Reservoir Sedimentation Prediction in the Sangatta River: A Comparative Study of the Schoklitsch Method and HEC-RAS Numerical Modeling

Muhammad Muhir
Doctoral Program in Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
muhammadmuhir@student.ub.ac.id

Lily Montarcih Limantara
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
lilymont@ub.ac.id (corresponding author)

Moh. Sholichin
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
mochsholichin@ub.ac.id

Sumiadi
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
sumiadi@ub.ac.id

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ABSTRACT

The Sangatta River in East Kalimantan plays an important role in water supply, transportation, and socio-economic activities of the nearby region. Intensive land-use changes and human interventions within the watershed have significantly increased sedimentation rates, leading to reduced river capacity and increased flood risk. This study aims to compare the estimation of sediment transport using the empirical Schoklitsch method and numerical modeling with HEC-RAS to evaluate their applicability and limitations in a tropical river system. Hydrological analysis was conducted using the Snyder Synthetic Unit Hydrograph (SUH) to obtain a 1-year return period flood discharge of 257.88 m^3/s, which was applied as the dominant discharge for both approaches. The Schoklitsch analysis indicates substantial spatial variation in sediment transport, with sediment discharge ranging from 76.56 to 359,518.71 tons/day. Meanwhile, the HEC-RAS simulation produces sediment discharge values between 6,908.29 and 37,532.07 tons/day. The comparison shows that several river segments exhibit consistent estimates, with differences of less than 1%, while other segments show significant discrepancies exceeding 350%. These discrepancies highlight the limitations of empirical formulations in capturing local morphological controls and demonstrate the capability of numerical modeling to represent spatial variability in sediment transport. The findings indicate that the Schoklitsch method is suitable for rapid preliminary estimation, whereas HEC-RAS provides more reliable spatially distributed predictions to support sediment management and flood mitigation planning in the Sangatta River.

Keywords-sedimentation; Schoklitsch; HEC-RAS; Snyder SUH; Sangatta River

I. INTRODUCTION

Sedimentation is a natural process that involves the transport and deposition of rock fragments and mineral particles by flowing water, wind, or gravity. In fluvial systems, continuous sediment deposition can lead to siltation, which gradually reduces channel capacity and alters river morphology [1-2]. Sedimentation processes occur commonly in dynamic aquatic environments, such as rivers and estuaries, where interactions between flow conditions and sediment characteristics control erosion, transport, and deposition mechanisms [3-4]. In recent decades, human activities have increasingly intensified sedimentation processes in river systems. Land-use changes, deforestation, mining activities, and infrastructure development within watersheds significantly increase erosion rates and sediment delivery to river channels [5-6]. Excessive sedimentation can reduce river conveyance capacity, increase flood frequency, and disturb aquatic ecosystems, thereby posing serious challenges for sustainable river management [7]. Dredging is widely applied as a mitigation measure to remove accumulated sediments and maintain river capacity. However, the volume of dredged material is often estimated using limited secondary data due to the scarcity of continuous sediment monitoring records [8]. This limitation introduces considerable uncertainty in sediment management planning, highlighting the importance of reliable sediment transport estimation methods.

Sediment transport estimation methods generally range from empirical formulations to numerical modeling approaches. Empirical methods, such as the Schoklitsch formula, have long been applied to estimate bed-load transport based on flow discharge, channel slope, and sediment grain size [9-10]. These methods are computationally efficient and suitable for preliminary assessments; however, their simplified assumptions often limit their ability to represent spatial variability and complex river morphology. In contrast, numerical models such as HEC-RAS allow detailed simulation of hydrodynamics, sediment transport, and channel bed evolution by incorporating spatial variations in river geometry and sediment characteristics [11-12]. Despite the widespread application of both empirical and numerical approaches, comparative studies that systematically evaluate their performance in tropical river systems remain limited. In particular, the extent to which simplified empirical estimates differ from physically based numerical simulations across different river segments has not been sufficiently quantified. This knowledge gap is critical, as inappropriate method selection may lead to inaccurate sediment management decisions.

The Sangatta River, located in East Kalimantan, Indonesia, is one of the major rivers supporting water supply, transportation, and socio-economic activities in the region. However, rapid land-use changes and increasing human interventions within the Sangatta Watershed have accelerated sedimentation processes, reduced river capacity, and increased flood risk [7]. Therefore, a quantitative evaluation of sediment transport using different methodological approaches is required to support effective river management.

