

Flow Resistance Estimation Using the Empirical Chezy Method in Sediment-Laden Flow

Miskar Maini^{1,2,3✉}, Junita Eka Susanti^{1,3}

¹ Department of Civil Engineering, Faculty of Infrastructure and Regional Technology, Institut Teknologi Sumatera, Indonesia

² Water Resources Engineering Research Group, Institut Teknologi Sumatera, Indonesia

³ Sustainable Infrastructure Research Center, Institut Teknologi Sumatera, Indonesia

✉ **Corresponding Author** : Miskar Maini (e-mail: miskar.maini@si.itera.ac.id)

Article Information	ABSTRACT
Article History Received : September 15, 2025 Revised : October 01, 2025 Published : October 10, 2025	Hydraulic resistance, represented by the Chezy coefficient, is crucial in estimating flow discharge in open channels and serves as a fundamental parameter in designing hydraulic structures such as irrigation canals and river control facilities. This study investigates the behavior of the Chezy coefficient under non-sediment-laden (NSL) and sediment-laden (SL) flow conditions through controlled laboratory experiments using coarse sand, complemented by comparative analysis with data from irrigation channels and natural rivers. The results show that the ratio of mean velocity to shear velocity (U/u^*) exhibits a robust correlation with discharge (Q) under both flow conditions, with a determination coefficient (R^2) exceeding 0.96. The hydraulic radius (R_h) also shows a strong linear relationship with discharge ($R \approx 0.98$), confirming its role in the empirical estimation of the Chezy coefficient (C). The value of C increases with higher velocity ratios but tends to be slightly lower under SL conditions due to increased resistance from suspended sediments. The Mean Absolute Error (MAE) value of 0.02 indicates a slight difference between NSL and SL conditions. These findings suggest that the empirical method is unreliable and exhibits significant differences in estimating Chezy under sediment-laden flow. It highlights the need for supplementary approaches to improve irrigation and river management design accuracy.
Keywords: <i>Non-sediment laden;</i> <i>Sediment laden;</i> <i>Flow resistance;</i> <i>Chezy coefficient.</i>	

INTRODUCTION

Flow resistance is fundamental in open-channel hydraulics that governs the relationship between flow velocity, channel roughness, and energy loss (Chow, 1959; Maini et al., 2023, 2025; Maini et al., 2024; Song et al., 1998). Accurate flow resistance estimation is crucial for hydraulic modeling, sediment transport prediction, and designing hydraulic structures such as canals, floodways, and reservoirs. Among various approaches, the Chezy coefficient (C) has been widely used as an empirical representation of flow resistance due to its simplicity and physical interpretability (Bjerklie et al., 2005; Elgamal, 2021; Passeri et al., 2018; Torabizadeh et al., 2018; Zhou et al., 2021).

However, most empirical relationships for determining the Chezy coefficient have been developed under clear-water (non-sediment-laden) conditions. In natural rivers and engineering channels, suspended and bed-load sediments significantly modify the flow characteristics. Sediment concentration, particle size, and mode of transport alter velocity distribution, turbulence

intensity, and boundary roughness, leading to changes in flow resistance (Elgamal, 2021; Zhou et al., 2021). Therefore, applying conventional empirical Chezy equations to sediment-laden flows often results in substantial deviations from observed conditions.

In sediment-laden flows, the complexity of hydraulic resistance increases substantially. Introducing suspended and bedload particles modifies near-bed velocity structures, intensifies momentum exchange, and alters the effective hydraulic roughness (Cellino & Graf, 1999, 2000; Graf & Altinakar, 2005; Graf & Cellino, 2002). Such processes complicate the application of classical resistance formulas, as sediment modifies both mean velocity distribution and turbulence characteristics, leading to uncertainties in estimating resistance coefficients (Maini, 2024; Maini et al., 2025). Previous research has predominantly emphasized resistance evaluation through Manning and Darcy–Weisbach equations, whereas systematic empirical assessments of the Chezy coefficient under sediment-laden conditions remain limited.

Addressing this gap is essential, as many rivers, irrigation channels, and laboratory experiments operate under conditions where sediment transport plays a critical role in shaping hydraulic behavior. An improved understanding of the Chezy coefficient in such contexts would strengthen the theoretical foundations of flow resistance and enhance the reliability of hydraulic modeling for design and management purposes. Moreover, revisiting empirical formulations is particularly relevant to increasing sediment-related challenges in water resources engineering, such as channel siltation, reservoir sedimentation, and reduced conveyance capacity in irrigation networks.

In the Indonesian context, these challenges are particularly evident in sediment-laden river systems and irrigation channels, where high sediment loads frequently cause reduced conveyance, elevated flood risks, and rapid siltation of reservoirs. Cases such as the sedimentation of the Mataram irrigation channel in Yogyakarta (Kironoto & Yulistiyo, 2016) and the Kuning River studies adapted for tropical conditions (Kironoto et al., 2019) highlight the practical need for more accurate resistance formulations in sediment-laden flows. Therefore, empirical assessments of the Chezy coefficient under such conditions are crucial to provide engineers and researchers with reliable tools for predicting hydraulic behavior in sediment-prone waterways.

Accordingly, this study focuses on evaluating the influence of hydraulic parameters on the Chezy coefficient and assessing the reliability of empirical methods in determining the coefficient through a series of controlled laboratory experiments involving sediment-laden flows. By analyzing flow resistance behavior under various sediment concentrations and characteristics, this study aims to provide a more comprehensive understanding of the factors affecting the Chezy coefficient and to identify the limitations and applicability of empirical formulations in estimating the coefficient for sediment-laden flow conditions.

RESEARCH METHODS

The present study employed a twofold methodological approach, combining controlled laboratory experiments with an empirical assessment based on previously published experimental and field datasets. The laboratory experiments were conducted in a recirculating sediment flume with a total length of 10 m, an internal width of 0.6 m, and a flow depth capacity of 0.45 m (see Figure 1). The flume was designed to replicate sediment-laden flows under well-controlled hydraulic conditions, ensuring repeatability and accuracy in measurements. Two types of very coarse sand were selected as bed materials, with characteristic grain diameters of approximately 1.55 mm and 1.85 mm. Experimental runs were performed under varying hydraulic conditions, with flow discharges between 40 L/s and 120 L/s, and nine adjustable bed slopes in the 0.05% to 0.45% range (see Figure 2). To maintain uniform flow distribution and suppress secondary currents, the upstream section of the flume was equipped with a series of flow-straightening devices, including honeycombs and stabilizers. Sediment transport was introduced by regulating the sediment feed rate, which was varied between 0.0124 kg/s and 0.0396 kg/s. Hydraulic and sediment measurements were carried out at a designated section 6.6 m downstream from the flume

inlet, representing a zone where the flow was fully developed and dominated by turbulent characteristics (See Flowchart in Figure 3).

Beyond the laboratory framework, the study also incorporated an empirical evaluation of the Chezy coefficient using a combination of experimental and field datasets. The empirical assessment was based on extended laboratory data reported by Maini et al., (2024) and Maini et al., (2025), which provided additional insight into sediment-laden flow resistance across different hydraulic and sediment regimes. Field observations from natural and engineered channels were also included to broaden the scope further and strengthen the reliability of the analysis. These datasets consist of suspended-sediment flows observed in the Mataram irrigation canal (Kironoto & Yulistiyanto, 2016), high-sediment transport conditions in the Kuning River (Kironoto et al., 2019), and sediment-laden flow measurements from the Opak River (Kironoto et al., 2019).

