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Spatial Modeling of Flood-Vulnerability as Basic Data for Flood Mitigation

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Abstract

Identifying risks in flood-prone areas is necessary to support risk management decisions. This research was conducted to establish a vulnerability model of flood hazards in the city of Pontianak. The model was based on the scoring and weighting of biophysical factors. The AHP method and logical formulations were used to establish the model. The result showed that the accuracy of the model used by AHP to determine the vulnerability of floods was 80% in Pontianak City. The accuracy of the model using logical formulations to determine the vulnerability level of a flood was 84%. The Kappa accuracy value in model 1 is 76.7%. The model of flood vulnerability explains that most of Pontianak City has a very high level of flood vulnerability, which is 31,440,568.8 m^2 or 29.11% of the total research area of 108,003,319.8 m^2. The vulnerable area is 29,945,485.7 m^2 or 27.73%, and the less safe area is 22,126,936.3 m^2 or 20.49%, with the safe area being 24,490,328.7 m^2 or 22.67% of the total area. This research contributes to the government to establish policies regarding flood management and urban development in the future, and as an effort to mitigate against flooding.

Keywords: Spatial Model; Flood Vulnerability; Bio-Physical; AHP; Kappa Accuracy.

1. Introduction

Flooding is a natural phenomenon that causes widespread destruction, disrupts daily life, and increases vulnerability, including physical, social, economic, and environmental impacts. The geographic information system provides an effective environment for mapping and precise analysis to mitigate the flood disaster [1–3]. This study is concerned with how flood risk can be estimated in specific flood-prone areas. There are many examples of flood studies in different countries [4–6], but Indonesia is one where a significant number of flood studies have been conducted. In this study, Pontianak-West Kalimantan, Indonesia, was selected for the purpose of flood risk assessment. Flooding is the most common natural disaster in Pontianak. Floods cause disruption of social and economic activities [7–9], damage roads, damage property, cause deaths, and increase vulnerability. Floods are mainly caused by prolonged heavy rains, rapid development, unplanned urbanization, poor drainage systems, and environmental degradation. This annual flood event has had a huge impact on people's lives as well as other living things. Due to the negative impact of flooding, we need to take serious precautions and find alternative ways to mitigate this disaster. In this study, five bio-physical parameters will be used, namely rainfall, land use, land cover, soil type, and slope. To determine the weight of each parameter, the AHP method is used; to determine the accuracy of the map, Kappa accuracy is used; and the results will be compared with field checks. The research location can be seen in Figure 1. Innovative technologies should be considered to reduce vulnerability and build resilience for sustainable disaster risk reduction.

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Figure 1. Location of research

Mapping of flood vulnerability using GIS technology and remote sensing can be relied upon as disaster mitigation. GIS technology is able to complete spatial tasks quickly and consistently, while remote sensing is able to provide up-to-date, reliable, and accurate data. GIS is a suitable tool for mapping spatial data from natural disaster hazards. GIS can also spatially integrate several variables that may cause natural disasters. Spatial analysis is very useful for predicting an event that can help decision making through the process of geographic data simulation [10–12].

The benefits of this research are: for residents to know that their homes are located in areas that are very vulnerable, vulnerable, less safe, and safe to flooding; for Regional Disaster Management Agencies (BPBD), they can get information to take preventive measures and respond more quickly to flood hazards; for the government, it can be used as a basis for setting policies and directions for urban development in the future; and for researchers, it can be used as a reference for further research and application using the science and technology of GIS and remote sensing.

2. Materials and Method

The materials used in this study are: Collection of raster data and spatial information (vectors), which are variables (biophysical conditions) that affect flooding at the location of the relevant institution. Collected maps: river layers/maps, government administrative boundary maps, road maps, land type maps, and topographic maps of the earth. Weather data that includes rainfall, wind speed from the weather station of the West Kalimantan Meteorology, Climatology, and Geophysics Agency (BMKG) [13–15]. The slope map is obtained from the ALOS PALSAR DEM image derivative, and the land cover map is the result of the interpretation of Landsat OLI 8, image lines 121. 060. Landsat 8 image data and ALOS PALSAR DEM images for all study sites. The land use map is the result of digitization from photo map data or extension images (jpg).

The model is a representation of reality, and the purpose of making a model of the level of flood vulnerability in Pontianak is to help understand, describe, or predict how floods occur in Pontianak City. Modeling is done using the available variables. Variables that cause flooding in Pontianak City, namely: rainfall (R), slope (SL), soil type (ST), land use (LU), and land cover (LC). The next step is to overlap all variables. The variables forming the flood vulnerability model are collected and given a score based on the level of influence of each variable on the flood. The greater the effect, the greater the scoring value. Then the map projections of each variable are equated, then overlap or overlap through the analysis tool process with the union command found in ArcGIS 10.3 software. The union result is a new map that provides information on all variables. This union map must then be given the weight of each variable [16–18].

The assessment of each variable is carried out by experts by means of pairwise comparison analysis arranged in the same order matrix. This assessment method is a method that has been popularized by Saaty in the AHP (Analytic Hierarchy Process) [19–21]. Then the consistency is tested; if it meets the requirements, it will be used in determining the weight of the model. For the model to be validated, field verification is needed. For each condition, the level of vulnerability is assessed in terms of inundation height based on field checking: very vulnerable (inundation height > 40 cm), vulnerable (inundation height 26–40 cm), less safe (inundation height 11–25 cm), safe (inundation height 0–10 cm). As a reference for field verification, 25 locations are set, with the distribution on the map of flood vulnerability levels as follows: very vulnerable (11 locations), vulnerable (6 locations), less safe (5 locations), and safe (3 locations) [22].

Model validation is a way to determine the accuracy of the model [23–25]. The model with the highest level of accuracy is a good model because it has high accuracy, and low error, so that confidence in the model is also high. From the 3 models produced, the best model must be chosen. To determine which model is the best, an accuracy test must be performed on the three models using a confusion matrix (error matrix), in order to obtain the results of user accuracy, producer accuracy, and overall accuracy. The model with the highest accuracy overall value will be determined as the best Pontianak flood hazard level.

The methodology that we used is shown in Figure 2.

