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# Analysis of Rainwater Flow in the Lower Reach of the Dua Jembatan River, Jayapura Regency

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**ABSTRACT**

*Surface runoff plays a significant role in increasing the risk of flooding in river basins, particularly in areas with land-use changes and limited channel capacity. This study aims to analyse the characteristics of surface runoff, evaluate the stability of riverbank slopes, and assess the hydraulic capacity of the Jembatan Dua River in Jayapura Regency. The methods employed include hydrological analysis using the Nakayasu Synthetic Unit Hydrograph, land-use analysis based on spatial data, and hydraulic analysis based on channel geometry measurements and Manning's equation. The results indicate that the peak flood discharge for a 10-year return period is 0.787 m³/s, with a time to peak of approximately 1.2 hours, indicating a rapid hydrological response. Flow velocity in the river channel ranges from 1.21 to 1.86 m/s. Land-use analysis indicates a decline in forest cover and an increase in built-up areas, which contribute to increased runoff. Slope stability analysis indicates that most river banks are in a stable condition, with a Safety Factor (FoS) > 1.5, although several critical points have FoS < 1.5. Hydraulic analysis results show that the river channel capacity is unable to accommodate the 10-year return period flood discharge, thus potentially causing flooding in the downstream section.*

**Keywords:** *Surface Runoff; Channel Capacity; River Discharge; River Basin Hydrology.*

## 1. Introduction

Surface runoff is one of the most important components of the hydrological cycle and plays a significant role in determining a river basin's response to rainfall events. Surface runoff occurs when rainfall intensity exceeds the soil's infiltration capacity, causing excess water to flow over the ground surface towards rivers or drainage channels. This process contributes significantly to flooding, particularly in river basins undergoing rapid land-use changes and physical development. Changes in river basin characteristics such as vegetation cover, soil properties, and impervious surfaces can substantially alter runoff generation and increase peak discharge within river systems [1], [2].

Recent studies indicate that changes in land use and land cover (LULC) significantly influence hydrological processes and flood risk. Urbanisation and the expansion of built-up areas increase impervious surfaces, reducing infiltration capacity and accelerating the formation of surface runoff [3]. Furthermore, watershed characteristics such as topography, soil texture, drainage density, and rainfall variability play a crucial role in controlling surface runoff formation and river discharge dynamics [4]. These factors are particularly critical in small watersheds, where hydrological responses to rainfall tend to be faster and more sensitive to environmental changes.

Previous research has also highlighted that hydrological responses within a river basin are closely linked to channel capacity and riverbank stability. Inadequate channel capacity can lead to river flooding during extreme rainfall events, whilst unstable riverbanks can accelerate erosion and sediment transport, which in turn reduces the channel's conveyance capacity [5]. Therefore, a comprehensive assessment of flood risk that integrates analysis of rainfall, river basin characteristics, hydraulic capacity, and slope stability is crucial for effective flood mitigation and river basin management.

Vol. 7, No. 1, pp. 76-89
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Publish: 07-06-2026 |

The downstream section of the Jembatan Dua River in Sentani Timur Sub-district, Jayapura Regency, frequently experiences flooding during periods of intense rainfall. Although sediment control structures have been constructed in the upstream area, flooding still occurs in the downstream section. This indicates that other hydrological and hydraulic factors, including surface runoff generation, river channel capacity, and riverbank stability, may influence flooding in this river basin.

Therefore, this study aims to analyse the characteristics of surface runoff, evaluate the stability of riverbank slopes, and assess the hydraulic capacity of the Jembatan Dua River channel. The main research issues addressed include: (1) estimating the magnitude of surface runoff generated within the river basin, (2) evaluating the stability of riverbank slopes, and (3) determining the river channel's capacity to convey peak discharge.

The uniqueness of this study lies in its integrated analysis of rainfall characteristics, land-use conditions, the hydraulic capacity of the river channel, and the stability of riverbank slopes within a small river basin system. Unlike many previous studies that focused solely on hydrological modelling or flood discharge estimation, this study combines hydrological and hydraulic analyses to evaluate flood risk and channel performance simultaneously in the downstream section of the Jembatan Dua River. The results of this study are expected to provide quantitative information to support flood mitigation strategies and sustainable river basin management in Jayapura Regency.

## 2. Literature Review

### Surface Runoff and Hydrological Response

Surface runoff is a key component of a river basin's hydrological response, forming when rainfall intensity exceeds the soil's infiltration capacity. The interactions among rainfall characteristics, soil properties, land cover, and river basin morphology influence the magnitude of runoff. Changes in land use, particularly urbanisation and deforestation, have been shown to increase the area of impervious surfaces, thereby accelerating runoff formation and increasing peak discharge [3], [4].

