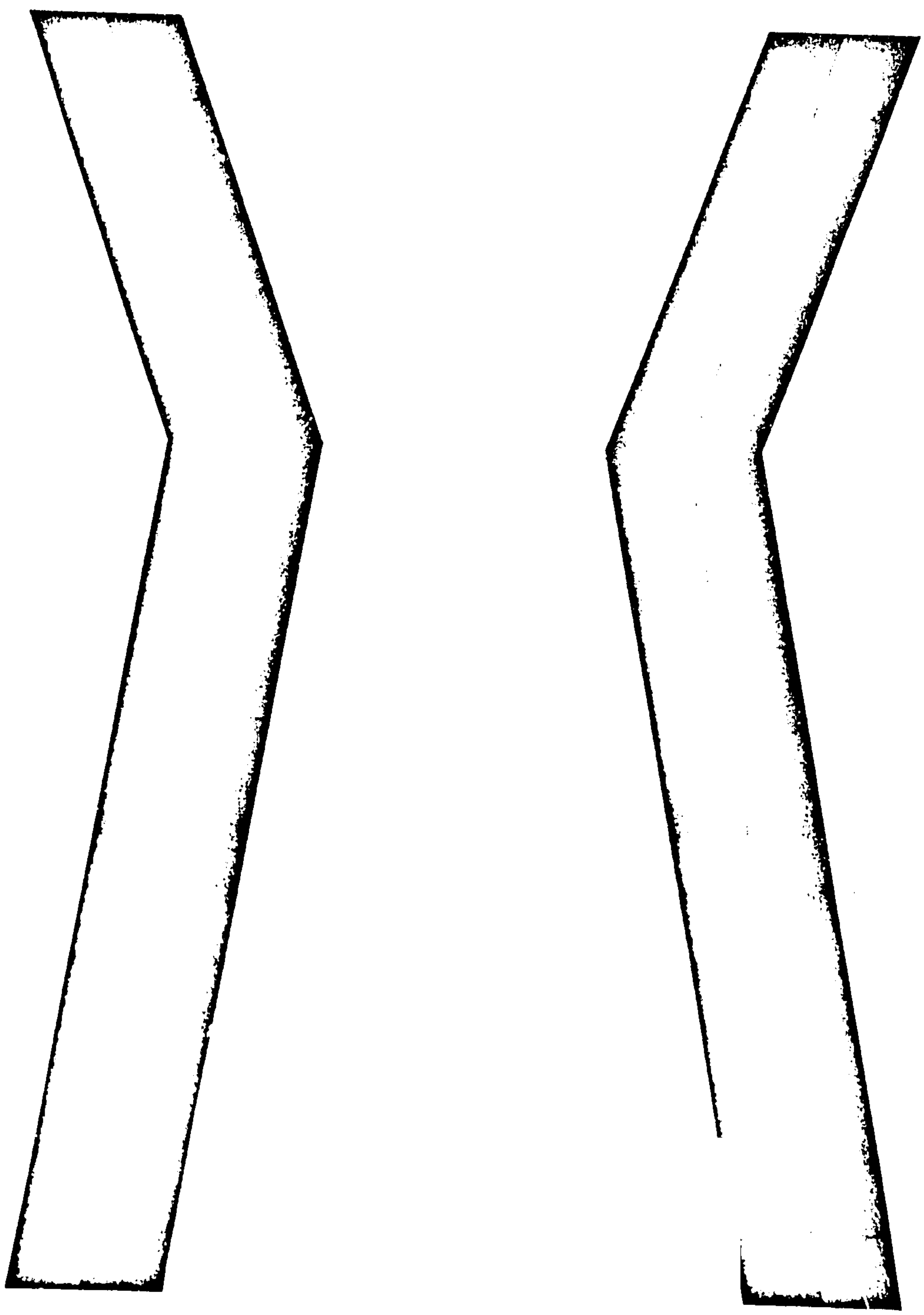
Recalibration Of Small Cutthroat Flumes For Use In Pakistan

Water Management Research Project
Engineering Research Center
Colorado State University



