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Comparative analysis of hydraulic performance of oblique and triangular labyrinth weirs with equal crest length: An experimental investigation

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Abstract
Optimizing discharge capacity while maintaining low upstream water levels remains a challenge in hydraulic engineering, especially in constrained channels such as urban waterways, valleys, and flood-prone corridors. Oblique and triangular labyrinth weirs have been developed to increase effective crest length without widening the channel; however, the lack of direct experimental comparison under identical geometric conditions still leads to uncertainty in practical design selection. This study presents an experimental investigation and comparative performance analysis of an oblique and a triangular labyrinth weir with equal crest length (100 cm) under controlled laboratory conditions. The models, constructed from 10 mm acrylic sheets, were tested under steady free-flow conditions in a laboratory flume measuring 16.00 m × 0.50 m × 0.40 m. Discharge and upstream head were systematically measured to evaluate the discharge coefficient as a function of normalized head. The results showed that both nonlinear weirs outperformed a conventional linear weir (maximum discharge coefficient of 0.62), with the oblique weir achieving the highest performance with a peak discharge coefficient of 0.70, followed by the triangular labyrinth weir (0.66). At an equivalent upstream head of approximately 0.025 m, the oblique weir conveyed approximately 10–12% higher discharge than the labyrinth weir and 35–40% higher than the linear weir. The oblique weir outperformed the others due to reduced contraction, better flow alignment, and lower energy losses. In contrast, the triangular labyrinth weir suffered from nappe interference at higher heads, reducing efficiency. Overall, the oblique weir performed better and was more practical.

Keywords:
Discharge coefficient;
Experimental investigation;
Nappe interference;
Oblique weir;
Triangular labyrinth weir;

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INTRODUCTION

Traditionally, linear weirs constructed perpendicular to the flow direction have been widely used in hydraulic systems due to their structural simplicity and predictable hydraulic behavior. However, under high-flow conditions, such configurations often lead to higher upstream water levels and require extended embankments to convey the increased discharge [1] safely. These limitations reduce hydraulic efficiency, increase land-use requirements, and raise construction costs, particularly in settings with spatial constraints or stringent environmental regulations. Consequently, recent research has increasingly focused on alternative crest geometries such as oblique and labyrinth weirs that enhance discharge capacity without widening the channel [2][3].

Among these alternatives, oblique weirs and labyrinth weirs have received considerable attention. Both designs aim to extend the effective crest length and improve flow conveyance but employ distinct geometric strategies. The oblique weir accomplishes this by inclining the crest relative to the primary flow direction. In contrast, the triangular labyrinth weir increases crest length by folding the crest platform within the existing channel width. These configurations offer practical solutions for sites with limited space, such as urban channels, narrow floodways, or steep valley streams, where conventional linear weirs would be hydraulically or economically inefficient [4][5].

Recent studies have highlighted the hydraulic advantages of oblique weirs. Noori [6] reported that circular-crested oblique weirs with small inclination angles can increase discharge capacity by up to 175% compared to sharp-crested linear weirs, underscoring the strong influence of crest orientation on flow behavior. Une et al. [7] further showed that although oblique weirs effectively reduce upstream head, they may induce asymmetric flow patterns and promote downstream scour. More recently, an experimental investigation of combined oblique weir–gate systems has demonstrated the potential of such hybrid structures for enhanced flow regulation and operational flexibility [8]. In parallel, advanced computational tools have been employed to improve performance prediction; for example, Norouzi et al. [9] demonstrated that machine learning models can outperform conventional empirical equations in estimating discharge coefficients for nonlinear crest geometries. However, these studies focus mainly on isolated parameters or predictive modeling, lacking direct comparative evaluation of oblique weirs with other nonlinear crest geometries under equivalent conditions.

In contrast, labyrinth weirs, particularly triangular configurations, employ folded planforms to achieve crest-length amplification without increasing channel width. This geometry enables higher discharge rates at lower upstream heads, making them effective for spillway applications where precise water-level regulation is required [10, 11, 12]. Comparative studies have shown that triangular labyrinth weirs generally exhibit superior head–discharge performance relative to trapezoidal and rectangular configurations [13, 14, 15].

Furthermore, integrated laboratory and CFD investigations, such as those conducted by Aydın et al. [16], have clarified the mechanisms of nappe interference under varying flow conditions. Complementary numerical work by Idrees et al. [17] demonstrated that CFD models can reliably reproduce key hydraulic features, including nappe aeration and sub-atmospheric pressures, thereby reinforcing their value for design verification. In parallel, ongoing geometric refinements and the application of soft-computing techniques have further contributed to performance optimization and predictive modeling of labyrinth weirs [18, 19, 20, 21, 22, 23]. However, these studies are primarily confined to individual weir categories and lack direct comparison with other nonlinear geometries, limiting their relevance for comparative hydraulic design.

Despite substantial prior work, few studies directly compare oblique and triangular labyrinth weirs. Oblique weir research has mainly addressed inclination angle, approach depth, and upstream slope, while labyrinth weir studies have focused on crest-length ratio, nappe interference, and submergence. Although both outperform conventional linear weirs, their hydraulic behavior has rarely been assessed under identical experimental conditions [24][25]. This limitation prevents reliable comparison of the relative hydraulic performance of the two geometries under normalized conditions, such as equal crest length.

Existing evidence suggests that oblique weirs can enhance discharge capacity by increasing effective crest length, although their discharge coefficient generally decreases with steeper inclination angles [26]. Triangular labyrinth weirs, in contrast, typically provide greater crest-length amplification and higher discharge potential but are more susceptible to nappe interference, apex-angle sensitivity, and reduced efficiency at elevated relative heads [27, 28, 29]. However, the relative significance of these competing hydraulic mechanisms remains unquantified within a controlled experimental framework. The lack of systematic side-by-side comparisons limits practical design decisions, particularly when balancing discharge capacity, upstream afflux, and flow-regime stability [1].

To address this knowledge gap, this study experimentally compares oblique and triangular labyrinth weirs with the same effective crest length. The oblique weir geometry is transformed into an equivalent triangular labyrinth configuration ($L = 2A$), as schematically illustrated in Figure 1. Accordingly, the novelty of this study lies in a controlled experimental comparison of two nonlinear weir geometries under identical crest length and boundary conditions, enabling clearer isolation of crest-geometry effects. This approach provides a more rigorous evaluation of discharge behavior and supports more reliable design selection in space-constrained applications.

