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Flood susceptibility mapping based on watershed geomorphometric characteristics and land use/land cover on a small island

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ABSTRACT

BACKGROUND AND OBJECTIVES: Flooding is the most frequent hydrological disaster which greatly impacts humans and the environment. Lombok, a small tropical island, experiences severe flooding almost yearly. Flood susceptibility mapping is important to determine the priority watershed in implementing flood mitigation action, including improving the spatial planning in watershed management. Several methods of determining flood susceptibility require the support of long data series and a variety of monitoring equipment in the field where not every region has the resource capacity. Compared to other methods that require the support of long data series and a large number of evenly distributed monitoring equipment, the geomorphometric parameters and land use/cover in a watershed are closely related to the hydrological responses and are potentially applicable in flood susceptibility mapping. This research aimed to classify the watershed flood susceptibility on a small island based on the geomorphometric characteristics and land use/land cover of the watershed.

METHODS: This study was carried out on Lombok Island, located in southern Indonesia, representing a small island in the tropical region. Watershed classification was carried out using 24 geomorphometric variables and land use/land cover, representing aspects of the river network, geometry, texture, and watershed relief. The principal component analysis approach was carried out to determine the most significant variable, and the weight of each variable was determined using the weighted sum approach method. Then, compound values were calculated based on the weighted values and preliminary ranking to indicate the flood susceptibility levels, which were divided into five classes.

FINDINGS: The analysis found that the variables most related to flood events are the total number of rivers, relief ratio, elongation ratio, river density, stream frequency, and dry agricultural land use. These most related geomorphometrics indicate that the watersheds with higher flood susceptibility have low rock permeability, relatively low infiltration capacity, and relatively high surface runoff, thus triggering flooding. The flood susceptibility mapping classified 16 watersheds as having very high flood susceptibility. This research shows that analysis of the geomorphometric characteristics and land use/land cover can be relied upon to determine the flood susceptibility level, which is useful in spatial planning and flood disaster mitigation.

CONCLUSION: Geomorphometric characteristics and land use/land cover can be used to determine a watershed's hydrological characteristics or behaviour. Based on the geomorphometric characteristics of the watersheds on Lombok Island, some identifying variables that are highly related to flood processes were obtained. Based on these characteristics, watersheds with high and very high flood susceptibility levels have low rock permeability, relatively low potential infiltration capacity, and relatively high surface runoff potential. Flooding still occurs despite good forest cover because the geomorphometric characteristics of the watershed also play a major role in flood events.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
57	6	3

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INTRODUCTION

Vulnerability to hydrometeorological catastrophes is one of the repercussions of Indonesia's astronomical position (Djalante *et al*., 2017). Natural disasters caused by hydrometeorology, such as floods, droughts, landslides, forest fires, and extreme climates, are the most frequent disasters in Indonesia (Rosyida *et al*., 2018). Among the hydrometeorological disasters, floods are the most frequent and have wide-reaching impacts (Das, 2019). Indonesia is a country that has a high frequency of flood events and the intensity is increasing every year (Nurulita and Ningrum, 2018). Floods are caused by various natural factors, e.g., meteorological factors, physical characteristics, and land cover (Pariartha *et al*., 2023) and anthropogenic factors, e.g., community behaviour, land use/land cover (LULC) changes, deforestation (Ramadhan *et al*., 2023), and environmental management (Handayani *et al*., 2020). Various studies have stated that the rise in hydrometeorological disasters is related to the global climate change phenomeno the world in the last few decades (Thomas and López, 2015; Frimawaty *et al*., 2023). The flood risk level is increasing due to extreme weather phenomena caused by climate change (Brunner *et al*., 2018; Puno *et al*., 2022). Coastal areas will be more vulnerable to climate change disasters (Mycoo *et al*., 2022), such as flooding, due to water level rises (Gaborit, 2022). Lombok, a small island in Indonesia, has specific characteristics in terms of the landscape, geology, hydrology, and climate patterns that influence resource management (Bengen *et al*., 2012). With a diverse topography ranging from mountainous to coastal areas, the island also has different climatic conditions. A climate analysis conducted by Nandini and Narendra (2011) stated that Lombok Island has been experiencing climate change, characterized by the tendencies of decreased rainfall, increased air temperature, and shifts in climate types from 1961 to 2008. In addition, Yasa *et al*. (2022) predicted climate changes marked by rain patterns in 2018–2035, during which the pattern will tend to be wetter, thereby increasing the chances of flooding. Several factors, such as rainfall, watershed characteristics, LULC changes, and an increase in degraded land, have influenced the occurrence of floods on Lombok Island. In the last few years, floods have inundated rice fields, settlements, and infrastructures in Mataram, the biggest city on the island, which has caused large material losses (Rahadiati *et al*., 2021). In 2022, there were 30 flood incidents on Lombok Island. The high number of flood events on Lombok Island cannot be separated from the level of susceptibility of this island regarding the potential for flooding. The Regional Disaster Management Agency also stated that in 2017–2022, 57,301 people spread across 758 villages with a moderate level of flood susceptibility were affected by the flood disaster that occurred on Lombok Island (Yunus *et al*., 2019). Flood events, such as those occurring in Senggigi Beach and the Mandalika area, have disrupted tourism and economic activities by cutting off road access and several bridges (Suarantb, 2023). Mitigation measures, including spatial planning based on the level of disaster susceptibility of an area, must be taken to minimize disaster risk (Umar and Dewata, 2018). Lombok, as a small island, necessitates rigorous spatial planning, including flood susceptibility mapping (Setiawan and Nandini, 2021). Information on flood susceptibility for watershed level in Indonesia has not been mapped in detail. Several methods, such as statistical and hydrological modelling, can be used to map the flood susceptibility level. However, these methods require the support of long data series from many widely distributed monitoring equipment (Ahmed *et al*., 2021). Good DEM and LULC data availability and easy acquisition are other reasons the use of geomorphological and LULC parameters has good potential for flood susceptibility mapping in Indonesia. Research on flood events related to the geomorphological aspects of a watershed on a small island is rarely performed in Indonesia. Flood events with extreme magnitudes are largely influenced by geomorphological characteristics, which are uncontrollable natural factors. Flood disasters can be minimized by taking into account other aspects, including LULC, which is influenced by human activities and constitutes the main factor determining flood vulnerability (Ahn and Merwade 2015). This study aims to map flood susceptibility based on geomorphological conditions and watershed LULC on a small island. The results of the mapping of flood-prone areas will be useful for spatial planning and flood disaster mitigation strategies, and ~~they~~ methods can also be applied to other small islands. This study was carried out on Lombok Island in 2021.

MATERIALS AND METHODS

Descriptions of the study area, data sources for analysis, the geomorphometric characterization, LULC classification, and integrated approach (PCA and WSA) are explained in detail as follows.

