Research Article

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Discharge coefficient and energy dissipation on stepped weir

Abstract: High volumes of kinetic energy are generated as water is transported to the dam downstream. Stepped weir are some of the best in lowering the kinetic energy of a flow traveling downstream. In stepped weirs, the steps' design can impact how much of the flow's kinetic energy is transferred downstream. Because these weirs could dissipate more power, recently, pooled designs have been more common than smooth ones. Therefore, this work investigated the impact of sills at the ends-edge of the steps and discharge values on flow patterns, particularly energy dissipation. Seventy-five experiments were conducted and five models were used with a slope angle of 35° with different step dimensions, different numbers of steps (14, 10, 7, 5, and 3), and other discharges. Three-step configurations were used: flat, fully pooled, and zigzag pooled steps. The results indicated that increasing the number of steps increased the energy dissipation rate. In addition, an increase in the discharge leads to an increase in the discharge coefficient and thus decreases the energy dissipation rate. A coefficient of determination R^2 gives a good agreement for the discharge coefficient (0.73).

Keywords: stepped weir, energy dissipation, discharge coefficient, end-sill

1 Introduction

According to the needs and characteristics of the area, many hydraulic structures are built in open channels [1]. One of these structures, the weir, is used to measure discharge and the depth of rising water in irrigation channels [2–4]. The weir channel is typically one of a dam's most essential aspects. The weir channel offers a practical and secure method of transferring flood flows to the region downstream of the barriers [5]. Stepped weirs have become common hydraulic structures in recent years, with steps on their faces running from close to the crest to the toe [6]. The efforts substantially accelerate the rate of energy dissipation on the weir surface. Stilling basin length should be as small as possible to minimize the required downstream energy dissipation basin size. However, using a stepped weir can reduce cavitation risk by boosting self-aerated flow compared to more traditional smooth weirs [7–10]. According to the discharge and the stepped weir's dimensions, flow over a stepped weir can be generally classified into three flow patterns: nappe, transition, and skimming. The various features of each flow pattern choose the flow pattern as an essential component in the construction of stepped spillways [11,12]. The first, a sequence of little successive falls, occurs for low discharger flow rates and/or essential step lengths. The transition flow regime, which was initially introduced, happens for various intermediate discharges when transitioning from the nappe flow to the skimming flow [13]. This regime's most distinguishing feature is the presence of horizontal step-face stagnation and significant splashing. A skimming flow system is formed when the flowing water completely submerges the steps. Usually, horizontal-axis recirculation zones are formed between the outer edges of the step, which are created for efficient flow rates and short step lengths [14].

Since each step serves as a small stilling basin for low discharges, most of the flow energy is dissipated over the steps [15].

The research focuses on identifying the relationship between discharge coefficient, energy dissipation, and relative discharges and how the arrangement of the step affects the discharge coefficient and energy loss.

2 Theoretical study

2.1 Energy dissipation

The energy between the inlet section and the approach channel of the weir can be used to calculate and measure

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the energy dissipation E_0 and any area of an intriguing phase E, as shown in Figure 1.

$$E_0 = H_{\text{dam}} + y_0 + \frac{v_0^2}{2g}. \tag{1}$$

Along with the datum, the section on the significant step is also superimposed. The velocity head and depth flow, which are measured vertically from the datum, combine the energy E_1.

$$E_1 = y_1 + \frac{v_1^2}{2g}. \tag{2}$$

The energy loss ΔE is the difference between the energy at the entrance section E_0 and the energy at the exciting section E_1. The dissipation of energy, one of the dimensionless parameters frequently used to research the energy dissipation characteristic, is $\Delta E/E_0$.

By multiplying the non-dimensional parameters according to Buckingham's theory, the aforementioned variables can be decreased, and equation (3) can be expressed as follows:

$$E\% = f(y_c/h_s, \ l_s/y_c, \ \text{Fr}, \ N_s, \theta). \tag{4}$$

Dimensionless characteristics are necessary for the investigation of energy dissipation in spillways.

