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Discharge formula based on brink depth over sharp-crested weirs

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ABSTRACT

Weirs are among the most essential hydraulic structures for measuring water discharge in open channels. The prediction of water discharge over weirs should be as precise and straightforward measured as feasible. The experimental investigation of flow prediction over varied heights of a conventional rectangular sharp-crested weir was conducted in the present work. The investigation evaluated five ratios of weir height to length, P/b, of 0.33, 0.4, 0.47, 0.53, and 0.6, different water discharges, Q, of up to 17.25 L/s, and different bed slopes, S, between 0.001 and 0.01. The experiment's findings reveal that a change in the bed slope has no significant effect on the brink depth, h_b, for a constant water discharge. However, it influences the head over the weir, h, which is usually measured upstream of the weir location and used to predict water discharge. A simple, accurate formula was developed for predicting water discharge over rectangular sharp-crested weirs depending on the brink depth with mean absolute percent error (MAPE) and root-mean-square error (RMSE) of 1.714% and 0.229, respectively. In addition to having a simple form, the developed formula performs well, is unaffected by the bed slope, and applies to a wide range of h/P values, from 0.158 to 0.945.

Key words: sharp-crested weirs, simple formula, open channel, weir, brink depth, predicting discharge

HIGHLIGHTS

- The discharge equation for a sharp-crested weir was predicted according to the brink depth.
- The normal water depth affects when reduced or increased channel bed slope. Therefore, the discharge equations which depend on normal depth were affected.
- The relationship between brink depth and critical depth was developed statically.

1. INTRODUCTION

The weir can be characterized as a hydraulic structure placed over open channels or rivers for several hydraulic uses. It is the most straightforward hydraulic construction for measuring, diverting, and regulating the flow (Khodier & Tullis 2022). In addition, it can be used for reasons such as flood passage (Borghei *et al.* 1999, Mahtabi & Arvanaghi 2018).

Weirs have been studied in recent decades and continue to attract the attention of several researchers due to their presence in numerous hydraulic constructions (Zhang *et al.* 2018). These investigations considered different shapes and kinds of weirs such as sharp-crested weirs (Li *et al.* 2021; Azimi & Salehi 2022; Azimi & Rajaratnam 2023; Li *et al.* 2023; Salehi *et al.* 2023), arched sharp-crested weir (Mirzaei & Sheibani 2021), compound sharp-crested (Zahiri *et al.* 2014), sharp and semicircular weirs crested with semicircular openings (Irzooki *et al.* 2014), sharp versus notch weir (Saadatnejadgharahassanlou *et al.* 2020a, 2020b; Nicosia *et al.* 2023), broad crested weir (Imanian *et al.* 2021), gear-shaped weir (Zhang *et al.* 2018; Alomari *et al.* 2023), circular-crested weir with a triangular plan form (Noori & Aaref 2017), piano key weir (Roushangar *et al.* 2021; Behroozi & Vaghefi 2022), labyrinth weir (Carrillo *et al.* 2020), and so many shapes and kinds. Despite the similarity of their definitions, their applications and hydraulic behaviour vary considerably (Borghei *et al.* 1999; Emiroglu & Kaya 2011).

Increasing the accuracy and efficiency of flow measurements is one technique to improve water management (Kassaye *et al.* 2022). When precise discharge measurements are necessary, sharp-crested weirs are commonly utilized to determine the flow discharge. It has both field and laboratory applications (Kumar *et al.* 2011). Recent studies have been conducted on various types and configurations of sharp-crested weirs for various applications. For instance, Wu & Rajaratnam (1996) experimentally

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investigated sharp-crested weir under full-width conditions. They separated the submerged flow into two sections: the impinging jet and the surface flow regime. They created a graphic to predict the various regimes. On the basis of their findings, Borghei *et al.* (1999) analysed 250 laboratory experiments and presented a discharge coefficient for sharp-crested side weir in a subcritical flow. Johnson (2000) conducted studies to determine the discharge coefficient for flow over flat-topped and sharp-crested weirs. He discovered that the coefficient may be used to forecast the discharge for weirs with flat-topped or sharp-crested edges. Afzalimehr & Bagheri (2010) estimated the discharge coefficient of rectangular sharp-crested weirs using the potential flow theory. They discovered that the proposed experimental equation for the discharge coefficient yielded reasonable results for a wide range of relative overflow depths. Bagheri & Heidarpour (2010) applied a free vortex theory to experimental data to estimate the discharge coefficient for sharp-crested weirs. The proposed theoretical analysis was found to correspond well with experimental observations. Aydin *et al.* (2011) empirically investigated the weir at various heights and widths. In the case of rectangular weirs, they discovered that the average flow velocity over the weir may be used instead of the discharge coefficient to calculate the discharge. Kumar *et al.* (2011) conducted studies to determine the discharge capacity of a sharp-crested triangular plan form weir under free-flow conditions. They discovered that the triangular plan form weirs were more effective than conventional weirs. During the circular sharp-crested weir investigation, Ghobadian & Meratifashi (2012) demonstrated that the disparity between the calculated and theoretical discharge for each stage of the weir increases with each step. A modification of the theoretical stage–discharge relation with the excellent agreement was obtained based on measured data. Mahtabi & Arvanaghi (2018) used the optimization method to establish the optimal discharge coefficient equation based on the statistical analysis. In addition, the accuracy of the numerical method used to simulate the flow over the sharp-crested weir was evaluated. When the ratio of water head over the weir crest to weir height is equal to or greater than 0.6, and the Reynolds number is similar to or more than 2000, the study found that the discharge coefficient is constant and equal to approximately 0.7. Al-Husseini *et al.* (2020) investigated experimentally and numerically inclined sharp-crested weirs and two types of vertical arch weirs (2020). Comparing these various types of weirs with standard sharp-crested weirs in terms of local scour depth revealed that the scour depth might be reduced thrice in the case of a 120° inclined sharp-crested weir.

