International Journal of Aquatic Research and Environmental Studies 6(2) 589-596 2026

Empirical Estimation of Strong Hydraulic Jump Length in a Rectangular Channel for Sustainable Stilling Basin Design

Very Dermawan[1]*, Evi Nur Cahya[2], Linda Prasetyorini[3]

[1]Associate Professor, Department of Water Resources Engineering, Faculty of Engineering, Universitas Brawijaya, Malang 65145, East Java, Indonesia, Email: perydrma@ub.ac.id
[2]Associate Professor, Department of Water Resources Engineering, Faculty of Engineering, Universitas Brawijaya, Malang 65145, East Java, Indonesia.
[3]Assistant Professor, Department of Water Resources Engineering, Faculty of Engineering, Universitas Brawijaya, Malang 65145, East Java, Indonesia.

Abstract

Hydraulic jump length is a critical parameter for determining the required length of stilling basins and downstream energy dissipation structures. However, existing empirical equations may not adequately represent strong hydraulic jumps generated under high pre jump Froude number conditions. This study investigates strong hydraulic jump behavior in a rectangular laboratory channel and develops empirical relationships for predicting hydraulic jump length. Experiments were conducted using a physical spillway model with two chute slopes, 1V:1H and 1V:0.8H. Seventeen discharge conditions ranging from 5 to 27 liters per second were tested. The observed pre jump Froude number ranged from 10.05 to 22.09, indicating strong hydraulic jump conditions. The main measured parameters were pre-jump depth, post-jump depth, post-jump Froude number, jump height, and hydraulic jump length. Calibration results showed good agreement between analytical and observed values, with mean absolute percentage errors of 4.86% for pre-jump depth and 7.96% for pre jump Froude number. The observed hydraulic jump length ranged from 85 to 315 centimeters. Regression analysis showed strong relationships between hydraulic jump length and pre jump depth, post jump depth, jump height, and upstream Froude number. The dimensionless formulation based on hydraulic jump length to pre jump depth ratio and pre jump Froude number produced the best predictive performance, with a mean absolute percentage error of 3.93%. Comparison with previous equations showed that most existing formulas underestimated the observed jump length. The proposed relationship provides an improved basis for estimating stilling basin length under strong hydraulic jump conditions.

Keywords: strong hydraulic jump; hydraulic jump length; Froude number; rectangular channel; stilling basin; spillway model.

1. Introduction

Hydraulic jumps are key phenomena in open-channel hydraulics, marking the rapid transition from supercritical to subcritical flow. This transition is characterized by an abrupt rise in water depth, roller formation, air entrainment, pressure fluctuations, and intense energy dissipation. Accordingly, hydraulic jumps are widely used downstream of spillways, sluice gates, weirs, chutes, and stilling basins to reduce excess kinetic energy and protect hydraulic structures from scour and erosion [1]; [2]; [3].

Beyond their hydraulic function, hydraulic jumps are closely linked to river environment stability. If the jump is not properly formed or if the stilling basin cannot accommodate its full length, residual energy may be transferred downstream, intensifying bed scour, bank erosion, sediment remobilization, turbidity, and riverbed degradation, while also affecting aquatic habitats and water quality [1]; [3]; [4]; [5]. Such failures may extend beyond the river corridor by increasing local flood risk, damaging irrigation and drainage infrastructure, accelerating erosion of agricultural land, depositing sediment in canals or fields, and reducing the reliability of water delivery. Therefore, stilling basin design is not only a structural concern but also an environmental and water-resources management issue. Among the governing parameters, hydraulic jump length, (L_j), is particularly important because it defines the longitudinal extent of the transition zone. Accurate estimation of (L_j) is essential for stilling basin design: underestimation may expose downstream beds to scour and instability, whereas overestimation results in unnecessarily long and costly structures [6]; [7]; [8]. This challenge becomes more critical for strong hydraulic jumps ($F_1>9$), where turbulence intensity, roller development, air water interaction, and energy dissipation are highly pronounced [9].

Although the sequent depth ratio can be estimated using the classical Bélanger momentum equation, predicting jump length remains difficult due to the complex interaction of turbulence decay, roller dynamics, air entrainment, bed shear, boundary conditions, and tailwater control. Previous studies have shown that bed roughness, channel slope, compound geometry, and sluice gate opening significantly influence hydraulic jump characteristics and jump length [10]; [11]; [12]; [13]; [14]; [15]. Related investigations also highlight that toe location, slab stability, and basin length are strongly associated with (L_j), further emphasizing its design relevance [16]; [17]. Recent studies confirm that hydraulic jump behavior is highly sensitive to channel configuration, bed condition, and flow regime. Experimental and semi-theoretical investigations have demonstrated that roughness, compound sections, adverse or positive slopes, and trapezoidal geometries can alter the sequent depth ratio, roller length, jump length, and energy dissipation [18]; [19]; [20]; [21]; [22]. Additional studies on compact energy dissipation structures indicate that sill and stepped weir geometries can improve jump control and energy dissipation; for example, double sill arrangements have been shown to enhance energy dissipation under strong jump conditions, while brink depth-based modelling over stepped weirs can support discharge and energy dissipation estimation [23]; [24].

