

## CALIBRATION OF A NEW SIZE OF CUT- THROAT FLUME FOR SUBMERGED FLOW CONDITION

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### Abstract

This research aimed to conduct a series of laboratory experiments in the case of steady-state flow for the new size of the cutthroat flume. The new size is to attempt 0.1778 m (7") for throat width, where this type of flume at this width is not taken into investigation under submerged flow condition before. There is a need for field application to provide an empirical equation for discharge measurements. The proposed equation was experimentally calibrated for this size of cutthroat flume under submerged condition. Accordingly, that size will be useful in some applications such that, field canals, sites of desalination and treatment plants, and small seasonal streams. In the present study, five different lengths were adopted for this size: 0.535 m, 0.46 m, 0.40 m, 0.325 m, and 0.27 m. A series of experiments were conducted to investigate the hydraulic characteristics, and the calibrated design formulas, charts, and tables are presented for submerged flow implementation at discharge ranging between 0.006 m<sup>3</sup>/s and 0.025 m<sup>3</sup>/s. The calibration results show that, under suitable operating conditions, the suggested empirical formulas can accurately predict the values of discharge with an error  $\pm 8\%$ .

Keywords: Cutthroat flume, Ditchrider table, Empirical formulas, Submerged flow, Throat width.

## 1. Introduction

There are many methods and devices which can be applied to the task of measuring volumetric flow rate in open channels. The selection of a flow measurement device for given conditions involves considerations of accuracy, ease of construction, and economic feasibility. Several hydraulic structure types have been developed and applied to measure open-channel flow, including a variety of weirs and flumes. There are several different designs of flow measurement flumes, one of which is the Cutthroat flume, which has been used extensively in irrigation canals. Compared to many other flume designs, the cutthroat lends itself to easy construction and installation, and comparable flow measurement accuracy under both free and submerged conditions. The cutthroat flume is also flexible in terms of sizing, as long as technical recommendations concerning geometric proportions are followed. The cutthroat flume was developed by Skogerboe and Hyatt [1] for measuring the flow rate in open channels. The cutthroat flume geometry, so named because of a zero throat length, includes a 3:1 upstream converging section, a 6:1 downstream diverging section, to prevent the separation of flow, and a fixed throat width. Unlike some other open-channel flow measurement flumes, the Cutthroat has a flat-level floor from inlet to outlet.

The profile of the water surface changed quickly in the section of the throat as compared to the section of the exit where the surface of the water was almost horizontal. The height of the flume ( $H$ ) should be calculated for the desired height of the freeboard and the max allowable head upstream must be less than  $1/3$  flume length ( $h_u, \max \text{ or } y_u, \max \leq L/3$ ), where  $L$  is the length of the flume [1].

Keller [2] rightly pointed out that the effect of non-similar entrance features contributed to scale effects in the earlier works, this finding is considered a confirmation of the work that has been done by Skogerboe et al. [3]. Later, Keller [4] also conducted systematic tests on throatless flumes under submerged conditions, where Keller [2, 4] (quoted from Das et al. [5]) recommend that the input and output widths of the flume are the same for cutthroat flume, in addition to the head measurement locations should be moved from the wall of the flume to the flume floor centreline. The flow in a cutthroat flume in the case of a free flow regime is changing from a subcritical state in the section of the inlet to the critical state in the section of the throat and then to the supercritical state in the section of the outlet.

The cutthroat Flume (CTF) discharge is related to the head of upstream and downstream in case of submerged flow. Nevertheless, if the depth of the downstream flow increases to the point where it is submerged upstream flow depth, in this case, the regime is called submerged. In this case, the relationship of discharge relates to the difference in head and the ratio of submergence, where the submerged flow formula is as a following:

$$Q_{\text{submerged flow}} = \frac{C_s (h_a - h_b)^{n_f}}{\{-\log(S)\}^{n_s}} \quad (1)$$

The main factor and the first on which these parameters are based, as concluded by all the related previous research is the width of the throat, and came in the second order, the effect of the CTF length. Therefore, the width/length ratio has been adopted and its impact is studied extensively by the relevant studies, Weber et al. [6]. A new calibration approach in which a single equation accounts for the

discharge more accurately without the need for separate free- and submerged flow equations was suggested by Torres and Merkley [7].

