

Impact of Discharge Fluctuations on River Morphological Changes: A Case Study of the Palu River

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Abstract

The Palu River in Central Sulawesi has experienced significant morphological changes driven by fluctuations in discharge and sediment transport dynamics, particularly in the Kalukubula segment. These changes reduce channel conveyance capacity and increase flood risk. This study aims to analyze sediment transport capacity and changes in riverbed elevation induced by discharge fluctuations, and to evaluate the agreement between numerical simulations and field observations. A quantitative approach was applied using one-dimensional HEC-RAS modeling, integrating river topography data from 2015, sediment characteristics, and discharge records (2002–2007). Simulations were conducted under minimum, average, and maximum discharge scenarios to predict riverbed changes for 2015–2018, and the results were validated using field measurements from 2018. The results show that discharge fluctuations strongly control spatial morphological patterns. The model indicates bed degradation at upstream and midstream sections (–0,08 m at SP.414 and –0,12 m at SP.257) and relatively minor change at the downstream section (–0,003 m at SP.193). In contrast, field measurements reveal more intensive degradation upstream (0,38 m and 0,48 m) and significant aggradation downstream (0,56 m), highlighting the influence of sediment supply and human activities not fully captured by the model. Model validation using RMSE indicates acceptable agreement, particularly under average discharge conditions, confirming that HEC-RAS can reliably represent general morphological trends despite inherent uncertainties in sediment transport modeling. This study contributes a validated modeling framework that supports sediment management planning and flood risk mitigation in the Palu River Basin.



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Introduction

A river is a natural flow system that functions as a medium for conveying water and sediment from upstream to downstream under the influence of gravity, while also shaping and controlling the geomorphological dynamics of the Earth's surface. Rivers are essential components of the Earth's

hydrological cycle and among the most ecologically and economically vital systems on the planet. The world's large rivers and their floodplains are home to approximately 2.7 billion people and support indispensable ecological functions, including freshwater provision, sediment transport to coastlines, floodplain nutrient replenishment, and aquatic habitat maintenance (Best, 2019). Rivers play a strategic role in supporting water resource resilience, flood management, and ecosystem sustainability. However, river systems are inherently dynamic and highly susceptible to disturbances, whether natural or anthropogenic, that can alter their hydrological and morphological equilibrium (Maryono, 2015; Knighton, 2014). Such disturbances increasingly threaten river stability, particularly by influencing discharge fluctuations and the resulting morphological changes in channel geometry and bed configuration.

Over the past decade, increases in flood events in many regions have been attributed not only to high rainfall intensity but also to land-use changes and watershed degradation driven by human activities (Blöschl et al., 2019; Wohl et al., 2015). Globally, anthropogenic pressures such as deforestation, sand mining, urban expansion, and agricultural encroachment have accelerated transformations of river systems (Best, 2019). Land use changes in upstream areas increase surface runoff and soil erosion, thereby increasing sediment supply to river channels (Tarolli & Sofia, 2016; Asdak, 1995). Recent studies further confirm that intensive land use significantly increases sediment concentrations in rivers, particularly in developing regions (Dethier et al., 2022). These processes intensify discharge fluctuations and accelerate morphological changes in downstream river reaches.

The increased sediment load leads to riverbed aggradation, particularly in the midstream and downstream reaches, which alters bed elevation and channel geometry. River morphological changes are governed by interactions among flow characteristics, sediment grain size, and stream power (Bridge, 2003; Kondolf et al., 2014). Long-term sediment accumulation reduces channel capacity and increases flood risk (Lane et al., 2017). The magnitude and spatial pattern of these changes are strongly influenced by discharge variability, which controls the balance between erosion and deposition processes along the river.

The relationship between discharge fluctuations and river morphological changes can be analyzed quantitatively using numerical models of hydraulics and sediment transport. One-dimensional models such as HEC-RAS are widely used because they can simulate water-surface profiles, flow capacity, and bed changes due to scour and deposition with sufficient accuracy (Brunner, 2016; Istiarto, 2014). Integrating field-surveyed topographic data with steady-flow and sediment modules has proven effective in depicting tendencies toward aggradation and degradation over intermediate to long time scales (Han et al., 2024; Fernández et al., 2020).

In Indonesia, studies on river morphological changes driven by sediment transport remain limited, particularly in eastern regions with complex hydrological conditions. The Palu River has experienced significant environmental pressures due to watershed degradation, with deforestation and land-use changes increasing erosion and sediment supply, thereby accelerating changes in the riverbed, especially in the Kalukubula reach (Rusdin et al., 2014).

In addition to sediment supply, hydraulic structures also influence local morphological changes. Previous studies show that flow interacting with bridge piers generates vortices that intensify local scouring, especially under high-discharge conditions (Melville & Coleman, 2000; Sheppard et al., 2014; Link et al., 2020). This mechanism has been observed in the Palu River, where increased flow turbulence enhances riverbed degradation around bridge structures (Warliawati & Rusdin, 2025).

Furthermore, sediment processes along rivers are interconnected from upstream to downstream. Discharge fluctuations control sediment transport and deposition patterns throughout the river system, including downstream and estuarine areas (Syvitski & Kettner, 2011; Warrick, 2014). This is supported by studies at the Palu River mouth, which show that variability in discharge significantly affects sediment distribution and accumulation (Putra et al., 2025).

Therefore, a clear research gap exists in the current understanding of river morphological changes in the Palu River. Previous studies have primarily focused on specific aspects, such as sediment transport relationships, local scour processes, or sediment dynamics at the river mouth, without integrating these processes into a continuous analysis of the river system. In addition, existing studies have not combined multi-scenario discharge analysis, numerical modeling, and field-based validation within a single framework. Furthermore, quantitative evaluation of model performance using observed field data remains limited, particularly for rivers in eastern Indonesia with complex hydrological characteristics.