This study aimed to: (i) estimate sediment transport along the Sangatta River using the empirical Schoklitsch method, (ii) simulate sediment transport using the HEC-RAS numerical model, and (iii) compare the results of both approaches to evaluate their applicability, limitations, and level of agreement in the context of a tropical river system. The comparison is expected to provide practical insights for selecting appropriate sediment transport estimation methods to support sediment management and flood mitigation planning.

II. MATERIALS AND METHODS

A. General Illustration of Research Location

The Sangatta River is located in East Kalimantan Province, Indonesia, and constitutes one of the main river systems within the Sangatta Watershed, as shown in Figure 1. The river originates from the upstream mountainous area and flows eastward before discharging into the Makassar Strait. The Sangatta River plays a vital role in supporting domestic water supply, transportation, and socio-economic activities for communities living along its banks. The Sangatta Watershed is characterized by a humid tropical climate with relatively high annual rainfall, which strongly influences river discharge and sediment transport processes. Seasonal rainfall variability causes significant fluctuations in river flow, particularly during the rainy season, when high discharges accelerate erosion and sediment delivery from upstream areas to the river channel. These hydrological conditions make the Sangatta River highly susceptible to sedimentation and flooding.

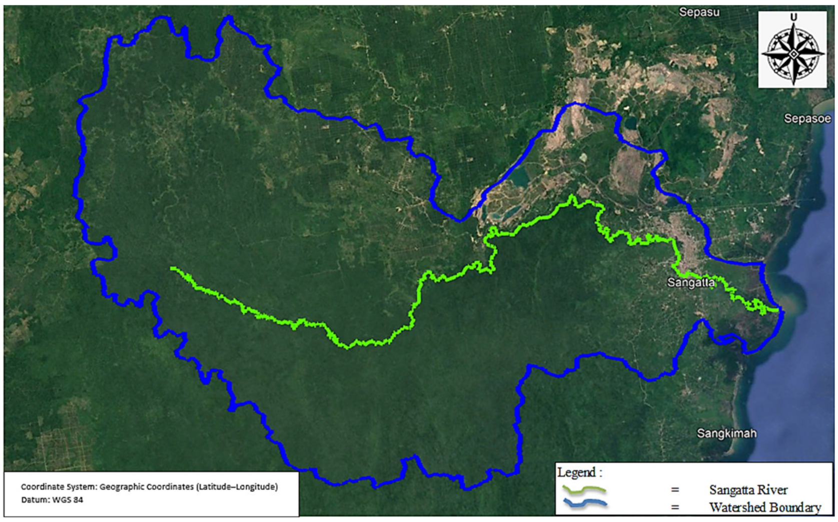

Fig. 1. Location of the Sangatta watershed, East Kutai Regency, Indonesia. Source : Google Earth Imagery (2024).

Land-use conditions within the watershed have undergone considerable changes in recent years. The expansion of settlements, agricultural activities, mining operations, and infrastructure development has increased surface runoff and soil erosion rates, thereby intensifying sediment inflow into the river system [5-6]. As a result, sediment deposition has become more pronounced in several river segments, leading to reduced channel capacity and altered river hydraulics.

From a geomorphological perspective, the Sangatta River exhibits longitudinal variations in channel slope, width, and bed material characteristics. The upstream reaches are generally characterized by steeper slopes and coarser bed materials, whereas the downstream reaches tend to have gentler slopes and finer sediments. This spatial variability significantly influences sediment transport capacity and deposition patterns along the river course.

For analytical purposes, the study area was divided into several river segments based on changes in channel geometry and hydraulic characteristics. These segments were used as the basis for sediment transport estimation using both the empirical Schoklitsch method and the HEC-RAS numerical model. The spatial segmentation of the Sangatta River provides an appropriate framework for evaluating the performance of empirical and numerical sediment transport approaches in a tropical river system affected by intensive land-use changes.

B. Methodology

1) Boundary Conditions

Boundary conditions in the HEC-RAS model were defined to represent upstream and downstream hydraulic conditions of the Sangatta River reach. At the upstream boundary, a steady flow discharge equal to the 1-year return period flood (257.88 m^3/s) was applied as the dominant discharge. This discharge represents frequent flow conditions that significantly contribute to sediment transport processes. At the downstream boundary, a normal depth condition was specified based on the average channel slope to ensure numerical stability of the simulation.