Cutthroat flumes that have width/length ratios of 1: 9, 2: 9, 3:9, and 4:9 and of throat width 2", 4", 5", 6", 8", 10", and up to 48" have been studied firstly by Skogerboe and yang in 1993 [8]. Das et al. [5] conducted an experimental study restricted to a 5"- throat flume. Almost no research work was found in the literature about cutthroat of 7" throat width for any scale length, but recently, Maatooq and Ibraheem [9] conducted an experimental program to test a 7"-Cutthroat flume operating under free-flow condition. Five different lengths as listed in Table 1 have been adopted for this "new size" of CTF not, for discharge ranged between 0.006 m<sup>3</sup>/s to 0.025 m<sup>3</sup>/s. The analysis of results has been concluded to suggest an empirical formula for discharge calculation at a 3% error.

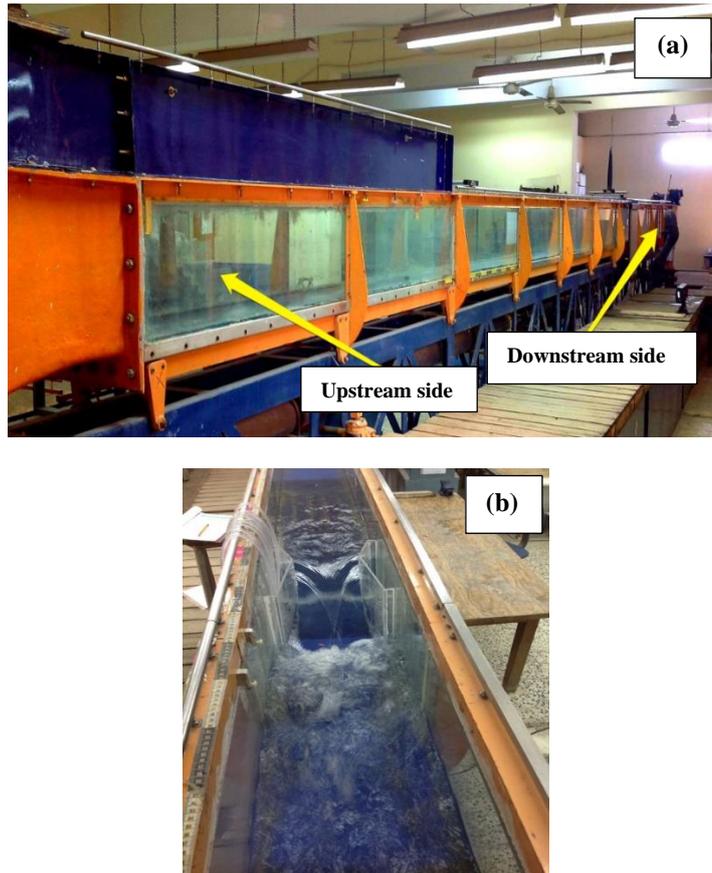
The present study is an extension of Maatooq and Ibraheem [9] study, by adopting the case of submerged flow-through 7"throat width for width/length ratios of 3:9, 3.5: 9, 4:9, 5:9, and 6:9. The aim is to derive an empirical formula, design charts and tables proposed to be used for discharge calculation when this new size of the flume is operated under submerged flow conditions. It should be mentioned that the measurements in this study were done using the point gauge.

## 2. Methodology of the Models Design and Experimental Work

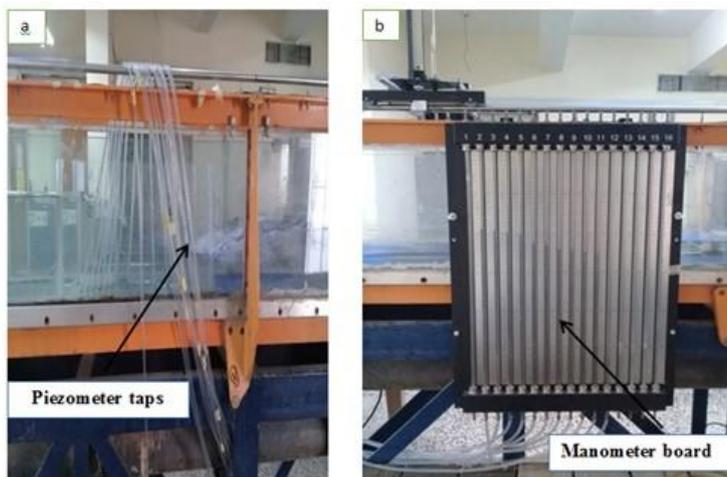
Cutthroat flume models were manufactured in the hydraulic laboratory of the Civil Engineering Department, University of Technology, Iraq. These models are installed in the middle section of a 15 m laboratory flume of cross-section 0.3 m in both width and depth, as shown in Fig. 1(a). The depth of flow into the flume was controlled via an overshoot gate located at the end section. Figure 1(b) illustrates one of the cutthroat flume models at operation. A 0.1 m in diameter delivery pipe was installed below the flume to supply the water from the sump tank to the inlet of the flume. Whereas the discharge was organized utilizing a valve tied on the rotameter type flowmeter which was calibrated with the aid of an ultrasonic flowmeter.

