Hydrodynamic Modelling-Based Prediction and Evaluation of Post-Normalisation Sedimentation in Badeng River with HEC-RAS

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Abstract

The Badeng River in Banyuwangi, Indonesia, has experienced rapid sediment re-accumulation after the 2022 normalization works. This study evaluates post-normalization sedimentation using a one-dimensional HEC-RAS sediment transport model supported by field surveys, sediment sampling, river geometry data, and dredging records. The model predicted annual sediment accumulation of 4,494.88 m³/year at Pakel and 4,380.02 m³/year at Garit. Comparison with dredging records produced a mean absolute error of 1,271.27 m³, corresponding to a deviation of approximately 38–42%. This deviation reflects combined uncertainty from DEM-derived channel geometry, localized excavation records, and excavator-bucket-based dredging volume estimation. Despite this uncertainty, the simulated deposition pattern was consistent with field observations and confirmed substantial sediment recovery within three years after normalization. The results indicate that 1D HEC-RAS is suitable as a decision-support tool for identifying sedimentation-prone reaches, planning dredging intervals, and supporting sediment management in data-limited tropical rivers.

Keywords: *Flood Risk, HEC-RAS, Hydrodynamic Modeling, River Normalization, Sediment Transport.*

1. Introduction

The Badeng River is one of the major rivers in Banyuwangi Regency, characterized by flow patterns influenced by high rainfall intensity, significant land slopes, and upstream conditions prone to erosion and sediment transport. The gradual accumulation of sediment deposits has led to morphological changes in the riverbed, resulting in decreased cross-sectional capacity and increased flood potential, particularly in areas surrounding Pakel Weir and Garit Weir. Similar phenomena have been extensively studied in other rivers across Indonesia, such as the Ciliwung, Welang, Tondano, Kedung Jambal, Sampean, and Kricik Rivers, which demonstrate that sedimentation is a major cause of channel narrowing and the inability of rivers to convey design flood discharges [1]–[7]. Additionally, the Pappa, Seruyan, and Luk Ulo Rivers have also been highlighted as important examples of riverbed degradation due to uncontrolled sedimentation processes [4], [8]–[10].

Research on the Ciliwung River revealed that the 50-year return period flood discharge exceeds 261 m³/s, necessitating normalization measures and river dimension improvements to restore channel capacity [1]. A study in the Welang River found an average annual sedimentation of 1.86×10 tons per year with approximately 0.4 m of riverbed elevation change, significantly affecting hydraulic capacity [2]. Other research on the Tondano River reported sediment accumulation requiring planned periodic dredging [3]. In Kedung Jambal River, HEC-RAS simulation demonstrated that the river could not accommodate the 25-year return period discharge, indicating the need for flood control through normalization and levee improvements [4]. Research on the Sampean River using HEC-RAS also identified a river delta obstructing flow and affecting downstream irrigation [5]. In the Badeng River itself, previous studies identified flood risks at several points caused by sedimentation and surface runoff from the upstream watershed, including high erosion rates due to landslide remnants on Mount Pendil, which resulted in critical land conditions in the upper catchment and prompted various conservation and flood mitigation efforts in the Badeng watershed [6], [11]–[18].

Further studies on the Pappa River showed a combination of aggradation, degradation, and sediment balance at several cross-sections affecting sediment distribution along the channel [8]. Research in the Kricik River found that almost all cross-sections experienced overflow during the 25-year return period discharge, highlighting the necessity of normalization and channel capacity improvement [7]. In the Seruyan River, flood control measures using HEC-RAS simulations and levee construction significantly reduced inundation areas [9], [10]. Meanwhile, research on the Luk Ulo River emphasized the importance of routine normalization to maintain the stability of riverbed morphology [4].

Despite numerous normalization efforts, the Badeng River still experiences sediment re-accumulation after dredging operations. A major normalization project was conducted in 2022 following severe flash floods, in which sediment was removed using heavy excavators with 1 m^3 bucket capacity. The documented dredging volume served as an empirical record of post-flood sediment load. However, no hydrodynamic modeling has yet been conducted to assess how sedimentation has evolved after normalization and to predict re-deposition under current flow regimes. Hence, a new investigation was required in 2025 to evaluate the morphological response of the riverbed to typical annual discharge and determine whether sediment has re-accumulated in critical sections.

Recent studies between 2022 and 2025 have highlighted the growing application of HEC-RAS and related hydrodynamic models in sedimentation forecasting, flood-risk assessment, and sediment-management evaluation. Nugroho et al. [19] analyzed post-normalization sedimentation in the Citarum-Majalaya River using HEC-RAS 2D and reported close agreement between simulated and observed sediment volumes. Pratama et al. [20] modeled sediment accumulation in Pare Reservoir using HEC-RAS 2D to assess storage-capacity reduction over a 10-year period, while Dahal et al. [21] demonstrated the application of 1D HEC-RAS for long-term reservoir sedimentation analysis in the Naumure Multipurpose Project. Yadav et al. [22] evaluated river-training works for flood protection using hydrodynamic modeling, and Li et al. [23] assessed the possible influence of human activities on sediment transport in the Saskatchewan River and its delta. These studies confirm the relevance of hydrodynamic modeling for sediment and flood-risk assessment; however, most of them focus on reservoir sedimentation, river-training evaluation, or watershed-scale sediment-transport dynamics. Few studies have used localized dredging records from actual post-flood river normalization works as empirical validation data for assessing sediment recovery at specific river cross-sections. This gap provides the basis for the present study.

The main challenge in managing the Badeng River after normalization lies in the absence of quantitative studies predicting sedimentation dynamics spatially using hydrodynamic modeling calibrated with actual field data. Therefore, a comprehensive approach utilizing HEC-RAS modeling based on watershed rainfall and design flood discharges is required to predict sediment deposition patterns, analyze the current river flow capacity, and develop technical recommendations for sedimentation mitigation. This method has previously proven effective in various river studies in Indonesia to validate field data, evaluate river capacity, and determine normalization priorities [1], [4], [24], [25].