Description of the study area

The study was carried out on Lombok Island, which is positioned in the southern region of Indonesia (Fig. 1). The island is categorized as a small island and covers an area of approximately 4,700 square kilometers (km^2). Geographically, Lombok Island lies between 115°49’28” and 116°43’22” east (E) and between 8°12’41” and 8°57’20” south (S). −The island has experienced flood events, including flash floods, in at least the past five years. Another reason was that the island represents small islands in the tropical region, which are relatively vulnerable to climate change by the trigger factor of floods. These are essential reasons in the context of an evaluation of the applicability of the methods used for flood susceptibility mapping. Based on the watershed map of Indonesia (scale 1:50,000), the island has 194 watersheds. Watersheds on small islands are characterized by relatively small areas, flows directly heading to the sea relatively steep terrain in the upstream area, and flat terrain in the downstream area. The elevation of each watershed varies; generally, the elevation ranges from 0 to 3,726 meters above sea level (masl), with the highest elevation

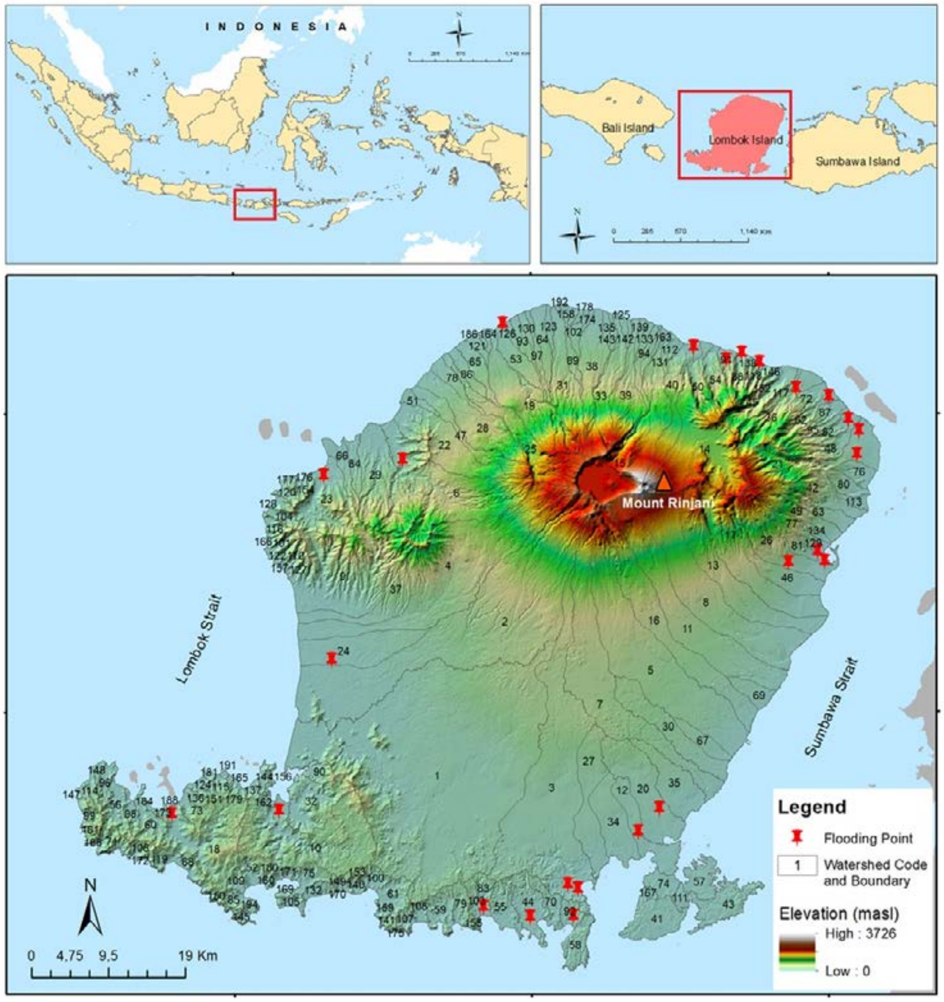

Fig. 1: Geographic location of the study area in Lombok Island, positioned in the southern region of Indonesia

being the peak of Mount Rinjani. Low areas mostly lie in the study area's southern part, while mountainous regions are in the northern part. Relatively flat slope gradients dominate the low areas, while steep slope gradients dominate the high-lying areas.

The research area's climate differs geographically. Based on the Schmidt-Fergusson classification, Lombok Island is dominated by a moderate climate (type D) distributed on the western and eastern parts of the island. Meanwhile, a slightly wet climate (type C) is found in the island's middle part, especially around Mount Rinjani. The northern and southern parts of Lombok Island have a slightly dry climate (type E) (Yasa *et al*., 2022). The average rainfall reaches 1,568 milimeters (mm)/year, with a unimodal rainfall pattern. The unimodal pattern indicates that rainfall has only one peak from December to March. Spatially, the areas at the high elevation of Mount Rinjani experience high rainfalls (> 1,000 mm), while the western and southern parts experience low rainfalls (< 1,000) (Widiatmaka *et al*., 2015). The highest and the lowest temperatures on Lombok Island occur in August and December, ranging from 24.7 degrees Cel~~e~~sius (°C) to 27.2 °C. Lombok Island's lithology is formed of sediment material that is Tertiary to Quaternary in age. The geology of Lombok Island is characterized by volcanic rocks, such as volcanic breccias, lavas, and sandstones. Some areas are also dominated by a fresh and unconsolidated sediment quarter. Tertiary rock formation dominates the eastern part of Lombok Island, including breccias, lavas, and tuffs. The rock arrangement in the west, generally an alluvial region, is formed of alluvial or loose rocks. Quaternary volcanic rocks from Mount Rinjani cover the northern part and almost two-thirds of Lombok Island (Agustawijaya and Syamsuddin, 2009). Lombok Island consists of four primary soil types: Litosols, Cambisols, Alluvials, and Vertisols. In a few areas, Mediterranean soil exists as a slightly developed soil type. According to the FAO soil system, these primary soil types are equal to Leptosols, Fluvisols, Cambisols, Vertisols, and Luvisols. Shallow solum, sandy texture, low soil nutrients, a low cation-exchange capacity (CEC), and low organic carbon content characterize Litosols/Leptosols. The soils with ~~a~~ quite a deep solum are Cambisols or Undepts. These are also slightly fertile with a loamy texture and medium organic carbon content and CEC. Alluvial or Fluvent soils are primarily used for paddy cultivation with various clay and organic carbon contents and depths and relatively fertile soil. Vertisols, also known as Uderts, are distinguished by a dominant clay texture, great difficulty in cultivation, high CEC, and moderately productive soil. Mediterranean soils or Udalfs are more developed soils with moderate CEC and moderately fertile soil (Priyono *et al*., 2019).

Data and data sources

Variables collected as the source data consisted of geomorphometric and LULC variables. Data from the digital elevation model were used for geomorphometric characterization. The DEM data, released by the Geospatial Information Agency of Indonesia, had 8.3 meters (m) spatial resolution (Sihombing *et al*., 2021) and consisted of 12 tiles in total for the study area. The boundaries of the watersheds on Lombok Island were obtained from the watershed map of Indonesia at a scale of 1:50,000. LULC data were interpreted from Landsat 8 multi-band optical images. The images, available on the United States Geological Survey website, have a medium spatial resolution and can be optimized up to 15 m resolution by using panchromatic band (Roy *et al*., 2014). An inventory of flood events in Lombok Island was carried out by mapping the last two years of flood occurrences from several sources, including report documents of the National Disaster Management Agency, online and offline news, previous research, and ground check. The complete workflow of this study is shown in Fig. 2.