A point gauge mounted on a movable trolley was used for measuring the depth of water at the desired location along the centerline of the CTF. The water depth downstream of the flume was controlled by the tailgate, also the tailgate regulation helped to get the desired submergence ratio of 70%, 80%, and 90%. Also, the depths of flow were measured by the piezometer taps distributed along the right side of the CTF to record the difference in water surface profile at the manometer board from the location of the  $h_a$  to the location of the  $h_b$ . It should be noted that the number of taps was ten for all models undertaken, four of them are attached to the right-side wall of the converging section and the remaining six are attached to the right-side wall of the diverging section. (see Fig. 2).

The cutthroat flume was designed based on standard arrangement as illustrated in Fig. 3 at a width of 0.1778 m (7") and implemented for five different lengths. These lengths were selected to give two standard width/length ratios along with three new not recommended before as listed in Table 1. The models were manufactured in the laboratory using a 4 mm thick transparent acrylic sheet.



**Fig. 1. (a) Overview of the straight laboratory flume and (b) 7" - cutthroat flume under operation.**



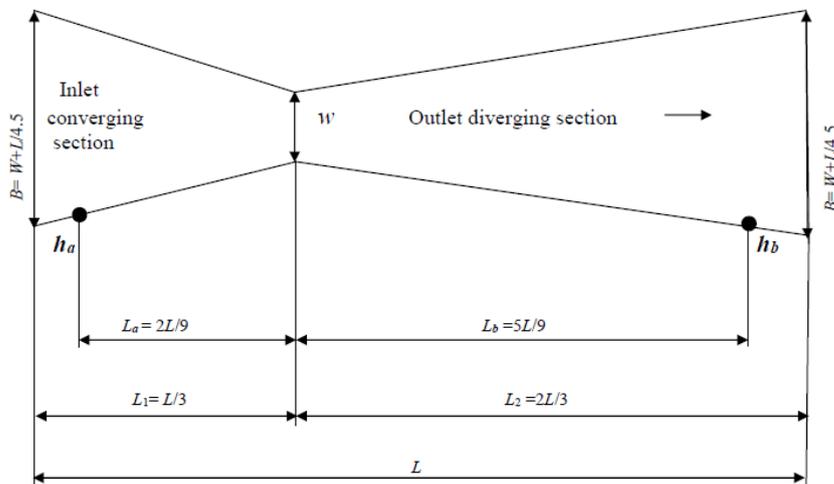
**Fig. 2. (a) Piezometer taps installed from cutthroat flume to manometer board (b) Manometer board.**

**Table 1. Details of models manufactured in the laboratory.**

Form code	$W$	$W/L$	$L$	$L_1$	$L_2$	$L_a$	$L_b$	$B$	$H$	No. of Piez. taps	Type of flume
	m		m	m	m	m	m	m	m		
CT3	0.1778	3/9	0.535	0.18	0.355	0.118	0.297	0.30	0.25	12	standard
CT3.5	0.1778	3.5/9	0.46	0.15	0.31	0.102	0.255	0.28	0.25	10	new
CT4	0.1778	4/9	0.40	0.13	0.27	0.088	0.222	0.27	0.25	10	standard
CT5	0.1778	5/9	0.325	0.11	0.215	0.072	0.180	0.25	0.25	10	new
CT6	0.1778	6/9	0.27	0.09	0.18	0.06	0.15	0.24	0.25	10	new

The upstream ( $h_a$ ) and downstream ( $h_b$ ) flow depths were measured by using the point gauge and also by piezometer taps 6 mm in diameter tuned from two sets along the right sidewalls: one set in the upstream converging section and the other in the downstream diverging section, where it created and located as recommended in the literature, e.g., Skogerboe et al. [3] and Torres and Merkley [7]. These taps are linked to the manometers boards by 6 mm in diameter transparent plastic tubes.

The length ( $L_a$ ) was the distance from the throat section to the inlet head  $h_a$  whereas the distance from the throat section to outlet head  $h_b$  was represented by the length ( $L_b$ ).

**Fig. 3. Scheme of the used CTF.**

### 3. Results and Discussion

For the submerged flow calibration, it was conducted about 120 experiments. The heads upstream and downstream were measured using both the point gauge and piezometer taps. The discharge value ranged from 0.006 m<sup>3</sup>/s to 0.025 m<sup>3</sup>/s. The tailgate regulation helped to get the required submergence ratio  $S = h_b/h_a$ . Figure 4 shows the different submergence conditions 70%, 80%, and 90% for discharge 0.025 m<sup>3</sup>/s. The tailgate was used to control the flow situation to achieve the required submergence ratio as it appears in pictures depicted to the run of a discharge equal to 0.025 m<sup>3</sup>/s and illustrated in Fig. 4.