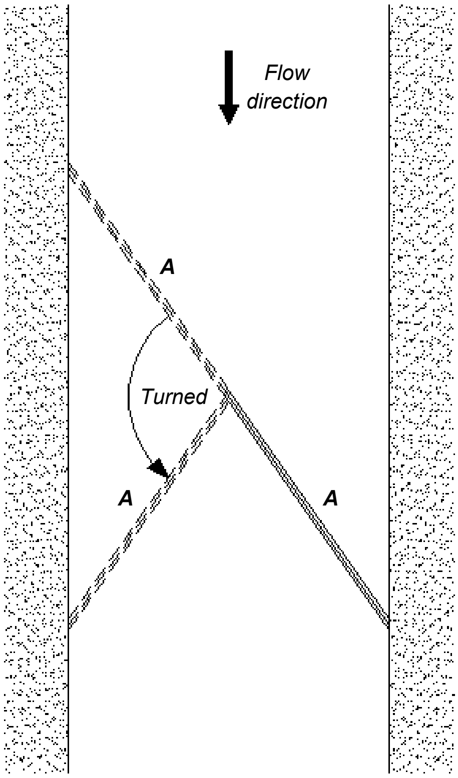

Figure 1. Schematic of converting an oblique weir to a triangular labyrinth weir with equal crest length $L = 2A$.

METHOD

Three weir models were tested in an open-channel flume (16.00 m × 0.50 m × 0.40 m) at the Civil Engineering Laboratory, Tadulako University, Indonesia. The flume is equipped with a reservoir tank, pump, piping network, inlet tank, flow control gate, and a Thomson weir for discharge measurement. The laboratory setup is shown in Figure 2.

Subsequently, the procedure included setup, fabrication, measurement, validation, calculation, and analysis, applied uniformly to all weirs. Figure 3 shows the research flowchart.

Methods and Theoretical Background

The following equations quantify discharge characteristics for each weir configuration. The theoretical framework employed in this study provides the basis for analyzing the hydraulic behavior observed in the physical experiments. Specifically, it defines key governing parameters such as upstream head, crest geometry, and approach flow conditions. It also establishes the fundamental discharge–head relationships for sharp-crested weirs.

For each weir configuration (linear, oblique, and triangular labyrinth), the framework relates the measured discharge to an effective crest length and a corresponding discharge coefficient, expressed as a function of normalized head. This enables systematic comparison of hydraulic performance across different geometries under dynamically similar conditions and supports interpretation of phenomena such as nappe interference, flow contraction, and variations in discharge efficiency.

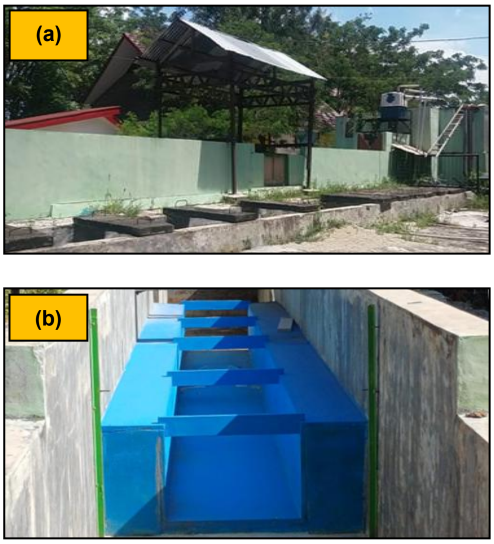

Figure 2. (a) Outdoor flume; (b) Open-channel test flume.

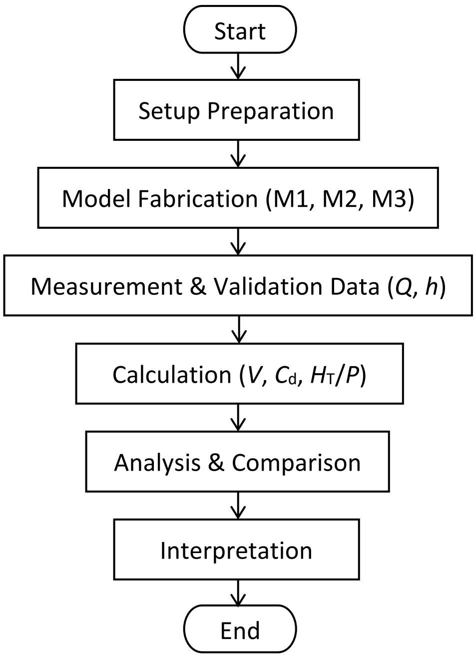

Figure 3. Research flowchart

The fundamental discharge principles governing these structures are applicable across all weir types, whether conventional straight-crested, oblique, or labyrinth. Under free-flow conditions in an open channel, the volumetric discharge over a weir can be expressed by the classical weir equation, as shown in (1) [30]:

$$Q = \frac{2}{3} C_d \, L \, \sqrt{2g} \;\, {H_T}^{1.5} \quad (1)$$

where Q is the discharge rate, C_d is the discharge coefficient, L is the effective crest length, g is the gravitational acceleration, and H_T is the total upstream head above the weir crest.

The discharge coefficient C_d is not a constant; it is a complex function of both geometric and hydraulic parameters. These include weir height (P), crest thickness (t), upstream head (h), approach flow velocity (V), and crest shape (e.g., linear, oblique, labyrinth, circular). For nonlinear weir geometries in particular, these interdependencies make it essential to accurately characterize C_d in order to obtain reliable predictions of hydraulic performance.

The total head (H_T), which governs the discharge capacity over the weir, is obtained by combining the hydrostatic and kinetic energy components, as expressed in (2),

$$H_T = h + V^2/2g \quad (2)$$

where h is the static head measured vertically from the weir crest to the upstream water surface, and V is the mean approach flow velocity at a specified distance upstream of the weir. This formulation incorporates the contribution of kinetic energy to the total head, which can be significant in rapidly varying flows or in relatively narrow channels where approach velocities are non-negligible. By including the velocity head, the total energy state of the flow is more accurately represented, leading to improved reliability in discharge calculations, particularly when the velocity component forms an appreciable portion of the total head.