2.3 Discharge coefficient

Horton [16] proposed that discharge coefficient, C_d, is directly dependent on the upstream head (y_0)-to-crest length (L_c) ratio, y_0/L_c, and that viscosity and surface tension effects may be disregarded if $y_0 > 30$ mm. Singer [17] proposed using y_0/L_c to classify flow over weirs with finite crest
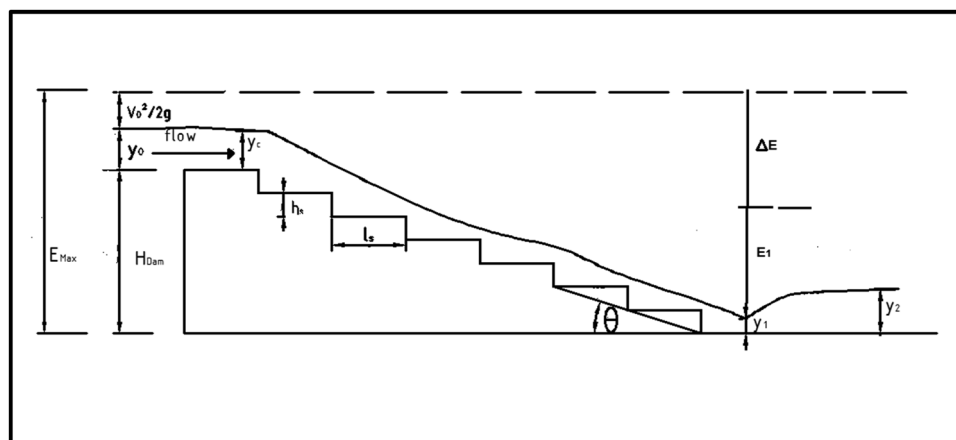

Figure 1: Variables used in calculating energy dissipation.

2.2 Dimensional analysis

Energy dissipation of hydraulic jump downstream stepped weir was affected by several factors, including geometric characteristics of the stepped weir (such as the width of the stepped weir [W], the height of the weir [H_{dam}], and the slope of the weir [θ]), length, height, and number of steps (l_s, h_s, and N_s, respectively). The kinematic flow characteristics are also affected by other flow characteristics such as gravity acceleration (g), velocity (V), dynamic viscosity (μ), mass density (ρ), surface tension (o), and critical depth flow (y_c).

Thus, the energy dissipation of flow is a function of these variables:

$$f(E, \ H_{\text{dam}}, \ W, \ N_s, \ l_s, \ h_s, \ V, \ y_c, \ g, \ \rho, \ \mu, \acute{o}, \ \theta). \tag{3}$$

lengths. Standing waves on the weir for $y_0/L_c < 0.08$ indicated that surface tension and viscosity effects might need to be considered in this range. The weirs with finite crest lengths are classified into four groups based on y_0/L_c:
1. Long-crested weir ($0 < y_0/L_c \leq 0.1$),
2. Broad crested weir ($0.1 < y_0/L_c \leq 0.4$),
3. Short crested weir ($0.4 < y_0/L_c \leq 2$),
4. Sharp crested weir ($y_0/L_c > 2$).

3 Experimental work

All experiments were performed at the hydraulic laboratory of the Middle Technical University at Kut Technical Institute in Iraq, as shown in Figure 2 [18], using a
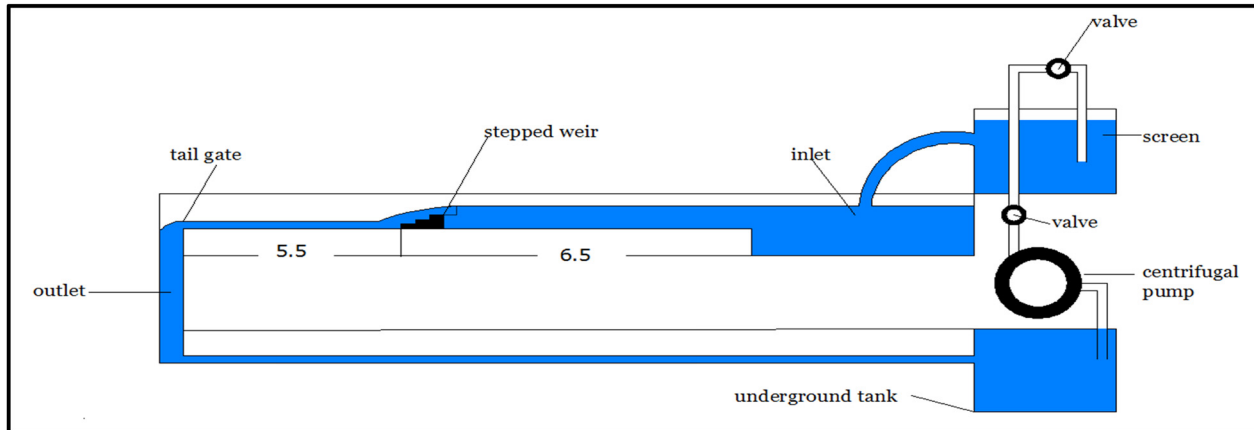
Figure 2: Experimental setup for stepped weir.