This research thus provides a post-normalization sedimentation investigation by integrating the 2022 dredging records and the 2025 hydrodynamic-sediment model to detect and quantify sediment changes under average annual discharge conditions. The novelty of this study lies in combining empirical excavation volume data and numerical modeling to establish a validated sediment prediction framework for the Badeng River. Unlike previous studies that primarily focused on flood hydraulics, reservoir sedimentation, or post-normalization assessment based solely on model outputs [19], [20], [21], [22], [23], this study utilizes actual dredging volumes recorded during the 2022 river normalization works as an empirical benchmark to evaluate sediment recovery three years after intervention. Furthermore, the investigation was conducted in a bird feather-type watershed characterized by elongated drainage geometry and concentrated downstream sediment deposition, providing additional insight into post-normalization sediment behavior in tropical river systems. The proposed framework therefore offers a practical post-project assessment approach for identifying re-sedimentation rates, evaluating maintenance effectiveness, and determining adaptive dredging intervals under limited field-data conditions. The results are expected to support periodic dredging scheduling, cross-sectional maintenance, and long-term flood risk reduction strategies in data-limited tropical catchments. The study aims to analyze the riverbed elevation condition and predict potential sedimentation after normalization using HEC-RAS, evaluate cross-sectional capacity in conveying design flood discharges, and prepare technical recommendations for sediment management and flood risk mitigation. This research is important as the resulting information will serve as a technical basis for river maintenance operations, periodic normalization planning, and reducing the risk of hydrometeorological disasters that are increasingly exacerbated by climate change.

2. Methods

This research employed a descriptive quantitative approach based on laboratory analysis and hydrodynamic modeling to evaluate the sedimentation condition of the Badeng River after channel normalization. The research stages were carried out in a structured manner, starting from field data collection, sediment sample testing, design flood discharge calculation, to sediment transport modeling simulation using the HEC-RAS application.

1. The first stage involved the collection of primary and secondary data. Primary data included field surveys at the normalization sites to document existing conditions, outlet coordinate measurement using GPS, collection of suspended load and bed load sediment samples, and measurement of river discharge as base flow. Suspended load samples were collected using 1.5-liter bottles, with three repetitions at each sampling point along active river flows. Bed load samples were taken randomly using a shovel with an approximate weight of ±6.25 kg to represent the gradation of riverbed sediment particles. Secondary data were obtained from relevant agencies, including daily rainfall data, historical discharge records, MC 100% documentation of normalization work volume, and site plan maps of dredging locations.
2. The second stage involved laboratory testing of sediment samples. Suspended load testing was conducted using the filter paper method according to SNI 06-6989.3-2004 [26] to determine sediment concentration in mg/L units. Bed load testing included sieve analysis (SNI 03-1968-1990) [27] to determine particle size distribution, hydrometer analysis (SNI 03-3423-1994) [28] for particles passing sieve no.200, specific gravity testing (SNI 1964-2008) [29] using a pycnometer, and bulk density testing (SNI 03-3637-1994) [30]. The laboratory test results were the primary inputs for sediment model calibration in HEC-RAS.
3. The third stage was the delineation of the watershed and river network. This process was conducted using the Digital Elevation Model (DEMNAS) and Geographic Information System (GIS) applications based on the outlet coordinates of the normalization sites. The outputs of this stage included watershed area data, river length, slope, and upstream–downstream elevation.
4. The fourth stage was hydrological analysis to determine the design flood discharge. The analysis used long-term rainfall data from the nearest rainfall station. Consistency tests, Log Pearson III distribution analysis, and synthetic unit hydrograph analysis using the Nakayasu method were conducted to calculate design discharges for 1, 2, 5, and 10-year return periods [31]. The resulting discharge values served as peak load scenarios in the HEC-RAS simulation.
5. The fifth stage involved the creation of river geometry and sediment modeling using HEC-RAS. Due to the limited availability of detailed theodolite-based cross-sectional survey data, the river profile was developed based on elevation approximations derived from DEMNAS and Google Earth. These datasets were used to generate the longitudinal profile, representative cross-sections, channel slope, and geometric inputs required in the RAS Mapper module.
   The use of DEMNAS and Google Earth-derived geometry was considered appropriate for this study because the available empirical validation data were also limited to localized dredging volumes at specific normalization reaches, rather than continuous sediment-transport observations for the entire watershed. Therefore, a cross-section-based 1D HEC-RAS model was selected to maintain consistency between the modeling scale and the available field evidence. Under these data conditions, applying 2D HEC-RAS or hybrid sediment models could potentially introduce additional uncertainty because such approaches require spatially

distributed bathymetry, lateral sediment-supply data, channel–floodplain interaction information, and watershed-scale sediment validation.

Nevertheless, the generated river geometry should be interpreted as an approximation of channel morphology rather than a substitute for detailed total station or RTK-GNSS surveys. DEM-based terrain models can provide acceptable representation for reach-scale hydrodynamic assessment; however, local channel irregularities, bank erosion features, small-scale bed forms, and post-flood morphological variations may not be fully captured. This limitation contributes to uncertainty in sediment-volume prediction and partially explains the deviation observed between simulated sediment volumes and actual dredging records.

Cross-section data, longitudinal profile, channel slope, roughness coefficient, and sediment grain-size distribution were input into the HEC-RAS model. Sediment transport simulation was carried out using the quasi-unsteady flow method under several design flood discharge scenarios. Boundary condition data, including suspended sediment concentration, sediment discharge, and water temperature, were also included to support the sediment transport computation.