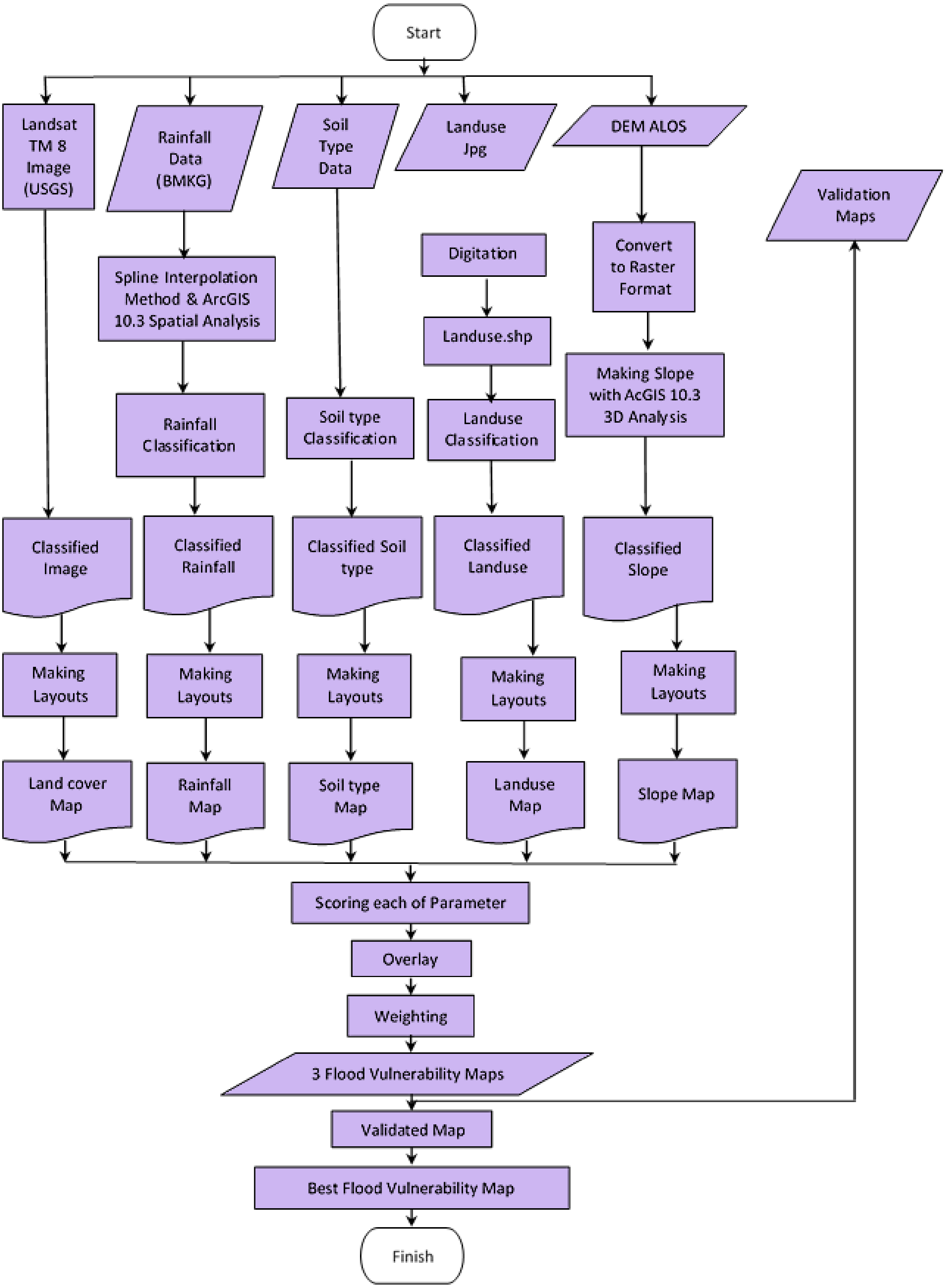

Figure 2. Flowchart of methodology

3. Results and Discussions

Stressed that ecological criteria should be taken into account, in addition to socioeconomic considerations, when discussing flood vulnerability in every area. The vulnerability of floods can be measured by classifying them into separate groups, such as natural, economic, and social vulnerability. Age, population density, impoverished settlements, and failure to access social resources can all be used to measure population exposure to flooding. Indicators such as degraded forests and land erosion may determine the environmental aspect. For social and economic elements, poverty, land resource base, and infrastructure usability may be considered [2].

Different techniques have been used to measure flood vulnerability for a long time. Therefore, precise comparative assessment is vital in other dimensions. Previous studies indicated various methods used to assess the vulnerability. These methods include the vulnerability curve method, indicator-based method, analytical hierarchy process, mapping method, disaster loss data method, and modeling methods through geographic information systems [26].

The selection of variables forming the Pontianak City flood hazard model considers the influence of natural or physical factors of the land, namely: rainfall, slope, soil type, land use and land cover. The stages in this study include: making thematic maps of each flood variable, making models (modeling) and validating the model of flood hazard levels and the benefits of flood hazard maps of Pontianak.

The spline method is considered suitable for use in locations that do not have adequate rainfall data or rain monitoring stations that are very minimal, as is the case in Pontianak City [15, 16]. When viewed from the perspective of the movement of the wind, wind is air that moves from areas of high air pressure to areas of low air pressure (usually from west to east). A high-pressure sea breeze during the day brings rain clouds from the ocean to the mainland, so that rainfall is more frequent.

On the thematic map of rainfall that can present the state of rainfall in Pontianak City more clearly and relative to the actual conditions is based on the results of interpolation using the Spline method (Figure 3). This is based on the distribution of data showing that the Spline method provides evenly distributed data, in the Eastern Pontianak City area is an area that has very high rainfall (3001 - 3500 mm), and the Western Pontianak City area is an area which has high rainfall (2500 - 3000 mm) [16].

