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Determination of Flow Rate Coefficient for Compound Weir: Trapezoidal-Rectangular Shape

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Abstract

Effective water resource management is vital for sustainable development and environmental resilience, with hydraulic structures such as compound weirs playing a key role in flow regulation. This study investigates the discharge coefficient, C_d and relationships between flow rate (Q), water height (H), and C_d of trapezoidal-rectangular compound weirs. Nine weir models with varying geometric configurations were tested to through controlled laboratory experiments at the Fluid Mechanics Laboratory at Universiti Tun Hussein Onn Malaysia. The Bernoulli equation was applied as the primary tool to compute theoretical flow rates and discharge coefficients. The findings reveal significant variations in C_d values where coefficients of determination (R^2) ranged from 0.95 to 0.99. It indicates strong relationships and high data reliability. For weirs with L_1 = 0.03 m and L_2 = 0.06 m, the average C_d values were between 0.54 and 0.63 for trapezoidal angles of 40°, 25°, and 15°, respectively. In contrast, weirs with L_1 = 0.05 m and L_2 = 0.08 m showed lower C_d values of 0.53, 0.51, and 0.47 for the same angles. This study enhances understanding of hydraulic behaviour in compound weirs and facilitates optimized design, providing significant insights for flood control, irrigation, and sustainable water management.

1. Introduction

Water resource management is essential for sustainable development, particularly in flood control and irrigation, where hydraulic structures such as compound weirs (e.g., trapezoidal–rectangular configurations) play a crucial role in regulating water flow [1]. Despite their widespread application, challenges persist due to limited understanding of complex hydraulic interactions, uncertainties in determining the discharge coefficient (C_d), and insufficient characterization of the relationship between flow rate (Q), water height (H), and C_d [2,3]. These limitations can lead to inaccuracies in flow measurement and reduced efficiency in hydraulic system design and operation.

Weirs are fundamental hydraulic structures used to measure and regulate water flow, with common types including rectangular, trapezoidal, and triangular (V-notch) weirs [4]. Among these, trapezoidal–rectangular compound weirs are preferred for their ability to accommodate a wide range of discharge conditions while maintaining high measurement accuracy [2]. Flow analysis over weirs is commonly based on the Bernoulli equation, which relates pressure, velocity, and elevation to estimate theoretical discharge [5]. Previous studies have demonstrated that geometric parameters—such as trapezoidal opening angles and hybrid configurations—significantly influence discharge coefficients, with sharper angles often enhancing hydraulic efficiency [6, 7]. Furthermore, experimental and numerical investigations conducted under controlled laboratory conditions have shown that weir geometry plays a critical role in governing flow characteristics and discharge behaviour in both simple and compound weirs [8].

In response to these challenges, this study experimentally investigates nine trapezoidal–rectangular compound weir models with varying geometric configurations under controlled laboratory conditions at Universiti Tun Hussein Onn Malaysia. The objectives are to measure water height at different flow rates, determine optimal discharge coefficients, and establish stronger hydraulic relationships between flow rate (Q), water height (H), and discharge coefficient (C_d). The findings are expected to enhance flow measurement accuracy, improve flow regulation performance, and support flood mitigation and irrigation systems through optimized hydraulic structure design [2, 8–9].

