicated that one criterion was much more important than another [SAATY 1980]. Each pair of criteria was assessed for importance. The verification of the consistency of expert opinions was carried out by setting the value of consistency ratio (*CR*) as described by BOZDAĞ *et al.* [2016].

The scoring value was assigned based on a literature review and an assessment of the expert team. The score for each sub-criterion was given by giving a value of 0 to 10, where 0 indicated the influence of the lowest sub-criteria and 10 represented the most important sub-criteria [WIDIATMAKA *et al.* 2016].

### Preparing data input for analysis of land suitability for settlements

In this study, a land suitability map for settlement was developed based on ten criteria which are slope, elevation, distance from main road, distance from water spring, distance from river, distance from growth center, rock type, soil depth, soil drainage, and soil texture. The land suitability map is obtained by multiplying the weight of the criteria and the sub-criteria scores

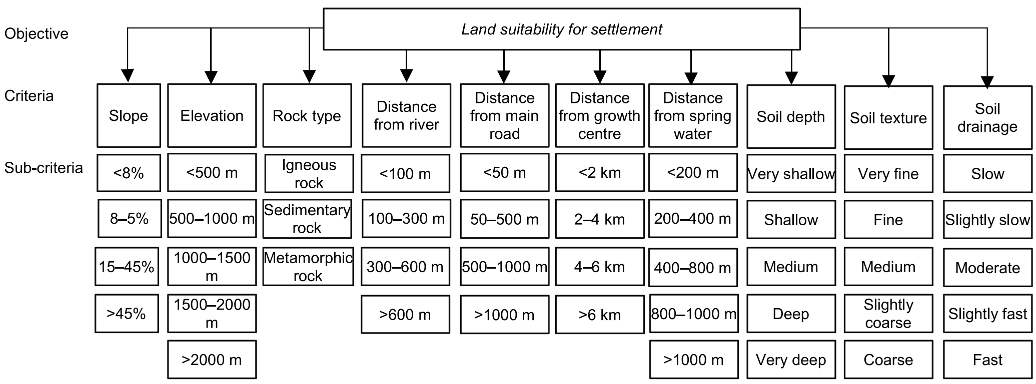



**Fig. 3.** Structure of land suitability decision making for settlements; source own elaboration

according to Equation (1) [Widiatmaka *et al.* 2016]. The level of suitability of the settlements was divided into four classes: highly suitable (S1), suitable (S2), marginally suitable (S3), and unsuitable (N).

$$S = \sum_{i=1}^{n} w_i x_i \quad (1)$$

where: $S$ = land suitability; $w_i$ = weight of land suitability criteria; $x_i$ = score of sub-criteria $i$; $n$ = number of land suitability criteria.

**Slope** is one of the main criteria that affects the direction of development planning in an area related to topography [Omar, Raheem 2016]. The slope was created from the contour layers on the topographic map. Generally, settlements are recommended in flat areas (<8%) since construction costs are cheaper, and constructions are more stable. The slopes (in %) were classified into four classes which are: (i) <8, (ii) ⟨8; 15), (iii) ⟨15; 45), and (iv) ≥45.

**Elevation** is related to soil stability, accessibility, construction costs, and disaster risk. The elevation was created from the topographic map contour layer. The elevation (in m a.s.l.) was divided into five classes which are: (i) <500, (ii) ⟨500; 1000), (iii) ⟨1000; 1500), (iv) ⟨1500; 2000), and (v) ≥2000.

**Distance from rivers** was modelled from the river layers on the topographic map. Buffer zones were created from the river bed boundaries from both sides and were classified into four classes, namely: (i) <50, (ii) ⟨50; 500), (iii) ⟨500; 1000), and (iv) ≥1000 m.

**Distance from main roads** were established from the road layers on the topographic map. The buffer zone was established around the main road, and it was classified into four classes, namely:(i) <50, (ii) ⟨50; 500), (iii) ⟨500; 1000), and (iv) ≥1000 m.

**Distance from growth center** was created from the building layer of topographical map. The centroid of the regency and sub-district government was selected as a growth center point. The buffer zone was created around the centroids and was classified into four classes which are: (i) <2, (ii) ⟨2; 4), (iii) ⟨4; 6), and (iv) ≥6 m.

**Distance from water spring** was considered as an important criterion for the location of settlements and was established from the lake layers of the topographic map. Buffer zones were created around springs and lakes and were divided into five classes, which are: (i) <200, (ii) ⟨200; 400), (iii) ⟨400; 800), (iv) ⟨800; 1000), and (v) ≥1000 m.

**Rock type** was derived from the geological map at a scale of 1:100.000. It consisted of three classes: (i) igneous, (ii) sedimentary, and (iii) metamorphic rocks.

**Soil texture** is an important criterion for determining an area's suitability for the construction of houses. Soil texture was split into five classes: (i) very fine, (ii) fine, (iii) medium, (iv) slightly coarse, and (v) coarse.

**Soil drainage** was classified into five classes. They are: (i) slow, (ii) slightly slow, (iii) moderate, (iv) slightly fast, and (v) fast.

