Watershed Management by GIS-Based Morphometric Analysis of the Lampir Watershed, Central Java

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Abstract. The decline of Indonesia's quality of watershed environment nowadays requires proper management. This research was initiated to obtain the watershed morphometrics using the automatic GIS method, mainly for Flow Direction Analysis. The study was conducted in Lampir Watershed. Lampir Watershed plays a significant role in Central Java. For short, Central Java is the second most populated province in Indonesia. The analysis was achieved using a Digital Elevation Model (DEM) and processed using ArcGIS. The result shows that the Drainage density (Dd) value in the Lampir Watershed is coarse at 0.95, with an average stream length ca. 10.59. The Stream length ratio (Rt) in the Lampir Watershed increases from lower order to higher order except for Rt IV/III, but increases in the following Rt values. Infiltration capacity is the only important factor affecting the drainage texture. The length of overland flow (Lo) in the Lampir Watershed is petite (<1). The Lo result indicates that the stream will get faster to the channel and has a high potential for flash floods.

Keywords: Morphometry · Watershed · Drainage Density · Flow Direction

1 Introduction

A watershed conceptual approach is ideal for managing natural resources and disaster mitigation in sustainable development (Cahyadi, 2012). However, watershed management is a significant effort due to the decline in the quality of the watershed environment in Indonesia. The decline is caused by the management of natural resources that are not environmentally friendly. It is also caused by the increasing potential of the sectoral and regional ego due to the exploitation of natural resources, which involves various sectors' interests.

Watershed management can be done through morphometric analysis. Morphometry is a form of quantification of morphology. The value of each morphometric parameter

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in a watershed determines the characteristics of the watershed (Rai, Mishra, & Mohan, 2017).

Morphometric analysis of watersheds is considered an appropriate method for understanding the relationship between various aspects of a watershed. Watershed analysis based on morphometric parameters is essential for watershed planning. It is crucial to provide information on slope characteristics, runoff characteristics, topography, surface water potential, etc. (Chandrashekar, Lokesh, & Sameena, 2015; Dimyati, Trihatmoko, & Marfai, 2021). The interaction between geomorphological conditions and hydrological characteristics can be reflected in the morphometric aspects of the watershed. In analyzing watershed morphometry, Geographic Information System (GIS) technology can be used as an effective tool.

a Digital Elevation Model (DEM) in a GIS-based evaluation has provided an accurate, simple, and low-cost method for analyzing hydrological systems (Grohmann, 2004). In a GIS setting, the DEM of the region was created to conclude morphometric parameters in the GIS environment (Rai, Mohan, Mishra, Ahmad, & Mishra, 2017). The drainage area can be detected and differentiated using a combination of remote sensing imagery, hydrological, and spatial analysis in a GIS setting (Pirasteh S., Safari H.O, Pradhan B., & Attarzadeh I., 2010; Rai, Mohan, et al., 2017).

Besides watershed management, watershed morphometric analysis is often used for disaster studies (Aher, Adinarayana, & Gorantiwar, 2014; Kar, Kumar, & R. Singh, 2009; Magesh & Chandrasekar, 2014; Rai, Mishra, et al., 2017). Watershed morphometry analysis for flood studies and erosion have been carried out through the last decade (Nugraha & Cahyadi, 2012; Vinutha & Janardhana, 2014; Yangchan. J, Jain A.K., Tiwari A.K., & Sood A., 2015; Youssef & Pradhan, 2011). The watershed morphometric analysis in this paper is intended to study the hydrological characteristics.

2 Methodology

2.1 Study Area

The Lampir Watershed is located in the coordinate position between 109°50′31"-110°03′38" East and between 6°54′14"-7°12′02" Southern Latitude (Prihutomo, 2014). The width of Lampir Watershed is 69,266.58 ha or 2.04% of the total area of the watershed. Lampir Watershed has a Circumference of 101.21 km. The geographical location of Lampir Watershed is in the northern part of Central Java, the second most populated province of Indonesia. The watershed crosses three regencies, starting from the widest Batang Regency (50,081.82 ha), Kendal Regency (18,911.32 ha), and Banjarnegara Regency (272.40 ha) Fig. 1.