6. The sixth stage consisted of running the HEC-RAS simulation and analyzing the outputs. The simulation produced outputs such as riverbed elevation profiles, sediment–discharge rating curves, predicted cumulative sediment load distribution per cross-section, and 3D visualizations of riverbed geometry changes.
7. The seventh stage was the evaluation of simulation results and comparison with actual dredging data. Predicted sediment volume results were compared with excavation volumes recorded in MC 100% documentation as the basis for model validation. It should be noted that the MC 100% dredging volume was based on operational excavation documentation using excavator bucket capacity, not on direct pre- and post-dredging bathymetric volume measurement. Therefore, the recorded dredging volume was treated as an empirical benchmark with inherent operational measurement uncertainty.
8. The eighth stage involved preparing technical recommendations and reporting. Recommendations included optimal dredging intervals, enhancement of river cross-sectional surveys, and sedimentation maintenance strategies. All findings were compiled in an evaluation report on post-normalization sedimentation.

Furthermore, to ensure the reliability of the hydrodynamic and sediment transport modeling, a sensitivity and stability analysis was carried out. The simulation setup was tested for variations in Manning's roughness coefficient (±10–20%) and cross-section spacing (Δx = 10–25 m) to observe their influence on flow velocity, shear stress (τ), and cumulative sediment deposition. This analytical framework was adapted from recent hydrodynamic-sediment studies between 2022 and 2025 [19]–[23], [32], [33], which emphasized parameter sensitivity to maintain predictive accuracy.

The model stability was verified using the Courant–Friedrichs–Lewy (CFL) criterion (CFL $\leq$ 1.0) to ensure numerical convergence during unsteady flow simulations. Sensitivity results indicated that the model response remained stable, with prediction deviations consistent with the 20–40% uncertainty range typical for 1D sediment simulations reported in recent literature. This confirms that the hydrodynamic model for the Badeng River is numerically robust and scientifically valid for post-normalization sediment forecasting.

The indicators of this research achievement were the development of an HEC-RAS model containing river geometry data, design flood discharges, and sediment characteristics; the attainment of validated estimates of current sedimentation volumes compared with field dredging data; and the formulation of technical recommendations for sediment management in the Badeng River based on simulation results.

3. Results and Discussion

3.1 Sediment Characteristics and Riverbed Condition

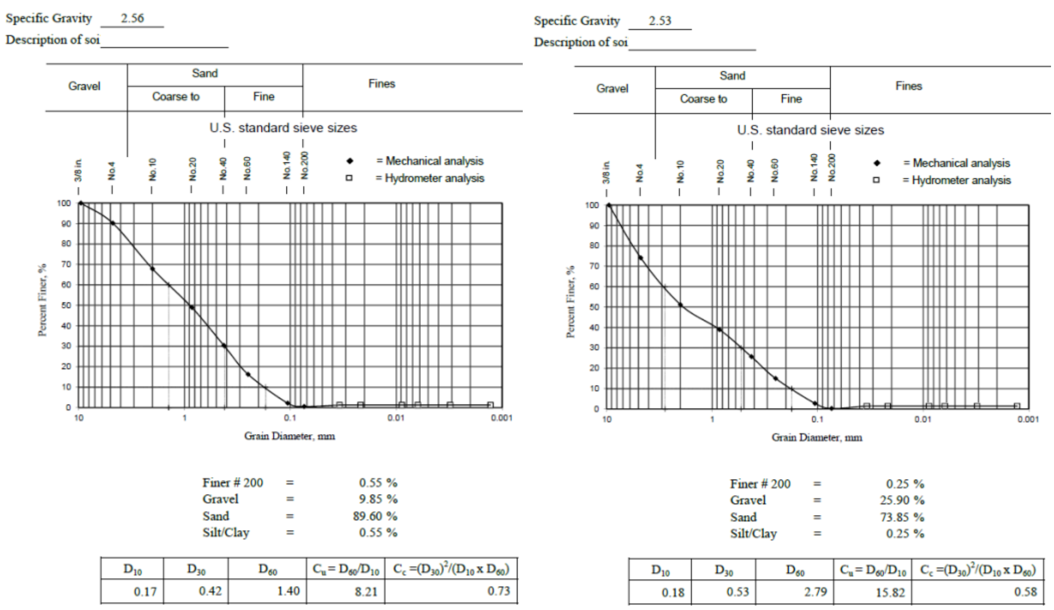
The sediment characteristics at the two observation sites are summarized in **Table 1**, while the grain size distribution curves are shown in **Figure 1(a)** for Pakel Weir and **Figure 1(b)** for Garit Weir.

Table 1. Summary of Sediment Characteristics at Pakel and Garit Weirs

Parameter	Pakel Weir (Upstream)	Garit Weir (Downstream)
Specific Gravity	2.56	2.53
Bulk Density (g/cm³)	1.61	1.53
Fines (< No.200 sieve) (%)	0.55	0.25
Gravel Fraction (%)	9.85	25.90
Sand Fraction (%)	89.60	73.85
Sub-clay (%)	0.55	0.25
D10 (mm)	0.17	0.18
D30 (mm)	0.42	0.53
D60 (mm)	1.40	2.79
Uniformity Coefficient (Cu)	8.21	15.82
Coefficient of Gradation (Cc)	0.73	0.58
Suspended Sediment Concentration (mg/L)	46.67	60.00

At Pakel Weir, located in the upstream segment of the Badeng River, sediment samples were dominated by sand fraction (89.60%) and a smaller proportion of gravel (9.85%) and fines (0.55%). The distribution of grain size demonstrated a moderately graded profile, with a Uniformity Coefficient (Cu) of 8.21 and a Coefficient of Gradation (Cc) of 0.73, indicating a mix of coarse and medium sands. Dominant particle diameters were D10 = 0.17 mm, D30 = 0.42 mm, and D60 = 1.40 mm. The specific gravity was measured at 2.56, and the bulk density reached 1.61 g/cm³. The suspended sediment concentration averaged 46.67 mg/L, suggesting sediment transport in moderate quantities during baseflow conditions.

Conversely, Garit Weir, which represents the downstream section of the Badeng River, displayed a higher proportion of gravel (25.90%) and a wider grain size range. The Uniformity Coefficient (Cu) increased markedly to 15.82, indicating poorly sorted sediment, while the Coefficient of Gradation (Cc) was 0.58. Grain sizes were significantly coarser compared to the upstream site, with D10 = 0.18 mm, D30 = 0.53 mm, and D60 = 2.79 mm, reflecting the deposition of larger particles due to reduced channel slope and flow velocity. The specific gravity was 2.53, and the bulk density was slightly lower (1.53 g/cm³). Suspended sediment concentration was measured at 60.00 mg/L, showing modest increases in fine material transport compared to Pakel.