This study aims to analyze sediment transport capacity and riverbed changes in response to discharge fluctuations using a combination of field measurements and one-dimensional HEC-RAS modeling. The novelty of this study lies in: (1) the integration of multi-temporal field data (2015–2018) with numerical modeling, (2) the evaluation of morphological responses under multiple discharge scenarios (minimum, average, and maximum), and (3) the validation of simulation results using RMSE against observed field measurements. By combining numerical modeling with field observations, this study provides a more comprehensive understanding of river morphological dynamics and contributes to improved sediment management and flood risk mitigation strategies in the Palu River Basin.

Research Method

Research Approach

This study employs a quantitative methodology based on numerical modeling to analyze the relationships between flow discharge fluctuations, sediment transport capacity, and morphological changes in riverbed configuration. The research approach integrates multi-temporal field-measurement data with one-dimensional sediment-transport simulations in HEC-RAS to evaluate spatial and temporal trends in aggradation and degradation along the Palu River.

Study Area and Cross-Section Selection

The study area is located along the Palu River in Central Sulawesi Province, specifically within the Kalukubula segment, which spans approximately 6 km (see Figure 1). The analysis focused on three representative cross-sections: SP.414 (upstream), SP.257 (midstream), and SP.193 (downstream). These cross-sections were selected based on variations in hydraulic conditions and channel geometry, as well as their proximity to sediment accumulation zones, making them suitable for representing the river's morphological dynamics throughout the study segment. Although only three cross-sections were analyzed, they were selected to represent the upstream, midstream, and downstream conditions of the river. These locations capture the key variations in hydraulic behavior and sediment dynamics along the study reach.

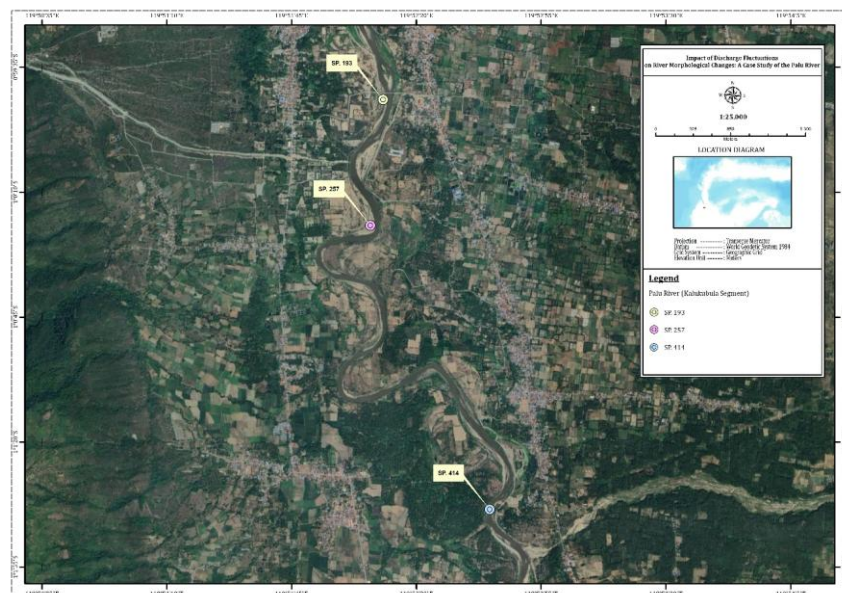


Figure 1. Study Area of the Palu River Kalukubula Segment

Data and Sediment Parameters

The data used in this study consist of: (1) river geometry obtained from a 2015 topographic survey, which served as the initial condition for the numerical model (Balai Wilayah Sungai Sulawesi III, 2015); (2) field measurement data collected in 2018 to evaluate morphological changes in riverbed elevation; (3) sediment characteristic data derived from laboratory sieve analysis, with the median grain size (d_{50}) parameter used to determine hydraulic roughness coefficients and as input for the sediment

transport module; and (4) river discharge fluctuation data from the Palu River Automatic Water Level Recorder (AWLR) records, used to develop minimum, average, and maximum discharge scenarios. This approach enables direct analysis of the relationships among discharge fluctuations, sediment responses, and river morphological changes.

The 2015 Palu River topographic data were obtained from the Study on Sedimentation Mitigation and Mining Regulation in the Palu River, conducted by the Directorate General of Water Resources, Balai Wilayah Sungai Sulawesi III. These data represent the 2015 riverbed configuration and were used as the initial topographic input for the numerical model. See Figure 2 below.

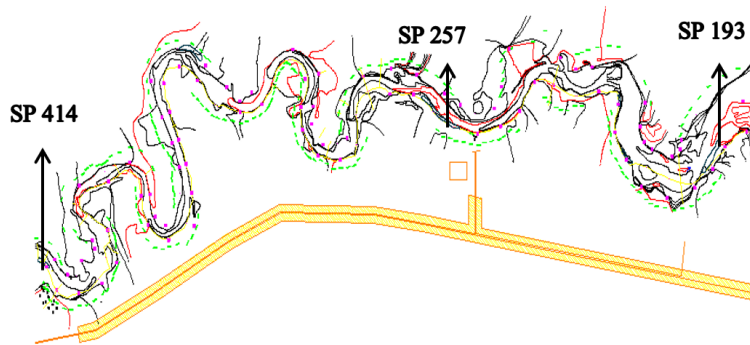


Figure 2. Topography of the Palu River at the Kalukubula Segment

The 2018 Palu River topographic data were obtained from direct field surveys conducted at three locations corresponding to those shown on the 2015 topographic map, namely SP.414 (upstream), SP.257 (midstream), and SP.193 (downstream). See Figures 3, 4, and 5 below.