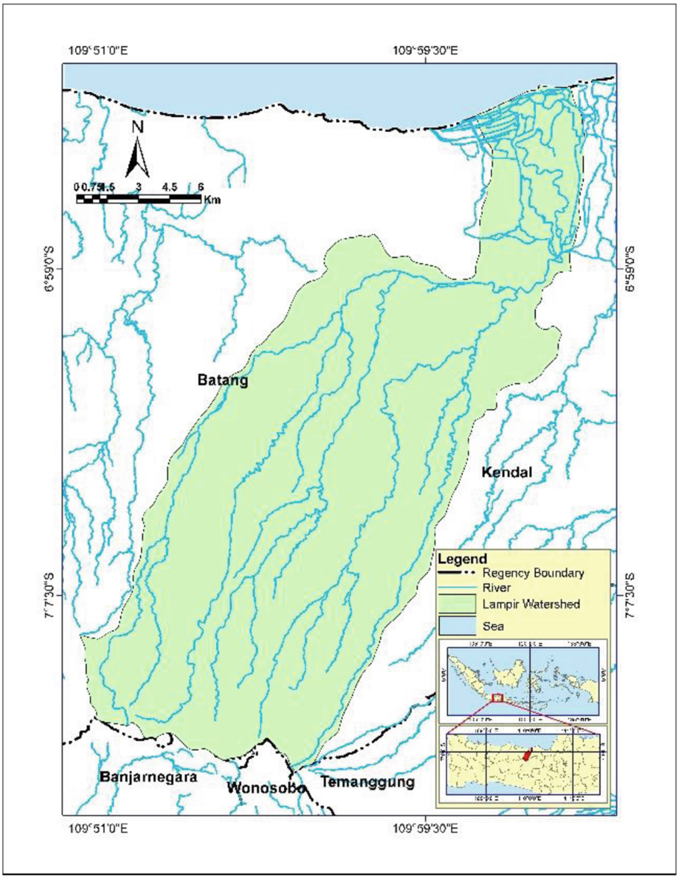

Fig. 1. Lampir watershed map

2.2 Tools and Materials

A GIS-based morphometric analysis used ArcGIS software. The Flow Direction tool in ArcGIS was used for modeling the flow direction. Calculate geometry tools in ArcGIS software were utilized for calculating morphometrics parameters. The DEM data with 30 m spatial resolution published by Indonesian Geospatial Information Agency was used as an input raster for the flow direction tool and calculate morphometric parameters. As a base map, the Lampir Watershed map (Fig. 1) was prepared from watershed boundary data published by the Ministry of Environment and Forestry and river data from the Indonesian Geospatial Information Agency.

2.3 Flow Direction

Flow direction is a tool in ArcGIS that creates flow direction for each cell in raster data to its downslope neighbors. The input raster to run the tool must represent a continuous elevation surface (ESRI, n.d.). In the present study, the DEM data were used as input raster, as it is widely used to define the flow direction in distributed hydrological models for the simulation of streamflow (Zhao, Gao, Tian, & Tian, 2009).

The flow direction tool provided by ESRI in ArcGIS was used to create the flow direction model data. In determining the flow direction, the DEM data must be filled in. The filling process is carried out if the DEM data is created from the contour data interpolation process. The filling process is needed to eliminate most of the generalized flat and pit areas during the DEM interpolation process. Flow Direction can be applied to create sub-watershed boundaries, determine relationships between sub-watersheds, and calculate the geophysical characteristics of watersheds.

2.4 Morphometric Parameters

There are thirteen morphometric parameters calculated. The parameters used were divided into two aspects, namely linear and shape. The detailed list of various morphometric parameters is presented in Table 1 and Table 2.

Table 1. Estimation of linear parameters.