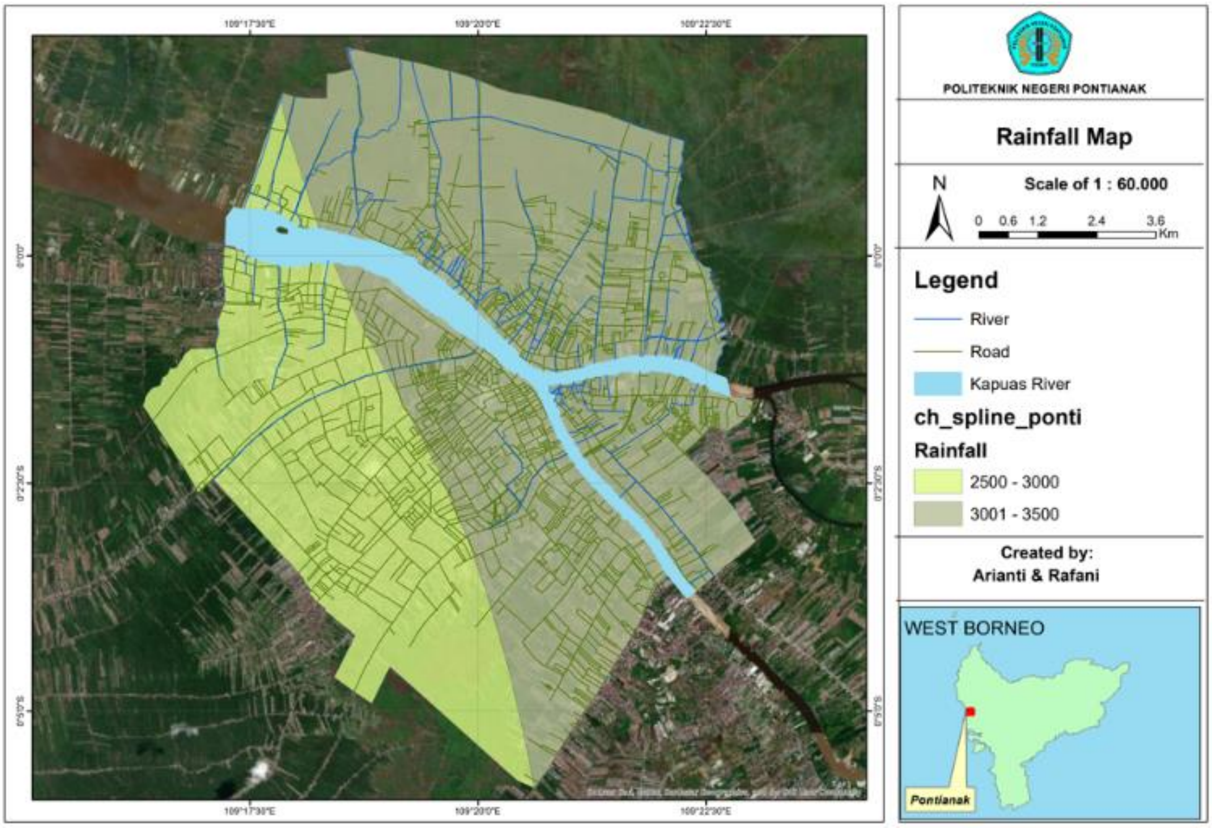

Figure 3. The rainfall map Pontianak City by Spline method

Slope map in Figure 4, Pontianak City only consists of 2 slope classes, namely 0-5% flat category and 6-15% sloping category. Based on the slope map in Figure 2, Pontianak City is dominated by areas with 0-5% slope class area of 72 km^2 or 66.7% and areas with slope class 6-15% covering 36 km^2 area or 33.3%. This shows that Pontianak City is located in a flat area.

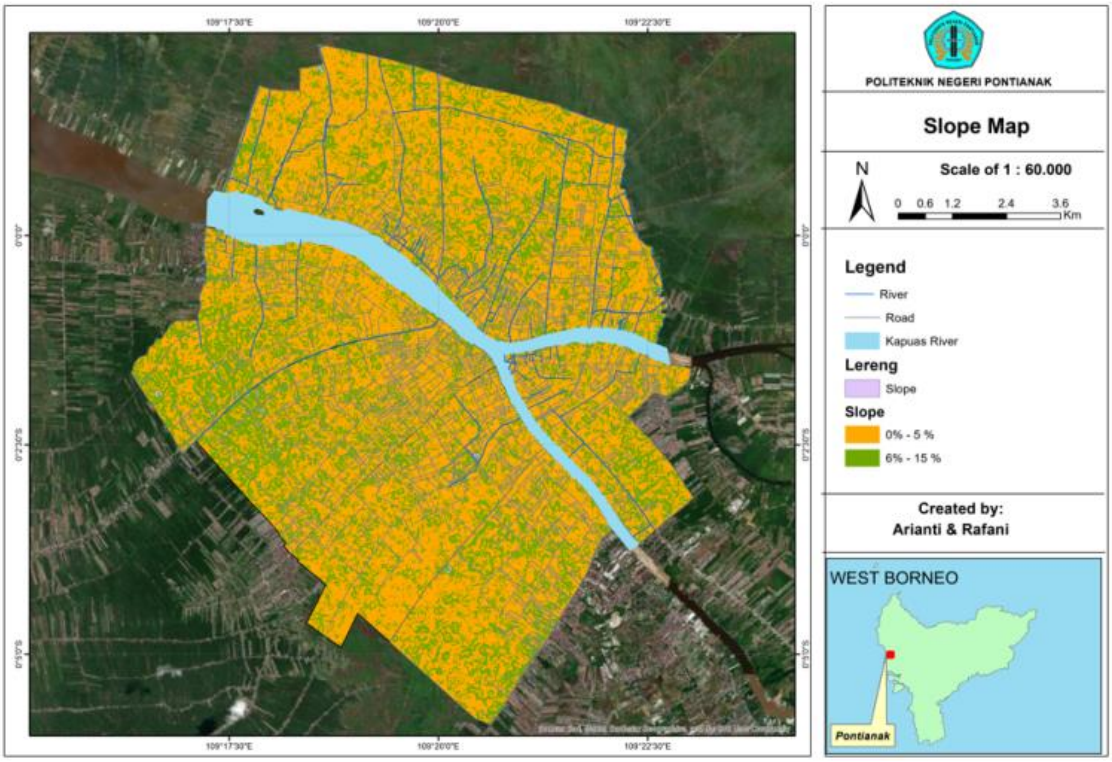

Figure 4. Map of the slope of Pontianak City

On the map of soil types in Figure 5, it can be seen that the type of soil in Pontianak City consists of only 2 (two) classes, namely alluvial land covering an area of 30 km^2 equivalent to 27.8%, and peat land covering an area of 78 km^2 equivalent to 72.2%.