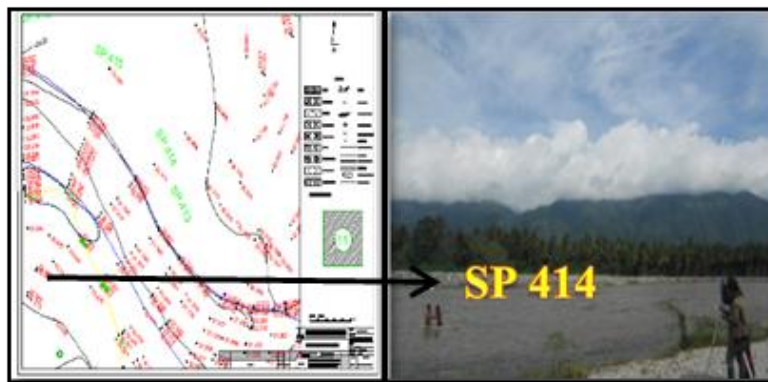


Figure 3. Location of Palu River SP.414

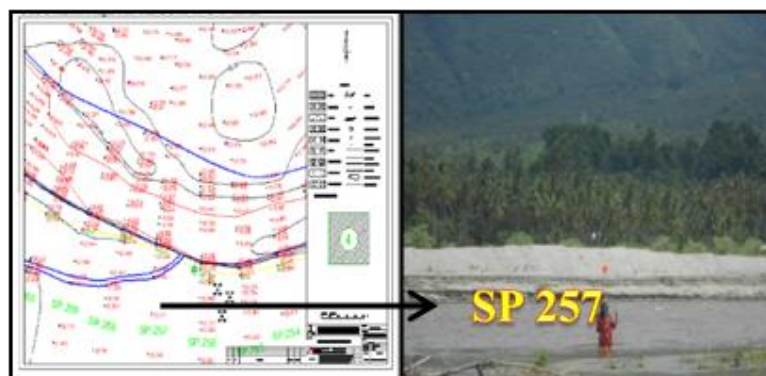


Figure 4. Location of Palu River SP.257

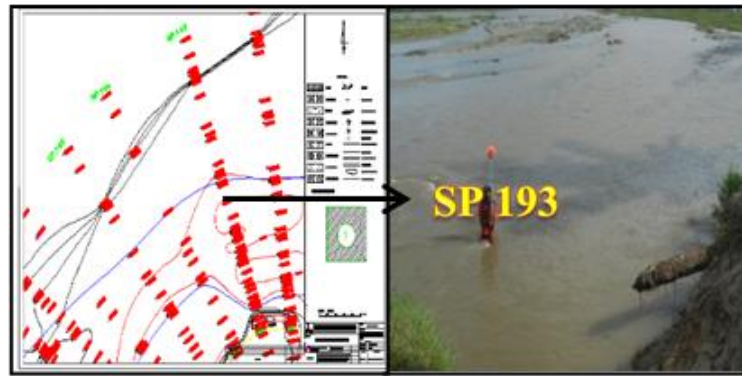


Figure 5. Location of Palu River SP.193

The measurement data consist of x, y, and z coordinates, where x and y represent the horizontal measurement positions and z indicates the riverbed elevation. The cross-section profiles from both the direct field measurements and the 2015 and 2018 topographic data are presented in Figures 6, 7, and 8 below.

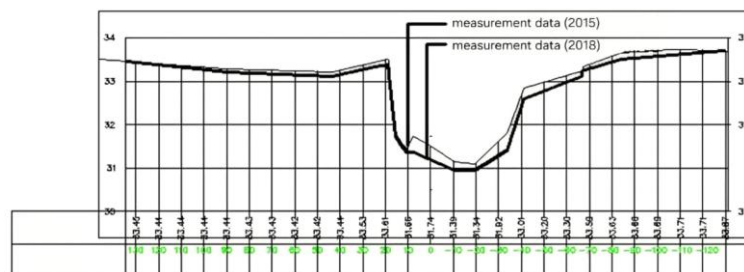


Figure 6. Cross-Section Profiles of 2015 and Field Survey at Palu River SP.414

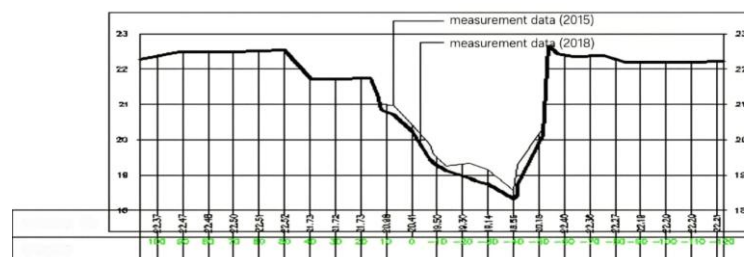


Figure 7. Cross-Section Profiles of 2015 and Field Survey at Palu River SP.257

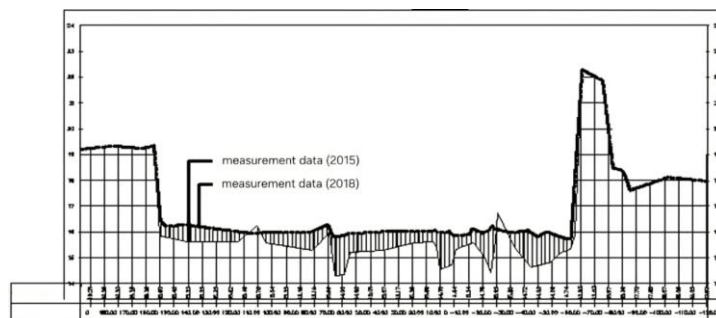


Figure 8. Cross-Section Profiles of 2015 and Field Survey at Palu River SP.193

The bed sediment samples were collected from the study area and analyzed using sieve analysis in the Soil Mechanics Laboratory at the Faculty of Engineering, Tadulako University. The median grain

size parameter (d_{50}) obtained from the analysis was used to calculate the Manning's roughness coefficient using the Stickler equation (Table 1). This Manning's n value was then applied as input to the river geometry model of the Palu River. See Figures 9, 10, and 11 below.