The fundamental distinction between the different weir configurations used in this study arises from the way their effective crest length, L, is defined and computed. This parameter directly governs the discharge capacity for a given upstream head and is therefore central to the comparison of hydraulic performance.

For a conventional normal (linear) weir, which is aligned perpendicular to the direction of flow, the effective crest length is equal to the channel width:

$$L = B \quad (3)$$

In this expression, B represents the channel width, which, in the present experimental setup, coincides with the crest length of the flume itself. As a result, the linear weir does not introduce any geometric extension of the crest beyond the physical width of the channel.

In contrast, the oblique weir increases the effective crest length by tilting the crest at an angle relative to the main flow direction. For an oblique weir, the effective crest length is given by:

$$L = \frac{B}{\sin\theta} \quad (4)$$

Here, θ denotes the inclination angle measured between the weir crest and the longitudinal axis of the channel. As θ decreases from 90º (the linear case) toward smaller angles, sinθ decreases, and the effective crest length L increases. Thus, without enlarging the channel width, the oblique arrangement geometrically extends the crest and potentially enhances discharge capacity.

For the triangular labyrinth weir, the increase in crest length is achieved by folding the crest into a repeating zigzag pattern within the same channel width. The effective crest length for a triangular labyrinth weir can be expressed as:

$$L = N \text{ x } 2A \quad (5)$$

In this relation, N is the number of complete cycles (or repeating triangular units) along the weir, and A denotes the leg length of each triangular segment in plan view. Each cycle contributes two legs of length A to the total crest length, hence the factor 2A.

Furthermore, a schematic representation of the hydraulic profile, geometric parameters, and flow characteristics associated with weir structures is shown in Figure 4 [31].

Material and Limitations

Three weir models were built from 10 mm acrylic for accuracy, transparency, and durability. A conventional linear weir with a crest length L = 50 cm (equal to the flume width) served as the reference. The oblique and triangular labyrinth weirs each had an effective crest length L = 100 cm, inclination angle θ = 30°, and height P = 15 cm, allowing isolation of crest geometry effects on hydraulic performance.

A half-round crest was used on all weirs to standardize flow and ensure uniform nappe formation. The triangular labyrinth weir employed a single cycle for direct comparison, with key dimensions shown in Table 1 and Figure 5.

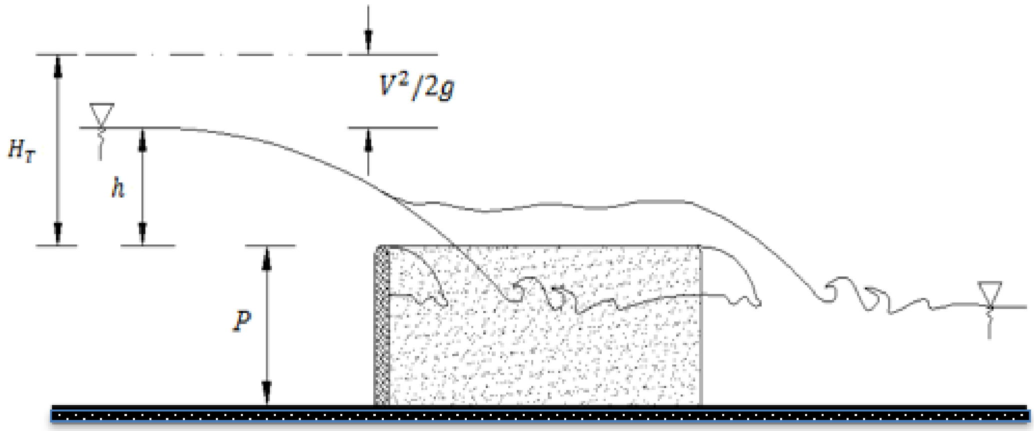

Figure 4. Hydraulic parameters of the weir.

Table 1. Geometric characteristics of the weir model tests

Model	Weir Type	Effective Length *L* *(cm)*	Weir Height *P* *(cm)*	Number of Cycles *N*	Crest Shape
M1	Normal weir	50	15	-	HR
M2	Oblique weir	100	15	-	HR
M3	Triangular labyrinth weir	100	15	1	HR

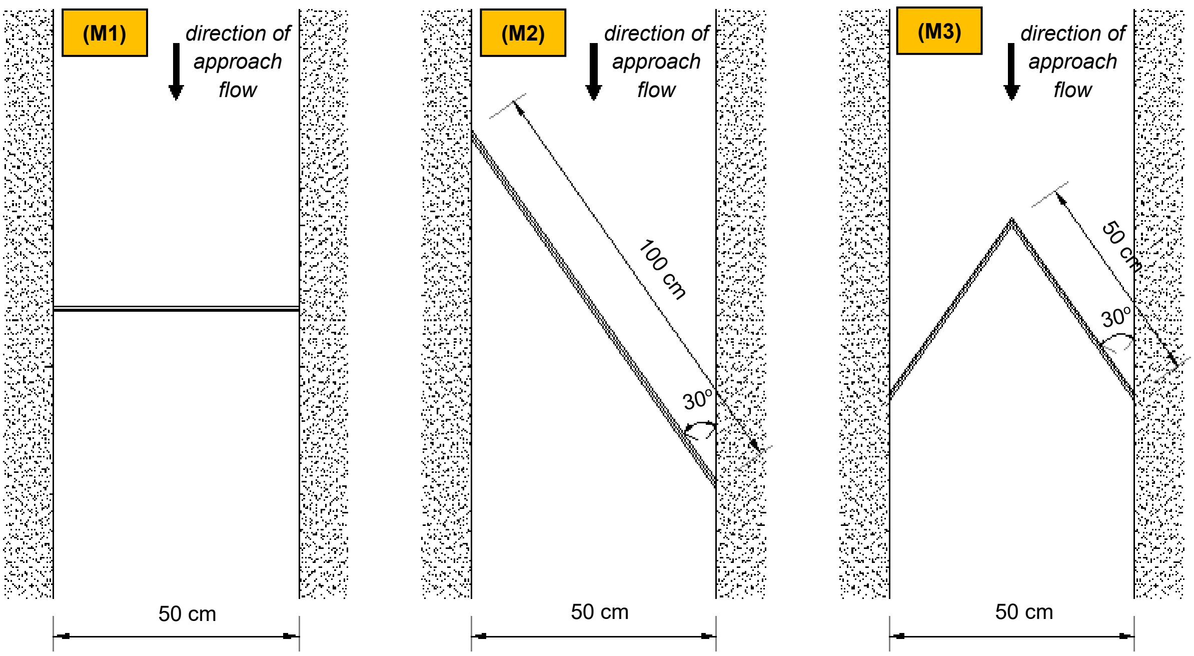

Figure 5. Weir configurations tested in the laboratory: (M1) conventional linear weir; (M2) oblique weir; and (M3) triangular labyrinth weir.

