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Development of Flood Hazard Index (FHI) of the Kelantan River Catchment Using Geographic Information System (GIS) Based Analytical Hierarchy Process (AHP)

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ABSTRACT

Kelantan has been facing several cases of catastrophic flooding, causing significant damage to this area. Heavy monsoon rainfall is believed to trigger those floods. This study aims to identify and classify the flood occurrence using the Kelantan River catchment's flood hazard index (FHI) based on the Analytical Hierarchy Process (AHP). This study developed the FHI using the AHP based on spatial analysis in the geographic information system (GIS) environment. Six physical parameters were selected: annual rainfall, slope, river density, land use and land cover (LULC); elevation; and soil permeability. According to the AHP model, the annual rainfall was the first ranked parameter in terms of importance weight score. Moreover, Tanah Merah and Jeli were the high-risk areas for floods. The present study suggests that the GIS-based AHP method can be highly effective for mapping flood hazards and benefit flood management decision-making.

Keywords: Analytical Hierarchy Process, flood hazard index, geographic information system, multi-criteria decision analysis

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INTRODUCTION

Flooding is one of the most common and destructive natural hazards, posing a serious threat to society due to its devastating effects on human lives and socio-economic conditions (Qi & Altinakar, 2011). Furthermore, flooding problems are getting more severe as a result of environmental changes such as land-use change (Du et

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al., 2015), fast urbanisation (Suriya & Mudgal, 2012), and climate change, regardless of topographical and meteorological circumstances (Detrembleur et al., 2015). Therefore, a flood risk assessment is required to be conducted before deploying mitigation strategies to mitigate or control the flood hazard (Tariq et al., 2020; Green et al., 2000).

In general, flood risk can be developed using two approaches: the flood simulation approach utilising numerical modelling (such as the hydrological and hydrodynamic models) and the index-based approach using various parameters that control floods. In this study, the index-based approach is focused on. The selected approach uses various parameters based on derived information from the digital elevation model (DEM) and raster images, economic activity, infrastructure, demographic aspects, and mitigation policy and rehabilitation issues (Burby et al., 2000). Therefore, calculating the danger using this approach is particularly useful for creating and implementing a catastrophe mitigation strategy.

Many studies have used multiple-criteria decision analysis (MCDA) to estimate index-based flood hazards and risk (Wu et al., 2015; Xiao et al., 2016). In addition, MCDA has been integrated with GIS to organise the criteria hierarchically through spatial analysis effectively. Meanwhile, the AHP calculates the relative weights, relevance, or worth of each important component to the problem once the criteria have been aggregated and classified within the MCDA. From their literature review, de Brito and Evers (2016) found that the AHP in MCDA is quite popular in Asian and European countries, contributing to 72% of the studies. Mudashiru et al. (2022) also found that the AHP can be adopted as a tool for effective flood decision-making over Peninsular Malaysia.

Various techniques have been used to develop the AHP for flood hazard and risk, and the number of parameters used varies from one study to another (Chen et al., 2015; Kazakis et al., 2015). For example, Seejata et al. (2018) prepared the FHI of the lower part of the Yom River basin in Thailand using six parameters: slope, elevation, river density, land use, rainfall intensity, and soil permeability. Meanwhile, Sharir et al. (2019) identified the flood susceptibility level (FSL) of a small area in Sabah, Malaysia, using eight parameters: rainfall, drainage, flow accumulation, land use, elevation, slope gradient, soil texture, and slope curvature.

The Kelantan River catchment in Malaysia is a large catchment with a tendency to experience extreme flooding (Fadhliani et al., 2021; Jaafar et al., 2016). Saadatkhah et al. (2016) revealed a significant impact of land use on the flood experience of the catchment: a 13.7% decrease in forest land and a 6.2% increase in oil palm plantations. Therefore, these reports have garnered the attention of experts to study flood modelling and risk in the area. However, most of the studies adopted numerical modelling to study flood risk. This study attempts to adapt the AHP method to an index-based approach. Hence, the effectiveness of the AHP application can be evaluated for this catchment compared to previous studies that used numerical modelling for flood risk.

Therefore, the objectives of this study are to develop the FHI using the AHP method for the Kelantan River catchment. Six parameters are used in the development: annual rainfall, slope, river density, LULC, elevation, and soil permeability. In the following sections, the methods are presented, followed by the results and discussion. Then, the conclusion is elaborated.