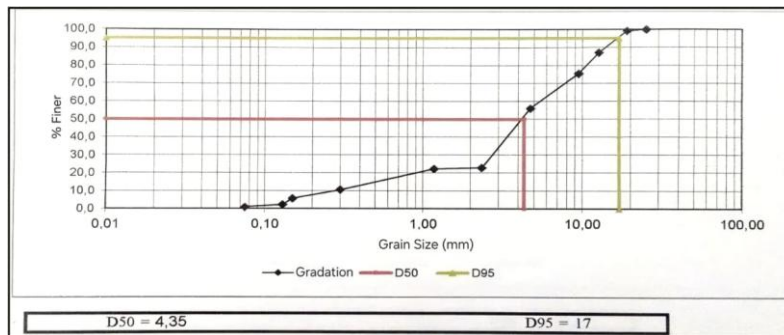


Figure 9. Sediment Gradation Curve at SP.414

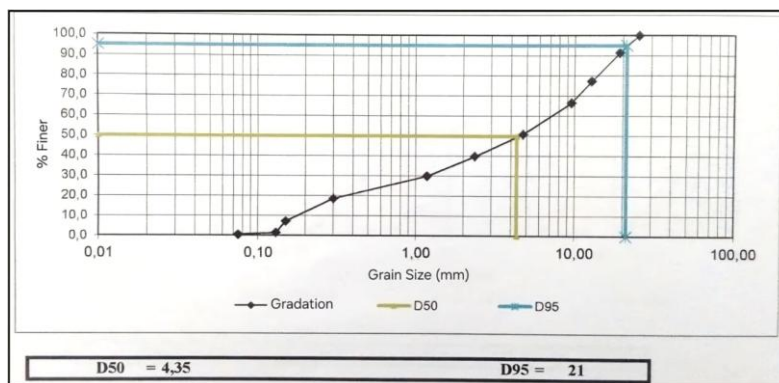


Figure 10. Sediment Gradation Curve at SP.257

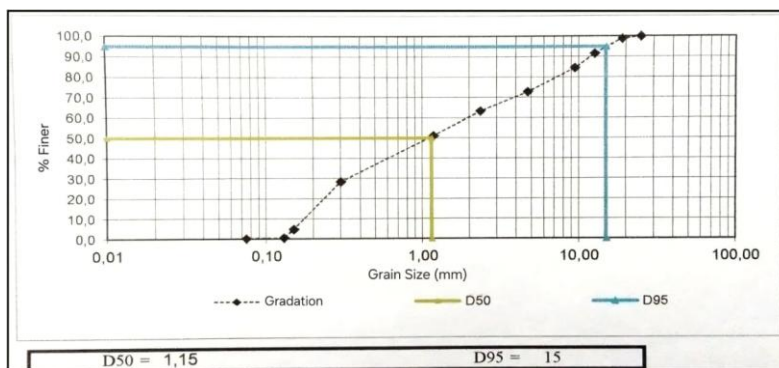


Figure 11. Sediment Gradation Curve at SP.193

Table 1. The Manning's Value

Cross Section	d_{50} (mm)	Manning's $n = \frac{d_{50}^{1/6}}{21.1}$
SP.414	4,35	0,019
SP.257	4,35	0,019
SP.193	1,15	0,016

The discharge data were used as upstream boundary input for the flow simulations and were also varied together with channel bed slope values as downstream boundary inputs in the steady flow simulation. See Table 1 below.

Table 2. Discharge Data for the Palu River

Discharge (m ³ /s)	
Maximum	423,110
Average	83,659
Minimum	9,190

Source: Balai Wilayah Sungai Sulawesi III (2015)

Hydraulics and Sediment Transport Modeling

The modeling was conducted using the one-dimensional HEC-RAS software (Hydrologic Engineering Center, 2023) following these steps: (1) constructing the river geometry by inputting longitudinal and cross-sectional profiles to build a numerical representation of the channel under initial conditions; (2) determining hydraulic parameters, where Manning's roughness coefficients were estimated based on bed sediment grain size using empirical relationships to reflect actual physical conditions of the river; (3) performing steady flow simulations for three discharge fluctuation scenarios to assess the hydraulic response of the river to flow variations. The upstream boundary condition was defined using steady discharge values representing minimum, average, and maximum flow scenarios. The downstream boundary condition was defined using normal depth based on channel slope, which is commonly applied in one-dimensional steady flow modeling; and (4) conducting sediment transport and bed change simulations using the Sediment Transport/Movable Boundary module to simulate riverbed elevation morphological changes resulting from scour and deposition processes. The sediment transport simulation was performed using the Meyer-Peter Müller (MPM) transport function available in HEC-RAS. This method was selected because it is widely applied for non-cohesive sediment and is particularly suitable for coarse bed material conditions, where sediment transport is primarily governed by bed load processes (Brunner, 2016). The Meyer-Peter Müller (MPM) transport function is based on bed shear stress and is widely used for coarse, non-cohesive sediment transport where bed load dominates. In this study, no additional calibration factors were applied due to limited sediment transport measurements; therefore, default parameters in HEC-RAS were used. The model assumes one-dimensional flow conditions, uniform sediment characteristics, and steady flow for each discharge scenario.