No	Morphometric Parameters	Formula/Definition
1	Stream order (μ)	Hierarchical rank
2	Number of the stream (N_μ)	Based on stream order
3	Stream length (L_μ)	The total length of the stream segments of that particular order
4	Average stream length (L_x)	The mean length of all stream segments of a given order(μ); $L_x = L_\mu/N_\mu$
5	Stream length ratio (R_t)	$R_t = L_x/L_{x(\mu\text{-}1)}$; $L_{x(\mu\text{-}1)}$ is the mean length of all stream segments of one order less than the given order(μ)
6	Bifurcation ratio (R_b)	$R_b = N_\mu/N_{(\mu+1)}$; N_μ is the Total number of stream segments of the order "μ"/$N_{(\mu+1)}$ is the number of stream segments of the next higher order
7	Drainage density (*Dd*)	$Dd = \sum L_\mu/A$; $\sum L_\mu$ is the total length of the stream segments of all orders; A is an area of the river basin or grid (km^2)
8	Texture ratio	Number of stream segments of all order present per perimeter of that area

(*continued*)

Table 1. (*continued*)

No	Morphometric Parameters	Formula/Definition
9	Stream frequency	Total number of channel segments of all stream orders per unit area
10	Length of overland flow (L_O)	$L_O = 1/Dd$

Source: (Choudhari, Nigam, Singh, & Thakur, 2018)

Table 2. Estimation of shape parameters.

No	Morphometric Parameter	Formula/Definition
1	Circularity ratio (Rc)	Rc = 4πA/P in sq; P is the perimeter (km)
2	Form factor (Ff)	Ff = A/L in sq; Where A = area of the basin (km2), L = Basin length (km)
3	Drainage texture (T)	T = Dd. Ff

Source: (Choudhari et al., 2018)

3 Results and Discussion

3.1 Flow Direction Analysis

To analize the Flow Direction, the Flow Accumulation phase was used to determine the location where several directions of water combined to become a new flow direction (Fig. 2). Alternatively, it can be interpreted by forming an area that is predicted to be a river. The value ≥ 3 is the pixel value, which means that the river with an area < 3 (Pixel Resolution) will not be displayed on the results of the conditional function. The spatial resolution of DEM data is 30 m, so the river area < 30 m will not be displayed. This limitation means that rivers with an area of < 90 m will not be shown on the results of the conditional function.

3.2 Morphometric Parameter Analysis

Figure 3 shows that the Lampir Watershed has five stream orders, otherwise Fig. 4 shows the line density distribution. The distribution of line density shows that there is a place where density occurs in each river network. After the density distribution was obtained, the Dd value will be obtained and followed by the other watershed characteristics (Table 3 and Table 4).