**Soil depth** was classified into five classes (in m). They are: (i) very shallow (<25), (ii) shallow (25–50), (iii) medium (51–75), (iv) deep (76–100), and (v) very deep (>100).

### Preparing land availability maps for settlement

The land availability map was analysed using the RSPP and LULC maps. The result was a delineation of available land and unavailable land for settlement. The first map used was the RSPP map of the Sukabumi regency [PEMKAB Sukabumi 2012] which contained information on land allocation for various formal sectors. The RSPP map of the Sukabumi regency consisted of 13 space allocations, which were Protected Forest Area (PFA), Conservation Forest Area (CFA), Production Forest Area (DFA), Limited Production Forest Area (LPFA), Reserve Forest Area (RFA), Plantation Allocation Area (PAA), Wetland Agriculture Area (WAA), Upland Agriculture Area (UAA), Enclave Area (EA), Rural Settlement Area (RSA), Urban Settlement Area (USA), Coastline Boundary Area (CBA), and River Boundary Area (RBA). Among these 13 available space allocations, only the allocation of urban settlement areas and rural settlements could be used for settlement development. The second map used was the LULC Map which described the existing LULC conditions. The LULC map was created using SPOT 7 imagery [Dharma 2020]. The satellite image was georeferenced to the UTM 48S zone projection system. The image's visual interpretation for LULC was carried out. The LULC, which reflected vegetation cover, was classified into 11 categories as follows: (i) forest, (ii), dry land iii) building area, (iv) barren area, (v) plantation, (vi) irrigated rice field (vii) rainfed rice fields, (viii) shrubs, (ix) lakes, (x) rivers, and (xi) ponds. Among these 11 LULC categories, the LULCs that were not available for settlement were built-up areas, lakes, rivers, and ponds. The remaining eight LULC were deemed available for settlements.

### Establishing land suitability maps for settlements on available land in earthquake-prone areas

This step involved three input maps, which included a land suitability map for settlements, land availability map for settlements, and map of earthquake vulnerability. The overlay process was carried out with equal weight for the three input maps using the ArcGIS software. Subsequently, the final map was reclassified into four classes, which were highly suitable (S1) and available, suitable (S2) and available, marginally suitable (S3) and available, and unsuitable (N) for settlement. The final map was presented in two output maps: (i) a land suitability map for settlements on available land in medium earthquake-prone areas, which were then given symbols (S1, S2, S3, and N) and (ii) the land suitability map for settlements in highly earthquake-prone areas, which were named as S1, S2, S3, and N.

The earthquake vulnerability map of the Sukabumi regency (Fig. 4M) was used in this research to identify areas that are prone to earthquakes. The map was taken from the earthquake vulnerability map of Banten and West Java at a scale of 1:50,000 [PVMBG 2014]. Based on this map, the entire Sukabumi regency is located in an area that has the potential to be affected by high and moderate earthquake shocks. Areas that are potentially affected by high earthquakes with an intensity scale greater than VIII Modified Mercally Intensity (MMI) covered 77% of the study area, while areas with moderate earthquake intensity scales between VII–VIII MMI accounted for the remaining 23%.

## RESULTS

### WEIGHTING CRITERIA AND SCORING SUB-CRITERIA WITH ANALYTICAL HIERARCHY PROCESS

This study considered ten criteria for determining suitable locations for a settlement, which were slope, elevation, rock type, distance from the road, distance from the river, distance from springs, distance from the growth center, soil texture, soil depth, and soil drainage. Several researchers have previously used criteria such as slopes, flooding, drainage, gravel, texture, and effective depth for the study of selecting locations for settlements [HARDJOWIGENO, WIDIATMAKA 2007]. SANTOSO *et al.* [2019] studied land suitability for settlements in Palu, Indonesia using criteria such as slope, distance to the road network, distance to education facilities, distance to health facilities, distance to trade facilities, and disaster vulnerability. Likewise, research conducted by DEĞERLIYURT [2014] used lithology criteria, distance from the fault line, shear speed, groundwater, distance to the sea, and slope as determining factors. RUSDI *et al.* [2015] conducted land suitability assessments for settlements based on soil permeability, topography, and geology parameters at the same location, namely Banda Aceh. These researchers showed that the land suitability criteria for settlements varied widely and were highly dependent on regional conditions, the availability of spatial data, research focus, and the researchers involved. It has been shown that a very important stage in the evaluation of land suitability is the determination of the criteria [AL-SHALABI *et al.* 2006]. The selection of criteria in land evaluation must pay attention to the number of decision makers, the number of objectives, the number of alternatives, the existence of constraints, and risk tolerance [RIKALOVIC *et al.* 2014]. So far, there are no standard criteria for settlements. Several researchers have stated that the general criteria for settlements consisted of geomorphological, socio-economic, and environmental factors [AKINCI *et al.* 2013]. There was one parameter, slope, which was used by all researchers, including in this study.