River Morphological Change Analysis

Morphological changes were analyzed by comparing simulated riverbed elevations with field measurement data. The analysis focused on identifying zones of aggradation and degradation, quantifying morphological changes in bed elevation, and evaluating morphological responses to variations in flow discharge fluctuations. This approach enables a quantitative assessment of morphological change trends in the Palu River at both cross-sectional and reach scales.

Model Validation

Model validation was conducted by comparing the simulated changes in riverbed elevation with field measurement data using the Root Mean Square Error (RMSE) metric. The Root Mean Square Error (RMSE) value was used to assess the accuracy of the model in representing the actual morphological conditions of the river.

Results and Discussion

Steady Flow Simulation

The steady flow simulation of the Palu River represents the variation of water surface elevations at the selected cross sections (SP.414, SP.257, and SP.193) under minimum, average, and maximum discharge conditions, as shown in Figures 12–14.

The simulation results show that increasing discharge leads to a significant rise in water surface elevation across all cross sections. Under the maximum discharge condition, the water surface approaches the channel banks, particularly in the midstream (SP.257) and downstream (SP.193) reaches, indicating a reduction in channel conveyance capacity and an increased potential for overbank flow. These results indicate that discharge increase enhances flow energy and shear stress, which in turn

raises water levels when channel capacity becomes insufficient. This condition is particularly evident in the downstream reach, where sediment accumulation reduces flow velocity and promotes backwater effects, leading to higher water surface elevation.

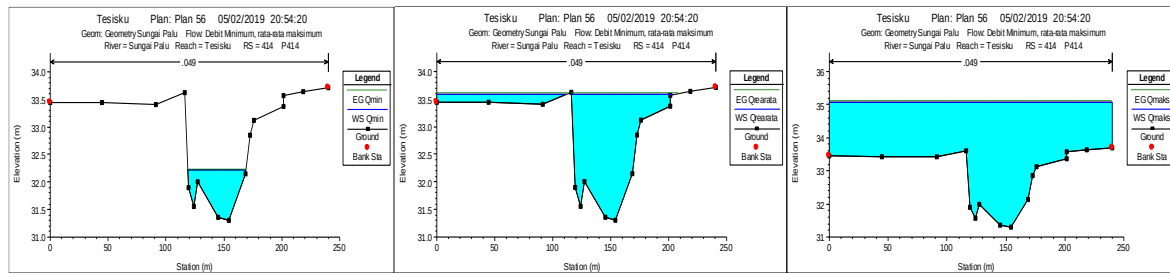


Figure 12. Water surface profiles at sp.414 (upstream) for minimum ($9,19 \text{ m}^3/\text{s}$), average ($83,659 \text{ m}^3/\text{s}$), and maximum ($423,11 \text{ m}^3/\text{s}$) discharge conditions

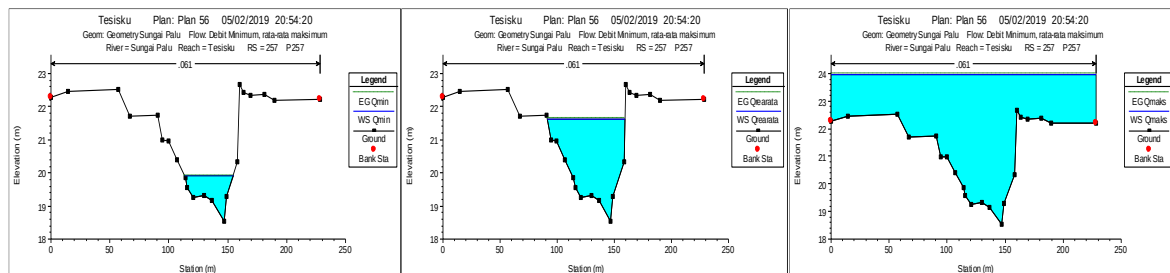


Figure 13. Water surface profiles at sp.257 (midstream) for minimum ($9,19 \text{ m}^3/\text{s}$), average ($83,659 \text{ m}^3/\text{s}$), and maximum ($423,11 \text{ m}^3/\text{s}$) discharge conditions

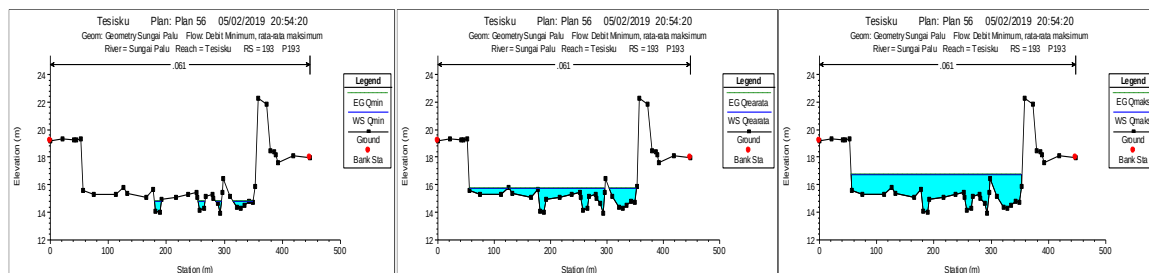


Figure 14. Water Surface Profiles at sp.193 (downstream) for Minimum ($9,19 \text{ m}^3/\text{s}$), Average ($83,659 \text{ m}^3/\text{s}$), and Maximum ($423,11 \text{ m}^3/\text{s}$) discharge conditions

Differences in hydraulic response among the cross sections reflect variations in channel geometry and bed slope. In the upstream reach (SP.414), increasing discharge results in a more pronounced increase in flow energy, whereas in the downstream reach (SP.193), the rise in water surface elevation is more strongly influenced by reduced flow velocity due to sediment accumulation and channel widening.