Despite these advances, strong hydraulic jumps in rectangular spillway channels at high upstream Froude numbers remain insufficiently represented in existing empirical formulations for (L_j). Many available equations were developed for moderate Froude numbers or non-rectangular geometries and therefore tend to underestimate the longer jump lengths observed under strong-jump laboratory conditions. This limitation may compromise the reliability of stilling basin design and downstream protection systems.

To address this gap, the present study develops a new empirical relationship for hydraulic jump length, (L_j), based on laboratory observations of strong jumps (F_1>9) in a rectangular channel. The proposed formulation is expressed using dimensional and dimensionless variables and is validated against classical and recent equations. By improving the prediction of jump length under strong-jump regimes, this study provides a more reliable basis for stilling basin design and offers a practical contribution to safer and more sustainable hydraulic engineering practice.

2. Material and Methods

The experimental investigation was conducted at the River Engineering Laboratory, Department of Water Resources Engineering, Faculty of Engineering, Universitas Brawijaya. A physical hydraulic model was constructed to simulate flow over a spillway system. The flume had a width of 0.40 m and a height of 0.60 m, while the spillway crest height was (P = 1.00) m. Two chute slopes were examined: 1V:1H, tested under ten discharge variations, and 1V:0.8H, tested under seven discharge variations. The downstream channel extended approximately 8.0 m from the spillway toe and was equipped with an end sill to regulate tailwater depth. Flow was supplied by a 30 L/s electric pump, which continuously recirculated water from the upstream reservoir through the flume and back via the downstream section. Discharge measuring devices were installed in both reservoirs, and point gauges were placed along the channel to monitor steady flow conditions. In total, seventeen discharge conditions ranging from 5 to 27 L/s were tested. The hydraulic model layout is shown in Figure 1.

(a) Upstream part (b) Typical model channel (c) Running model

Figure 1. The layout of the hydraulic model in the laboratory

Hydraulic observations encompassed critical flow depth (y_c), pre jump depth (y_1), post jump depth (y_2), critical velocity (V_c), velocity before the jump (V_1), velocity after the jump (V_2), hydraulic jump height (y_j), and hydraulic jump length (L_j). The upstream Froude number prior to the jump (F_1) was adopted as the principal governing parameter, with all experimental conditions designed to ensure F_1>9, corresponding to a strong hydraulic jump regime. Analytical evaluation of the hydraulic parameters within the spillway system was conducted using standard open channel flow relationships.

Analytical calculations were derived from fundamental hydraulic principle, specifically the law of continuity, the law of energy conservation, and the conjugate depth relationship, as outlined below:

$$Q = VA \tag{1}$$

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{2}$$

$$y_c = \sqrt[3]{\frac{Q^2}{B^2 g}} = \sqrt[3]{\frac{q^2}{g}} \tag{3}$$

$$F = \frac{V}{\sqrt{gy}} \tag{4}$$

$$\frac{y_2}{y_1} = \frac{1}{2}\sqrt{1 + 8F_1^2} - 1 \tag{5}$$

$$E = y + \frac{v^2}{2g} \tag{6}$$

To evaluate the discrepancy between the model observations and the theoretical values, several equations are employed as follows:

$$RE = \left|\frac{y_i - \hat{y}_i}{y_i}\right| x100\% \tag{7}$$

$$MAPE = \frac{100\%}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \tag{8}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{9}$$

Where B = channel width (m), E = flow energy (m), F = Froude number, g = gravitational acceleration (m/s^2), Q = discharge (m^3/s), q = discharge per unit width (m^2/s), V = flow velocity (m/s), y_c = critical flow depth (m), y_i = flow depth expected (m), $\hat{y}_i$ = flow depth observed (m), y_1 = pre jump flow depth (m), y_2 = post jump flow depth (m), MAPE = mean absolute percentage error (%), RE = relative error (%), and RMSE = root mean square error. Model calibration and verification are performed by comparing the analytical calculation results (expected) with the measurement on the model (observed). Analytical calculations are based on the law of flow continuity, the law of energy conservation, and the conjugation depth.

The length of the hydraulic jump (L_j) in an open channel can be calculated using several classical formulas, which are generally categorized based on the flow parameters involved, including: flow depth after hydraulic jump (y_2), jump height ($y_j = y_2 - y_1$), and Froude number before the jump (F_1) summarized by [25], [26]:

$$L_j = C_j\, y_2 \tag{10}$$

For Equation (10), Safranetz (1927) and Douma (1934) proposed C_j = 5.2, while Page (1935) suggested C_j = 5.6.

$$L_j = C_j\,(y_2 - y_1) \tag{11}$$

For Equation (11), Riegel & Beebe (1917) and Bakhmeteff, Matzke (1936) reported C_j = 5.0; Aravin (1935) C_j = 5.4; Smetana (1934) C_j = 6; Kinney (1935) C_j = 6.02; Posey (1941) C_j = 4.5 to 7; Marques et al. (1997) C_j = 8.5; and Simoes et al. (2012) C_j = 9.52.