laboratory flume of 12 m long, 50 cm high, and 50 cm wide. The flume obtains water from a permanent upper tank through a 6-inch pump tube. This is located at a 90° angle at the water outlet from the upper tank. The three-point carriages in the channel are used to measure the height of the point with an accuracy of 0.5 mm [19]. The examined stepped weir models were created from foam, as seen in Figure 3. The total height, width, and length of the crest, and slope of the weir are all the same for all models and are 35, 50, 50, 10 cm, and 35°, respectively. Each model had a different length, height, and number of steps. Five discharge pumps (7, 12, 15, 20, and 25 L/s) for each model during 75 experiments were done in the free flow state, as indicated in more detail in Table 1. The study investigated three steps: flat, pooled, and zigzag. The formula gives the dimensions of the step h_s/l_s, where h_s is the height of the step and l_s is the horizontal length. The height (h_p) of the end-sill was 1.5 cm and the length (l_p) was 1 cm in the case of the pooled steps. Used number of steps (N_s) (14, 10, 7, 5, and 3).

4 Discussions and analysis of results

The laboratory observations of the effect of step number, step geometry, step end-sill shape, and discharge on energy dissipation on the step, as well as establishing a relationship between energy dissipation and the ratio of the critical depth flow to step height (y_c/h_s) and the discharge coefficient CD versus the length of step to critical water depth ratio (l_s/y_c), are presented here. The stepped weirs showed three flow patterns: the nappe flow, the transition flow, and the skimming flow, as shown in Figure 4(a–c), respectively.

Observed is the fact that the nappe flow occurred at step 3 with a significant step height and low discharge, while the transitional flow occurred at the intermediate discharge and actions (5 and 7).

As for the skimming flow, it was in steps 14 and 10 with a small step height and at all discharges.

The flow energy dispersed over a stepped weir in steps 14, 10, 7, 5, and 3 was depicted as a function of distance from critical flow depth (y_c)   and the step height (h_s), applied as the dimensionless parameter (y_c/h_s). It should be noted that the rate of energy dissipation increases by decreasing that percentage, as shown in Figure 5, and this corresponds to the previous researchers such as Jahad et al. [20].

The results additionally showed the relationship between the length step-to-the critical depth flow ratio (l_s/y_c) and the energy dissipation ratio (E%), as shown in Figure 6. Because the length of the step causes the size of the extrusion to increase and hence create a gradual flow, it was discovered that the percentage of the flow energy dissipation increases as the length of the step to the depth of critical water increases. The fully pooled step achieves the highest dissipation of the flow energy. This is supported by numerous researchers' findings, including those of Nasiralla AL-Talib et al. [21].

The pooled steps have dissipated energy more than flat and zigzag pooled stages. With the entire end-sill in phases, the relative energy loss rises by 5% since the characteristic height of the end-sill increases the amount of water trapped. The hydraulic jump and the impact of the jet on the step face account for the majority of energy loss in the nappe flow, so the characteristic height has less of an effect there. However, the characteristic height has a more significant influence on the transition flow than on the nappe flow, and its impact on the skimming flow is evident.

