



Experimental Study to Determine Flow Parameters over Roughed Crump Weir Models

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ABSTRACT

A crump weir is commonly used to measure discharge in open flow channels. The objective of this study was to determine the effect of surface roughness of crump weir. 18 crump weir models of different apex angle 80°, 90°, 100°, 110°, 120° and 130°. Also by decreasing upstream angles to have the following values 85°, 70°, 55°, 40°, 25° and 10°. The increasing values of the downstream angles are 15°, 20°, 25°, 30°, 35° and 40° respectively to obtain the sum angle of the triangle to be 180° were developed. For each type of crump three types of surface roughness were used. The first one was a smooth PVC, the second one is coated with a uniform sand $D_{50} = 1.18\text{mm}$ (D_{50} is the sieve diameter in which 50% of material are finer), while the third is covered by gravel of $D_{50} = 4.0\text{mm}$. Eighteen models were used to conduct the experimental study. From the result obtained model 17 is the most efficient crump weir having the least C_d of 1.14914 and least percentage error of 12.97412. And the model has been optimised using GA with a C_d value of 1.14815. The obtained results show that C_d values increase with increasing flow rate as well as with decreasing crump height; an increase in surface roughness of crump weir can make a great reduction in C_d value. The h/P effect on C_d values increases with an increase in crump weir height. The C_d value is also directly proportional to the upstream slope and inversely to the downstream slope.

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INTRODUCTION

The Crump section flat-vee weir is favoured by hydrometricians because of the accuracy and range of flow measurement but is disliked by fisheries officers because it can present a barrier to fish migration. [Rickard *et al.* 2003]. It is very important to investigate the behaviour of the flow over the crump weir. A few studies have been devoted to the flow over this type of weirs, [Bos, 1989] was the first to study the flow characteristics of trapezoidal profile weirs systematically. He conducted a series of experiments on these types of weirs with both upstream and downstream side slopes. The discharge coefficient was determined for free-flow conditions using different discharge values. [Al-Naely *et al.*, 2018] Hydraulic Structures such as crump weir are placed in channels to estimate or

measure flow rate and flow control devices. In this study, there is a new performance for crump weir which appears by adding opening holes in the model of the crump weir. Opening holes are working as an energy dissipater and as an improver for the discharge coefficient (C_d). Where the discharge coefficient (C_d) is improved and recorded higher values in comparison with conventional weir under the same laboratory conditions. (Khalifa & Umar, 2018) A crump weir is commonly used to measure discharge in open flow channels. The laboratory test was conducted on six crump weir models of different apex angles 80°, 90°, 100°, 110°, 120° and 130°.

Increasing the amount of flow rate in different structures was always a field of interest for researchers. Decreasing sedimentation in reservoirs (Zahabi *et al.* 2018) and the creation of

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an opening in a broad-crested weir body to increase the discharge coefficient (Daneshfaraz et al. 2019) are examples of improving the flow rate. The other vital structures that can control the flow rate are weirs. The volume of flow over the weirs depends on the length and shape of the crest of the weir. Many types of research have been done on the effect of the hydraulic and geometric parameters on the C_d and the amount of flow discharged effective ways to increase the weir length at a given width is to use weirs with nonlinear plans such as triangular, trapezoidal, circular, and parabolic.

Crump weir has many features such as straightforward structure, giving high precision in flow measurement. Also, it is comparatively insensitive to submerged conditions and ease of determination of flow curves for any width. In addition to that, it has many advantages like the coefficient of discharges remains stable and constants through undrawn condition; and moderately unresponsive to drowned condition.

THEORETICAL BACKGROUND

The discharge equation for the crump weir was used to compute the estimated discharge using the flow heads. Point gauge will be used to measure the flow head (h) above the crump weir (Arora, 2005).

$$Q_m = C_d \sqrt{g} \cdot b H_o^{\frac{3}{2}} \quad (1)$$

$$C_d = 1.163 \left(1 - \frac{0.0003}{h} \right)^{1.5} \quad (2)$$

$$H = y + \frac{v^2}{2g} \quad (3)$$

$$f = Q/Q_m, \quad (4)$$

METHODOLOGY

Fabrication of the Experimental Models

The experimental work was conducted on six crump weir models of different apex angles 80° , 90° , 100° , 110° , 120° and 130° . Also by decreasing upstream angles to have the following values 85° , 70° , 55° , 40° , 25° and 10° . The increasing values of the downstream angles are 15° , 20° , 25° , 30° , 35° and 40° respectively to obtain the sum angle of the triangle to be 180° . Plywood of thickness 22mm was used for fabricating the main body of the crump weir.