Furthermore, rainfall variability and topographic conditions also play a role in controlling the hydrological response, particularly in small catchments, which tend to have short concentration times [15]. In this context, runoff estimation methods such as the Synthetic Unit Hydrograph (SUH) are widely used to estimate flood discharge in catchments lacking measured flow data. One commonly used approach is the Nakayasu method, which can represent the temporal relationship between rainfall and runoff, including peak discharge characteristics and time-to-peak [16].

However, most previous studies have focused solely on estimating flood discharge, without directly linking it to the channel's physical conditions and concurrent land-use changes. This has led to limitations in understanding the contribution of each factor to increased flood risk within a catchment.

### River Channel Capacity and Hydraulic Characteristics

River channel capacity is determined by the channel cross-section's ability to convey flow without causing overflow. Hydraulic analysis is generally conducted by considering channel geometry parameters, bed slope, hydraulic radius, and roughness coefficient, which are typically calculated using Manning's Equation [18].

In practice, channel capacity often decreases due to sedimentation, narrowing of the channel cross-section, and vegetation growth, thereby reducing the river's ability to convey flood discharge [19]. Therefore, evaluating channel capacity is crucial for identifying potential critical points at risk of overflow.

However, some previous studies have tended to analyse channel capacity separately from hydrological analysis, thereby failing to provide a comprehensive picture of the correspondence between the flood discharge generated by the catchment and the river channel's actual capacity [20].

### Stability of River Bank Slopes

Riverbank stability is a key factor influencing the sustainability of channel geometry and hydraulic capacity. Slope instability can lead to erosion and landslides, which contribute to increased

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Publish: 07-06-2026 |

sedimentation and a reduction in channel capacity. Slope stability is generally analysed using the Safety Factor (FoS), with an FoS value > 1.5 indicating a stable condition [21], [22].

In addition to geotechnical factors, increased discharge and flow velocity can increase shear stress on river banks, thereby accelerating erosion and triggering slope failure [23].

However, many previous studies have continued to separate slope stability analysis from hydrological and hydraulic analysis, leaving the interaction between increased runoff, changes in discharge, and riverbank stability unexamined in an integrated manner.

**Integrated Hydrological and Hydraulic Assessment**

An integrated approach combining hydrological and hydraulic analysis is increasingly being used to assess flood risk in river basins. Hydrological analysis focuses on estimating the relationships among rainfall, runoff, and peak discharge, whilst hydraulic analysis assesses the capacity of watercourses to convey such discharges. The integration of these two approaches allows for a more realistic evaluation of potential flooding and the performance of river systems [11].

Furthermore, several studies emphasise the importance of incorporating geomorphological stability factors, such as riverbank slope stability, into flood risk analysis. This approach is considered more comprehensive, as it integrates interactions among hydrological processes, channel capacity, and river morphological dynamics within a single analytical framework [25].

However, most previous research has continued to apply hydrological, hydraulic, and slope stability analyses in a piecemeal or non-integrated manner. Consequently, the relationship among increased runoff discharge, channel capacity limitations, and the potential for slope failure remains poorly understood. Therefore, an integrated analytical approach is required to link these three components and provide a stronger foundation for flood mitigation planning.

## 2. Materials and Methods

**Study Area and Research Period**

This study was conducted downstream of the Jembatan Dua River, located in Sentani Timur Sub-district, Jayapura Regency, Papua, Indonesia. The study area is a small river basin that frequently experiences flooding and waterlogging during the rainy season. The study was conducted during the 2025 research period, encompassing the field survey, data collection, and data analysis stages.

**Figure 1.** Study Area
Source: Field survey and GIS processing

Vol. 7, No. 1, pp. 76-89
Submit: 03-01-2026 |
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Publish: 07-06-2026 |

The selected location was deemed appropriate as it is directly influenced by land-use changes upstream, river morphology, and existing hydraulic structures.

**Data collection**

The data used in this study consists of primary and secondary data.

**Primary data**

Primary data were obtained directly from field surveys conducted along the lower reaches of the Jembatan Dua River. The primary data collected includes:

a. river cross-sectional geometry,
b. flow depth,
c. flow velocity,
d. river width and wet perimeter, and
e. characteristics of the riverbed and banks.

Flow velocity is measured with a current meter, whilst the river cross-section and water depth are measured manually with surveying equipment.

**Secondary data**

Secondary data primarily consists of hydrological and spatial data, including:

a. daily and annual rainfall data from the three nearest rainfall stations,
b. river catchment boundary data, and
c. land use and land cover maps for different years of observation.

