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Discharge Coefficient of Contracted Rectangular Sharp-Crested Weirs, an Experimental Study

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ABSTRACT

An experimental study is made here to investigate the discharge coefficient for contracted rectangular Sharp crested weirs. Three Models are used, each with different weir width to flume width ratios (0.333, 0.5, and 0.666). The experimental work is conducted in a standard flume with high-precision head and flow measuring devices. Results are used to find a dimensionless equation for the discharge coefficient variation with geometrical, flow, and fluid properties. These are the ratio of the total head to the weir height, the ratio of the contracted weir width to the flume width, the ratio of the total head to the contracted width, and Reynolds and Weber numbers. Results show that the relationship between the discharge coefficient and these variables is a non-linear power function with a determination coefficient of 0.97. The importance and normalized importance analysis show that 56.3 % of the discharge coefficient variation is explained by the head-to-contracted width of the weir ratio followed by lower effects of the other variables, namely 16.5, 13.7, 12.4, and 1.2 % for contracted width to flume width ratio, Reynolds number, the head to the contracted width ratio, and Weber, respectively. The effect of the Weber number on the discharge coefficient is much lower than that of the Reynolds number.

Keywords: Contracted Rectangular Sharp-Crested weirs, Discharge Coefficient, Multivariate nonlinear regression, Reynolds Number, and Weber Number

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معامل تصريف الهدارات الحادة المستطيلة المتقلصة, دراسة تجريبية

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الخلاصة

تمَ إجراء دراسة مُختبرية عَملية لإيجاد مَعامل التصريف لِهَدارة حادة مُستطيلة ذات مَقطع مُتقلص. تَمَ بناء ثلاثة نماذج لهدارة، كل نموذج بنسبة مختلفة لعرض الهدار إلى عرض القناة و كالتالي (0.333 و0.500 و 0.666). تم إجراء التجارب بقناة صناعية مزودة بمقايس جريان و شحنة ذات دقة عالية. تم استخدام القراءات المقاسة لإيجاد معادلة لابعدية لمعامل التصريف كدالة للمتغيرات التي لها علاقة بابعاد الهدار و خصائص كل من الجريان و الماء. هذه المتغيرات اللابعدية هي نسبة الشحنة الكلية إلى ارتفاع الهدار، نسبة عرض المتقلص إلى عرض القناة، نسبة الشحنة الكلية إلى العرض المتقلص ، رقم رينولدز و رقم ويبر. أظهرت النتائج بأن أفضل علاقة لمعامل التصريف مع هذه المتغيرات هي علاقة لاخطية أسّية و بمعامل مطابقة قدره 0.97. كما أجري تحليل الأهمية و تحليل الأرتباط للمتغيرات المشار اليها أعلاه و أظهرت النتائج بأن المتغير الأكثر تأثيراً على معامل التصريف هو نسبة الشحنة الكلية الى عرض الهدار المتقلص حيث انه يفسر 56.3% من تباين معامل التصريف. أما بقية المتغيرات فانها تؤثر على معامل التصريف بنسب (16.5، 13.7، 12.4 و 1.2)% لعرض الهدار المتقلص إلى عرض القناة، رقم رينولدز، نسبة الشحنة إلى نسبة العرض المتقلص و رقم ويبر على التوالي. كما تبين بأن رقم رينولدز له تأثير أكبر بكثير من تأثير رقم ويبر.

الكلمات الرئيسية: الهدار المستطيل الحاد المتقلص، معامل التصريف ، نموذج الشبكة العصبية الاصطناعية، رقم رينولدز و رقم ويبر.

1. INTRODUCTION

Rectangular sharp-crested weir is an important instrumental structure for monitoring and managing flow in open channels. The weir opening is either fully, partially, or non-contracted, i.e., the opening is the full width of the rectangular sharp-crested weirs. If the weir width is less than the channel width, the weir is considered contracted from both sides, thus, increasing the section's ability to control the flow of hydraulics through the weir. As the width of the opening to the width of the channel ratio reduces, the side wall effect decreases on this hydraulic performance. When the weir height is relatively high, the channel bed has minimal influence on the flow over the weir. In addition, when the ratio of the head over the weir to its height is high, boundary layer effects on the sidewalls of the measuring channel may be considerable **(Aydin et al., 2011).**

In recent years, many studies have been conducted to precisely estimate the hydraulic characteristics of the discharge over weirs. Some of these studies were experimental. These studies can be classified according to the weir type and the research limitations. This research aimed to examine the flow behavior of the weirs and derive a discharge coefficient that represents the actual behavior **(Mahtabi et al., 2018).** When calculating the discharge coefficient for a weir, it is important to take into consideration the relative crest height of the weir. Calculating the actual discharge over the weir is difficult due to this height's impact on the streamlines' curvature in both the vertical and horizontal flow directions. Accordingly, the best approach is the experimental evaluation of the discharge coefficient.

(El-Alfy, 2005) conducted an experimental investigation to determine the effects of change in weir crest height on the vertical curvature of flow streamlines. (**Sisman, 2009)** conducted experimental work measuring actual discharge and head over the weir for various heights of the contracted and full-width weir. (**Aydin et al., 2002)** conducted an experimental investigation of slit weirs with a very small width to accurately measure extremely small discharges. They used a wide range of weir heights and slit widths. (**Aydin et al., 2006)** expanded the rectangular sharp crested slit weir experiments to investigate the influence of slit width. (**Tekade and Vasudeo, 2016)** conducted an experimental investigation to develop a precise approach for conducting flow studies on rectangular sharp-crested weirs. To achieve this, he used mild steel and galvanized iron to build the physical models of the weirs with varying crest heights for different contracted width channel width ratios. (**Alwan and Al-Mohammed, 2018)** conducted many experimental tests to investigate the impact of the upstream head and weir dimensions on the discharge coefficient. (**Ramamurthy et al., 1987)** extended their prior study on the slit weir concept by performing experiments on sharp-crested multi-slit weirs. The variation between the discharge coefficient and the geometrical and hydraulic parameters was studied. (**Aydin et al., 2011)** developed the weir velocity principle, demonstrating that the discharge in rectangular crested weirs can be computed more accurately and realistically using weir velocity rather than the discharge coefficient. They proposed the concept of average weir velocity and stated the discharge relation in terms of weir velocity. (**Gharahjeh et al., 2012)** conducted experiments for a certain range of discharge over the weir. This experimental research is consistent with the previous works of (**Sisman, 2009; Aydin et al., 2011)**. Weir velocity was employed instead of a discharge coefficient to establish the discharge relation because weir velocity seems to be more suitable. **(Altan-Sakarya et al., 2020)** utilized the Flow-3D program to compare numerical simulations with experimental data for a sharp-crested contracted weir. Assessed the empirical data and numerical results reveal that discharge rates reasonably agree. Moreover, weir and gate discharge coefficients are estimated separately using the capabilities of numerical modeling, which were difficult to achieve in experimental research. The present experimental investigation aims to determine the discharge coefficient of the flow over the contracted rectangular sharp-crested weirs of varying heights to obtain a precise flow. To accomplish this, the relations between the coefficient of discharge and different dimensionless parameters were formulated. Then a discharge equation for flow over a contracted rectangular sharp crested weir was established to predict the discharge flow.