Li & Han (2022) assessed the performance of several known discharge formulae of the characteristics of the flow discharge over a sharp-crested weir under free-flow conditions utilizing their experimental data and earlier data. The statistical analysis indicated that the weir velocity method proposed by Aydin *et al.* is suitable for representing discharges.

Brink depth or end depth (water depth at the end of the open channel) of freefall flow in open channels and hydraulic structures, which is usually located at the end of the channel of any hydraulic structures, has been utilized in the past (Rouse 1936) and is still being researched by numerous researchers for water discharge estimation (Abrari *et al.* 2019, Khosravinia *et al.* 2020, Afsharpour & Farhoudi 2021, Muhsin & Noori 2021). This depth can be used for flow metering as a single depth (Abrari *et al.* 2017, Zeidan *et al.* 2021). Ahmad & Azamathulla (2012) simulated the freefall from a circular channel and treated it as a flow over a sharp-crested, zero-height weir. The simulation anticipated the subcritical flow discharge based on end depth (brink depth). Using experimental data, the proposed equation was confirmed. Vatankhah (2013) established a theoretical relationship for forecasting the freefall water discharge in the trapezoidal open channel based on end depth (Brink depth) with an excellent agreement with experimental results. Khosravinia *et al.* (2020) studied the free fall flow discharge estimation in an open channel with a trapezoidal cross-section utilizing characteristics such as (h_b), channel bed and side slope, and bed width. This purpose was achieved by experimental data, and multiple computer techniques were developed based on numerous geometric circumstances. Direct and indirect estimations of freefall water of a semicircular cross-section open channel utilizing water depth at the brink were developed by Zeidan *et al.* (2021).

A simple formula with an accurate prediction of the flow discharge is essential from a practical and hydraulic viewpoint since it is straightforward to implement with high precision. Although numerous types and shapes of sharp-crested weirs have been extensively studied experimentally, numerically, and statistically, most proposed equations for calculating the water discharge over sharp-crested weirs are dependent on the water head at a particular distance upstream of the weir (h). However, measuring this water head at some field locations may be impossible due to the short length of the channel or the installation of a weir at the beginning or entry of the channel. In other instances, the water head upstream weir (h) may be affected by a nearby weir, the diversion channel, or other obstruction. In addition, the water head upstream weir (h) is affected by the channel bed slope, which is not considered in most published equations for predicting the water discharge over the sharp-crested weir. Therefore, the present work aims to experimentally investigate the sharp-crested weir to suggest a simple formula with high accuracy for estimating water discharge over the sharp-crested weirs based on brink depth (h_b) measured over the weir crest.

2. EXPERIMENTAL METHODOLOGY

The experimental work was conducted using a 10 m long, 0.3 m wide, and 0.45 m deep rectangular open channel flume. The bed of the channel was a plate with a smooth surface. The maximum flow rate of 17.25 L/s water was recirculated into the flume. An electrical valve regulated the release of water into the channel. The flow goes through a fiberglass tank at the entrance of the flume to eliminate flow turbulence before entering the flume. Figure 1 is a schematic representation of the laboratory flume.

The volumetric calibrated weir, 10 cm in height, was installed temporarily at the start of each experiment and removed after water discharge was measured, and it was replaced by the research weir model.

A full-width, rectangular, sharp-crested weir was the subject of 160 experiments. As illustrated in Figure 2, the sharp-crested weir was constructed using British Standards Institution BSI 3680-4A (1965).

This study examined five different heights (*P*) of a sharp, full-width weir: 10, 12, 14, 16, and 18 (five ratios of height to length of the weir (*P*/*b*): 0.33, 0.4, 0.47, 0.53, and 0.6). In the study, the bed slope was also taken into account. The bed slope was changed 10 times for the maximum and minimum weir heights, between 0.001 and 0.01. During all of the experiments, the freefall condition was maintained.

Steel rails supported a point gauge carriage along the top of the flume walls. The point gauge can move along the channel's length and width with this carriage's assistance. The water head over the weir was measured in each experiment using a point gauge (with a precision of up to 0.1 mm). Two places were used to gauge the water's head. These locations are at the brink of the weir crest, denoted by brink depth (*hb*), and upstream weir location, denoted by a head over the weir (*h*), as shown in Figure 2. The head over the weir is usually measured at a distance between three and four times the maximum value of the water head over the weir (*to*) (British Standards Institution BSI 3680-4A 1965), which is, in this study, less than 10 cm. Therefore, *h* was measured at a distance equal to about 35 cm upstream weir location.

3. THEORETICAL METHODOLOGY

This study considered 160 experiments of various models of rectangular sharp-crested weirs with changing bed slopes, water flows, and weir heights to develop an equation for discharge estimation using brink depth (h_b). The investigation also evaluated several (h/P) values ranging from 0.158 to 0.945.

