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Assessing Watershed Characteristics and Hydrological Response Using SWAT: A Case Study in the Raya Watershed, West Kalimantan

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ABSTRACT

The watershed is primarily influenced by land use and population activities within the watershed area. Along with the increasing number of people, there is the potential for land-use changes that lead to a change in the land's function. This condition can cause soil erosion in the upstream areas and potential flooding in the downstream area of the watershed. This study aims to determine the hydrology response based on watershed characteristics in terms of annual flow coefficient (AFC) and geomorphology. Geospatial hydrological modeling was built to assess hydrological characteristics using the SWAT (Soil and Water Assessment Tool). The analysis utilized primary data from field surveys and secondary spatial data, including geological maps, DEM, land use, soil, and daily rainfall, from 2013 to 2022. The study area covers the Raya Watershed in West Kalimantan. It was found in the Raya Watershed that open land use is prominent, with slopes ranging from sloping to steep in the upstream areas. The type of soil generally had porosity that did not support water absorption. These conditions caused more rainfall to be discharged as surface flow than absorbed into the soil. The AFC value during the study period ranged from 0.36 to 0.45, indicating a moderate hydrological response. Thus, groundwater storage in the watershed was very low. Consequently, the hydrological response of the watershed is unable to function optimally in its current condition. To overcome these problems, land conservation strategies, reforestation, and rehabilitation of old mine fields in upstream sub-basins are needed to reduce runoff and improve the watershed's ability to maintain a sustainable water balance.

Keywords: Raya Watershed, SWAT, hydrology response, land conservation

INTRODUCTION

A watershed is a land area topographically bounded by mountain ridges that collect rainwater to be channeled to the sea through the main river [1]. The condition of the watershed is greatly influenced by land use and human activities within the watershed. Along with the increasing population, there is a potential for land clearing, including forests and other green areas. This causes a change in the function of the land, which was originally a forest, to become agricultural or mining. This condition can cause soil erosion in the upstream area and increase the potential for flooding in the downstream area of the watershed.

Soil erosion is a serious problem that causes land degradation, loss of agricultural productivity, and alters geomorphic processes and sediment fluxes in a river basin [2].

Damage caused by erosion is characterized by the decline of chemical and physical properties of the soil, including the loss of nutrients and organic components, increased density and resistance to soil penetration, decreased capacity of the soil to absorb water, and reduced ability of the soil to retain water. The consequences of this event include decreased land productivity and reduced groundwater levels. The nutrients lost due to erosion depend on the magnitude of erosion and the nutrients contained in the eroded soil [3].

At the same time, flooding occurs almost every year in Kalimantan, for example, in residential areas located along the Kapuas River in West Kalimantan and the Barito River in South Kalimantan, especially in downstream regions such as Pontianak and Banjarmasin. This condition causes major losses, especially in areas near river discharge points. High rainfall in the upstream area can increase river discharge until the river's capacity is exceeded, resulting in flooding. As was the case in Sungai Raya Village, Subdistrict Sungai Raya Pulau experienced a flash flood on March 7th, 2023, affecting 3,539 people and 1,036 families due to two days of heavy rainfall [4].

The change in hydrological characteristics affects the increase in river discharge during the rainy season, but it causes water shortages during the dry season [5]. The problems in the upper watershed are thought to occur due to simultaneous land use change patterns. This increases the chances of river overflows and flooding. This study was conducted to determine the hydrological response based on watershed characteristics, specifically in terms of annual flow coefficient and geomorphology. The results of this study are expected to provide a comprehensive understanding of the potential threat posed by hydrometeorological hazards in the Raya Watershed. This study hypothesizes that integrating geomorphological characteristics into AFC analysis will improve the accuracy of Raya Watershed's hydrological response prediction.

The study was conducted on the Raya Watershed, located on the western coast of West Kalimantan Province, Indonesia. Shown on Figure 1, Raya Watershed ranges between 0°39'51.9"–0°50'38,2" North latitude and 109°13'30.6"–108°52'43.9" East longitude. Administratively, the Raya Watershed covers the Bengkayang Regency, which consists of the sub-districts: Kepulauan Sungai Raya, Monterado, Sadaniang, Samalantan, and Singkawang City, with the latter comprising only the South Singkawang sub-district. The Raya River is considered the main river of the Raya Watershed.