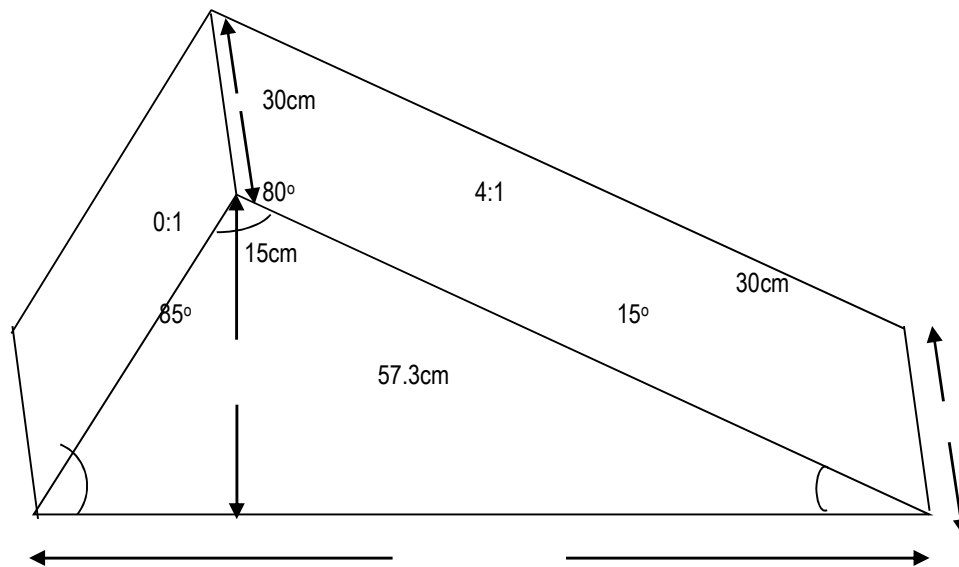


Figure 1: The schematic view of crump weir model 1 of apex angle 80° , upstream angle and slope, 85° and 0:1, downstream angle and slope, 15° and 4:1 respectively.

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Table 1.0: Geometric Factors of Crump Weir Models

Model	Upstream Slope	Downstream Slope	Model width 'b' (cm)	Crest Height 'P' (cm)	Apex Angle (degree)	Upstream Angle(degree)	Downstream Angle(degree)
7	0:1	4:1	30	15	80	85	15
8	0:3	3:1	30	15	90	70	20
9	0:7	2:1	30	15	100	55	25
10	1:1	2:1	30	15	110	40	30
11	2:1	1:1	30	15	120	25	35
12	6:1	1:1	30	15	130	10	40



Plate I: Side view of the Tilting Flume

Experimental Procedure:

The crump weir was installed in the flume with the help of sealants to prevent leakage, which has to be levelled. One vernier was located downstream the weir and the other upstream. The verniers were zeroed with the bed of the channel. Fifty-Four models were fabricated for which the angles were varied, 80°, 90°, 100°, 110°, 120°, and 130°. The experiment was then be run for each model and various heads and their corresponding discharges were recorded; The procedure has five (5) runs. Each run has a different flow rate and a set of four (4) y_o and y_1 depths; two sets for modular flow condition and the other two sets for non-modular flow condition. The initial flow rate was set. Then, y_o and y_1 depths were recorded for the following conditions: Modular flow: without stop block (gate). Modular flow: one full stop block (gate) (y_1 should be the only depth that changes). Non-modular flow: Add half of the one-stop block (gate). (y_1 and y_o depth that change). Non-modular flow: Add one-quarter of a stop block (gate). The flow rate was increased at a constant interval.

Heights (P=10cm, 15cm, 20cm) were used as a crump weir models. For each type of crump three types of surface roughness were used. The first one was a smooth PVC, the second one is coated with a uniform sand $D_{50}=0.72\text{mm}$ (D_{50} is the sieve diameter in which 50% of material are finer), while the third is covered by gravel of $D_{50}= 3.6 \text{ mm}$. Eighteen models were used to conduct the experimental study. In each run, the selected model was inserted along the width of the flume. Then the pump started at desired flow rate and after the flow stability was achieved the water surface level upstream and above the weir model were measured using a point gauge. For each type of crump weir, a series of tests under different flow rates were conducted. The pump was activated and the discharge was adjusted using a control valve and the reading of the point gauge were recorded to give the head above the crump weir required for the calculation of estimated discharge; At the beginning of each run the control valve was adjusted to alter the head; For each head recorded, the actual discharge was

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measured by the direct method using the weighing arrangement provided at the tail end of the flume; The previous steps were repeated for each of the five runs of experiments to be conducted for each model. A total of 360 runs were conducted.