The results of expert judgment in determining the land suitability weight for settlements are shown in Table 1. Such results showed that the slopes had a highest weight (29%), meaning that slopes played an important role in determining land suitability for settlements, followed by the distance from the road (21%). The distance from the water spring and the distance from the river had the lowest weight, which were 1.9% each. Similar results were obtained in research conducted by DEĞERLIYURT [2014] in Turkey and ZHAO *et al.* [2014] in China which indicates that slopes affect the spatial distribution of settlements. AL-SHALABI *et al.* [2006] stated that areas with a slope of more than 10% were not suitable for settlement development. Proximity to roads was one of the important criteria that should be considered in terms of accessibility, economy, and social aspects, as well as evacuation in the event of a natural disaster. According to OMAR and RAHEEM [2016] road accessibility is one of the important parameters for urban development because it provides connectivity between settlements; besides that, the presence of roads represents human activity. YEH and LI [1998] stated that the location of the settlements should be close to the road. In areas with a low population density, a distance of one to five km from the main and secondary roads is recommended.

Judging from the consistency of the experts involved in determining the weight using AHP, the ratio of consistency was 0.05 which was calculated using Equations (1)–(4). In the details of the assessment, the maximum eigenvalue ($\gamma_{max}$) was obtained = 10.73453477, $n$ = 5; $CI$ = 0.081614974; $RI$ = 1.49 and $CR$ = 0.054775151. SAATY [1988] reported that the acceptable consistency ratio ($CR$) should be ≤0.1. Thus, the experts involved in this study were quite consistent in making assessments.

## THEMATIC INPUTS MAP AND SETTLEMENT SUITABILITY MAP

The land suitability map for settlement was established by considering ten criteria and 45 sub-criteria resulting from the AHP and GIS approaches are presented in Table 2 and Figure 4. The result found that the study area was dominated by a slope of over 15 to 45% (43.4%) and flat areas which had a slope of 0–8% (29%) (Fig. 4A). A higher score was assigned to lower slope values (Tab. 2). Considering elevation, the study area was dominated by an elevation <500 m a.s.l. (57%) which was generally found in the southern and western parts of the study area. Meanwhile, elevations between 500 and 1000 m a.s.l. (36%) were generally found in the eastern part of the study area (Fig. 4B). The highest

**Table 1.** A pairwise comparison matrix for calculating the weight (relative importance) of criteria for settlement suitability.

| Criterion | Criterion | | | | | | | | | | Weight |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | DMR | RT | DGC | E | ST | SD | SDr | DWS | DR | |
| S | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 9 | 0.2905 |
| DMR | 1/2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 8 | 0.2103 |
| RT | 1/3 | 1/2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 7 | 0.1517 |
| DGC | 1/4 | 1/3 | 1/2 | 1 | 2 | 3 | 4 | 5 | 6 | 6 | 0.1093 |
| E | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 2 | 3 | 4 | 5 | 5 | 0.0784 |
| ST | 1/6 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 2 | 3 | 4 | 4 | 0.0558 |
| SD | 1/7 | 1/6 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 2 | 3 | 3 | 0.0392 |
| SDr | 1/8 | 1/7 | 1/6 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 2 | 2 | 0.0272 |
| DWS | 1/9 | 1/8 | 1/7 | 1/6 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 1 | 0.0188 |
| DR | 1/9 | 1/8 | 1/7 | 1/6 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 1 | 0.0188 |

Explanations: S = slope, DMR = distance from main road, RT = rock type, DGC = distance from growth centre, E = elevation, ST = soil texture, SSD = soil depth, SD = soil drainage, DWS = distance from water spring, DS = distance from river.
Source: own study.

score was assigned to low altitude areas (<500 m) and the lowest scoring occurred in the highland areas (1500–2000 m a.s.l.) – Table 2. Areas with an elevation >2000 m a.s.l. were a constraint and were not included in the analysis, because based on the statutory regulations on spatial planning [Keputusan … Nomor 32; Undang-Undang … Nomor 26], settlements cannot be installed at these heights.

Based on Table 2 and Figure 4C, the study area was dominated by locations that had a distance from the river greater than 600 m (87%). The most ideal areas for settlement were those that were situated between 100 and 300 m from the river, but in this study, this range of distances covered only 4% of the area. The highest score referred to the areas at distances ranging from 100 to 300 m from the river. Areas <100 m from a river were defined as a constraint that could not be used for settlement, according to regulations [Keputusan … Nomor 32]. According to the distance from main roads (Fig. 4D), the research site was dominated by areas with a distance from the main road of >1000 m (77%). While areas which were <50 m away from the main roads comprised only 1% of the entire Sukabumi regency. The most suitable sites for settlement were at distances from roads ranging from 50 to 500 m and were assigned the highest score (Tab. 2).

Referring to the criteria of distance from growth center, the research area was dominated by areas that were far from the center of growth (>2 km); these comprised about 86% of the study area, while those <2 km away only covered 14%. The highest score referred to the nearest class (<2 km) from the growth center. Based on the criteria for distance from springs, 98% of the study area was located >1000 m from water springs and only 2% were located <1000 m away. The highest value referred to the class of areas located between 200 and 400 m from water spring, while areas <200 m away were defined as a constraint, as stipulated in statutory regulations [Keputusan … Nomor 32].