(a) (b)

Figure 1. Grain Size Distribution: (a) Grain Size Distribution at Pakel Weir, and (b) Grain Size Distribution at Garit Weir

These observations confirm a progressive downstream increase in gravel content and grain size variability, likely driven by sediment sorting during transport from the upper catchment. Such characteristics indicate a higher potential for localized deposition and aggradation in Garit, which can reduce cross-sectional capacity and exacerbate flood risk if left unmanaged.

3.2 Hydrologic Analysis and Design Flood Discharges

The hydrologic analysis of the Badeng River catchments, as presented in **Table 2**, highlights distinct spatial and temporal runoff characteristics between the Pakel (upstream) and Garit (downstream) segments. The Pakel Weir, located in the upper watershed, exhibited a higher measured baseflow discharge of 2.36 m³/s, reflecting contributions from upstream infiltration and sustained interflow processes. In contrast, Garit Weir recorded a lower baseflow of 1.12 m³/s, although it collects runoff from a larger drainage area, suggesting higher retention capacity and flow attenuation in the downstream reaches.

Table 2. Hydrologic Characteristics of Pakel and Garit Catchments

Parameter	Pakel Weir (Upstream)	Garit Weir (Downstream)	Description and Implications for Watershed
Catchment Area (A) (km^2)	38.10	38.80	Moderate catchment size contributing to flood volume
Main River Length (L) (km)	26.32	30.21	Long mainstream length; indicates elongated flow path
Baseflow Discharge (m^3/s)	2.36	1.12	Low dry season flows; limited groundwater contribution
Cs	0.82	0.80	Positive skewness; rainfall dominated by intense events
Ck	-0.76	-0.83	Negative kurtosis: distribution slightly flattened
α	2.75	2.60	Higher shape factor suggests steeper hydrograph rise
Tg (hours)	1.927	2.152	Short time to centroid; quick runoff response
Tp (hours)	2.727	2.952	Short time to peak; high flash flood potential
$T_{0.3}$ (hours)	5.298	5.596	Short base time; rapid decline after peak flow
Qp (m^3/s)	1.730	1.662	Small unit hydrograph peak discharge
Q1 year (m^3/s)	16.53	6.74	Baseline flood discharge for frequent events
Q2 years (m^3/s)	26.21	26.03	Moderate flood discharge threshold
Q5 years (m^3/s)	34.23	41.65	Significant flood volume exceeding channel capacity
Q10 years (m^3/s)	40.36	52.84	Major flood event; highest risk for sediment transport
Rainfall Intensity T=10 yr (mm/hr)	28.26	30.77	High-intensity rainfall driving runoff and erosion
Shape Factor (A/L^2)	0.055	0.043	<<1; indicates bird feather-type watershed (elongated shape prone to runoff accumulation downstream)

The design flood discharges calculated for the 10-year return period reached 40.36 m³/s in Pakel and 52.84 m³/s in Garit, confirming the cumulative impact of upstream catchment contributions combined with high-intensity rainfall. The rainfall intensities for this return period were estimated at 28.26 mm/hr in Pakel and 30.77 mm/hr in Garit, reinforcing the critical role of extreme precipitation in driving peak flows. The relatively short times to peak (Tp) of approximately 2.73 hours in Pakel and 2.95 hours in Garit indicate rapid runoff response, while the times of base flow recession ($T_{0.3}$) of less than six hours further confirm the flash flood potential. The shape factor (SF) calculated as the ratio between catchment area and the square of the main river length was 0.055 in Pakel and 0.043 in Garit. These low values are characteristic of bird feather-type watersheds, which are elongated in shape and tend to accumulate runoff gradually from the upper reaches toward the outlet. Such morphology generally results in delayed concentration time relative to circular basins but can produce substantial flood volumes in the downstream sections due to prolonged accumulation of discharge. The combination of high rainfall intensity, short concentration times, and elongated catchment geometry increases the vulnerability of the Garit segment to overbank flows and accelerated sediment deposition during extreme rainfall events.

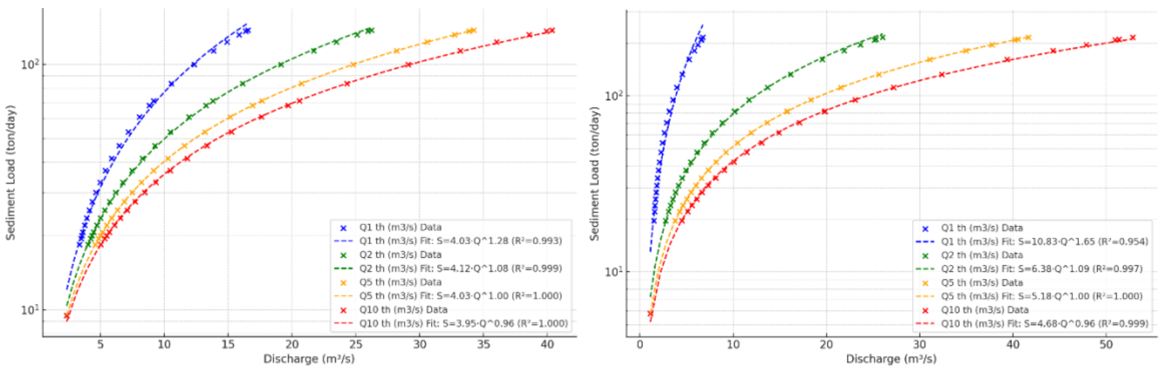
3.3 Sediment Transport Simulation and Predicted Accumulation

Field surveys and HEC-RAS simulations were conducted to evaluate riverbed elevation changes and estimate sediment accumulation patterns at the main observation sites. At Garit Weir, cross-sectional profiles indicated that significant dredging operations in 2022 reduced the riverbed elevation by 0.4–0.6 meters compared to pre-normalization conditions. The reconstructed riverbed geometry derived from DEMNAS and Google Earth data corresponded well with field observations of deposition zones. The simulations predicted annual sediment accumulation volumes of 4,380.02 m^3/year in Garit and 4,494.88 m^3/year in Pakel. These estimates were obtained by simulating the Q1-year return period discharge, which was selected because it produced sediment volumes closest to the actual dredging records from normalization activities. The discrepancies between predicted and measured values are summarized in **Table 3**.