To plot the water surface profile for 70%, 80%, and 90% submergence ratios, the readings of piezometer taps were taken for the manometers connected to the

taps as well illustrated in Fig. 5. The water surface profiles for the ranges of discharges undertaken at CT5 were chosen as illustrative examples. The decline that appears on the profile is due to the converging section at which the flow reaches its lowest level at a throat, thereafter, the energy of the flow is recovered again along the diverging section. The  $x$ -axis refers to the length of the flume while the  $y$ -axis refers to the equivalent water level measured by the piezometer taps. From this figure, the state of the different submergence conditions can be seen clearly.

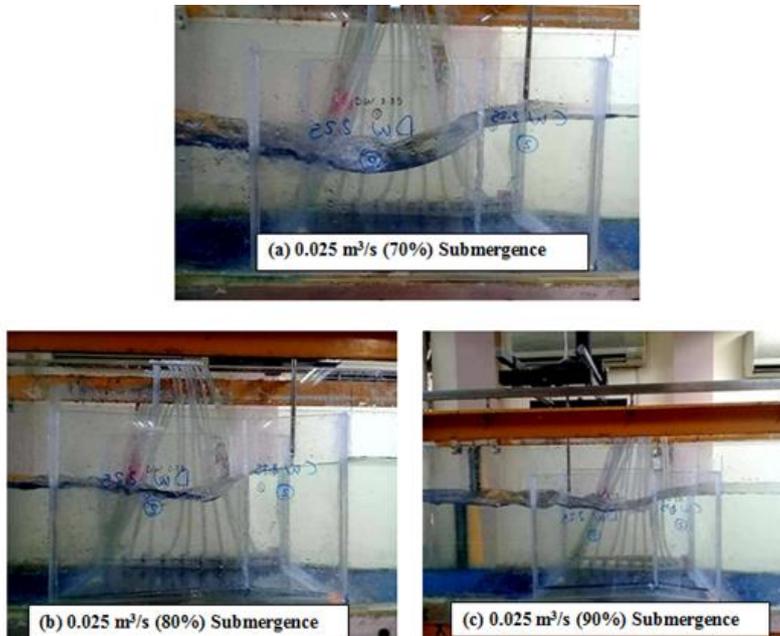


Fig. 4. The experimental run (a), (b) and (c) submerged flow with different submergence ratio 70% , 80% and 90%.

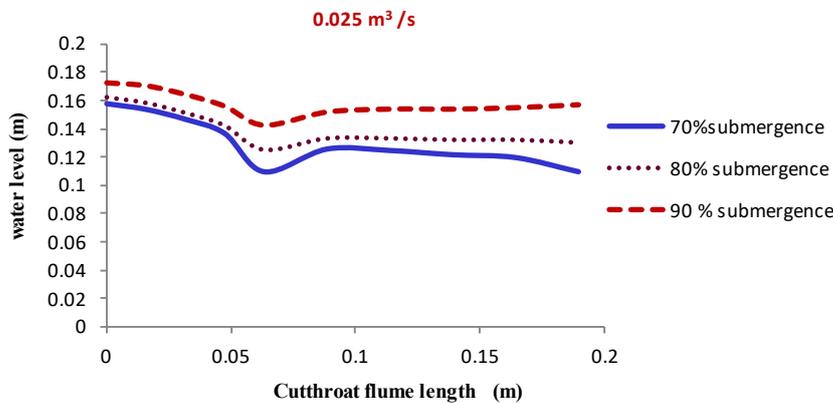


Fig. 5. (a) Water profile of model W/L ratio 6:9 for discharge at 0.025 m<sup>3</sup>/s.

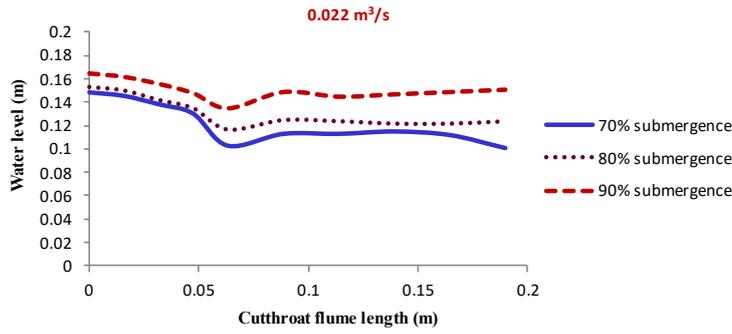


Fig. 5. (b) Water profile of model W/L ratio 6:9 for discharge at 0.022 m³/s.