RECALIBRATION OF
SMALL CUTTHROAT FLUMES
FOR USE IN PAKISTAN

Special Technical Report

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ABSTRACT

The Master Planning Division of the Water and Power Development Authority (WAPDA), Government of Pakistan has been conducting watercourse surveys throughout Pakistan in the last few years. A basic data component of this sample survey is the use of Cutthroat flumes for measuring flows and water losses in each of the 61 watercourses included in the survey. The three Cutthroat flume sizes are 8" x 18", 8" x 36", and 12" x 36", where the first dimension is the throat width and the last dimension is the flume length. The recalibration work performed in the laboratory for these flumes, along with refinement of the data analyses, would indicate that the free flow ratings for the 8" x 18" Cutthroat flume would be reduced 3 percent, the free flow rating for the 8" x 36" Cutthroat flume would be reduced 1.3 percent, and the free flow rating for the 12" x 36" Cutthroat flume would be reduced 2 percent.

Laboratory studies have shown that the 8" x 18" Cutthroat flume is affected by entrance conditions. Consequently, the use of three piezometer taps at both h_a and h_b, compared with using a single tap connected to each stilling well, has a significant impact upon the free flow and submerged flow rating.

KEY WORDS: Cutthroat flumes, Discharge measurement; Flow measurement; Hydrometry; Irrigation water; Open channel flow; Water management (applied).

FOREWORD

The effort reported herein was undertaken in response to some serious questions being raised in Pakistan about the Cutthroat flumes commonly being used; namely, 8" x 18", 8" x 36" and 12" x 36", where the first dimension is the throat width and the last dimension is the flume length. Although I have never recommended the use of 18-inch length Cutthroat flumes for use in Pakistan, they have been extensively used. Consequently, a need arose to provide accurate calibrations for the 8" x 18" Cutthroat flume.

The report has been an attempt to respond to various criticisms made about the Cutthroat flume. For this reason, I have listed myself as senior author, while listing those individuals who have provided significant assistance to this report as junior authors. This was done only because I felt it was my responsibility to face the brunt of these criticisms, as well as anv criticisms that might be made of this report.

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INTRODUCTION

The Master Planning Division of the Water and Power Development Authority (WAPDA), Government of Pakistan has been conducting watercourse surveys throughout Pakistan in the last few years. A basic data component of this sample survey is the use of Cutthroat flumes for measuring flows and water losses in each of the 61 watercourses included in the survey. One of the Cutthroat flume sizes being used has a throat width of eight inches and a flume length of eighteen inches, which would be called an 8" x 18" Cutthroat flume.

The writer has always advocated the use of longer flume lengths for measuring discharge in the typical watercourses encountered in Pakistan. However, since the 18" flume length is being used, there is a necessity to have accurate discharge ratings for such flume lengths.

There are two other sizes of Cutthroat flumes being used in the watercourse surveys; namely, 8" x 36" and 12" x 36". The 12" x 36" Cutthroat flume has never been calibrated in the laboratory by the writer. Instead, the free flow and submerged flow ratings for the 12" x 36" Cutthroat flume were interpolated from the laboratory ratings for 8" x 36" and 16" x 36" Cutthroat flumes.

This particular report has been prompted by hydraulic laboratory studies undertaken by Harza Engineering Company in Lahore, Pakistan to recalibrate the three flume sizes being used in the Master Planning watercourse surveys. Their results, along with additional laboratory and data analysis undertaken by Colorado State University (CSU), are reported herein. In addition, the writer has attempted to respond later in this report to some criticisms of Cutthroat flumes.

Section 2

CSU RECALIBRATION OF 18-INCH LENGTH CUTTHROAT FLUMES

The original calibration of Cutthroat flumes having a length of 18 inches was accomplished by Bennett (1972) as part of his M.S. thesis in Agricultural Engineering at Colorado State University (CSU). This research was done under the supervision of the writer. The experimental facilities were excellent for measuring discharge very accurately using weighing tanks. However, a major drawback was the difficulty in having discharges less than one cusec (cfs). The result was that the discharge range was very limited for the shorter lengths (18-inches) and narrower throat widths of Cutthroat flumes. Because of this limitation, the discharge ratings for 18-inch flume lengths were not published in our users manual (Skogerboe, Bennett and Walker, 1973); however, generalized discharge relations for flume lengths between 1.5-9 feet and throat widths from 1-inch to 6-feet were reported by Skogerboe, Bennett and Walker (1972). The generalized free flow discharge equation for 18-inch flume lengths was reported as,

$$Q = 6.10\, W^{1.025} h_a^{\;2.15} \quad \ldots\ldots\ (1)$$

Mr. Abbas Ali Fiuzat, who is pursuing a Ph.D. degree in Agricultural Engineering at CSU, undertook some additional laboratory research to better define the discharge ratings for 18-inch length Cutthroat flumes. The results of this research are reported below.