Determination of Observed Discharge (Q_o)

The observed discharge, Q_o , was measured experimentally using the gravimetric method. Throughout the experiment, 100kg of water were collected using the weighing balance (see plate II) attached to the flume and a stopwatch was used to obtain the time taken to collect the 100kg for onward determination of discharge.

Volume, $V = \text{mass}/\text{density}$

Observed discharge, $Q_o = \text{Volume} / \text{average time}$

$$\text{Average time} = \frac{(t_1 + t_2)}{2} \quad (5)$$

Determination of Estimated Discharge (Q_e)

The discharge equation for the crump weir was used to compute the estimated discharge using the flow heads.

Point gauge will be used to measure the flow head (h) above the crump weir (Arora, 2005).

$$Q_m = C_d \sqrt{g} \cdot b H_o^{\frac{3}{2}} \quad (1)$$

$$C_d = 1.163 \left(1 - \frac{0.0003}{h} \right)^{1.5} \quad (2)$$

$$H = y + \frac{v^2}{2g} \quad (3)$$

Accuracy of Discharge Measurement

In this study, the indicator employed to compare the accuracy of the crump weir models in measuring discharge is the average percentage error (E) expressed as:

$$E = \frac{100}{N} \sum_{i=1}^N \left| \frac{Q_o - Q_e}{Q_o} \right| \quad (6)$$

Where $N =$ number of experiments conducted per model

Q_o And Q_e are observed and estimated discharges obtained for each run.

Derivation of Discharge Coefficient

The discharge coefficients for simple rectangular and triangular weirs suggested respectively by French (1986) and Martinez et al. (2005) were adopted in this study. Expression for the global discharge coefficient (C_d) of the models was obtained by multiple regressions of the variables (i.e. h/P , C_d , and b).

To validate the suitability of the theoretical equations, the maximum of the absolute value of the deviation of the data from the model was obtained as:

$$\text{MaxErr} = \max(\text{abs}(C_{do} - C_{de})) \quad (7)$$

Where, $C_{do} =$ Experimental Discharge Coefficient = Q_o / Q_e

$C_{de} =$ Estimated Discharge Coefficient

$$Cd = (D_{50}, P, h, Q, \theta) \quad (8)$$

Thus, by dimensional analysis and using the approach of Buckingham's π -theorem, Equation (8) becomes:

$$Cd = f \left(\frac{D_{50}}{P} \theta, \frac{h}{P} \right) \quad (9)$$

It follows that Equation (9) can be expressed as Equation (10) based on dimensional homogeneity:

$$C_d = k_1 \left[\frac{D_{50} \theta}{P} \right]^a + k_2 \left[\frac{h}{P} \right]^b \quad (10)$$

Where, K_1 , K_2 , a , and b are parameters to be estimated by regression analysis.

RESULTS AND DISCUSSION

Computation of Discharge Coefficients (C_d)

Tables 2 show the values of C_d obtained from Equations 1 and 2 respectively. The head measurements were obtained using the point gauge.

Table 2: Discharge characteristics for model 1:

$Q_o=V/t/m^3/s$	y_o/m	$h_o=y_o - 0.10/m$	y_1/m	H_o/m	H_1/m	C_d	$Q_e/m^3/s$	% Error
0.001515	0.120	0.020	0.060	0.121	0.065	1.13693	0.00133	12.04391
0.001563	0.160	0.060	0.110	0.175	0.115	1.15429	0.00135	13.36654
0.001613	0.194	0.094	0.135	0.210	0.140	1.15744	0.00139	13.60220
0.001667	0.210	0.110	0.130	0.228	0.150	1.15825	0.00144	13.66252
0.001724	0.218	0.118	0.100	0.235	0.160	1.15857	0.00149	13.68652
Average						1.15310	0.001400	13.27234

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Estimated discharge and C_d for PVC