As illustrated in the following equation, it is well known that the critical depth (y_c) of a uniform flow in a rectangular open channel has a straightforward relationship with unit discharge (q) (Chow 1959):

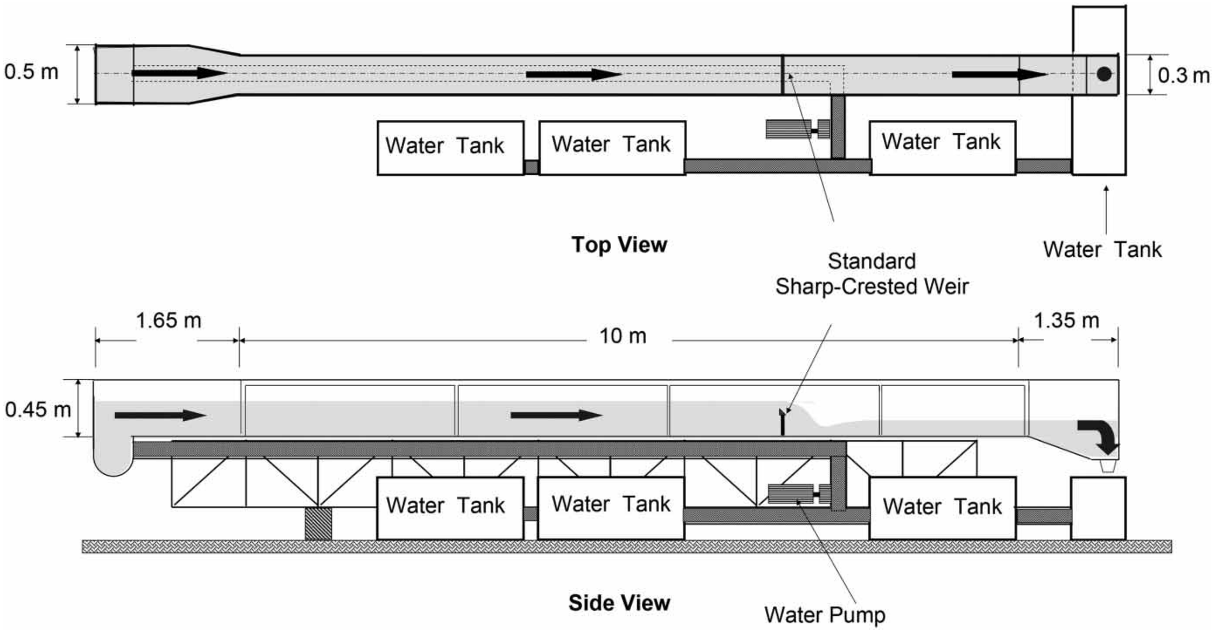

Figure 1 | Schematic diagram of the laboratory flume.

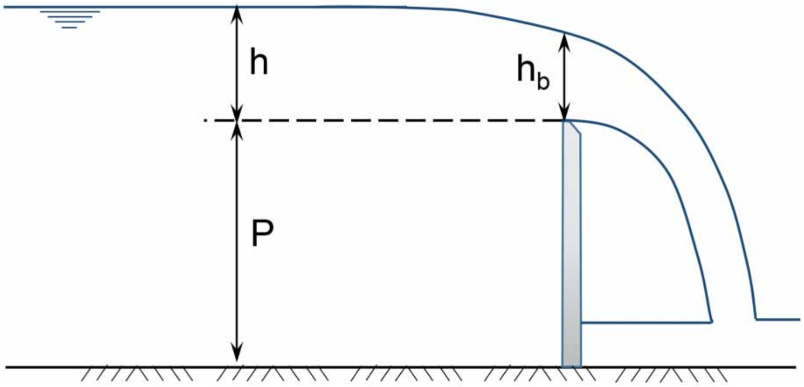

Figure 2 | Schematic of sharp-crested weir.

$$q = \sqrt{g y_c^3} \tag{1}$$

where g is the gravity acceleration; therefore, if y_c is known, Equation (1) can be used to compute the discharge in the channel. As shown in Figure 3, the relationship between the brink depth above the weir crest (h_b) and the critical depth (y_c) was displayed for experimental data with varying bed slopes (as bed slope does not affect brink depth, as stated previously), water discharges, and weir heights.

A correlation between (h_b) and (y_c) was established (Equation (2)). It is evident from the graph that a strong relationship exists, and the best-fitting straight-line equation is $R^2 = 0.9973$:

$$y_c = 0.8354\ h_b \tag{2}$$

Substituting Equation (2) into Equation (1) results in a relationship between unit discharge (q) and brink depth (h_b) as illustrated in Equation (3), allowing direct estimation of unit discharge (q) based on h_b value:

$$q = \sqrt{g}\ (0.8345 h_b)^{3/2} \tag{3}$$

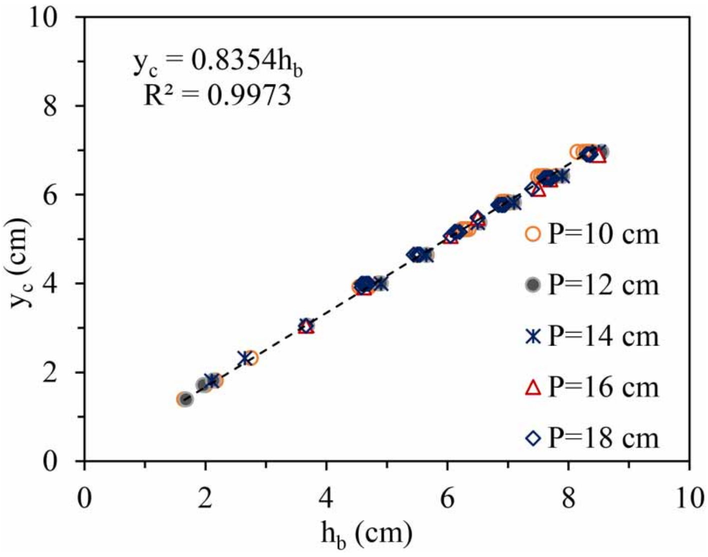

Figure 3 | Relation between critical depth and brink depth over the weir crest.