Geomorphometric characterization

Geomorphometric characterization aimed to extract the geometric features of all the watersheds in the study area. Many studies have shown that geomorphometric analysis can be used to prioritize watersheds regarding hydrological issues, such as erosion (Obeidat *et al*., 2021) and flooding (Mahmood and Rahman, 2019). The relationship between geomorphological features and hydrological processes can provide comprehension of the hydrological behavior within the watershed. There were several steps involved in the analysis of the geomorphological parameters: mosaicking 12 DEM data tiles, overlaying the DEM data and the provided watershed map, and computation of the geomorphological parameters for each watershed. The environment of a geographic information system

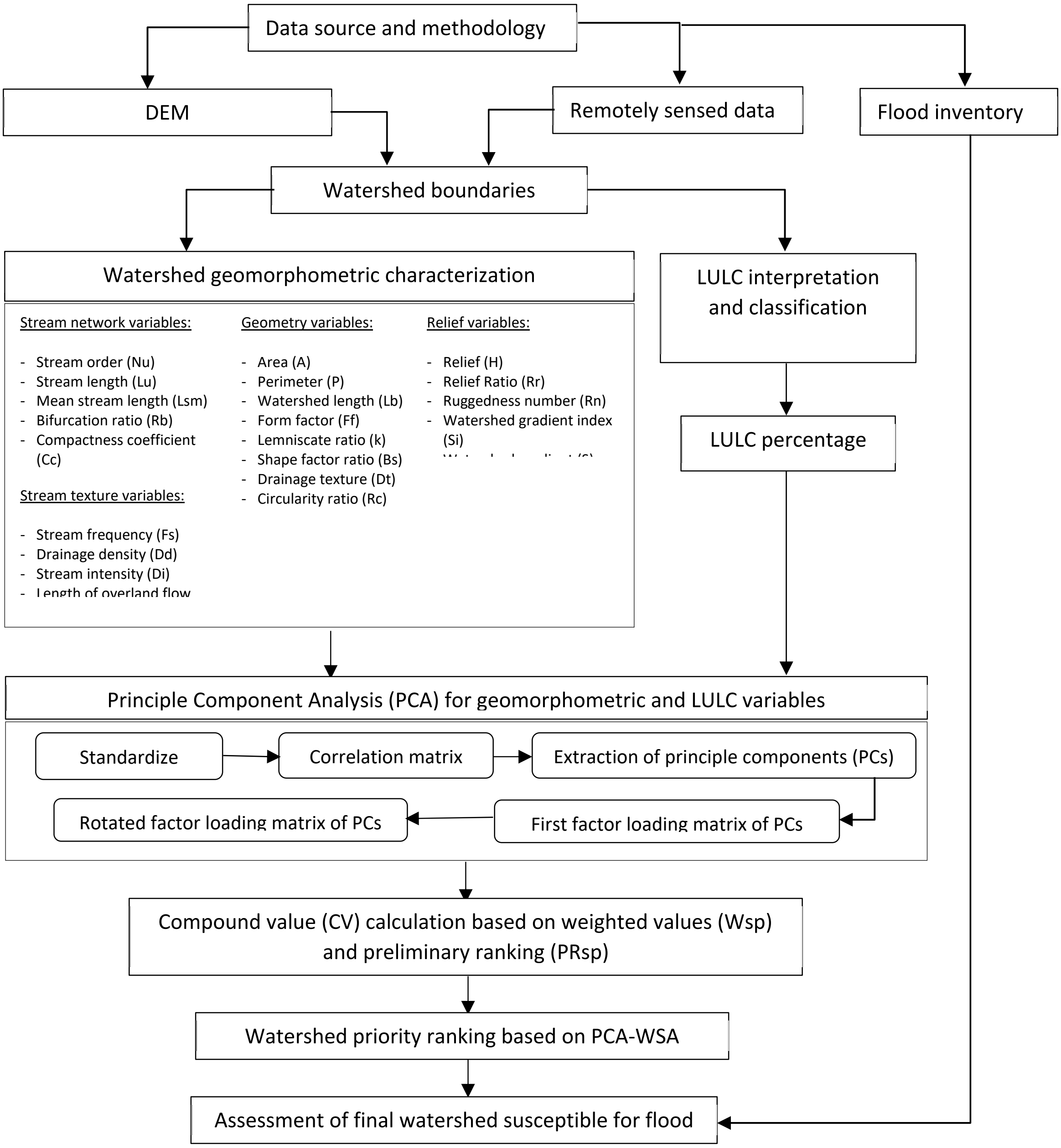

Fig. 2: The workflow of the study

was employed to derive the main parameters from the DEM data, drainage network, and watershed maps. The main parameters included the area, perimeter, watershed length, stream order, number of streams, stream length, and relief. Computation of the main parameters was conducted to obtain the stream network variables, stream texture variables, geometry variables, and relief variables. All the variables (Table 1) were calculated using standard and well-known formulas proposed by previous

Table 1: Geomorphological variables used in the study

Geomorphometric variables	Formula
Geometry variables	
Area (km^2)	Estimated by GIS
Perimeter kilometer (km)	Estimated by GIS
Watershed length (km)	Estimated by GIS
Form factor	$Ff = A/Lb^2$
Lemniscate ratio	$K = Lb^2/4 \times A$
Shape factor ratio	$Bs = Lb^2/A$
Drainage texture	$Dt = Nu/P$
Circularity ratio	$Rc = 4 \times \pi \times A/P^2$
Elongation ratio	$Re = 1.129 \times \sqrt{A}/Lb$
Stream network variables	
Stream length	$Lu = L1 + L2 + ... + Ln$
Stream order	$Nu = N1 + N2 + N3 + ... + Nn$
Mean stream length (km)	$Lsm = Lu/Nu$
Compactness coefficient	$Cc = 0.282 \times P/\sqrt{A}$
Channel maintenance (km)	$Cm = 1/Dd$
Bifurcation ratio	$Rb = Nu/Nu + 1$
Stream texture variables	
Stream frequency (no./km^2)	$Fs = Nu/A$
Drainage density (km/km^2)	$Dd = Lu/A$
Stream intensity	$Di = Fs/Dd$
Length of overland flow (km)	$Lg = 1/2\ Dd$
Relief variables	
Relief	$R = Hmax – Hmin$
Relief ratio	$Rr = R/Lb$,
Ruggedness number	$Rn = Dd*(H/1000)$
Gradient index	$Si = H/Lb$
Average gradient	$S = Lb/H$

studies (Ghasemlounia and Utlu, 2021; Obeidat *et al*., 2021; Kant *et al*., 2022; Tiwari and Kushwaha, 2021).

LULC classification

The LULC map was obtained by image interpretation of Landsat 8 remote sensing data of 2020. Mosaiking, radimettric and geometric correction conducted prior to the interpretation process. The method used for interpretation was the maximum ikelihood method (Chandniha and Kansal, 2017). The LULC categorization employed the national standard of LULC classes (Badan Standardisasi Nasional, 2010), including forest, dryland farming, paddy field, fishpond, shrub, bare land, pasture, water body, airport, mangrove, and resettlement. The obtained LULC map was then overlaid with the watershed bounda~~e~~ries to acquire an LULC map of each watershed, which was calculated as a percentage of the total area of watersheds.