In addition, Chertoussov (1935), Ivanchenko (1935) and Wu (1949) formulated L_j as function of y_1, y_2, and F_1, respectively, as follow:

$$L_j = 10.3\, y_1\,(F_1 - 1)^{0.81} \tag{12}$$

$$L_j = 10.6\,(y_2 - y_1)(F_1^2)^{-0.185} \tag{13}$$

$$L_j = 10\,(y_2 - y_1)\,F_1^{-0.16} \tag{14}$$

3. Result and Discussion

Based on theoretical calculations, the expected values of the pre jump depth (y_1) and post jump depth (y_2) were established. These values served as reference conditions for the initial hydraulic model runs. To achieve conformity between the theoretical and observed flow parameters, the downstream end sill height was adjusted accordingly. For the seventeen discharges series tested, appropriate end sill heights were determined to reproduce the expected y_1 and y_2 values.

With the downstream end sill height settings, the observed and expected values of y_1, y_2, F_1, and F_2 summarized in Table 1.

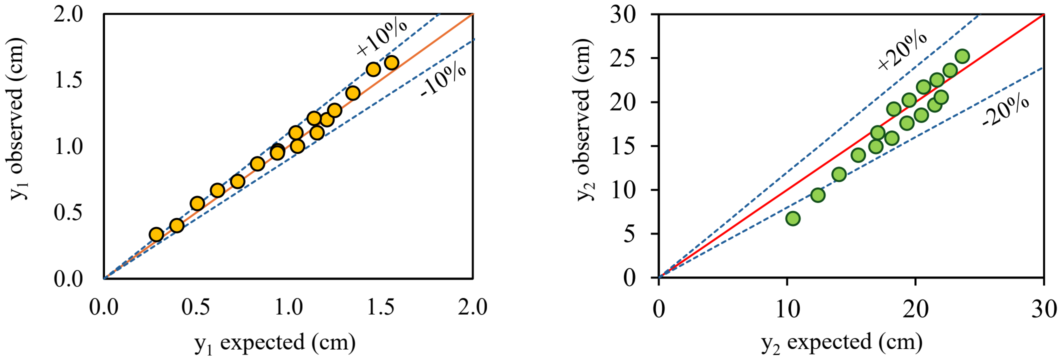
Table 1: Result of hydraulic parameters (expected and observed)

Slope V:H	Q (L/s)	End sill		Expected				Observed				L_j (cm)
		height Z (cm)	Distance X_s (cm)	y_1 (cm)	y_2 (cm)	F_1	F_2	y_1 (cm)	y_2 (cm)	F_1	F_2	
1:1	5	4.5	180	0.28	10.45	26.40	0.12	0.33	6.70	20.74	0.23	85
	7	5.5	277	0.39	12.38	22.51	0.13	0.40	9.37	22.09	0.19	105
	9	6.5	370	0.51	14.04	20.00	0.14	0.57	11.73	16.84	0.18	115
	11	7.5	455	0.61	15.53	18.21	0.14	0.67	13.93	16.13	0.17	130
	13	8.5	498	0.72	16.89	16.84	0.15	0.73	14.93	16.52	0.18	145
	15	9	540	0.83	18.15	15.77	0.15	0.87	15.87	14.84	0.19	155
	17	10	610	0.94	19.32	14.87	0.16	0.97	17.57	14.28	0.18	170
	19	10.5	644	1.05	20.43	14.13	0.16	1.00	18.50	15.17	0.19	185
	21	11	705	1.16	21.48	13.50	0.17	1.10	19.67	14.53	0.19	200
	22	11	788	1.21	21.99	13.22	0.17	1.20	20.53	13.36	0.19	215
1:0.8	15	9.5	700	0.94	17.04	13.14	0.17	0.95	16.50	12.93	0.26	205
	17	10.5	700	1.04	18.30	12.79	0.17	1.10	19.20	11.76	0.14	215
	19	10.5	700	1.14	19.48	12.46	0.18	1.21	20.20	11.39	0.15	235
	21	11.0	700	1.25	20.60	11.99	0.18	1.27	21.70	11.71	0.15	255
	23	11.0	700	1.35	21.66	11.70	0.18	1.40	22.50	11.08	0.16	270
	25	12.0	700	1.46	22.67	11.31	0.18	1.58	23.60	10.05	0.16	285