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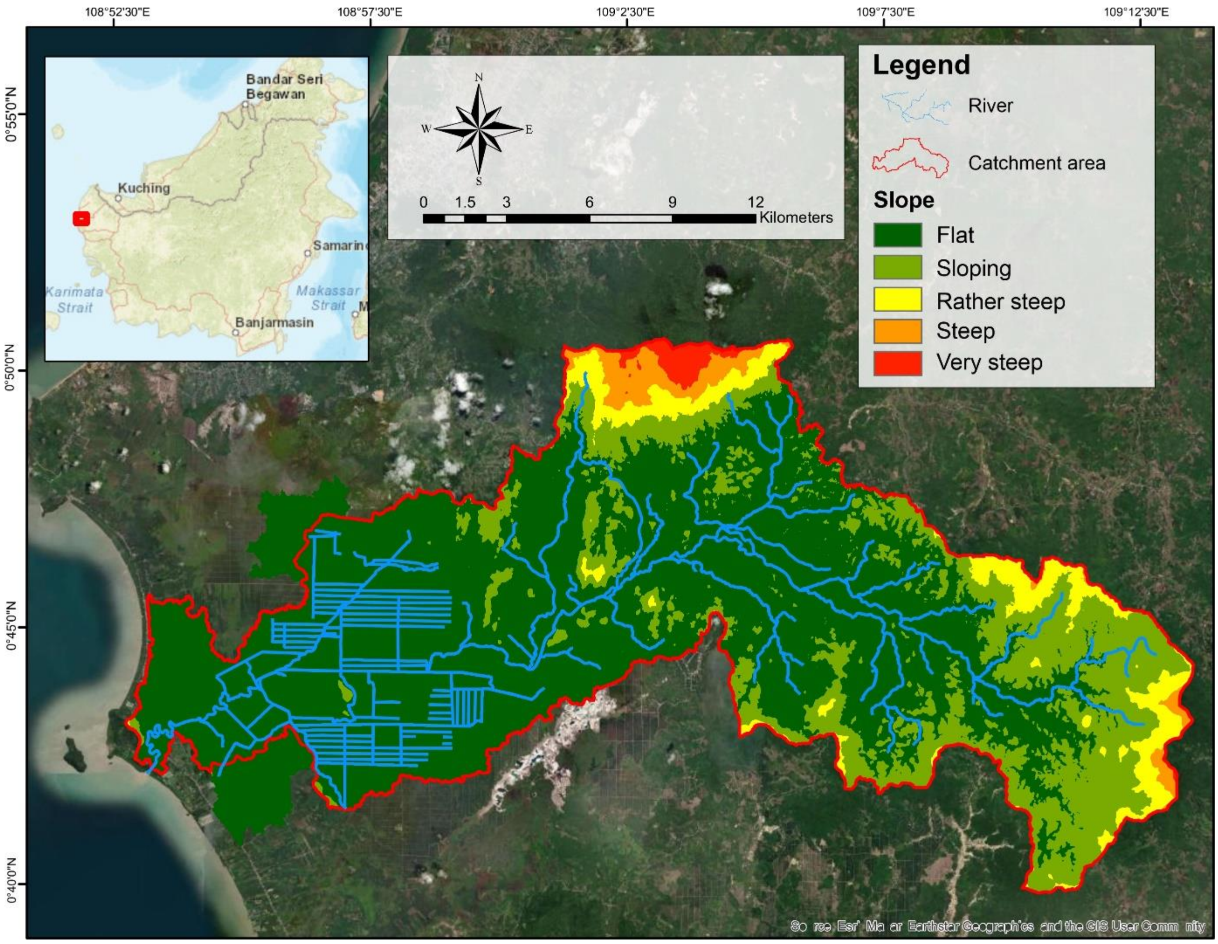

Figure 1. Location of study area.