According to the ratio (y_0/L_c) mentioned previously, the crested in this study is the short-crested weir because
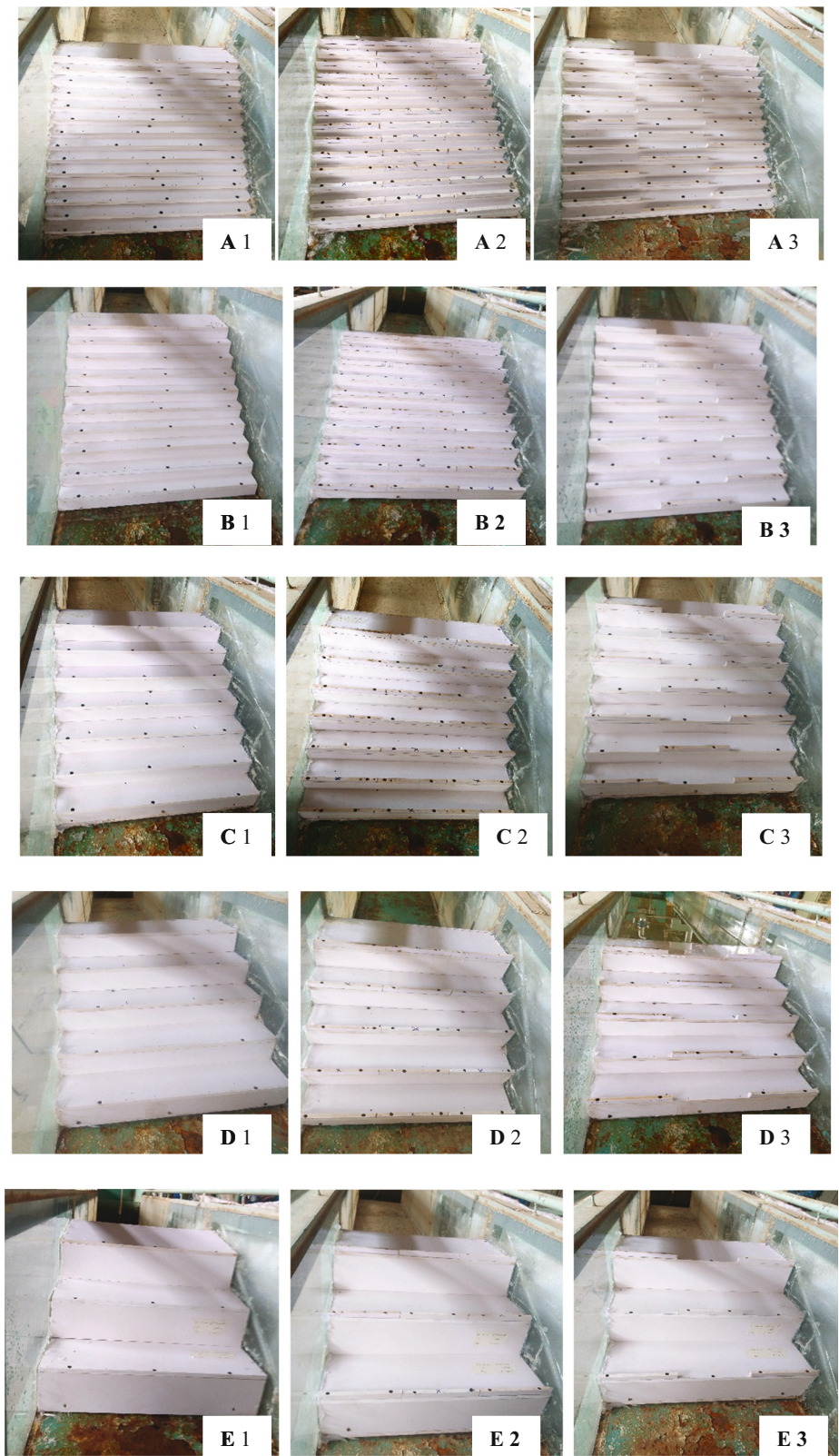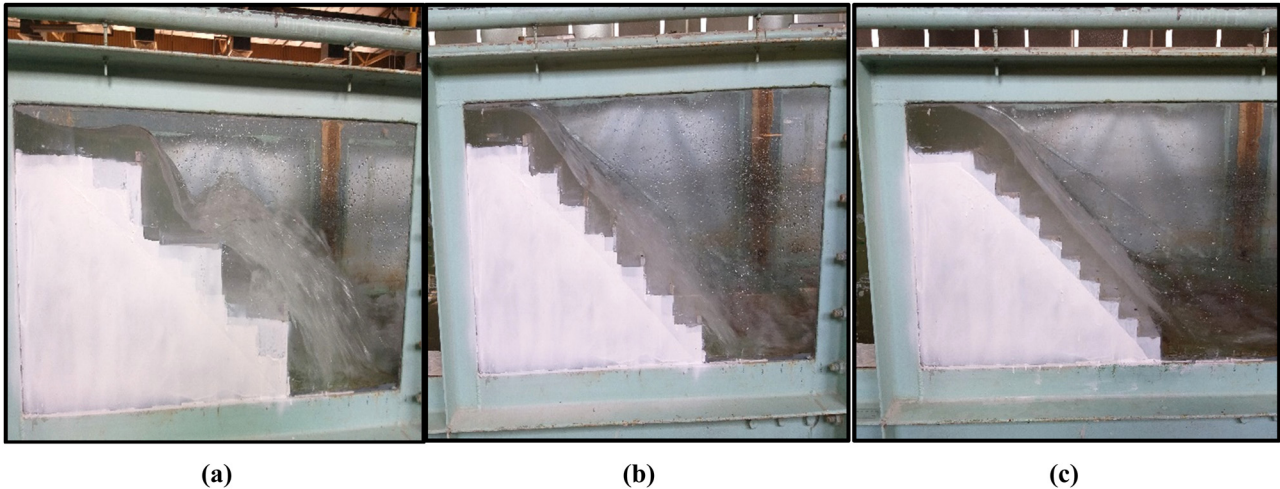
Figure 3: Experimental models (θ = 35°).