2. Materials and Methods

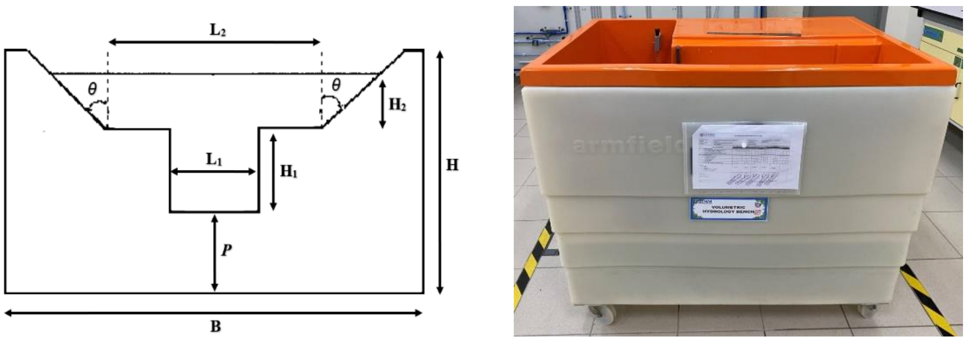
The study was conducted at the Fluid Mechanics Laboratory, Universiti Tun Hussein Onn Malaysia, using nine trapezoidal-rectangular compound weir models with varying geometric configurations. The materials included acrylic plates for the weir models, a hydraulic flume to control water flow, and measuring tools such as flow meters and point gauges. Each model was tested under controlled conditions by adjusting the flow rate and recording the corresponding water height. The Bernoulli equation was applied to calculate the flow rate coefficient (C_d), and the collected data were analyzed to evaluate the effects of geometry and angles on hydraulic performance.

2.1 Experiment Equipment

The experiment utilized nine trapezoidal-rectangular compound weir models designed with specific dimensions to analyze flow dynamics. Fig 1(a) illustrates the sketch of the trapezoidal-rectangular compound weir, while Fig 1(b) depicts the hydraulic bench used in the experiment.

Meanwhile, Table 1 shows the dimensions of the weir models with trapezoidal angles of 40°, 25°, and 15°, with rectangular opening lengths denoted as L_1 and L_2. The dimensions of the openings were L_1 = 0.03m, 0.04 m, 0.05m, and L_2 = 0.06m, 0.07m, 0.08m. Constant parameters for all models included the height of the weir from the datum, *P*=0.08 m, the width of the weir plate, B = 0.25m, the total height of the weir, 0.16 m, and the thickness of the plate, 3mm.

The hydraulic bench provided a controlled flow environment for precise experimentation. It featured a recirculating water tank connected to a pump, which maintained consistent flow rates. Measurement tools, including flow meters, point gauges, and a stopwatch, were used to accurately record flow rate and water height. A piezometer was incorporated to enhance the accuracy of flow rate measurement, ensuring reliable data for analysis.



(a) (b)

Fig. 1 *(a) Sketch of trapezoidal-rectangular compound weir; (b) Hydraulic bench*

J. Adv. Environ. Solut. Resour. Recover. Vol. 3 No. 1 (2026) p. 61-68

Table 1 *Dimension of weir model*

MODEL	1	2	3	4	5	6	7	8	9
Trapezoidal angle, θ	40°	25°	15°	40°	25°	15°	40°	25°	15°
Rectangular width, L_1	0.03	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.05
Trapezoidal width, L_2	0.06	0.06	0.06	0.07	0.07	0.07	0.08	0.08	0.08

2.2 Experimental procedures

Laboratory safety measures were carefully identified and strictly followed at every stage of the experiment, including preparation, execution, and conclusion. To ensure the reliability of the experimental setup, the equipment was thoroughly inspected to confirm it was functioning optimally. The experiment utilized nine different weir plates, with data collection focusing on water height and flow duration. The experimental process was conducted as follows:

a. The weir model was securely positioned on a hydraulic bench, and any gaps between the model and the bench were sealed with plasticine to prevent water leakage.
b. The control valve was adjusted to achieve the target water level in the tank.
c. Key measurements included the initial and final water heights (H_1 and H_2) as well as the time required to collect 5 liters of water in a volumetric tank. Each measurement was repeated three times at the designated water levels to ensure accuracy and consistency.
d. The procedure was repeated for each weir configuration, with incremental adjustments to the control valve to gradually increase the water level.