Equation (3) can be reformulated to estimate water discharge (Equation (4)) by multiplying Equation (3) by the width of the channel bed:

$$Q = B\sqrt{g}\,(0.8345h_b)^{3/2} \tag{4}$$

where Q is channel discharge in m^3/s, h_b is represented in m, and B is the channel bed width in m and equal length of the weir (b).

Numerous scholars have already developed different equations for estimating water discharge over the sharp-crested weir, including the well known Equation (5) (British Standards Institution BSI 3680-4A 1965) and Mahtabi & Arvanaghi's (2018) equation (Equation (6)):

$$Q = \frac{2}{3}\sqrt{2g}.C_d.b.h_e^{\frac{3}{2}} \tag{5}$$

C_d may be obtained from the Rehbock equation, Equation (5.1) (British Standards Institution BSI 3680-4A 1965), and h_e (in meters) can be obtained from Equation (5.2):

$$C_d = 0.602 + 0.083\,\frac{h}{P} \tag{5.1}$$

$$h_e = h + 0.0012 \tag{5.2}$$

Mahtabi & Arvanaghi's (2018) equation was mathematically derived for different weir heights, $P = 10$, 15, and 20 cm, and can be used to estimate the coefficient of discharge (C_d) from Equation (6) and then to compute water discharge by inserting (C_d) into Equation (5):

$$C_d = 0.0434\,^{(h/P)^{0.522}} + 0.653 \tag{6}$$

4. RESULTS AND DISCUSSION

This study's experimental measurement data ranges are summarized in Table 1. As is well known, most proposed equations for estimating water flow over sharp-crested weirs rely on the head of water at a specific distance upstream of the weir (h). However, as shown in Table 1 and Figure 4, the bed slope affects the water head above the weir (h) and decreases as the bed slope increases. Figure 4 depicts an example of the effect of the bed slope on the water surface profile with a constant water flow discharge, Q, and weir height, P.

To clearly show the effect of bed slope, S, on the head over the weir, h, 10 different bed slopes between 0.001 and 0.1 for weir heights of 10 cm and 18 cm were investigated in this study. The water head was measured at two locations (h and h_b). The relationships between the slope of the bed and the ratio of the water head to the height of the weir (h_b/P and h/P) are shown in Figure 5 for water discharge of 13.25 L/s and P of 10 cm (Figure 5(a)) and water discharge of 13.025 L/s and P of 18 cm (Figure 5(b)) as the sample. The other relations for different discharges almost follow the same trends. From Figs. 4 and 5, the bed slope has an inverse effect on the head over the weir upstream weir location (h) for the constant water discharge value; this is because increasing the flow velocity with the increase in the bed slope leads to a decrease in the depth of water (energy conservation law) (Chow 1959). That affects the accuracy of any equation for estimating water discharge over the weir dependent on the water head at a particular distance upstream of the weir (h), which does not consider the bed slope. However, as shown in Figs. 4 and 5, changing the bed slope does not affect the brink depth (h_b) as it is located at a zero distance from the weir. Therefore, using h_b for the water discharge estimation of over the weir is more accurate than using h.

Table 1 | Experimental data ranges

No.	Q (L/s)	P (cm)	S	h_b (cm)	h (cm)
1	7.298–17.250	10–18	0.001–0.01	1.65–8.55	1.8–9.75