Table 1: Dimensions of the stepped weir models

Model type of step	Model	No. of steps	Dimension of steps			Dimension of pooled steps		
			h_s (cm)	l_s (cm)	w_s (cm)	h_p (cm)	l_p (cm)	w_p (cm)
Flat step	A1	14	2.5	3.6	50	—	—	—
	B1	10	3.5	5				
	C1	7	5	7.1				
	D1	5	7	10				
	E1	3	11.7	16.6				
Fully pooled step	A2	14	2.5	3.6	50	1.5	1	50
	B2	10	3.5	5				
	C2	7	5	7.1				
	D2	5	7	10				
	E2	3	11.7	16.6				
Zigzag pooled step	A3	14	2.5	3.6	50	1.5	1	16.5
	B3	10	3.5	5				
	C3	7	5	7.1				
	D3	5	7	10				
	E3	3	11.7	16.6				

(a)   (b)   (c)

Figure 4: Flow patterns over the stepped weir. (a) Nappe flow (N_s = 3, Q = 12 L/s); (b) transition flow (N_s = 7, Q = 15 L/s); and (c) skimming flow (N_s = 10, Q = 25 L/s).

the ratio (y_0/L_c) for the current study ranges between (0.5 < y_0/L_c < 1.3), equation (5) was applied to calculate C_d:

$$Q = C_d \cdot B \cdot y_0^{1.5}. \tag{5}$$

The C_d values range from 0.7 to 1.25 and are affected by the ratio of y_0/L_c, as shown in Figure 7. In addition, an increase in the discharge leads to an increase in the discharge coefficient, as shown in Figure 8, and thus, the rate of energy dissipation decreases, as shown in Figure 9, which is consistent with previous studies [22]. Based on the experimental data, the discharge coefficient for the stepped weir with the coefficient of determination R^2 of 0.73 was predicted.

$$C_d = 0.823 + 0.268\left(\frac{y_0}{L_c}\right). \tag{6}$$

for 0.5 < y_0/L_c < 1.3.