Rock type of the study area was dominated by sedimentary rocks (53%) which were mainly distributed in the southern and middle parts of the study area (Fig. 4G). Igneous rocks (45%) are one of the most stable lithologies and are therefore very suitable for settlement, resulting in its high score value (Tab. 2). Soil texture is an important criterion for determining an area's suitability for the construction of houses. The study area was dominated by soils with a fine texture (73%) and slightly fine texture (21%). Meanwhile, coarse and slightly coarse soils were only found in the northern part of the study area (Fig. 4H). The highest score referred to the medium (slightly fine) texture, while the lowest score was assigned to the very fine and fine texture classes. Soil drainage of the study area was dominated by moderately drained soils (94.91%) (Fig. 4I). The study area was dominated by deep soil (86%). Meanwhile, very deep soil (>100 cm) covered 12% of the area and was generally found in the north-western part of the research area (Fig. 4J). The highest score was given to very shallow soils, followed by shallow soils; both soils were found only in the northern part and around Mount Gede (2%).

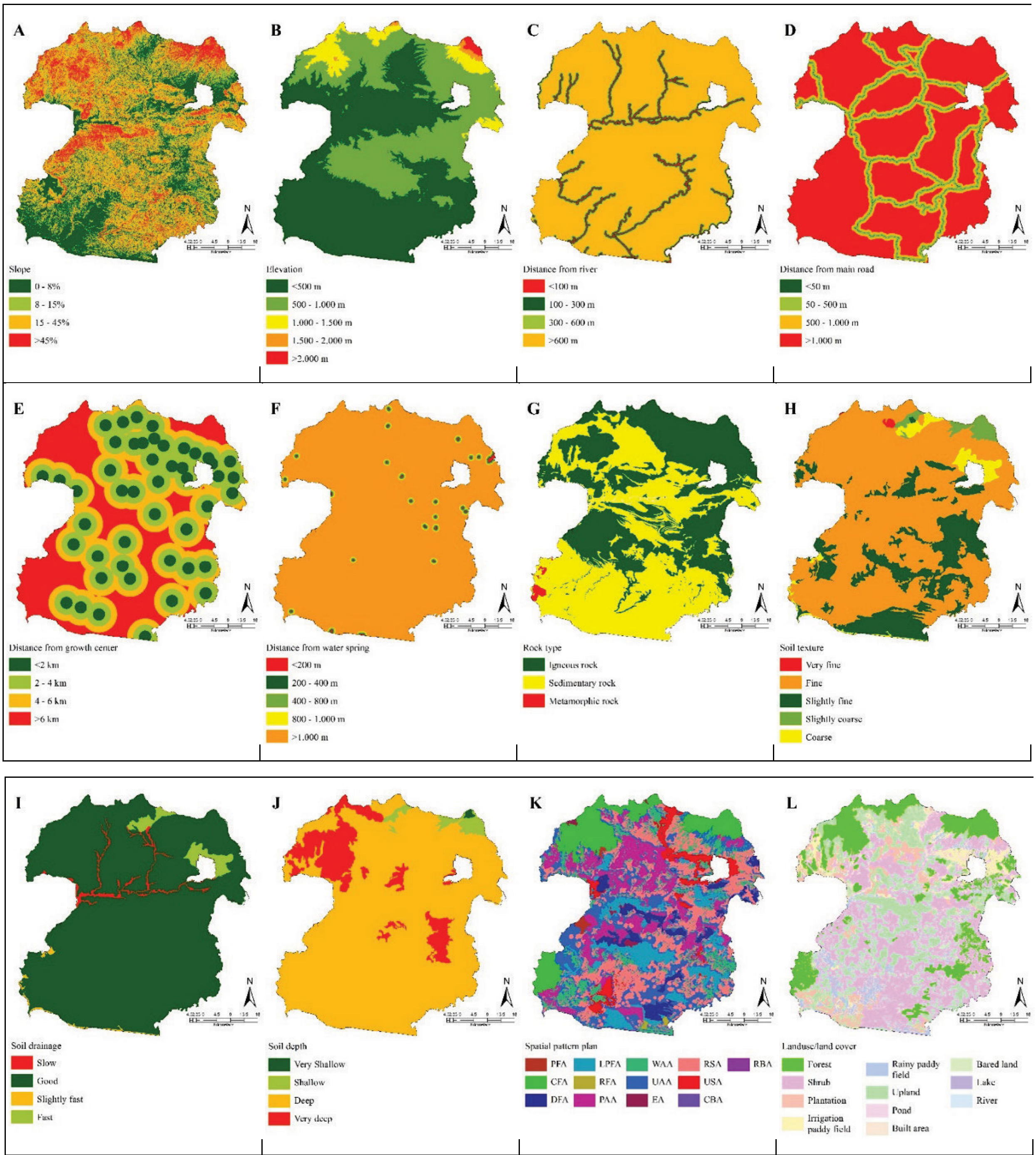
## LAND SUITABILITY FOR SETTLEMENT

Land suitability maps for settlements were made by considering the ten criteria and 45 sub-criteria produced at the stage of determining the criteria weight using AHP. The land suitability

