

Bed-Slope Amplification of Non-Cohesive Sediment Transport under Supercritical Open-Channel Flow

Fayyad Fauzi*, Akhmad Fikri, Farida Gaffar, Kasmawati

Department of Water Resources Engineering, Faculty of Engineering, Universitas Muhammadiyah Makassar, Makassar, Indonesia

ABSTRACT

Bed slope and discharge control the capacity of open-channel flow to mobilize sediment, yet their relative effects are often difficult to separate because bed-load transport is intermittent and empirical equations are sensitive to hydraulic context. This study quantifies the effects of bed slope and discharge on non-cohesive sand transport in a controlled tilting flume. Sand with a nominal diameter of 0.6 mm and a specific gravity of 2.71 was tested at bed slopes of 1.5%, 2.0%, and 2.5% under discharges of 252.92 and 391.42 cm³ s⁻¹. Three independent trials were conducted for each treatment combination, and trial means were analyzed using two-factor ANOVA on the logarithmic scale. Sediment transport increased consistently with both slope and discharge. Bed slope produced the stronger effect ($p < 0.001$; partial $\eta^2 = 0.794$), while discharge was also significant ($p = 0.0086$; partial $\eta^2 = 0.450$); their interaction was not significant. Excess bed shear stress explained 83.8% of variation among treatment means. Schoklitsch predictions were closer to measurements than the implemented Shields-based estimates, although both generally underestimated transport. The results show that modest slope changes can sharply amplify sediment mobility under supercritical flow.

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1. Introduction

Open channels rarely convey water without also redistributing sediment. In irrigation and drainage networks, river-training works, steep conveyance structures, and laboratory models, the hydraulic conditions that carry water also determine whether bed material remains stable, moves intermittently, or is transported continuously. Deposition can reduce conveyance capacity and raise maintenance demands, whereas excessive transport can degrade the bed and increase erosion risk. For this reason, channel design is not only a problem of water delivery; it is also a problem of matching discharge, bed geometry, roughness, and sediment properties so that the resulting transport regime remains compatible with the intended function.

Bed slope is a direct geometric control because it alters the energy gradient available to drive flow and, consequently, the near-bed forces acting on sediment. Recent scaling work for sand- and gravel-bed channels treats discharge, water depth, bed slope, width, and grain size as mutually dependent controls rather than independent descriptors [1,2]. Laboratory studies likewise show that bed slope and discharge influence flow resistance, turbulence, and the conditions under which bed load is maintained [2,3]. A recent beam-type sabo-dam experiment showed that increasing channel slope altered Froude number and debris passage, with steeper conditions producing more energetic downstream flow [4]. Although debris flow is not equivalent to uniform sand bed load, the experiment provides a useful local comparison: relatively

small geometric changes can reorganize the hydraulic regime and modify the amount of mobile material.

The mechanics of grain motion are commonly framed through a balance between driving stress and resistance. Motion begins when the hydrodynamic forcing acting on exposed grains exceeds a threshold, but transport magnitude above that threshold depends on more than critical shear alone. Cheng et al. [5] showed that bed-material sediment discharge can be represented more effectively when shear velocity is combined with bulk velocity in a mixed velocity scale. Large compiled datasets also identify the Shields parameter, Froude number, discharge, and other hydraulic variables as important predictors of bed-load rate [6]. Mobile-bed experiments provide a physical explanation for this multivariable behavior: sweep and ejection events organize near-bed momentum transfer and can trigger sediment motion even when bulk flow quantities appear similar [7,8].

These effects become especially important in supercritical flow. High-speed flume experiments demonstrate that particle trajectories, impacts, and saltation dynamics respond to hydraulic state and bed roughness [9]. Under supercritical conditions, changes in roughness can also alter resistance, velocity distribution, turbulence, and energy dissipation [10]. The same sensitivity appears when flow-control devices are introduced. Nurizkitha et al. [11], working in an open-channel laboratory setting, reported that a reinforced porous-cylinder deflector reduced local velocity and shifted Froude conditions toward a more stable regime. Baharuddin et al. [12] similarly found that increasing discharge increased velocity and maximum scour depth around an unprotected bridge pier, while a porous

underwater current deflector attenuated near-bed flow and scour. Together, these studies reinforce a central point for movable-bed channels: sediment response is governed by the way slope, discharge, and local hydraulic structure translate into near-bed forcing.