2.3 Equations

The Bernoulli equation is widely applied in engineering to solve problems related to force and energy, which are frequently encountered in practical scenarios. It provides a fundamental theoretical framework for performing hydraulic calculations in real-world engineering applications. In this study, these equations played a crucial and significant role in the analysis. The relevant equations are as follows:

$$Q_{experiment} = AV \quad (1)$$

$$Q_{theory} = \frac{2}{3} C_{rd}\sqrt{2g}\, L_1 H_1^{3/2} + \left(\frac{2}{3} C_{rd}\sqrt{2g}\, L_2 H_2^{3/2} + \frac{8}{15} C_{td}\sqrt{2g}\, tan(\theta/2) H_2^{5/2}\right) \quad (2)$$

$$C_d = Q_{experiment}/Q_{theory} \quad (3)$$

The coefficient of determination or R-squared, R^2 and linear regression are critical tools for assessing the strength of the relationship between two variables, enabling the prediction of one value within a model. This statistical technique is widely employed in studies that investigate the strength of relationships between variables.

3. Results and Discussion

Based on the nine trapezoidal-rectangular compound weir models, Table 2 presents result from experiments conducted with varying rectangular widths (L_1), trapezoidal extension width (L_2), and sidewall angles (θ = 15° , 25° , 40°). The table includes water heights (H), experimental and theoretical discharge values ($Q_{experiment}$, Q_{theory}), and the computed discharge coefficient (C_d). The data provides a comparative view of flow behavior across models with different geometric configurations.

The average water height across models ranged from 0.033 m to 0.065 m, showing consistent head development in the hydraulic bench setup. Models 3 and 6 recorded the highest average heads (0.065 m and 0.040 m respectively), while Model 7 showed the lowest average head of 0.033 m. These variations reflect the effect of different geometric designs on water level buildup upstream of the weir.

Across all models, the average values of $Q_{experiment}$ and Q_{theory} generally showed good consistency, indicating that the theoretical equations used (based on Bernoulli's principle) provided a reliable prediction of flow. For instance, Model 2 showed an average $Q_{experiment}$ of 0.044×10^{-3} m^3/s compared to Q_{theory} of 0.758×10^{-3} m^3/s, suggesting lower experimental discharge, possibly due to flow resistance or energy loss. On the other hand, Models 3 and 6 showed smaller gaps between theoretical and experimental values, reflecting more efficient discharge behavior.

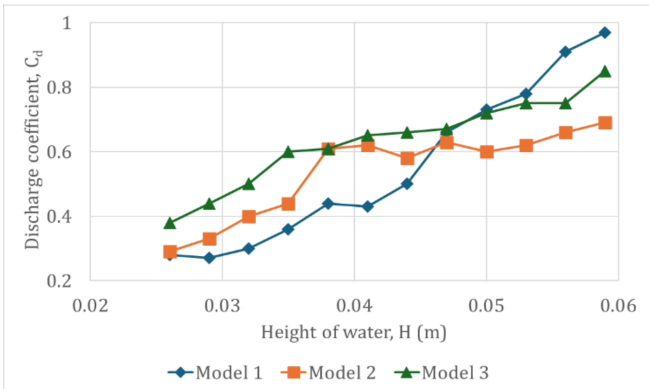
Meanwhile, the discharge coefficient C_d ranged from 0.47 to 0.63, with Model 3 achieving the highest average C_d of 0.63, followed by Model 6 and 5. These values suggest that certain weir geometries provide more efficient discharge with less energy loss. In contrast, Model 9 recorded the lowest C_d (0.47), indicating a greater deviation from ideal flow conditions. The variation in C_d reflects the influence of trapezoidal angles and rectangular lengths on flow dynamics. Higher C_d values are typically associated with smoother transitions and reduced turbulence, supporting the performance of optimized weir geometries. Overall, Table 2 demonstrates that model geometry significantly impacts flow efficiency, with experimental discharge performance improving in models that align closely with theoretical predictions. These insights are crucial for optimizing compound weir designs for flood control, irrigation, and flow regulation in hydraulic systems.