The differences in water surface profile shapes among the cross sections clearly reflect variations in channel geometry. At SP.414, the relatively narrow and deeper channel produces a more pronounced increase in flow depth as discharge increases, indicating higher flow energy and velocity. In contrast, at SP.257 and especially SP.193, the wider channel geometry results in a more gradual increase in water surface elevation. This condition suggests reduced flow velocity and possible backwater effects, which are commonly associated with sediment deposition in downstream reaches.

Sediment Transport Simulation

Based on sediment transport simulations from 2015 to 2018, morphological changes in riverbed elevation were observed throughout the Palu River, driven by aggradation and degradation in response to fluctuations in flow discharge.

The simulation results indicate that at SP.414, under minimum discharge fluctuation conditions, the riverbed elevation decreased by 0,07 m; under average discharge conditions, it decreased by 0,08 m; and under maximum discharge conditions, it increased by 0,91 m. The simulated results for SP.414 are presented in Figure 15 below.

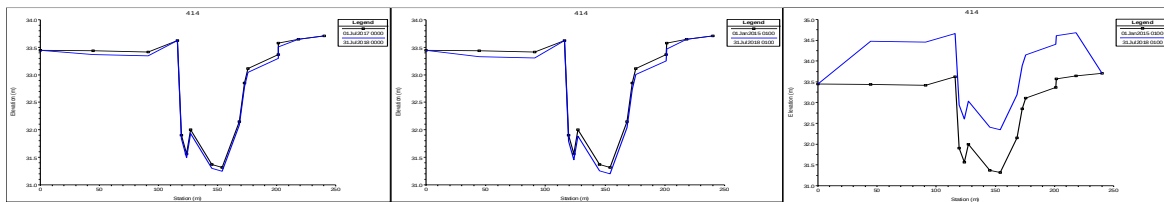


Figure 15. Simulated Bed Elevation Changes at SP.414 Under Minimum, Average, and Maximum Discharge Conditions

Based on the simulation results, at SP.257, the riverbed elevation decreased by 0,12 m under minimum discharge, 0,10 m under average discharge, and 0,16 m under maximum discharge conditions. The simulated results for SP.257 are presented in Figure 16 below.

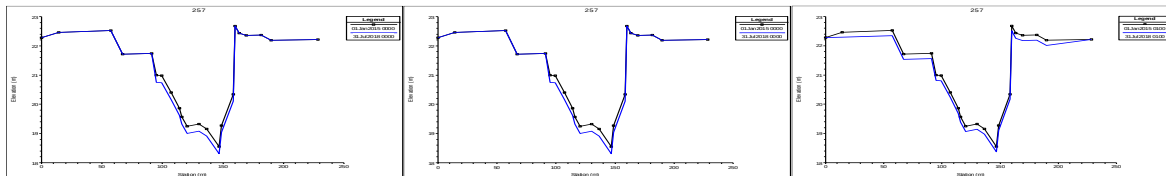


Figure 16. Simulated Bed Elevation Changes at SP.257 Under Minimum, Average, and Maximum Discharge Conditions

Based on the simulation results, at SP.193, the riverbed elevation decreased by 0,21 m under minimum discharge, 0,003 m under average discharge, and increased by 0,49 m under maximum discharge conditions. The simulated results for SP.193 are presented in Figure 17 below.

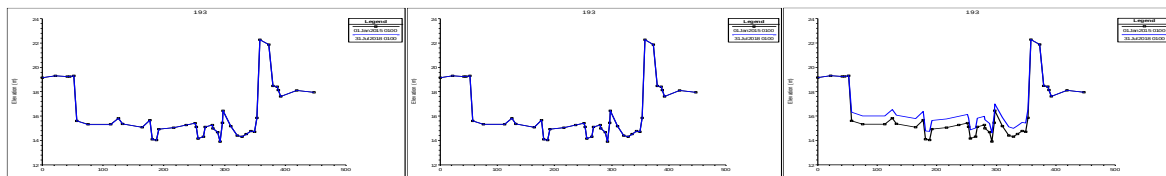


Figure 17. Simulated Bed Elevation Changes at SP.193 Under Minimum, Average, and Maximum Discharge Conditions

To facilitate comparison across all discharge scenarios and cross sections, the simulated riverbed elevation changes are summarized in Table 4.

Table 3. Summary of Simulated Riverbed Elevation Changes

Bed Elevation Changes (m)			
Cross Section	Minimum Discharge	Average Discharge	Maximum Discharge
SP.414	-0,07	-0,08	+0,91
SP.257	-0,12	-0,10	-0,16
SP.193	-0,21	-0,003	+0,49

The simulation results at SP.414 indicate that under minimum and average discharge conditions, the riverbed experiences degradation of 0,07 m and 0,08 m, respectively. However, under maximum discharge conditions, a significant aggradation of +0,91 m is observed. This contrasting behavior suggests that during high discharge events, sediment supply from upstream exceeds the transport

capacity of the flow, resulting in localized deposition. This condition indicates a sediment overloading phenomenon influenced by upstream sediment input and channel geometry constraints.

At SP.257, all discharge scenarios consistently show riverbed degradation, ranging from 0,10 m to 0,16 m. This indicates that the midstream reach has a relatively high sediment transport capacity, allowing incoming sediment to be effectively conveyed downstream. In addition, anthropogenic activities such as sand mining may contribute to the increased degradation observed in this segment.

In contrast, SP.193 exhibits a more complex morphological response. Under minimum and average discharge conditions, only minor degradation occurs, whereas under maximum discharge conditions, significant aggradation of +0,49 m is observed. This pattern suggests that reduced flow velocity due to channel widening and proximity to the downstream boundary promotes sediment deposition, particularly when large sediment loads are transported during high discharge events.