A second challenge concerns prediction. Classical equations remain attractive because they are transparent and inexpensive, yet their performance can deteriorate when applied outside the conditions for which they were derived. Contemporary work has therefore emphasized calibration, model comparison, and uncertainty rather than reliance on a single universal formulation. Data-driven studies have achieved high predictive accuracy by combining several hydraulic variables [13], while formula-comparison studies show substantial differences between empirical and numerical estimates when local morphology or supply limitation is important [14,15]. The broader lesson is consistent with current discussions of empirical hydrologic relations: simple equations can remain useful, but their validity and uncertainty must be made explicit [16].

Experimental design introduces an additional source of uncertainty. Bed-load transport is intermittent, and short collection intervals can differ markedly even under nominally identical forcing. Repeatability studies in large flumes show that sediment flux may vary from event to event because turbulence and evolving bed configuration change the availability of mobile grains [17]. Repeated unsteady-flow experiments also reveal that the same nominal hydrograph can generate non-identical bedforms and transport histories [18]. This makes the experimental unit important: repeated measurements taken within one run improve precision, but they should not automatically be treated as independent hydraulic realizations.

The present study addresses this problem with a compact factorial experiment in which three bed slopes (1.5%, 2.0%, and 2.5%) were crossed with two discharge regimes. The work focuses on three questions: (1) how strongly bed slope changes measured non-cohesive sediment transport when discharge is controlled; (2) how much increasing discharge amplifies transport across the tested slope range; and (3) whether Schoklitsch and Shields-based estimates reproduce the magnitude and pattern of the observations. We expected sediment transport to increase with both slope and discharge, with slope acting primarily through increased excess bed shear, and we expected the empirical equations to capture treatment ordering more reliably than absolute flux. The study contributes trial-level effect sizes, uncertainty estimates, and explicit model-bias metrics for a supercritical small-flume configuration relevant to hydraulic modeling and sediment-sensitive channel design. At the catchment scale, recent erosion mapping also emphasizes the role of slope in erosion hazard and sediment-source processes [19], providing a broader context for why geometric controls on sediment mobilization matter from hillslope supply to channel conveyance.

2. Methods

2.1 Experimental facility and design

The experiments were conducted in the Hydraulics Laboratory, Faculty of Engineering, Universitas

Muhammadiyah Makassar, during 10-30 September 2024. A laboratory flume equipped with a tilting mechanism was connected to a recirculating water-supply system and a downstream sediment-collection arrangement. Supporting measurements were obtained with a point gauge, current meter, piezometric equipment, volumetric containers, and a stopwatch. The longitudinal bed was adjusted to 1.5%, 2.0%, and 2.5%. The same general channel geometry and sediment configuration were maintained while slope and discharge were varied.

Two discharge regimes were established by volumetric calibration. Three measurements at the lower setting were 252.22, 253.43, and 253.11 $\text{cm}^3 \text{s}^{-1}$, giving a mean discharge of 252.92 $\text{cm}^3 \text{s}^{-1}$ (Q1). The corresponding values at the higher setting were 391.69, 394.37, and 388.20 $\text{cm}^3 \text{s}^{-1}$, giving 391.42 $\text{cm}^3 \text{s}^{-1}$ (Q2). Thus Q2 was approximately 1.55 times Q1. In the transport calculations, discharge was also expressed per unit channel width as q_w . Figure 1 summarizes the experimental arrangement and the three imposed slopes.

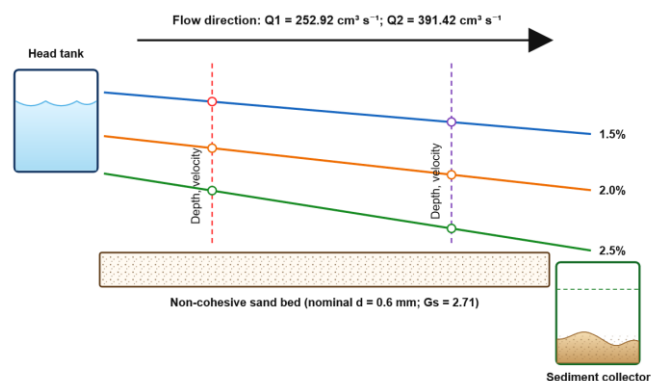


Figure 1. Schematic of the tilting-flume experiment; bed slopes are exaggerated for readability.