However, due to limitations in the laboratory flume geometry, the upstream head was maintained within a relatively low range (*h* = 0.007–0.036 m). This range is close to the threshold where surface tension and viscous forces may begin to influence the flow. Nevertheless, similar low-head conditions have been reported in previous experimental studies. For instance, Ghasemvand et al. [1] reported that hydraulic losses and discharge behavior exhibit increased sensitivity at low hydraulic heads, while still enabling reliable measurements under well-controlled laboratory conditions.

This study aims to compare the hydraulic behavior of oblique and triangular labyrinth weirs under controlled laboratory conditions, rather than to replicate full-scale prototype performance. The experimental setup ensures consistent boundary conditions for a systematic evaluation of discharge characteristics across different crest geometries.

Although the upstream head range approaches the lower limit of ideal hydraulic conditions, it remains adequate for capturing reliable trends and relative performance differences. Therefore, the results are considered valid for analyzing flow mechanisms, discharge efficiency, and comparative behavior between weir configurations within a controlled experimental context.

Furthermore, to determine whether the increase in discharge is commensurate with the associated design complexity and construction cost, a qualitative assessment was carried out based on the geometric configuration and structural requirements of each weir type. A single inclined crest characterizes the oblique weir, whereas the triangular labyrinth weir involves a folded crest geometry with higher structural complexity. These differences were systematically evaluated in relation to their respective discharge capacities to assess the balance between hydraulic performance, design complexity, and construction considerations.

Moreover, the C_d was evaluated to examine how it is influenced by crest shape, flow angle, and interactions between adjacent flow paths. The coefficient was determined from measured discharge and upstream head using standard weir equations. Variations in crest geometry and inclination were analyzed in terms of their effects on flow contraction, nappe aeration, and energy losses. For nonlinear weirs, including oblique and labyrinth configurations, interactions between flow paths, such as nappe interference and localized turbulence, were also considered. In addition, the dependence of C_d on water level was analyzed to evaluate its variability and to assess its implications for the accuracy of discharge calculations.

Data Validation and Analysis

All measuring instruments were calibrated prior to testing to ensure accuracy. Furthermore, measurements were conducted under steady-flow conditions, and each test was performed three times, with the average values used for subsequent analysis. This procedure also served as a repeatability test, with variations among repeated measurements remaining below 3%, indicating good experimental consistency.

In addition, an uncertainty analysis was carried out by considering the accuracy of discharge and head measurements. The uncertainty in head measurement was ±0.1 mm, while discharge uncertainty was primarily related to the calibration of the Thomson weir. Overall, the uncertainty of the discharge coefficient (C_d) was estimated to be within ±5%.

RESULTS AND DISCUSSION

Figure 6 presents photographic documentation of the physical models and their installation within the laboratory flume, providing visual confirmation of crest geometries, structural dimensions, and the overall experimental layout. These images also illustrate the relative positioning of each weir type within the flume, highlighting the standardized boundary conditions and uniform approach flow applied throughout the testing program.

In addition to visual observations, detailed hydraulic measurements, including discharge rates, upstream water surface elevations, and related flow parameters, are reported in Table 2. This table summarizes the complete range of tested flow conditions and corresponding head values for each model, enabling a systematic comparison of their hydraulic performance. Using this controlled dataset, the behavior of the conventional, oblique, and triangular labyrinth weirs can be quantitatively assessed, allowing a rigorous evaluation of discharge capacity, head-discharge relationships, and overall flow conveyance efficiency under laboratory conditions.

Based on this dataset, the variation of the discharge coefficient (C_d) with the dimensionless upstream head ratio (H_T/P) for all three weir configurations is presented in Figure 7. As illustrated, the fitted trend lines and their corresponding coefficients of determination (R^2) indicate a very strong correlation between C_d and H_T/P for each model, with R^2 values consistently exceeding 0.98. These relationships were derived using regression analysis, demonstrating a high level of statistical reliability in the experimental data. The regression equations for each weir configuration can be expressed as second-order polynomial functions of H_T/P. A predictive model is proposed as follows:

- **Linear weir (M1)**:

$$C_d = -28.76\left(\frac{H_T}{P}\right)^2 + 11.01\left(\frac{H_T}{P}\right) - 0.42 \qquad (6)$$

- **Oblique weir (M2)**:

$$C_d = -50.67\left(\frac{H_T}{P}\right)^2 + 15.31\left(\frac{H_T}{P}\right) - 0.46 \qquad (7)$$

- **Triangular labyrinth weir (M3)**:

$$C_d = -52.61\left(\frac{H_T}{P}\right)^2 + 15.51\left(\frac{H_T}{P}\right) - 0.48 \qquad (8)$$