2) Sediment Transport Setting

Sediment transport simulation in HEC-RAS was configured using the built-in sediment transport module. Bed material properties, including representative grain size, were defined consistently with those used in the Schoklitsch empirical analysis to ensure comparability. The model was set to simulate bed-load transport under steady flow conditions, assuming uniform sediment characteristics within each river segment. This configuration allows spatial variation of sediment transport to be captured along the river reach while maintaining consistency with the empirical approach.

3) Time-Step and Computational Control

A numerical simulation was conducted using a steady flow regime with an appropriate computational time step to ensure model convergence and numerical stability. The time step was selected to satisfy the Courant condition and to avoid excessive numerical diffusion. Iteration limits and convergence criteria were adjusted to ensure stable sediment transport calculations without oscillation in bed level changes during simulation.

4) Calibration and Validation

The calibration of the model was performed by adjusting the hydraulic roughness coefficients and sediment transport parameters within reasonable ranges to achieve physically realistic sediment transport results. Due to the limited availability of observed sediment transport data in the Sangatta River, direct validation using measured sediment discharge was not feasible. Therefore, validation was conducted qualitatively by comparing model outputs with expected sediment transport patterns and channel characteristics observed in the field and reported in previous studies. This approach is commonly adopted in data-scarce river basins.

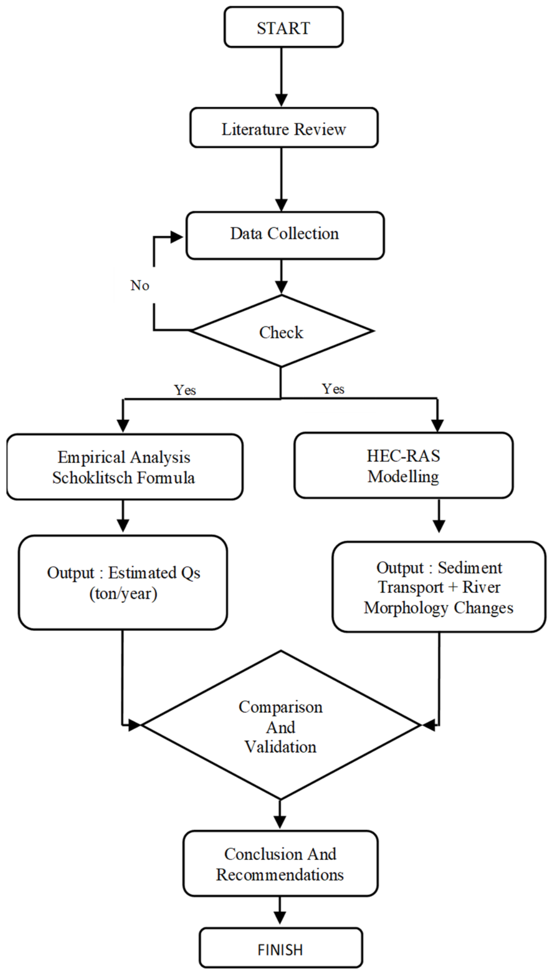

Fig. 2. Flowchart of research method.

5) Sensitivity Discussion

A sensitivity assessment was conducted to evaluate the influence of key input parameters on sediment transport results. Parameters such as flow discharge, channel slope, and sediment grain size were identified as the most influential factors affecting sediment transport estimates. Variations in these parameters resulted in noticeable changes in simulated sediment discharge, particularly in river segments with gentler slopes. This sensitivity highlights the importance of accurate input data and supports the comparative evaluation between the empirical and numerical methods conducted in this study.

C. Literature Study

This stage was intended to strengthen the theoretical base, to study the previous research, and to identify the research gap. The literature study becomes the foundation to determine the methodology that is used, especially regarding the use of the Schoklitsch formula and the HEC-RAS modeling for the analysis of the sediment transport.

D. Collecting and Analyzing Data

The data used in this research consists of as follows:

- Hydrology data, including the daily or periodical river flow discharge obtained from the related institutional and rainfall data, are used to support the analysis of the discharge hydrograph.
- River morphology data, including the river length, the slope of the river bed and the cross section of the river from a field survey, and river geometric data at the cross section [8] that are needed for HEC-RAS modeling.
- Sediment data, such as the sediment grain size (d_{50}, distribution of gradation) from the laboratory analysis results, and the information on the material type of the river bed (sand, gravel, or mixture).
- Topography data, such as data of Digital Elevation Model (DEM) and contour map, is used for building the geometric model in the HEC-RAS.