Table 2 *Experiment results for compound weirs models*

Model		1	2	3	4	5	6	7	8	9
Height of water, H = $H_1 + H_2$ (m)	Min	0.023	0.026	0.025	0.020	0.022	0.023	0.016	0.017	0.020
	Max	0.056	0.059	0.058	0.053	0.055	0.056	0.049	0.050	0.053
	Ave	0.036	0.043	0.065	0.037	0.039	0.040	0.033	0.034	0.037
$Q_{experiment}$ (x10^{-3} m^3/s)	Min	0.086	0.109	0.132	0.103	0.115	0.142	0.114	0.123	0.141
	Max	0.885	0.896	0.871	0.861	0.885	0.858	0.962	0.890	0.888
	Ave	0.383	0.044	0.450	0.397	0.444	0.475	0.448	0.456	0.459
Q_{theory} (x10^{-3} m^3/s)	Min	0.309	0.371	0.350	0.334	0.385	0.412	0.299	0.327	0.418
	Max	0.915	1.290	1.025	1.123	1.400	1.260	1.255	1.418	1.429
	Ave	0.613	0.758	0.671	0.729	0.832	0.817	0.783	0.839	0.911
C_d	Min	0.27	0.29	0.38	0.31	0.30	0.34	0.38	0.37	0.34
	Max	0.97	0.69	0.85	0.77	0.63	0.68	0.77	0.63	0.62
	Ave	0.55	0.54	0.63	0.49	0.50	0.53	0.53	0.51	0.47

3.1 Relationship Between Coefficient of Flow Rate, C_d and Height of Water, H

Figure 2 shows the relationship between C_d and H for model with variation trapezoidal-rectangular length opening L_1 and L_2. In Figure 2(a), Model 3 (green line, 15°) shows the highest discharge coefficient across nearly all water heights, indicating enhanced flow efficiency at a smaller trapezoidal angle. Model 1 (40°) and Model 2 (25°) show comparatively lower C_d values, but Model 1 demonstrates a sharp increase in C_d with higher H, suggesting improved discharge behaviour at elevated heads. Meanwhile, in Figure 2(b), the difference between the three models becomes less pronounced. All models show a consistent positive correlation between H and C_d, but the gaps between lines are smaller than in group (a), indicating more uniform performance. However, Model 4 still shows slightly better efficiency at higher heads. However, in Figure 2(c), which includes models with the largest geometric configuration, the discharge coefficient increases more gradually with height. While Model 7 records the highest C_d at the maximum water height, Models 8 and 9 show similar behaviour throughout. The reduced slope of the lines suggests that at larger opening sizes, the discharge becomes more stable but less sensitive to increases in head. Across all three configurations, a clear trend emerges: C_d generally increases with H, though the rate of increase and peak values depend on the geometric design. Smaller trapezoidal angles (e.g., 15°) appear to produce more stable and higher C_d, especially at higher water levels, while larger openings (higher L_1 and L_2) tend to reduce sensitivity to head variation but also slightly lower discharge efficiency. These trends confirm that geometry and angle selection are critical in optimizing compound weir performance, where sharper angles and shorter widths can improve discharge efficiency at specific flow conditions.



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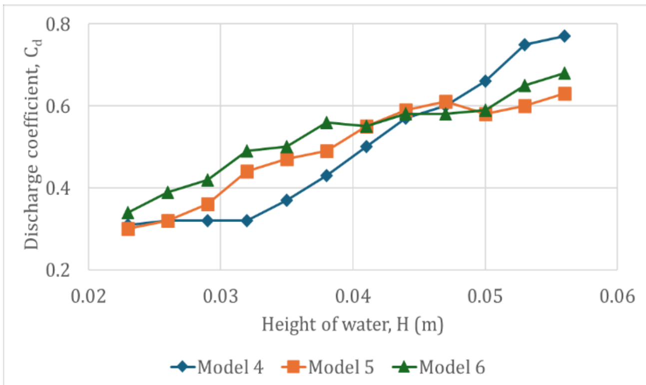