Rainfall data were obtained from the regional meteorological agency and used as the primary input for hydrological analysis.

**Research Design and Approach**

This study employs a descriptive quantitative approach. It focuses on the description, analysis, and interpretation of hydrological and hydraulic conditions in river catchments and watercourses, using field measurements and secondary data.

The main objectives of this study are:

1. To analyse surface runoff in the Jembatan Dua River area.
2. To assess the safety factor of river slopes against flood runoff.
3. To determine the adequacy of the river's capacity to accommodate runoff.

To achieve these objectives, this study applies an integrated analytical framework combining hydrological analysis, land-use assessment, hydraulic modelling, and slope stability evaluation. Such an integrated approach is highly recommended in hydrological studies of river basins because hydrological processes, river channel hydraulics, and geomorphological stability are interrelated components that influence flooding within a river basin [26].

The first stage of the analysis involves a hydrological assessment using rainfall data obtained from the nearest rainfall station. Statistical analysis of rainfall data is performed to determine the design rainfall and the rainfall distribution characteristics. This rainfall data is then used to estimate runoff discharge using the Synthetic Unit Hydrograph approach. The Nakayasu Synthetic Unit Hydrograph method is applied to estimate peak discharge and runoff hydrographs, as it has been widely used in hydrological studies of ungauged river basins and small catchment areas [16].

The second stage involves analysing land-use and land-cover conditions within the catchment using spatial data. Changes in land use are known to significantly influence hydrological response, as the conversion of natural vegetation to urban areas increases impervious surfaces and reduces infiltration capacity. These conditions lead to increased surface runoff and higher flood peaks within the river basin system [28]. Therefore, evaluating land-use patterns is crucial for understanding how river basin characteristics contribute to the formation of surface runoff.

The third stage consists of a hydraulic analysis of the river channel. Hydraulic parameters such as channel width, flow depth, wetted perimeter, hydraulic radius, and channel slope are obtained from field measurements. These parameters are used to estimate flow velocity and channel discharge

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Publish: 07-06-2026 |

capacity using Manning's Equation. Hydraulic analysis enables an assessment of whether the existing channel cross-section can accommodate the calculated flood discharge [29].

The final stage involves an evaluation of the stability of the riverbank slopes. Riverbank stability analysis is conducted based on slope geometry, soil characteristics, and hydraulic loading conditions. Riverbank stability is expressed as the Safety Factor (FoS), which is the ratio of the resisting force to the driving force acting on the slope. According to geotechnical engineering principles, slopes with an FoS greater than 1.5 are generally considered stable, whereas those with a lower FoS are potentially unstable and at higher risk of failure [30].

All analysis results are then integrated to explain the interactions between rainfall variability, land-use changes, river channel capacity, and riverbank stability. This integrated analysis provides a comprehensive understanding of the hydrological and hydraulic processes governing flood occurrence downstream of the Jembatan Dua River. Such integration is crucial in river basin management studies because flood hazards are rarely caused by a single factor alone, but rather by the combined influence of hydrological conditions, river basin characteristics, and river channel performance [11].

## 3. Results and Discussions

### Land Use Characteristics

The Jembatan Dua River Basin (DAS) is a sub-basin in the Sentani area of Jayapura Regency, Papua Province. Geographically, this location:

1. North: Borders the IPDN Papua Campus
2. East: Borders Bukit Bintang
3. South: Borders Lake Sentani
4. West: Borders the Campsite Area

Geographically, this river basin covers an area with varied topography, ranging from the lowlands around Lake Sentani to the hills in the upper reaches, Figure 2.


**Figure 2.** Location of the lower river basin
Source: Processed from satellite imagery and GIS analysis

Topographical variation significantly influences runoff formation within the river basin. Areas with steeper slopes tend to accelerate surface flow velocity and reduce infiltration time, thereby increasing surface runoff entering the river channel. Previous studies have shown that the slope of the river basin and land cover conditions strongly influence runoff response and peak flow formation in small catchments [11].

Land-use conditions within the Jembatan Dua river basin are still dominated by forest cover, as shown in Figure 3. However, minor changes in land cover were observed between 2020 and 2021, particularly an increase in built-up areas and open land.