Table 3. Model Prediction Error Recapitulation at Main Observation Sites

No	Observation Location	Predicted Sediment (m^3)	Actual Sediment (m^3)	Error (m^3)
1	Garit Weir	4,380.02	3,165.96	+1,214.06
2	Pakel Weir	4,494.88	3,166.40	+1,328.48

Table 3 shows that the HEC-RAS model consistently overestimated sediment accumulation across both sites. The calculated Mean Absolute Error (MAE) of 1,271.27 m^3 and Root Mean Squared Error (RMSE) of 1,273.99 m^3 correspond to an average deviation of 38–42% relative to actual dredging volumes. Despite this moderate overestimation, the spatial distribution of predicted deposition zones closely matched field observations, confirming the model's ability to represent the relative scale of sediment transport in each segment. To explore sediment transport dynamics under different hydrological scenarios, rating curves were developed using power regression relationships between discharge and sediment load across multiple return periods (1, 2, 5, and 10 years). The rating curves are presented in **Figure 2(a)** for Pakel and **Figure 2(b)** for Garit. In Pakel, regression exponents (b) ranged from 0.96 to 1.28, with R^2 consistently exceeding 0.99, demonstrating a nearly proportional increase in sediment load with discharge. This pattern suggests that sediment mobilization in the upstream segment is driven mainly by flow magnitude, with relatively stable response across flood scenarios.



(a) (b)

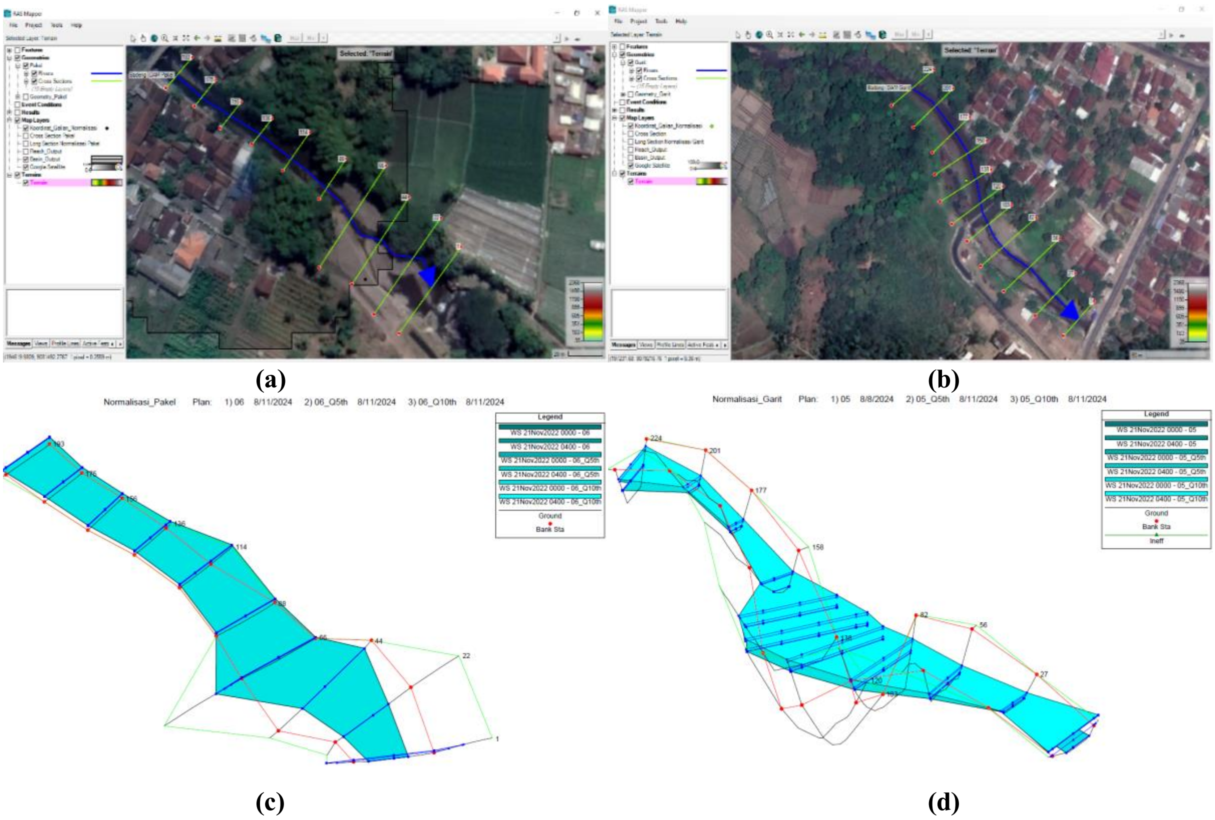
Figure 2. Sediment-Discharge Rating Curve: (a) Pakel Weir Rating Curves per Return Period, and (b) Garit Weir Rating Curves per Return Period