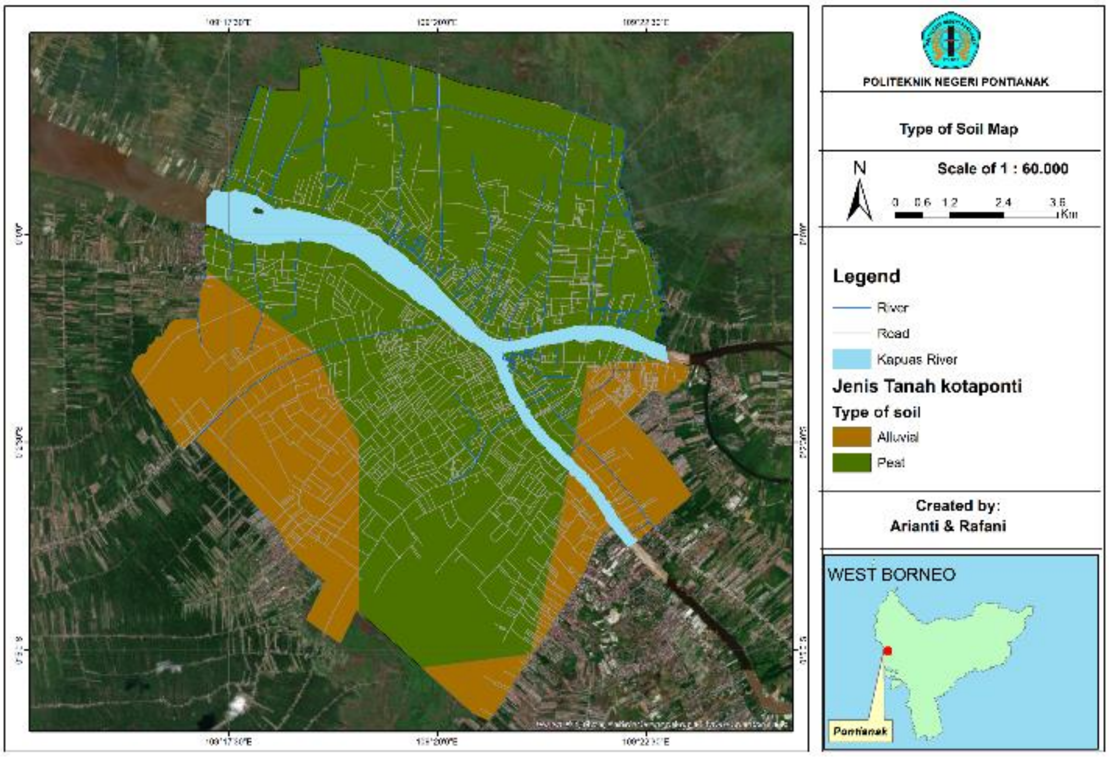

Figure 5. Map of soil types Pontianak City

Land use map in Figure 6, with division based on 5 (five) classes, service and industrial areas covering 7.1 km^2 equivalent to 6.6%; the area of education and offices covering an area of 3.2 km^2 equivalent to 2.9%; settlement areas with an area of 26.2 km^2 equivalent to 24.3%; paddy area is 21.3 km^2 equivalent to 19.7%, and green open space area is 50.2 km^2 equivalent to 46.5% [1].

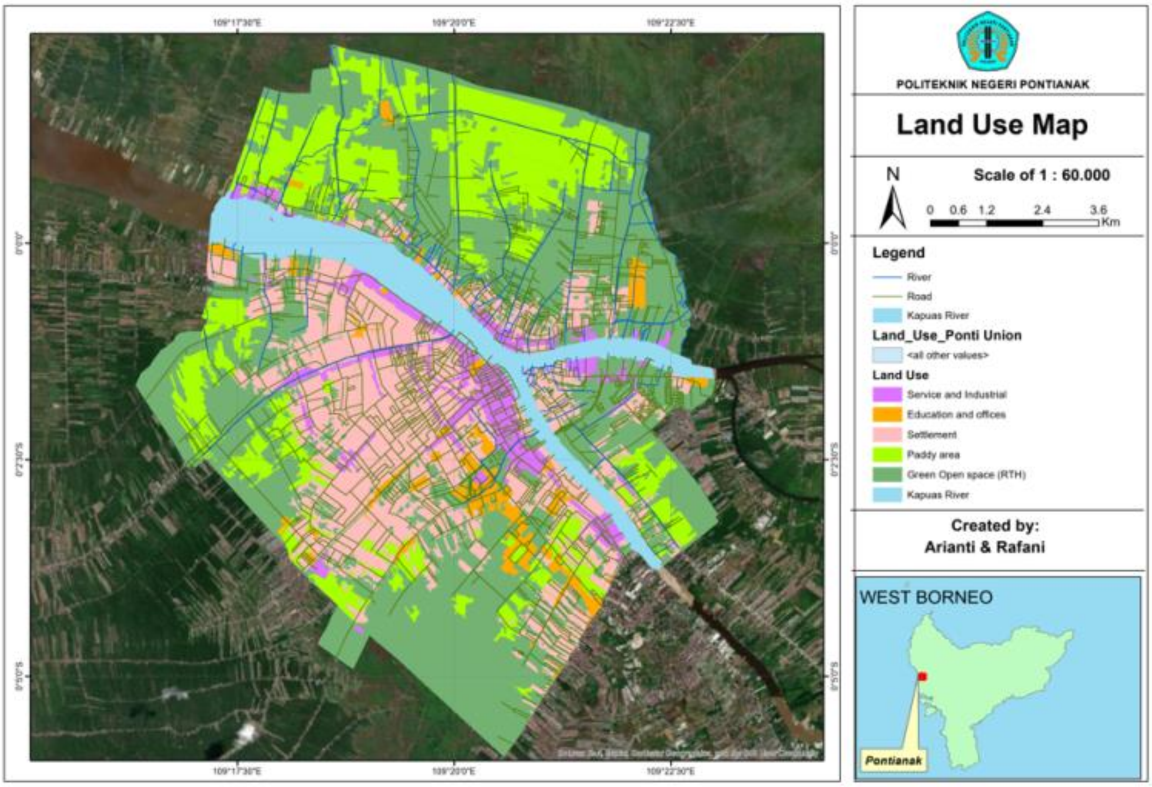

Figure 6. Map of Land use of Pontianak City

Land cover is a biophysical cover on the surface of the earth that can be observed as a result of the regulations, activities, and human treatment carried out on the type of land cover. Land cover found in Pontianak City is classified into three classes, namely: mixed gardens, open land, and settlements [9].