Vol. 7, No. 1, pp. 76-89
Submit: 03-01-2026 |
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Publish: 07-06-2026 |

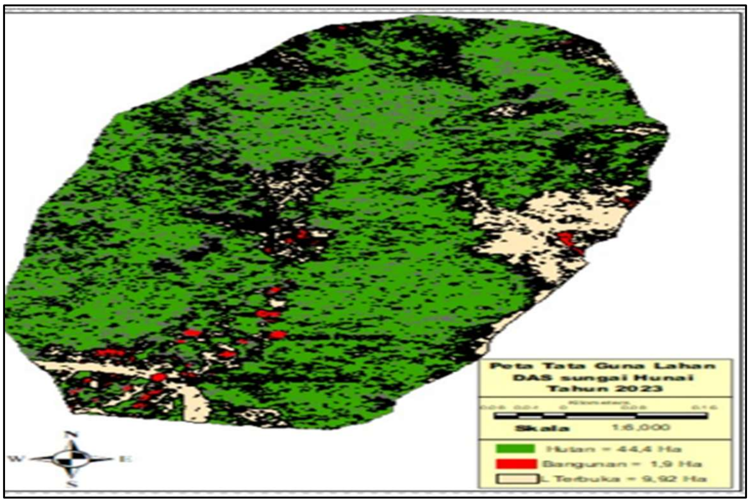


**Figure 3**. Land cover conditions in the Jembatan Dua river basin in 2023
Source: Analysis of land use and land cover maps based on satellite imagery

The land cover area for each condition of the river basin every two years is shown below:

**Table 1.** Land Use Changes in the Jembatan Dua River Basin (2020–2021)

| Land Use Type | 2020 (ha) | 2021 (ha) |
|---|---|---|
| Forest | 45.53 | 44.40 |
| Residential Areas / Settlements | 1.60 | 1.90 |
| Open Land | 9.10 | 9.92 |
| Total Area | 56.23 | 56.22 |

Source: Results of land use analysis based on GIS data.

The results indicate a decrease of 1.13 ha (±2%) in forest area, and an increase in built-up areas and open land. Although these changes are relatively small in terms of area, their impact on hydrological processes cannot be ignored. In small catchments, an increase in impervious surfaces can significantly increase the runoff coefficient and peak discharge, due to reduced soil infiltration capacity [16].

Compared with previous studies, small-scale land-use changes can accelerate concentration time and disproportionately increase runoff response. Consequently, land-use changes in the Jembatan Dua catchment have the potential to increase runoff volume and heighten the risk of flooding in the downstream section.

Furthermore, an increase in open land also implies a greater potential for surface erosion, which can increase sediment load in river channels. This condition can reduce the channel's effective capacity due to sedimentation, thereby exacerbating the risk of flooding.

**Rainfall characteristics**

Corrected rainfall data obtained from three rainfall stations over the period 2014–2024 show considerable inter-annual variability. Some years recorded relatively high maximum rainfall, indicating significant potential for extreme runoff events.

In hydrological analysis, statistical parameters such as the skewness coefficient (Cs) and the kurtosis coefficient (Ck) are commonly used to determine the most appropriate probability distribution for rainfall data. The skewness coefficient (Cs) describes the degree of asymmetry in the rainfall distribution, whilst the kurtosis coefficient (Ck) represents the peak of the distribution curve [28].

Vol. 7, No. 1, pp. 76-89
Submit: 03-01-2026 |
Accepted: 16-04-2026 |
Publish: 07-06-2026 |

**Table 2.** Distribution Methods Meeting Statistical Requirements

| No. | Type of Distribution | Requirements | Calculated Value | Description |
|---|---|---|---|---|
| 1 | Normal | Cs = 0<br>Ck = 3 | Cs = 1.85<br>Ck = 4.17 | Does not meet |
| 2 | Gumbel | Cs = 1.14<br>Ck = 5.4 | Cs = 1.85<br>Ck = 4.17 | Approximate |
| 3 | Log-normal | Cs = 0.149<br>Ck = 3.0383 | Cs = 0.30<br>Ck = -0.84 | Does not meet |
| 4 | Pearson's Log III | In addition to the values above | — | — |

Source: Results of hydrological analysis

The values obtained, namely Cs = 1.85 and Ck = 4.17, indicate that the rainfall data exhibits a positively skewed distribution, which is common in extreme rainfall data. The Normal and Log-Normal distributions do not meet the criteria, whilst the Gumbel distribution shows the closest fit to the data characteristics.

Compared with standard practice in hydrological analysis, the Gumbel distribution is indeed frequently used to model extreme events, such as annual maximum rainfall and flood discharge. This suggests that the selection of the Gumbel distribution in this study is sufficiently representative to describe the conditions of extreme rainfall in the Jembatan Dua catchment [29].

However, because the distribution's suitability is based solely on statistical parameter approaches (Cs and Ck) and does not include additional goodness-of-fit tests, these results still carry a degree of uncertainty that must be taken into account when interpreting the flood discharge results.