Experimental Design

Five Cutthroat flumes of length 1.5 ft and throat widths of 1, 2, 4, 6 and 8 inches were used in this study. Figure 1 shows the dimensions of the flumes used. All of the flumes had a wall height of 12 inches.

The tests were run in a wooden flow channel with a recirculating pump in the Engineering Research Center. The flow channel setup had an orifice for measuring the flow rate, but that was inaccurate for the range of flows involved in this study. Therefore, another Cutthroat flume with proven accuracy was used to measure the flow rate. Figure 2 shows the experimental setup. The flow measuring flume was installed so that it would always operate under free flow conditions, to insure proper accuracy.

The experimental flume had a seat, so one flume could be removed, and the next flume installed easily, while still maintaining a level flume floor. A sluice gate installed at the downstream end of the experimental flume was used to control the downstream depth of water, thereby allowing the desired level of submergence to be produced. The two flumes were far enough apart so that the turbulence in the approaching water was minimized.

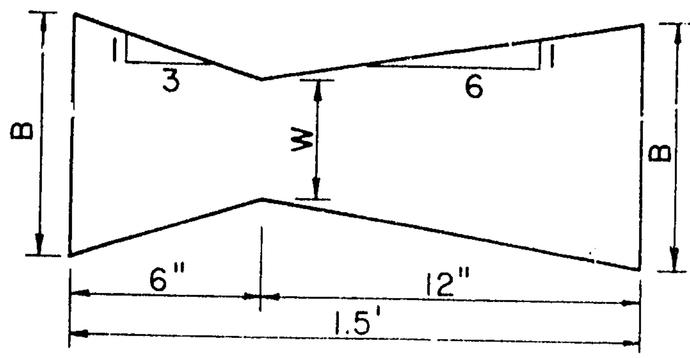
Water depths were measured using stilling wells (piezometers). Depths of water in the stilling wells were read off a graduated steel tape, glued to the transparent side of each stilling well. Depths were measured at six different positions along the experimental flume (Figure 3). The conventional depths h_a and h_b were measured at 1/9 of the flume length from each end. Other readings were taken as h_{II} and h_V, at midway of the converging and diverging sections respectively, tapping the flume wall, and h_{III} and h_{IV} at the same places as h_a and h_{II} respectively, but tapping the flume floor.

Readings were taken in decimal fractions of a foot. Two digits after the decimal (.01) were read with absolute certainty, and the third digit was an eye estimate between two graduation lines on the tape. In case of fluctuations of water level in the stilling wells, a time average was read. Depth readings were taken in the primary flow measuring flume every time readings were taken on the experimental flume. Since this could be done within a matter of seconds, it was assured that no flow changes occurred during the depth readings. Every time the flow rate or any other setting (e.g. downstream flow depth) was changed, repeated depth readings were taken, until the readings remained constant with time, indicating the establishment of a steady flow. The time required to reach steady flow ranged, in general, between 30 and 90 minutes.

Free Flow Analysis

Under free flow conditions, the flow rate depends only on the upstream head. The governing relation is

$$Q = Ch_a^{n_1} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$



W, inches	B, inches
1	5
2	6
4	8
6	10
8	12

Fig. 1. The dimensions of the 18-inch length Cutthroat flumes used in the study.