METHODOLOGY

This study was conducted in three different stages: primary and secondary data collection, data processing, and data analysis. In this first stage, primary data were collected through a direct survey in the study area. This data was obtained directly by measuring and observing the physical environment in the field, including the soil data and geomorphological processes. Soil data, in terms of physical properties, was collected through visual observation and soil samples. The location of observation and soil sampling was at the same point. The soil samples taken totaled 10 samples, each weighing 2 kg. The boundaries of the soil sample area are determined based on the relationship between landforms and soil morphological properties. The selection of sample locations is based on landform stratification, with one sample at each boundary of the soil sample, which is considered representative of the population members at the soil sampling location. Direct observation in the field involves observing geomorphological processes at specific sample points. This is an identification of erosion events, rock weathering, and sedimentation at each observation location, as well as information on land use and vegetation. Secondary data was obtained from various sources (Table 1). These included geological maps at a scale of 1:100.000 obtained from the Ministry of Energy and Mineral Resources. Understanding watershed characteristics through geological data, especially lithology, is essential, as different rock types can influence weathering processes, runoff patterns, infiltration capacity, and erosion susceptibility. Additional secondary data included Digital Elevation Models (DEM) in GeoTIFF format with an 8m spatial resolution, streamlines, and land-use data from the Geospatial Information Agency, as well as soil and meteorological data (such as daily rainfall, maximum and minimum temperatures, air humidity, wind speed, and solar radiation) obtained from global data websites.

Table 1. Secondary datasets utilized in the research

Type of Data	Source
Watershed boundaries	DEMNAS: https://demnas.go.id/
Slope	DEMNAS: https://demnas.go.id/
Land use	INA Geoportal: https://tanahair.indonesia.go.id/map USGS: https://earthexplorer.usgs.gov/
Soil	Soilgrids: https://soilgrids.org Indonesian Soil Research Institute (ISRI) – Bogor
River network	DEMNAS: https://demnas.go.id/
Rainfall	Jaxa Global Rainfall Watch: https://sharaku.eorc.jaxa.jp/GSMaP/index.htm
Temperature	Powerlarc: https://power.larc.nasa.gov/
Relative humidity	Powerlarc: https://power.larc.nasa.gov/
Wind speed	
Solar radiation	Powerlarc: https://power.larc.nasa.gov/
Land systems	INA Geoportal: https://tanahair.indonesia.go.id/map
Geology	Ministry of Energy and Mineral Resources

Data processing was performed as the second stage. At this stage, hydrological modeling was conducted using the Soil and Water Assessment Tool (SWAT), a geospatial hydrological model used to assess the watershed's hydrological characteristics [6]. Several studies have previously been conducted on the hydrological characteristics of watersheds using SWAT [7].

SWAT is a hydrological model integrated with ArcGIS version 10.8 [8], licensed to BATAN, which is physically based and a semi-distributed model [9], [10]. It uses the Hydrology Response Unit (HRU) as an analysis unit to assess the similarity of characteristics and level of hydrological response. While SWAT modeling is widely used in Indonesia, the application with detailed geomorphological input remains limited in Kalimantan watersheds. Due to the limited hydrological data at the study site, the SWAT model was validated using a spatial approach through field collection of erosion evidence.

In determining the hydrological cycle that occurs in an area, the SWAT model used the water balance equation [11] as follows:

$$SW_t = SW_0 + \sum_{n-1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \quad (1)$$

where SW_t is the water content in the soil (mm), t is the time (day), SW_0 is the initial water storage (mm), R_{day} is the rain (mm), Q_{surf} is the surface runoff (mm), E_a is evapotranspiration (mm), W_{Seep} is percolation (mm) and Q_{gw} as groundwater discharge (mm).

Rainfall intensity is a critical factor in determining the hydrological response of a watershed, as it directly influences the generation of surface runoff and groundwater discharge. Comprehending the relationship between rainfall intensity, discharge, and surface flow is essential for effective water resource management and flood mitigation. Studies have demonstrated a strong linear correlation between the total rainfall during an event and the resulting runoff volume, indicating that higher rainfall intensity directly leads to increased water discharge and surface flow [12], [13]. Surface runoff results from the complex interactions between the land surface and incoming precipitation. During high-intensity rainfall events, this runoff can

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transport sediments, fertilizers, and pesticides, which may significantly impact the health of aquatic ecosystems. In many watersheds, the primary mechanism of runoff is saturation excess runoff, where water flows overland to streams from soil surfaces that have become saturated [14].