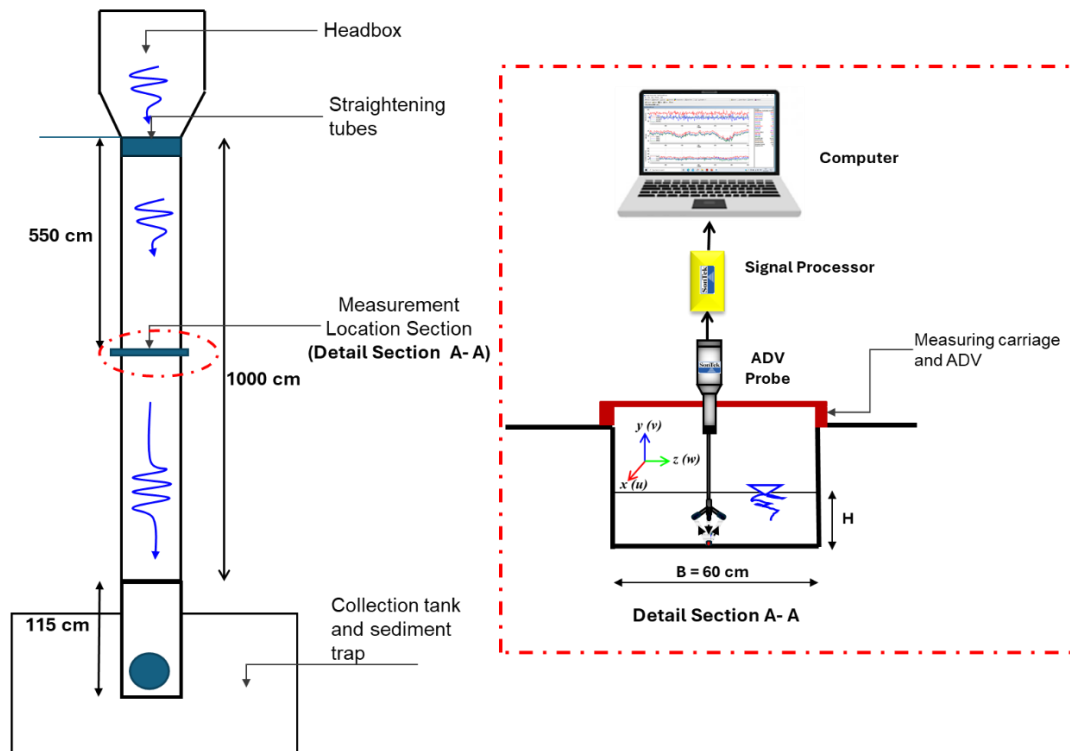


Figure 1. Experimental Setup (Flume Schematic)

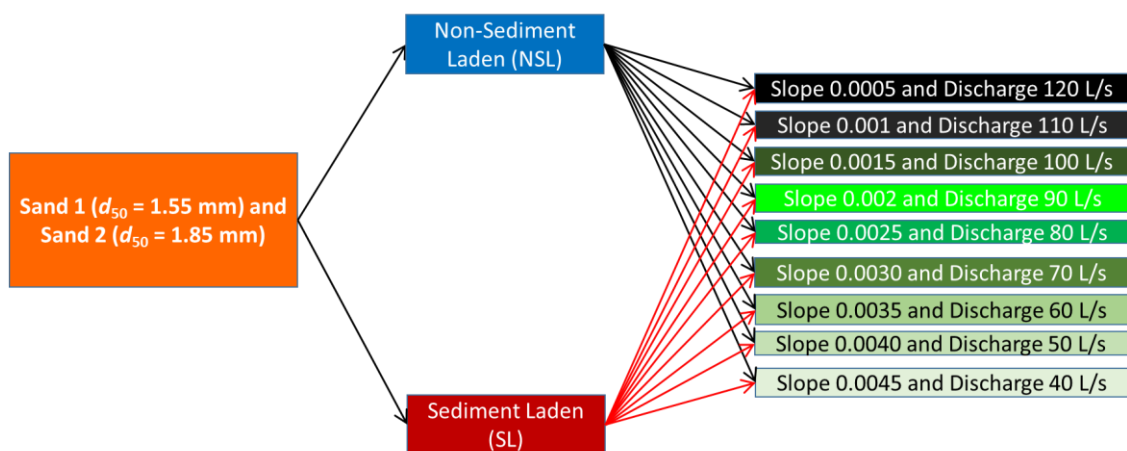


Figure 2. Experimental Running Variations

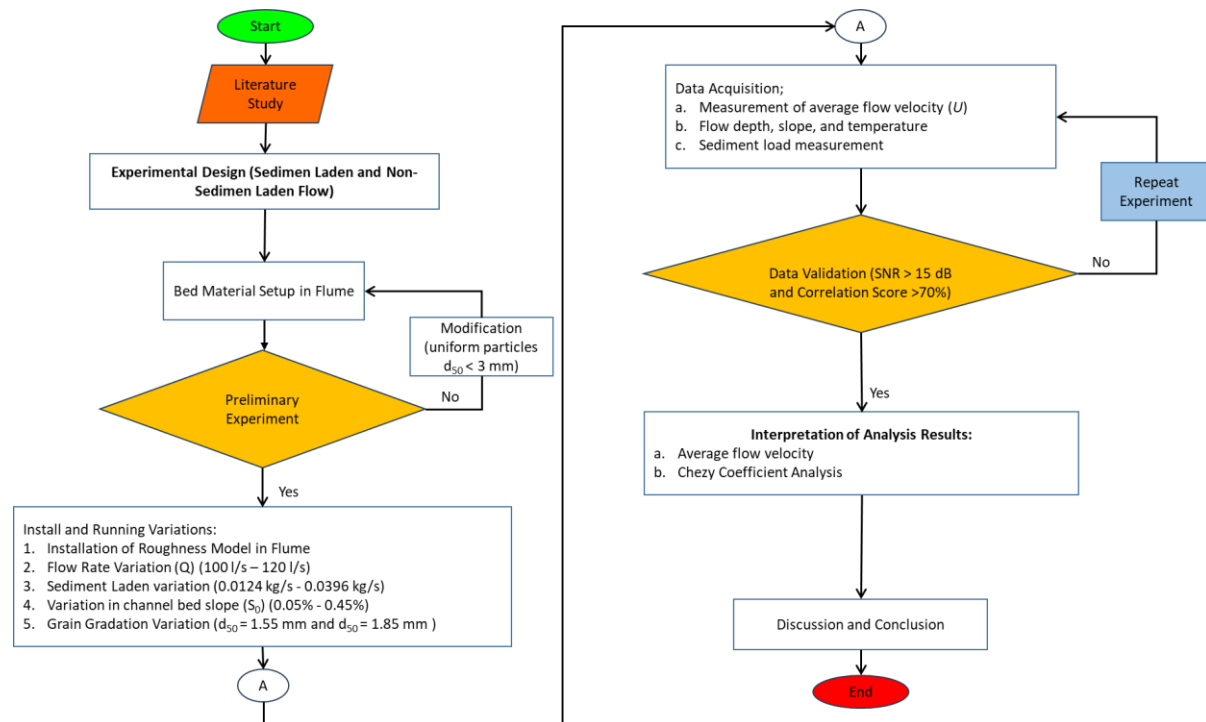


Figure 3. Flow chart of research

Hydraulic Parameter Analysis Method

Analyzing hydraulic parameters is essential in understanding open channels' flow characteristics. The main parameters commonly used include the mean flow velocity, hydraulic radius, and shear velocity. These parameters describe the flow's hydraulic behavior and provide valuable insights into the variation and influence on the Chezy roughness coefficient. By examining the trends of these parameters, it becomes possible to evaluate how changes in flow regime or boundary conditions affect the resistance to flow, thereby improving the accuracy of hydraulic modeling and channel design.