The land cover map of Pontianak City in Figure 7 shows a settlement area of 80.2 km^2 equivalent to 74.2%; an open land area of 5.9 km^2 equivalent to 5.5%; and a mixed garden area of 21.9 km^2 equivalent to 20.3%.

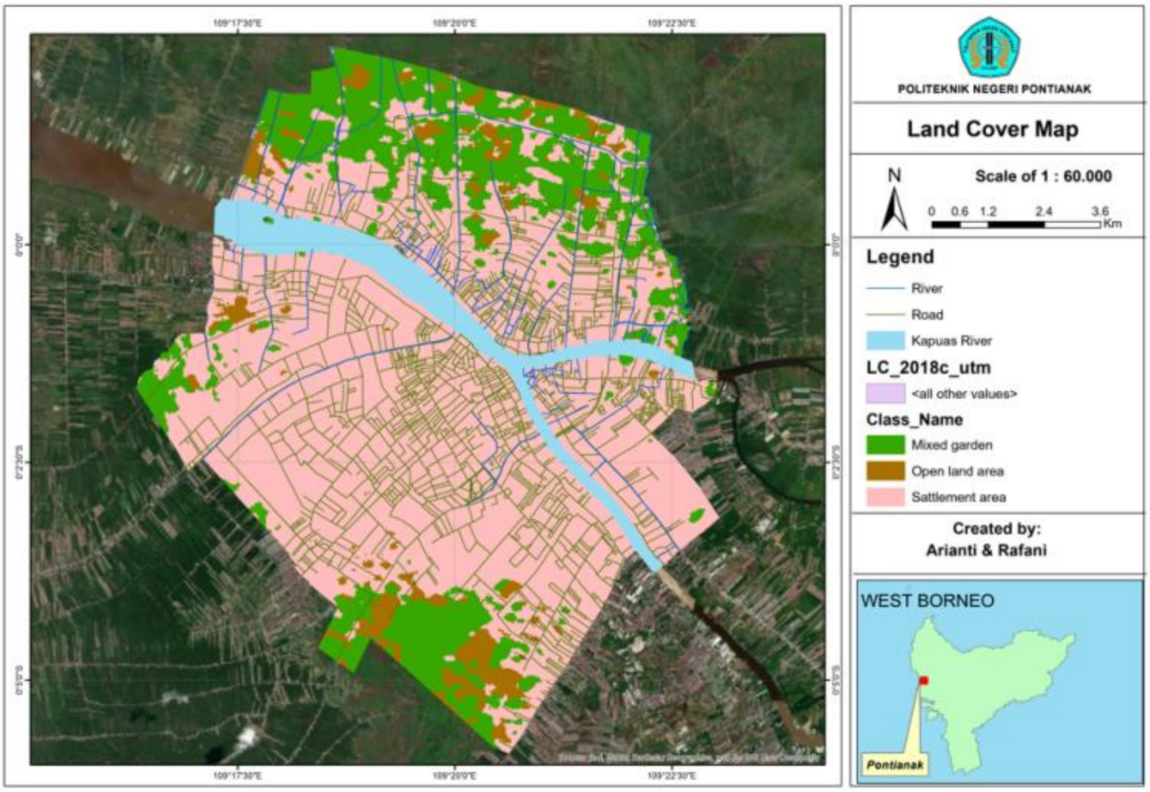

Figure 7. Map of Land cover of Pontianak City

After making and preparing thematic maps for each variable forming the Pontianak City flood hazard model, the next step is scoring each variable. Scoring is given in order of influence. The scoring of each variable that affects flooding is done to quantify textual data into numerical data. Scores are made with consideration of the logical formulation of the order of influence of each variable [23-25]. The higher the influence of a variable on flood events, the higher the score given. Overlay or overlapping is done to determine the vulnerable area of several determinants of flood area by scoring method, namely scoring. From the results of overlap, the area with the highest total score is the area with the potential for flood hazard [27-30].

Weighting is giving weight to each variable based on consideration of how much influence each variable has on flood events. The greater the influence of these variables on flooding, the greater the weight given. Weighting is intended to give weight to each variable using the Analytic Hierarchy Process (AHP) [14-16]. Determination of the weight for each thematic map is based on consideration, of how likely flooding is affected by each geographic variable that will be used (Table 1).

Table 1. Normalized weight matrix

	R	LC	LU	SL	ST	Σ	Eigen Vector
R	0.5595	0.5185	0.5806	0.5556	0.5294	2.7436	0.5487
LC	0.0799	0.0741	0.0645	0.0556	0.1176	0.3917	0.0783
LU	0.1865	0.2222	0.1935	0.2222	0.1765	1.0010	0.2002
SL	0.1119	0.1481	0.0968	0.1111	0.1176	0.5856	0.1171
ST	0.0622	0.0370	0.0645	0.0556	0.0588	0.2781	0.0556

Eigen value maximum (λ_{max}) as follows:

$$[1.7873 \quad 13.5000 \quad 5.1667 \quad 9.0000 \quad 17.0000] * \begin{bmatrix} 0.5487 \\ 0.0783 \\ 0.2002 \\ 0.1171 \\ 0.0556 \end{bmatrix} = [5.0723] \tag{1}$$