MATERIAL AND METHODS

Study Area and Data

The catchment of the Kelantan River is in north-eastern Peninsular Malaysia. It is one of the major rivers in Malaysia and the longest river in the state of Kelantan. It is 248 km long and covers an area of 13,100 km^2, as shown in Figure 1. The elevation of the catchment ranges from 8 to 2,174 m above the mean sea level and mountains in the west and southwest regions. The mean annual rainfall and temperature of the catchment are more than 2,500 mm and about 27.5^{o}C, respectively (Tan et al., 2017). During the northeast monsoon, between November and January, the river's catchment frequently experiences flood events (Bronstert et al., 2002). Recent flood events in 2014 and 2017 caused immense losses in agricultural production, lives, and property (Alias et al., 2020; Nashwan et al., 2018). Therefore, assessing the flood risk of the catchment is crucial because it can identify the pattern and location of the flood. The outcome of this study can be used as a guideline for the local authorities in providing potential flood mitigation.

The secondary sources in this study were collected from different sources, as shown in Table 1. This study used satellite images from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) at a 30 m resolution to derive the DEM and produce the map of LULC. The ASTER data are freely available via the Internet from the United States Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) (see http://earthexplorer.usgs.gov). The soil map was derived from the Food and Agriculture Organization (FAO)-UNESCO (1990). The data were obtained from the Department

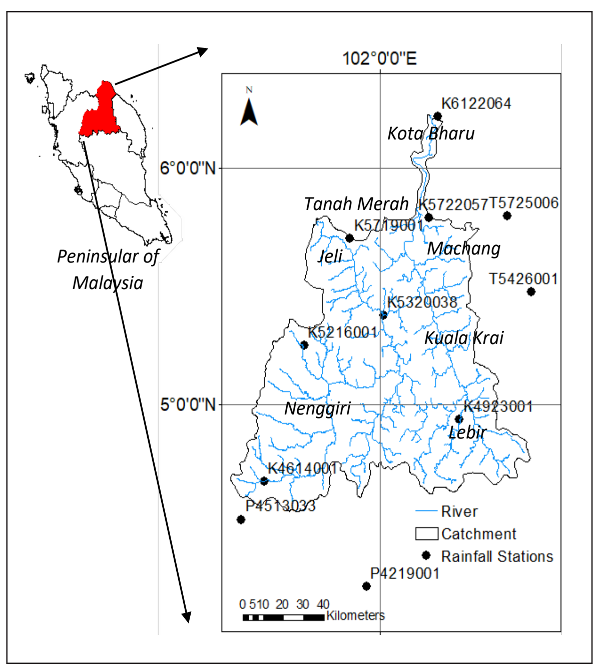

Figure 1. Location of the study area

of Irrigation and Drainage Malaysia in terms of rainfall. Daily rainfall data for 2014 at several rainfall stations (refer to Table 2) were selected, and the data were aggregated to the annual rainfall.

Table 1
Sources of studied data input

Data	Sources
Soil Map	FAO-UNESCO (1990)
Land Use and DEM	USGS Center for EROS
Rainfall Data	Department of Irrigation and Drainage Malaysia
Historically Flooded Map	Alias et al., 2020; DID, 2014

Table 2
Rainfall stations

Station	Long(°)	Lat (°)
K4614001	101.485	4.676
K4923001	102.353	4.938
K5216001	101.663	5.251
K5320038	102.015	5.378
K5719001	101.867	5.701
K5722057	102.219	5.788
K6122064	102.257	6.217
T5426001	102.675	5.476
T5725006	102.565	5.797
P4219001	101.940	4.233
P4513033	101.383	4.517

Table 3
Scale of preference among parameters (Saaty, 1980)

Intensity of Importance	Description
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values

Analytical Hierarchy Process (AHP)

AHP is a value-judgement approach for semi-quantitative decision-making that serves the decision maker's goals (Razandi et al., 2015). This method allows planners to use their experience and knowledge to break down a problem into a hierarchical structure and solve it using the AHP (Murali et al., 2013; Sar et al., 2015). The method also normalises controlling factor weights (as shown in Table 3) and selects the best alternatives by considering objective and subjective factors.