Mean Flow Velocity (U)

The mean flow velocity is calculated using the following equation:

$$U = \frac{Q}{A} \quad (1)$$

where Q is the discharge (m^3/s) and A is the cross-sectional flow area (m^2). This equation represents the average velocity of the flow, assuming that the velocity distribution is uniform across the wetted section. The mean velocity serves as the basis for evaluating flow energy, sediment transport capacity, and overall hydraulic conditions in the channel.

Hydraulics Radius (R_h)

The hydraulic radius is defined as the ratio of the cross-sectional flow area to the wetted perimeter:

$$R_h = \frac{A}{P} \quad (2)$$

where P is the wetted perimeter (m). The hydraulic radius is a key variable in hydraulic computations since it strongly influences the magnitude of bed shear stress and is used in fundamental flow resistance equations such as Manning's or Chezy's formula.

Shear Velocity (u_*)

The shear velocity, or friction velocity, characterizes the intensity of shear forces generated by the interaction between the flow and the channel bed. It can be expressed in terms of the bed shear stress (τ_0) and fluid density (ρ) :

$$u_* = \sqrt{\frac{\tau_0}{\rho}} \quad (3)$$

The bed shear stress is calculated as:

$$\tau_0 = \rho g R_h S \quad (4)$$

Where g is the gravitational acceleration (m/s^2), R_h is the hydraulic radius (m), and S is the energy slope (or channel bed slope).

The shear velocity is a critical parameter in open-channel hydraulics since it directly relates to sediment entrainment, bed stability, and flow resistance. A higher u_* indicates stronger shear forces acting on the channel bed, which increases the potential for sediment transport.

By analyzing the mean velocity (U), hydraulic radius (R_h), and shear velocity (u_*), a comprehensive understanding of the channel's hydrodynamic behavior can be achieved. These parameters form the foundation for evaluating flow conditions under both non-sediment-laden and sediment-laden scenarios and assessing flood control measures, channel stability, and sediment transport dynamics.

Chezy Coefficient (C)

The empirical determination of the Chezy coefficient was performed by applying established resistance equations, where flow resistance was expressed as a function of mean velocity, hydraulic radius, and energy gradient. Relationships were then tested and calibrated against the observed data to examine their applicability under sediment-laden flow conditions. Regression analysis and statistical evaluation were applied to assess the degree of agreement between observed and predicted Chezy values.

This methodological framework enables a systematic assessment of the empirical behavior of the Chezy coefficient under varying sediment transport regimes, thereby providing insight into the influence of sediment load on flow resistance.

The calculation of the flow resistance coefficient was carried out using the empirical Chezy formulation. The Chezy coefficient, C , can be determined by applying Equation (5), which defines the relationship between the mean flow velocity (U), hydraulic radius (R_h), and energy slope (S):

$$C = \frac{U}{\sqrt{R_h \cdot S}} \quad (5)$$

This Equation provides a practical means of quantifying flow resistance in open-channel hydraulics. By relating velocity and hydraulic parameters, the Chezy coefficient serves as an indicator of the overall hydraulic efficiency of the channel. Furthermore, its empirical application enables the assessment of resistance under various flow conditions, including sediment-laden flows, making it highly relevant for both laboratory experiments and field-based studies.

Statistical Analysis of the Relationship Between Hydraulic Parameters and the Chezy Coefficient

A statistical analysis was conducted using the Pearson correlation method to examine the relationship between hydraulic parameters and the Chezy coefficient (C). The analyzed hydraulic parameters include mean flow velocity (U), hydraulic radius (R_h), and shear velocity (u_*). Each parameter plays a significant role in characterizing open-channel flow conditions; therefore, evaluating their quantitative relationships with the Chezy coefficient is essential.

The correlation coefficient (R) was calculated to measure the strength and direction of the linear relationship between each hydraulic parameter and the Chezy coefficient. The Pearson correlation is expressed as:

$$R = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (6)$$

where x_i represents the values of hydraulic parameters (e.g., velocity or hydraulic radius) and y_i represents the corresponding Chezy coefficient values obtained from measurements or computations. The correlation coefficient (R) ranges from -1 to +1, where positive values indicate a direct relationship and negative values indicate an inverse relationship between the variables.

The results show that the correlation between the mean velocity (U) and the Chezy coefficient (C) exhibits a strong positive relationship, indicating that higher flow velocity generally corresponds to higher Chezy values. Similarly, the hydraulic radius (R_h) also shows a positive correlation with Chezy, though with a slightly weaker degree of association. This trend suggests that larger hydraulic radii reduce flow resistance, increasing flow efficiency as reflected by higher Chezy coefficients.

Overall, the correlation analysis provides a statistical foundation for understanding the interdependence between geometric and hydrodynamic characteristics of open-channel flow and the flow efficiency represented by the Chezy coefficient. The strong correlations observed among these parameters may be a basis for developing empirical models to estimate Chezy values using more easily measurable hydraulic parameters in field applications.

Mean Absolute Error (MAE)

This study aims to analyze the differences between non-sediment laden (NSL) and sediment laden (SL) flows by employing the statistical measure Mean Absolute Error (MAE). MAE is selected as it is a widely used method for quantifying the deviation of a parameter from its reference value. In this research, MAE is applied to evaluate the extent to which the hydraulic parameters of SL flow deviate from those of NSL flow. The analyzed hydraulic parameters include the ratio of mean velocity to shear velocity (U/u_*), the hydraulic radius (R_h), and the Chezy coefficient (C).

The MAE is calculated by taking the average of the absolute differences between the SL values and the corresponding NSL reference values. Thus, MAE represents the average magnitude of errors without considering their direction (positive or negative). Mathematically, the MAE formula can be expressed as follows:

$$MAE = \frac{1}{n} \sum_{i=1}^n |X - Y| \quad (7)$$

RESULTS AND DISCUSSION

Experimental Description

This laboratory study investigated 36 experimental data sets focusing on velocity profile distributions and their hydraulic characteristics under two distinct flow regimes: sediment-laden and non-sediment-laden. In this context, sediment-laden flow is defined as flow conditions where water actively transports sediment particles in suspension and bedload, thereby altering the velocity structure and turbulence characteristics. Conversely, non-sediment-laden flow refers to clear-water conditions, in which no sediment transport occurs and the flow dynamics are governed solely by hydraulic parameters.

The experimental program was designed to incorporate the physical properties of granular material and the variability of hydraulic conditions. Two types of non-cohesive sand were employed as sediment material: Sand D1 with a mean grain diameter of 1.55 mm and Sand D2

with a mean grain diameter of 1.85 mm. These materials were selected to represent very coarse sands that exhibit distinct sediment-transport behavior. In addition, a wide range of hydraulic parameters was systematically varied, including bed slope and flow discharge, to capture a comprehensive set of flow conditions.

All experiments were conducted in a recirculating flume with a fixed bed configuration, ensuring that only controlled variables such as slope, discharge, and sediment presence affected the results. Flow velocity profiles were measured at multiple verticals along the test section, and specific parameters were carefully defined to allow consistent comparison between experimental cases. The measured hydraulic variables include flow depth, mean velocity, Reynolds number, Froude number, and sediment concentration (for sediment-laden cases).

A coding scheme was developed to facilitate systematic identification of each dataset. The code begins with either “SL” representing sediment-laden flow or “NSL” representing non-sediment-laden flow. It is followed by an indication of sediment type, where “D1” refers to sand with a diameter of 1.55 mm and “D2” refers to sand with a diameter of 1.85 mm. Variations in bed slope are denoted as S1–S9, while variations in discharge are labeled as Q1–Q9. For instance, the code “NSLD1S1Q1” corresponds to a non-sediment-laden experiment using Sand 1 (1.55 mm), under slope condition S1, and flow discharge condition Q1. The complete summary of the primary flow parameters, including hydraulic conditions, sediment type, and corresponding experimental codes, is presented in Table 1. These tables serve as a reference framework for analyzing the influence of sediment transport, bed slope, and flow discharge on the velocity profile characteristics.