**Table 2.** The selected criteria and sub-criteria involved in the suitability evaluation for settlements

| Criterion | Sub-criterion | Scoring | Area | |
|---|---|---|---|---|
| | | | km$^2$ | % |
| Slope (%) | <8 | 10 | 1,212.25 | 29.35 |
| | ⟨8; 15) | 8 | 622.16 | 15.06 |
| | ⟨15; 45) | 6 | 1,794.05 | 43.44 |
| | ≥45 | 0 | 501.48 | 12.14 |
| Elevation (m a.s.l.) | <500 | 10 | 2,362.77 | 57.21 |
| | ⟨500; 1000) | 8 | 1,489.17 | 36.06 |
| | ⟨1000; 1500) | 6 | 232.39 | 5.63 |
| | ⟨1500; 2000) | 4 | 25.41 | 0.62 |
| | ≥2000 | 0 | 20.20 | 0.49 |
| Distance from main road (m) | <50 | 10 | 58.14 | 1.41 |
| | ⟨50; 500) | 8 | 449.44 | 10.88 |
| | ⟨500; 1000) | 4 | 424.35 | 10.27 |
| | ≥1000 | 2 | 3,198.01 | 77.43 |
| Distance from water spring (m) | <200 | 0 | 9.66 | 0.23 |
| | ⟨200; 400) | 10 | 12.81 | 0.31 |
| | ⟨400; 800) | 8 | 40.67 | 0.98 |
| | ⟨800; 1000) | 6 | 27.36 | 0.66 |
| | ≥1000 | 4 | 4,039.44 | 97.81 |
| Distance from river (m) | <100 | 0 | 116.67 | 2.83 |
| | ⟨100; 300) | 10 | 181.56 | 4.40 |
| | ⟨300; 600) | 8 | 251.21 | 6.08 |
| | ≥600 | 6 | 3,580.49 | 86.70 |
| Rock type | igneous rock | 10 | 1,881.39 | 45.55 |
| | sedimentary rock | 8 | 2,226.86 | 53.92 |
| | metamorphic rock | 6 | 21.69 | 0.53 |
| Soil depth (cm) | very shallow (<25) | 10 | 6.81 | 0.16 |
| | shallow (25–50) | 8 | 86.59 | 2.10 |
| | medium (51–75) | 6 | – | – |
| | deep (76–100) | 4 | 3,559.92 | 86.18 |
| | very deep (>100) | 2 | 477.39 | 11.56 |
| Soil drainage | slow | 6 | 78.64 | 1.90 |
| | slightly slow | 6 | – | – |
| | moderate | 10 | 3,919.82 | 94.91 |
| | slightly fast | 8 | 21.78 | 0.53 |
| | fast | 8 | 109.70 | 2.66 |
| Soil texture | very fine | 6 | 9.50 | 0.23 |
| | fine | 6 | 3,034.82 | 73.48 |
| | medium | 10 | 860.75 | 20.84 |
| | slightly coarse | 8 | 93.40 | 2.26 |
| | coarse | 8 | 131.48 | 3.18 |
| Distance from growth center (km) | <2 | 10 | 566.15 | 13.71 |
| | ⟨2; 4) | 8 | 1,252.62 | 30.33 |
| | ⟨4; 6) | 4 | 1,086.23 | 26.30 |
| | ≥6 | 2 | 1,224.95 | 29.66 |

Source: own study.



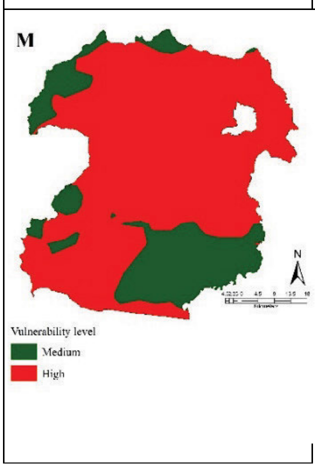




**Fig. 4.** Thematic maps of the factors involved in this study: A) slope, B) elevation, C) distance from river, D) distance to main road, E) distance from growth center, F) distance from water spring, G) rock type, H) soil texture, I) soil drainage, J) soil depth, K) map of Regional Spatial Planning Pattern, L) map of Land Cover / Land Use, M) the earthquake vulnerability map; source: own study

map was classified into four categories for further analysis: highly suitable (S1), suitable (S2), marginally suitable (S3), and unsuitable (N). The spatial distribution of land suitability for the settlements is shown in Figure 5 and a summary of the results is presented in Table 3.