This study used the AHP approach to appoint weights for flood hazard factors. First, pairwise comparisons were deployed for all parameters of flood hazard. In this study, several parameters were selected since they are major contributors to floods (Wang et al. 2020): Annual rainfall, slope, river density, LULC, elevation, and soil permeability. Those parameters were assigned their relative importance values ranging between 1 and 9 in Table 4. Second, with a comparison matrix, priority vectors or the normalised Eigenvectors of the matrix could be calculated (see Table 5). Third, calculations were made by dividing each column by its corresponding amounts. In the last step, the mean values of each row were calculated and used as a weight in the objective hierarchy to evaluate the flood hazard, as recorded in Table 5.

The Eigenvector of a matrix will have its consistency checked using the consistency ratio (CR) as Equation 1:

$$CR = \frac{CI}{RI} \tag{1}$$

Table 4
Comparison matrix of flood hazard parameters

Parameters	Annual Rainfall	Slope	River Density	LULC	Elevation	Soil Permeability
Annual Rainfall	1	3	3	7	5	5
Slope	1/3	1	1/3	3	3	3
River Density	1/3	3	1	7	3	5
LULC	1/7	1/3	1/7	1	1/3	1/3
Elevation	1/5	1/3	1/3	3	1	3
Soil Permeability	1/5	1/3	1/5	3	1/3	1

Table 5
Normalised matrix of flood hazard parameters, where W_i is the weight of each parameter

Parameters	Annual Rainfall	Slope	River Density	LULC	Elevation	Soil Permeability	Mean	W_i
Annual Rainfall	0.45	0.38	0.60	0.29	0.39	0.29	0.40	4.0
Slope	0.15	0.13	0.07	0.13	0.24	0.17	0.15	1.5
River Density	0.15	0.38	0.20	0.29	0.24	0.29	0.26	2.6
LULC	0.06	0.04	0.03	0.04	0.03	0.02	0.04	0.4
Elevation	0.09	0.04	0.07	0.13	0.08	0.17	0.10	1.0
Soil Permeability	0.09	0.04	0.04	0.13	0.03	0.06	0.06	0.6

CI is the consistency index, and RI is the random index (Kaoje et al., 2021). Therefore, CI can be defined as Equation 2:

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

The RI is referred to in Table 6, and in this study, the number of parameters, n and the RI was 6 and 1.25, respectively.

Using Equation 1, the CR is 0.087 if the λ_{max} is 6.55, reporting a CR value lower than the threshold of 0.1. Hence, the consistency of weights in Table 5 was affirmed.

After determining the W_i and the rating (r_i) of each parameter, the parameters were classed as shown in Table 7. Next, the FHI in Equation 3 was developed using the Raster Calculator tool in ArcGIS through a combination of parametric input maps. Finally, the values of the FHI raster were grouped into five classes to obtain the hazard zones.

$$FHI = \sum_{i=1}^{n} r_i . W_i \tag{3}$$

Table 6
RI used to compute CR (Saaty, 1980)

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.55	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Table 7
r_i of the parameters and their W_i

Parameters	Class	r_i	W_i	$r_i.W_i$
Annual Rainfall (mm)	>3,200 mm	10	4.0	4.00
	2,500–2,700 mm	8		3.60
	2,700–2,900 mm	6		3.20
	2,500–2,700 mm	4		2.80
	<2,500 mm	2		2.40
Slope	0–1°	10	1.5	1.46
	1–2°	8		1.17
	2–3°	6		0.88
	3–5°	4		0.58
	>5°	2		0.29
River Density	Very High	10	2.6	2.57
	High	8		2.06
	Medium	6		1.54
	Low	4		1.03
	Very Low	2		0.51
LULC	Water Bodies	10	0.4	0.37
	Built-Up	8		0.30
	Agriculture	6		0.22
	Forest	2		0.07
Elevation	0–200 m	10	1.0	0.96
	200–400 m	8		0.77
	400–600 m	6		0.58
	600–800 m	4		0.38
	>800	2		0.19
Soil Permeability	Low	8	0.6	0.51
	Medium	6		0.38
	High	4		0.25

RESULTS AND DISCUSSION

Spatial Variations of Flood Parameters

Figure 2 presents the thematic map of flood parameters prepared for each pixel/cell of the Kelantan River catchment in the ArcGIS environment. For rainfall intensity, as illustrated in Figure 2(a), the distribution of the annual rainfall in 2014 at 12 stations of the studied