Table 1. Summary of main flow parameters from the experiment

Run	S (-)	H (m)	R_h (m)	U (m/s)	Q (l/s)	Q_s (kg/s)
Non-Sediment Laden Flow (Sand 1 = $d_{50} = 1.55$ mm)						
NSLD1S1Q1	0.0005	0.301	0.150	0.665	120	0
NSLD1S2Q2	0.001	0.232	0.131	0.790	110	0
NSLD1S3Q3	0.0015	0.194	0.118	0.859	100	0
NSLD1S4Q4	0.002	0.167	0.107	0.901	90	0
NSLD1S5Q5	0.0025	0.145	0.098	0.917	80	0
NSLD1S6Q6	0.0030	0.127	0.089	0.921	70	0
NSLD1S7Q7	0.0035	0.110	0.080	0.909	60	0
NSLD1S8Q8	0.0040	0.095	0.072	0.877	50	0
NSLD1S9Q9	0.0045	0.081	0.064	0.828	40	0
Sediment Laden Flow (Sand 1 = $d_{50} = 1.55$ mm)						
SLD1S1Q1	0.0005	0.301	0.150	0.665	120	0.0396
SLD1S2Q2	0.001	0.232	0.131	0.790	110	0.0363
SLD1S3Q3	0.0015	0.194	0.118	0.859	100	0.033
SLD1S4Q4	0.002	0.167	0.107	0.901	90	0.0297
SLD1S5Q5	0.0025	0.145	0.098	0.917	80	0.0264
SLD1S6Q6	0.003	0.127	0.089	0.921	70	0.0231
SLD1S7Q7	0.0035	0.110	0.080	0.909	60	0.0198
SLD1S8Q8	0.004	0.095	0.072	0.877	50	0.0165
SLD1S9Q9	0.0045	0.081	0.064	0.828	40	0.0132
Non-Sediment Laden Flow (Sand 2 = $d_{50} = 1.85$ mm)						
NSLD2S1Q1	0.0005	0.305	0.151	0.656	120	0

Run	S (-)	H (m)	R_h (m)	U (m/s)	Q (l/s)	Q_s (kg/s)
NSLD2S2Q2	0.001	0.236	0.132	0.777	110	0
NSLD2S3Q3	0.0015	0.197	0.119	0.844	100	0
NSLD2S4Q4	0.002	0.169	0.108	0.885	90	0
NSLD2S5Q5	0.0025	0.148	0.099	0.901	80	0
NSLD2S6Q6	0.003	0.129	0.090	0.906	70	0
NSLD2S7Q7	0.0035	0.113	0.082	0.888	60	0
NSLD2S8Q8	0.004	0.097	0.073	0.861	50	0
NSLD2S9Q9	0.0045	0.081	0.064	0.826	40	0
Sediment Laden Flow (Sand 2 = $d_{50} = 1.85$ mm)						
SLD2S1Q1	0.0005	0.305	0.151	0.656	120	0.037
SLD2S2Q2	0.001	0.236	0.132	0.777	110	0.034
SLD2S3Q3	0.0015	0.197	0.119	0.844	100	0.031
SLD2S4Q4	0.002	0.169	0.108	0.885	90	0.028
SLD2S5Q5	0.0025	0.148	0.099	0.901	80	0.025
SLD2S6Q6	0.003	0.129	0.090	0.906	70	0.022
SLD2S7Q7	0.0035	0.113	0.082	0.888	60	0.019
SLD2S8Q8	0.004	0.097	0.073	0.861	50	0.016
SLD2S9Q9	0.0045	0.081	0.064	0.826	40	0.012

Note: Sw = slope of the water surface; B : channel width (= 0.60 m); B/H = aspect ratio width to depth; T = temperature; d_{50} : median diameter of particle; U : cross-section mean velocity ($U = Q/A$); Re = Reynolds number; Fr = Froude number; Q : flow discharge; Q_s : measured sediment bedload (kg/s).

Flow Characteristics

The relationship between discharge (Q) and the dimensionless velocity ratio (U/u^*) under different flow conditions is presented in Figures 4(a) and (b). Figure 4(a) corresponds to non-sediment-laden (NSL) flow, while Figure 4(b) represents sediment-laden (SL) flow. Two sediment diameters were examined in the present study: Sand 1 with a median size of 1.55 mm and Sand 2 with a median size of 1.85 mm.

In the NSL condition (Figure 4a), both sediment sizes exhibit a consistent positive correlation between (U/u^*) and discharge. The data reveal that Sand 2 consistently yields higher discharge values than Sand 1 for a given velocity ratio, indicating that the presence of coarser sediment particles corresponds to reduced flow resistance under clear-water conditions. It suggests that channel roughness generated by bed material size plays a significant role in modulating the hydraulic efficiency of the flow.

The overall trend remains increasing for the SL condition (Figure 4b); however, the data distribution shows a noticeable shift compared to the NSL case. Introducing suspended sediment reduces the slope of the discharge–velocity ratio relationship, suggesting that additional resistance is imposed by sediment–fluid interactions. This effect becomes more pronounced as the sediment concentration increases, reflecting the dual role of suspended particles as both momentum carriers and dissipative agents. Similar to the NSL results, Sand 2 produces higher discharge than Sand 1 at equivalent velocity ratios, underscoring the sediment size's influence on the system's hydraulic response.

The statistical analysis of the experiments under Sand 1 and Sand 2 conditions demonstrates a strong correlation between the flow velocity ratio to shear velocity (U/u_*) and discharge (Q). As shown in Figures 4(a) and (b), the relationship exhibits a clear linear trend, indicating that an increase in U/u_* is directly proportional to an increase in discharge.