$Q_o=V/t/m^3/s$	y_o/m	$h_o=y_o - 0.10/m$	y_1/m	H_o/m	H_1/m	C_d	$Q_e/m^3/s$	% Error
0.00150	0.125	0.025	0.060	0.130	0.060	1.14213	0.00131	12.44421
0.00158	0.167	0.067	0.100	0.177	0.110	1.15520	0.00136	13.43472
0.00164	0.193	0.093	0.120	0.208	0.140	1.15738	0.00142	13.59774
0.00170	0.208	0.108	0.060	0.227	0.150	1.15816	0.00146	13.65596
0.00175	0.215	0.115	0.060	0.232	0.150	1.15845	0.00151	13.67792
Average						1.15426	0.001412	13.36211

Estimated discharge and C_d for 1.18mm

$Q_o=V/t/m^3/s$	y_o/m	$h_o=y_o - 0.10/m$	y_1/m	H_o/m	H_1/m	C_d	$Q_e/m^3/s$	% Error
0.001579	0.127	0.027	0.060	0.130	0.060	1.14367	0.00138	12.56224
0.001639	0.170	0.070	0.100	0.180	0.100	1.15553	0.00142	13.45974
0.006969	0.195	0.095	0.135	0.210	0.135	1.15750	0.00602	13.60657
0.001695	0.210	0.110	0.060	0.225	0.060	1.15825	0.00146	13.66252
0.001818	0.218	0.118	0.070	0.235	0.070	1.15857	0.00157	13.68652
Average						1.15470	0.002370	13.39552

Estimated discharge and C_d for 4.00mm

$Q_o=V/t/m^3/s$	y_o/m	$h_o=y_o - 0.10/m$	y_1/m	H_o/m	H_1/m	C_d	$Q_e/m^3/s$	% Error
0.001456	0.128	0.028	0.060	0.130	0.060	1.14436	0.00127	12.61484
0.001563	0.171	0.071	0.105	0.180	0.105	1.15564	0.00135	13.46761
0.001613	0.198	0.098	0.135	0.213	0.135	1.15766	0.00139	13.61913
0.001667	0.212	0.112	0.060	0.230	0.060	1.15833	0.00144	13.66884
0.001754	0.220	0.120	0.070	0.238	0.070	1.15864	0.00151	13.69202
Average						1.15493	0.001392	13.41249

Table 4.3: Summary of models performance

Model 1	θ_A	θ_u	θ_d	Range of Q_o (l/s)	Range of Q_e (l/s)	Average C_d	E (%)	Rank
N	80°	85°	15°	6.781 – 8.228	5.881 – 7.128	1.15310	13.27234	9
PVC	80°	85°	15°	6.781 – 8.228	5.881 – 7.128	1.15426	13.36211	
1.8mm	80°	85°	15°	6.781 – 8.228	5.879 – 7.123	1.15470	13.39552	
4.0mm	80°	85°	15°	6.781 – 8.228	5.877 – 7.121	1.15493	13.41249	
Average $C_d = 1.15425$						13.36062		
Model 2								
N	90°	70°	20°	4.644 – 7.813	4.033 – 6.775	0.98353	1.68016	2
PVC	90°	70°	20°	4.644 – 7.813	4.033 – 6.775	0.97408	2.70565	
1.8mm	90°	70°	20°	4.644 – 7.813	4.032 – 6.770	0.98483	1.54263	
4.0mm	90°	70°	20°	4.644 – 7.813	4.032 – 6.769	0.98511	1.54263	
Average $C_{d0} = 0.98189$						1.86777		
Model 3								
N	100°	55°	25°	4.601 – 6.110	4.000 – 5.301	1.15412	13.35118	13
PVC	100°	55°	25°	4.601 – 6.110	4.000 – 5.301	1.15422	13.35942	

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1.8mm	100 ⁰	55 ⁰	25 ⁰	4.601 – 6.110	3.997 – 5.300	1.15456	13.38700
4.0mm	100 ⁰	55 ⁰	25 ⁰	4.601 – 6.110	3.996 – 5.299	1.15507	13.42232
Average C _{do} = 1.15449						13.37998	

The ranking is based on the closeness of average C_d to unity and also on the minimum average percentage error (E)