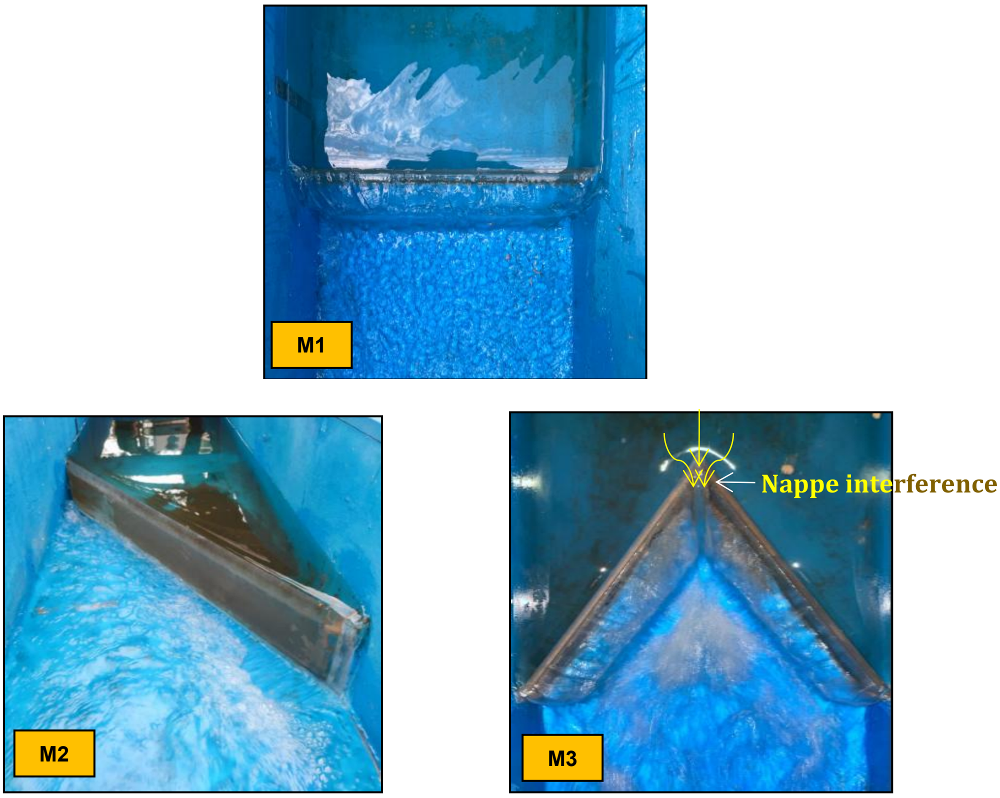

Figure 6. Photograph of the flow condition in all physical model tests.

Table 2. Summary of the data ranges obtained from the weir model experiments.

Model	Weir type	Discharge Q (m^3/s)	Head over the weir h (m)	Upstream head ratio H_T/P	Discharge coefficient C_d	Number of runs
M1	Normal weir	0.0003-0.0059	0.0100-0.0365	0.07-0.24	0.20-0.64	18
M2	Oblique weir	0.0003-0.0083	0.0070-0.0260	0.05-0.18	0.17-0.71	20
M3	Triangular labyrinth weir	0.0002-0.0075	0.0071-0.0250	0.05-0.17	0.14-0.67	20

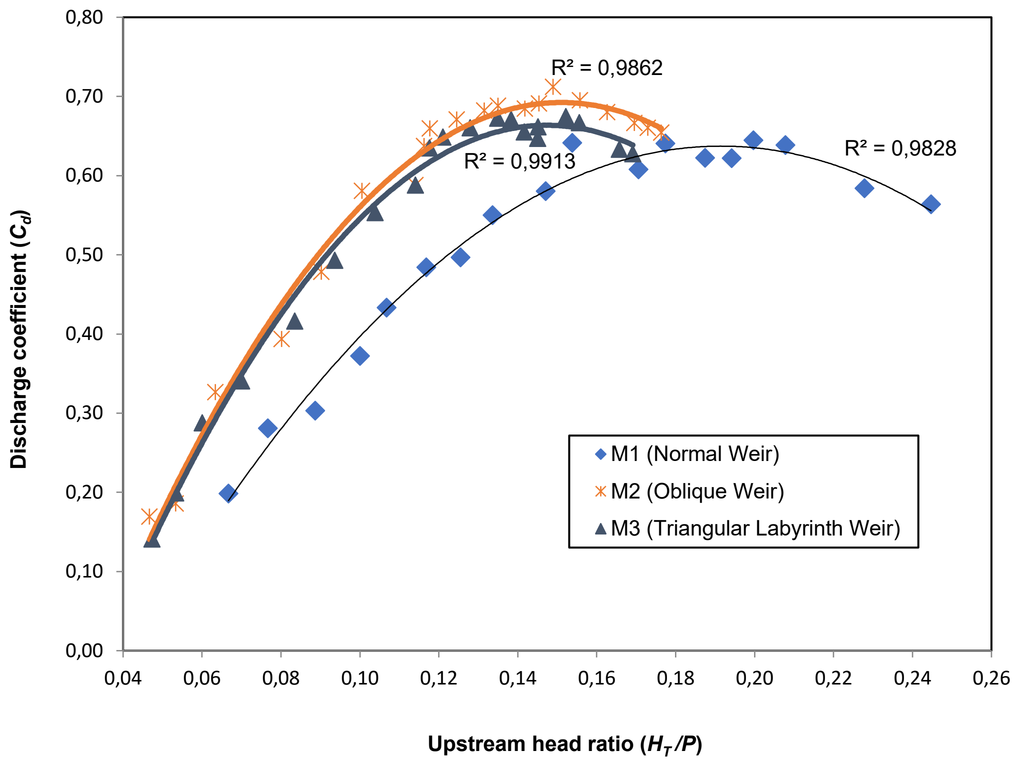

Figure 7. Discharge coefficient (C_d) vs. normalized head (H_T/P) for all models.

Furthermore, to strengthen the statistical interpretation, a one-way ANOVA was conducted to assess the statistical significance of the differences in discharge coefficient (C_d) among the three weir configurations. The analysis yielded an F-value of 15.72 with a p-value < 0.001, indicating statistically significant differences. This result confirms that the observed variations in hydraulic performance are primarily governed by crest geometry rather than experimental variability, consistent with the high regression coefficients (R^2 > 0.98) and low measurement uncertainty reported in this study.

A closer examination of the curves in Figure 7 reveals that the oblique weir (M2) attains a slightly higher maximum discharge coefficient than the triangular labyrinth weir (M3). Although modest, this difference indicates that the oblique crest improves hydraulic efficiency by increasing effective crest length and reducing the required upstream head. As a result, the oblique configuration outperforms the labyrinth arrangement under similar operating conditions. A comparative assessment indicates that the differences in discharge coefficients among the tested configurations remain consistent across the examined head range, confirming the robustness of the observed hydraulic behavior.