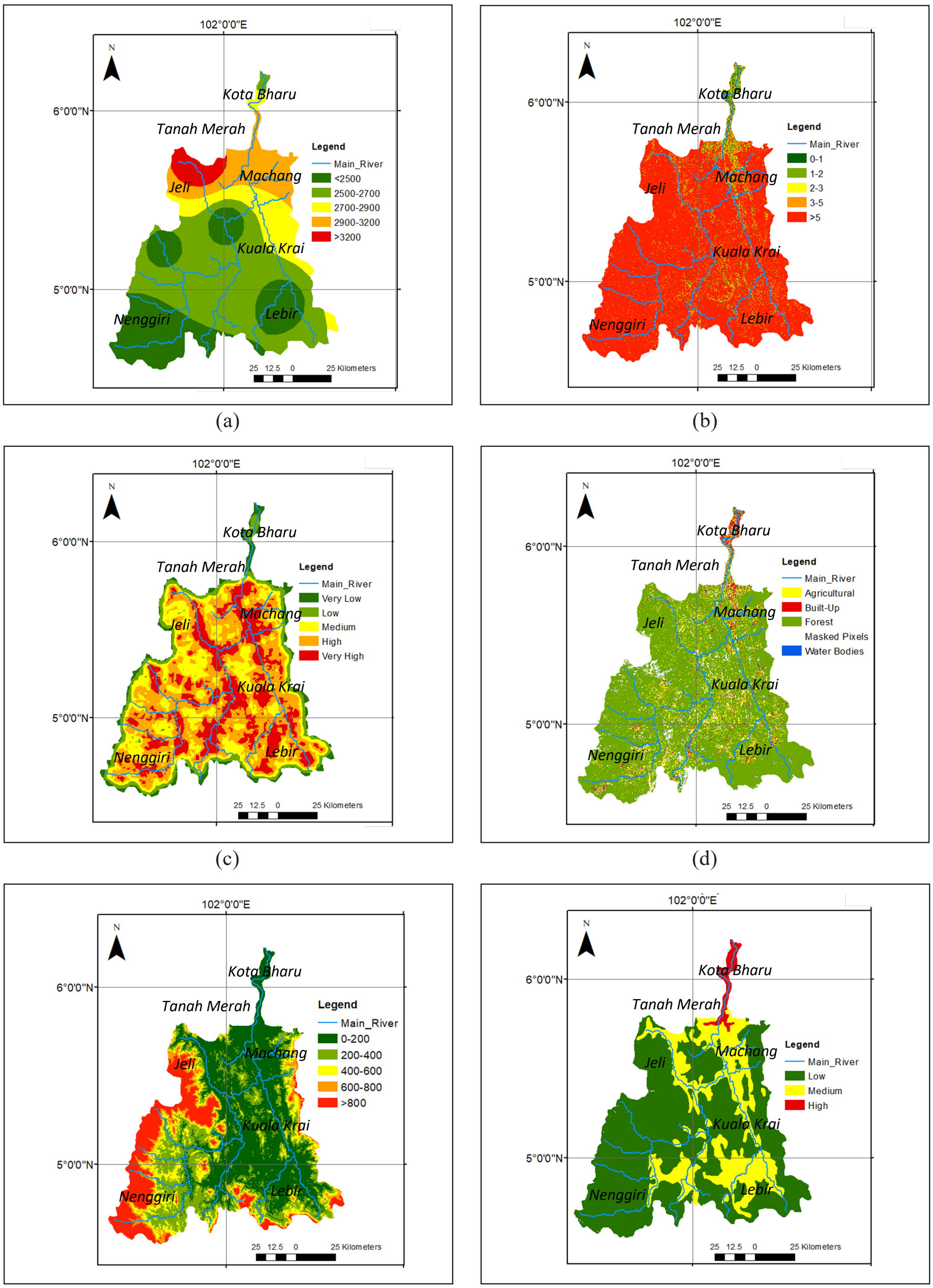

Figure 2. Thematic maps of parameters, used for MCDA, such as of (a) annual rainfall (mm); (b) slope (°); (c) river density; (d) LULC; (e) elevation (m); and (f) soil permeability

catchment was generated using the Kriging interpolation method. The spatial annual rainfall ranged from 2,500 to 3,200 mm. Figure 2(a) shows that the area near Jeli and Tanah Merah received the highest annual rainfall, over 3,200 mm. However, the amount of annual rainfall decreased towards the southern part of the catchment, such as Nenggiri and Lebir, in which annual rainfall was recorded to be less than 2,700 mm. Rainfall was the most important parameter for the FHI, and a higher rainfall amount usually increases the chance of floods. Hence, the areas of Tanah Merah and Jeli would face frequent flood events during the rainy season at the end of the year. In general, the annual rainfall of the catchment in 2014 was slightly higher than the mean annual rainfall of Peninsular Malaysia, around 2,300 mm, as reported by Wong et al. (2009).