2. DIMENSIONAL ANALYSIS

One of the mathematical techniques used to solve several complicated problems in hydraulic engineering is the dimensional analysis approach, which is usually applied in conjunction with laboratory work to deal with complex problems. The variables influencing the flow over this type of weirs consist of three groups. The first is the geometric characteristics, which include the height of the crest (P) and the width of the testing flume and the weir (B and b), respectively. The second is the characteristics of the flow, which include discharge (Q) and upstream water head over the weir crest (H). The third is the fluid properties which are kinematic viscosity (μ), the mass density of water (ρ), the surface tension (σ), and the gravitational acceleration (g)

The mathematical formula for the discharge flowing over the depressed sharp-crested rectangular weirs is represented by Eq. (1), which is dependent on several variables, as shown in **Fig. 1.**

$$Q = f_1(H, P, B, b, \rho, \mu, g, \sigma) \quad (1)$$

Adopting the approach of dimensional analysis and using variables (μ, H, g) as repeating variables, as shown in Eq. (1), the total number of variables is 9, i.e., n = 9. According to Buckingham's π theorem **(Li et al., 2020)**, the number of dimensionless groups is (9-3) = 6; these are:-

$\pi_1 = \frac{Q}{bg^{1/2}H^{3/2}}$; $\pi_2 = \frac{b}{H}$; $\pi_3 = \frac{b}{B}$; $\pi_4 = \frac{P}{H}$; $\pi_5 = \frac{\rho b g^{1/2} H^{1/2}}{\mu}$ or π_5 =Re in which Re is

Reynold's number and finally $\pi_6 = \frac{\sigma}{\mu\, g^{1/2}H^{1/2}}$

To cast the dimensionless terms into those which represent the discharge coefficient and the Weber number, the following adjustment are made:

$\pi_1^* = \pi_1 = \frac{Q}{bg^{1/2}H^{3/2}} = C_d$ = discharge coefficient ; $\pi_2^* = 1/\pi_2$; $\pi_3^* = \pi_3$; $\pi_4^* = 1/\pi_4$;

$\pi_5^* = \pi_5 = \frac{\rho b g^{1/2} H^{1/2}}{\mu} = \text{Re}$; and $\pi_6^* = \frac{\pi_5}{\pi_6} = \frac{\frac{\rho b g^{1/2}H^{1/2}}{\mu}}{\frac{\sigma}{\mu\, g^{1/2}H^{1/2}}} = \frac{\rho bgH}{\sigma} = W_e$

In which We is the Weber number, so Eq.(1) can be rewritten as:-

$$f_2\left(\frac{Q}{bg^{1/2}H^{3/2}}, \frac{H}{b}, \frac{b}{B}, \frac{H}{P}, \frac{\rho b g^{1/2}H^{1/2}}{\mu}, \frac{\sigma}{\mu\, g^{1/2}H^{1/2}}\right) = 0 \quad (2)$$

From Eq. (2), it appears the term ($\frac{\rho b g^{1/2}H^{1/2}}{\mu}$), representing the Reynolds number, and the term ($\frac{Q}{bg^{1/2}H^{3/2}}$), representing the discharge coefficient, and the product of division (π5/π6) representing the Weber number. Therefore, the dimensional analysis equation becomes:-

$$f_2\left(C_d, \frac{H}{b}, \frac{b}{B}, \frac{H}{P}, R_e, W_e\right) = 0 \quad (3)$$

Or it can be formulated as:-

$$C_d = f_3\left(\frac{H}{b}, \frac{b}{B}, \frac{H}{P}, R_e, W_e\right) \quad (4)$$

3. EXPERIMENTAL WORK

The sharp-crested weir comprises a vertical obstacle with a sharp top edge normally oriented in the channel bed **(Al-Hassani, and Mohammad 2021)**, as depicted in **Fig. 2.** The thickness of the top of the weir ranged from 1-2 mm on its upstream side, after which the

crest is sloped by 45° to 60° angle to the downstream edge, as shown in **Fig. 2.** The upstream thickness is theoretically considered as zero **(Jaafar, 2009).**
Previous research recommended that the weir operates fully contracted when b/B ≤ 0.25. Thus, the width ratio of all models ranged from 0.33 to 0.66. The pressure head over the weir crest is measured at a sufficient distance from the upstream, at least three to four times the maximum head to be used, as shown in **Fig. 2 (States, 1984).**