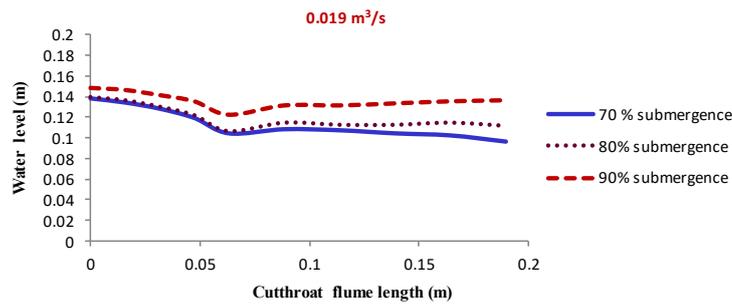


Fig. 5. (c) Water profile of model W/L ratio 6:9 for discharge at 0.019 m³/s.

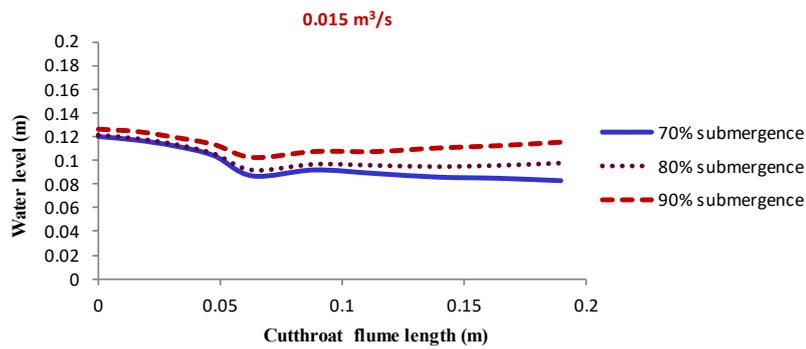


Fig.5. (d) Water profile of model W/L 6:9 for discharge at 0.015 m³/s.

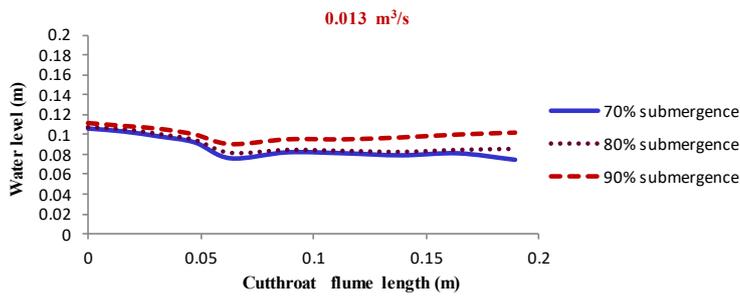


Fig. 5. (e) Water profile of model W/L 6:9 for discharge at 0.013 m³/s.

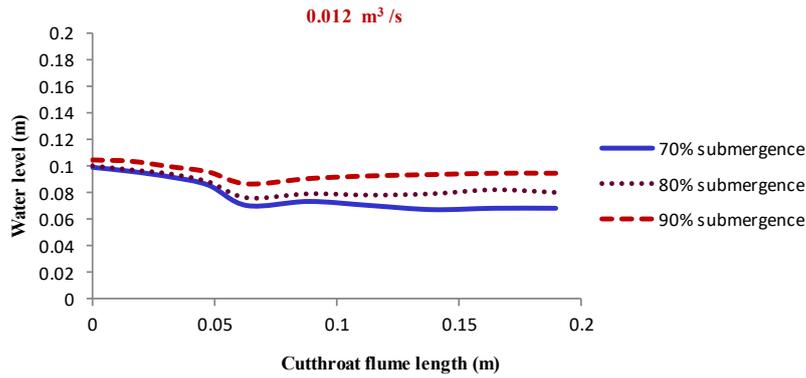


Fig. 5. (f) Water profile of model W/L ratio 6:9 for discharge at 0.012 m<sup>3</sup>/s.

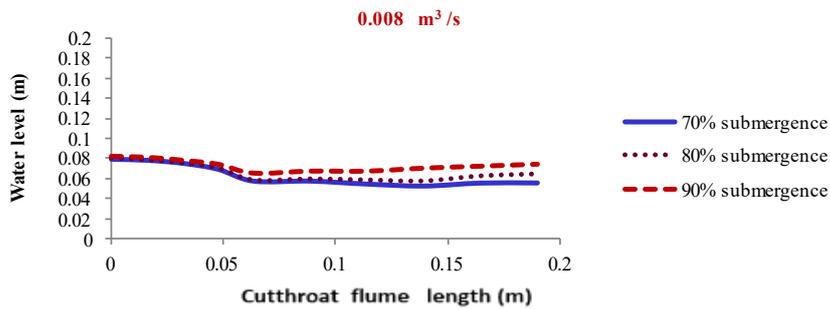


Fig. 5. (g) Water profile of model W/L ratio 6:9 for discharge 0.008 m<sup>3</sup>/s.