In the final stage, a hydrological response analysis was carried out using a watershed characteristic approach that focuses on assessing the potential for surface flow based on rainfall and watershed geomorphological conditions. Annual flow coefficient (AFC) is used to determine the influence of measured river discharge fluctuations based on rainfall in the upstream Raya Watershed. The analysis of the calculation of AFC refers to the classification of the Ministry Regulation of the Ministry of Environmental and Forestry Number 61/Menhut-II/2014 concerning the monitoring and evaluation of watershed management. The following formula was used to calculate AFC.

$$AFC = \frac{Q}{P} \quad (2)$$

AFC is defined as a comparison of the total value of surface flow with the total value of rainfall. AFC is the amount of rainfall (in percent) that can become surface flow (runoff) in the upper Raya Watershed. Annual flow thickness (Q) is the value of the ratio of direct runoff flow (m^3/sec) multiplied by the coefficient and divided by the water catchment area in m^2 units. Annual flow and rainfall were obtained from the results of the SWAT model that had been carried out. The AFC class criteria are presented in Table 2 for direct runoff and base flow.

Table 2. Classification of Annual Flow Coefficient [15].

Annual Flow Coefficient (AFC)	
Value	**Class**
AFC ≤ 0.2	Very low
0.2 ≤ AFC ≤ 0.3	Low
0.3 ≤ AFC ≤ 0.4	Medium
0.4 ≤ AFC ≤ 0.5	High
AFC ≥ 0.5	Very high

Meanwhile, the hydrological response is also influenced by geomorphology. The combination of landform, soil type, and topography determines how fast and how far the water flows into the Raya river system and how it is absorbed or discharged on the surface. Descriptive analysis is conducted based on landform maps, soil data, and morphometry (catchment area, longest flow path length, and average slope) of the Raya watershed to investigate the hydrological response. The stages of this research are systematically presented in Figure 2.

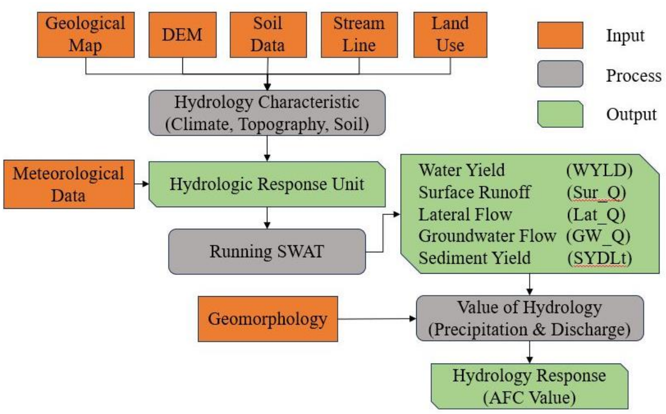

Figure 2. Methodology flow chart.

RESULTS AND DISCUSSION

Hydrological Characteristics in Raya Watershed

The SWAT analysis shows that the Raya Watershed consists of 34 sub-watersheds. The total area of the watershed formed is 365,817 km^2. The Raya Watershed has an elongated shape, with an upstream area in the east and a downstream area on the west side of the Kalimantan coast, and it bends in the middle. The detailed hydrology characteristics of the Raya Watershed can be found in Table 3. The main characteristics of Raya Watershed are divided into three parameters: climate (rainfall and evaporation), topography (catchment area, longest flow path length, and average flow), and soil (drainage density, silt, clay, and clay loam).