2.2 Sediment and hydraulic measurements

The bed material was non-cohesive sand with a nominal particle diameter of 0.6 mm. Specific gravity was determined by pycnometer in two measurements (2.71 and 2.70), yielding a mean of 2.71. Sediment was placed in the test section before flow was initiated. After the selected hydraulic condition had stabilized, sediment leaving the test section was collected volumetrically. The primary response was unit-width sediment transport, q_s ($\text{cm}^3 \text{s}^{-1} \text{cm}^{-1}$). This measure represents the sediment volume flux normalized by channel width and was retained for all statistical and empirical comparisons.

Each combination of discharge and bed slope was tested in three independent trials. Within every trial, three sediment-collection measurements were obtained, producing nine observations per treatment combination and 54 individual collections overall. The three within-trial measurements were treated as repeated observations of the same hydraulic run. Their mean was therefore used as the inferential replicate, giving 18 trial means for hypothesis testing. This hierarchy avoids pseudoreplication while retaining the individual observations for descriptive estimates of variability. Using trial means also makes the reported confidence intervals and effect sizes correspond to replicated runs rather than to repeated readings collected

from the same run, which is the relevant level for comparing imposed hydraulic treatments.

Flow depth was recorded after approximately steady conditions had developed. The hydraulic calculations yielded Froude numbers of 2.49, 2.68, and 2.67 for Q1 at slopes of 1.5%, 2.0%, and 2.5%, respectively, and 2.92, 3.00, and 3.73 for Q2. All conditions were therefore supercritical. The corresponding bed shear stresses increased with slope. For Q1, the reported values were 0.013, 0.025, and 0.037, compared with a critical stress of 0.006; for Q2 they were 0.015, 0.030, and 0.039. Excess bed shear stress, $\tau_0 - \tau_c$, was consequently 0.007, 0.019, and 0.031 for Q1 and 0.009, 0.024, and 0.033 for Q2 in the original calculation units.

2.3 Empirical calculations and statistical analysis

The experimental transport data were compared with two engineering approaches. The Schoklitsch calculation uses flow discharge in excess of a critical discharge, whereas the implemented Shields-based calculation uses applied and critical bed shear stress. For each of the six slope-discharge conditions, empirical predictions were averaged and compared with the corresponding measured mean. Performance was summarized by relative bias, root-mean-square error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE). This comparison was intended as a condition-specific evaluation rather than a universal validation of either formulation.

Statistical inference was performed on natural-log-transformed trial means because q_s was positive and right-skewed. A two-factor ANOVA included discharge regime, bed slope, and their interaction as fixed effects. Residual diagnostics supported the analysis: the Shapiro-Wilk test did not indicate non-normality ($p = 0.947$), and Levene's test did not indicate unequal variance among the six treatment combinations ($p = 0.777$). Partial eta squared (partial η^2) quantified effect size. Tukey's honestly significant difference procedure was used for pairwise slope contrasts when the overall slope effect was significant. An additive log-linear model was fitted to express main effects as multiplicative changes in transport, and a simple regression across the six treatment means related q_s to excess bed shear stress. Statistical significance was assessed at $\alpha = 0.05$.

3. Results and Discussion

3.1 Hydraulic regime and transport variability

All six hydraulic conditions were supercritical, and both Froude number and excess bed shear generally increased toward the steeper and higher-discharge treatments. The highest Froude number, 3.73, occurred at Q2 and a 2.5% slope. At the same time, excess shear rose from 0.007 at Q1-1.5% to 0.033 at Q2-2.5%. The measurements therefore span a coherent gradient in transport potential rather than six arbitrary combinations. This is important because supercritical flow can produce strong near-bed momentum transfer and intermittent grain motion; recent work on particle saltation and roughness effects shows that changes in energetic flow structure can modify particle trajectories and energy exchange even when the bed material itself is unchanged [9,10].

The individual sediment collections were variable, with coefficients of variation from about 24% to 51% across treatment cells. That spread is consistent with the pulsed

nature of bed-load transport. It should not be interpreted as a failure of experimental control, because short observations can capture different phases of grain entrainment, saltation, and temporary bed reorganization. Particle-tracking work has similarly emphasized the need for adequate replication to stabilize statistics of grain motion [20], and repeated flume studies show that sediment transport can diverge even when the imposed forcing is closely reproduced [21]. Figure 2 therefore presents trial-level behavior rather than treating all 54 collections as independent points.