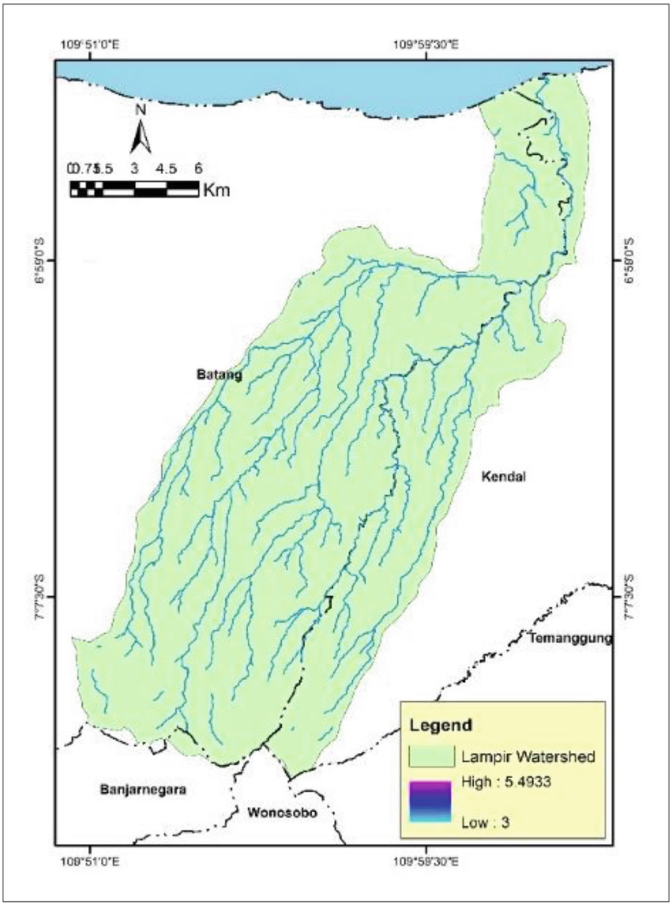

Fig. 2. Flow direction map of Lampir Watershed

Dd is an expression of closeness between channels. A high or fine Dd value indicates the area is composed of impermeable subsurface material, a mountainous area with sparse vegetation. The low value or coarse value of Dd in the Lampir watershed is related to waterproof subsurface material, sparse vegetation, and mountainous relief.

In general, the higher the river order, the smaller the stream segments. While regarding the stream length, the higher the stream order indicates the smaller total river length (Vittala, Govindaiah, Gowda, State, & Sensing, 2004). But it seems there are some exceptions. There is a river flow at a very high elevation, lithological variations, and steep slopes in the watershed in question (Vittala et al., 2004). If the stream order is higher than the minimum value, the number of stream length will decrease. Still, the river's total length is not always getting smaller.

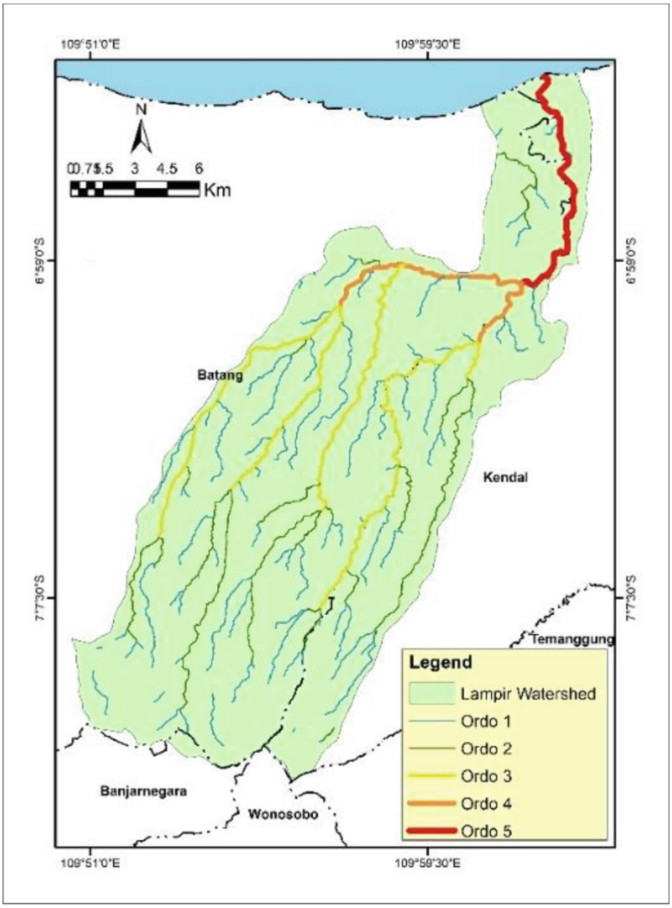

Fig. 3. Stream order distribution map.

In this assessment, the value of stream length ratio (Rt) was obtained for the second-order/first-order (II/I), third-order/second-order (III/II), fourth-order/third-order (IV/III), and fifth-order/fourth-order (V/IV). The existence of trends (values) increasing the Rt value from lower order to higher order indicates further geomorphic significance in the watershed (Vinutha & Janardhana, 2014). The Rt values of the Lampir watershed have an added value of Rt that increases from lower order to higher order except for Rt IV/III, which decreases but increases in the following Rt values (Table 5).