Although three discharge scenarios were simulated, the average discharge condition is considered the most representative of typical river conditions. This is because it reflects the dominant flow regime and provides the closest agreement with field observations, as indicated by lower RMSE values compared to the minimum and maximum discharge scenarios.

Furthermore, the profiles in Figures 15–17 show that morphological changes are not uniformly distributed across the channel cross sections. At SP.414, the most significant changes occur near the center of the channel, indicating concentrated flow energy and sediment transport pathways. At SP.257, the relatively uniform degradation across the section suggests stable sediment transport conditions with minimal deposition. In contrast, SP.193 exhibits irregular bed variations, reflecting complex flow patterns influenced by reduced velocity, channel widening, and downstream boundary effects.

The differences between simulated and observed results are likely influenced by anthropogenic activities such as sand mining, as well as limitations of the one-dimensional model in representing complex flow patterns. Furthermore, these findings are consistent with previous studies (Rusdin et al., 2014; Putra et al., 2025), which highlight the significant role of discharge fluctuations in controlling sediment transport and morphological changes in the Palu River.

Comparison of Riverbed Elevation Based on 2015 Data, Simulation Results, and 2018 Field Measurements

Figure 18 shows that the comparison of riverbed elevations exhibits a similar pattern. The 2018 field measurements indicate a decrease in riverbed elevation relative to the 2015 survey, with changes ranging from 0,00 to 0,38 m. Meanwhile, the simulation results fall between the 2015 baseline and the 2018 observed conditions.

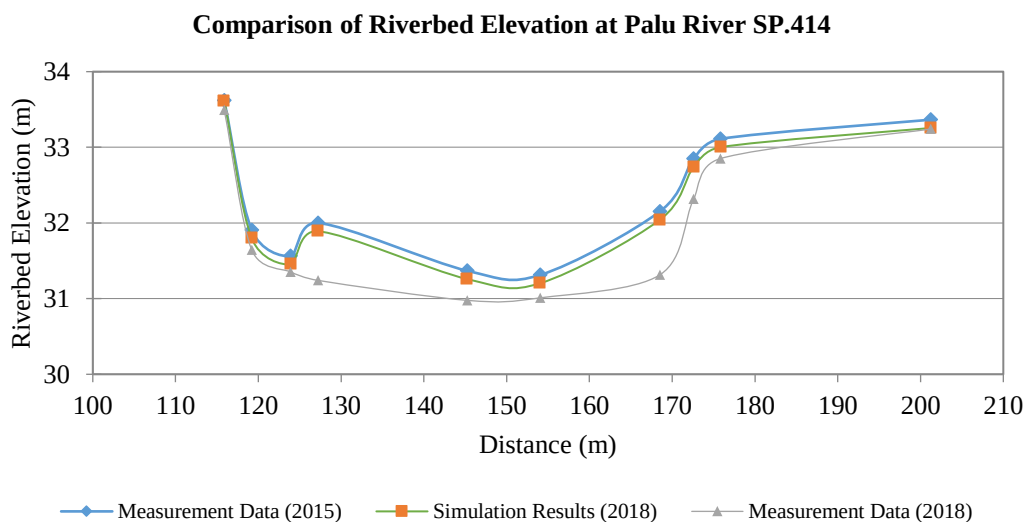


Figure 18. Comparison chart of riverbed elevation at Palu River SP.414

Figure 19 shows that the comparison of riverbed elevation exhibits a similar pattern. Based on field measurements, changes in riverbed elevation are attributed to sand mining activity. The 2018 measurements indicate a decrease in riverbed elevation relative to the 2015 data, ranging from 0,00 to

0,48 m. Meanwhile, the simulation results lie between the 2018 field measurements and the 2015 survey data.

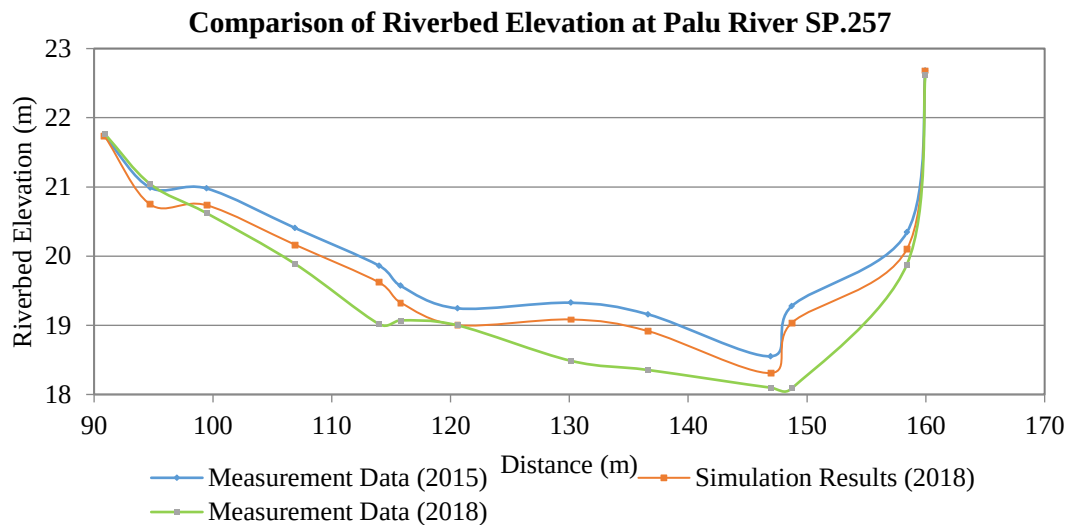


Figure 19. Comparison chart of riverbed elevation at palu river SP.257

Figure 20 shows that the comparison of riverbed elevation exhibits a similar pattern. The 2018 field measurements indicate an increase in riverbed elevation relative to the 2015 survey data, with changes ranging from 0,00 to 0,56 m. Meanwhile, the simulation results lie between the 2018 field measurements and the 2015 survey data.