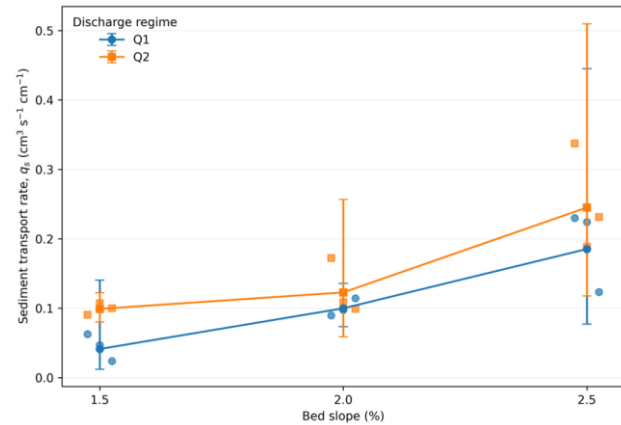


Figure 2. Trial-level sediment transport across bed slopes and discharge regimes. Error bars show back-transformed 95% confidence intervals on the log scale.

Table 1. Experimental hydraulic conditions and sediment-transport responses by discharge regime and bed slope. Values are reported as mean $\pm$ SD. Q1 and Q2 denote the lower and higher discharge regimes, respectively; q_w is discharge per unit channel width and q_s is unit-width sediment transport.

Regime	Q (cm³ s⁻¹)	Slope (%)	Mean $q_w \pm$ SD (cm³ s⁻¹ cm⁻¹)	Mean $q_s \pm$ SD (cm³ s⁻¹ cm⁻¹)	Froude no.
Q1	252.92	1.5	32.75 $\pm$ 0.60	0.0446 $\pm$ 0.0212	2.49
Q1	252.92	2.0	32.54 $\pm$ 1.08	0.1004 $\pm$ 0.0240	2.68
Q1	252.92	2.5	32.23 $\pm$ 1.17	0.1926 $\pm$ 0.0624	2.67
Q2	391.42	1.5	47.30 $\pm$ 1.85	0.0993 $\pm$ 0.0508	2.92
Q2	391.42	2.0	47.99 $\pm$ 1.53	0.1267 $\pm$ 0.0623	3.00
Q2	391.42	2.5	47.91 $\pm$ 1.43	0.2524 $\pm$ 0.1082	3.73

Table 1 shows a clear treatment-level pattern. At Q1, mean q_s increased from 0.0446 cm³ s⁻¹ cm⁻¹ at a 1.5% slope to 0.1004 at 2.0% and 0.1926 at 2.5%. The 2.5% condition transported 4.32 times as much sediment as the 1.5% condition on the arithmetic mean scale. Under Q2, the corresponding means were 0.0993, 0.1267, and 0.2524 cm³ s⁻¹ cm⁻¹; the steepest bed transported 2.54 times the amount measured at 1.5%. Increasing discharge from Q1 to Q2 raised mean transport at every slope, by factors of 2.23, 1.26, and 1.31 for 1.5%, 2.0%, and 2.5%, respectively.

3.2 Effects of bed slope and discharge

The dominance of slope was confirmed by the trial-level analysis (Table 2). Bed slope produced $F_{2,12} = 23.12$ ($p < 0.001$) with partial $\eta^2 = 0.794$. Discharge was also significant ($F_{1,12} = 9.83$, $p = 0.0086$; partial $\eta^2 = 0.450$), whereas the slope

× discharge interaction was not ($F_{2,12} = 2.14$, $p = 0.161$). These results indicate that slope and discharge both changed transport, but the evidence does not support a strongly different slope response between Q1 and Q2. On the log scale, their contributions were broadly additive, which is equivalent to multiplicative effects on the original transport scale.

Table 2. Two-factor ANOVA for log-transformed trial-mean sediment transport ($n = 18$).

Effect	df	F	p	Partial η^2
Discharge	1, 12	9.83	0.0086	0.450
Bed slope	2, 12	23.12	<0.001	0.794
Discharge × slope	2, 12	2.14	0.161	0.263

The additive log-linear model sharpens the interpretation. After adjustment for slope, Q2 was associated with a 1.57-fold increase in q_s relative to Q1 (95% CI: 1.13–2.20). After adjustment for discharge, the 2.0% slope produced an estimated 1.73-fold increase over the 1.5% slope (95% CI: 1.15–2.61), while the 2.5% slope produced a 3.33-fold increase (95% CI: 2.21–5.01). Tukey comparisons showed that 2.5% differed significantly from both 1.5% (adjusted $p = 0.0003$) and 2.0% (adjusted $p = 0.034$). The 1.5%–2.0% contrast was positive but did not reach the multiplicity-adjusted 0.05 threshold ($p = 0.079$). Thus the strongest evidence concerns the transition to the steepest tested bed.