Slope V:H	Q (L/s)	End sill		Expected				Observed				L_j (cm)
		height Z (cm)	Distance X_s (cm)	y_1 (cm)	y_2 (cm)	F_1	F_2	y_1 (cm)	y_2 (cm)	F_1	F_2	
	27	12.5	700	1.56	23.64	11.06	0.19	1.63	25.20	10.36	0.16	315

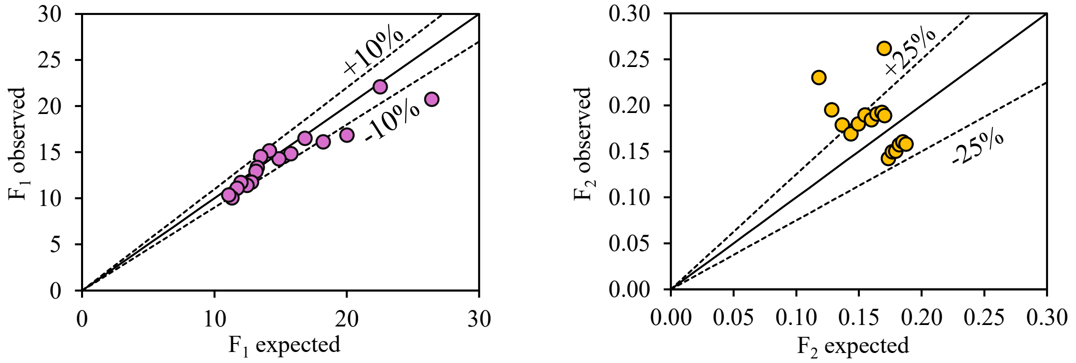
The result of observed and expected pre jump depth (y_1), post jump depth (y_2), pre jump Froude number (F_1), and post jump Froude number (F_2) are illustrated on Figure 2.

The comparison between observed and expected hydraulic parameters yielded MAPE (%) values of 4.86% and 12.59% for y_1 and y_2, respectively, while the corresponding RMSE values were 0.0527 and 1.8650. Meanwhile, F_1 and F_2 have MAPE (%) values of 7.96% and 20.62%, respectively, while the RMSE values are 1.7969 and 0.0465. Thus, for flow depth and Froude number parameters before jump (y_1, F_1) between observed and expected are in excellent agreement. While flow depth after jump (y_2) is in good agreement, and Froude number after jump (F_2) is in reasonable agreement.



(a) Relationship between expected and observed pre jump depth (y_1) with ±10% deviation boundaries

(b) Relationship between expected and observed post jump depth (y_2) with ±20% deviation boundaries



(c) Relationship between expected and observed pre jump Froude number (F_1) with 10% deviation boundaries

(d) Relationship between expected and observed post jump Froude number (F_2) with 25% deviation boundaries

Figure 2: Scatter plot comparing observed and expected of y_1, y_2, F_1, and F_2 with deviation boundaries

Following calibration of the primary parameters y_1 and y_2, subsequent analysis focused on the measured hydraulic jump length (L_j), which represents the central topic of this study. Based on the laboratory observations, relationships among dimensional parameters as well as correlations between dimensionless parameters were examined. The experimental results for hydraulic jump length were further compared with and evaluated against several formulations previously proposed in the literature.

From the observational data and correlation analysis, the correlation coefficients between L_j and y_1, y_2, y_j, and F_1 were found to be 0.9841, 0.9608, 0.9577, and -0.9210, respectively. The relationships among the dimensional parameters, specifically between L_j and y_1, y_2, y_j, and F_1, in SI unit (meter), along with the corresponding regression results as follows:

$L_j = 80.466\ y_1^{0.8081}$	; $R^2 = 0.9606$	(15)
$L_j = 11.423\ y_2^{1.0258}$	; $R^2 = 0.9250$	(16)
$L_j = 12.43\ (y_2 - y_1)^{1.0398}$	; $R^2 = 0.9201$	(17)
$L_j = 113.53\ F_1^{-1.567}$	; $R^2 = 0.9261$	(18)

Furthermore, the correlation coefficients between (L_j/y_1) and F_1, as well as (y_2/y_1), were determined to be 0.7147 and 0.6178, respectively. The relationships among the dimensionless parameters, specifically (L_j/y_1), (y_2/y_1), and

F_1, along with the corresponding regression results, are presented as follows:

$$(L_j/y_1) = 1.0331\ F_1^2 - 27.325\ F_1 + 367.3 \qquad ;\ R^2 = 0.8109 \qquad (19)$$

$$(L_j/y_1) = 1.4938(y_2/y_1)^2 - 49.704\ (y_2/y_1) + 601.85 \qquad ;\ R^2 = 0.5037 \qquad (20)$$

Meanwhile, the relationship of the dimensionless parameter (L_j/y_1) with two dimensionless parameters (y_2/y_1) and F_1 simultaneously is presented as follows:

$$(L_j/y_1) = 94.381\ (y_2/y_1)^{-0.1521} F_1^{\ 0.4489} \qquad ;\ R^2 = 0.4522 \qquad (21)$$

The equations describing the relationships among both dimensional and dimensionless parameters were subsequently compared with the analytical formulations for hydraulic jump length (L_j). The analysis revealed that the closest agreement with the laboratory observations was obtained from the formulations proposed by Marques et al. (1997) and Simões et al. (2012). However, the laboratory model observations indicated that the hydraulic jump length was generally longer than that predicted by most of the previous formulations.