Determine the Consistency Index:

$$CI = \frac{\lambda_{max} - n}{n-1} = \frac{5.0723 - 5}{5-1} = 0.0181 \tag{2}$$

Determine the Consistency Ratio:

$$CR = \frac{CI}{RI} = \frac{0.0181}{1.12} = 0.0161 \tag{3}$$

Table 2. Random Index

N	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Decision making for spatial modelling, which often uses many variables, must be faced with the problem of determining the level of influence of one variable on other variables that make up the decision level [31–34]. The decision makers must weight each variable based on the influence or importance of the variable. These variables are then compared based on their effects [7, 21]. The variable that has the highest weight is a variable that greatly influences the flooding in Pontianak City, while the smallest weighting shows the variable that has the least effect [18, 24]. Each model is formed by multiplying the weights and scores of each variable (Figures 8 to 10). Model 1: (20*[Score_R]) + (20 * [Score_LU]) + (20 * [Score_SL]) + (20 * [Score_ST]) + (20* [Score_LC]), Model 2: (54.87 * [Score_R]) +(20.02 * [Score_LU])+ (11.71 * [Score_SL]) + (7.83 * [Score_LC]) + (5.56 * [Score_ST]), Model 3: (49.29 * [score_R]) + (18.56 * [Score_LU]) + (18.56 * [Score_SL]) + (8.21 * [Score_ST]) + (5.39 * [Score_LC]).

Determining the selection of the best flood hazard modeling and the benefits of the flood hazard map [25, 28]. The best model selection indicator is based on model validation. Validation to obtain accuracy values that have the highest level of confidence is the best model because the level of errors that occur is minimum [1, 23, 28].