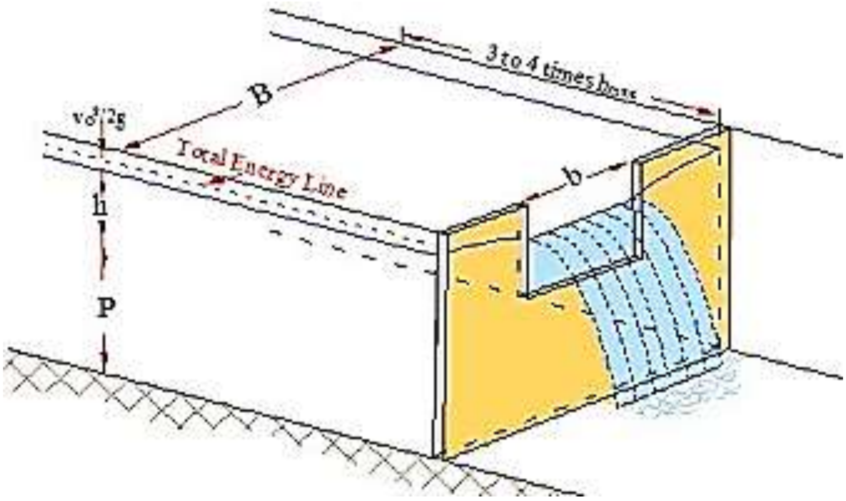

Figure 1. Front view of the contracted rectangular sharp crested weir

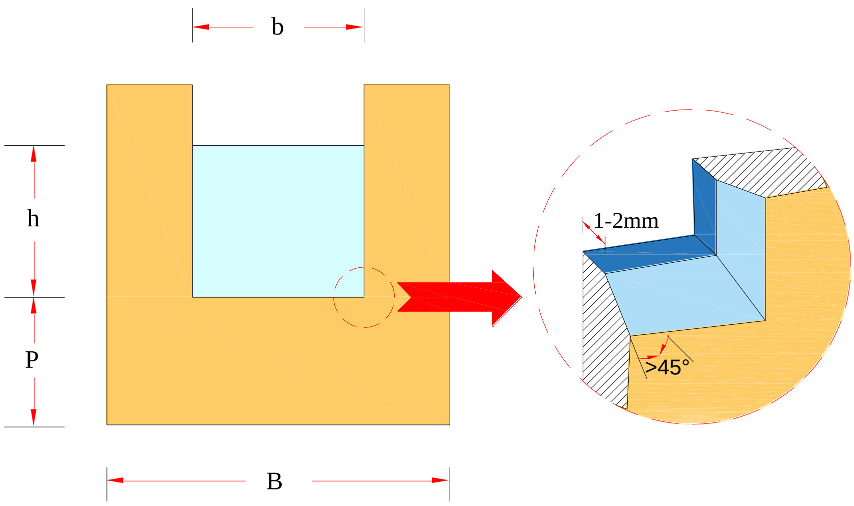

Figure 2. Cross section and edge crest of the weir

Fig. 1 shows a sketch of the front view of our experimental setup. The following notations are used: B is the width of the flume, b is the contracted width, P is the height of the weir, h is the head above the weir, and the total head is ($H = h + h_a$), where h_a is the approach velocity head **(Al-Zubaidy et al., 2016; Karim and Mohammed, 2020).** The experimental work of this research was conducted in the Fluid Mechanics Laboratory of the Department of Water Resources Engineering at the University of Sulaimani. The experiments were conducted for water flow over contracted rectangular sharp-crested weir models on a horizontal rectangular stainless-steel bed and glass-sided tilting flume, which has a 7.50 m length, 0.30 m wide, and 0.45 m height utilized for all tests. The weir models are made of plexiglass with a 10 mm thickness. The flow-wetted edges of the models are beveled at 45° so that the crest is 2.0 mm thick to create nappe shapes. The experiments were performed on three contracted rectangular sharp-crested weir models with crest lengths (b) 10 cm, 15 cm, and 20 cm and a basic crest height of 5 cm. To obtain a wide range of weir height (P), four extensions, each with length (B) of 30 cm and different heights (P) of 1 cm, 2 cm, 5 cm, and 10 cm, is prepared. Combining the basic crest height model (5 cm) and some of these extensions attached vertically using silicon provided different crest height ranges. The summary of the model characteristics and test conditions is shown in **Table 1**.

Table 1. Summary of model characteristics and test conditions.

Model	b (cm)	B (cm)	b/B	P (cm)	H (cm)	H/P	Q (l/s) range
A	10	30	0.33	11 - 34	1 - 26	0.091 - 0.76	0.27 - 28.95
B	15	30	0.50	11 - 34	1 - 23	0.091 - 0.67	0.32 - 31.45
C	20	30	0.66	11 - 34	1 - 18.9	0.91 - 0.55	0.38 - 30.72

The minimum weir height used in all the experiments is 10 cm following Bos's recommendation to use at least 10 cm as a minimum height to prevent the development of boundary layers **(Bos, 1989).** Vernier scales point gages that could accurately measure ±0.1mm were utilized. However, surface fluctuations mostly affect the water head measurement accuracy.

(Bos, 1989) suggested that the point gauge was installed at a distance of 3 to 4 times the maximum head over the weir location. Considering the maximum h for this research, which is 26 cm, the location of the point gauge should be 4 x 0.26 = 1.04 ≈ 1.0 meters. Therefore, the chosen point gauge position is suitable for this research. Water circulation is accomplished using a centrifugal pump that provides a total flow of 30 l/sec with an accuracy of ±0.5%. Using a manually adjustable butterfly valve, the water flow into the flume is controlled. The flow rate is determined using an electromagnetic flowmeter. After the water head had been balanced, discharge measurements were conducted. Each weir is evaluated with heads ranging from 1 cm to 26 cm, and all tests are conducted under free-flow conditions.

4. THEORETICAL CONSIDERATIONS

For a rectangular sharp-crested weir, the theoretical discharge (Q_{ideal}) is obtained assuming parallel and horizontal flow ignoring friction loss **(Munson et al., 2002). Fig. 3** illustrates a view of the weir flow.

Appling the Bernoulli's equation for the flow along an arbitrary streamline 1-2, **Fig. 3**:-

$$\frac{P_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + z_2 \quad (5)$$

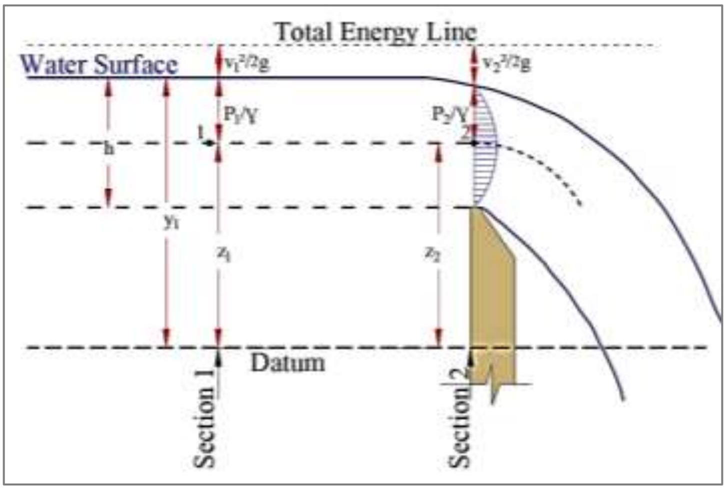

Figure 3. Theoretical considerations of the weir **(Munson et al., 2002)**

The pressure heads at sections 1 and 2 are atmospheric pressure such that $P_1 = P_2 = 0$, also $z_1 = y_1$, where y_1 is the upstream depth of flow, so Eq. (5) can be written as:

$$\frac{v_1^2}{2g} + y_1 = \frac{v_2^2}{2g} + z_2 \quad (6)$$

The velocity of water passes over the weir is:

$$v_2 = \sqrt{2g\left(y_1 + \frac{v_1^2}{2g} - z_2\right)} \quad (7)$$

For a weir with a width of b and a δz depth area element, the flow is as follows:

$$\delta Q_{ideal} = v_2 . b . \delta z \quad (8)$$

Substitute Eq. (8) into Eq. (7) and integrate Q_{ideal} over z yields:

$$Q_{ideal} = \frac{2}{3} . \sqrt{2g} . b . \left[\left(h + \frac{v_1^2}{2g}\right)^{1.5} - \left(\frac{v_1^2}{2g}\right)^{1.5}\right] \quad (9)$$

It can be assumed that the velocity head at section 1 is insignificant. Therefore, the equation for theoretical discharge is expressed below:

$$Q_{ideal} = \frac{2}{3} . \sqrt{2g} . b . h^{3/2} \quad (10)$$

The actual discharge is functional of fluid properties and weir geometry as shown below:

$$Q_{actual} = \frac{2}{3} . C_d . \sqrt{2g} . b . h^{3/2} \quad (11)$$

where C_d is the discharge coefficient that determines the precision of discharge. According to his experiments, James B. Francis (1852) observed that the end contraction would decrease the effective length of the weir crest weir by 0.1h from each side. Francis formulated the flow equation as follows:

$$Q_{actual} = \frac{2}{3} * C_d * \sqrt{2g} * (b - 0.1 * n * h) . h^{3/2} \quad (12)$$

where n is the number of end contractions. For the contracted rectangular sharp-crested weirs, there are two end contractions only. Substitute n = 2, and g = 9.81m/sec^2 in Eq. (12), the discharge passing over rectangular sharp-crested weirs can be expressed as below:

$$Q_{actual} = 2.95 * C_d * (b - 0.2 * h) * h^{3/2} \quad (13)$$

5. RESULTS AND DISCUSSION

As mentioned above, experiments are conducted for three models, A, B, and C, with different configurations, as shown in **Table 1**. **Figs. 4 a, b, and c** show the variation of the measured discharges with the head over the weir for models A, B, and C, respectively.

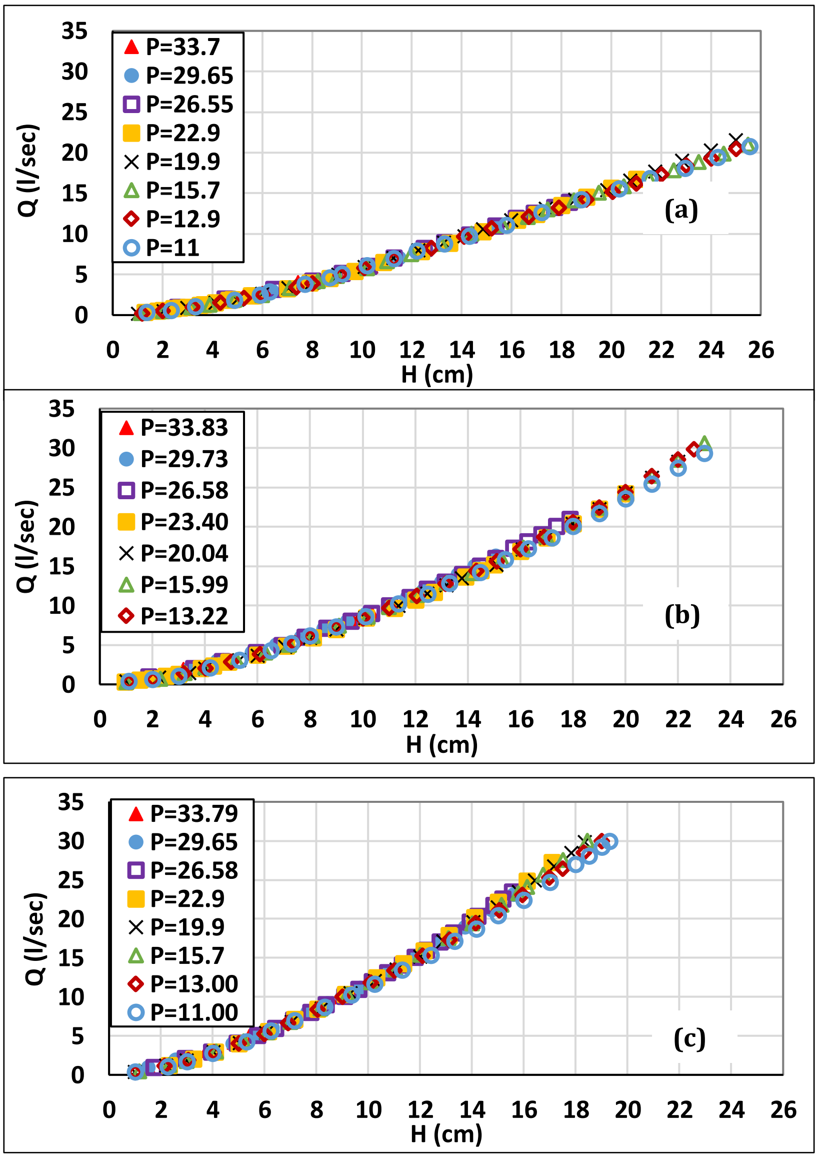

Figure 4. Discharge versus head for various weir heights for: a) Model (A), (b/B=0.333), b) Model (B)(b/B=0.5), and c) Model (C)(b/B=0.666)

For each model, this relation is shown for different values of weir height P. Investigating these figures show that the experimental results agree with the expected theoretical discharge-head variation. Moreover, the variation of discharge with the weir height is relatively small.