5 Conclusions

These tests showed that as the number of steps increased, the relative dissipation of energy increased due to the high level of roughness of the steps, which increased friction and caused the conversion of kinetic energy into thermal
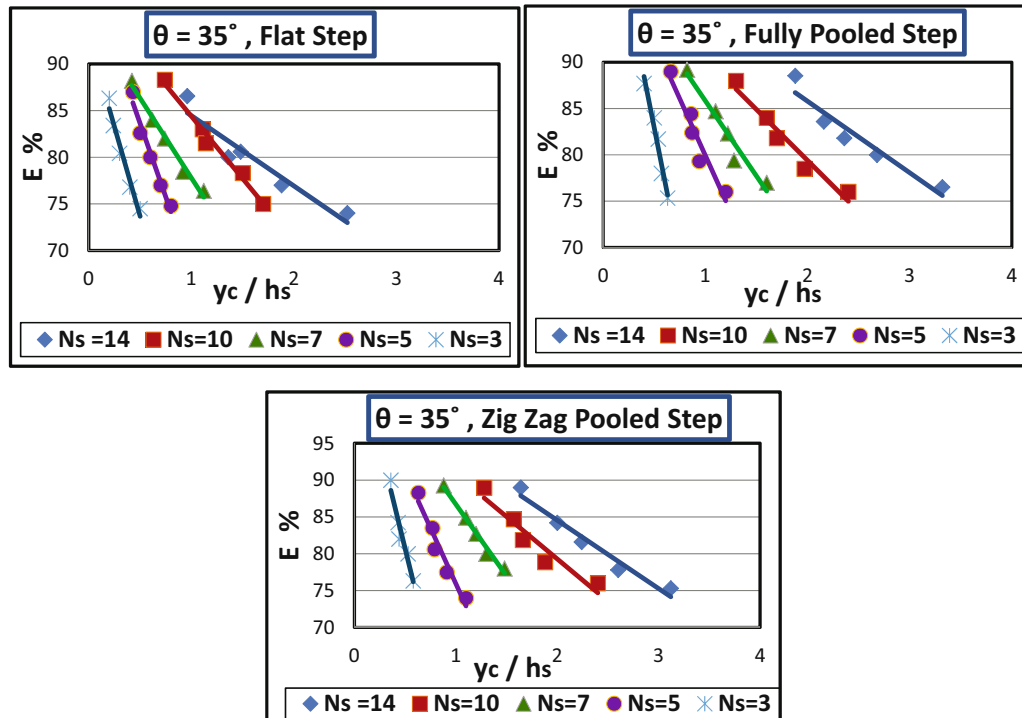
Figure 5: The relative energy loss with $\frac{y_c}{h_s}$.

energy. The flow patterns on the stepped weir are affected by the discharge flow rate, where nappe flow occurred at a few discharges. With increasing discharge, the critical flow depth increases, and the flow becomes skimming. The height of the sills at the ends-edge of the steps affects the amount of energy dissipation compared to flat steps. Fully pooled steps dissipate more energy than zigzag pooled steps. Also, more discharge leads to a larger discharge coefficient, which reduces the amount of energy dissipation.
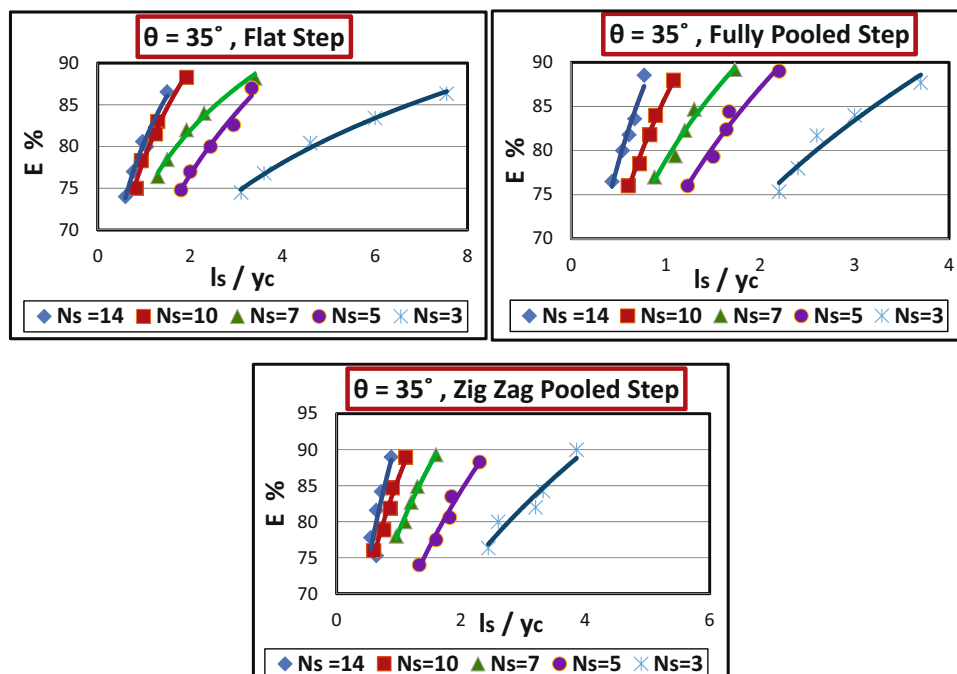