The surface slope of the Kelantan River catchment is presented in Figure 2(b), with 1.45% of the area being categorised as 0–1^{o}, 2.79% as 1–2^{o}, 3.27% as 2–3^{o}, 6.52% as 3–5^{o}, and 85.97% as more than 5^{o}. Most low gradients (less than 3^{o}) were distributed downstream of the catchment (near Kota Bharu and Tanah Merah) and along the river line. It is because the area at the slope is usually low, and rain or excessive water from the river always gathers in this area (Ouma & Tateishi, 2014). Therefore, the possibility of a flood occurring is high. However, most of the upstream areas of the catchment, such as Nenggiri and Lebir, had high gradients (greater than 3^{o}). Thus, the high slopes help to drain water quickly (Seejata et al., 2018).

In terms of river density, the results in Figure 2(c) suggested that a higher drainage density can be seen near the river line. Most high and very high river densities could be derived near the river line. This observation indicated that the area near the catchment's river line is prone to erosion, resulting in sedimentation at the lower grounds. This finding is consistent with other studies, such as Sharir et al. (2019), which found that the drainage density or river density is highest in the areas near the river. River density was one of the important hazard-controlling factors in this study that indicated the nature and properties of the soils.

The catchment is 80.7% surrounded by tropical rainforests, followed by 9.7% agricultural sites (such as rubber and oil palm plantations), 3.5% built-up (residential, commercial, and industrial buildings), and 1.2% water bodies, as illustrated in Figure 2(d). It is evident that the study area has not been extensively explored for development and agricultural activities. Most of the exploration occurred downstream of the catchment, such as in the areas near Kota Bharu and Machang. Rapid exploration without control of slope cutting can trigger flash floods in urban areas. The surrounding forest usually allows a higher infiltration rate than the urban area or pastureland (Seejata et al., 2018). The LULC is one of the significant concerns in flood hazards and was selected as a parameter in this study. The LULC reflected the current use and infiltration of the land.

Figure 2(e) shows the elevation of the catchment. It is considered the fourth important parameter of the weight scores of the AHP (see Table 7). Figure 2(e) depicts that most areas of the catchment had an elevation of 0–200 m, while high elevations (greater than 600 m) were found in the eastern and western regions near Nenggiri and Lebir. Low elevations would indicate flat areas usually prone to flood occurrences, such as Kota Bharu, Tanah Merah, and Kuala Krai. Most of the previous flood events occurred in those areas with low elevations (Jaafar et al., 2016; Tan et al., 2017). Therefore, elevation became a significant parameter for the development of the FHI in this study.

For soil permeability, as presented in Figure 2(f), the soil type was reclassified into three classes based on the water permeability following the FAO's soil map. In this study, high soil permeability, in which water easily infiltrates the soil, could be found in the mountainous ranges in the eastern and western regions (composed of silt soils). On the other hand, low soil permeability, in which the soil is impermeable, could be identified downstream of the catchment (made of clay and granite soils).

Spatial Variations of FHI

Figure 3(a) shows the FHI prepared for each pixel/cell of the Kelantan River catchment in the ArcGIS environment based on particular features, each criterion's weight and normalised rank (refer to Table 7) calculated using the AHP approach. From Figure 3(a), the spatial variability of the index within the entire district could be obtained and was categorised into five levels of risk, namely very low (<2 FHI), low (2–5 FHI), medium (5–7 FHI), high (7–8 FHI), and very high (>8 FHI) flood zones using Equation (3). The finding showed a very high FHI covering 1,207.6 km^2 or 9.4% of the catchment area. The areas near Tanah Merah and Jeli were mainly part of the very high flood zone. It is because those areas are flat in slope and at low elevations. The areas also intersect two main rivers, the Galas and Lebir Rivers, at the left and right sides of the catchment, respectively. Both rivers contribute a high-water volume to the river downstream during the rainy season. This situation worsens due to the higher rainfall intensity in those areas, proven by the parameter of rainfall density achieving the first objective hierarchy rating score in the FHI development.