Figs. 5 a, b, and c show the variation of the measured actual discharge with the total head-to-weir height for different weir heights for models A, B, and C, respectively. Comparing the three figures, the variation is similar. As the weir height decreases, lower discharge variation is obtained. **Fig. 6** shows the variation of the actual discharges with the head over the weir for three weirs to flume width ratios (0.333, 0.5, and 0.666). As this ratio decreases, the variation in the discharges decreases. As the increase, higher discharges are obtained for the same head over the weir.

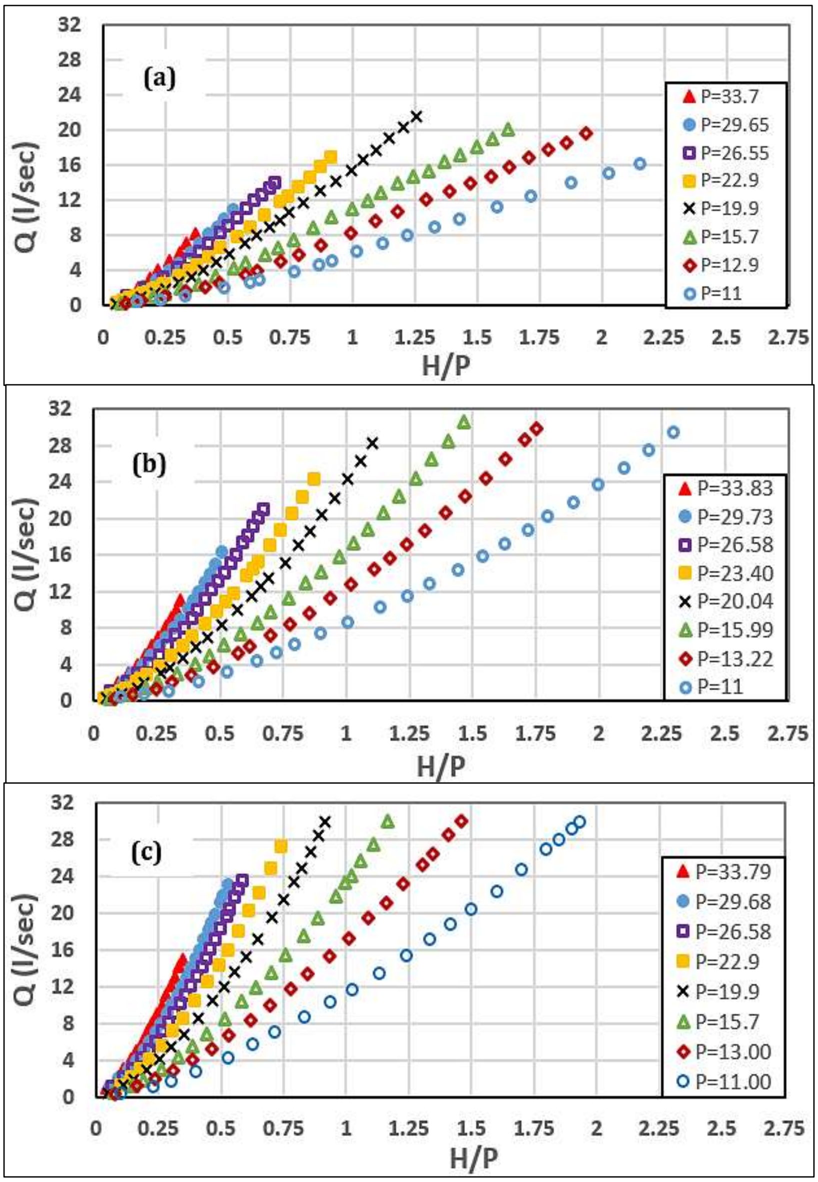

Figure 5. Flow rate versus H/p for different heights for a) Model (A), b) Model (B), and c) Model (C)

Fig. 7 shows the variation of the measured actual discharge with the head-over-weir height ratio for the three weirs to flume width ratios (0.333, 0.5, and 0.6). The obtained variation is similar to that of **Fig. 6**.

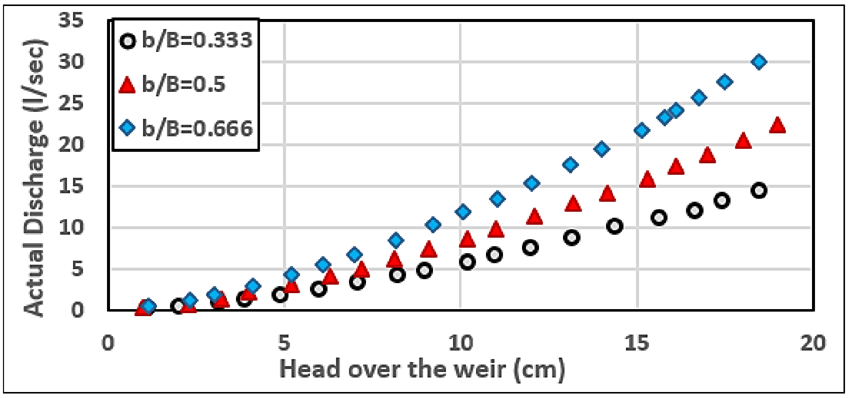

Figure 6. Discharge versus head for various weir heights, for P=16 cm

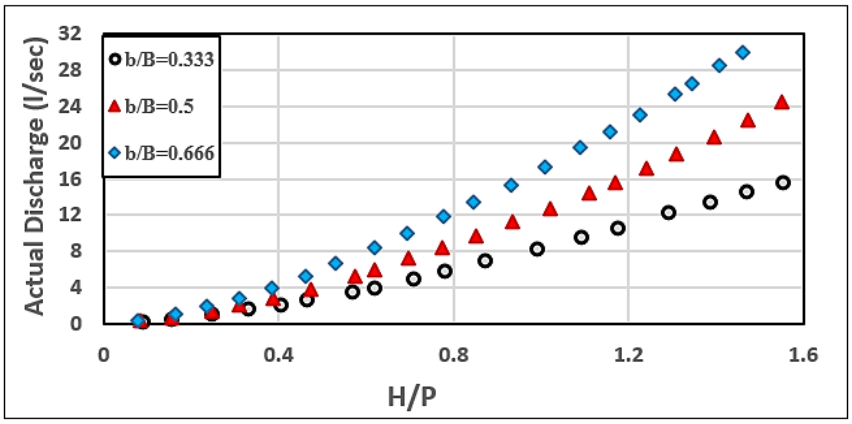

Figure 7. Actual discharge versus H/P for various b/B

Figs. 8 a, b, and c show the discharge coefficient variation with the total head-to-weir height ratio for models A, B, and C (b=10, 15, and 20 cm), respectively. A general trend of an increase in the discharge coefficient is observed as the H/p increases. However, it is observed that for small H/P values up to 0.15, the discharge coefficient has a very low decreasing variation, after which it has a considerable increasing variation for H/P values greater than 0.15. This may be attributed to the low differences in losses between successive low-head values where the accuracy of measurements has a considerable effect, compared to high differences in losses between successive high-head values.