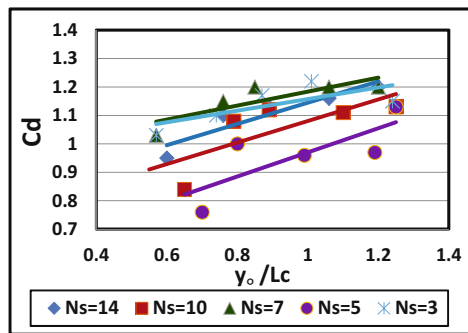**Figure 6:** The relative energy loss with l_s/y_c.

Figure 7: Relationship between discharge coefficient and y_0/L_c.
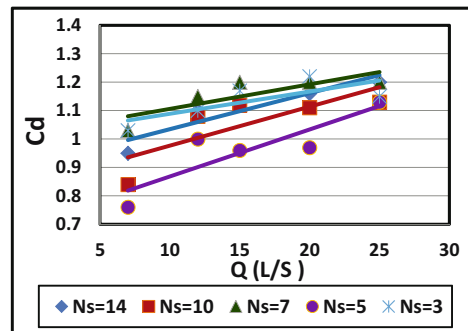

Figure 8: Relationship between discharge coefficient and discharge.
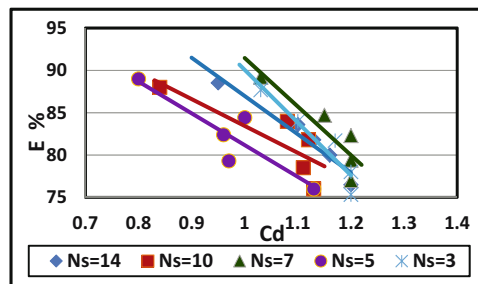

Figure 9: Energy dissipation with discharge coefficient.

List of symbols

Parameters		Unit
H_{dam}	Height of weir	m
W	Width of weir	m
L_c	Length of crest	m
y_0	Depth flow upstream	m
y_c	Critical depth	m
y_1	Depth flow before hydraulic jump	m
y_2	Depth flow after hydraulic jump	m
v_0	Velocity	m/s
v_1	Local mean velocity	m/s
h_s	Step height	m
l_s	Step length	m
W_s	Width of step	m
h_p	Height of pooled	m
l_p	Length of pooled	m
W_p	Width of pooled	m
N_s	Number of steps	—
θ	Slope of weir	—
g	Acceleration gravity	m/s^2
F_r	Froude number	—
C_d	Discharge coefficient	—
Q	Discharge flow	m^3/s
E_0	Head upstream of the weir	m
E_1	Local energy head	m
ΔE	The difference between energy upstream and downstream of the weir	m
$E\%$	Flow energy dissipation ratio	—

Conflict of interest: The authors state no conflict of interest.

Data availability statement: Most datasets generated and analyzed in this study are comprised in this submitted manuscript. The other datasets are available on a reasonable request from the corresponding author with the attached information.

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