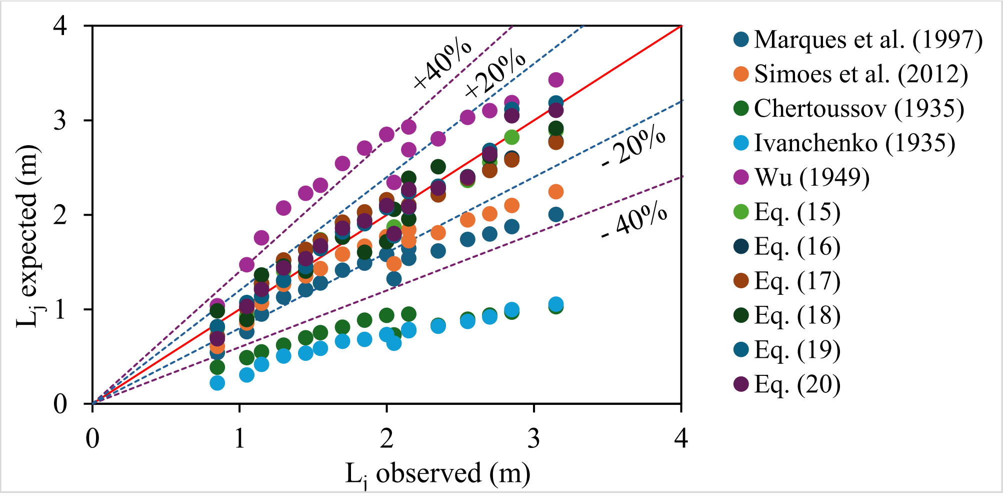


Figure 3: Comparison of observed hydraulic jump length with previous formulations based on dimensional and dimensionless parameters

Among the equations, those yielding MAPE < 10% are Eq. (15), Eq. (16), Eq. (17), Eq. (18), Eq. (19), Eq. (20), and Eq. (21), with respective value of 6.58%, 9.46%, 9.70%, 9.01%, 3.93%, 6.41%, and 8.29%. The smallest MAPE = 3.93% is obtained from Equation (19), indicating that the prediction of hydraulic jump length (L_j) based on pre jump Froude number (F_1) provides the best accuracy.

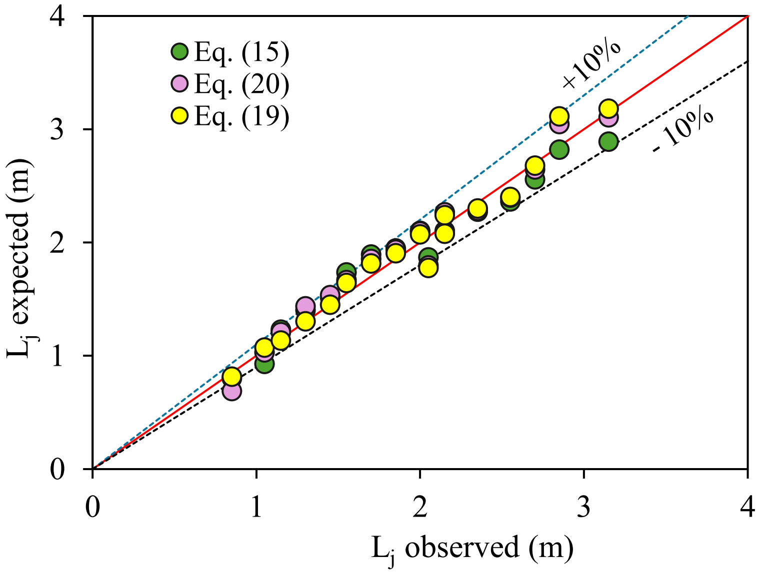


Figure 4: The optimal equation of observed hydraulic jump length based on dimensional and dimensionless parameters

The experimental results confirm that strong hydraulic jumps in a rectangular channel exhibit a highly developed turbulent structure and require a considerable longitudinal distance to complete the transition from supercritical to subcritical flow. The observed jump length (L_j) ranged from 85 to 315 cm under high upstream Froude number conditions, indicating that strong jumps generated downstream of steep spillway configurations may require longer stilling basins than those predicted by several classical formulations. This finding is consistent with the physical understanding that strong jumps involve intense roller development, air entrainment, and turbulence decay, all of which control the spatial extent of the jump rather than the sequent depths alone [4]; [1]. The relatively long L_j observed in the present study can be attributed to the strong jump regime and the absence of roughness induced shortening along the basin floor. Previous studies on rough or sloping channels generally reported that bed roughness and slope tend to reduce jump length or roller length by increasing turbulence and bed shear resistance [5]; [27] ; [28]; [22]. Therefore, the longer L_j measured in this smooth rectangular channel is physically reasonable and highlights the need for separate empirical treatment of strong jumps under high F_1 conditions. The influence of structural geometry is further supported by recent experimental work on stilling basins and stepped weirs, where sill arrangement, step-induced turbulence, and brink-depth-based modelling were shown to affect energy dissipation and hydraulic-jump-related flow behaviour [23]; [24].