Figs. 9 a, b, and c show the discharge coefficient variation with the Reynolds number based on actual velocity for the three weirs models A, B, and C (b=10, 15, and 20 cm), respectively. A general trend is an increase in the discharge coefficient as the Reynold number increase. For small Reynolds numbers, higher fluctuation is observed in the discharge coefficients, which then decreases as the Reynolds number increases. More fluctuation in the discharge coefficient at a low Reynolds number is observed for model A than for the other models.

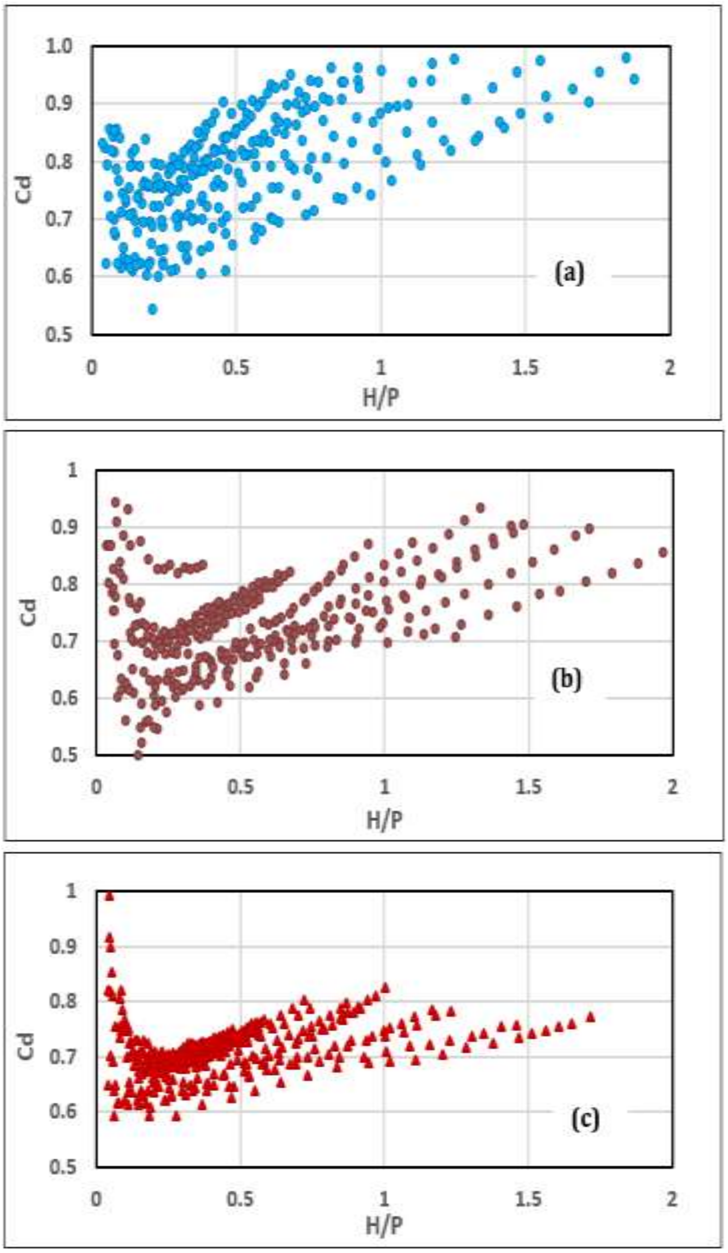

Figure 8. Coefficient of discharge versus H/P for:
a) Model (A), b) Model (B), and c) Model (C).

Figs. 10 a, b, and c show the discharge coefficient variation with the Weber number based on actual velocity for the three weirs models A, B, and C (b=10,15 and 20 cm), respectively. A general trend of increase of the discharge coefficient as the Weber number increase. For small Weber numbers, higher fluctuation is observed in the discharge coefficients, which decrease as the Weber increases. More fluctuation in the discharge coefficient at a low Weber number is observed for model A than for the other models.
For the sake of comparing the discharge coefficient variation with each of the Reynolds and Weber numbers with different weir widths, the results are plotted as shown in **Figs. 11 and 12**, respectively. These figures support the previously obtained observations that as b

increases, smaller discharge coefficients are observed, and high discharge value fluctuations are obtained for low Reynolds and Weber numbers.