The pattern is physically consistent with other open-channel experiments. [Kohandel Gargari et al. \[2\]](#) reported that bed slope and discharge modify turbulence under self-cleansing bed-load conditions. [Rezaie et al. \[22\]](#) showed that geometry, vegetation-induced resistance, velocity, and bed shear can alter sediment transport together in compound channels. [Yusuf et al. \[4\]](#) observed that increasing channel inclination changed Froude behavior and debris passage across a beam-type sabo dam. These studies differ in geometry and transported material, so their numerical effects are not directly transferable; nevertheless, they support the mechanism observed here: increasing the energy gradient changes the near-bed forcing available to mobilize sediment.

The discharge response is equally plausible. Higher discharge increases the momentum supplied to the channel, but the resulting sediment response depends on how that momentum is redistributed near the bed. [Baharuddin et al. \[12\]](#) found that higher discharge increased local scour and flow velocity around an unprotected bridge pier, while [\[23\]](#) showed that higher flow rates can extend scour and sediment removal upstream of a piano-key weir. In a separate non-cohesive sediment experiment, removal was closely linked to local velocity and bed shear [\[23\]](#). The present results isolate this general effect in a simpler straight-flume geometry and show that discharge remained significant even after slope was controlled statistically.

3.3 Excess shear stress and transport mechanism

[Figure 3](#) provides the strongest mechanistic bridge between the factorial treatment and the measured flux. Across the six treatment means, excess bed shear stress explained 83.8% of the variation in q_s ($R^2 = 0.838$, $p = 0.010$). The positive fitted

slope indicates that transport increased as the margin above the critical stress widened. The regression is based on only six condition means and should not be interpreted as a calibrated transport law, but it confirms that the observed slope effect was accompanied by a physically expected increase in tractive forcing.

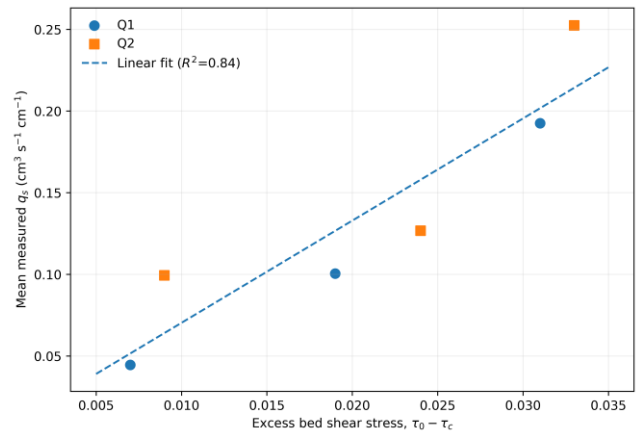


Figure 3. Mean measured sediment transport versus excess bed shear stress across the six treatment conditions. The dashed line indicates the fitted linear regression ($R^2 = 0.838$).

Excess shear is therefore best interpreted as an organizing variable rather than a complete description of transport. The threshold itself can change when turbulence, vegetation, or local geometry reorganizes near-bed momentum. For example, [Rismani et al. \[24\]](#) showed that emergent vegetation modified turbulent kinetic energy and the conditions for sediment motion in a bend. In the present straight flume, no vegetation or structural obstruction was present, so the monotonic increase in excess shear provides a comparatively clean explanation for the treatment ordering. Even so, the scatter around the fitted line indicates that identical values of bulk shear would not necessarily produce identical instantaneous flux. Grain packing, local exposure, bed roughness, and turbulent bursts remain plausible contributors to the residual variability. This distinction is important when translating a laboratory shear-stress relation into design: the regression supports the mechanism observed here, but the measured coefficients should not be exported as a general sediment-transport equation.

This relationship also helps explain why small point-to-point changes in q_w did not always produce monotonic changes in q_s within a treatment. Sediment flux depends on instantaneous grain exposure, local packing, turbulence, and bedform state. [\[8\]](#) documented strong modifications of the turbulent kinetic-energy budget within sediment-laden near-bed layers, while [\[25\]](#) showed that bedform development feeds back on resistance and transport. [\[26\]](#) likewise found that sediment feeding and mobile-bed conditions alter velocity profiles and Manning resistance. Under such conditions, realized flux at a given instant is not determined by bulk discharge alone. Treatment means are therefore more informative for the experimental question than short within-run regressions.