The results found that from the total study area (4,129.94 km$^2$), 2,313.49 km$^2$ (56%) was classified as land suitable for settlements. The land suitability varied from highly suitable (S1), suitable (S2), and marginally suitable (S3) classes, which were 9.43, 27.48, and 19.11%, respectively. However, the study area was dominated by the suitable class (S2). The highly suitable class (S1) could only be found in the northern part of the study area, more precisely around the city of Sukabumi. Meanwhile, locations that were unsuitable for settlement covered an area of 1,143.74 km$^2$ (27.69%) of the total study area and it was the dominant class. Locations which were unsuitable for settlement were scattered in almost the entire study area. The high proportion of areas of class of N and S3 were due to the fact that the study area was dominated by areas with slopes exceeding 15%, a distance from the highway of more than 1000 m, a distance from a river >600 m, and a distance from a growth center >2 km. In this study, about 16% of the area was a constrained area, generally found in the northern part, more precisely around Mount Gede and around the Cimandiri Fault. Based on the expert's assessment, the constraint area is an area that is not recommended for residential locations due to its physical characteristics. In this study the constraint areas were located on a slope >45%, at an elevation >2000 m, at a distance from the water spring <200 m, and a distance from the river <100 m. Those obstacles were implemented by the laws and regulations which are in effect in Indonesia [Keputusan … Nomor 32].

## LAND AVAILABILITY FOR SETTLEMENT

Land availability for settlement considers RSPP and LUCC (Fig. 5B). This figure provides information that the available land for settlement was 946.49 km$^2$ (23% of the total area) which was sporadically spread throughout the study area. Meanwhile, 77% of the land was not available for settlement and was widespread in all study area. When we considered only RSPP, suitable lands for settlement were urban settlement areas and rural settlement areas, which covered 299.03 km$^2$ (7.20%) of the total study area. Whereas land that was unsuitable based on the considerations of the RSPP were Protected Forest Areas, Conservation Forest Areas, Production Forest Areas, Limited Production Forest Areas, Reserved Forest Areas, Plantation Allocated Areas, Wetland Agricultural Areas, Dry Land Agricultural Areas, Enclave Areas, Coastal Border Areas, and River Border Areas, which were found on around 3,863.38 km$^2$ (92.80%) of the study area. Most of the areas which were not available coincided with the areas allocated as Protected Forest Areas. This protected area must be obeyed because this area is the upstream part of a large watershed which includes the Cimandiri River and the Cikaso River. Analysis of land availability by considering only LULC showed that the land which was suitable for settlement included almost all the LULC classes, namely forest, fields/moor, open land, plantations/gardens, rice fields, rainfed rice fields, and shrubs with a total area of 3,888.68 km$^2$ (93.42% of the study area). Meanwhile, areas which were not available for settlements were ponds, rivers, lakes, and built-up land, which covered an area of 273.81 km$^2$ (6.58% of the total study area). Although theoretically available, lands such as rice fields should prudently be considered as available, considering that converting rice fields into settlements will affect

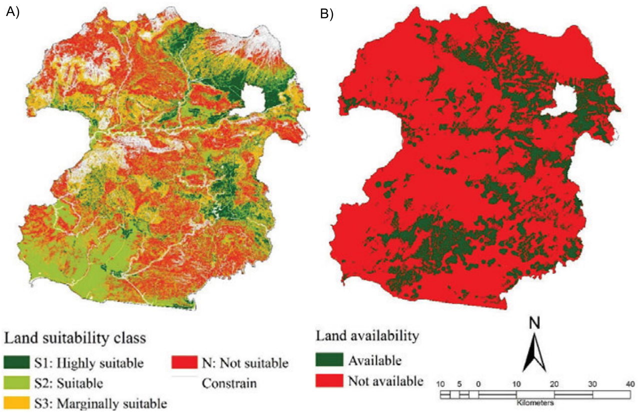



**Fig. 5.** The spatial distribution of land suitability for the settlements: A) settlement suitability map, B) map of land availability for settlement of the Sukabumi regency; source: own study

**Table 3.** Suitable and available lands for settlement in earthquake-prone areas in the Sukabumi regency

| Suitability/ availability | Suitability | | Suitable and available considering RSPP and LULC | | Suitable and available considering RSPP, LULC and earthquake hazard level | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | medium (VI–VIII MMI) | | high (>VIII MMI) | |
| | km$^2$ | % | km$^2$ | % | km$^2$ | % | km$^2$ | % |
| S1 | 389.36 | 9.43 | 128.42 | 13.57 | 7.51 | 3.86 | 120.92 | 16.08 |
| S2 | 1,135.06 | 27.48 | 301.33 | 31.84 | 50.09 | 25.73 | 251.24 | 33.42 |
| S3 | 789.06 | 19.11 | 188.61 | 19.93 | 32.65 | 16.77 | 155.96 | 20.74 |
| N | 1,143.74 | 27.69 | 246.03 | 25.99 | 78.57 | 40.36 | 167.46 | 22.27 |
| Constrain | 672.72 | 16.29 | 82.09 | 8.67 | 25.86 | 13.28 | 56.23 | 7.48 |
| Total | 4,129.94 | 100 | 946.49 | 100 | 194.68 | 100 | 751.85 | 100 |