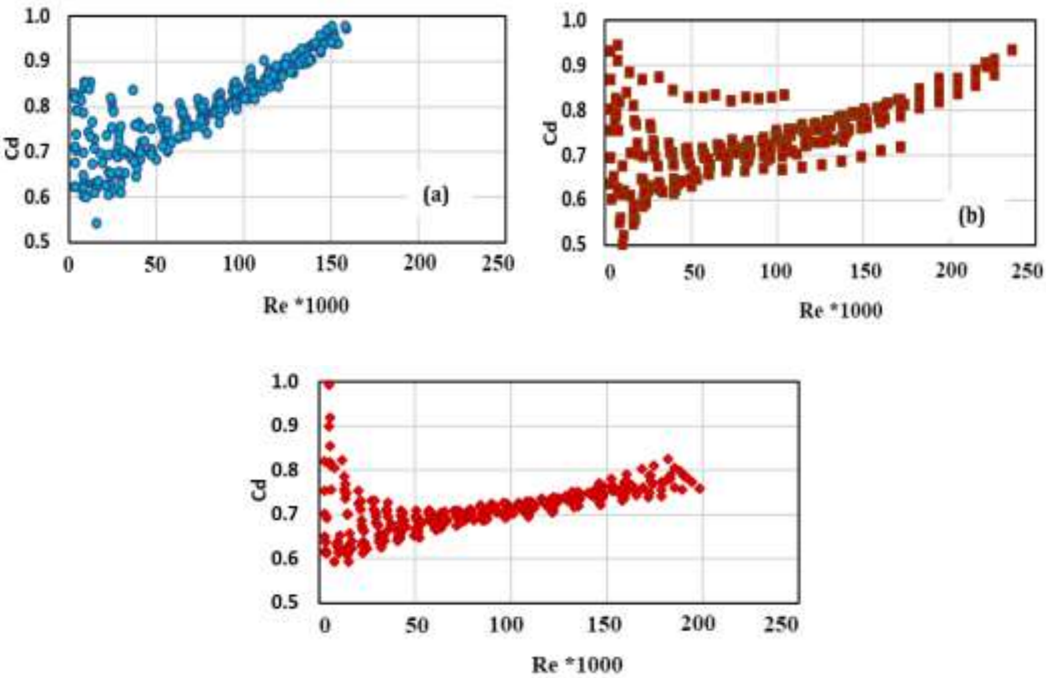

Figure 9. Variation of the coefficient of discharge with Reynolds number for: a) Model (A), b) Model (B), and c) Model (C)

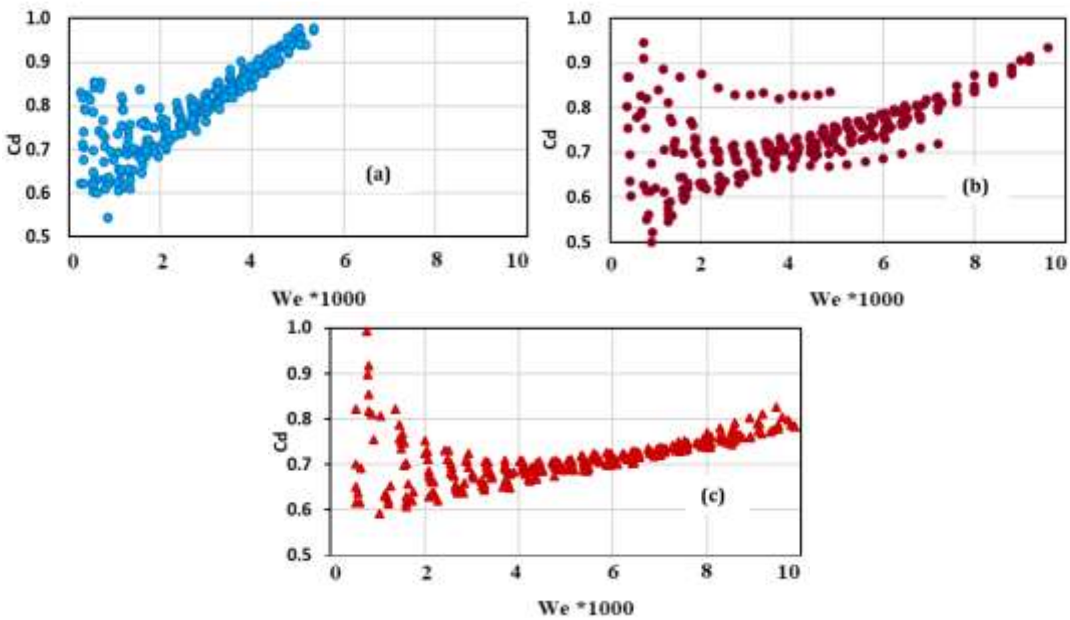

Figure 10. Relation between the coefficient of discharge and Weber number for: a) Model (A), b) Model (B), c) Model (C)

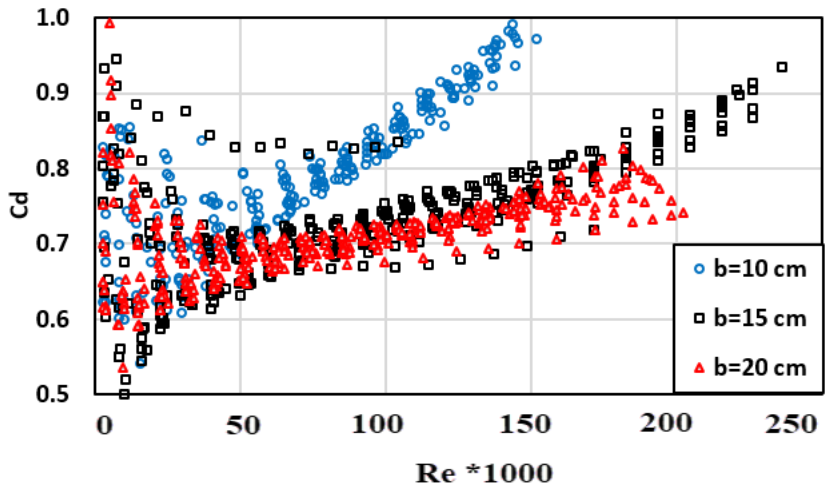

Figure 11. Relation between the coefficient of discharge and Reynolds number for various weir widths.

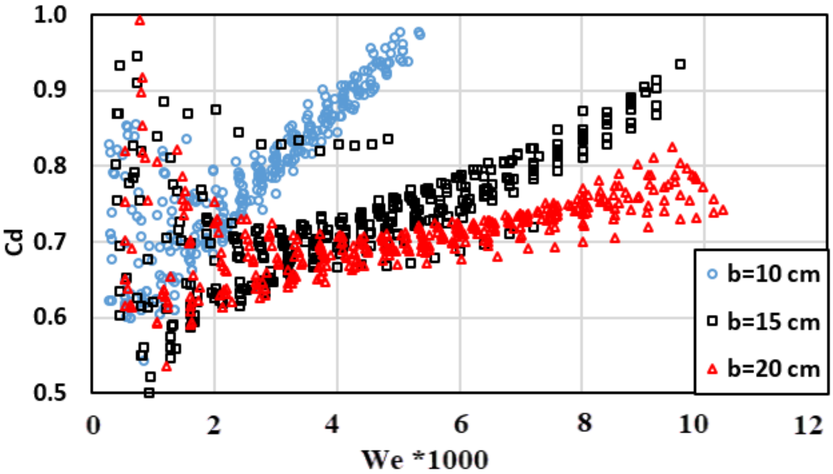

Figure 12. Relation between the coefficient of discharge and Weber number for various weir widths.