The runoff hydrograph was calculated using the Nakayasu Synthetic Unit Hydrograph method (Figure 4), which is commonly used in small catchment areas where observed discharge data is limited [30].

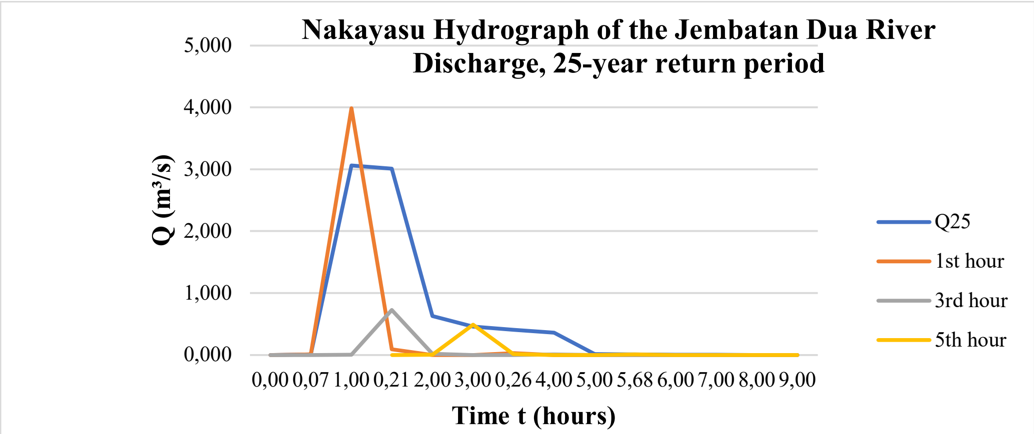


**Figure 4.** Nakayasu Synthetic Unit Hydrograph for a 25-Year Return Period
Source: Results of hydrological analysis

The runoff hydrograph calculated using the Nakayasu Synthetic Unit Hydrograph method is shown in Figure 4. This method is widely used to estimate runoff response in catchments lacking direct discharge observation data [30]. The analysis results indicate that the peak discharge for a 10-year return period is 0.787 m³/s, with a time to peak of approximately 1.2 hours. This relatively short time to peak indicates that the Jembatan Dua catchment has a rapid hydrological response. Compared with the characteristics of small catchments in general, which have time-to-peak ranging from 1 to 3 hours, this value falls into the category of a rapid response (flashy watershed), which is typically influenced by steep slopes and limited storage capacity [27].

JICE Journal Innovation of Civil Engineering
Vol. 7, No. 1, pp. 76-89
Submit: 03-01-2026 |
Accepted: 16-04-2026 |
Publish: 07-06-2026 |

Furthermore, an increase in rainfall duration to approximately 3 hours caused runoff discharge to rise significantly to 2,729 m³/s, about 3.5 times the initial peak discharge. This indicates that rainfall duration is a highly influential factor on runoff magnitude. Compared with studies of other small catchments, the significant increase in discharge associated with longer rainfall duration suggests that the Jembatan Dua catchment has low retention capacity and is dominated by surface runoff [28].

Technically, these hydrological characteristics indicate that the Jembatan Dua catchment has a high potential for flash flooding, particularly under high-intensity rainfall over a relatively short duration. Therefore, the planning of drainage and flood control systems in this area must account for rapid hydrological responses, including the implementation of early warning systems and efforts to increase retention capacity, such as the construction of retention ponds or infiltration wells, to reduce surface runoff.

**Riverbank Slope**

Soil texture along the Jembatan Dua River varies, and slope instability in the river basin is influenced by topographical conditions, soil properties, and land-use changes caused by human activities.

Field measurements indicate that most riverbank slopes are relatively stable. The cross-sectional geometry of the river channel is shown in Figure 5.