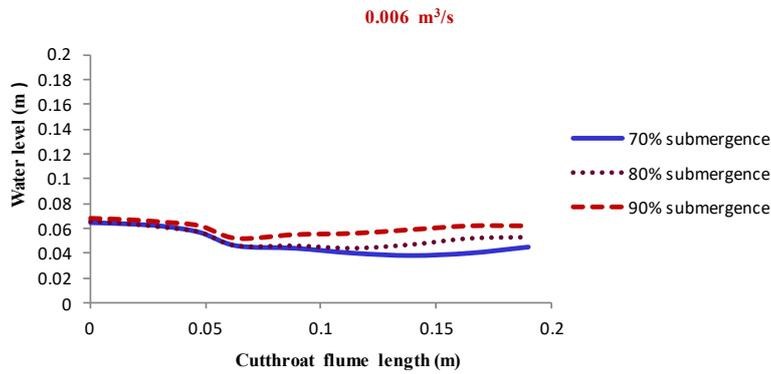
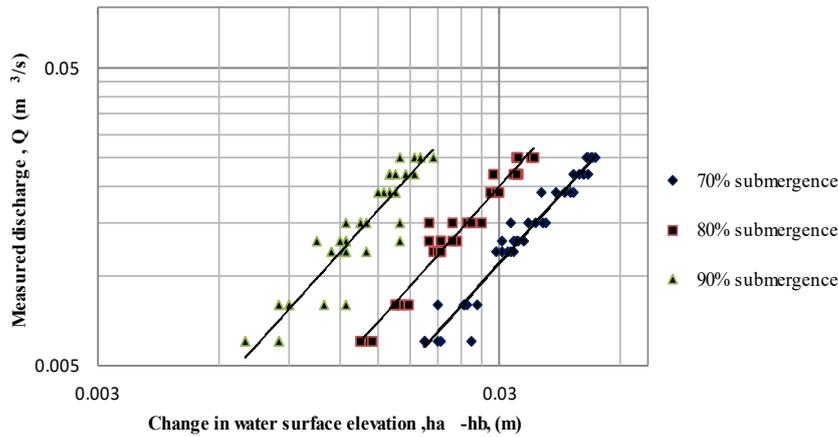


Fig. 5. (h) Water profile of model W/L ratio 6:9 for discharge at 0.006 m<sup>3</sup>/s.

### Rating empirical formula using point gauge data

Because of the presence of suspended substances in the flow, the piezometers are often exposed to clogging, which requires periodic maintenance and cleaning. For this reason, piezometer taps do not seem like the preferred option.

To measure the depth of flow in such a case, there is an alternative method like the measurement scale attached to the sidewall or using a point gauge. In this work, the point gauge was utilized for measuring the flow depths at the specified locations. The rating curve in the case of the submerged flow condition is obtained by plotting the measured discharge ( $Q$  measured) against the difference between the head of upstream ( $h_a$ ) and the head downstream ( $h_b$ ), i.e., ( $h_a-h_b$ ) for all submergence ratios 70%, 80% and 90% as shown in Fig. 6, where the value of the exponent  $n_f$  for the head difference which appears in the numerator of Eq. (1) is 1.516



**Fig. 6. Calibration curve for the submerged flow condition using the point gauge data.**

The equations obtained from the graph of submerged flows are given below:

For SF= 70%:

$$Q (SF_{70}) = 2.2294 (h_a - h_b)^{1.516} \tag{2}$$

For SF= 80%

$$Q (SF_{80}) = 4.0597 (h_a - h_b)^{1.516} \tag{3}$$

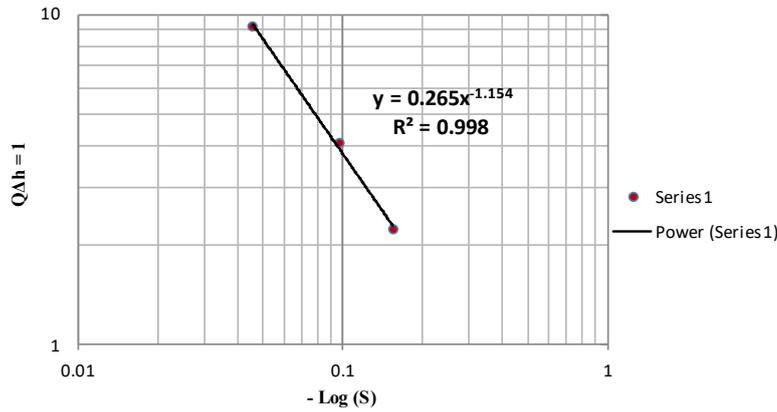
For SF= 90%

$$Q (SF_{90}) = 9.1799 (h_a - h_b)^{1.516} \tag{4}$$

The discharge parameter  $C_s$  and the exponent  $n_s$  of the submerged flow condition are obtained by plotting  $Q$  measured against submergence ratio at  $h_a-h_b=1$  m to neutralize the effect of the difference in heads so that the results are expressed solely for the relation between the discharge and submergence ratio. The graph is plotted on a logarithmic scale as shown in Fig. 7. This procedure was previously adopted by Das et al. [5].

Thus, from Fig. 7, the exponent  $n_s = 1.154$  and the submerged flow discharge parameter  $C_s = 0.265$  are obtained. The rating Empirical equation of the Cutthroat flume its throat width of 0.1778 m ( $7''$ ) operating under submerged flow condition is given by:

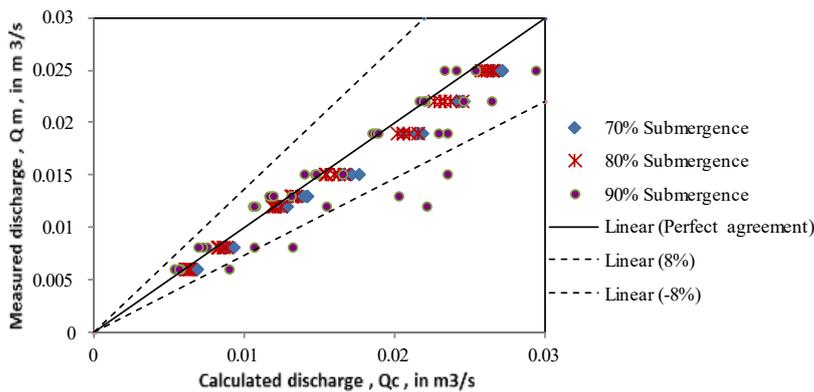
$$Q_{submerged\ flow} = \frac{0.265(h_a-h_b)^{1.516}}{\{-\log(S)\}^{1.154}} \tag{5}$$



**Fig. 7. Developing the coefficient and exponent of submerged flow condition using point gauge data.**

If the heights  $h_a$  and  $h_b$  are known, it is clear that the discharge can be easily obtained by utilizing Eq. (5) for submerged flow condition.

The calculated data using Eq. (5) are compared with the measured data as shown in Fig. 8. It is evident from Fig. 8; the calculated data is in good agreement with measured data at only some points that deviate by more than  $\pm 8\%$  from the perfect line of agreement. Thus, the suggested equations help to assess the discharge values in the flume to be easily calculated and accurate.



**Fig. 8. Submerged flows calculated data comparison with measured data using point gauge data.**

The Ditchrider table is important to the flume field implementation. The increase in discharge by 0.001 m (1 mm) indicates an increase in  $h_a$ , i.e., the upstream water level goes up in the free-flow condition and an increase in  $(h_a-h_b)$ , i.e., the difference between the water levels upstream and downstream by 0.001 m (1 mm) for submerged flow condition. In the tables, the first row indicates an increase in the head by 0.001 meters (1 mm) and the first column indicates a head increase of 0.01 meters (1 cm).

The rest of the data refer to discharge values. The range of the table was set according to the current experimental range, i.e., 0.006 m<sup>3</sup>/s to 0.025 m<sup>3</sup>/s. All the Ditchrider tables of the submerged flow 70%, 80%, and 90% are shown in Tables 2 to 4. The additional graph is drawn using the Ditchrider table as shown in Fig. 9, where the graphical representation for the Ditchrider table in the case of Submerged flow is very useful as it is easy to calculate the values of the discharge from these figures.