The calibration results show that the observed pre jump parameters were well represented by analytical estimates. The larger deviations for y_2 and F_2 reflect the greater uncertainty in the post jump region, where flow aeration, surface fluctuation, and roller instability are more pronounced. Similar uncertainties have been reported in studies emphasizing the sensitivity of hydraulic jump profiles and locations to tailwater condition, inflow development, and turbulence structure [6]; [29].

The regression analysis demonstrates that L_j has very strong relationships with y_1, y_2, and y_j, with R^2 values exceeding 0.92. This confirms that dimensional flow depth parameters remain reliable predictors of jump length under the tested conditions. However, the dimensionless formulation based on (L_j/y_1) and (F_1) provided the best predictive accuracy, with MAPE of 3.93%, suggesting that Froude-based scaling is more transferable for design use. This supports previous findings that F_1 remains the dominant parameter governing jump geometry, although roughness, slope, and channel configuration may alter its effect [10]; [11]; [12].

Comparison with previous equations shows that the laboratory observations are closest to the formulations of Marques et al. (1997) and Simões et al. (2012), yet the measured L_j values are generally longer than most published predictions. This indicates that strong-jump conditions may not be adequately captured by conventional equations derived from broader or lower-Froude datasets. The proposed formulation therefore provides a more suitable basis for estimating stilling basin length under the present experimental conditions and helps reduce uncertainty in downstream energy-dissipation design. The strong performance of the dimensionless formulation based on (L_j/y_1) and F_1 is consistent with previous studies showing that the incident Froude number remains the principal governing parameter for hydraulic jump geometry, although its influence may be modified by slope, roughness, and cross-sectional shape. This agrees with studies on sloped channels, rough beds, compound channels, and trapezoidal channels, where F_1 was consistently retained as a primary variable in empirical or semi-theoretical formulations [30]; [20]; [31].

4. Conclusion

This study addressed the uncertainty in estimating hydraulic jump length, L_j, under strong hydraulic jump conditions in a rectangular channel. Although many empirical equations are available in the literature, their applicability to high Froude number jumps remains limited because L_j is strongly affected by roller development, turbulence intensity, air entrainment, and tailwater control. This limitation is important for stilling basin design, where underestimation of jump length may compromise downstream protection, while overestimation may lead to uneconomical basin dimensions.

Laboratory observations were conducted for strong hydraulic jumps generated downstream of two spillway chute configurations. The experimental results showed that the observed hydraulic jumps were fully developed and relatively long, with L_j varying from 85 to 315 cm. The calibration of the main hydraulic parameters showed good agreement between analytical and observed values, particularly for pre-jump depth and upstream Froude number, confirming the reliability of the experimental setup for further jump length analysis.

Regression analysis demonstrated that hydraulic jump length has strong relationships with pre-jump depth, post-jump depth, jump height, and upstream Froude number. Among the tested formulations, the dimensionless relationship involving (L_j/y_1) and F_1 produced the best predictive performance, with the lowest MAPE of 3.93%. This indicates that Froude based scaling provides a more reliable representation of hydraulic jump length under the tested strong jump conditions than purely dimensional formulations.

Comparison with previous empirical equations showed that the laboratory observations were closest to the formulations of Marques et al. and Simões et al.; however, most existing equations tended to underestimate the observed jump length. Therefore, the proposed empirical relationship provides a more suitable basis for estimating L_j in the present experimental range.

The key takeaway is that strong hydraulic jumps may require longer stilling basin lengths than those predicted by many classical equations. The proposed formulation can support safer and more economical design of downstream energy-dissipation structures, particularly for spillway systems operating under high upstream Froude number conditions.

Acknowledgments

The authors express their gratitude to the Faculty of Engineering, Universitas Brawijaya, Community Service Division (BPPM), and Badan Penerbitan Jurnal (BPJ) FTUB for providing insight and support that greatly assisted the publication of this paper.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

References

[1] D. De Padova and M. Mossa, "Hydraulic Jump: A Brief History and Research Challenges," *Water (Basel).*, vol. 13, no. 1733, pp. 1–15, Jun. 2021.