3.4 Performance of empirical transport equations

The empirical comparison (Figure 4) reveals a second important result. Schoklitsch predictions were consistently closer to the measured condition means than the implemented Shields-based estimates. For Q1, Schoklitsch biases were -37.7%, -17.7%, and -22.0% at slopes of 1.5%, 2.0%, and 2.5%, respectively. For Q2, the biases were -57.2%, -3.4%, and -11.2%. Across all six conditions, Schoklitsch produced $RMSE = 0.0328 \text{ cm}^3 \text{ s}^{-1} \text{ cm}^{-1}$, $MAE = 0.0277 \text{ cm}^3 \text{ s}^{-1} \text{ cm}^{-1}$, and $MAPE = 24.9\%$. The Shields-based estimates were substantially lower, with relative underprediction from 67.9% to 93.2% and $MAPE = 79.0\%$.

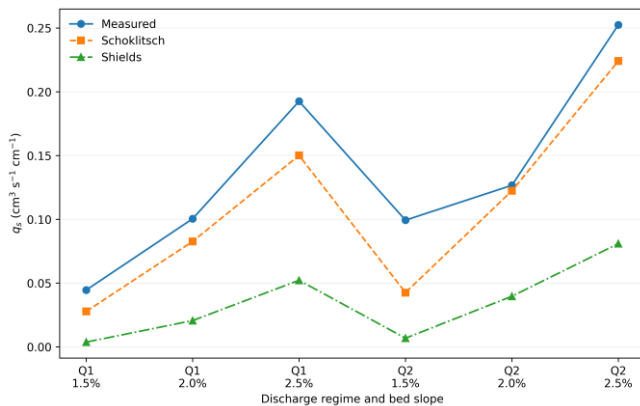


Figure 4. Comparison of measured condition-mean sediment transport with Schoklitsch and Shields-based predictions across the six discharge-slope conditions.

This difference should not be read as a universal ranking of the two frameworks. Shields-type reasoning is fundamentally tied to incipient motion and excess stress, whereas a transport-rate equation must also describe how flux grows after grains become mobile. Modern studies continue to refine bed-load prediction precisely because no single predictor is sufficient across channel types. Cheng et al. [5] improved discharge scaling by combining shear and bulk velocity, while Chabokpour [6] found that conventional formulas differed markedly in performance across hundreds of field measurements. Machine-learning approaches can exploit multivariable structure to reduce error further [13], but their additional complexity does not remove the need for physically interpretable calibration.

The Schoklitsch result is also consistent with recent evidence from tropical river modeling. Muir et al. [15] found that Schoklitsch estimates could agree closely with numerical predictions in some reaches but diverge strongly in others, leading them to characterize the formula as useful for preliminary estimation rather than as a universally reliable predictor. Similar caution is warranted here. At Q2 and slopes of 2.0%-2.5%, the mean Schoklitsch prediction was relatively close to the measurement, but it underpredicted more strongly at the mildest slope. Formula performance is therefore conditional on the hydraulic state. This pattern supports a practical workflow in which classical equations provide an initial estimate and local measurements are used to quantify bias before design decisions are finalized.

3.5 Engineering implications and limitations

The engineering implication is straightforward: a one-percentage-point increase in bed slope, from 1.5% to 2.5%, produced a several-fold change in sand transport under both discharges. In small irrigation, drainage, and conveyance channels, a slope selected solely for water-carrying capacity can therefore shift sediment behavior enough to alter deposition or erosion risk. Sediment-sensitive design should evaluate whether the expected bed shear exceeds the mobility threshold, estimate the corresponding transport rate, and then test the sensitivity of that estimate to plausible variations in slope and discharge. This is particularly relevant where steep catchments supply mobile sediment, as recent erosion-hazard mapping identifies topographic slope as a major component of land-surface erosion assessment [19]. The channel then determines whether that supplied material is stored or conveyed.