To enable a direct comparison of discharge capacity under equivalent upstream head conditions, the data were evaluated within similar head ranges. At $h \approx 0.025$ m, the oblique weir (M2) conveys approximately 0.0080 m^3/s, compared to about 0.0075 m^3/s for the triangular labyrinth weir (M3) and 0.0050 m^3/s for the conventional linear weir (M1). This corresponds to an increase of roughly 10–12% over the labyrinth weir and 35–40% over the linear weir. These results demonstrate that the oblique weir provides a notable enhancement in discharge capacity.

The C_d–H_T/P relationships for all models follow the expected pattern: the discharge coefficient increases at low H_T/P, reaches a maximum, and then decreases as H_T/P continues to grow. This behavior reflects the combined influence of nappe aeration, flow contraction, and approach flow conditions on crest efficiency. Within this general trend, the oblique weir consistently yields the highest C_d values. It reaches a peak discharge coefficient of approximately 0.70 at an H_T/P of about 0.14. The triangular labyrinth weir, although slightly less efficient, still performs favorably, achieving a maximum C_d of roughly 0.66 at a similar head ratio.

By contrast, the conventional normal (linear) weir (M1) exhibits the lowest discharge coefficients across the full range of H_T/P examined. Its peak C_d is only about 0.62, occurring at an H_T/P of approximately 0.18. This comparatively lower performance indicates a reduced capacity of the normal weir to convert upstream head into discharge for the same crest height, emphasizing the limitations of a shorter, perpendicular crest in constrained channels.

A more detailed quantitative comparison further clarifies these differences. The oblique weir shows an increase in the discharge coefficient (C_d) of approximately 12–13% compared to the conventional linear weir and about 5–6% relative to the triangular labyrinth weir under similar operating conditions. These results highlight the important role of crest geometry modification in improving discharge capacity.

Taken together, these findings clearly demonstrate that crest geometry exerts a strong and direct influence on hydraulic performance. The extended crest length and modified flow alignment provided by the oblique and labyrinth configurations yield measurable improvements over the traditional linear design. Among the tested models, the oblique weir delivers the highest overall efficiency, followed by the triangular labyrinth weir, while the normal weir is the least effective due to its shorter crest length and less favorable hydraulic characteristics. This hierarchy of performance is consistent with previous investigations that underscore the importance of crest length extension and geometric optimization in enhancing weir discharge capacity and reducing upstream water levels [32].

At relatively low head ratios ($H_T/P < 0.10$), the discharge characteristics of the oblique weir and the triangular labyrinth weir are practically indistinguishable, as evidenced by their nearly identical discharge coefficient (C_d) values over this range. This close agreement suggests that, when the available energy head is small, the potential hydraulic benefits associated with increasing the effective crest length or altering the flow direction through geometric modification are not yet fully realized or expressed in measurable performance differences.

In this low-head regime, the overflow nappe for both configurations is well aerated, coherent, and hydraulically stable along the crest. As a result, flow separation, nappe interference, and local contraction effects are minimal, leading both weir types to operate with comparable efficiency despite their distinct planform geometries.

As the dimensionless head ratio increases ($H_T/P \approx 0.10$–0.16), a clear divergence in hydraulic behavior emerges between the two configurations. Within this range, the oblique weir consistently exhibits higher discharge coefficients (C_d) than the triangular labyrinth weir under comparable conditions.

This improved performance is attributed to the oblique geometry, which extends the crest while maintaining a more favorable alignment with the primary flow direction. By avoiding sharp flow redirection and reducing local contraction, the oblique weir promotes smoother flow passage along the crest.

As a result, energy losses due to turbulence and secondary currents are reduced, leading to improved flow efficiency and increased discharge capacity compared with the triangular labyrinth configuration.

In contrast, the triangular labyrinth weir also benefits from an increased crest length and initially appears to provide similar hydraulic advantages to the oblique configuration. However, its internal flow structure behaves quite differently. As water approaches and passes over the crest of the triangular cycles, the flow is progressively guided and funneled toward the apex regions of each cycle. This geometric convergence promotes localized acceleration of the flow, which in turn intensifies turbulence and further disrupts the flow structure. The combined effect of these phenomena is a less efficient conversion of upstream head into discharge, which manifests as a slightly lower discharge coefficient (C_d) for the labyrinth weir when compared with the oblique design under the same operating conditions.

As the head ratio increases ($H_T/P > 0.14$), the inherent limitations associated with the labyrinth geometry become more evident. As the upstream water level rises, the nappes originating from adjacent triangular cycles begin to interact and overlap, resulting in nappe interference. This interaction reduces air entrainment beneath the nappe and promotes partial submergence, leading to increased energy dissipation.

In addition, the convergence of flow toward the apex regions intensifies turbulence and promotes the development of secondary currents, which further disrupt the flow structure. As a consequence, the effective discharge area is reduced, resulting in a decline in the discharge coefficient (C_d) at higher head ratios.

These observations align well with previously reported experimental results in the literature. Numerous researchers have shown that, although labyrinth weirs can provide notable improvements in discharge efficiency at lower upstream heads, primarily because of their substantially increased crest length and associated enlargement of the overflow perimeter, their performance does not continue to improve proportionally as the head increases [33][34].

Regarding submergence effects, although full submergence was not observed, partial submergence associated with nappe interference is evident in Figure 6 (M3), where overlapping nappes restrict air entrainment beneath the nappe. This reduced aeration leads to localized submergence conditions and decreases the effective discharge area. Consequently, the reduction in the discharge coefficient at higher head ratios observed in Figure 7 can be attributed to this mechanism.

In addition, the results indicate differences in operational reliability under fluctuating water levels. Based on the discharge and head ranges presented in Table 2, the oblique weir exhibits a more consistent hydraulic response, supported by the smoother trend of C_d in Figure 7. In contrast, the triangular labyrinth weir shows greater variability due to intensified flow disturbances and nappe interaction, indicating higher sensitivity to head variation.

In terms of downstream impact, the triangular labyrinth weir produces more concentrated and turbulent flow near apex regions, increasing the potential for localized scour. In contrast, the oblique weir generates a more uniform flow distribution, which may reduce downstream impacts [35].

Overall, the discussion highlights the dominant role of crest geometry in controlling hydraulic performance.