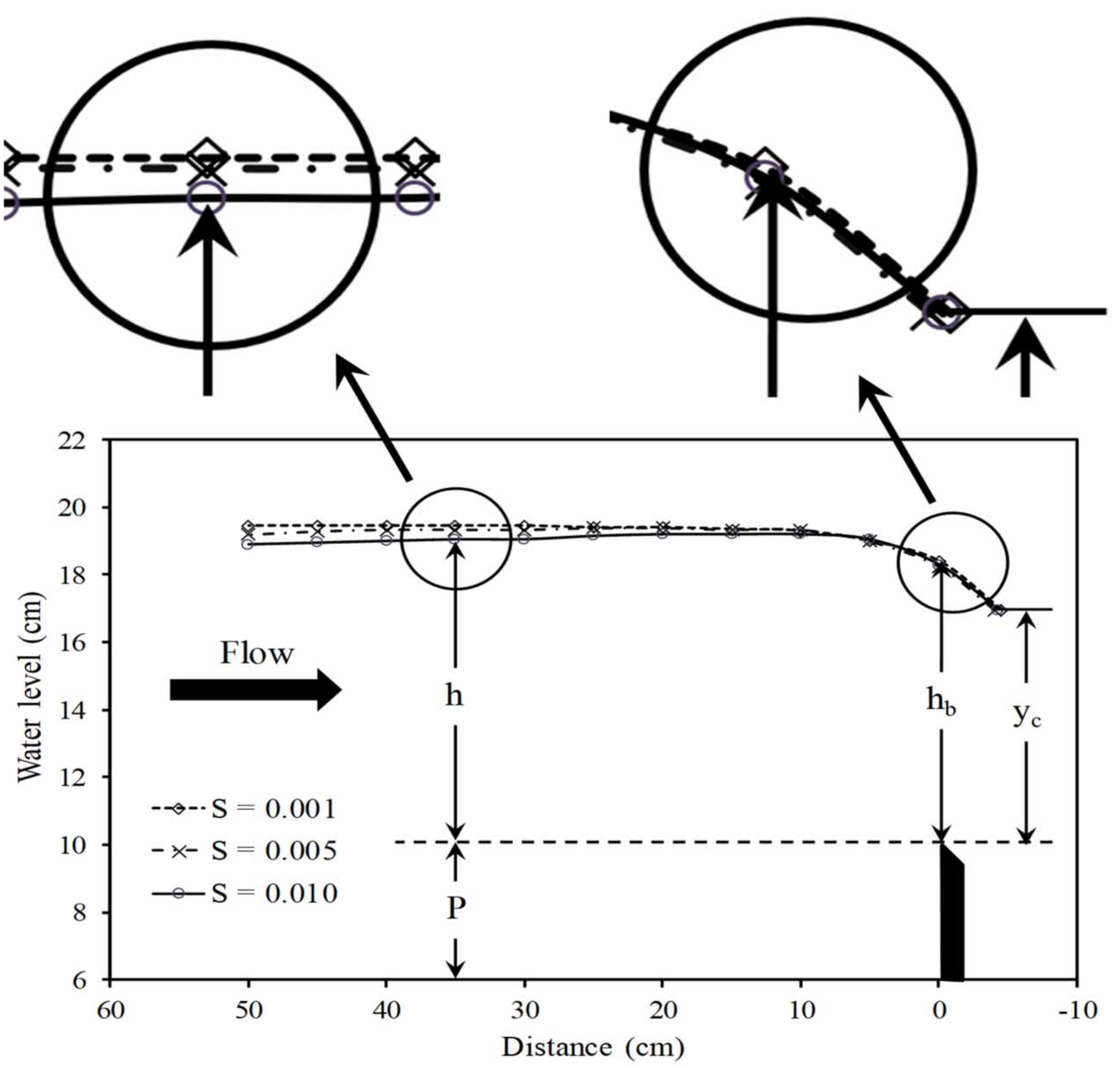

Figure 4 | Water surface profile for bed slope, $S = 0.001$, 0.005, and 0.010 ($Q = 17.25$ L/s and $P = 10$ cm).

As depicted in Figure 6, a comparison was made between the proposed formulae (Equations (4)–(6)) with the measured discharge values. Equations (7) and (8), which are often used to calculate the MAPE (Bowerman *et al.* 2005, Hanke & Wichern 2005, Kim & Kim 2016) and RMSE (Willmott *et al.* 2012, Alomari *et al.* 2018)), were utilized to evaluate the performance of Equation (4). Two-thirds of the datasets were randomly selected to generate an empirical relationship equation between the brink depth above the weir crest (h_b) and the critical depth (y_c). The other one-third of the datasets was used to examine the following equations:

$$\text{MAPE\%} = \frac{1}{n}\left[\sum_{i=1}^{n}\frac{|M_i - P_i|}{M_i}\right] \times 100 \tag{7}$$

$$\text{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - M_1)^2\right]^{0.5} \tag{8}$$

where M_i represents the measured values, P_i represents the values, n is the dataset's total number. Equation (4) has MAPE and RMSE values of 1.714% and 0.23, respectively. The MAPE and RMSE for Equation (5) are, respectively, 3.12% and 0.39.