**Table 2. Ditchrider's table in case of Submerged flow ( $S = 70\%$ ).**

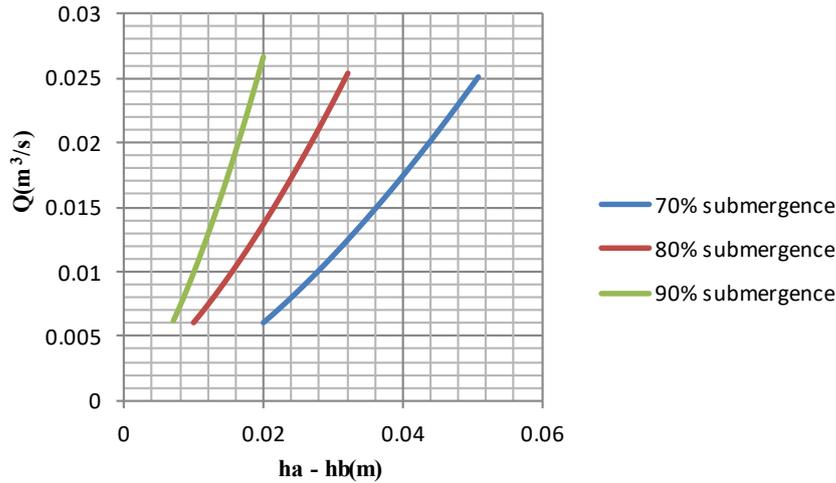
$h_a - h_b$ (mm)	$h_a - h_b$ (m)			
	0.02	0.03	0.04	0.05
<b>0</b>	0.00605	0.0112	0.01732	0.02429
<b>0.001</b>	0.00652	0.01177	0.01798	0.02503
<b>0.002</b>	0.00699	0.01235	0.01865	-
<b>0.003</b>	0.00748	0.01294	0.01933	-
<b>0.004</b>	0.00798	0.01354	0.02001	-
<b>0.005</b>	0.00849	0.01414	0.02071	-
<b>0.006</b>	0.00901	0.01476	0.02141	-
<b>0.007</b>	0.00954	0.01539	0.02212	-
<b>0.008</b>	0.01008	0.01602	0.02283	-
<b>0.009</b>	0.01063	0.01667	0.02356	-

**Table 3. Ditchrider's table in case of Submerged flow ( $S = 80\%$ ).**

$h_a - h_b$ (mm)	$h_a - h_b$ (m)		
	0.01	0.02	0.03
<b>0</b>	-	0.0104	0.01924
<b>0.001</b>	-	0.0112	0.02022
<b>0.002</b>	-	0.01202	0.02122
<b>0.003</b>	-	0.01286	0.02223
<b>0.004</b>	0.00606	0.01372	0.02326
<b>0.005</b>	0.00672	0.01459	0.02431
<b>0.006</b>	0.00742	0.01549	0.02537
<b>0.007</b>	0.00813	0.0164	-
<b>0.008</b>	0.00887	0.01733	-
<b>0.009</b>	0.00962	0.01828	-

**Table 4. Ditchrider's table in case of Submerged flow ( $S = 90\%$ ).**

$h_a - h_b$ (mm)	$h_a - h_b$ (m)		
	0.0	0.01	0.02
<b>0</b>	-	0.00865	0.02474
<b>0.001</b>	-	0.00999	0.02664
<b>0.002</b>	-	0.0114	-
<b>0.003</b>	-	0.01287	-
<b>0.004</b>	-	0.0144	-
<b>0.005</b>	-	0.01599	-
<b>0.006</b>	-	0.01764	-
<b>0.007</b>	0.00503	0.01933	-
<b>0.008</b>	0.00616	0.02108	-
<b>0.009</b>	0.00737	0.02289	-



**Fig. 9. Drawing of Ditchrider’s table data in case of submerged flow utilizing point gauge data.**

#### 4. Conclusions

In this study, the cutthroat flume is designed, calibrated, tested, and experiments results are presented. The measured depth-discharge ratios for submerged flows are set within a range (from 0.006 to 0.025  $m^3/s$ ) for the cutthroat flume. Based on the laboratory experiment results, equations were proposed for point gauge data. The following can be concluded from this study:

- The Ditchrider’s table is important to the flume field implementation. By the use of this table, a graph is drawn for the measurement of discharge in  $m^3/s$  units versus the head difference in m for the submerged flow condition.
- The Ditchrider’s table is equipped with Point Gauge data. Depending on available data, any of them can be used to calculate the discharge.
- The proposed equation for discharge calculation in the case of the Submerged flow is accurate where the discrepancy ratio was not exceeded  $\pm 8\%$ .

The measurement accuracy of discharge can be strengthened by increasing the range of calibration flow, in addition, to avoiding the observation errors for the depth of flow and rate of flow measurement.

Nomenclatures	
$h_a$	Flow depth at the inlet (upstream), m
$h_b$	Flow depth at the outlet (downstream), m
$L$	Cutthroat flume length, m
$L_1$	Length of the inlet section, m
$L_2$	Length of the outlet section, m
$L_a$	Distance of stilling well from throat section, m
$L_b$	Distance of stilling well from throat section, m
$W$	Flume throat width, m

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