The Lampir watershed bifurcation ratio (Rb) value is the Rb value for orders II/I, III/II, IV/III, and V/IV (Table 6). Bifurcation ratios ranging from 2.0 to 6.4 are owned by a watershed where the geological structure does not affect river flow patterns (Vinutha & Janardhana, 2014). For instants, a higher Rb value indicates more substantial structural control (Vittala et al., 2004). Based on the results, almost all Rb values in the Lampir watershed are within the stated value range (Vinutha & Janardhana, 2014). Still, they do not occur in Rb values in order III/II, whose values are < 2.0 (1.17).

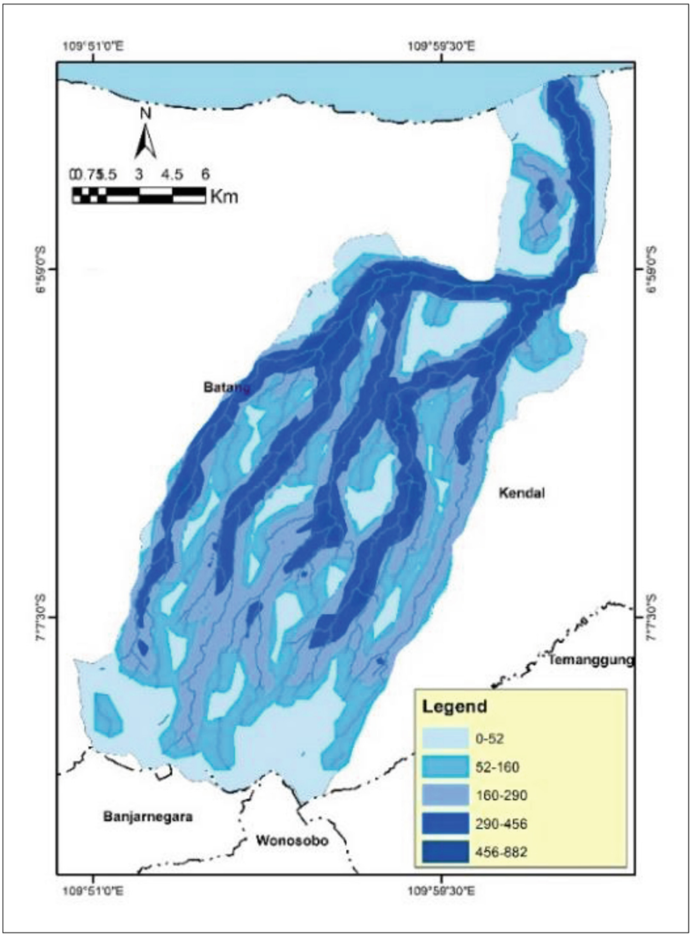

Fig. 4. Distribution of line density map.

Table 3. Area, Circumference, Length, and Drainage density (Dd) of Lampir Watershed.

Area (km)	Circumference (km)	Length (km)	Drainage density (Dd)
346.34	101.31	329.29	0.95

A high Rb value indicates that the area has rock layers with steep slopes and the distance between narrow valleys is limited by steep walls (Choudhari et al., 2018) or dominant geological control. Conversely, a low Rb value indicates non-dominant geological control. The bifurcation ratio (Rb) value is close to 4 (Order IV/III), showing that water flows on rocks resistant to erosion. Rb values of more than 3.5 indicate that the geological structure is not a factor in influencing the flow patterns in the area (Choudhari et al., 2018).

Table 4. Stream order (μ), Number of the stream per order (Nμ) Stream length (Lμ), and Average stream length (Lx) in the Lampir watershed.

Stream order	Lμ (km)	Nμ	Lx (km)
1	155.95	92	1.70
2	81.77	35	2.34
3	63.46	31	2.05
4	14.79	8	1.85
5	13.33	5	2.67
Total	329.29	171	10.59

Table 5. Stream length ratio (Rt).

Lu/Lu-1	Order			
	II/I	III/II	IV/III	V/IV
Stream length ratio (Rt)	0.53	0.79	0.24	0.97

Table 6. Bifurcation ratio (Rb).