Integrated approach: PCA and WSA

This study combined principal component analysis with the weight sum approach (WSA) in defining flood susceptibility at a watershed scale. The PCA aimed to reduce the geomorphometric and LULC variables based on variance within inter-correlated variables into principal components. As the roles of the influenced variables in flooding are in equal naturally, the WSA was used to define the weight value of each variable. Several studies have found that integrating PCA and the WSA provides more sophisticated results in watershed prioritization. (Singh and Pandey, 2021). The PCA technique in this study was carried out in several steps. First, the dataset was standardized as each variable had a different unit and aimed to gain PCA performance. Second, correlation matrix computation was carried out to define all possibilities of variable relationships. Third, the eigenvalues were determined for the PC number selection. In this case, the PC with eigenvalues of more than one–were chosen. The fourth and fifth steps were the computation of the first-factor loading matrix and the rotated factor loading matrix of the PCs, respectively. Based on the rotated factor loading matrix, the variable of each PC with the highest value was considered the most influenced variable used for the WSA and CV calculation for susceptibility class determination. The WSA was applied to the most influenced variables resulting from the PCA. Compound values were determined for the final flood susceptibility ranking based on the ranking and weights of the influenced variables. CV calculation was employed using Eq. 1 (Siddiqui *et al*., 2020).

$$CV = Riv \times Wiv \tag{1}$$

Where; CV = compound value, Riv = ranking of influenced variable, and Wiv = weight of influenced variable. The weight values of the influenced variables were obtained using a cross-validation technique using Eq. 2 (Malik *et al*., 2019).

$$W_{iv} = \frac{\text{Sum of correlation coefficients}}{\text{Total of coefficients}} \tag{2}$$

The ranking for each influenced variable was determined based on the relationship between the variable and the flooding process, whether ranking was directly proportional (ordered from the smallest) or inversely (sorted from the largest) for each watershed. The class of susceptibility to flooding was determined based on the CV. Susceptibility was divided into five classes: very low, low, medium, high, and very high, with the interval between classes obtained using the Jenks natural breaks approach. A high or very high flood susceptibility class illustrates a higher level of potential for flooding and a higher priority watershed to minimize flood risk. The final flood susceptibility map was also crosschecked with historical flood events based on flood inventory data.

RESULTS AND DISCUSSION

Geomorphometric characteristics

Geomorphometric~~s~~ analysis is the assessment and mathematical examination of the shape and pattern of the Earth's surface in a given landscape (Hajam *et al*., 2013). The results of the geomorphometric analysis are presented in Fig. 3. The evaluation of the morphometric and stream network plays a very significant role in identifying the geo-hydrological merit of the catchment area. The relation indicates the predominant function of geology, geomorphology, and climate in the formation of the catchment area in the landscape. Moreover, catchment area analysis is essential in any hydrological review to evaluate the groundwater hydrology, groundwater management, the soil as a natural landscape body, and the environment. The important geomorphometric elements are the stream network, drainage texture, geometry, and watershed relief.

a. Stream network

The first step in the catchment area analysis was to describe the river or stream order. Stream is defined as a positive whole number employed in morphometry to indicate the number or level of branching in a river system. The total number of streams has the highest range of all variables, with the value starting from 3 (Batu Payung Watershed) up to 2,876 (Dodokan Watershed). A high stream number in a watershed often reflects large discharge and rapid peak flow during rainstorm events, in comparison to a low number of streams (Ahmed *et al*., 2021). The stream length is a dimensional feature that reveals the distinctive size of the drainage network components and their contributing watershed surface. The value is calculated by dividing the overall length of an order's stream by the total number of segments in the order. A higher stream order, in most cases, indicates a smaller total stream length. In the field, however, a higher number of stream orders also reveals a greater total stream length. This study's highest stream length was~~is~~ 1,709.9 for the Dodokan Watershed, indicating lower infiltration and higher runoff. The mean stream length is a dimensional attribute reflecting the typical size of drainage network components and their contributing catchment surface. The value is produced by dividing the total stream length by the total stream cover for each stream order. A greater mean stream length is associated with a higher stream order, in which case the value of stream order 1 is less than that of stream order 2, and the value of stream order 2 is less than that of stream order 3, and so on. The characteristics of this catchment area are significantly influenced by some important variables, namely, the lithology, slope, and topography (Vinutha and Janardhana, 2014). The bifurcation ratio is the ratio of several stream segments of a specified order to several streams in the next higher order. The bifurcation ratio is directly connected to the river network structure. In this study, the highest bifurcation ratio value (21) was found in the Hangat Watershed. The high bifurcation ratio value represents significant structural control.