Table 3. Hydrology Characteristic of Raya Watershed

Main Catchment Characteristics	Catchment Characteristic	Value
Climate	Rainfall	3,359 mm/year
	Evaporation	342 mm/year
Topography	Catchment area	3,624.7 km2
	Longest flow path length	55.47 km
	Average slope	12.6 %
Soil	Drainage density	0.35
	Silt	9.5 %
	Clay	7.7 %
	Clay Loam	82.8 %

Watershed morphometry plays an important role in determining hydrological responses, such as catchment area, longest flow path length, and average slope. It will affect how rainwater is drained and stored in a watershed. Based on the geometry of the DEM, the Raya watershed is long and narrow, resulting in a longer journey to the outlet. The peak flow produced is lower and has a longer duration. Meanwhile, based on hydrological characteristic data, the Raya Watershed has a moderate drainage density of approximately 0.35. The upstream part of the slope tends to be sloping to steep, allowing for surface flow rates. However, the slope changes significantly from gentle to flat in the middle to downstream sections. This results in a lower hydrological response characterized by slower surface flow.

Annual Flow Coefficient (AFC) Value

The hydrological response of the watershed can be seen from the AFC value, which is based on the amount of rainfall against the annual flow thickness of the upstream Raya watershed. The average rainfall in the area for the last 10 years, from 2013 to 2022, was 2,514.2 mm. The annual flow thickness in 2018 was approximately 615.0 mm. The value of the annual flow coefficient for the Raya watershed for ten years tends to increase, which indicates that the condition of the Raya watershed is not good [16].

Based on AFC calculations, the largest AFC value occurred in 2020 at 0.45, and the lowest AFC value in 2013 at 0.36. There was an increase in the amount of water that became runoff for 10 years of around 0.09%. The difference in the AFC value indicates that the hydrological response of the upstream subbasin Raya watershed is experiencing problems. The average AFC value is in the moderate category. On the sub-basin level, some upstream areas consistently display high AFC values, especially those with steep slopes and low infiltration soils. The response of the upstream subbasin Raya watershed, when it rains, tends to overflow into water bodies rather than being retained or absorbed. This is reflected in the rise in AFC from 0.36 in 2013 to 0.45 in 2020, indicating a shift toward increased surface runoff. It has increased over the past ten years due to the intensity of rainfall. This finding aligns with Nuraiman &

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Harisuseno (2023) [17], who found that increased surface runoff and reduced groundwater storage resulted from decreased water catchment capacity due to unregulated land use changes in the Upper Ciliwung watershed.

The spatial distribution of AFC values across the subbasins of the Raya Watershed is presented in Figure 4. The results demonstrate that most of the watershed exhibits high to very high AFC values (≥0.4), reflecting a limited infiltration capacity and a dominance of surface hydrological response. In the central sector of the basin, elevated AFC values suggest that rainfall is preferentially partitioned into overland flow rather than percolating into the subsurface, thereby constraining groundwater recharge and enhancing the potential for rapid runoff generation.

From a land use data point of view (Figure 3), the location is a mining area, open land (former mine), and bushes with a loose land cover intensity. In comparison, the downstream and middle parts of the watershed have a high value of AFC, ranging from 0.4 to 0.5. Plantations and bushes dominate the land cover in these areas. Areas with dense vegetation tend to have better infiltration and reduce surface runoff because the canopy and plant roots retain water.