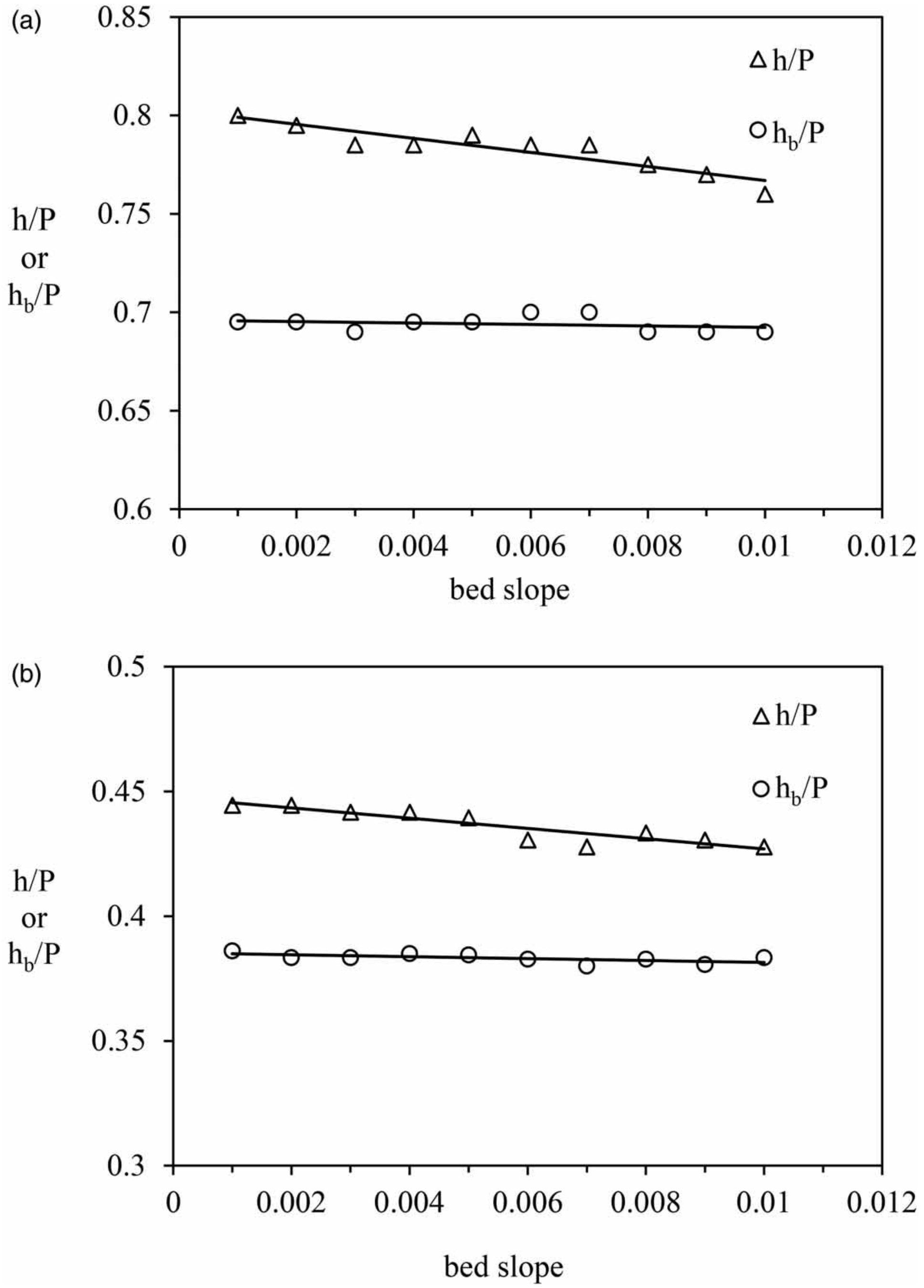

Figure 5 | Effect of bed slope on water depths: (a) water discharge of 13.25 L/s and weir height of 10 cm; (b) water discharge of 13.025 L/s and 18 cm.

5. CONCLUSIONS

Experiments were conducted on a full-width standard sharp-crested weir with heights ranging from 10 to 18 cm, variable water discharge (between 1.54 and 17.25 L/s), and variable channel slopes (between 0.001 and 0.01). Various experiments yielded (h/P) values ranging from 0.158 to 0.94. For each experiment, the brink depth over the weir crest (h_b) and head over the weir (h) (upstream of the weir location) were measured to find a simple and accurate formula for predicting water discharge over the sharp-crested weir based on brink depth with various weir conditions, as mentioned previously.

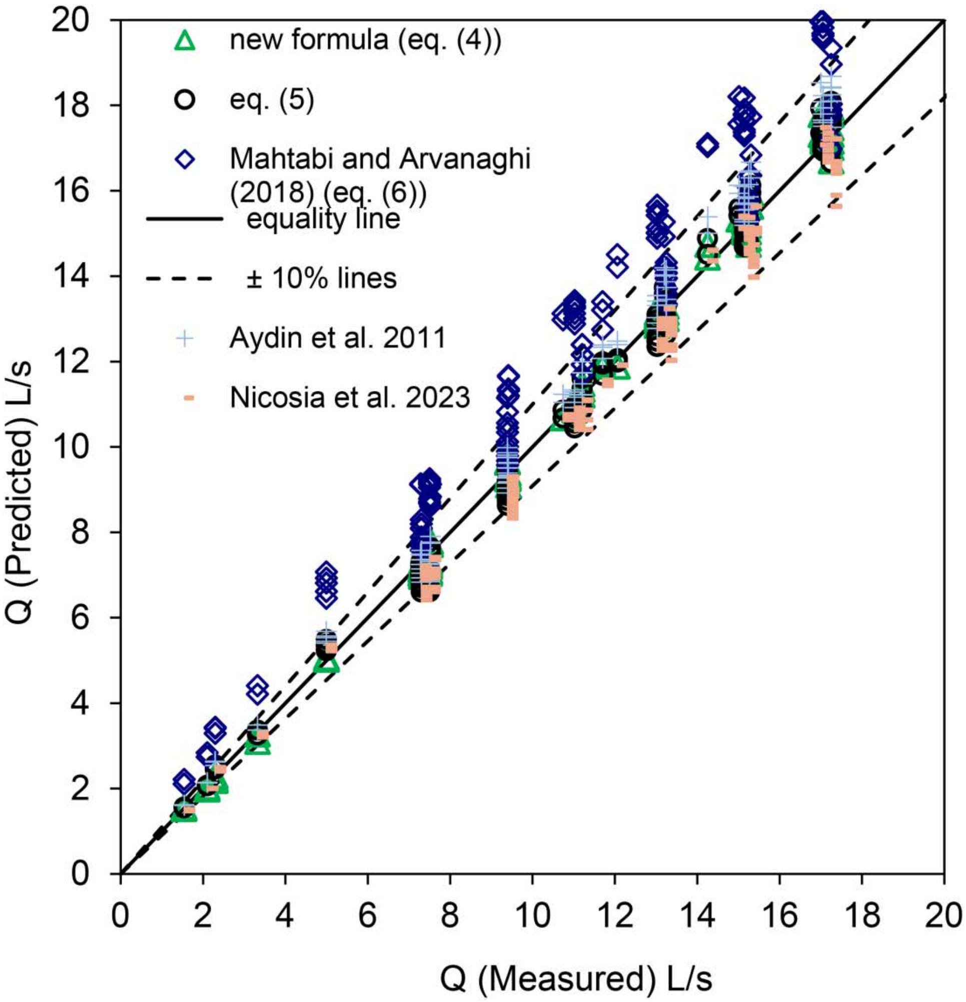

Figure 6 | Comparison between measured and predicted discharges from new formula (Equation (4)), Equation (6), Aydin *et al*. 2011, Nicosia *et al*. 2023, and Mahtabi & Arvanaghi (2018) equation (Equation (7)).

Based on the experimental result and within its limitations, the following can be concluded:

1. Regarding the influence of the bed slope on the water head for a constant water discharge, h was inversely affected by the bed slope; this resulted in a reduction in water depth, which was observed upstream of the weir due to the increased bed slope. Increasing the slope of the bed will increase the flow velocity and then decrease the water head over the crest (h). Therefore, the accuracy of the prediction discharge equations, which predict water discharge based on the h value, is diminished since they do not take the bed slope into account. However, the brink depth (h_b) is not affected by changing the slope of the bed as it is located at zero distance from the location of the weir.
2. Concerning the development of a new formula to predict water discharge over the sharp-crested weir, a relationship between brink depth and critical depth was developed statically, within the experiment's limitations (h/P values between 0.158 and 0.9455), with an R^2 value of 0.9973. This relationship was then used to formulate a simple form formula based on the brink depth over the weir crest (h_e) (Equation (4)). This formula was examined by comparing it with other formulae such as the well known standard equation (Equation (5)) and the equation of Mahtabi & Arvanaghi (2018), Aydin *et al*. 2011, and Nicosia *et al*. 2023. The new formula has proven to be quite accurate in computing the discharge, with MAPE and RMSE values of 1.714% and 0.23, respectively.