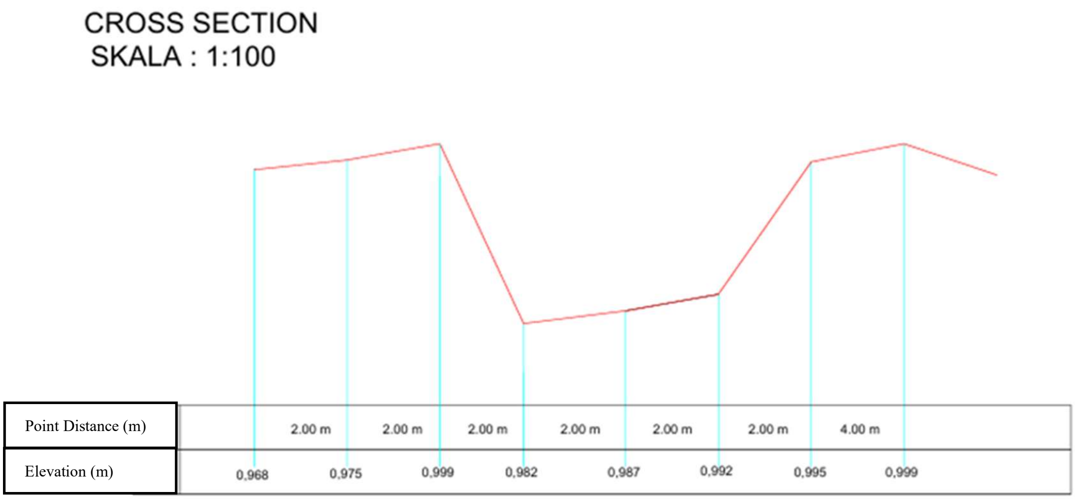


**Figure 5.** Cross-sectional geometry of the Jembatan Dua river measured (Scale 1:100).
Source: Field measurement results (2025)

The cross-sectional geometry of the Jembatan Dua River, as shown in the figure above, illustrates the existing channel conditions at the study site. Based on an analysis of soil characteristics and slope geometry, the stability of the river banks is generally classified as safe, with the majority of safety factor (SF) values exceeding 1.5, indicating adequate resistance to slope failure.

Some local sections show safety factors below 1.5, indicating potentially unstable riverbanks and a higher risk of slope failure. These critical locations are shown in Figure 6.

JICE Journal Innovation of Civil Engineering
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Publish: 07-06-2026 |

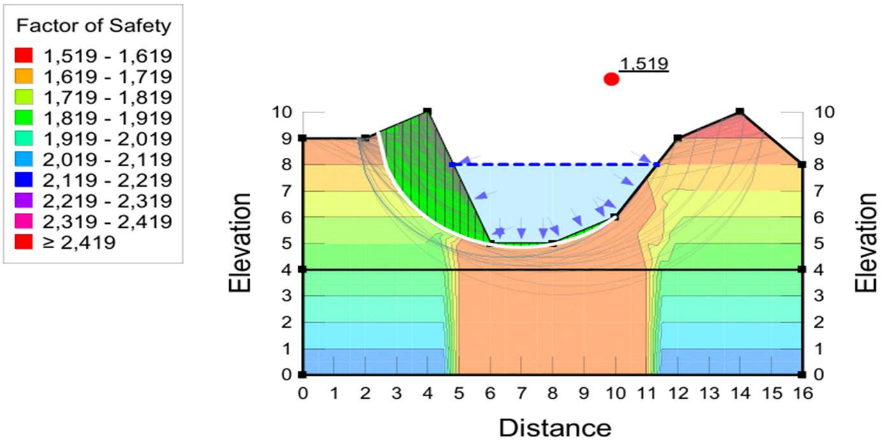


**Figure 6.** Slope Stability Analysis Cross-section (Safety Factor Contour Plot)
Source: Geotechnical analysis results

According to geotechnical standards, slopes with a FoS below 1.5 may fail under increased hydraulic loading, particularly during flood events when river discharge and flow velocity increase significantly [30]. Therefore, these critical locations require appropriate slope stabilisation measures to prevent riverbank erosion and slope collapse.

Hydraulic analysis was carried out using measured channel geometry and hydraulic parameters obtained from field surveys. Table 3 presents the calculated discharge values for various river channel cross-sections.