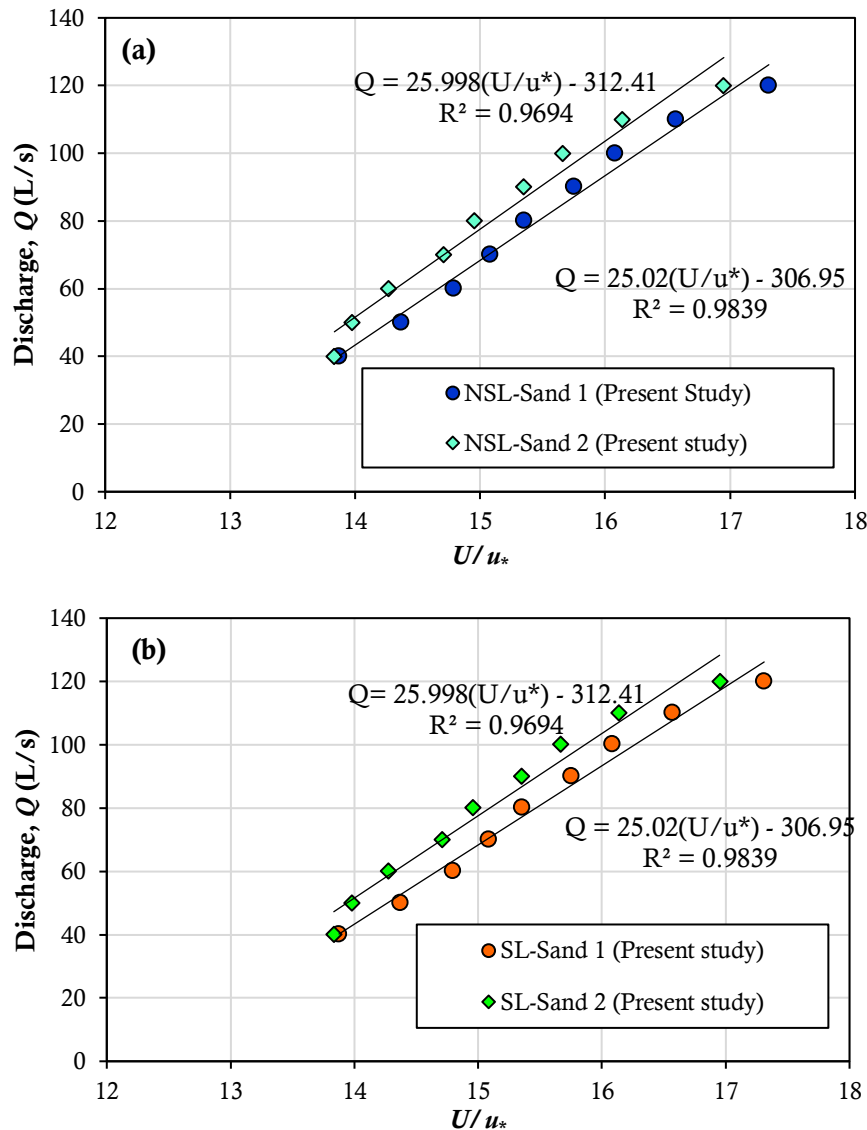


Figure 4. Ratio of Flow Velocity and Shear Velocity to Flow Discharge: (a) Non-Sediment Laden Flow, (b) Sediment Laden Flow

For Sand 1, the linear regression equation is $Q = 25.998(U/u_*) - 312.41$ with a coefficient of determination of $R^2 = 0.9694$. Meanwhile, Sand 2 yields a regression equation of $Q = 25.02(U/u_*) - 306.95$ with $R^2 = 0.9839$. Regarding correlation values, Sand 1 produces $R \approx 0.98$, while Sand 2 produces $R \approx 0.97$, indicating a powerful relationship. These findings suggest that flow velocity is dominant in controlling discharge estimation in clear-water and sediment-laden flow. Therefore, the ratio U/u_* can be a key indicator in predicting discharge, particularly in experimental studies and hydraulic calculations of open channel flows.

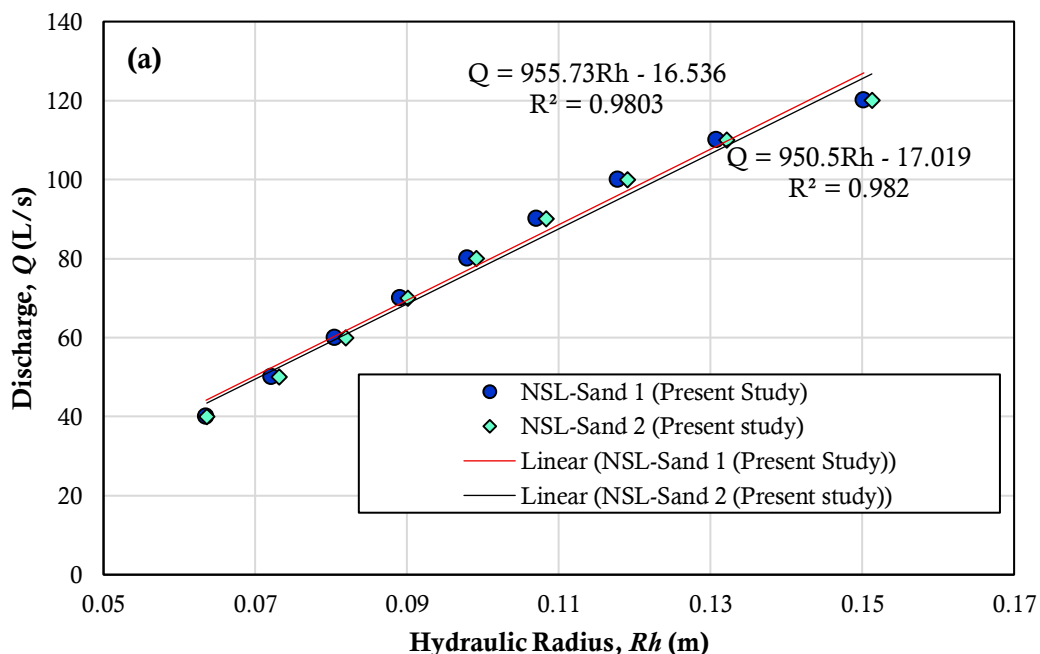
Figure 5(a) presents the relationship between discharge (Q) and hydraulic radius (R_h) for non-sediment-laden (NSL) flows with two sediment diameters, Sand 1 and Sand 2. The results

show a consistent increasing trend of discharge with hydraulic radius for both sediment sizes. The data for NSL-Sand 1 and NSL-Sand 2 exhibit close agreement, indicating that the influence of sediment size variation on discharge in clear-water conditions is relatively small. It suggests that the hydraulic behavior in non-sediment-laden flows is primarily governed by flow geometry and hydraulic radius. Importantly, Rh serves as a key parameter in the empirical estimation of the Chezy coefficient, as it directly influences the relationship between velocity, discharge, and resistance characteristics of the flow.

Figure 5(b) illustrates the corresponding relationship for sediment-laden (SL) flows under identical sediment diameters. Similar to the NSL condition, discharge increases progressively with the hydraulic radius; however, a closer examination shows that suspended sediment slightly reduces the discharge capacity compared to the NSL case. Both SL-Sand 1 and SL-Sand 2 maintain consistent patterns, with minor deviations attributable to sediment concentration and particle size. The reduced discharge in sediment-laden flow can be attributed to increased flow resistance and energy dissipation caused by sediment–turbulence interactions. In this context, the role of Rh becomes even more critical for Chezy coefficient estimation, as it not only reflects the geometric control of flow but also incorporates the compounded effects of sediment-induced resistance, making it an essential variable in empirical modeling of sediment-laden hydraulics.

The statistical analysis of the experiments under Sand 1 and Sand 2 conditions demonstrates a strong correlation between the hydraulic radius (R_h) and discharge (Q). As shown in Figures 5(a) and (b), the relationship exhibits a clear linear trend, indicating that an increase in R_h is directly proportional to an increase in discharge.

For Sand 1, the linear regression equation is $Q = 955.73R_h - 16.536$ with a coefficient of determination of $R^2 = 0.9803$. Meanwhile, Sand 2 yields a regression equation of $Q = 950.5R_h - 17.019$ with $R^2 = 0.982$. Regarding correlation values, Sand 1 produces $R \approx 0.98$, while Sand 2 produces $R \approx 0.98$, indicating a powerful relationship. These findings suggest that flow velocity is dominant in controlling discharge estimation in clear-water and sediment-laden flow. Therefore, the ratio R_h can be a key indicator in predicting discharge, particularly in experimental studies and hydraulic calculations of open channel flows.