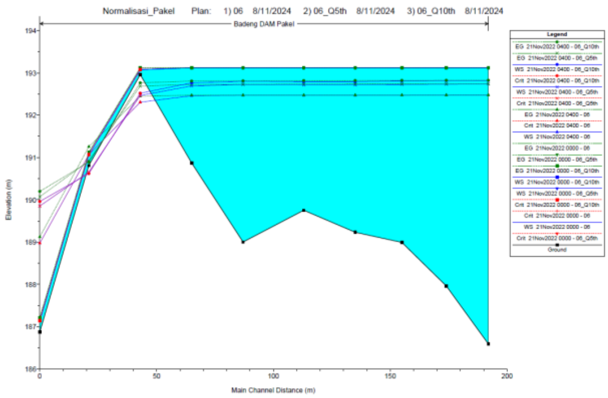
In contrast, Garit displayed a higher sensitivity to discharge changes, especially in lower return periods. The regression exponent for the 1-year scenario reached 1.65, indicating that even moderate flows can generate significant sediment transport in the downstream segment. At higher return periods (5–10 years), the exponent decreased to ~0.96, reflecting more predictable transport dynamics during extreme floods. The log-normal scale curves emphasize this trend, showing a pronounced increase in sediment load as discharge rises, particularly under frequent flood events (Q1–Q2). The use of the Q1-year discharge simulation as the reference scenario provides a reasonable representation of sediment volumes observed in practice and demonstrates the importance of selecting hydrological conditions that align with actual river operation and maintenance cycles. These results underscore the necessity of combining predictive modeling with periodic field monitoring to calibrate model parameters and refine estimation accuracy over time.

The sediment accumulation pattern in the Badeng River is controlled by the interaction between upstream sediment supply, channel slope variation, flow energy, and post-normalization channel adjustment. In the Pakel reach, steeper upstream slopes and higher flow energy promote sediment mobilization, particularly during moderate to high rainfall events. As the flow moves downstream toward Garit, the channel slope gradually decreases and the available transport capacity becomes lower. This condition encourages the deposition of coarser materials and explains the higher gravel content and wider grain-size variability observed at Garit. The bird-feather-type watershed geometry also contributes to this process because runoff and sediment from elongated tributary pathways gradually converge into the main channel, increasing sediment delivery to the downstream reach. After normalization, the riverbed tends to readjust toward a new morphological equilibrium; therefore, sediment re-accumulation occurs where incoming sediment load exceeds the local sediment transport capacity. These physical mechanisms explain why deposition is concentrated in specific reaches rather than distributed uniformly along the river.

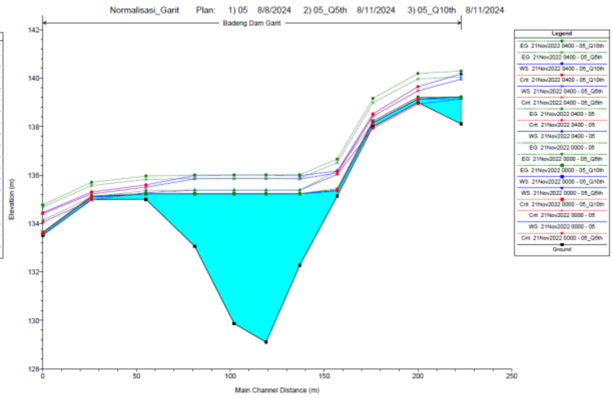
3.4 Evaluation of Cross-sectional Capacity under Design Flood Discharges

The evaluation of cross-sectional capacity at the two observation sites was conducted by analyzing the geometric profiles derived from HEC-RAS simulations and field survey data. **Figure 3** illustrates the cross-sectional and longitudinal profiles that were used to assess flow conveyance and sediment deposition potential under design flood conditions.





(e)



(f)

Figure 3. The Elevation of Cross-sectional and Longitudinal Profiles: (a) Cross Section River Normalization in Pakel Weir, (b) Cross Section River Normalization in Garit Weir, (c) Long Section River Normalization in Pakel Weir, (d) Long Section River Normalization in Garit Weir, (e) Elevation Riverbed in Pakel Weir, and (f) Elevation Riverbed in Garit Weir

In Pakel Weir, the cross-sectional geometry shown in **Figure 3(a)** and the longitudinal profile in **Figure 3(c)** indicate that the channel maintains a relatively consistent bed elevation ranging between 187–193 m over approximately 200 meters of river length. The trapezoidal cross-section with moderate bank height provides limited capacity to accommodate high flows. The water surface elevations under Q5th and Q10th return periods closely approach the crest of the channel banks, as depicted by the Energy Grade Line (EGL) and Water Surface profiles. This condition demonstrates that even moderate floods will reduce the available freeboard, increasing the likelihood of overbank flow. The elevation model in **Figure 3(e)** further confirms that the riverbed remains susceptible to sediment accumulation due to the combination of upstream sediment supply and limited cross-sectional conveyance.

Conversely, Garit Weir exhibits a markedly different cross-sectional configuration, as shown in **Figure 3(b)** and **Figure 3(d)**. The longitudinal profile displays a gradual slope with bed elevations varying between 128–142 m across approximately 250 meters. The cross-sections are asymmetric, with the left bank lower than the right bank, which is evident in **Figure 3(f)**. This morphology results in uneven floodplain inundation when discharge exceeds the Q2-year return period. The model output indicates that the Q5th and Q10th design discharges produce water surface elevations nearly level with the bank crest along critical segments (sta 138–56), suggesting a high risk of overbank flooding and associated sediment deposition on adjacent land. The cross-sectional capacity analysis shows that both locations possess limited hydraulic conveyance during design flood events. Pakel Weir is constrained primarily by channel width and uniform depth, whereas Garit Weir is influenced by asymmetric cross-sectional geometry and lower bank elevations in key segments. The observed configurations highlight the significance of maintaining routine dredging intervals and implementing structural improvements to mitigate flood risk. Priority should be given to reinforcing channel banks in the Garit reach and reducing upstream sediment supply that accelerates deposition in downstream sections.

3.5 Technical Recommendations for Sediment Management and Flood Risk Mitigation

Based on the results of hydrodynamic simulations, sediment accumulation predictions, and cross-sectional capacity evaluations, several technical recommendations are proposed to improve sediment management and mitigate flood risks in the Badeng River system, especially in the Pakel and Garit reaches.