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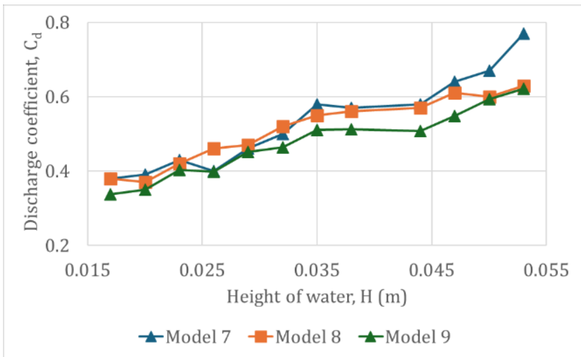

(c)

Fig. 2 *Relationship between Cd and H for model with trapezoidal-rectangular length opening L1 and L2; (a) L1=0.03 m and L2=0.06 m; (b) L1=0.04 m and L2=0.07 m; (c) L1=0.05 m and L2=0.08 m*

Table 3 presents the linear regression equations and corresponding R^2 values representing the relationship between the discharge coefficient (C_d) and water height (H) for all nine weir models. A positive correlation is observed in all models, where C_d increases with rising H, indicating that water height strongly influences flow efficiency. Models with larger trapezoidal opening angles (e.g., 40°) showed steeper gradients (e.g., Model 1: slope = 22.483, R^2 = 0.95), reflecting higher C_d at lower H. Conversely, models with smaller angles (15°), such as Model 9, achieved relatively consistent performance with a flatter slope (7.38) and high R^2(0.95), suggesting greater stability at higher water levels. All R^2 values exceed 0.80, ranging from 0.81 to 0.95 which demonstrating strong linear relationships and high reliability of the experimental data. These regression outcomes reinforce the influence of geometric design on discharge behaviour.

Table 3 *Equations from the relationship between Cd and H, and R2*

Model	1	2	3	4	5	6	7	8	9
Equation, y= mx+c	y = 22.483x - 0.403	y = 11.34x +0.0572	y = 12.238 x +0.111 6	y = 15.594x -0.1226	y = 10.443x +0.0825	y = 9.2657x +0.1615	y = 10.003x +0.1857	y = 7.2483x +0.2616	y = 7.3806x +0.2202
R^2	0.95	0.81	0.94	0.95	0.92	0.94	0.94	0.94	0.95

3.2 Relationship Between the Q_{theory} and $Q_{experiment}$

Figure 3 presents the comparison between experimental discharge ($Q_{experiment}$) and theoretical discharge (Q_{theory}) for nine compound weir models with different geometric configurations. In all subfigures (a, b, and c), the data exhibits a clear positive linear relationship, suggesting that the experimental results closely align with theoretical predictions, thus validating the reliability of the flow measurements and Bernoulli-based calculations. In Figure 3(a), which includes Models 1 to 3 with the smallest rectangular and trapezoidal openings (L_1 = 0.03m, L_2 = 0.06m), Model 2 shows the highest alignment between $Q_{experiment}$ and Q_{theory}, followed by Models 3 and 1. This indicates that a trapezoidal angle of 25° (Model 2) may provide more stable flow performance in this configuration. Figure 3(b), representing Models 4 to 6 (L_1 = 0.04m, L_2 = 0.07m), reveals consistently strong alignment across all three models. The overlapping trend lines suggest minimal variance in discharge behaviour, indicating that this mid-range geometric setup supports predictable and efficient flow conditions across the tested angles (15°, 25°, 40°). Figure 3(c), covering Models 7 to 9 with the largest openings (L_1 = 0.05m, L_2 = 0.08m), also demonstrates a strong linear trend, with Models 8 and 9 closely matching theoretical discharge rates. However, Model 7 slightly deviates at higher flow rates, possibly due to localized flow disturbances or increased turbulence.

Overall, the comparison validates the applicability of the theoretical model in predicting actual discharge values. Minor deviations in some models may be attributed to geometric influences on turbulence, flow separation, or energy losses, particularly in configurations with extreme angles or larger dimensions.