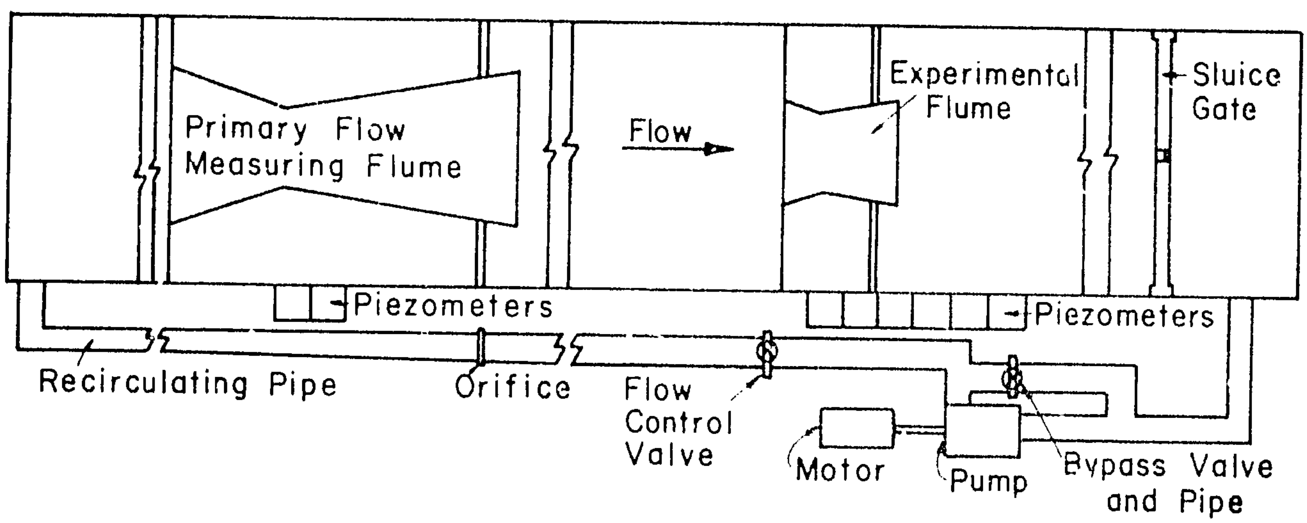


Fig. 2. The experimental setup for rating 18-inch length Cutthroat flumes.

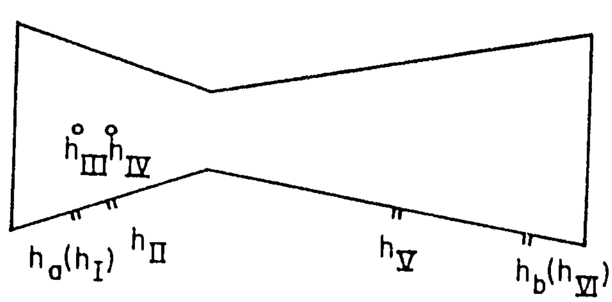


Fig. 3. Positions on the 18-inch length Cutthroat flume at which depth readings were taken.

where Q is the flow rate; C is the constant for each flume depending only on the flume width; h_a is the upstream head; and n_1 is the free flow exponent. If Q is plotted against h_a on logarithmic paper, a straight line should result with its slope as n_1 and its intercept as C. Figure 4 shows the free flow plots. On Figure 4, the information about the best fit line is given below every plot, but the drawn line is one with the slope of 2.0. All the free flow plots show that $n_1 = 2.0$ if rounded to one digit after the decimal. This is a very permissible modification since, as Figure 4 shows, the lines having a slope of 2.0 fit every set of data very accurately, and very little inaccuracy can be detected by eye.

Two important conclusions are drawn here.

(1) The upstream head, measured at the conventional position (h_a), is as good as that measured at the other experimental positions.

(2) The value of the free flow exponent is 2.0. This is in contrast to the previous study by Bennett (1972), where n_1 was reported to be 2.15.

Based on these two conclusions, it was decided that for submerged flow, that h_a and h_b will be used for analysis since they seem to be satisfactory, and at the same time the results will be consistent with the previous reports.