**Table 3.** Hydraulic Parameters and Discharge Calculations for River Channel Cross-Sections

| No | Cross-Section Shape | B (m) | b (m) | h (m) | m | A (m²) | P (m) | R (m) | S (%) | n | V (m/s) | Q (m³/s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Trapezoidal | 15.5 | 9.0 | 0.700 | 1 | 6.790 | 14.708 | 0.462 | 0.00261 | 0.025 | 1,221 | 8,288 |
| 2 | Trapezium | 13.0 | 8.0 | 0.700 | 1 | 6.090 | 13.294 | 0.458 | 0.00488 | 0.025 | 1,661 | 10,113 |
| 3 | Trapezium | 8.8 | 9.0 | 0.800 | 1 | 7,040 | 13,576 | 0.519 | 0.00228 | 0.025 | 1,233 | 8,679 |
| 4 | Trapezium | 9.73 | 5.72 | 0.810 | 1 | 5.289 | 10.380 | 0.510 | 0.00195 | 0.025 | 1.127 | 5,960 |
| 5 | Trapezium | 9.3 | 5.0 | 0.800 | 1 | 4,640 | 9,334 | 0.497 | 0.00247 | 0.025 | 1,248 | 5.788 |
| 6 | Trapezium | 8.79 | 4.5 | 0.800 | 1 | 4.240 | 8.627 | 0.491 | 0.00310 | 0.025 | 0.439 | 1,860 |
| 7 | Trapezium | 7.5 | 4.2 | 0.800 | 1 | 4.000 | 8.202 | 0.488 | 0.00312 | 0.025 | 1,384 | 5,537 |
| 8 | Trapezium | 7.59 | 4.5 | 0.800 | 1 | 4.240 | 8.627 | 0.491 | 0.00528 | 0.025 | 1,810 | 7,675 |
| 9 | Trapezium | 7.5 | 4.2 | 0.900 | 1 | 4.590 | 8.485 | 0.541 | 0.01144 | 0.025 | 2,840 | 13,037 |
| 10 | Trapezium | 7.59 | 4.5 | 0.800 | 1 | 4.240 | 8.627 | 0.491 | 0.00413 | 0.025 | 1,601 | 6,788 |

Source: Results of hydraulic analysis

These results indicate that the flow velocity within the channel varies between 1.21 m/s and 1.86 m/s, depending on the channel geometry and slope conditions. The calculated discharge values also vary across different cross-sections due to differences in channel width, depth, and hydraulic radius.

In relation to hydraulic conditions, locations with a FoS < 1.5 become more vulnerable to failure when there is an increase in discharge and flow velocity. An increase in flow velocity increases shear stress at the riverbank, accelerating erosion and reducing slope stability. This is consistent with previous studies stating that slopes with low FoS are highly sensitive to changes in hydrological conditions, particularly during flood events [30]. Consequently, these areas can be categorised as critical zones requiring priority attention.

JICE Journal Innovation of Civil Engineering
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## Discussion

### Land Use Characteristics and Hydrological Implications

The analysis of land use in the Jembatan Dua catchment indicates a slight decrease in forest area (±2%) and a corresponding increase in built-up areas and open land between 2020 and 2021. Although the magnitude of change appears relatively small, its hydrological impact is significant, particularly in small catchments where runoff response is highly sensitive to surface conditions.

This finding is consistent with previous studies, which report that even minor land-use conversion, especially from vegetated to impervious surfaces, can substantially increase runoff coefficients and peak discharge due to reduced infiltration capacity [3], [32]. In this context, the observed increase in runoff potential in the Jembatan Dua catchment aligns with the general understanding that land-cover change reduces the watershed's natural buffering capacity.

However, this relationship should not be interpreted as purely deterministic. Several studies highlight that runoff generation is not solely controlled by land-use change but also influenced by other factors such as topography, soil properties, antecedent moisture, and groundwater interactions [36], [37]. Therefore, the findings of this study do not contradict previous research but rather complement it, indicating that land-use change is a contributing factor that interacts with the catchment's inherent physical characteristics.

In addition, the increase in open land increases the potential for erosion, potentially increasing sediment transport into the river channel. This process can reduce channel capacity over time through sedimentation, thereby exacerbating flood risk in the downstream section. This result supports the integrated perspective that hydrological response, geomorphological processes, and hydraulic performance are closely interconnected in small river basins [31].

### Rainfall Characteristics and Runoff Response

The hydrological analysis using the Nakayasu Synthetic Unit Hydrograph indicates that the peak discharge for a 10-year return period is 0.787 $m^3/s$, with a time to peak of approximately 1.2 hours. This relatively short lag time reflects a rapid hydrological response, which is characteristic of small catchments with limited storage capacity.

This result is supported by previous studies, which demonstrate that small and steep catchments tend to exhibit "flashy" behaviour, in which rainfall is rapidly converted into surface runoff, producing sharp hydrograph peaks and short concentration times [33], [34]. Therefore, the runoff response observed in the Jembatan Dua catchment is consistent with the general hydrological behaviour of similar watershed systems.

Furthermore, the analysis shows that an increase in rainfall duration significantly amplifies runoff discharge. This indicates that the catchment has low retention capacity and is highly sensitive to rainfall persistence. Similar findings have been reported in other studies, which highlight that extended rainfall duration can produce disproportionately higher runoff in small catchments due to cumulative saturation effects [33].

However, some studies suggest that rainfall magnitude does not always translate directly into increased flood discharge, as subsurface processes, such as soil moisture storage and groundwater flow, may attenuate the runoff response [36], [37]. In this study, the rapid response and high sensitivity to rainfall duration indicate that such buffering mechanisms are relatively weak in the Jembatan Dua catchment. Therefore, while the findings partially differ from those studies, they do not contradict them but rather reflect site-specific hydrological conditions.