The study also discovered that high to extremely high FHI levels were found around the Kelantan River catchment's river line. It is because most of the runoff will flow to the river from high to low elevations, increasing the risk of flooding near the riverbanks (Ologunorisa & Abawua, 2005). The increased flood risk in the riverbanks is due to land use development in low-lying areas. Low-lying areas are undeniably more vulnerable to floods, but whether the soil facilitates or hinders water infiltration depends on the soil's texture. Land use development in low-lying areas, such as the construction of buildings or roads, exacerbates the situation by requiring clearing vegetation, slope cutting, and applying impermeable materials to the surface. As a result, the area becomes increasingly vulnerable to flooding. Meanwhile, the study found that low FHI levels were recorded at high elevations, such as at Nenggiri and Lebir.

The FHI in Figure 3(a), developed from the AHP method, was validated with the historically flooded areas in Figure 3(b) modified from the Department of Irrigation and Drainage Malaysia (DID, 2014) and Alias et al. (2020). The comparison revealed that most historical floods had occurred in zones with very high FHI levels, especially Tanah Merah, Jeli, Gua Musang, and Kuala Krai. Therefore, those areas closely matched the historic floods. However, the area between Tanah Merah and Kota Bharu, mainly classified as having a medium FHI, is not as frequently hit by floods as in historical flood areas. The finding is consistent with Roslan et al. (2019), who also evinced that the area near Kota Bharu is low-risk, based on their flood risk map. The findings showed that the estimated FHI matched the historical flood areas.

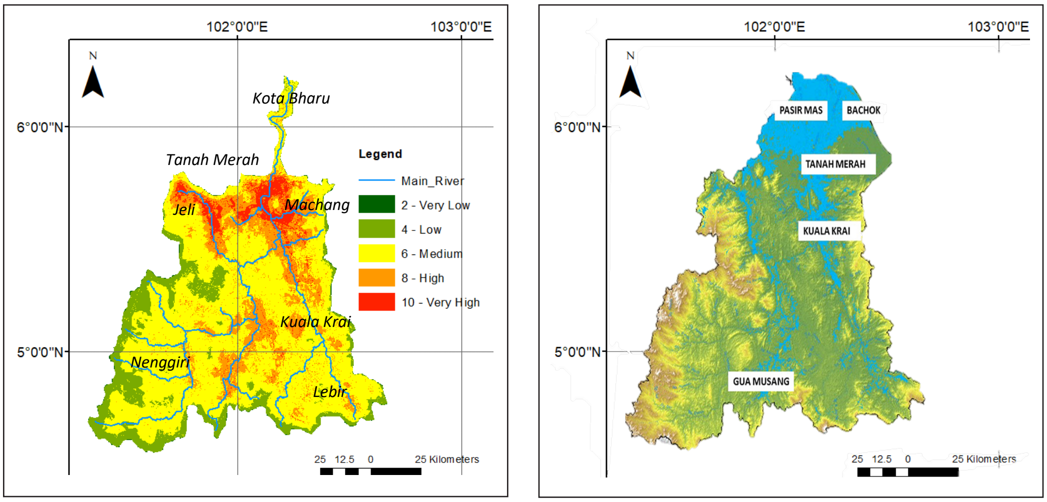

Figure 3. Distribution of (a) FHI derived from AHP and (b) historically flooded areas in Kelantan (Alias et al., 2020; DID, 2014)

CONCLUSION

The main objective of this study is to identify the FHI areas in the Kelantan River catchment, Malaysia. The weight of the relative importance of six flood parameters was identified using the pairwise matrix comparison. The results showed that very high-risk flood-prone areas with the highest FHI values were Tanah Merah and Jeli. Those areas were susceptible to flood mainly because of the highest annual rainfall in 2014; the annual rainfall generated the highest score from the AHP. Most of the flood areas' spatial patterns derived using the AHP model were similar to the historical flood map.

For future work, it is suggested to evaluate the inclusion of other parameters in developing the FHI value. For example, the weighing of relative importance should be revised due to changes in the parameters. In addition, incorporating comprehensive field data such as soil parameters, groundwater depth, and local drainage would improve the accuracy of the current approach.

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