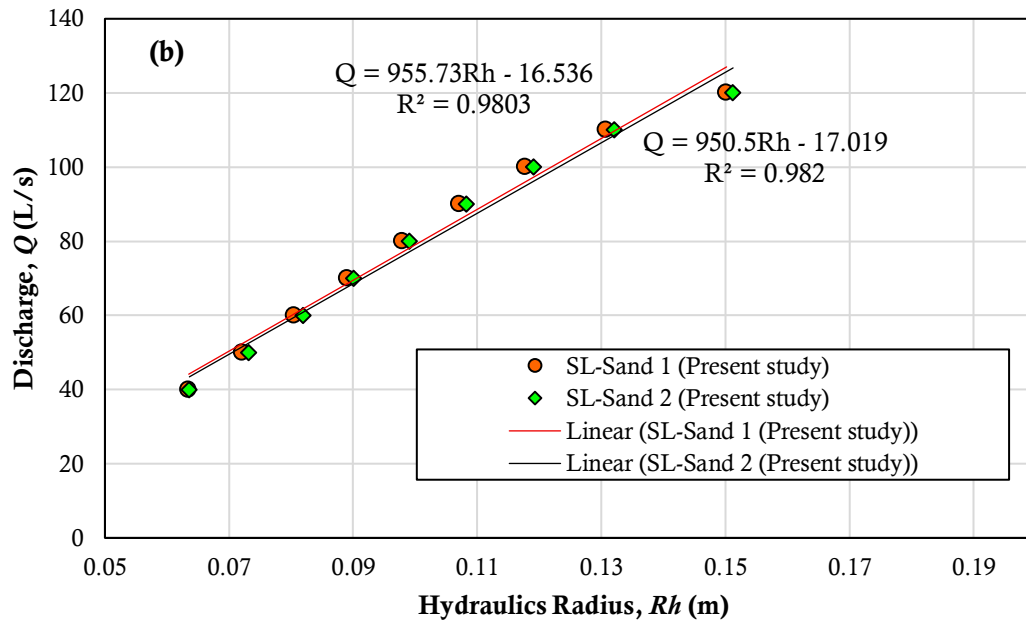


Figure 5. Comparison between the flow velocity distribution of non-sediment-laden and sediment-laden flow conditions

Empirical Method Flow Resistance Coefficient Value (Chezy Coefficient)

The estimation of the Chezy coefficient (C) with respect to the ratio of mean velocity (U) to shear velocity (u^*) reveals consistent patterns between the present study and previous research. The experimental data indicate that C generally increases with increasing U/u^* for non-sediment-laden (NSL) and sediment-laden (SL) flows. However, C values for NSL flows are consistently higher under comparable conditions than those for SL flows. It suggests suspended sediment enhances flow resistance, reducing hydraulic efficiency as reflected in lower Chezy coefficients (see Figure 6).

When compared with the literature, similar trends are observed in the laboratory experiments reported by Maini et al. (2025; 2024) and in field measurements from natural rivers and irrigation channels reported by Kironoto & Yulistiyanoto (2016), and Kironoto et al. (2019). The C values from the present study fall within a comparable range to those of these earlier works, reinforcing the validity of the finding that suspended sediment consistently contributes to increased flow resistance across laboratory and field conditions.

From an analytical perspective, the reduction of C in sediment-laden flows indicates that more flow energy is dissipated through particle–fluid interactions, including additional friction and turbulence generation (Apperley & Raudkivi, 1989; Chen et al., 2020; Hla, 2003; Zhong et al., 2015). Nevertheless, the results also highlight a limitation of conventional empirical formulations, as they cannot clearly differentiate Chezy coefficients between NSL and SL flows in detail. To overcome this, alternative approaches are required, such as those proposed by Maini et al. (2025; 2024), who introduced a method based on two-point velocity distribution measurements.

The statistical analysis presented in Table 2 reveals a robust linear correlation between the velocity ratio (U/u^*) and the Chezy coefficient (C) under various hydraulic conditions and sediment types. In general, an increase in the ratio between mean velocity and shear velocity corresponds to an increase in the Chezy coefficient, indicating a reduction in flow resistance and an enhancement of flow efficiency in energy transmission along the channel.

For the Sand 1 condition, both non-sediment-laden (NSL) and sediment-laden (SL) flows exhibit high coefficients of determination (R^2) of 0.9977 and 0.9584, respectively. These values indicate that more than 95% of the variation in the Chezy coefficient can be explained by changes in the velocity ratio, suggesting that the near-bed velocity structure and shear velocity play a dominant role in determining flow resistance.

A similar pattern is observed for the Sand 2 condition, with R^2 values of 0.9861 for NSL and 0.9213 for SL. Although the correlation under sediment-laden conditions is slightly lower, the linear relationship between the velocity ratio and the Chezy coefficient remains strong. It suggests suspended sediment does not significantly affect the statistical relationship, primarily because the mean velocity was computed using $U=Q/AU$. However, as indicated by Maini et al. (2024) and Maini et al. (2025), a notable difference exists between non-sediment-laden and sediment-laden flows, particularly within the inner region ($y/H < 0.2$). Therefore, determining the Chezy coefficient in sediment-laden flows may require a more detailed approach involving velocity distribution analysis and better investigation to capture the effects of turbulence and sediment transport.

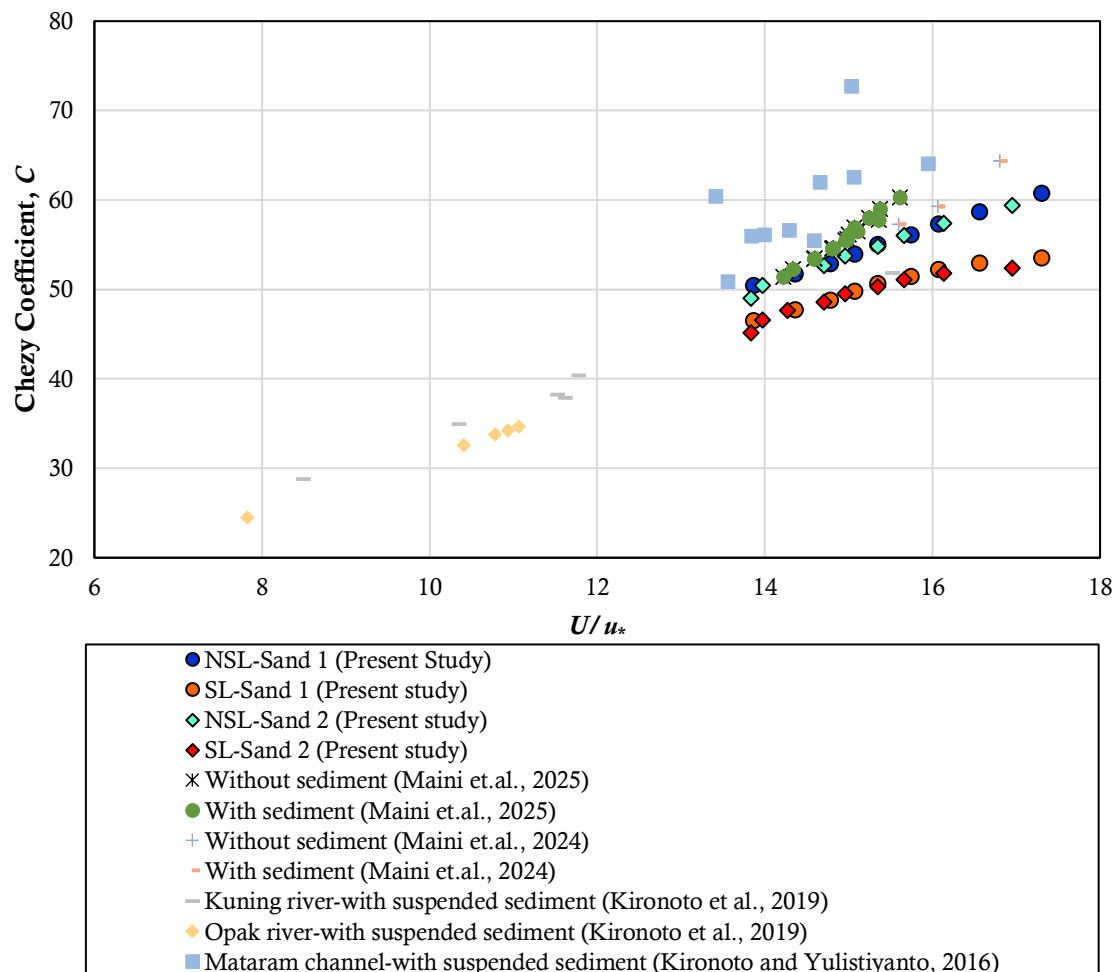


Figure 6. Chezy Coefficient vs. Ratio of Average Cross-Section Velocity and Shear Velocity

Compared with previous empirical studies on the estimation of the Chezy coefficient, the results of this study are consistent with the findings of Maini et al. (2024, 2025) and Kironoto et al. (2019). The correlation coefficients reported in those studies also indicate powerful

relationships, with R^2 values ranging from 0.9815 to 0.998, reinforcing the reliability of the velocity ratio (U/u^*) as a robust predictor of the Chezy coefficient under various flow and sediment conditions. Only in the Mataram Channel data ($R^2 = 0.4062$) was a considerably weaker correlation observed, likely due to field complexities such as irregular bed geometry, local flow separation, and unsteady sediment transport processes.