From an engineering perspective, these results imply that flood mitigation strategies in the study area must account for short-duration, high-intensity rainfall events and the cumulative effects of rainfall duration.

### Riverbank Stability and Hydraulic Interaction

The slope stability analysis indicates that most riverbanks are generally stable, with a Safety Factor (FoS) greater than 1.5. However, several local sections exhibit FoS values below 1.5, indicating potential instability and higher susceptibility to failure.

Vol. 7, No. 1, pp. 76-89
Submit: 03-01-2026 |
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This finding is consistent with previous research, which shows that riverbank stability is highly sensitive to hydraulic loading, particularly during flood events when increased discharge and flow velocity generate higher shear stress on the riverbanks [35]. In such conditions, even slopes that are marginally stable under normal flow may become unstable.

The hydraulic analysis further indicates that flow velocity ranges between 1.21 and 1.86 m/s across different cross-sections, depending on channel geometry and slope. Increased flow velocity directly increases shear stress, which can accelerate erosion at the slope toe and reduce overall stability.

This interaction between hydraulic forces and slope stability is widely recognised in previous studies [35], which show that riverbank failure is often triggered not only by geotechnical conditions but also by dynamic hydraulic processes. Therefore, the critical locations identified in this study should be considered high-risk zones, particularly during peak flow conditions.

**Channel Capacity and Flood Risk Assessment**

The hydraulic analysis shows that channel capacity varies across different cross-sections due to variations in geometry, slope, and hydraulic radius. Although some sections can convey flow efficiently, others exhibit limited capacity under expected runoff conditions.

This finding supports previous studies, which emphasise that flood risk is not solely determined by runoff magnitude but by the imbalance between generated discharge and channel conveyance capacity [38]. In many cases, local bottlenecks, sedimentation, or channel irregularities play a critical role in triggering overflow and flooding.

In this study, it is important to note that a relatively small peak discharge does not necessarily indicate low flood risk. Instead, flood occurrence is influenced by local channel constraints, sediment accumulation, and flow concentration at specific points. Therefore, the results of this study suggest that flooding in the downstream area of the Jembatan Dua River is more likely caused by localised hydraulic limitations rather than basin-wide discharge magnitude alone.

This interpretation is consistent with previous findings, which highlight that flood hazards in small river systems are often driven by localised hydraulic and geomorphological conditions rather than regional-scale hydrological extremes [38].

**Integrated Interpretation of Flood Risk**

Overall, the results of this study demonstrate that flood risk in the Jembatan Dua catchment is controlled by the interaction of multiple factors, including land-use change, rainfall characteristics, channel capacity, and riverbank stability.

This finding is consistent with integrated hydrological–hydraulic studies, which show that a single factor rarely causes flood hazards; rather, it is the combined influence of watershed processes and channel dynamics [11], [31], [34].

While some studies emphasise the dominant role of land-use change [32], and others highlight climatic or subsurface controls [36], [37], the results of this study indicate that flood risk in the Jembatan Dua catchment arises from the simultaneous interaction of these factors. Therefore, these differences are not contradictory but reflect the complexity and site-specific nature of hydrological systems.

The main contribution of this study is in demonstrate that runoff generation, channel capacity, and slope stability must be evaluated simultaneously to assess flood risk in small catchments accurately. This integrated approach provides a more realistic basis for flood mitigation planning, particularly in regions experiencing land-use change and rapid hydrological response.

## 4. Conclusion

The Jembatan Dua sub-catchment exhibits a rapid runoff response with a peak time of approximately 1.2 hours and a peak discharge of 0.787 $m^3/s$ for a 10-year return period, reflecting the characteristics of a small catchment with low retention capacity. Land-use changes, specifically a reduction in forest cover and an increase in built-up areas, contribute to increased surface runoff.

Vol. 7, No. 1, pp. 76-89
Submit: 03-01-2026 |
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Stability analysis indicates that most of the riverbanks are stable (FoS > 1.5), but there are critical locations with FoS < 1.5 that are vulnerable to failure, particularly when discharge and flow velocity increase. Hydraulic analysis indicates that channel capacity is uneven and unable to accommodate a 10-year return period flood discharge in some segments, thereby potentially causing flooding in the downstream section.

The main contribution of this study is to demonstrate that flood risk in small catchment areas is determined not only by the magnitude of runoff discharge, but also by the imbalance between channel capacity and riverbank stability. Therefore, flood mitigation must be carried out in an integrated manner through land-use control, increased channel capacity in critical segments, and riverbank slope stabilisation.

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