Model	θ_A	θ_u	θ_d	Range of Q _o (l/s)	Range of Q _e (l/s)	Average C _d	E (%)	Rank
N	80 ⁰	85 ⁰	15 ⁰	6.781 – 8.228	5.881 – 7.128	0.96112	4.06018	4
PVC	80 ⁰	85 ⁰	15 ⁰	6.781 – 8.228	5.881 – 7.128	0.96112	4.06018	
1.8mm	80 ⁰	85 ⁰	15 ⁰	6.781 – 8.228	5.879 – 7.123	0.96303	3.84641	
4.0mm	80 ⁰	85 ⁰	15 ⁰	6.781 – 8.228	5.877 – 7.121	0.96364	3.77912	
Average C _d = 0.96223						3.93647		
Model 17								
N	90 ⁰	70 ⁰	20 ⁰	4.644 – 7.813	4.033 – 6.775	0.99093	0.92858	1
PVC	90 ⁰	70 ⁰	20 ⁰	4.644 – 7.813	4.033 – 6.775	0.98596	1.42666	
1.8mm	90 ⁰	70 ⁰	20 ⁰	4.644 – 7.813	4.032 – 6.770	0.98895	1.12130	
4.0mm	90 ⁰	70 ⁰	20 ⁰	4.644 – 7.813	4.032 – 6.769	0.98872	1.14571	
Average C _{do} = 0.98864						1.15556		
Model 18								
N	100 ⁰	55 ⁰	25 ⁰	4.601 – 6.110	4.000 – 5.301	1.15506	13.42245	17
PVC	100 ⁰	55 ⁰	25 ⁰	4.601 – 6.110	4.000 – 5.301	1.15532	13.44080	
1.8mm	100 ⁰	55 ⁰	25 ⁰	4.601 – 6.110	3.997 – 5.300	1.15540	13.44853	
4.0mm	100 ⁰	55 ⁰	25 ⁰	4.601 – 6.110	3.996 – 5.299	1.15605	13.49741	
Average C _{do} = 1.15546						13.45230		

Table 4.4: Summary of models performance based on the dependence of Q_o on h_o

Model	R ²	%	Ranking
4	0.831	83.1	5
16	0.870	87.0	4
15	0.674	67.4	6
8	0.873	87.3	3
2	0.879	87.9	2
17	0.984	98.4	1

The ranking is based on the strong dependence of discharge on the upstream water head above the crest

Table 3: Summary of models performance based on C_d and Percentage Error

Model Number	C _d Average	Percentage Error	Ranking
17	1.14914	12.97412	1
2	1.15189	13.17617	2
8	1.15122	13.18413	3
16	1.15223	13.20521	4
4	1.15313	13.27629	5
15	1.15383	13.32875	6
5	1.15406	13.34741	7

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7	1.15414	13.35236	8
1	1.15425	13.36062	9
11	1.15425	13.36155	10
10	1.15433	13.36725	11
13	1.1544	13.37097	12
3	1.15449	13.37998	13
14	1.15476	13.39963	14
9	1.15483	13.40455	15
12	1.15527	13.43799	16
18	1.15546	13.4523	17
6	1.15553	13.45773	18

Table 4.8: The percentage of increase in Cd values with increase in weir roughness.

Coated D ₅₀ = 4.0mm		Coated D ₅₀ = 1.18mm		PVC		Normal	Weir height (cm)
(Cd3-Cd1/ Cd1) *100%	Cd3(1,2,3)	(Cd2-Cd1/Cd1) *100%	Cd2(1,2,3)		Cd1(1,2,3)		
P ₁ =10							
0.16	1.15493	0.14	1.15470	0.10	1.15426	1.15310	
0.14	1.15511	0.11	1.15483	-0.82	1.14408	1.15353	
0.08	1.15507	0.04	1.15456	0.01	1.15422	1.15412	
0.11	1.15381	0.05	1.15305	0.06	1.15316	1.15249	
0.13	1.15493	0.06	1.15411	0.04	1.15382	1.15339	
0.20	1.15647	0.18	1.15631	0.08	1.15514	1.15419	
Average	0.14	1.15505	0.10	1.15459	-0.09	1.15245	1.15347
P ₂ =15							
0.15	1.15501	0.11	1.15450	0.05	1.15382	1.15324	
0.22	1.15612	0.19	1.15580	0.16	1.15537	1.15358	
0.15	1.15550	0.13	1.15520	0.10	1.15486	1.15374	
0.10	1.15496	0.06	1.15443	0.03	1.15415	1.15377	
0.10	1.15491	0.05	1.15436	0.01	1.15391	1.15381	
0.15	1.15599	0.10	1.15544	0.09	1.15534	1.15430	
0.15	1.15542	0.11	1.15496	0.07	1.15458	1.15374	
P ₃ =20							
0.38	1.15605	0.36	1.15583	0.21	1.15404	1.15167	
0.19	1.15579	0.13	1.15509	0.08	1.15453	1.15364	
0.12	1.15438	0.07	1.15376	0.10	1.15416	1.15301	
0.22	1.15364	0.17	1.15303	0.00	1.15112	1.15112	
-0.19	1.14872	-0.17	1.14895	-0.26	1.14796	1.15093	
0.09	1.15605	0.03	1.15540	0.02	1.15532	1.15506	
0.13	1.15411	0.10	1.15368	0.02	1.15286	1.15257	
0.14		0.10		0.00		Average	