The plot of the free flow coefficients vs the throat width, W, is shown in Figure 5. Information about the best fit line for the points is given in Figure 5. However, in this case, since the previous reports on Cutthroat flumes

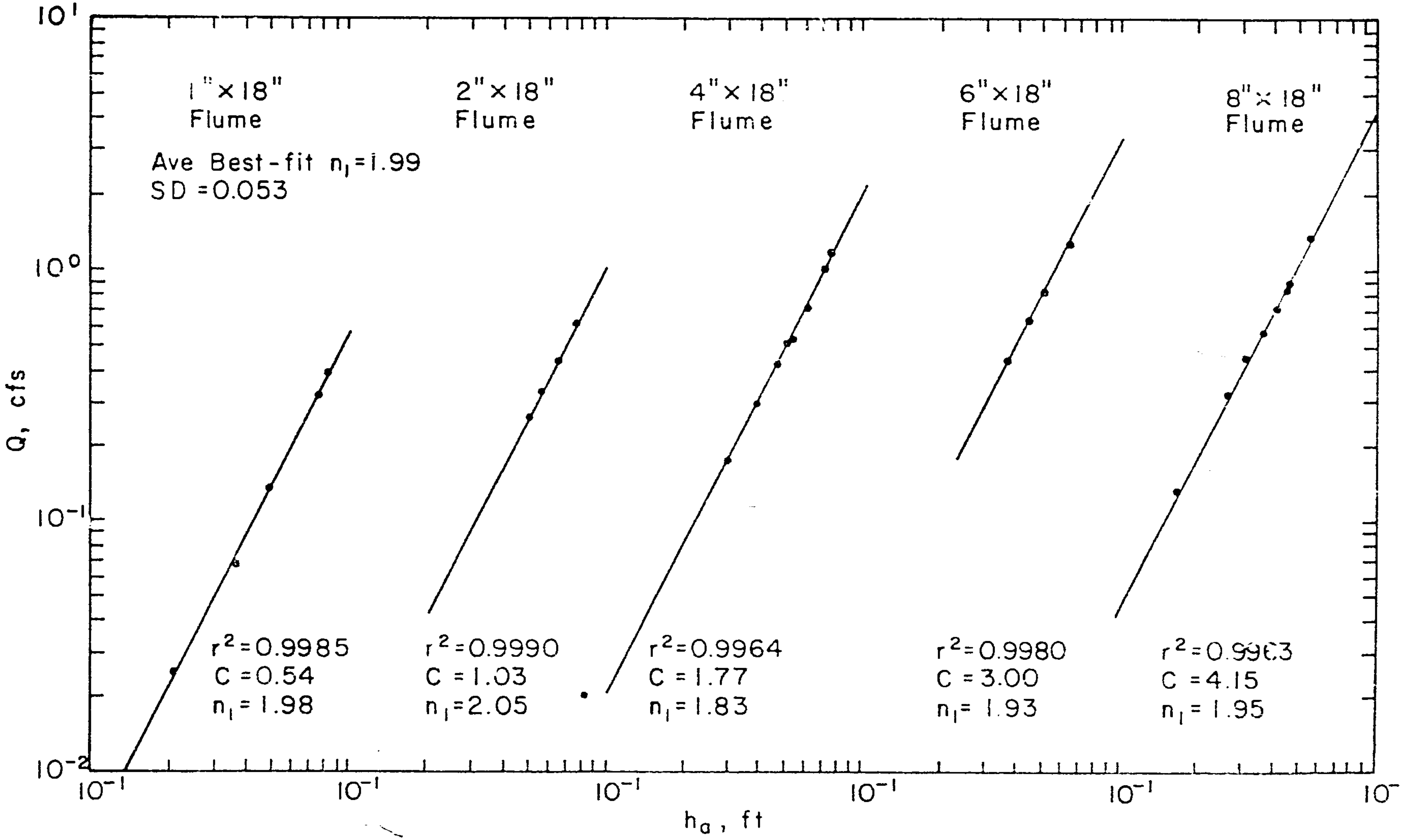


Figure 4. Free flow ratings for 18-inch length Cutthroat flumes, where $n_1 = 2.0$ for all throat widths.