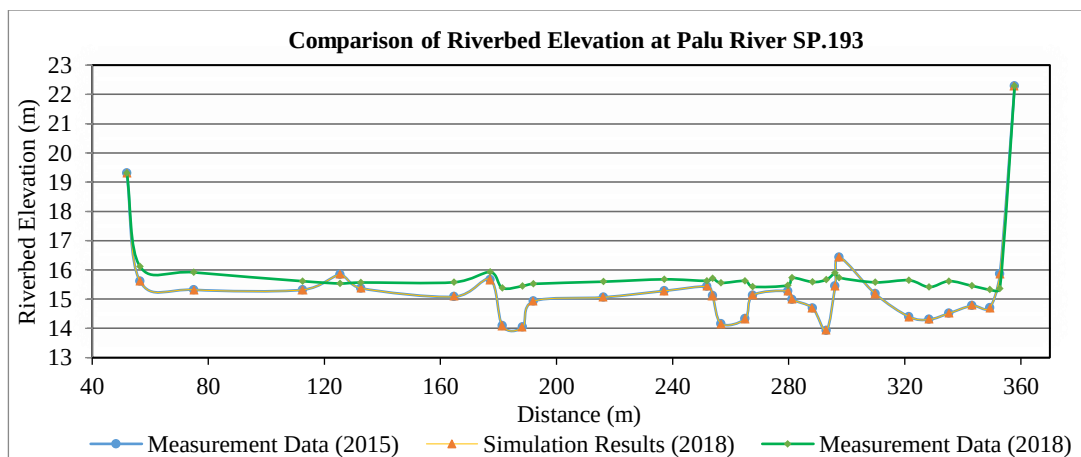


Figure 20. Comparison Chart of Riverbed Elevation at Palu River SP.193

The comparison of riverbed elevations between the 2015 topographic survey, HEC-RAS simulation results, and the 2018 field measurements reveals a consistent spatial pattern of morphological change. At SP.414 and SP.257, the field measurements indicate greater bed degradation than the simulation results, suggesting additional influences such as anthropogenic activities (e.g., sand mining) that are not fully captured in the model. In contrast, at SP.193, the field data show significant aggradation, reflecting sediment deposition processes in the downstream reach. Overall, the simulation results reasonably represent the observed trends, although some discrepancies remain due to complex natural and human-induced factors.

Validation of HEC-RAS Simulation Results and Field Measurements Using the Root Mean Squared Error (RMSE) Method

The Root Mean Square Error (RMSE) analysis was conducted to assess the degree of agreement between HEC-RAS-simulated and field-measured morphological changes in riverbed elevation across all discharge fluctuation scenarios (minimum, average, and maximum). The Root Mean Squared Error (RMSE) value represents the square root of the average of the squared deviations between the simulated

elevations and the observed field elevations, with values closer to zero indicating better model performance. The Root Mean Squared Error (RMSE) calculation results are presented in Table 2 below,

Table 4. Root Mean Squared Error (Rmse) Calculation Results

Locations	Discharges (Q)	RMSE
SP.414	Q min = 9,19 m ³ /s	0,116
	Q rerata = 83,659 m ³ /s	0,115
	Q maks = 423,11 m ³ /s	0,455
SP.257	Q min = 9,19 m ³ /s	0,116
	Q rerata = 83,659 m ³ /s	0,122
	Q maks = 423,11 m ³ /s	0,129
SP.193	Q min = 9,19 m ³ /s	0,255
	Q rerata = 83,659 m ³ /s	0,217
	Q maks = 423,11 m ³ /s	0,298

Source: Calculation Results (2019)

Based on the Root Mean Squared Error (RMSE) calculations, at SP.414, the average discharge scenario yielded the best agreement (RMSE = 0,115). At SP.257, the minimum discharge scenario produced the lowest RMSE = 0,116. For SP.193, the average discharge scenario yielded the best result (RMSE = 0,217). These results confirm that the HEC-RAS model performs most reliably under average discharge fluctuation conditions.

Conclusion

This study demonstrates that discharge fluctuations play a fundamental role in controlling sediment transport capacity and riverbed morphological changes along the Kalukubula segment of the Palu River. The results show that higher discharge increases sediment mobility and promotes both degradation and aggradation depending on local hydraulic conditions and channel geometry. Upstream and midstream sections tend to experience degradation due to higher transport capacity, while downstream sections are more prone to sediment deposition due to reduced flow velocity and backwater effects.

The comparison between simulation and field measurements reveals that, although the HEC-RAS model is capable of capturing general morphological trends, discrepancies still occur due to anthropogenic activities such as sand mining and the limitations of one-dimensional modeling in representing complex flow and sediment interactions. This finding highlights the importance of integrating field observations with numerical modeling to obtain a more realistic representation of river morphological processes.

From a practical perspective, the results indicate that discharge variability and sediment dynamics must be carefully considered in river management. The identification of degradation and deposition zones can support sediment control planning, channel maintenance, and flood risk mitigation, particularly in downstream areas where aggradation reduces channel capacity.

The main contribution of this study lies in the integration of multi-temporal field data with multi-scenario numerical modeling and validation, providing a more comprehensive framework for analyzing river morphological changes in data-limited regions such as eastern Indonesia.

For future research, it is recommended to incorporate two-dimensional modeling approaches, include more cross-sectional data, and consider the effects of human activities explicitly to improve model accuracy and better represent complex river processes.

Conflicts of Interest

The authors declare no conflict of interest.

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