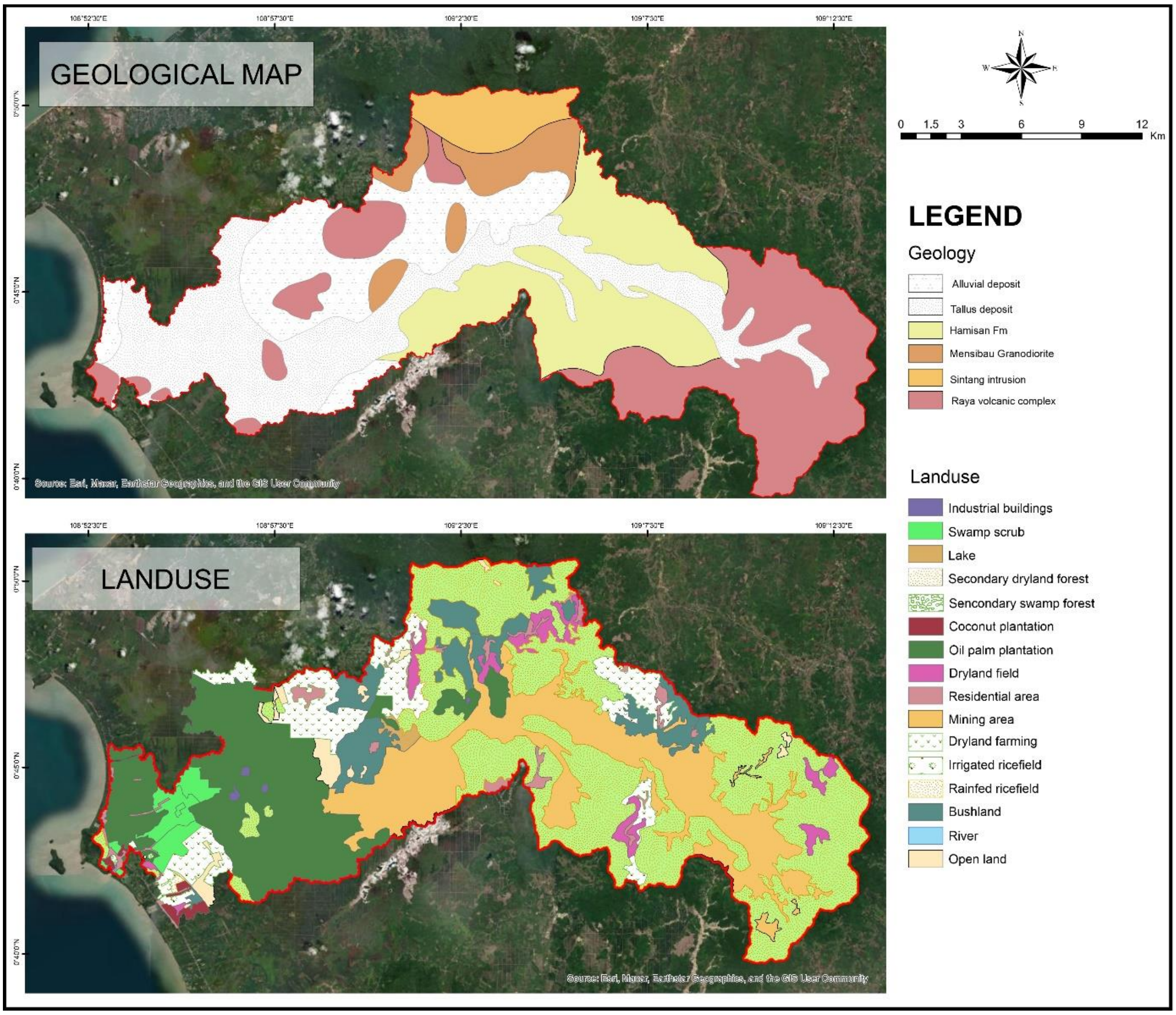

Figure 3. Geological condition and landuse of Raya Watershed

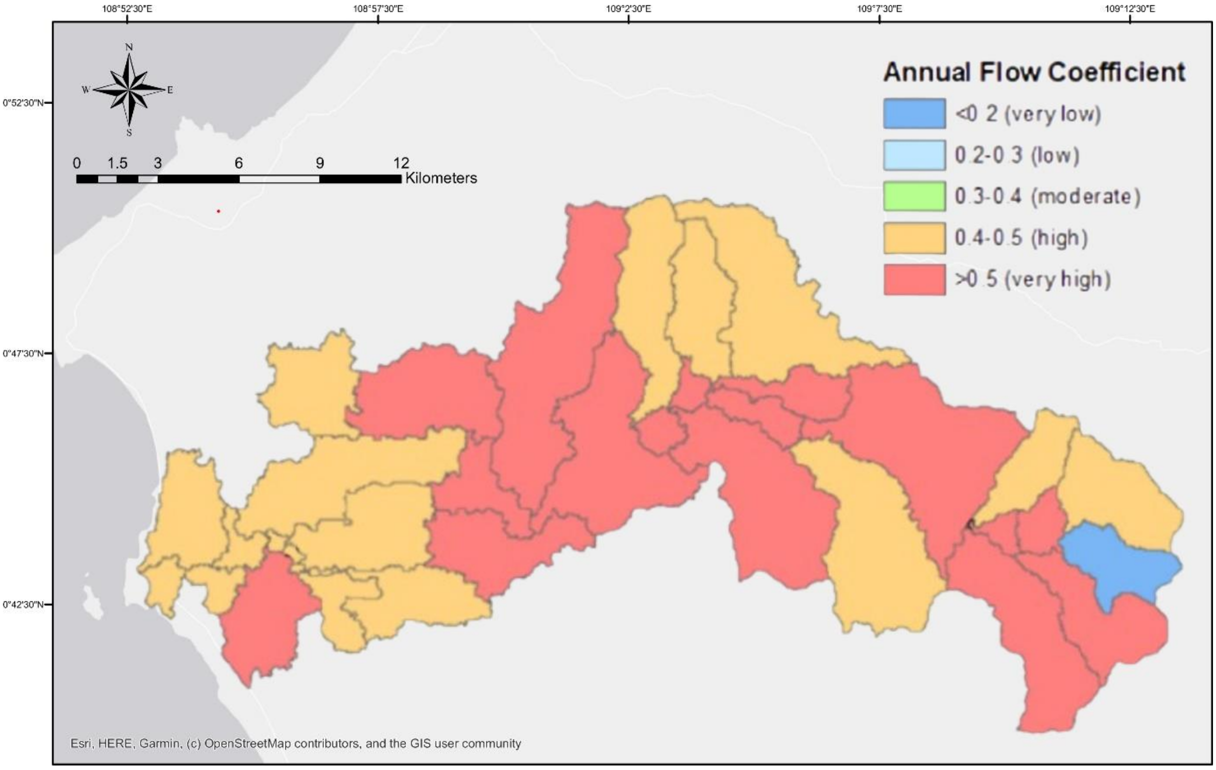

Figure 4. Spatial distribution of Annual Flow Coefficient (AFC) value of Raya Watershed.

Hydrology Response using Geomorphology Approach

Morphologically, the Raya Watershed is divided into three parts: upstream, middle, and downstream. The upstream watershed is characterized as a conservation area with high water flow density, dominated by slopes exceeding 15%. The middle and downstream watersheds are described as areas for utilizing water resources [18]. Shown in Figure 5, the morphology of the Raya Watershed is dominated by denudation hills in the middle to upstream, with a height of between 200 m and 500 m, and in the form of alluvial plains in the downstream. In the north and northeast, the elevation of the hills reaches 900 m, covering the Monterado area, which is the highest point in the Raya Watershed. The hills in the upstream form basins and tributary channels with a dendritic pattern. The middle part of the Raya Watershed is dominated by the foot of denudation hills covered by gardens, fields, and mining areas. This area has a relatively gentle topography compared to the upstream. It is a connecting location between the upstream and the estuary, as well as the area for transporting sediment material from erosion. The downstream part of the Raya Watershed is an alluvial plain with a gentle to flat slope. In this area, morphological changes are visible, resulting in a relatively slow water flow rate and making it a dominant area for sediment deposition. Sediment material enters the main river and flows into the estuary on the west side of the watershed.

The Raya Watershed is dominated by clay loam with medium to low porosity, which allows low infiltration to increase surface flow. The interaction of all geomorphological elements creates a specific hydrology response for each watershed with steep slopes, clay soils, and land use dominated by urban areas [19]. This will result in a rapid hydrological response to rainfall, making the area more