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DISCUSSION OF RESULT

Variation of Cd with (h/P)

The dimensional analysis for the variables affecting the Cd value of weirs shows that the value (h/p) (Where his head of the water on the weir, P height of the weir), has the greatest influence on the Cd value. The calculated values of h/P are plotted against the Cd values for each weir and for each surface roughness's as shown in Figure 4. The figure shows that the Cd value increase with increasing in h/P values for all the

cases. Also, it's evident from these figures that the gradient of the curve fit the points decrease with an increase in weir height, this means that the effect of h/P on Cd values will increase with the increase in weir height. Finally, the precision of the models in estimating the discharge passing the weir was evaluated using the root-mean-square error (RMSE), mean absolute percentage error (MAE), R² (coefficient of determination). The best values of these criteria were 0, 0, and 1 respectively.

$$RMSE = \sqrt{\frac{1}{n} \sum_{j=1}^n (y_j - \hat{y}_j)^2} \quad (12)$$

$$MAE = \frac{1}{n} \sum_{j=1}^n |y_j - \hat{y}_j| \quad (13)$$

$$\hat{R}^2 = 1 - \frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^n (Y_i - \bar{Y})^2} = 1 - \frac{\frac{1}{n} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{\frac{1}{n} \sum_{i=1}^n (Y_i - \bar{Y})^2} \quad (14)$$

In Eqs. (12)–(14), y is the actual Cd, \hat{y} is their average, n is the number of estimations.

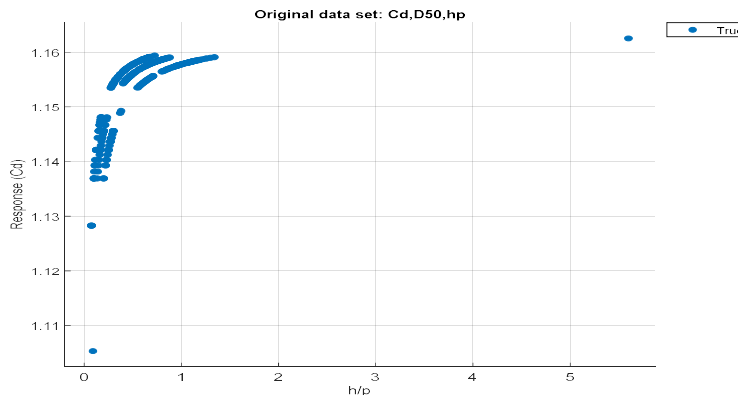


Figure 4: Relation of Cd and h/p using (MLR) model

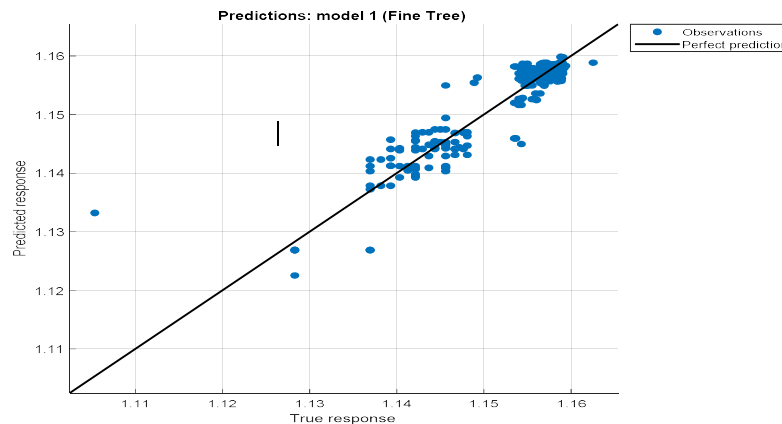


Figure 5: Relation of Cd predicted and Actual value using (MLR) model

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Thus, the parameters K_1 , K_2 , a and b in Equation (10) were determined through regression analysis and Curve Fitting Neural Network as expressed by Equation (15) as follows:

$$Cd = 0.5785 \left[\frac{D_{50}\theta}{P} \right]^{6.593 \times 10^{-5}} + 0.58 \left[\frac{h}{P} \right]^{0.006761} \quad (15)$$

The model equation has $R^2 = 0.9981$.