E. Estimation of Discharge by Using Snyder Synthetic Unit Hydrograph

In this research, the design flood used as the input of modeling is obtained from the hydrology analysis result by using the Snyder Synthetic Unit Hydrograph (SUH). This method is an empirical approach that is developed based on the characteristics of watershed morphometry, such as the length of the main river, the watershed area, and the regional coefficient. Table I presents the hydrological parameters for the Snyder SUH in the Sangatta watershed. In general, the equation that is used in the Snyder SUH is as follows [9]:

- Time to peak:

  $$T_p = C_t \,.\, (L \,.\, L_c)^{0,3}$$

  with T_p being the time to the peak of the hydrograph (hour), C_t being the Snyder regional coefficient, L being the length of the main river (km), and L_c being the length from the outlet to the weight point of the watershed (km).

- Peak discharge:

  $$Q_p = \frac{C_p \,.\, A}{T_p}$$

  with Q_p being the peak discharge (m^3/s), C_p being the peak coefficient of Snyder, and A being the watershed area (km^2).

TABLE I. HYDROLOGICAL PARAMETERS FOR SNYDER SUH IN SANGATTA WATERSHED

Parameter	Value	Unit
Area (A)	1878.60	km^2
Length of main river (L)	135	km
Length to the weight point (L_c)	67.5	km
Coefficient C_t	0.4	
Coefficient C_p	0.4	

F. Empirical Analysis by Using the Schoklitsch Formula

The empirical method used is the Schoklitsch formula [10], which is one of the classic formulas for analyzing the bed load. This formulation considers the flow discharge, river bed slope, and dominant sediment grain size [11]. The formulation is as follows: $Q_s = 0.00021 \cdot Q^{1.5} \cdot S^{1.5} \cdot d_{50}^{-0.25}$, with Q_s being the velocity of sediment transport (m^3/s), Q being the river flow discharge (m^3/s), S being the channel bed slope (m/m), and d_{50} being dominant sediment grain size (m). This formulation is mostly used in the initial analysis of sedimentation because of its simplicity. However, the main limitation is its sensitivity to the variation of discharge and grain size, as it does not analyze the complex spatial interaction.

G. Numerical Modelling by Using HEC-RAS

HEC-RAS (Hydrologic Engineering Centre's River Analysis System) is a software developed by the US Army Corps of Engineers for river flow modeling, including sediment transport and morphology change. The modeling stages are as follows [12]:

1. The arrangement of river geometry, including the input of cross-section, river length, and the boundary of upstream and downstream.
2. The input of hydrological data, consisting of flow discharge (unsteady flow).
3. The input of sedimentation data, consisting of grain size (d_{50}), distribution of fractions, and the condition of sediment transport.
4. The simulation of sediment transport by using HEC-RAS, which analyzes the sediment transport (bed load and suspended load) and the channel bed change.
5. The output is the volume of sediment transport (tons/day or tons/year), the location of dominant erosion, and the accumulation of sediment along the river.

H. Comparison and Validation

The sediment transport results from the Schoklitsch formula and HEC-RAS are compared, and validation is carried out by using two approaches:

- Quantitative comparison: the difference of estimation results in the error form (RMSE, MAPE).
- Qualitative comparison: the sediment distribution pattern and river morphology change towards the field data.

III. RESULTS AND DISCUSSION

A. Analysis of Design Flood by Using Snyder SUH

Snyder SUH is used to estimate the design flood based on the morphometry parameters of a watershed. This method is developed by an empirical approach, so it is more commonly used in hydrological studies, especially in watersheds that do not have continuous records of river flow discharge.

In this study, the parameters used for analysis with Snyder SUH are as follows: watershed area (A) = 1,878.60 km^2, the length of the main river (L) = 135.00 km, the river length from the outlet to the weight point of the watershed (L_c) = 67.50 km, coefficient C_t = 1.40 (1.1–1.4), coefficient C_p = 0.40 (0.4–0.8), and n = 0.40.

Based on the Snyder SUH analysis, the base peak discharge obtained was 9.596 m^3/s. Then, by using a design flood with several return periods, the design flood can be differentiated. Based on the analysis result, the design flood with 1 year returm period is 257.88 m^3/s. This discharge at a time is used as the dominant discharge because, generally, the flood discharge with a short return period (1-2 years) is assumed as the discharge that is the most important in the process of sediment transport and river morphology formation.

Then, the value of the design flood is used as the input in hydrology modelling (HEC-RAS) and to estimate sediment by using the empirical method. Therefore, the Snyder SUH method gives a clear quantification base in determining the potential of a flood in the Sangatta watershed.