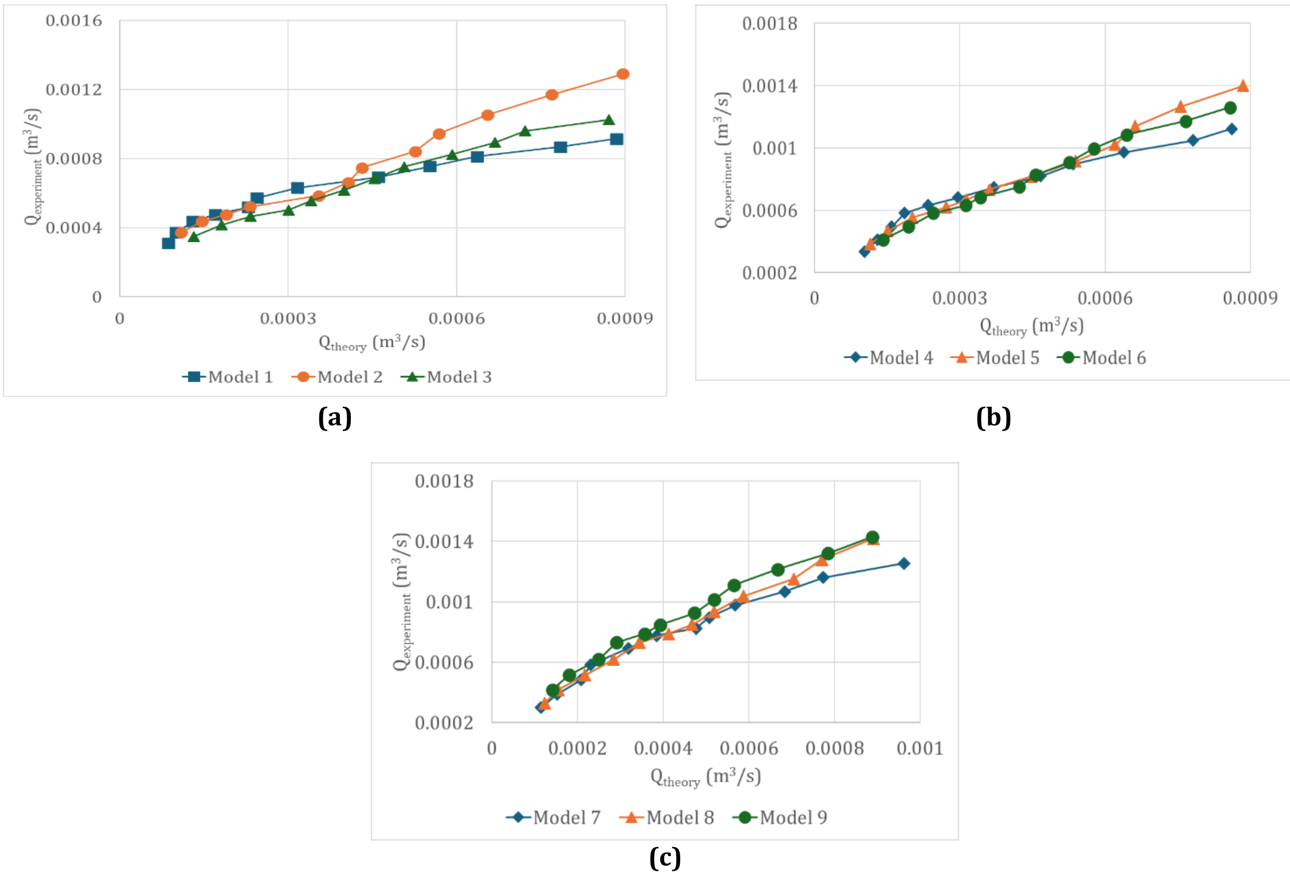

Fig. 3 *Comparison between Qexperiment and Qtheory of trapezoidal-rectangular compound weirs with opening L1 and L2; (a) L1=0.03 m and L2=0.06 m; (b) L1=0.04 m and L2=0.07 m; (c) L1=0.05 m and L2=0.08 m*

Table 4 outlines the linear regression equations y = mx + c , where y = $Q_{experiment}$ and x = Q_{theory}, along with the corresponding coefficients of determination (R^2) for each model. All nine configurations demonstrate a strong positive linear relationship, with R^2 values ranging from 0.9453 to 0.9896 for the smallest openings, 0.9507 to 0.9938 for medium openings, and 0.958 to 0.9946 for the largest openings. These values indicate high predictive accuracy and consistency between experimental and theoretical discharges.