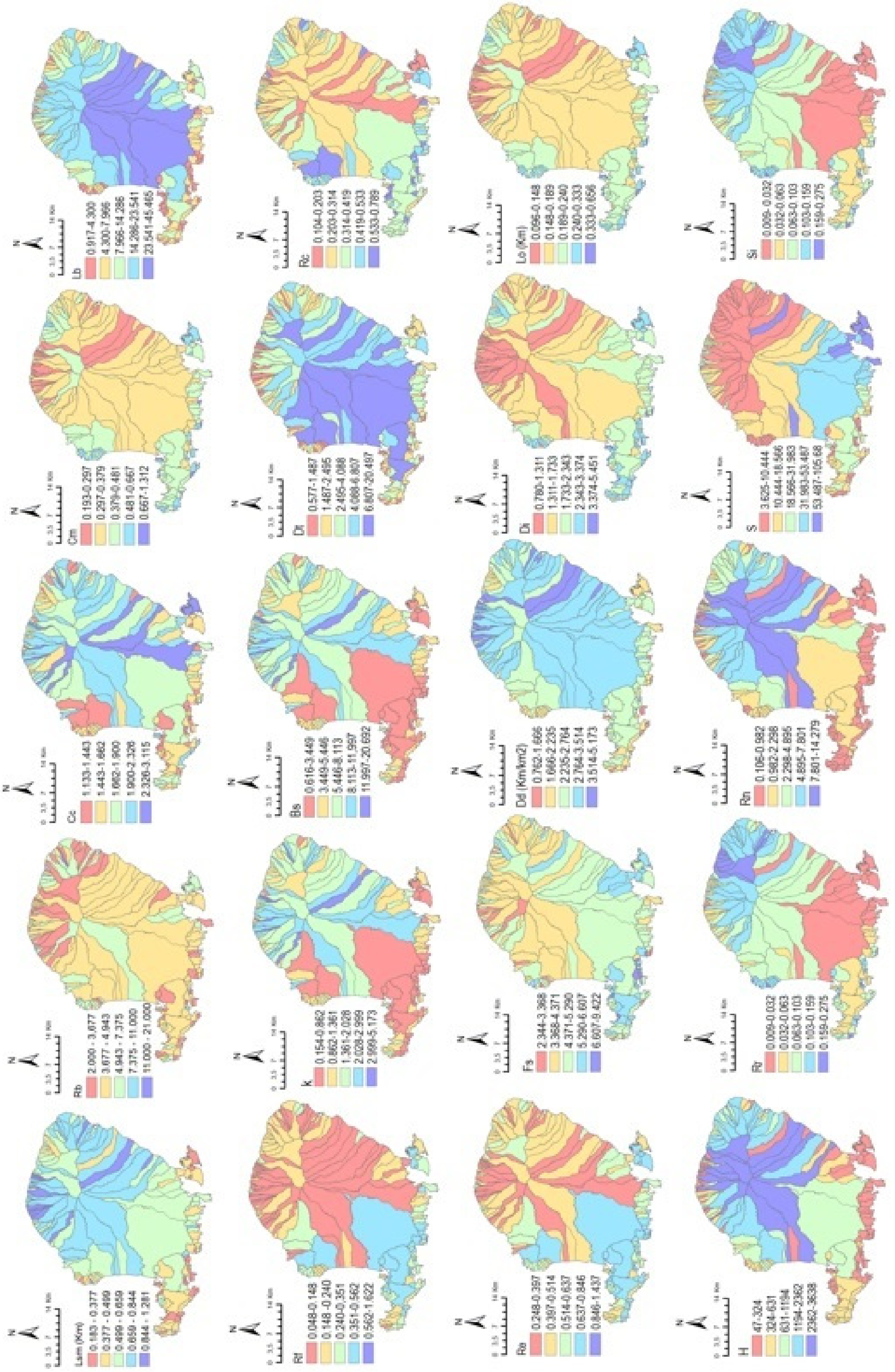

Fig. 3: Variable maps of stream network, stream texture, geometry, and relief

b. Drainage texture

There are four drainage texture variables, namely, stream frequency, drainage density, drainage intensity, and length of overland flow. In general, stream frequency values range from 3.00 to 9.99. The value of Fs depends on the lithological conditions of the catchment area and reflects the drainage texture (Albaroot *et al.*, 2018). The stream frequency values observed in the flooded watersheds on Lombok Island ranged from 3.06 to 6.61. Based on the Fs values, these watersheds have steep slopes, with low permeability rocks, relatively low water infiltration, and greater surface runoff, resulting in a greater potential for flooding (Markose *et al.*, 2014). Such conditions are also indicated by the characteristics of the soil found in the study site. The soil in the study area is formed out of volcanic rock, in which the weathering process produces a fairly high clay content (> 40%), as found in the Cambisol and Vertisol soil types in the study area (Iqbal *et al.*, 2020). The higher the clay content, the soil tends to have a lower infiltration capacity (Tejedor *et al.*, 2013). Water that is not able to infiltrate will become surface runoff, which under certain conditions will cause environmental problem (Sartohadi *et al.*, 2018). A high drainage density in a watershed implies high runoff and erosion potential (Malik and Shukla, 2018), resulting in low infiltration rates. Based on the classification of Altaf *et al.* (2013), the flooded watersheds on Lombok Island are described as follows: included in the low class (<2 km/km^2) is the Melempo Watershed; included in the medium class (2–2.5 km/km^2) are the Mentareng, Nangka, Pesiran, Pelangan, Asin, Bentek, and Belik Watersheds; the rest (15 watersheds) are classified as high (>2.5 km/km^2). Flooded watersheds have surface material with low permeability and a relatively low infiltration capacity, so the chances of surface runoff will be greater. A low stream intensity value reveals that the stream frequency and the drainage density have minimal influence on the degree of watershed subsidence by denudational processes (Gautam *et al.*, 2020). The intensity of the drainage for flooded watersheds on Lombok Island is quite high, namely, between 0.97 and 2.46, with an average of 1.72. This indicates that these watersheds are more vulnerable to flooding, valley erosion, and soil movement. The average length of overland flow is generally about half of the distance between river channels, or in other words, about half of the drainage density. The lengths of the overland flow values of flooded watersheds on Lombok Island are relatively low (0.12–0.27 km). This indicates that these watersheds have steep slopes and shorter flow paths.

c. Geometry

The geometry of the river network a critical function in determining river flow direction and the frequency and magnitude of flood incidents. The form factor is a part of the geometry parameter obtained from the proportion of the watershed area to the watershed length squared. The analysis results show that the form factor values ranged from 0.05 (Mumbul Watershed) to 0.62 (Tanjung Munah Watershed). Based on various studies, a high form factor value indicates a higher discharge of short-duration events (Bashir, 2023). The lemniscate ratio shows a watershed's elongated or circular shape. In this study, lemniscate ratio values ranged from 0.15 to 5.17, with an average of 1.38. A low K value confirms the watershed's circular shape and shorter lag time, making the watershed prone to flooding (Bhat *et al.*, 2019). The circularity ratio indicates the ratio of the watershed area to a circle area with the same circumference. This variable is essential in determining flood susceptibility in a watershed. The circularity ratio values of the study area varied from 0.1 to 0.79. A high circularity ratio value indicates a circular-shaped watershed with a high flash flood risk due to the peak flow being reachable in a relatively shorter time (Ahmed *et al.*, 2021). The elongation ratio compares the watershed area to the length of the watershed. The watersheds on Lombok Island have an average elongation ratio value of 0.53, with the highest value being 0.86 (Kelapa Watershed) and the lowest being 0.25 (Mumbul Watershed). A watershed that has a low elongation ratio value tends to be elongated with low flood risk.

d. Watershed relief

There are five variables of watershed relief, namely the relief value, relief ratio, ruggedness number, watershed slope, and watershed slope index. The flooded watersheds on Lombok Island generally have relatively high watershed relief. A high relief value indicates the potential for high erosion energy from the watershed system, especially during flood events

(Pathere and Pathere, 2021). The relief ratio allows for a comparison of the relative relief of any watershed regardless of differences in the topographical scale. The relief ratio values of the flooded watersheds on Lombok Island ranged from 0.01 to 0.24. If this parameter alone is used to determine erosion intensity, then the watersheds with larger relief ratio values are more susceptible to erosion. The ruggedness number implies a watershed's susceptibility degree to soil erosion (Puno and Puno, 2019). The flooded watersheds on Lombok Island had relatively large ruggedness number values, except for the Tebelo Asin, Pemokong, and Balak Watersheds. These watersheds are generally more susceptible to erosion. The average watershed slope of the flooded watersheds on Lombok Island was the lowest at 4.16 for the Mentareng Watershed and the highest at 95.42 for the Pemokong Watershed. In general, the S values of all watersheds were relatively high. The values show the magnitudes of the watershed relief. A great watershed slope plays an important role in flood events. A steep slope can cause severe flash floods, but the velocity of water will increase as the slope of the watershed increases. As the time required for water to reach the outlet decreases, the danger of flooding will ultimately increase. The slope index indicates the rate at which the erosion process occurs on the slopes of the watershed. Steep slopes will certainly contribute large amounts of eroded material into the river channel. The river's steep gradient allows the river flow to carry debris as a base load. The flooded watersheds on Lombok Island have relatively small slope index values, which indicates that the concentration time is relatively longer.

Based on the analysis of the geomorphometric characteristics of the flooded watersheds on Lombok Island, the uniformity of several variables was obtained. These variables consist of the total number of drainage, drainage density, stream frequency, watershed relief, and bifurcation ratio. According to these identifying variables, watersheds that experience flooding are generally characterized by many drainage segments, a high drainage density, a relatively high stream frequency, large watershed relief, and a relatively high bifurcation ratio value. This indicates that these watersheds have low rock permeability, a relatively low potential infiltration capacity, and relatively high surface runoff potential (Malik and Shukla, 2018).