Finally, it is necessary to evaluate the various types and shapes of the weir to examine the effect of bed slope on the water head and develop a new equation for calculating water discharge based on the brink depth, which is unaffected by bed slope.

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AUTHOR CONTRIBUTIONS

All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abrari, E., Beirami, M. K. & Ergil, M. 2017 Prediction of the discharges within exponential and generalized trapezoidal channel cross-sections using three velocity points. *Flow Measurement and Instrumentation* **54**, 27–38.

Abrari, E., Ergil, M. & Beirami, M. K. 2019 Flow measurement using free over-fall in generalized trapezoidal channels based on one velocity point method. *Flow Measurement and Instrumentation* **69**, 101615.

Afsharpour, M. & Farhoudi, J. 2023 Estimation of discharge coefficient of the overshot gates, based on the brink depth, under free and submerged conditions. *ISH Journal of Hydraulic Engineering* **29** (2), 115–120.

Afzalimehr, H. & Bagheri, S. 2010 Discharge coefficient of sharp-crested weirs using potential flow. *Journal of Hydraulic Research* **48** (5), 694–695.

Ahmad, Z. & Azamathulla, H. M. 2012 Direct solution for discharge in circular free overfall. *Journal of Hydrology* **446–447**, 116–120.

Al-Husseini, T. R., Al-Madhhachi, A.-S. T. & Naser, Z. A. 2020 Laboratory experiments and numerical model of local scour around submerged sharp crested weirs. *Journal of King Saud University - Engineering Sciences* **32** (3), 167–176.

Alomari, N. K., Yusuf, B., Mohammad, T. A. & Ghazali, A. H. 2018 Experimental investigation of scour at a channel junctions of different diversion angles and bed width ratios. *CATENA* **166**, 10–20.

Alomari, N. K., Altalib, A. N. & Al-Janabi, A. M. S. 2023 Discharge estimation using brink depth over a trapezoidal-shaped weir. *Flow Measurement and Instrumentation* **94**, 102454. doi: 10.1016/j.flowmeasinst.2023.102454.

Aydin, I., Altan-Sakarya, A. B. & Sisman, C. 2011 Discharge formula for rectangular sharp-crested weirs. *Flow Measurement and Instrumentation* **22** (2), 144–151.

Azimi, A. H. & Salehi, S. 2022 Hydraulics of flow over full-cycle cosine and rectangular sharp-crested weirs. *Canadian Journal of Civil Engineering* **49** (6), 954–68. doi: 10.1139/cjce-2020-0581.

Azimi, A. H. & Rajaratnam, N. 2023 A note on the discharge over full-width rectangular sharpcrested weirs and weirs of finite crest length. *Journal of Applied and Computational Mechanics* **9** (2), 458–63. doi: 10.22055/jacm.2022.41600.3779.

Bagheri, S. & Heidarpour, M. 2010 Application of free vortex theory to estimating discharge coefficient for sharp-crested weirs. *Biosystems Engineering* **105** (3), 423–427.

Behroozi, A. M. & Vaghefi, M. 2022 Experimental and numerical study of the effect of zigzag crests with various geometries on the performance of A-type piano key weirs. *Water Resources Management* **36** (12), 4517–4533.

Borghei, S. M., Jalili, M. R. & Ghodsian, M. 1999 Discharge coefficient for sharp-crested side weir in subcritical flow. *Journal of Hydraulic Engineering* **125** (10), 1051–1056.

Bowerman, B. L., O'Connell, R. T. & Koehler, A. B. 2005 *Forecasting, Time Series, and Regression: An Applied Approach*. Thomson Brooks/Cole, Belmont, CA.

British Standards Institution BSI 3680-4A. 1965 *Standard Test Method for Open-Channel Flow Measurement of Water with Thin-Plate*. British Standards Institution BSI 3680-4A, London.

Carrillo, J. M., Matos, J. & Lopes, R. 2020 Numerical modeling of free and submerged labyrinth weir flow for a large sidewall angle. *Environmental Fluid Mechanics* **20** (2), 357–374.

Chow, V. T. 1959 *Open Channel Hydraulics*. McGraw-Hill Book Company, Inc., New York.

Emiroglu, M. E. & Kaya, N. 2011 Discharge coefficient for trapezoidal labyrinth side weir in subcritical flow. *Water Resources Management* **25** (3), 1037–1058.

Ghobadian, R. & Meratifashi, E. 2012 Modified theoretical stage-discharge relation for circular sharp-crested weirs. *Water Science and Engineering* **5** (1), 26–33.

Hanke, J. E. & Wichern, D. W. 2005 *Business Forecasting*. Pearson, Prentice Hall, New Jersey.

Imanian, H., Mohammadian, A. & Hoshyar, P. 2021 Experimental and numerical study of flow over a broad-crested weir under different hydraulic head ratios. *Flow Measurement and Instrumentation* **80**.

Irzooki, R. H., Akib, S. M. & Fayyadh, M. M. 2014 Experimental study of characteristics of flow over weirs with semicircular openings. *Arabian Journal for Science and Engineering* **39** (11), 7599–7608.