B. Sedimentation Analysis Using the Schoklitsch Formula

The analysis of sediment transport by using the Schoklitsch formula was carried out at every observation segment along the Sangatta River. The design flood used is the result of the Snyder SUH method for a one-year return period, that is, 257.88 m^3/s, which was determined as the dominant discharge. By entering the parameter of dominant discharge, river bed slope, and sediment grain size at every segment, sediment transport results are obtained as presented in Table II.

The results show that the sediment discharge varies significantly between the segments. The highest sediment transport is at segment-3 (P.03), with an amount of 99,325.089 tons/hour; however, the lowest is at segment-75 (P.75), with an amount of 5,681.718 tons/hour. The average sediment transport from all of the segments is about 36,500 tons/hour. The spatial distribution shows that the segments with relatively big slope (for example, at P.03 with I = 0.0147 and at P.71 with I = 0.0109) produce sediment discharge that is much higher than at segments with less steep slope (for example, at P.75 with I = 0.0022). This shows that the river bed slope has a significant influence on the sediment transport.

In general, it is observed that sediment transport in the upstream until the center of the river tends to be smaller; however, in the downstream with a bigger gradient, the sediment transport is significantly increased. This condition is along with the theory of sediment transport, where the flow velocity is higher due to the steep slope that increases the energy of material transport. Therefore, the analysis of the results of the Schoklitsch formula indicates that the Sangatta River has a very high potential for sediment transport, mainly at river segments with steep bed slope. This requires attention in the analysis of sediment management that is not even, as it can influence the stability of river morphology and the performance of the control structure. Then, the empirical analysis result is compared with the numerical simulation result by using HEC-RAS to obtain a more comprehensive illustration.

TABLE II. ANALYSIS RESULT OF SEDIMENT RATE BY USING SCHOKLITSCH METHOD

River segment	Discharge (Q) m^3/s	Slope (I)	D (mm)	Sediment discharge (Q_s) (tons/day)
P.75	257.88	0.0022	0.5	5681.718
P.73	257.88	0.0032	0.5	11117.466
P.71	257.88	0.0109	0.5	63378.441
P.67	257.88	0.0143	0.5	95441.072
P.63	257.88	0.0005	0.5	682.356
P.60	257.88	0.0001	0.5	75.555
P.56	257.88	0.0005	0.5	619.131
P.53	257.88	0.0049	0.5	19098.031
P.50	257.88	0.0023	0.5	6138.121
P.46	257.88	0.0004	0.5	382.983
P.43	257.88	0.0006	0.5	814.785
P.40	257.88	0.0035	0.5	11526.871
P.39	257.88	0.0003	0.5	239.614
P.38	257.88	0.0088	0.5	45973.341
P.35	257.88	0.0085	0.5	43642.212
P.32	257.88	0.0139	0.5	91272.762
P.29	257.88	0.0141	0.5	93580.833
P.25	257.88	0.0041	0.5	14794.703
P.22	257.88	0.0030	0.5	9277.221
P.19	257.88	0.0023	0.5	6005.066
P.18	257.88	0.0085	0.5	43642.212
P.15	257.88	0.0158	0.5	110614.460
P.12	257.88	0.0058	0.5	24454.944
P.09	257.88	0.0066	0.5	30130.019
P.07	257.88	0.0347	0.5	359518.706
P.03	257.88	0.0147	0.5	99325.089

C. Simulation Results of Sedimentation Using the HEC-RAS Model

The sedimentation simulation by using HEC-RAS was carried out by using the flood hydrograph with a one-year return period as the unsteady flow input. The hydrograph is obtained from the analysis result of the Snyder SUH method, with a peak discharge of 257.88 m^3/s. Then, the hydrograph data is entered into the model to analyze the sediment transport at every segment.

The simulation results show that the velocity of sediment transport varies along the river stream. In the upstream segment, the sediment value is relatively small because the inflow is still limited, but then increases at the central segment, reaching a higher value in the downstream. This difference is influenced by the variation of discharge on the hydrograph, the condition of the river's geometry, and the characteristics of the river bed. Table III presents the simulation results of HEC-RAS in the form of average sediment discharge at every segment based on the flood hydrograph with a one-year return period.