6. MATHEMATICAL MODEL FOR THE DISCHARGE COEFFICIENT

A usual practice of similar research trends is to use the experimental results to fit a model for calculating the discharge Coefficient using regression. Unfortunately, the linear regression does not fit the tried linear equation of the discharge coefficients as a function of the pi-terms obtained before representing the geometrical, flow, and fluid properties. The software used is Statistical Product and Service Solutions (SPSS). This led to trying non-linear regression using a power multiplicative function. The non-linear multiplicative function is fitted with a determination coefficient 0.95, which is considered acceptable. Following is the obtained expression for the discharge coefficient.

$$Cd = 118.267\left(\frac{H}{p}\right)^{-0.046}\left(\frac{b}{B}\right)^{-0.018}\left(\frac{H}{b}\right)^{0.758}(Re)^{-1.023}(We)^{0.81} \quad (14)$$

Using this equation, the discharge coefficient was estimated and plotted versus the observed one, as shown in **Fig. 13**. This figure shows the good agreement observed per the observed high determination coefficient of 0.95. An important analysis is made to illustrate the effect of each independent variable on the discharge coefficient. The results are shown in **Table 2** and **Fig. 14**. The sequential descending order importance variables are (H/b, b/B, Re, H/p, and We) respectively. H/p accounts for 56.3 % of the variation, followed by 16.5% for b/B, 13.7% for Re, 12.4% for H/p, and as low as 1.2% for We.

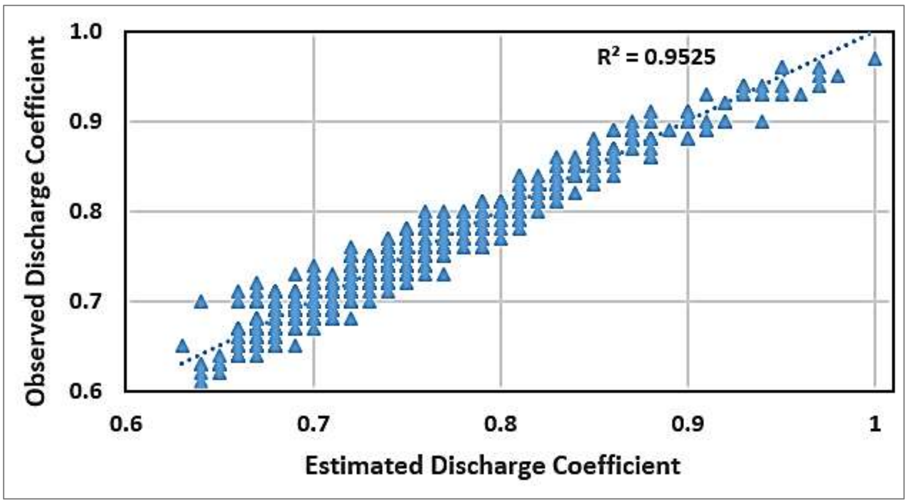

Figure 13. Observed versus estimated discharge coefficient chart

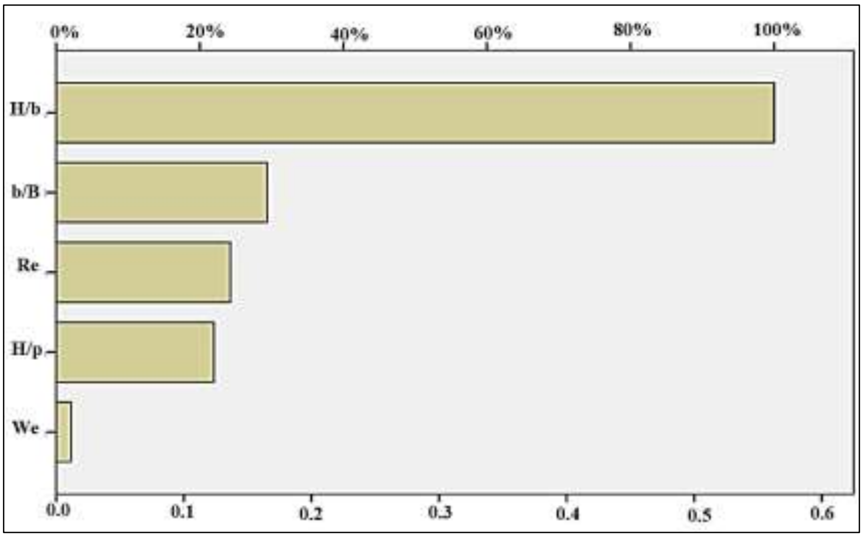

Figure 14. Importance analysis of the dependent variables on the discharge coefficient.

7. CONCLUSIONS

The following conclusion can be deduced from the results and analysis of the experimental data obtained herein. Three models are built herein A, B, and C, each with different widths of the weir b/B= 0.333, 0.5, and 0.66, respectively. Results show that the discharge-head variation followed the theoretically expected one for each model, with the weir height's

negligible effect on these variations. The observed variation of the discharge with (H/P) ratio is typical but affected by the weir height, as for any given H/P value, the discharge decreases as the weir height decrease. As expected, as the b/B ratio increases, higher discharges are observed for a given head, but this difference becomes more significant for relatively high heads. The observed discharge coefficients are all less than one with very few values close to 1, but the discharge coefficient generally decreases slightly as the weir width increases.
The discharge coefficient is more scattered for low Reynolds numbers. It exhibits a general linear variation with an increasing trend for high Reynolds values, namely when the Reynolds number is more significant than 60000. While the behaviour of the discharge coefficient with Weber number has less scattering. A linear increasing variation starts when the Weber number is more significant than 3000. The discharge coefficient for such weirs cannot be fitted by a linear function involving the independent variables (H/p, B/b, H/b, Re, and We). The best-fit equation is a non-linear multiplicative power equation. The observed non-linear equation fits well with a determination coefficient of (0.95). The importance and normalized importance analysis show that 56.3 percent of the variation of the discharge coefficient is explained by the head-to-contracted width of the weir ratio (H/b), followed by lower effects of the other variables, namely 16.5,13.7,12.4 and 1.2 % for b/B, Re, H/p and We, respectively. The effect of the Weber number on the discharge coefficient is much lower than that of the Reynolds number.

Table 2. Independent variable importance and normalized importance.

Variable	Importance	Normalized Importance (%)
H/p	0.124	22.0
b/B	0.165	29.4
H/b	0.563	100.0
Re	0.137	24.3
We	0.012	2.1

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