Johnson, M. C. 2000 Discharge coefficient analysis for flat-topped and sharp-crested weirs. *Irrigation Science* **19** (3), 133–137.

Kassaye, A. A., Mohammed, A. K. & Angello, Z. A. 2022 Evaluation of the flow measurement performance of compound sharp-crested overfall weirs and optimized discharge measurement in data scarce areas. *Water Resources* **49** (3), 402–412.

Khodier, M. & Tullis, B. 2022 Influence of crest roughness on weir flow conditions for improving nappe stability. *Jordan Journal of Civil Engineering* **16** (4), 681–689.

Khosravinia, P., Nikpour, M. R., Kisi, O. & Yaseen, Z. M. 2020 Application of novel data mining algorithms in prediction of discharge and end depth in trapezoidal sections. *Computers and Electronics in Agriculture* **170**, 105283.

Kim, S. & Kim, H. 2016 A new metric of absolute percentage error for intermittent demand forecasts. *International Journal of Forecasting* **32** (3), 669–679.

Kumar, S., Ahmad, Z. & Mansoor, T. 2011 A new approach to improve the discharging capacity of sharp-crested triangular plan form weirs. *Flow Measurement and Instrumentation* **22** (3), 175–180.

Li, J. & Han, J. 2022 Experimental study of discharge formulas for rectangular sharp-crested weirs under free flow condition. *Flow Measurement and Instrumentation* **84**, 102115.

Li, S., Yang, J. & Ansell, A. 2021 Discharge prediction for rectangular sharp-crested weirs by machine learning techniques. *Flow Measurement and Instrumentation* **79**, 101931.

Li, J., Han, J., Dai, W., Xiao, R., Liang, Q. & Ma, Y. 2023 A comprehensive experimental investigation on discharge formulae of free flow over fully contracted rectangular sharp-crested weirs. *Flow Measurement and Instrumentation* **94**, 102484. doi: 10.1016/j.flowmeasinst.2023.102484.

Mahtabi, G. & Arvanaghi, H. 2018 Experimental and numerical analysis of flow over a rectangular full-width sharp-crested weir. *Water Science and Engineering* **11** (1), 75–80.

Mirzaei, K. & Sheibani, H. R. 2021 Experimental Investigation of arched sharp-crested weir flow and comparing it with rectangular weir. *Iranian Journal of Science and Technology, Transactions of Civil Engineering* **45** (2), 1039–1048.

Muhsin, K. A. & Noori, B. M. A. 2021 Hydraulics of free overfall in smooth triangular channels. *Ain Shams Engineering Journal* **12** (3), 2471–2484.

Nicosia, A., Di Stefano, C., Serio, M. A. & Ferro, V. 2023 Effect of the crest height on the stage-discharge formula of rectangular and triangular sharp-crested weirs under free-flow conditions. *Flow Measurement and Instrumentation* **93**, 102421. doi: 10.1016/j.flowmeasinst.2023.102421.

Noori, B. M. A. & Aaref, N. T. 2017 Hydraulic performance of circular crested triangular plan form weirs. *Arabian Journal for Science and Engineering* **42** (9), 4023–4032.

Rouse, H. 1936 Discharge characteristics of the free overfall: Use of crest section as a control provides easy means of measuring discharge. *Civil Engineering* **6** (4), 257–260.

Roushangar, K., Majedi Asl, M. & Shahnazi, S. 2021 Hydraulic performance of PK weirs based on experimental study and Kernel-based modeling. *Water Resources Management* **35** (11), 3571–3592.

Saadatnejadgharahassanlou, H., Zeynali, R. I., Gharehbaghi, A., Mehdizadeh, S. & Vaheddoost, B. 2020a Three dimensional flow simulation over a sharp-crested V-notch weir. *Flow Measurement and Instrumentation* **71**, 101684. doi: 10.1016/j.flowmeasinst.2019.101684.

Saadatnejadgharahassanlou, H., Zeynali, R. I., Vaheddoost, B. & Gharehbaghi, A. 2020b Parametric and nonparametric regression models in study of the length of hydraulic jump after a multi-segment sharp-crested V-notch weir. *Water Science and Technology: Water Supply* **20** (3), 809–18. doi: 10.2166/ws.2019.198.

Salehi, S., Moghadam, A. M. & Esmaili, K. 2023 Flow regimes of submerged rectangular sharp-crested weirs in sand bed channel. *Sadhana - Academy Proceedings in Engineering Sciences* **48** (1), 1–12. doi: 10.1007/s12046-022-02053-4.

Vatankhah, A. R. 2013 Direct solution for discharge in generalized trapezoidal free overfall. *Flow Measurement and Instrumentation* **29**, 61–64.

Willmott, C. J., Robeson, S. M. & Matsuura, K. 2012 A refined index of model performance. *International Journal of Climatology* **32** (13), 2088–2094.

Wu, S. & Rajaratnam, N. 1996 Submerged flow regimes of rectangular sharp-crested weirs. *Journal of Hydraulic Engineering* **122** (7), 412–414.

Zahiri, A., Tang, X. & Azamathulla, H. M. 2014 Mathematical modeling of flow discharge over compound sharp-crested weirs. *Journal of Hydro-environment Research* **8** (3), 194–199.

Zeidan, R., Elshemy, M. & Rashwan, I. M. 2021 Using the brink depth in discharge measurement for inverted semicircular open channels. *Journal of Engineering Research* **5** (1), 43–49.

Zhang, J., Chang, Q., Zhang, Q.-h. & Li, S.-n. 2018 Experimental study on discharge coefficient of a gear-shaped weir. *Water Science and Engineering* **11** (3), 258–264.

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