Land use and land cover

LULC is another important factor that influences the incidence of flooding in a watershed. LULC changes are one of the triggers for an environmental change, which can increase the erosion process. LULC are generally influenced by anthropogenic factors (Malik and Bhat, 2014). The type of land use and vegetation cover also affect the runoff (volume and speed) that flows to lower areas (Alaghmand *et al.,* 2014). Areas with a higher density of vegetation cover tend to have higher infiltration and abstraction. Areas with sparse vegetation cover have increased shares of runoff. The LULC of the watersheds on Lombok Island is presented in Fig. 4.

The map shows that most of the watersheds on the island of Lombok are dominated by cultivated areas (66%). This agricultural land is mainly in the form of dryland agriculture (34%) and paddy fields (32%). Field observations show that dryland agriculture is mostly carried out on hillsides. Planting is only carried out during the rainy season, and land that is no longer productive is abandoned as shrubland. Forest cover also has a large proportion (21%). However, some watersheds have little forest cover, and others do not have forest cover at all. The Dodokan Watershed, the largest on Lombok Island, only has 2% forest cover. There are three watersheds with forest cover, namely, the Peretan, Balangpaku, and Batubuton Watersheds.

Flood susceptibility mapping using the PCA and WSA

The PCA was used to determine the most significant of both the geomorphometric and LULC variables. The results of the PCA show that six principal components can explain 89.16% of the variance of the data used and have more than one eigenvalue. The PCA also produces factor weights (loading factors) for each variable and each principal component. The variables in each principal component have correlation values (r) of various strengths: strong ($r > 0.90$), good ($0.90 \geq r > 0.75$), and moderate ($0.75 \geq r > 0.60$). The first principal component is directly proportional to the stream number, stream length, watershed area, circumference of the watershed, and drainage density, and is inversely proportional to the lemniscate index, shape factor ratio, and relief ratio. The second principal component correlates with the mean stream length, compactness coefficient, watershed length, circularity ratio, drainage density, relief, and ruggedness number. The constants of

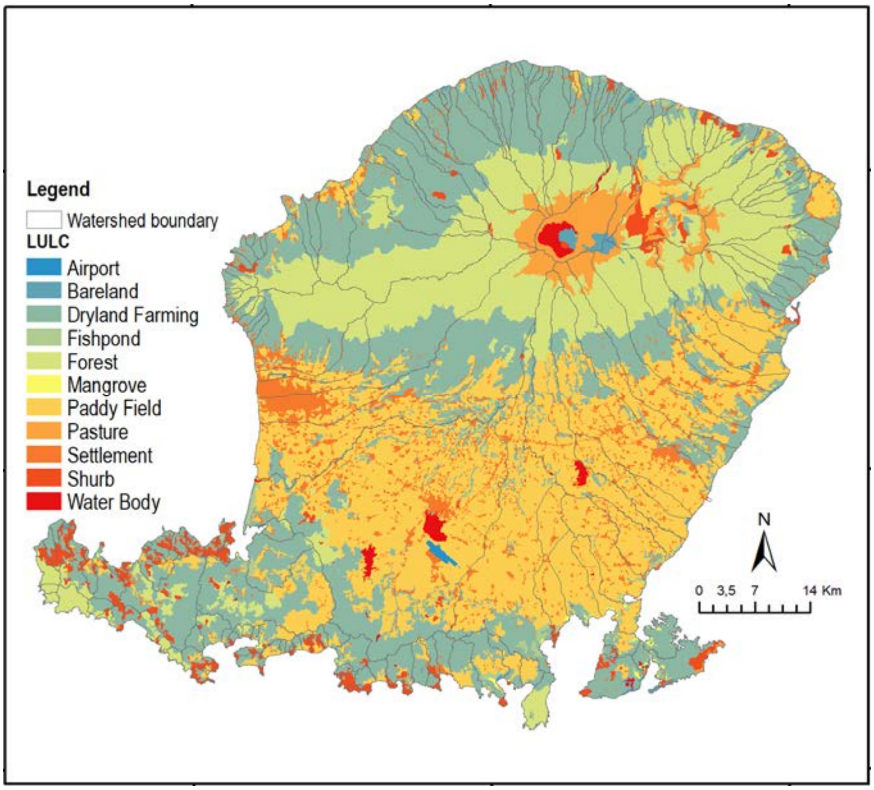

Fig. 4: LULC on Lombok Island

channel maintenance, drainage density, length of overland flow, and relief are either directly or inversely proportional to the third principal component. The fourth principal component only correlates with the compactness coefficient. The fifth principal component correlates only with stream frequency variables. The LULC variables, namely; dry land agriculture and settlements, correlate with the sixth principal component. The first factor weights do not show the most significant variable for each principal component. Therefore, the factor weights were rotated using the varimax method. Based on the factor weight rotation results, the most significant variables were obtained for each principal component, namely the total stream number, relief ratio, elongation ratio, drainage density, stream frequency, and dry land agriculture cover. Each variable represents aspects of the stream network, watershed geometry, river texture, and relief as geomorphometric variables, as well as LULC aspects. Based on these characteristics, the geomorphometric variables with low rock permeability, a relatively low potential infiltration capacity, and relatively high surface runoff potential can increase flooding. This study's findings align with several studies on sub-watershed prioritization using geomorphometric and land use variables and the PCA approach. For example, these previous studies have found various influenced variables, such as the stream frequency and relief ratio (Pathere and Pathere, 2021), drainage density and stream frequency (Kumar *et al*., 2023), elongation ratio and stream number (Rahman *et al*., 2022), and agricultural land use (Setiawan and Nandini, 2021). Each significant variable naturally has a different contribution to the flood event. The calculation of each variable weight is necessary for determining the final compound value. The variable weights were determined using the WSA approach. Table 2 presents the weight calculation using the WSA.

Based on the WSA value and the variable rating value for each watershed, the compound value was

Table 2: Cross-correlation of influenced variables of the PCA

Variables	Nu	Rr	Re	Dd	Fs	PL_P
Nu	1	-0.363	0.079	0.086	0.179	-0.183
Rr	-0.363	1	-0.302	-0.266	-0.316	-0.288
Re	0.079	-0.302	1	-0.266	0.115	0.176
Dd	0.086	-0.266	-0.266	1	0.341	0.373
Fs	0.179	-0.316	0.115	0.341	1	0.067
PL_P	-0.183	-0.288	0.176	0.373	0.067	1
Sum	0.799	-0.533	0.801	1.268	1.387	1.144
Grand Total	4.866	4.866	4.866	4.866	4.866	4.866
WSA	0.164	-0.110	0.165	0.261	0.285	0.235