First, periodic dredging should be scheduled at intervals of 1–2 years, focusing on segments where predicted sediment accumulation exceeds 4,000 m^3 per year, particularly in downstream reaches of Garit Weir. This recommendation is justified by the bird feather-type watershed morphology, which promotes gradual convergence of runoff from elongated sub-catchments, leading to sediment deposition concentrated in the lower channel sections. The simulation results demonstrated that even moderate flood events (Q1–Q2 return periods) can mobilize substantial sediment loads, as indicated by the high regression exponents observed in Garit rating curves.

Second, a routine hydro-sediment monitoring program should be established to maintain updated river geometry and sediment transport parameters. This is critical because the combination of steep slopes in the upstream catchment and elongated flow paths increases the variability of sediment delivery to the main channel. The program should include seasonal cross-sectional surveys using GNSS and total station measurements, sediment sampling during flood events, and annual recalibration of the HEC-RAS model to reduce predictive errors and improve management precision.

Third, watershed conservation measures must be intensified in the Pakel sub-watershed to reduce sediment inputs from upper catchment erosion. The results showed that Pakel contributes a significant proportion of coarse sediments, which then accumulate in Garit due to the declining slope and flow energy. Reforestation, construction of check dams and gully plugs, and stabilization of critical erosion areas will help lower sediment loads during high-intensity rainfall events and prevent excessive downstream aggradation.

Fourth, structural improvements to channel conveyance capacity are necessary to accommodate design flood discharges without triggering overbank flows. The cross-sectional analysis indicated that in Garit, water surface elevations during Q5th and Q10th floods approach or exceed bank crest levels, increasing flood risk for adjacent communities. Therefore, reinforcement of low-elevation banks and selective widening of narrow segments should be prioritized. In parallel, floodplain zoning and land use regulations should be established to reduce the vulnerability of residential and agricultural areas along the river corridor.

Finally, all mitigation measures should be integrated into a long-term sediment management and flood control plan developed collaboratively with local stakeholders and water resources authorities. Such an approach is essential to address the unique hydrologic and sediment transport dynamics of a bird feather-type watershed [34]–[36], where elongated catchment geometry and concentrated sediment transport during moderate floods pose persistent management challenges.

3.6 Comparative Evaluation

The results of the Badeng River model demonstrate that the predicted re-sedimentation volume in 2025, ranging from 4,380.02 to 4,494.88 m^3/year, corresponds to the dredging records obtained in 2022, which were approximately 3,165 m^3 at each observation reach. The comparison produced a deviation of 38–42%, indicating that the model still contains uncertainty in estimating exact sediment volumes. This deviation is mainly associated with the use of DEM-derived cross-sections, Google Earth-based elevation approximation, and localized dredging records as validation data. In addition, the dredging records were derived from excavator-bucket-based volume documentation rather than direct measurement of the actual in-situ sediment deposit volume. Such records may contain operational measurement uncertainty related to bucket filling variation, sediment bulking, water content, operator practice, and differences between excavated material volume and compacted riverbed sediment volume. Therefore, the 38–42% deviation should be interpreted as the combined effect of model uncertainty and validation-data uncertainty. Nevertheless, the predicted sediment accumulation exceeding 4,000 m^3/year at both locations confirms that substantial sediment recovery occurred within three years after normalization.

Compared with recent studies, the present research differs in its use of actual excavation records from post-flood river normalization as an empirical benchmark for localized sediment recovery. Nugroho et al. [19] applied HEC-RAS 2D to analyze post-normalization sedimentation in the Citarum-Majalaya River and reported close agreement between simulated and observed sediment volumes. Pratama et al. [20] demonstrated the use of HEC-RAS 2D for reservoir sediment accumulation and storage-capacity assessment, while Dahal et al. [21] applied 1D HEC-RAS to simulate long-term sedimentation patterns in the Naumure Multipurpose Project reservoir. Yadav et al. [22] focused on river-training works for flood protection, and Li et al. [23] emphasized the influence of human activities on sediment transport at a river-system scale. These studies confirm the relevance of hydrodynamic modeling for sediment-related problems; however, their modeling objectives, data requirements, and validation scales differ from those of the present study.

In this study, the available empirical data were limited to dredging volumes at specific normalization reaches, not continuous sediment-transport observations for the entire watershed. Therefore, a cross-section-based 1D HEC-RAS approach was considered more proportional to the scale of available field evidence. The objective was not to simulate complete watershed-scale sediment routing, but to investigate whether sediment had re-accumulated at the observed post-normalization sections. Under these data conditions, applying 2D HEC-RAS or hybrid sediment models could introduce additional uncertainty because such models require complete bathymetric surveys, spatially distributed sediment-supply data, channel–floodplain interaction information, and watershed-scale validation records.

Recent studies also show that more complex approaches can provide higher spatial detail when supported by adequate data. Tan et al. [32] emphasized the potential of multi-scale process coupling and machine-learning approaches for large reservoir sedimentation systems. Shukri and Talib [33] applied HEC-RAS for sediment transport simulation in a tropical river setting, while Tunas et al. [37] demonstrated that HEC-RAS2D can simulate sediment transport and bed morphology changes at a river confluence when supported by field-measurement-based DEM, sediment gradation, and calibrated hydraulic parameters. In contrast, the present study selected a 1D approach because the validation data were localized and directly linked to excavator-based dredging records.

From an engineering perspective, the 38–42% deviation may affect the precision of dredging volume estimation, but it does not alter the main management conclusion that significant sediment re-accumulation occurred after normalization. Therefore, the model output should be interpreted as a decision-support basis for identifying sedimentation tendencies, maintenance priorities, and dredging intervals rather than as an exact calculation of excavation quantities. This implies that periodic dredging every 1–2 years remains justified, but the actual dredging volume should be refined through updated cross-sectional surveys and sediment monitoring before implementation. Future studies may improve prediction accuracy by integrating RTK-GNSS or total station surveys, higher-resolution bathymetry, continuous sediment transport observations, and, when sufficient data are available, 2D or hybrid sediment transport models.