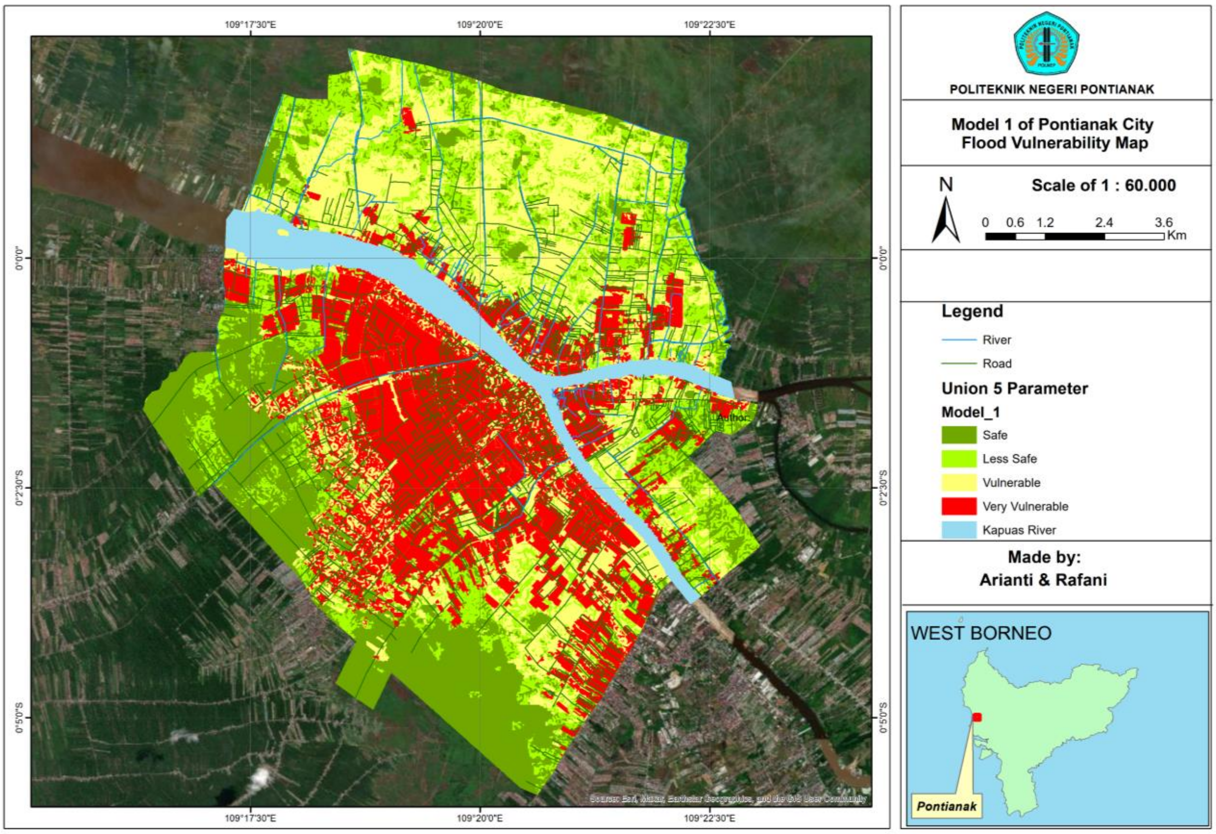

Figure 8. Model 1 of Pontianak city flood vulnerability

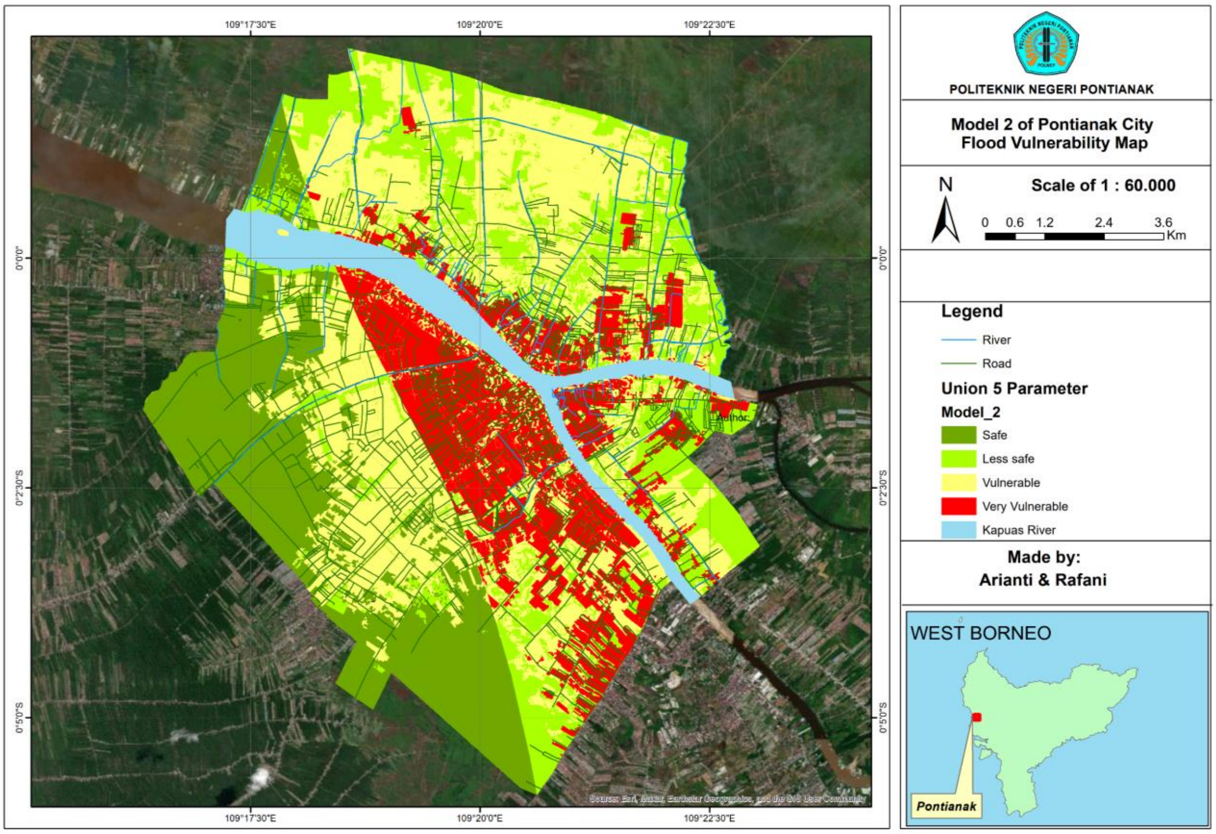

Figure 9. Model 2 of Pontianak city flood vulnerability

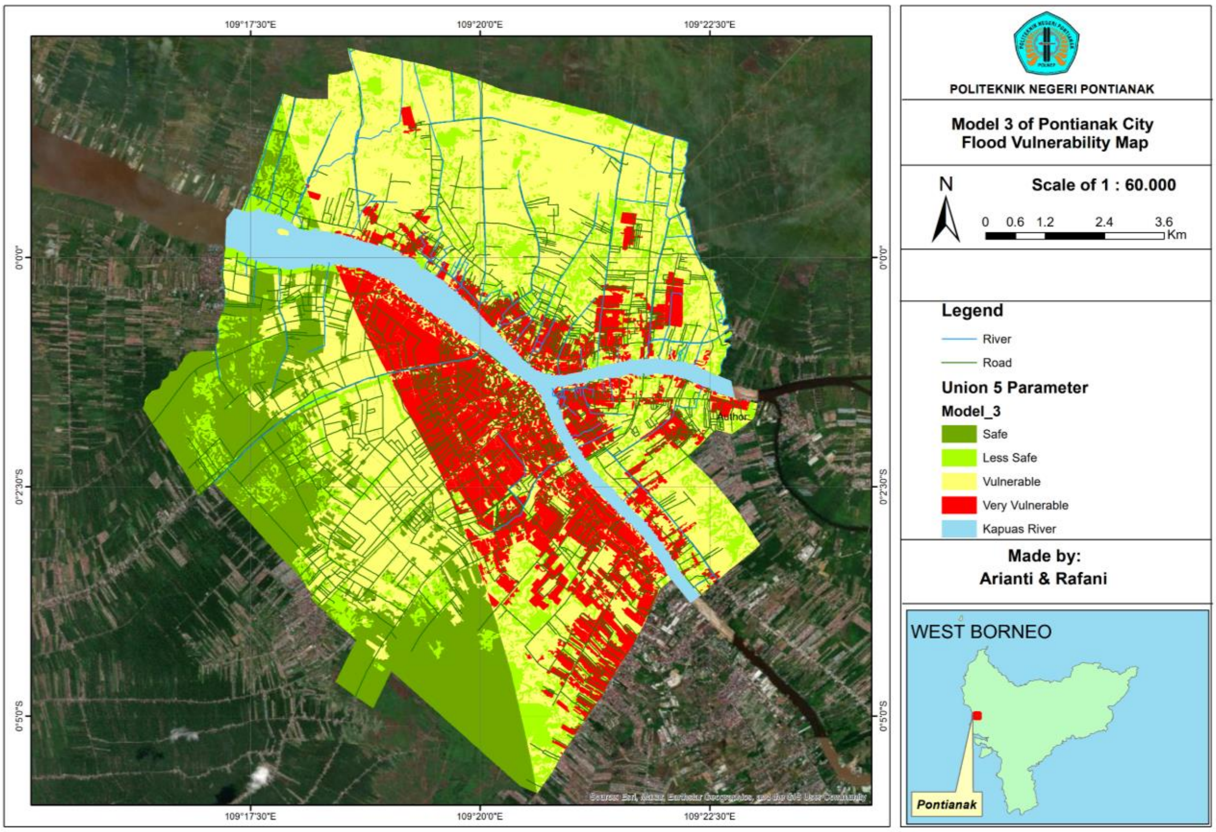

Figure 10. Model 3 of Pontianak city flood vulnerability

The results of the model validation show that Model 1 has an overall accuracy of 84% while Model 2 and Model 3 are 80%. Based on the calculation results of Kappa accuracy it turns out that models 2 and 3 have the same Kappa accuracy values of 71.3% and 71.3%. The model 1 has a better Kappa accuracy value of 76.7%. Therefore, model 1 was chosen, which was formed by five variables with a higher overall accuracy of 84%. The overall accuracy value indicates the number of pixels that are correctly classified in each class compared to the number of samples used for accuracy testing in all classes [24]. In the example of Table 3, the overall accuracy shows a value of 84.0% which means 84.0% of the pixels in the classification result are correctly classified. The value of this accuracy test is the most widely used to test the accuracy of an interpretation or classification results [35-37].