CONCLUSION

Crest geometry strongly controls weir hydraulics. For all models, the discharge coefficient (C_d) rose with head ratio (H_T/P), reached a peak, then declined. The oblique weir was most efficient ($C_d \approx 0.70$), followed by the triangular labyrinth weir ($C_d \approx 0.66$), while the normal weir performed worst ($C_d \approx 0.62$). At low heads ($H_T/P < 0.10$), both nonlinear weirs exhibited similar hydraulic behavior; however, as the head increased, the oblique weir maintained higher efficiency due to reduced flow disturbances, lower energy loss, and more stable flow conditions. In contrast, the triangular labyrinth weir became increasingly affected by nappe interference and partial submergence, which reduced aeration and, consequently, discharge efficiency. Accordingly, these findings are consistent with previous studies, which indicate that hydraulic performance is strongly governed by crest geometry, flow interaction, and energy dissipation mechanisms [35][36].

Furthermore, in terms of practical application, this study clarifies the difficulties associated with planning, implementation, and maintenance. In this context, a clear trade-off exists between hydraulic performance and ease of implementation, where the oblique weir offers a better balance due to its simpler geometry and lower construction complexity. By contrast, the triangular labyrinth weir requires a more complex configuration, which may increase design and maintenance challenges, despite its advantage in space-constrained conditions.

Finally, this study employed small-scale physical models under controlled steady-state conditions; therefore, scale effects and transient flow phenomena in full-scale systems may not be fully represented. Further research is needed to capture real hydraulic behavior better and strengthen the reliability of the findings.

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REFERENCES

[1] R. G. Ghasemvand, M. Heidarnejad, A. Masjedi, and A. Bordbar, “Experimental study of hydraulic losses in linear and nonlinear weirs: A comparative analysis,” *Water Science.*, vol. 38, no. 1, pp. 378–390, 2024, doi: 10.1080/23570008.2024.2373954.

[2] A. H. Shehata, T. F. Youssef, H. A. Hamada, M. M. Ibrahim, and A. Samy, “Optimizing trapezoidal labyrinth weir design for enhanced scour mitigation in straight channels,” *Water*, vol. 16, no. 17, p. 2443, 2024. doi: 10.3390/w16172443.

[3] A. Samadi, F. Salmasi, H. Arvanaghi, and M. Mousaviraad, “Effects of geometrical parameters on Labyrinth Weir hydraulics,” *Journal of Irrigation and Drainage Engineering*, vol. 148, no. 10, p. Art. no. 06022006, 2022, doi: 10.1061/(asce)ir.1943-4774.0001695.

[4] A. Hidayat, R. D. Praptoyo, M. Isradi, and S. Suprapti, “Analysis of floodwater: A case study of the Tukad Buluk Poh River,” *SINERGI*, vol. 28, no. 2, pp. 435–442, 2024,

doi: 10.22441/sinergi.2024.2.022.
[5] Juliastuti, T. K. Wihartono, O. Setyandito, Y. Wijayanti, L. Safitri, and I. S. D. Sebayang, "The assessment of drainage performance in the residential area using SWMM," *SINERGI*, vol. 27, no. 2, pp. 281–288, 2023, doi: 10.22441/sinergi.2023.3.016.
[6] B. M. A. Noori, "Hydraulic performance of circular crested oblique weirs," *Ain Shams Engineering Journal*, vol. 11, no. 4, pp. 875–888, Dec. 2020, doi: 10.1016/j.asej.2020.02.014.
[7] H. Une, T. Ohmoto, and K. Kuranaga, "Effect of opening depth of oblique weir with an opening on river bed morphology," *IOP Conference Series: Earth and Environmental Science*, vol. 851, no. 012010, 2021, doi: 10.1088/1755-1315/851/1/012010.
[8] S. S. Ibrahim, R. A. Jafer, and B. M. A. S. Ali, "An experimental study of a combined oblique cylindrical weir and gate structure," *Engineering, Technology & Applied Science Research*, vol. 13, no. 2, pp. 10483–10488, 2023, doi: 10.48084/etasr.5646.
[9] R. Norouzi, H. Arvanaghi, F. Salmasi, D. Farsadizadeh, and M. A. Ghorbani, "A new approach for oblique weir discharge coefficient prediction based on hybrid inclusive multiple model," *Flow Measurement and Instrumentation*, vol. 76, 2020, doi: 10.1016/j.flowmeasinst.2020.101810.
[10] A. H. Haghiabi, M. R. Ghaleh Nou, and A. Parsaie, "The energy dissipation of flow over the labyrinth weirs," *Alexandria Engineering Journal*, vol. 61, no. 5, pp. 3729–3733, May 2022, doi: 10.1016/j.aej.2021.08.075.
[11] A. K. Idrees and R. Al-Ameri, "Investigation of flow characteristics and energy dissipation over new shape of the trapezoidal labyrinth weirs," *Flow Measurement and Instrumentation*, vol. 89, p. 102276, Mar. 2023, doi: 10.1016/j.flowmeasinst.2022.102276.
[12] A. Ghaderi, R. Daneshfaraz, M. Dasineh, and S. Di Francesco, "Energy dissipation and hydraulics of flow over trapezoidal-triangular labyrinth weirs," *Water*, vol. 12, no. 7, 2020, doi: 10.3390/w12071992.
[13] R. A. Hussain, S. A. Hassan, and A. A. J. Jamel, "Experimental study on flow over triangular labyrinth weirs," *International Journal of Design and Nature and Ecodynamics*, vol. 17, no. 2, pp. 249–255, 2022, doi: 10.18280/ijdne.170211.
[14] A. Tanga, M. G. Ishak, S. R. Oktavia, and Y. Arafat, "Effect of the length of the weir wall sections on hydraulic characteristics of labyrinth weir," *IOP Conference Series: Earth and Environmental Science*, vol. 1355, no. 1, p. 012025, Jun. 2024, doi: 10.1088/1755-1315/1355/1/012025.
[15] P. Urkudkar, S. Yerunkar, K. Zade, P. Watkar, and P. R. Prof, "Experimental study and analysis of labyrinth weir," *International Journal of Aquatic Science*, vol. 15, no. 01, pp. 230–235, 2024.
[16] M. C. Aydin, A. E. Ulu, and E. Işik, "Experimental and numerical investigation of rectangular labyrinth weirs in an open channel," *Proceedings of the Institution of Civil Engineers - Water Management*, vol. 178, no. 1, pp. 1–17, Feb. 2025, doi: 10.1680/jwama.22.00112.
[17] A. K. Idrees, R. Al-Ameri, and S. Das, "Using CFD modelling to study hydraulic flow over labyrinth weirs," *Water Supply*, vol. 22, no. 3, pp. 3125–3142, 2021, doi: 10.2166/ws.2021.424.
[18] S. M. Seyedian, A. H. Haghiabi, and A. Parsaie, "Reliable prediction of the discharge coefficient of triangular labyrinth weir based on soft computing techniques," *Flow Measurement and Instrumentation*, vol. 92, p. 102403, 2023, doi: 10.1016/j.flowmeasinst.2023.102403.
[19] M. D. Mustafa, T. Mansoor, and M. Muzzammil, "Support vector machine (SVM) approach to develop the discharge prediction model for triangular labyrinth weir," *Water Supply*, vol. 22, no. 12, pp. 8942–8956, 2022, doi: 10.2166/ws.2022.393.
[20] H. Emami, S. Emami, and J. Parsa, "A Walnut optimization algorithm applied to discharge coefficient prediction on labyrinth weirs," *Soft Computing*, vol. 22, pp. 12197–12215, 2022, doi: 10.1007/s00500-022-07041-8.
[21] W. Chen, D. Sharifrazi, G. Liang, S. S. Band, K. W. Chau, and A. Mosavi, "Accurate discharge coefficient prediction of streamlined weirs by coupling linear regression and deep convolutional gated recurrent unit," *Engineering Applications of Computational Fluid Mechanics*, vol. 16, no. 1, pp. 965-976., 2022, doi: 10.1080/19942060.2022.2053786.
[22] S. Nematollahi, E. Izadinia, and A. Khoshfetrat, "Investigation of discharge coefficient and flow energy loss in sinusoidal-labyrinth weirs," *Iranian Journal of Science and Technology*, vol. 49, pp. 6103–6112, 2025, doi: 10.1007/s40996-025-01820-7.
[23] A. M. Ahmed and A. N. Altalib, "Determination of discharge coefficient of arced labyrinth weir with semicircular