Overall, the correlation analysis confirms that the velocity ratio (U/u^*) exhibits a statistically strong relationship with the Chezy coefficient (C), particularly under controlled laboratory flow conditions. This relationship suggests that the velocity ratio can serve as a representative parameter to describe the interaction between hydraulic resistance, sediment characteristics, and energy transfer efficiency in open channel flow systems.

Table 2. Statistical Analysis of the Relationship Between Hydraulic Parameters and the Chezy Coefficient

No	Case Study	Linear Regression Equation	R^2
1	NSL- Sand 1 (Present Study)	$C = 3.0855(U/u^*) + 7.4223$	0.9977
2	SL- Sand 1 (Present Study)	$C = 2.1732(U/u^*) + 16.726$	0.9584
3	NSL- Sand 2 (Present Study)	$C = 3.222(U/u^*) + 5.252$	0.9861
4	SL- Sand 2 (Present Study)	$C = 2.2654(U/u^*) + 15.04$	0.9213
5	Without Sediment (Maini et al., 2025)	$C = 6.3292(U/u^*) - 38.834$	0.9815
6	With Sediment (Maini et al., 2025)	$C = 6.3292(U/u^*) - 38.834$	0.9815
7	Without Sediment (Maini et al., 2024)	$C = 5.9733(U/u^*) - 36.203$	0.9881
8	With Sediment (Maini et al., 2024)	$C = 5.9733(U/u^*) - 36.203$	0.9881
9	Kuning River-with suspended sediment (Kironoto et al., 2019)	$C = 3.2869(U/u^*) + 0.7281$	0.9925
10	Opak River-with suspended sediment (Kironoto et al., 2019)	$C = 3.1321(U/u^*) + 0$	0.998
11	Mataram Channel-with suspended sediment (Kironoto and Yulistiyanto, 2016)	$C = 4.9766(U/u^*) - 12.158$	0.4062

The comparison of Chezy coefficients derived from the empirical method for non-sediment-laden (NSL) and sediment-laden (SL) flows shows that the results are nearly indistinguishable. The data indicate that both conditions yield closely aligned coefficients, with the curves almost overlapping along the discharge range. The Mean Absolute Error (MAE) between the two datasets is only 0.02, confirming that the deviation between NSL and SL conditions is minimal and statistically insignificant. This very low MAE value indicates that the empirical method produces highly consistent estimates of the Chezy coefficient, with only a negligible average deviation across the entire discharge spectrum.

This outcome suggests that the empirical approach generates consistent values regardless of whether the flow carries suspended sediment. The percentage difference between NSL and SL conditions is close to zero (see Figure 7), implying that the empirical formulation cannot effectively capture the additional resistance generated by sediment presence. While this highlights the method's empirical validity for general flow applications, it also reveals its inability to account for subtle hydraulic changes in sediment-laden conditions. Such insensitivity may reduce the accuracy of resistance estimation in natural rivers or laboratory experiments involving significant sediment transport.

These findings point to the necessity of adopting alternative or complementary methods when analyzing sediment-laden flows. Approaches based on velocity distribution profiles or direct hydraulic measurements may provide greater sensitivity to sediment effects. Integrating such methods with empirical formulations would allow for more reliable estimation of the Chezy coefficient and improve the applicability of resistance models to both experimental and field-scale studies.

This approach has the potential to provide more representative estimates of flow resistance in sediment-laden conditions, underscoring the need for further research and deeper investigation. Furthermore, it should be emphasized that empirical methods for practical field purposes, particularly in sediment-laden flow conditions, must be approached cautiously. The inherent simplifications in empirical equations may not fully capture the complex interactions between flow and suspended sediments, which could lead to under- or over-estimation of hydraulic resistance. Therefore, while empirical methods remain applicable for preliminary assessments, careful validation with field measurements and more advanced approaches is necessary to ensure reliability in engineering design and water resources management.

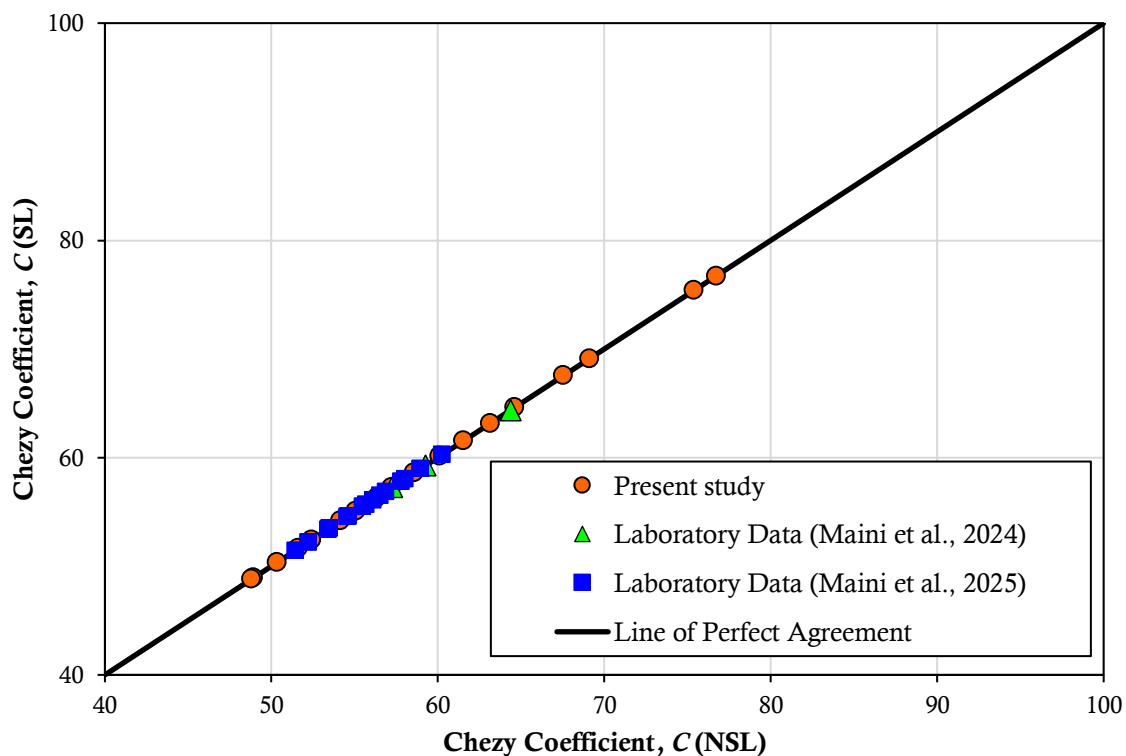


Figure 7. Comparison Between Chezy NSL Flow and SL Flow Coefficients

CONCLUSION

The results of this study demonstrate that the ratio of flow velocity to shear velocity (U/u^*) exhibits a robust correlation with discharge (Q) under both non-sediment-laden (NSL) and sediment-laden (SL) conditions, with a coefficient of determination (R^2) greater than 0.96. The increase in velocity ratio is proportional to the rise in discharge, indicating that flow velocity serves as a dominant parameter in discharge control and can be used as a primary indicator in open-channel hydraulic predictions.