TABLE III. SIMULATION RESULT OF SEDIMENT USING HEC-RAS

River segment	Station (m)	Discharge (Q) m³/s	Sediment discharge (Q_s) tons/day
P.75	3577	257.88	9457.692
P.73	3457	257.88	6895.887
P.71	3257	257.88	25398.209
P.67	3132	257.88	22223.646
P.63	2982	257.88	27076.875
P.60	2822	257.88	26983.326
P.56	2722	257.88	23133.514
P.53	2622	257.88	18491.863
P.50	2422	257.88	20168.43
P.46	2257	257.88	20295.242
P.43	2107	257.88	18385.395
P.40	2007	257.88	18055.746
P.39	1857	257.88	28165.48
P.38	1757	257.88	30448.623
P.35	1657	257.88	33802.387
P.32	1457	257.88	33597.992
P.29	1307	257.88	37532.07
P.25	1157	257.88	34122.742
P.22	982	257.88	32765.135
P.19	757	257.88	26449.922
P.18	657	257.88	15180.313
P.15	607	257.88	8910.269
P.12	427	257.88	3913.398
P.09	177	257.88	26580.613
P.07	102	257.88	11471.73
P.03	0	257.88	6908.29

D. Comparison of the Results of Schoklitsch and HEC-RAS

Table IV presents the comparison of sediment transport analysis results by using the Schoklistsch empirical formula and the simulation results of the HEC-RAS model. In general, both methods produce different sediment discharges at most of the river segments, although there are segments that indicate almost the same value.

The comparison between sediment transport estimates obtained from the Schoklitsch method and the HEC-RAS model shows varying levels of agreement across river segments. Several segments exhibit close correspondence between the two approaches, with percentage differences of less than 1%, indicating that simplified empirical assumptions remain applicable under relatively uniform hydraulic conditions. However, substantial discrepancies are observed in other segments, with differences exceeding −350%. Such discrepancies suggest that the Schoklitsch method may overestimate sediment transport in segments influenced by complex channel geometry or non-uniform flow conditions, which are not explicitly captured by empirical formulations. In contrast, the HEC-RAS model accounts for spatial variations in channel geometry and hydraulic conditions through cross-sectional representation, resulting in more physically consistent sediment transport estimates. These differences highlight the influence of hydraulic energy, channel slope, and sediment characteristics on sediment transport processes and demonstrate the respective strengths and limitations of empirical and numerical approaches.

TABLE IV. COMPARISON OF RESULTS FROM SCHOKLITSCH AND HEC-RAS

River segment	Sediment discharge (Q_s) Schoklitsch	Sediment discharge (Q_s) HEC-RAS	Difference (%)	Interpretation
P.75	5681.718	9457.692	-0.66	Comparable
P.53	19098.031	18491.863	0.03	Comparable
P.60	75.555	26983.326	-356.13	Extreme discrepancy
P.07	359518.706	11471.73	0.97	Large discrepancy
P.29	93580.833	37532.07	0.60	Large discrepancy

IV. CONCLUSION

This study compares sediment transport estimation along the Sangatta River using the empirical Schoklitsch method and numerical modeling with HEC-RAS under a consistent dominant discharge condition. The results show that sediment transport estimates vary spatially along the river, reflecting differences in hydraulic conditions, channel geometry, and sediment characteristics. In several river segments, both methods produce closely comparable results, with percentage differences of less than 1%, indicating that simplified empirical assumptions remain applicable under relatively uniform hydraulic conditions. However, significant discrepancies are observed in other segments, with differences exceeding –350%. These discrepancies are associated with complex channel morphology and non-uniform flow conditions, which are not fully represented by empirical formulations. In contrast, the HEC-RAS model accounts for spatial variations in channel geometry and hydraulic parameters through cross-sectional representation, resulting in more physically consistent sediment transport estimates.

The novelty of this study lies in the segment-based comparison of empirical and numerical sediment transport estimates using the same dominant discharge within a tropical river system. This approach allows a clear assessment of how physical river processes influence the performance and limitations of each estimation method under varying hydraulic and morphological conditions. From an engineering perspective, the results indicate that the Schoklitsch method is suitable for a rapid preliminary assessment of sediment transport under data-limited conditions, while the HEC-RAS model provides more reliable spatially distributed information for detailed applications such as dredging design, river capacity evaluation, and flood mitigation planning. From a river management perspective, the findings support the integrated use of empirical and numerical approaches to improve sediment management strategies and enhance decision-making for sustainable river system management in tropical environments.

DATA AVAILABILITY STATEMENT

The datasets used in this study are available from the corresponding author upon reasonable request.

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