Explanations: RSPP = Regional Spatial Planning Pattern, LULC = Land Cover / Land Use, MMI = Modified Mercally Intensity, S1, S2, S3 and N as in Fig. 5. Source: own study.

the supply of rice which is a staple food [Undang-Undang … Nomor 41]. This can be a separate topic of discussion in the context of regional food security, but in this study, it was still considered as available land that could be used for settlements. Meanwhile, land availability by considering the RSPP and LULC maps can be seen in Table 3. The results of the analysis showed that the suitable and available area for settlement was quite wide, covering an area of 618.36 km$^2$ (65.33% of the total available area – 946.49 km$^2$). Most of the area (301.33 km$^2$ or 31.84% of the available area) was suitable (S2). Meanwhile, there were 246.03 km$^2$ of unsuitable lands for settlements (25.99% of the available area).

## SUITABLE LAND WHICH IS AVAILABLE FOR SETTLEMENT IN POTENTIAL EARTHQUAKE-PRONE AREAS OF SUKABUMI REGENCY

The land which was suitable and available for settlements in earthquake-prone areas was obtained from overlaying three maps, which were land suitability maps for settlements, land availability maps for settlements, and earthquake vulnerability maps. The results of the analysis are shown in Figure 6 (medium level earthquake), Figure 7 (high level earthquake) and Table 3 (suitable and available considering RSPP, LULC & earthquake hazard level).

According to the earthquake vulnerability map, entire Sukabumi regency is situated in an earthquake-prone area; namely the high potential for earthquakes covers an area of 3,195.89 km$^2$ (77%) and medium earthquake area of 934.05 km$^2$ (23%). Meanwhile, lands that were suitable for settlements on available land (946.49 km$^2$) covered 618.36 km$^2$ or 65.33% of the study area. The results of the overlay of three maps are presented in Table 3, showing that the suitable and available lands for settlements in moderately earthquake-prone areas (S1, S2, and S3) covered 90.25 km$^2$ or 46.36% of the total land area in moderate earthquake-prone areas (194.68 km$^2$) and is displayed in Figure 6. The land suitability varied from being highly suitable (S1), suitable (S2), to marginally suitable (S3). Meanwhile, the unsuitable (N) areas were dominant (40.36%).

Figure 6 shows the distribution of the suitable lands which were available for settlements in areas with a moderate potential for earthquakes. The dark green area symbolising S1 was only found in a small part in the northern part of the study area (see box A). Settlement development in earthquake-prone areas was being prioritised in this S1 class area. Meanwhile, S2 class was scattered near S1 class in the north (see box A) and the south (see box C). S3 clasas was mostly found in the western part (see box B) and in the north (see box A).The area with a high earthquake vulnerability area is displayed in Figure 7 and Table 3. The suitable and available lands for settlements (S1, S2, and S3) covered 528.11 km$^2$ or 70.25% of the total land area in the high earthquake hazard zone (751.81 km$^2$). The suitable class (S2) was dominant in areas prone to a high frequency of earthquakes. Figure 7 illustrates the land distribution of suitable lands on available lands for settlements in areas with a high potential for earthquakes. S1 class was a dark green area, generally found around the city of Sukabumi (see box A) and in the northern part of the study area, and to a lesser extent in the south (see box B). S1 class was a highly suitable location for settlements and development in high earthquake-prone areas. Especially all the existing criteria in this area made it the most suitable location for settlements because the location was on a flat slope, close to the center of growth, close to the main road, at an elevation of < 500 m, and close to water springs and river networks providing an environment which is convenient and accessible. Meanwhile, S2 class was generally found sporadically in almost all regions and mostly in the southern part (box B), while S3 class was found sporadically in the middle of the study area and in the western part of Sukabumi city (see boxes A and B).