Table 3: Flood hazard classes of the watersheds on Lombok Island

No	Compound value	Susceptibility class	Watershed
1	<44.217	Very low	Bengkang, Blongas 1, Blongas 2, Brangbantun, Jelateng, Kumbu, Labuanpoh, Lancing, Lendang Lombok, Leong, Luk Lombok, Medang, Midang, Palung, Rambanperia, Temeran, Tiupupus
2	44.218–82.673	Low	Airberi, Ankopang, Bagekrarit, Bat, Bentek, Braringan, Bumbang, Jerengkang, Kemangi, Kengkang, Ketapang Lombok, Koloh Belik, Kukusan, Labu Lombok, Lokok Peria, Luncing, Malimbu, Menanggen, Mumbul, Nangka, Nawan, Ngolang, Padek 1, Padek 2, Peak, Pemokong 1, Pemokong 2, Persani, Pewaringan, Rangsot, Sacut, Sauh, Segara, Segoar, Selindungan, Selodong, Sependok, Supak, Tawun, Temodo, Ujunggol
3	82.674–108.363	Medium	Aikampat, Amoramor, Aruina, Balak, Bangkobangko, Batu Payung, Batubuton, Batulayar, Batuleong, Cereme, Dodokan, Duduk, Dundang, Eat Brang, Erat Pandanan, Jerenjeng, Jorong, Kali Geres, Kandang, Kelep, Kenyaru, Koangan, Kokok Menanga Paok, Krandangan, Kuang, Kuang Bulu, Labuankuwe, Lebahpebali, Lendangluar, Lendangre, Lengkulun, Mawun, Meang, Moyot, Orongudang, Pancor, Paok, Penggolong, Peretan, Pesugulan, Putih, Rajak, Rembat, Rere Penembem, Rowok, Selinggahan, Selongblanak, Sepang 2, Serangan, Sesager, Siung, Sokong, Tampah, Tanjung Puramalikan, Tanjungkates, Tantang, Tebelo, Tebi, Teluk Kowal, Tibu, Tibuborok, Tomangomang, Torokaikbelik
4	108.364–137.286	High	Airsintu, Akar, Asin, Babak, Bange, Bangketlamin, Batubolong, Bebanan, Belangpaku 1, Belik, Berenyok / Ancar, Buangpaok, Desa, Eat Panggang, Embarembar, Gereneng, Gol, Hangat, Jangkok, Kedome, Kelapa, Koloh Pandanan, Koloh Tujorong, Kombang, Kurbian, Lebuanbetung, Lempenge, Lendang Bahagia, Mansit, Melempo, Menangabaris, Meninting, Mentareng, Mentigi, Pangsing, Pekendangan, Pelangan, Pemalikanagung, Pengantap, Pengembulan, Puramalikan, Reak, Renggung Perempung, Sambelia, Senggigi, Sengkurik, Teba, Teluk Mekaki 1, Teluknara, Tembowong, Tenung, Terake, Tg. Munah, Tibulele, Tongker, Trawas, Uluan
5	>137.287	Very high	Batu Jonggat, Beburung, Blimbing, Kelui, Leper, Marmadi, Nipah, Pemalikanalit, Pengawisan, Pesiran, Runggang, Selain, Sepi 2, Sidutan, Tibubunut, Tojang

determined using Eq. 3 (Siddiqui *et al*., 2020).

$$CV = (0.164 \times R\_Nu) + (-0.110 \times R\_Rr) + (0.165 \times R\_Re) + (0.261 \times R\_Dd) + (0.285 \times R\_Fs) + (0.235 \times R\_PL\_P) \quad (3)$$

The values of variables for each watershed were determined by ranking according to the variable's relationship with flood events. Variables with a directly proportional relationship determine the ranking from the smallest value to the largest. If the variables are inversely proportional, the ranking starts from the largest value. Based on some of the literature, only the significant elongation ratio variable is inversely related to flooding events. The compound value calculation was held for all watersheds. The flood susceptibility class was determined using the Jenks natural breaks approach based on the compound value. Table 3 presents the distribution of the flood susceptibility classes of the watersheds on Lombok Island, while the spatial distribution is presented in Fig. 5.

High or very high flood susceptibility categories

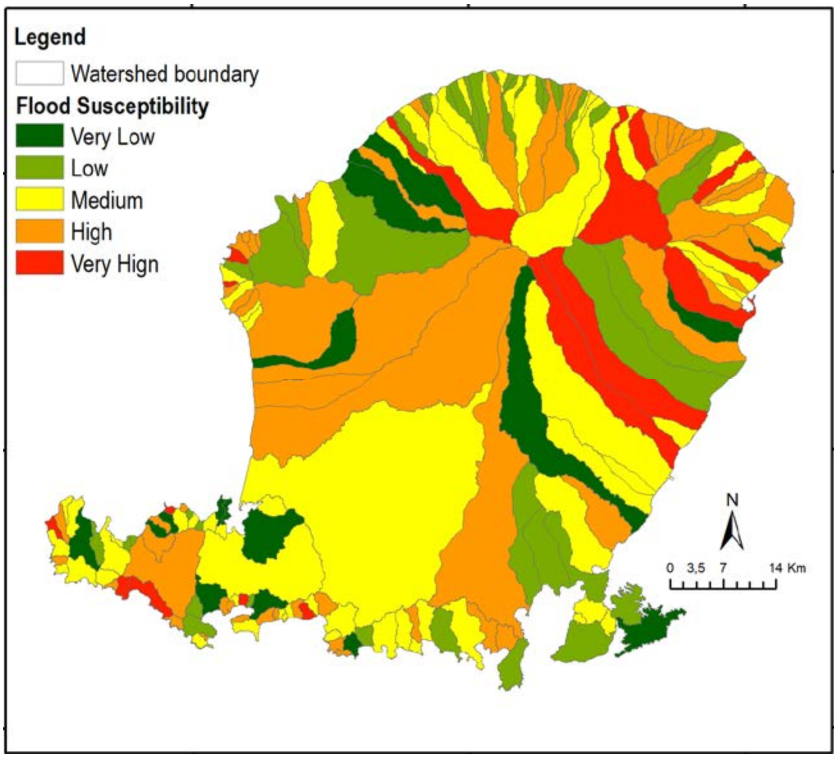

Fig. 5: Spatial distribution of watershed susceptibility to flooding on Lombok Island

illustrate a higher potential for flooding and a higher potential to be designated as priority watersheds to minimize flood susceptibility. The low category has good geomorphometric characteristics and existing LULC in response to rainfall.

Flood susceptibility mapping results can have several critical applications and uses for disaster preparedness and land management on a small island. The potential applications include developing early warning systems, assisting emergency management agencies in developing effective response plans, utilizing land use planning, guiding the planning and design of critical infrastructure, contributing to effective environmental management and conservation efforts, raising public awareness about flood risks and educating communities on preparedness and mitigation measures. When comparing flood susceptibility on small islands to larger landmasses or mainland areas, some unique challenges and considerations are specific to the island environment. A few key points to consider include 1) limited land area, which amplifies the potential impacts of flooding coastal vulnerability due to their exposure to storm surges, sea-level rise, and tidal influences; 2) diverse topographical features, which influence the flow of water during flooding events and can lead to localized areas of higher susceptibility; 3) challenges related to limited data availability, including historical flood records, topographic data, and hydrological information; 4) limited connectivity and access to remote or less developed areas that impact data collection efforts, field surveys, and the implementation of flood mitigation measures; and 5) vulnerability to the impacts of climate change, including sea-level rise, changing rainfall patterns, and increased frequency and intensity of storms. The strategy for flood mitigation based on disaster mitigation in flood-prone areas in Lombok Island is divided into two, namely 1) Structural mitigation in the form of construction of flood control buildings, such as making embankments, making drainage network structures, and making drop structures; 2) non-structural mitigation in the form of training and simulation of disaster mitigation, as well as evaluating