[2] D. Wüthrich, R. Shi, and H. Chanson, "Hydraulic jumps with low inflow Froude numbers: air–water surface patterns and transverse distributions of two-phase flow properties," *Environmental Fluid Mechanics*, vol. 22, no. 4, pp. 789–818, Aug. 2022, doi: 10.1007/s10652-022-09854-5.

[3] S. Mondal, R. Das, S. Das, and S. Mukherjee, "Experimental investigation of dissolved oxygen improving aeration efficiency by hydraulic jumps," *Flow Measurement and Instrumentation*, vol. 100, p. 102715, Dec. 2024, doi: 10.1016/j.flowmeasinst.2024.102715.

[4] H. Wang and F. Murzyn, "Experimental assessment of characteristic turbulent scales in two-phase flow of hydraulic jump: from bottom to free surface," *Environmental Fluid Mechanics*, vol. 17, no. 1, pp. 7–25, Feb. 2017, doi: 10.1007/s10652-016-9451-6.

[5] S. K. Gupta and V. K. Dwivedi, "Prediction of Depth Ratio, Jump Length and Energy Loss in Sloped Channel Hydraulic Jump for Environmental Sustainability," *Evergreen*, vol. 10, no. 2, pp. 942–952, Jun. 2023, doi: 10.5109/6792889.

[6] B. Nandi, S. Das, and A. Mazumdar, "Experimental Analysis and Numerical Simulation of Hydraulic Jump," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 505, no. 1, p. 012024, Jul. 2020, doi: 10.1088/1755-1315/505/1/012024.

[7] S. Mnassri and A. Triki, "Numerical investigation towards the improvement of hydraulic-jump prediction in rectangular open-channels," *ISH Journal of Hydraulic Engineering*, vol. 28, no. 2, pp. 135–142, Apr. 2022, doi: 10.1080/09715010.2020.1836684.

[8] L. A. M. Saleh and S. I. Khassaf, "Evaluating the Hydraulic Performance of USBR II Stilling Basin with Rough Bed," *Tikrit Journal of Engineering Sciences*, vol. 31, no. 3, pp. 93–104, Jul. 2024, doi: 10.25130/tjes.31.3.9.

[9] K. Laishram, T. T. Devi, and N. B. Singh, "Experimental Comparison of Hydraulic Jump Characteristics and Energy Dissipation Between Sluice Gate and Radial Gate," 2022, pp. 207–218. doi: 10.1007/978-981-19-0304-5_16.

[10] S. Pagliara and M. Palermo, "Hydraulic jumps on rough and smooth beds: aggregate approach for horizontal and adverse-sloped beds," *Journal of Hydraulic Research*, vol. 53, no. 2, pp. 243–252, Mar. 2015, doi: 10.1080/00221686.2015.1017778.

[11] N. Hassanpour, A. Hosseinzadeh Dalir, D. Farsadizadeh, and C. Gualtieri, "An Experimental Study of Hydraulic Jump in a Gradually Expanding Rectangular Stilling Basin with Roughened Bed," *Water (Basel).*, vol. 9, no. 12, p. 945, Dec. 2017, doi: 10.3390/w9120945.

[12] A. Ghaderi, M. Dasineh, F. Aristodemo, and A. Ghahramanzadeh, "Characteristics of free and submerged hydraulic jumps over different macroroughnesses," *Journal of Hydroinformatics*, vol. 22, no. 6, pp. 1554–1572, Nov. 2020, doi: 10.2166/hydro.2020.298.

[13] U. Türker and M. Valyrakis, "Hydraulic jump on rough beds: conceptual modeling and experimental validation," *Water Supply*, vol. 21, no. 4, pp. 1423–1437, Jun. 2021, doi: 10.2166/ws.2020.292.

[14] R. Daneshfaraz, S. Sadeghfam, V. Hasanniya, J. Abraham, and R. Norouzi, "Experimental Investigation on Hydraulic Efficiency of Vertical Drop Equipped with Vertical Screens," *Teknik Dergi*, 2022, doi: 10.18400/tekderg.755938.

[15] A. Rehman, H. ur Rehman, N. M. Khan, and A. M. Rasool, "Experimental evaluation of energy dissipation in modified USBR-IV stilling basins with downstream abrupt drops," *Journal of Applied Water Engineering and Research*, pp. 1–14, Dec. 2025, doi: 10.1080/23249676.2025.2585848.

[16] S. M. Kori, A. A. Mahessar, M. Channa, A. A. Memon, and A. R. Kori, "Study of flow characteristics over a rounded edge drop structure in open channel," *Engineering, Technology & Applied Science Research*, vol. 9, no. 3, pp. 4136–4139, Jun. 2019.

[17] G. Y. Luo, H. Cao, and H. Pan, "Method to Locate the Toe of a Hydraulic Jump on Sloping Channels," *KSCE Journal of Civil Engineering*, vol. 25, no. 1, pp. 124–139, Jan. 2021, doi: 10.1007/s12205-020-0081-7.