openings," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, vol. 49, pp. 4941–4952, 2025, doi: 10.1007/s40996-025-01747-z.
[24] S. Balahang and M. Ghodsian, "Evaluating performance of various methods in predicting triangular sharp-crested side weir discharge," *Applied Water Science*, vol. 13, p. Art. no. 171, 2023, doi: 10.1007/s13201-023-01971-w.
[25] E. D. Mattos-villarroel, W. Ojeda-bustamante, D. Carlos, H. Salinas-tapia, J. Flores-vel, and C. B. Capetillo, "Methodological proposal for the hydraulic design of labyrinth weirs," *Water*, vol. 13, no. 722, pp. 1–29, 2023, doi: 10.3390/w15040722.
[26] A. A. Ismael, S. J. Suleiman, R. R. O. Al-Nima, and N. Al-Ansari, "Predicting the discharge coefficient of oblique cylindrical weir using neural network techniques," *Arabian Journal of Geosciences*, vol. 14, no. 1670, 2021, doi: 10.1007/s12517-021-07911-9.
[27] T. H. Aurahman, J. M. F. S. Suleimany, and T. K. Hamad, "Determination of discharge coefficient for both semicircular and triangular labyrinth weirs," *Polytechnic Journal*, vol. 11, no. 2, pp. 56 – 64, 2021, doi: 10.25156/ptj.v11n2y2021.pp56-64.
[28] K. Xu *et al.*, "Numerical simulation study on hydraulic characteristics of asymmetric and symmetric triangular labyrinth weirs: A comparative analysis," *Water*, vol. 17, no. 21, p. 3114, 2025, doi: 10.3390/w17213114.
[29] E. D. Mattos-Villarroel *et al.*, "Influence of the semicircular cycle in a labyrinth weir on the discharge coefficient," *Water*, vol. 17, no. 21, p. 3151, 2025, doi: 10.3390/w17213151.
[30] J. P. Tullis, N. Amanian, and D. Waldron, "Design of labyrinth spillways," *Journal of Hydraulic Engineering*, vol. 121, no. 3, pp. 247–255, 1995, doi: 10.1061/(ASCE)0733-9429(1995)121:3(247).
[31] A. Tanga, M. G. Ishak, and Y. Arafat, "Effect of plan shape on hydraulic characteristics of labyrinth weirs," *Jurnal Sains dan Teknologi Tadulako*, vol. 9, no. 1, pp. 10–18, Apr. 2023, doi: 10.22487/jstt.v9i1.446.
[32] H. Elahifar, O. Tayari, N. Yazdanpanah, and M. Momeni, "Experimental investigation of the discharge coefficient of labyrinth weirs with asymmetric cycles," *Water SA*, vol. 48, no. 3, pp. 317–323, 2022, doi: 10.17159/wsa/2022.v48.i3.3911.
[33] O. S. Q. Yousif and M. Karakouzian, "Effect of corner shape on hydraulic performance of one-cycle rectangular labyrinth weirs," *Fluids*, vol. 5, no. 3, p. 117, Jul. 2020, doi: 10.3390/fluids5030117.
[34] A. Tanga, M. G. Ishak, V. W. Andiese, and Y. Arafat, "Experimental study on flow over labyrinth weirs with rounded angle," *Advances in Engineering Research Series*, pp. 188–195, 2025, doi:10.2991/978-94-6463-768-7_21.
[35] A. Tanga, M. G. Ishak, and Y. Arafat, "Wave labyrinth weir : A new shape spillway to minimize the effect of the vertex angle," *International Journal of Integrated Engineering (IJIE)*, vol. 17, no. 9, pp. 409–419, 2025, doi: 10.30880/ijie.2025.17.09.028.
[36] P. Mirkhorli, A. Ghaderi, H. Mohammadnezhad, M. Mohammadi, and O. Kisi, "Hydraulic behavior and energy dissipation in Piano key weirs vs. Rectangular labyrinth weirs: A comparative study," *Flow Measurement and Instrumentation*, vol. 102, p. 102830, Mar. 2025, doi: 10.1016/j.flowmeasinst.2025.102830.