Lu/Lu-1	Order			
	II/I	III/II	IV/III	V/IV
Bifurcation ratio (Rb)	2.7	1.17	4.43	2.0

The texture ratio is another essential factor in morphometric analysis (Table 7). The ratio regarding drainage depends on the underlying lithology, infiltration capacity, and relief aspects. A high texture ratio indicates the potential for erosion and high surface flow. The value of the texture ratio in all areas in Lampir watersheds is very rough because it has a value of 1.69. This value indicates that the amount of erosion and surface runoff will be small based on this factor. Besides, the value of stream frequency in the Lampir watershed is also low (Table 7). This value is closely related to low permeability, low infiltration capacity, and waterproof assistance to the Lampir watershed. Therefore, a low stream frequency value will cause high surface flow.

Table 7. Texture ratio and Stream frequency of Lampir Watershed.

Ordo	Texture ratio	Stream frequency
1	0.91	0.27
2	0.35	0.10
3	0.31	0.09
4	0.08	0.02
5	0.05	0.01
Total	1.69	0.49

The drainage texture (T) classification mentioned by (Yangchan. J et al., 2015) is (1) very rough for values < 2, (2) rough for grades 2–4, (3) moderate for grades 4–6, (4) subtle for grades 6–8, (5) very subtle for values > 8. The value of drainage texture of the Lampir watershed is shown in Table 8. Infiltration capacity is the only important factor affecting the value of drainage texture (Vittala et al., 2004).

The length of overland flow (Lo) is the water on the ground's surface before it concentrates in a channel. The Lo in the Lampir Watershed has a low value (<1) (Table 8). This Lo means it will cause the flow to get faster to the channel, and the potential for flash floods will be high.

Based on the watershed morphometry data presented in the previous tables, the Lampir Watershed has the potential for erosion due to the high value of Dd. The Dd value of the Lampir Watershed presented in Table 3 is classified as very coarse because the value is below two (Rai, Mohan, et al., 2017), which is 0.95. Then it can be indicated as a process of denudational landform due to high Dd that can cause erosion.

The downstream area of Lampir Watershed is also frequently flooded, caused by sedimentation from erosion in the upstream area. Based on data from the Regional Disaster Management Agency (BPBD) of Kendal Regency in January 2019, the flood height reached between 50 cm - 100 cm. Therefore, downstream of Lampir Watershed is the highest flooded area (Priyatin, 2019). The flood also happened in the Batang Regency as part of the downstream area (Fig. 5). Department of Water Resources and Spatial Planning explained that the deposition occurred in several water gates and needed to be dredged out immediately (Fadli, 2020).

A high or fine Dd value implies runoff can quickly be accumulated in a channel so that it can be a low possibility of flooding. In contrast, watersheds with smaller or coarse Dd value indicates the likelihood of high flooding potential. This is because the higher Dd will affect the flow increase that causes surface runoff accumulation to the nearest

Table 8. Length of overland flow (Lo), Drainage texture (T), Form factor (Rf), and Circularity ratio (Rc) of Lampir Watershed.

Lo	T	Rf	Rc
0.53	1.69	0.00319	0.42

Fig. 5. Lampir high discharge with high accumulation of sediment. . Source: (Humas Polda Jawa Tengah, 2020)

runoff very quickly (Ajin. R. S., R. R. Krishnamurthy, M. Jayaprakash, & Vinod. P. G., 2013).

4 Conclusions

A morphometric analysis through morphological quantification is achievable.The analysis can be done using DEM data with the ArcGIS tool. In this study, flow patterns were automated with Flow Direction to assess the distribution of drainage competencies and their values.

Based on the study results, the Dd value in the Lampir Watershed is coarse, ca. 0.95, while the average stream length is 10.59. The value of the Stream length ratio (Rt) in the Lampir watershed increases from lower order to higher order except for Rt IV/III, which decreases but increases in subsequent Rt values. Infiltration capacity is the only important factor affecting the value of drainage texture. The Lo in the Lampir Watershed has a low value (<1). This value means it will cause the flow to get faster to the channel, and the potential for flash floods will be high. Therefore, the high land occupation on the specific river orders mentioned is not suitable.

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