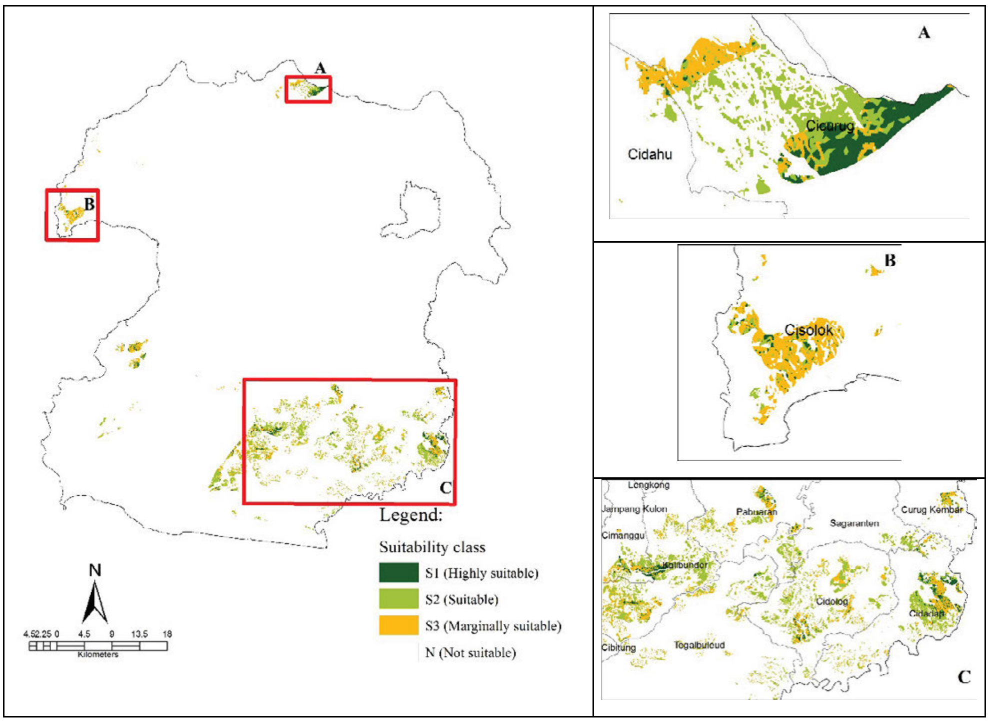



**Fig. 6.** Map of suitability and availability of land for settlements in medium potential earthquake areas of the Sukabumi regency; source: own study

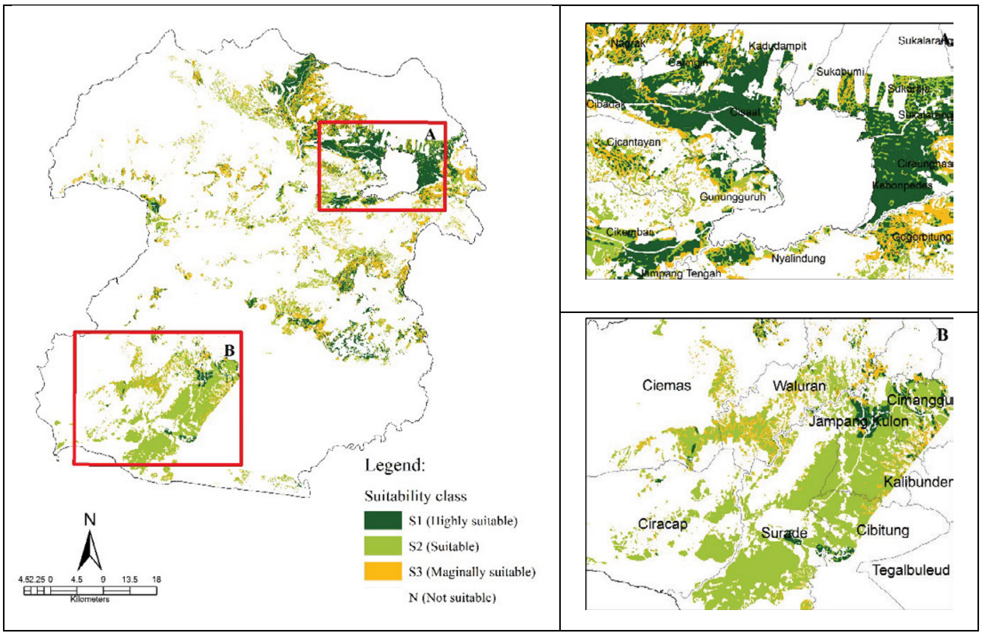



**Fig. 7.** Map of suitability and availability of land for settlements in high potential earthquake areas of the Sukabumi regency; source: own study

## CONCLUSIONS

This study aimed to provide basic guidelines for identifying suitable and available lands for settlements in areas prone to earthquakes. The integration of Analytical Hierarchy Process (AHP) and Geographical Information System (GIS) was used to determine the suitability of lands for settlements in the Sukabumi regency by considering ten criteria, which were slope, altitude, rock type, distance from the road, distance from the river, distance from springs, distance from the center, growth, soil texture, soil depth, and soil drainage.

The results showed that suitable and available lands for settlements in areas that were moderately prone to earthquakes covered an area of 90.25 km$^2$ or 46.36% of the total land area in moderately earthquake-prone areas (194.68 km$^2$). Unsuitable lands (N) were dominant this area, namely covering 40.36% of the study site. Meanwhile, in areas with high earthquake vulnerability, the suitable lands on available lands for settlements covered 528.11 km$^2$ or 70.25% of the total land area in the high earthquake vulnerability zone (751.81 km$^2$). The suitable class (S2) dominated the land suitability class for settlements in highly earthquake-prone areas.

This research succeeded in utilising AHP and GIS to map land suitability for settlements in earthquake-prone areas. The results of the analysis can be used by planners to prioritise settlement development in the Sukabumi regency. The methodology developed in this research can be applied to other regions in Indonesia. In the context of Indonesia, selecting a location that is suitable for settlement but with a minimum level of disaster risk is necessary considering that Indonesia is one of the countries with the highest earthquake rates in the world.

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