Table 7: Sensitivity analysis of C_d for input parameters with ANN model.

Function	Training		Testing	
	MSE $\times (10^{-4})$	R^2	MSE $\times (10^{-4})$	R^2
$Cd = \left[\frac{D_{50}\theta}{P} \right]$	7.5421	0.9782	7.6801	0.9884
$Cd = \left[\frac{h}{P} \right]$	3.7313	0.9841	3.8513	0.9971
$Cd = \left(\frac{D_{50}\theta}{P}, \frac{h}{P} \right)$	0.1534	0.9883	0.1635	0.9981

Table 7, shows the sensitivity analysis of the Coefficient of discharge, C_d . The sensitivity analysis was carried, to evaluate the significance of input variables on the Coefficient of discharge. The sensitivity analysis was performed using the ANN model due to the high value of the correlation coefficient and minimum error is produced.

Consequently, the parameter $\left(\frac{h}{P} \right)$ was found to be the most effective parameter with $R = 0.9971$, $MSE = 3.8513 \times 10^{-4}$ on the prediction of C_d . While the function $\left(\frac{D_{50}\theta}{P} \right)$ was found to be the least effective parameter on the prediction of C_d .

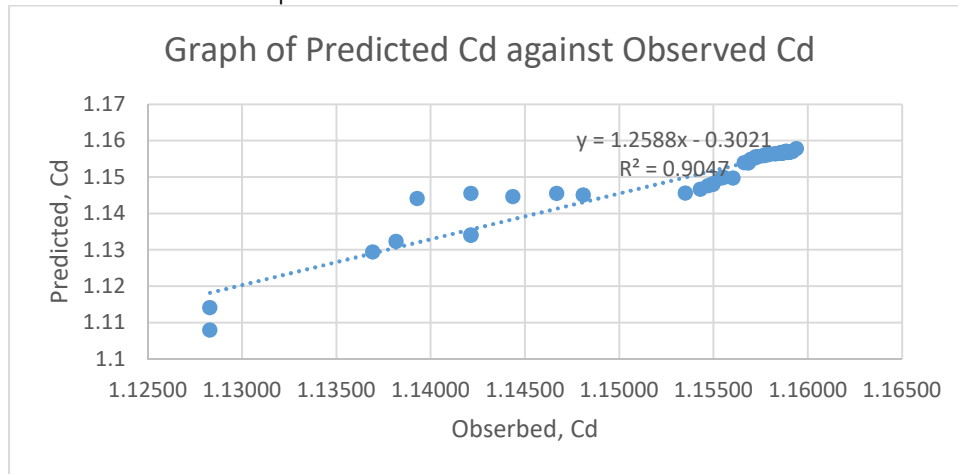


Figure 11: Relation of predicted C_d and observed C_d using (MLP) model

CONCLUSION

By using the equations which have been discussed in the literature, the raw data was calculated and processed using ANN. Based on the results of the investigation, the following conclusions are reached:

1. C_d increases with the increasing flow rate.
2. The effect of the increase of surface roughness on h values will be more on

small heights of the crump weir than large ones.

3. C_d decreases from model 1 to model 18 with model 17 having the least C_d close to unity and least percentage error making model 17 to be more efficient.
4. C_d values increase with the increase in the surface roughness. For the same weir height under equal flow

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rate. An increase in the surface roughness of the weir from $D50 = 0\text{mm}$ (PVC) to $D50 = 1.18\text{mm}$ reduces C_d value around 0.1%, while an increase from $D50 = 0\text{mm}$ to 4.0mm reduces about 0.14%.

RECOMMENDATIONS

The recommendations below are some of the improvements that can be carried out for further study:

1. Depth of weir and width of the channel in variable value is suggested to get the best flow rate for the hydraulic structure of crump weir design.
2. A calibration device for better data collection suggested using a volume meter to get the flow rate over a crump weir.
3. A similar study should be carried out using stones and cement models instead of wooden models.

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