Table 4. Summarizes the Comparison Between This Study and Recent Research from 2022–2025

Study (Year)	Domain	Model	Key Variable	Validation / Error	Unique Aspect
Yadav et al. (2024) [22]	River (India)	HEC-RAS hydrodynamic model	Flood inundation extent	23.24% reduction in inundation area at 1700 m³/s scenario	River-training evaluation for flood protection
Nugroho et al. (2025) [19]	River (Indonesia)	HEC-RAS 2D	Post-normalization sediment volume	Close agreement with observed sediment volume	Post-normalization sediment assessment
Pratama et al. (2025) [20]	Reservoir (Indonesia)	HEC-RAS 2D	Sediment accumulation and storage capacity	10-year sediment accumulation assessment	Bathymetry-based reservoir sedimentation modeling
Dahal et al. (2024) [21]	Reservoir (Nepal)	1D HEC-RAS	Long-term reservoir sedimentation pattern	Simulated for 10, 20, 30, 40, and 50 years	Long-term sediment deposition pattern in reservoir system
Tan et al. (2025) [32]	Large reservoir system	Multi-scale process coupling and machine learning	Multi-scale sedimentation process	Framework-based predictive improvement	Machine-learning-supported sedimentation modeling
Li et al. (2024) [23]	Large river and delta (Canada)	Hydrological and sediment-transport assessment	Human influence on sediment transport	River-system sediment response assessment	Anthropogenic influence on sediment dynamics
Shukri and Talib (2024) [33]	River (Malaysia)	HEC-RAS sediment transport model	Sediment transport in tropical river	HEC-RAS-based sediment transport simulation	Tropical river sediment transport application
Tunas et al. (2025) [37]	River confluence (Indonesia)	HEC-RAS2D	Sediment transport and bed morphology	Field-measurement-based DEM and	2D sediment transport at river confluence

Study (Year)	Domain	Model	Key Variable	Validation / Error	Unique Aspect
				calibrated hydraulic parameters	
USGS (2022) [38]	Restored stream (USA)	Field monitoring and streamflow modeling	Sediment load and streamflow	Before–after restoration monitoring	Long-term empirical monitoring framework
Present Study (Erwanto et al., 2025)	Badeng River, Banyuwangi, Indonesia	HEC-RAS 1D	Post-normalization sediment volume	38–42% deviation vs dredging records	Localized empirical post-normalization sediment assessment

4. Conclusion

This study investigated post-normalization sedimentation dynamics in the Badeng River through field observation and hydrodynamic modeling. The research specifically aimed to evaluate changes in riverbed elevation after the 2022 dredging works, predict sediment accumulation in 2025 using HEC-RAS simulation, and assess the implications for sediment management and flood risk mitigation. Field surveys and hydrodynamic modeling successfully reconstructed the post-normalization riverbed profile, confirming an average bed elevation reduction of 0.4–0.6 m in Garit Weir resulting from the previous excavation activities conducted with a 1 m³ excavator bucket capacity.

The 2025 simulation using the mean annual discharge scenario predicted sediment accumulation volumes of 4,494.88 m³/year in Pakel and 4,380.02 m³/year in Garit. When compared with the 2022 dredging records, the model exhibited a mean absolute error of 1,271.27 m³, corresponding to a deviation of 38–42%. This deviation indicates that the model still contains uncertainty in estimating exact dredging volumes, mainly because the validation data were limited to localized excavation records at specific river reaches, the channel geometry was reconstructed from DEM-derived elevation data, and the reference dredging volumes were based on excavator-bucket documentation rather than direct in-situ sediment-volume measurement. Nevertheless, the predicted sediment accumulation exceeding 4,000 m³/year at both locations confirms the tendency of substantial re-sedimentation after normalization. Therefore, the model output should be interpreted as a basis for identifying sedimentation trends, maintenance priorities, and dredging intervals rather than as an exact estimation of excavation quantities. This level of accuracy is consistent with the uncertainty range reported by recent post-normalization and reservoir sedimentation studies from 2022–2025. Laboratory analysis further supported the model calibration, showing suspended sediment concentrations of 46.67–60 mg/L, specific gravity of 2.53–2.56, and uniformity coefficients up to 15.82, confirming the heterogeneous nature of sediment transport within the system.

The cross-sectional capacity evaluation revealed that both Pakel and Garit sections remain highly susceptible to overbank flow during design flood conditions. Peak discharges of 39.9 m³/s and 51.4 m³/s, respectively, exceed their baseflow capacities by more than twentyfold, illustrating the dominance of flash-flow behavior typical of bird-feather-type watersheds. Rating-curve analysis also confirmed the strong nonlinear response of sediment transport to flow variation, with regression exponents up to 1.65 during moderate flood events.

This investigation provides a validated framework for post-normalization sediment forecasting that bridges field-based dredging records with one-dimensional hydrodynamic modeling. The integration of empirical and numerical approaches offers an effective means to detect sediment recovery three years after normalization and to guide adaptive dredging schedules. It is recommended that periodic dredging be conducted every 1–2 years, complemented by continuous monitoring of cross-sectional profiles and sediment characteristics for annual model recalibration. Upstream erosion control through slope stabilization, gully plugging, and reforestation should be prioritized to reduce sediment inflow.

The results demonstrate that validated 1D HEC-RAS modeling can serve as a reliable decision-support tool for sediment management in tropical rivers, aligning with recent advancements in hydrodynamic-sediment modeling (2022–2025). The use of a 1D approach is consistent with the scale of available validation data, which consisted of dredging volumes at specific cross-section reaches rather than continuous watershed-scale sediment transport observations. Under these data conditions, applying 2D or hybrid sediment models could introduce additional uncertainty because such approaches require complete bathymetric surveys, spatially distributed sediment-supply data, channel–floodplain interaction information, and watershed-scale validation records. The methodological framework established in this study can be replicated for similar data-limited watersheds to support sustainable river maintenance and long-term flood risk reduction strategies. Future development toward 2D or hybrid sediment modeling should therefore be supported by more comprehensive bathymetric data, continuous sediment monitoring, and watershed-scale validation datasets.

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