[18] A. Benabdesselam, B. Achour, and L. Houichi, "Hydraulic Jumps in a Straight Rectangular Compound Channel: Theoretical Approach and Experimental Study," *Larhyss Journal*, vol. 29, pp. 323–340, 2017.

[19] F. Riguet, M. Debabeche, and A. Ghomri, "Experimental Study of the Sequent Depth Ratio of the Hydraulic Jump in a Straight Compound Rectangular Channel," *Journal of Fundamental and Applied Sciences*, vol. 12(IS), pp. 56–65, 2020.

[20] N. M. Ngoc and T. N. Thang, "A Study of an Empirical Sequent Depths Equation of the Hydraulic Jump in a

Horizontal Trapezoidal Channel," *Engineering, Technology & Applied Science Research*, vol. 13, no. 6, pp. 12307–12313, Dec. 2023, doi: 10.48084/etasr.6431.

[21] H. Ibtissam, K. Samir, G. Ali, K. Haroun, and B. Djamel, "Experimental investigation of the sequent depth ratio in hydraulic jumps occurring in a sloped compound rectangular channel with a rough minor bed," *Water Pract. Technol.*, vol. 20, no. 8, pp. 1745–1762, Aug. 2025, doi: 10.2166/wpt.2025.101.

[22] I. Herri, S. Kateb, A. Ghomri, H. Khechiba, and D. Besser, "Experimental Insights into Hydraulic Jump Roller Length: The Impact of Compound Geometry, Slope, and Bed Roughness," *Journal of Applied Fluid Mechanics*, vol. 19, no. 2, Feb. 2026, doi: 10.47176/jafm.19.2.3709.

[23] V. Dermawan, S. Erryanto, E. N. Cahya, and S. Sumiadi, "Experimental Evaluation of Sill Configurations in Stilling Basins for Efficient Energy Dissipation in Hydraulic Structures," *Water Conservation and Management*, vol. 10, no. 01, pp. 220–229, Jan. 2026, doi: 10.26480/wcm.01.2026.220.229.

[24] V. Dermawan, Edijatno, R. Asmaranto, E. N. Cahya, and N. Roostrianawaty, "Empirical Modeling of Flow Behavior over Stepped Weirs Using Brink Depth for Sustainable Irrigation Applications," *Engineering, Technology & Applied Science Research*, vol. 16, no. 3, pp. 35620–35629, Jun. 2026, doi: 10.48084/etasr.16662.

[25] H. E. Schulz, A. L. A. Simões, and J. D. Nóbrega, "Roller lengths, sequent depths, surface profiles for pre-design of dissipation basins," in *Proceedings of the 2 nd International Workshop on Hydraulic Structures: Data Validation*, R. F. Carvalho and S. Pagliara, Eds., Coimbra: IAHR, University of Coimbra, MARE, May 2015, pp. 81–93.

[26] H. E. Schulz, J. D. Nóbrega, A. L. A. Simões, H. Schulz, and R. de M. Porto, "Details of Hydraulic Jumps for Design Criteria of Hydraulic Structures," in *Hydrodynamics - Concepts and Experiments*, InTech, 2015. doi: 10.5772/58963.

[27] S. K. Gupta and V. K. Dwivedi, "Experimental investigation of hydraulic jump characteristics in sloping rough surfaces for sustainable development," *Engineering Research Express*, vol. 6, no. 2, p. 025103, Jun. 2024, doi: 10.1088/2631-8695/ad3acf.

[28] D. Besser, A. Ghomri, H. Khechiba, and I. Herri, "An Experimental Investigation of the Relative Length of Hydraulic Jump in a Rectangular Channel with a Composite Section, Featuring a Rough Major Bed and Positive Slope," *Engineering, Technology & Applied Science Research*, vol. 15, no. 5, pp. 26676–26682, Oct. 2025, doi: 10.48084/etasr.11629.

[29] M. S. Saleh, S. A. M. Al-Hashimi, and A. T. Al-Madhhachi, "Effect of Tail Water Depth on Characteristics of Hydraulic Jump Formed Downstream of Stepped Weir," *Mathematical Modelling and Engineering Problems*, 2024, doi: 10.18280/mmep.111105.

[30] F. G. Carollo, V. Ferro, and V. Pampalone, "Sequent depth ratio of B-jumps on smooth and rough beds," *Journal of Agricultural Engineering*, vol. 44, no. 2, p. 12, Oct. 2013, doi: 10.4081/jae.2013.e12.

[31] K. Haroun, A. Ghomri, D. Besser, and I. Herri, "A Semi-Theoretical Study on the Effect of Rough Beds on the Conjugate Depth Ratio in Hydraulic Jumps," *Engineering, Technology & Applied Science Research*, vol. 15, no. 3, pp. 23082–23087, Jun. 2025, doi: 10.48084/etasr.10754.