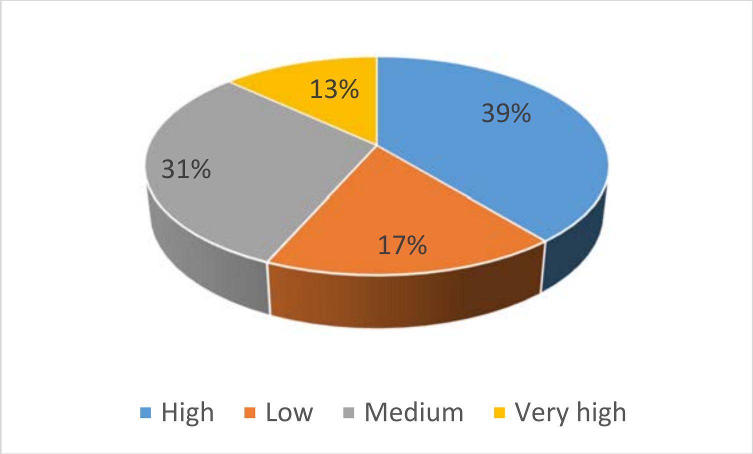

Fig. 6: Percentage of 23 flood event watersheds related to obtaining the flood susceptibility map

policies on reducing the risk of flood disasters in flood-prone areas in Lombok Island. Regarding spatial planning, local governments are required to rearrange their territorial space and create a water-friendly environment in a sustainable manner. Five steps can be taken: 1) check the applicable regulations through space or land use audits that can be carried out in accordance with applicable regulations such as master plans, regional spatial planning, and detailed spatial planning; 2) check the legality of the land/house for violations against the use of space in water resources conservation areas with applicable laws or regulations; 3) the government, academia, the community, and experts are expected to sit together to formulate directions and strategies that can be implemented to find a win-win solution for all parties regarding flood mitigation efforts; 4) regional governments can normalize rivers, canals, lakes, and reservoirs and save beaches and mangrove forests whose land has been converted; 5) the regional government needs to carry out social engineering on residents who live close to water conservation areas such as riverbanks, beaches and so on to help the residents change habits such as littering and throwing wastewater into rivers so that these bad habits can be gradually reduced and even eliminated.

Comparison of flood susceptibility map and flood inventory

The results of the flood susceptibility mapping have been validated by comparison with records of flood events on the island of Lombok, as shown in Fig. 6.

The validation results show that the resulting flood susceptibility map is good enough to describe the watershed conditions on Lombok Island. Of the 23 flood events whose damage was recorded, only four flood events (17%) occurred in the low-susceptibility areas, precisely at the Nangka, Segara, Bentek, and Pemokong Watersheds. This indicates that the accuracy of this flood susceptibility map is approximately 83%, where the flood-experienced watersheds were included in the medium- to very high-susceptibility classes. The map accuracy is good enough to represent the flood susceptibility in the study area. The accuracy is also supported by the result of Samanta *et al*. (2018), who found the accuracy of their study to be about 81%. The limitation of this study lies in the flood event data used, which provide only information on the total inundated areas and damage levels and no information on flooding depths. The results of the flood susceptibility map may help guide local policy- and decision-making to better cope with future floods. Some of the flooded watersheds on Lombok Island have forest land cover of more than 30%, namely the Mentareng, Melempo, Tibubunut, Nangka, Pesiran, Sambelia, Rajak, Segara, and Belik Watersheds. Other watersheds have agricultural land use as the dominant land use. More than 30% of forest cover still allows flooding to occur. The natural factors of a watershed, in this case, the geomorphometric characteristics of the watershed, have a major role in flood events.

CONCLUSION

Lombok, a small tropical island, now frequently experiences floods, threatening the economic potential and welfare of the people. Flood mitigation measures, including better spatial planning, need to be supported by the availability of a flood susceptibility map. Geomorphometric characteristics and land use/land cover supported by a geographic information system, remote sensing techniques, and a detailed digital elevation model able to determine the hydrological characteristics and behavior of the watersheds were used as the basis for flood susceptibility mapping. Based on the analysis of the geomorphometric characteristics of the watersheds on Lombok Island, the identifier variables strongly related to flood events were obtained, namely the total number of drainage, relief ratio, elongation ratio, drainage density, and stream frequency. Dry land agricultural cover, which is predominantly carried out on hillsides, has the most influence on flood susceptibility from the LULC aspect. Based on these characteristics, the watersheds with high or very high flood susceptibility have low rock permeability, a relatively low potential infiltration capacity, and relatively high surface runoff, thus triggering flooding. High or very high flood susceptibility categories indicate a greater risk of flooding and a greater likelihood of being identified as priority watersheds to reduce flood susceptibility. Several watersheds that experience flooding on Lombok Island have more than 30% forest land cover. Other watersheds have agricultural land use as the dominant land use. In other words, more than 30% of forest cover still allows flooding to occur. Thus, the natural factors of a watershed, in this case, the geomorphometric characteristics of the watershed, have a major role in flood events. The flood susceptibility map, a result of utilizing the geomorphometric characteristics and land use/land cover parameters, has adequate validation in describing the level of flood susceptibility for each watershed on Lombok Island. The use of geomorphometric characteristics and land use/land cover parameters in this study was able to produce a flood susceptibility map in an accurate and efficient manner. Documenting more detailed flood disaster events will help improve the accuracy of the resulting susceptibility map, because this map is important for consideration in prioritizing flood disaster mitigation including improving the spatial planning in each watershed.

AUTHOR CONTRIBUTIONS

All Authors have equal roles as main contributors in this study. B.H. Narendra performed the research conception, and literature review. O. Setiawan performed the study methodologies, and managed data collection. R.A. Hasan drafting of the manuscript, and managed data collection. C.A. Siregar performed the research conception, and edited the manuscript. Pratiwi analysed the data, and preparation the manuscript text. N. Sari drafting of the manuscript, and literature review. A. Sukmana compiled the data and performed data processing. I.W.S. Dharmawan analysed the data, and edited manuscript. R. Nandini compiled the data and performed data processing.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
°C	Degree Celsius
A	Area
Bs	Shape factor ratio
CEC	Cation-exchange capacity
Cm	Channel maintenance
Co	Compactness coefficient
CV	Compound value
Dd	Drainage density
DEM	Digital elevation model
Di	Stream intensity
Dt	Drainage Texture
E	East
FAO	Food and Agriculture
Ff	Form factor
Fs	Stream frequency
GIS	Geographic information system
H	Relief
ha	Hectare
K	Lemniscate ratio
km	Kilometer
km^2	Square kilometer
Lb	Watershed Length
Lo	Length of overland flow
Lsm	Mean stream length
Lu	Stream length
LULC	Land use and land cover
LULC	Stream length
m	Meter
masl	Meter above sea level
mm	Milimeter
Nu	Stream order
P	Perimeter
PCA	Principle component analysis
PCs	Principal components
PRsp	Preliminary ranking
r	Correlation value
Rb	Bifurcation ratio
Rc	Circularity ratio
Re	Elongation ratio
Riv	Ranking of influence variable
Rn	Ruggedness number
Rr	Relief ratio
S	South
S	Average gradient
SD	Standard deviation
Si	Gradient index
Wiv	Weight of influence variable
WSA	Weight sum approach
Wsp	Weighted value

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