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susceptible to flash floods. Meanwhile, watersheds with flatter topography, permeable soils, and natural vegetation are better able to absorb water and reduce surface flow, so their hydrological response is slower. Permeable geological layers (e.g., sandstone) can absorb and store water in the aquifer. Soil type significantly influences the watershed's ability to absorb water. To enhance infiltration capacity and reduce surface runoff in the Raya Watershed, land management interventions should be tailored to spatial conditions and hydrological characteristics. In the upstream areas, characterized by steep slopes and low-permeability clay-loam soils, reforestation with deep-rooted native vegetation is crucial to improve soil structure and increase water absorption. In the former mining lands located in the middle sub-basins, soil amendment combined with vegetative cover restoration is recommended to reduce erosion and improve water retention [20]. Meanwhile, in the downstream alluvial plains, adaptively designed riparian buffer zones, considering width, vegetation type, and landscape configuration, can effectively filter sediments and nutrients from runoff while reinforcing riverbank stability [21]. Overall, applying interventions according to topographic zonation and watershed morphology can slow runoff, enhance infiltration, and support more sustainable water balance management.

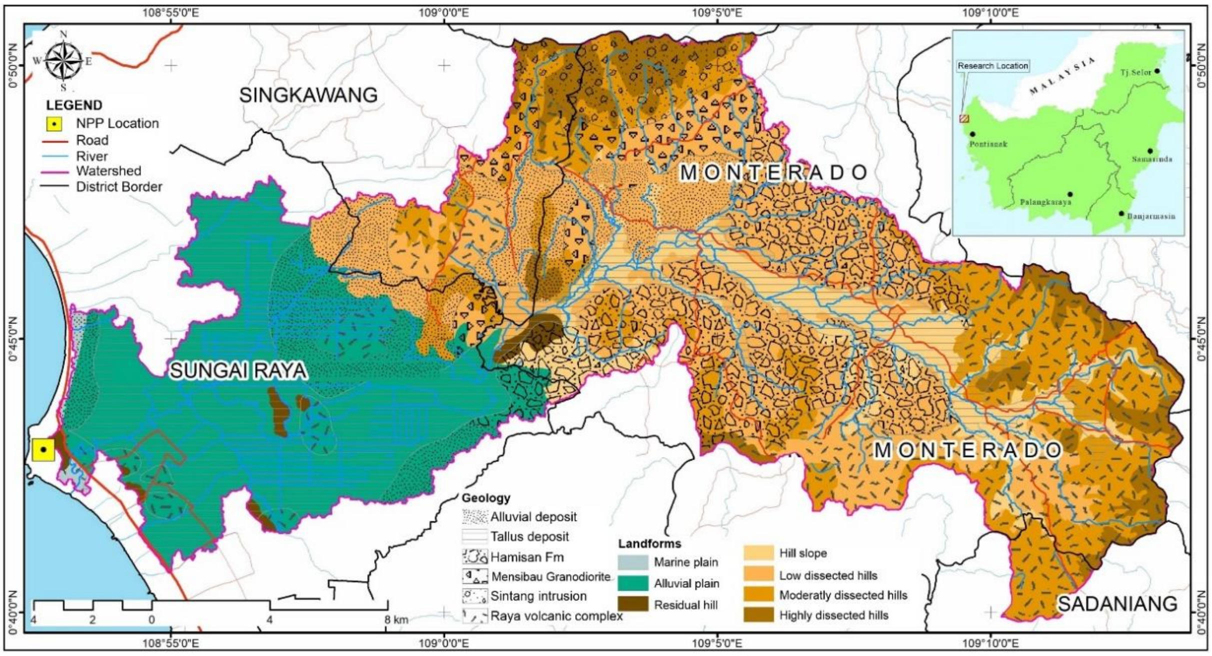

Figure 5. Spatial distribution of landforms in Raya Watershed.

CONCLUSION

In the Raya watershed, it was found that open land use is dominant, with slopes ranging from sloping to steep in the upstream areas. The type of soil generally had porosity that did not support water absorption. These conditions caused more rainfall to be discharged as surface flow than absorbed into the soil. Thus, groundwater storage in the watershed was very low. An average AFC score between 0.36 and 0.45, which falls within the moderate to high runoff range, indicates that the hydrological response of the watershed was relatively poor. To overcome these problems, targeted land management actions are necessary to enhance the watershed's ability to maintain a sustainable water balance. This includes the rehabilitation of old minefields to improve infiltration and reduce surface runoff, as well as reforestation in the upstream steep slope, which also supports sustainable watershed management through regional land use planning efforts.

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