Table 3. Error Matrix

Sites cross-check	A (10 cm)	B (25 cm)	C (40 cm)	D (55 cm)	Total sample	User Accuracy (%)	Error Commission (%)
A	3	0	0	0	3	100.0	0.0
B	0	5	0	0	5	100.0	0.0
C	0	1	3	2	6	50.0	50.0
D	0	0	1	10	11	90.9	9.1
Total	3	6	4	12	25	-	-
Prod. Accuracy (%)	100.0	83.3	75.0	83.3	OA	84.0	-
Error Omission (%)	0.0	16.7	25.0	16.7	Kappa	76.7	-

This model shows that the research area is dominated by very vulnerable areas in the amount of 31,440,543.1 m^2 or 29.12% of the total research area of 107,958,782.1 m^2, followed by vulnerable areas in 29,907,481.0 m^2 or 27.70% and less safe areas of 22,120,432.1 m^2 or 20.49% and safe areas of 24,490,325.9 m^2 or 22.67% of the total area of research (Figure 11). When viewed in a very vulnerable area per subdistrict it turns out that Pontianak City sub-district was the widest namely 8,299,516.9 m^2 then followed by South Pontianak sub-district 6,980,141.8 m^2, West Pontianak sub-district 5,638,021.4 m^2, North Pontianak sub-district 4,095,410.0 m^2, Southeast Pontianak sub-district 3,830,011.8 m^2 and East Pontianak sub-district 2,597,441.2 m^2.

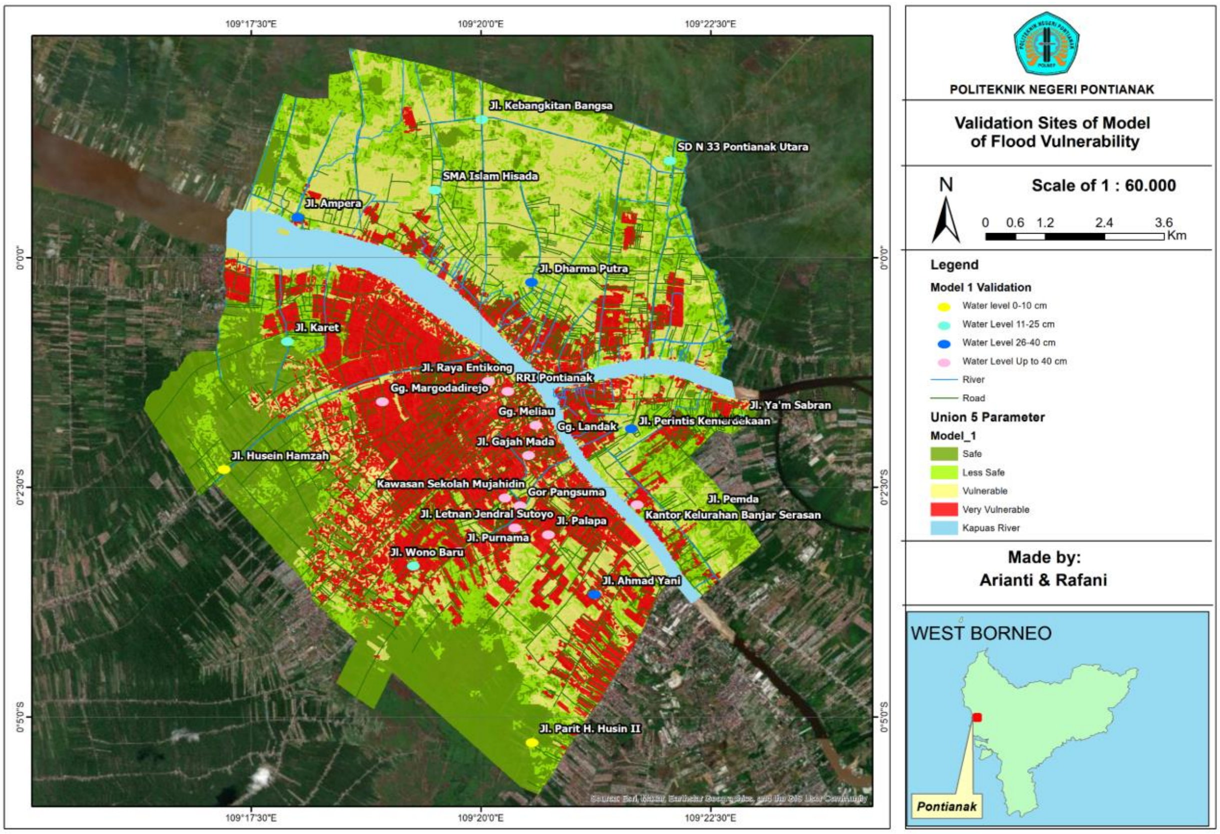

Figure 11. Validation sites of model of flood vulnerability

4. Conclusion

Variables that cause floods in Pontianak City are: rainfall > 3,000 mm/year; soil type consisting of alluvial and peat; land use consisting of services and industry, education and offices, settlements, rice fields, green space; land cover consisting of mixed gardens, open land, settlements; and a flat slope. It turns out that with bio-physical variables, the accuracy of the model (model 1) has reached 84%, after cross-checking the flood vulnerability maps directly at the locations of the floods with each variable's weight (20*[Score_R])+(20*[Score_LU])+(20*[Score_SL])+(20*[Score_ST]) (20*[Score_LC]). The Kappa accuracy value in model 1 is 76.7%, which means it is able to avoid 76.7% of errors. This flood vulnerability level model explains that most areas of Pontianak City have a very high level of flood hazard (very vulnerable), which is 31,440,568.8 m^2 or 29.11% of the total area of the research area of 108,003,319.8 m^2. The vulnerable area is 29,945,485.7 m^2 or 27.73%, the less safe area is 22,126,936.3 m^2 or 20.49%, and the safe area is 24,490,328.7 m^2 or 22.67% of the total area studied.

5. Declarations

5.1. Author Contributions

Conceptualization, I.A., M.R., N.F., and N.; methodology, I.A.; validation, I.A., M.R., N.F., and N.; formal analysis, I.A.; investigation, M.R., N.F., and N.; resources, I.A., M.R., N.F., and N.; data curation, I.A., M.R., N.F., and N.; writing—original draft reparation, I.A. and M.R.; writing—review and editing, M.R.; visualization, I.A. and M.R.; supervision, I.A.; project administration, I.A.; funding acquisition, I.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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