The results also clarify the difference between sediment supply and transport capacity. Catchment erosion determines how much material reaches a channel, whereas channel hydraulics determine how much of that material can be conveyed. Field work in the Palu River estuary identified discharge as a primary control on sediment-transport patterns under varying hydrodynamic conditions [27]. At open-channel junctions, numerical simulations show that flood-driven increases in bed shear can deform the bed and expand scour zones [28]. Steep Himalayan rivers provide a larger-scale counterpart: high flows increase sediment-carrying capacity, but prediction models developed for lowland settings do not necessarily transfer reliably to steep systems [29]. These examples reinforce why a controlled flume result is valuable without being universal. It isolates the hydraulic sensitivity of transport to slope and discharge, while field applications still require sediment-supply information, scale-aware calibration, and local boundary conditions.

The same reasoning applies to hydraulic structures. Field monitoring of sediment-bypass tunnels shows that sediment transport, hydraulic conditions, and abrasion interact in a strongly site-specific manner. Physical-model studies of mountain-river intakes use Froude-scaled experiments to redirect bed load and limit sediment entry [30]. Around bridge piers, turbulent sweeps and high near-bed stresses organize scour and transport [31], while porous flow-control devices can reduce local velocity and Froude number [11]. These applications are more complex than the present flume, but they illustrate why the measured slope sensitivity should be interpreted as a design warning: local geometry changes the hydraulic forcing that sediment actually experiences.

Several limitations define the range over which the findings should be applied. First, only one nominal grain size and one sediment density were tested, so the results do not describe hiding-exposure effects in mixed-size beds or cohesive behavior. Second, the factorial design included three slopes and two discharges. It establishes a clear monotonic pattern within 1.5%-2.5% but cannot determine the functional form beyond that interval. Third, the experiment did not include time-resolved bed topography or three-dimensional velocity measurements. This prevents

direct separation of supply limitation, evolving microtopography, and turbulence-driven bursts. Recent particle-tracking and numerical studies show that these processes can be resolved in far greater detail [20,32].

A final limitation concerns model transfer. The empirical comparison evaluates the equations as implemented for this experiment; it does not recalibrate them against a larger external database. Classical formulas can become structurally mismatched when geometry, supply regime, or hydraulic scale differs from the original calibration conditions [14]. Future work should therefore add intermediate slopes and discharges, record bed evolution and local velocity fields, and compare several contemporary transport relations under consistent units and parameter definitions. The statistical hierarchy should also be retained: independent experimental runs, rather than repeated collections within one run, should define the inferential sample. This approach offers a more defensible basis for uncertainty estimation in small-flume sediment studies.

3.6 Conclusion

Bed slope and discharge both altered non-cohesive sediment transport under the tested supercritical conditions, but slope was the stronger control. Mean q_s increased monotonically from 1.5% to 2.5% at both discharge regimes, and the trial-level ANOVA produced a large slope effect (partial $\eta^2 = 0.794$) compared with the discharge effect (partial $\eta^2 = 0.450$). After adjustment for discharge, the 2.5% bed transported about 3.33 times the sediment transported at 1.5%, while Q2 produced an average 1.57-fold increase over Q1 after adjustment for slope. The non-significant slope $\times$ discharge interaction indicates that the two controls were broadly multiplicative rather than strongly conditional within the tested range. Excess bed shear stress explained 83.8% of the variation among the six treatment means, supporting a tractive-force interpretation of the slope response. Schoklitsch reproduced the measured magnitude more closely than the implemented Shields-based calculation, but it still underpredicted several conditions and should therefore be treated as a preliminary engineering estimate rather than a substitute for local calibration. For small sediment-bearing channels, the results show that seemingly modest adjustments in bed gradient can produce large changes in conveyance of sand. Design and physical-model studies should consequently evaluate slope, discharge, excess shear, and model bias together, and should base statistical inference on independent runs rather than repeated collections from the same hydraulic realization.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, OpenAI ChatGPT was used to support manuscript organization, language refinement, and the presentation of calculations derived from the study data. All authors subsequently reviewed and edited the manuscript and independently verified the data, calculations, references, interpretations, and scientific conclusions. The authors take full responsibility for the accuracy, integrity, and content of the published work.

CRedit authorship contribution statement

Fayyad Fauzi and **Akhmad Fikri** : Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Farida Gaffar**: Conceptualization, Methodology, Validation, Supervision, Writing – review & editing. **Kasmawati**: Methodology, Validation, Supervision, Project administration, Writing – review & editing. All authors have read and approved the final version of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All numerical data supporting the findings of this study are presented within the manuscript, tables, and figures. The underlying sediment-transport measurements and calculation worksheets may be made available by the corresponding author upon reasonable request.

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