Notably, the steepest regression slopes were observed for models with the largest openings, such as Model 9 (y = 1.3769x + 0.0002), Model 8, and Model 5, confirming that larger geometric openings result in more efficient flow behavior and higher discharge rates. Among the models with smaller openings, Model 2 (y = 1.1951x + 0.0002) also displayed a strong correlation, indicating that even narrow configurations can achieve reliable performance under optimal flow conditions.

Table 4 *Equation from the relationship between Qexperiment and Qtheory , and R2*

Model	1	2	3	4	5	6	7	8	9
Equation, y= mx + c	y = 0.6994x +0.003	y = 1.1951x +0.0002	y = 0.964x +0.0002	y = 0.964x +0.002	y = 1.2862x +0.0003	y = 1.2014x +0.0003	y = 1.1316x +0.0003	y = 1.339x +0.0003	y = 1.3769x +0.0002
R^2	0.95	0.99	0.99	0.95	0.99	0.99	0.95	0.99	0.99

Overall, the findings suggest that larger rectangular and trapezoidal openings consistently lead to superior discharge performance. This is reflected in higher regression slopes, which indicate steeper and more responsive flow relationships; stronger R^2 values, suggesting strong agreement between theoretical and measured data; and greater $Q_{experiment}$ values, which align well with predicted trends. While the 25° sidewall angle demonstrated stable performance across all opening sizes, the 40° and 15° angles appeared to favour larger configurations, likely due to smoother flow transitions and reduced energy losses.

In conclusion, the results support the reliability of the theoretical discharge model, as all computed C_d values fall within the acceptable theoretical range of 0.1 to 0.9. The high correlation between $Q_{experiment}$ and Q_{theory} further validates the experimental procedure and affirms the applicability of the Bernoulli-based discharge prediction model for compound weirs with various geometric designs.

4. Conclusion

This study successfully analyzed the hydraulic performance of trapezoidal-rectangular compound weirs by examining the relationships between the flow rate coefficient (Cd), water height (H), and discharge (Q) across varying geometric configurations. The results showed that smaller trapezoidal opening angles, particularly 15° and 25°, consistently produced higher Cd values, indicating superior discharge efficiency. Among all models, the configuration with L_1 = 0.03 m, L_2 = 0.06 m, and θ = 15° recorded the highest average Cd of 0.63. In contrast, the model with L_1 = 0.05 m, L_2 = 0.08 m, and θ = 15° showed the lowest average Cd of 0.47. Strong alignment between experimental and theoretical discharge values was confirmed, as evidenced by R^2 values exceeding 0.90 in most cases. These findings emphasize the importance of geometric optimization in enhancing hydraulic efficiency and contribute valuable insights into the design of compound weirs for effective water resource management.

Furthermore, the study demonstrated the adaptability of compound weirs under different hydraulic conditions. Smaller trapezoidal angles were effective in scenarios requiring high discharge efficiency, while larger angles offered consistent performance across a wider range of flow conditions. This adaptability supports the application of compound weirs in irrigation, hydropower, and environmental water systems where precision and flexibility are essential. Finally, the integration of advanced monitoring techniques with optimized geometric design opens new opportunities for performance enhancement. These findings not only validate the theoretical foundation of compound weir design but also pave the way for future innovations in sustainable water resource management. By refining design parameters and adopting modern engineering technologies, compound weirs can be further optimized to address contemporary hydrological challenges and infrastructure demands.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.

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