The relationship between the hydraulic radius (R_h) and discharge (Q) also shows a strong linear trend ($R \approx 0.98$), emphasizing the significance of R_h in the empirical estimation of the Chezy coefficient (C), as it reflects the influence of channel geometry and flow resistance. The Chezy coefficient increases with the velocity ratio (U/u^*), but the values are slightly lower under SL conditions than those under NSL due to increased resistance caused by suspended sediment.

A comparison of C values obtained from the empirical method under NSL and SL conditions reveals a high degree of similarity, with a Mean Absolute Error (MAE) of 0.02, indicating minimal deviation and firm consistency. However, the empirical method shows limitations in capturing subtle variations induced by sediment effects. Therefore, incorporating additional approaches based on velocity distribution analysis or direct hydraulic measurements is recommended to enhance the accuracy of Chezy coefficient estimation, particularly for sediment-laden flows.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to the “Direktorat Jenderal Riset dan Pengembangan, Kementerian Pendidikan Tinggi, Sains, dan Teknologi Republik Indonesia (Program Penelitian Dosen Pemula BIMA Tahun 2025)”, for the financial support of this research through the Research Contract No. 1483ee/IT9.2.1/PT.01.03/2025, Fiscal Year 2025.

REFERENCES

- Apperley, L. W., & Raudkivi, A. J. (1989). The entrainment of sediments by the turbulent flow of water. *Sediment/Water Interactions. Proc. 4th Symposium, Melbourne, 1987*. https://doi.org/10.1007/978-94-009-2376-8_5
- Bjerklie, D. M., Dingman, S. L., & Bolster, C. H. (2005). Comparison of constitutive flow resistance equations based on the Manning and Chezy equations applied to natural rivers. *Water Resources Research*, 41(11). <https://doi.org/10.1029/2004WR003776>
- Cellino, M., & Graf, W. H. (1999). Sediment-Laden Flow in Open-Channels under Noncapacity and Capacity Conditions. *Journal of Hydraulic Engineering*, 125(5). [https://doi.org/10.1061/\(asce\)0733-9429\(1999\)125:5\(455\)](https://doi.org/10.1061/(asce)0733-9429(1999)125:5(455))
- Cellino, M., & Graf, W. H. (2000). Experiments on suspension flow in open channels with bed forms. *Journal of Hydraulic Research*, 38(4). <https://doi.org/10.1080/00221680009498328>
- Chen, X., Zhang, M., & Yu, G. (2020). Depth-Averaged von Kármán Coefficient in Sediment-Laden Flows Using a Turbulent Kinetic Energy Balance. *Journal of Hydraulic Engineering*, 146(4). [https://doi.org/10.1061/\(asce\)hy.1943-7900.0001713](https://doi.org/10.1061/(asce)hy.1943-7900.0001713)
- Chow, V. Te. (1959). *Open-Channel Hydraulics*. Ven Te Chow. McGraw-Hill, New York, 1959. xviii+ 680 pp. Illus. \$17. *Science*, 131(3408).
- Elgamal, M. (2021). A moment-based chezy formula for bed shear stress in varied flow. *Water (Switzerland)*, 13(9). <https://doi.org/10.3390/w13091254>
- Graf, W. H., & Altinakar, M. S. (2005). Transport of Sediments. In *Encyclopedia of Hydrological Sciences*. <https://doi.org/10.1002/0470848944.hsa147>
- Graf, W. H., & Cellino, M. (2002). Suspension flows in open channels; experimental study. *Journal of Hydraulic Research*, 40(4). <https://doi.org/10.1080/00221680209499886>
- Hla, M. M. (2003). Application of modified log-wake law in sediment-laden flows. In *Journal of Applied Fluid Mechanics* (Vol. 1, Issue 2).
- Kironoto, B. A., & Yulistiyo, B. (2016). The simplified of suspended sediment measurement method for predicting suspended sediment load as a basic of reservoir capacity design as renewable energy resource. *International Journal of Renewable Energy Research*, 6(1). <https://doi.org/10.20508/ijrer.v6i1.3026.g6788>
- Kironoto, B. A., Yulistiyo, B., Giarto, B., Kiptiah, M., & Tantowi, M. L. (2019). The Simplified of Suspended Sediment Measurement Method in Natural River (Case study of Kuning

- River in Yogyakarta, Indonesia). *Journal of the Civil Engineering Forum*, 5(3). <https://doi.org/10.22146/jcef.47061>
- Maini, M. (2024). *Pengaruh Transpor Sedimen terhadap Koefisien Kekasaran Manning di Saluran Terbuka* [Dissertation, Universitas Gadjah Mada]. <https://etd.repository.ugm.ac.id/penelitian/detail/243794>
- Maini, M., Kironoto, B. A., Istiarto, & Pamudji, A. P. (2024). Evaluating Manning's Roughness Coefficient for Flows with Equilibrium and Non-equilibrium Sediment Transport. *Jordan Journal of Civil Engineering*, 18(1), 65–80. <https://doi.org/10.14525/JJCE.v18i1.06>
- Maini, M., Kironoto, B. A., Rahardjo, A. P., & Istiarto. (2023). Flow Characteristics of Equilibrium and Non-equilibrium Sediment Transport Flows. *International Journal of GEOMATE*, 25(110), 77–86. <https://doi.org/10.21660/2023.110.3957>
- Maini, M., Kironoto, B. A., Rahardjo, A. P., & Istiarto. (2024). Effect of equilibrium and non-equilibrium sediment transport flows on the shear velocity in an open channel. *IOP Conference Series: Earth and Environmental Science*, 1311(1). <https://doi.org/10.1088/1755-1315/1311/1/012013>
- Maini, M., Kironoto, B. A., Rahardjo, A. P., & Istiarto. (2025). Alternative Method for Determining Manning's Roughness Coefficient Using Two-Point Velocity in Equilibrium and Nonequilibrium Sediment Transport. *Civil Engineering Journal*, 11(7), 2666–2685. <https://doi.org/10.28991/CEJ-2025-011-07-02>
- Passeri, D. L., Long, J. W., Plant, N. G., Bilske, M. V., & Hagen, S. C. (2018). The influence of bed friction variability due to land cover on storm-driven barrier island morphodynamics. *Coastal Engineering*, 132. <https://doi.org/10.1016/j.coastaleng.2017.11.005>
- Song, T., Chiew, Y. M., & Chin, C. O. (1998). Effect of Bed-Load Movement on Flow Friction Factor. *Journal of Hydraulic Engineering*, 124(2). [https://doi.org/10.1061/\(asce\)0733-9429\(1998\)124:2\(165\)](https://doi.org/10.1061/(asce)0733-9429(1998)124:2(165))
- Torabizadeh, A., Tahershamsi, A., & Tabatabai, M. R. M. (2018). Measurement of dimensionless Chezy coefficient in step-pool reach (Case Study of Dizin River in Iran). *Flow Measurement and Instrumentation*, 61. <https://doi.org/10.1016/j.flowmeasinst.2018.03.012>
- Zhong, D., Zhang, L., Wu, B., & Wang, Y. (2015). Velocity profile of turbulent sediment-laden flows in open-channels. *International Journal of Sediment Research*, 30(4). <https://doi.org/10.1016/j.ijsrc.2014.09.005>
- Zhou, J., Bao, W., Tick, G. R., Moftakhari, H., Li, Y., & Cheng, L. (2021). A modified chezy formula for one-dimensional unsteady frictional resistance in open channel flow. *Journal of Fluids Engineering, Transactions of the ASME*, 143(5). <https://doi.org/10.1115/1.4049681>