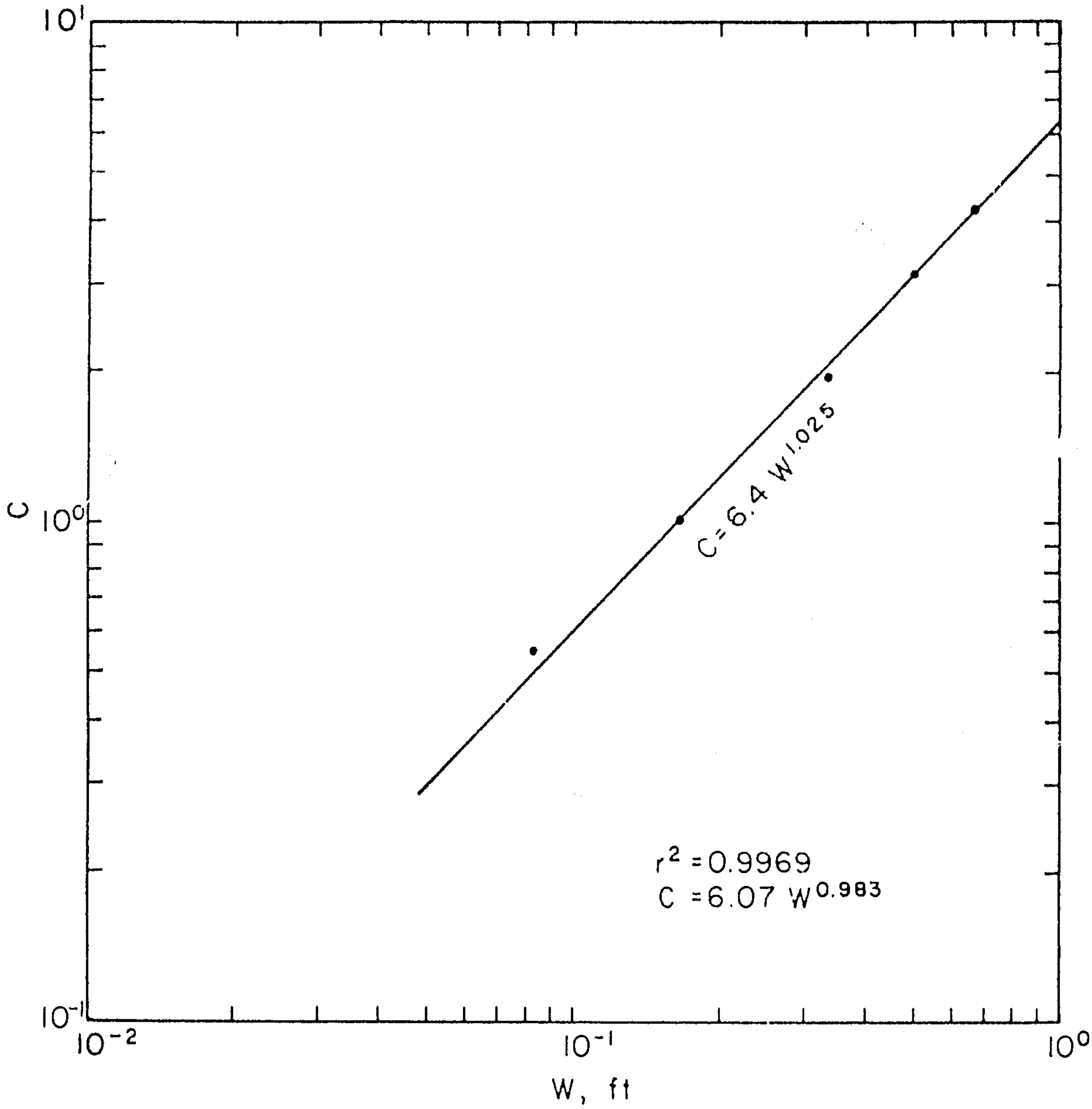


Figure 5. Plot of the free flow coefficient C against throat width W for 18-inch length Cutthroat flumes.

have used an exponent for W as 1.025, the line fit to the points in Figure 5 has been drawn with a slope of 1.025. Since the line of best fit has a slope of 0.983, there is a question as to whether or not the relation between the free flow coefficient, C, and the throat width, W, is linear (a slope of 1.00).

In the case of the free flow discharge coefficient C, although the plot presented in Figure 5 represents the points moderately well, there seems to be a curvilinear relationship among the points. This may suggest that the actual relation is $C = K(W + b)^{1.025}$. However, this formula indicates that if W = 0, there could still be a flow rate, which is absurd. Therefore, the other alternative may be that the relation between C and W should plot curvilinear on a logarithmic scale. This point will be discussed in a separate report to be published later.

Summary

Five 1.5 ft long Cutthroat flumes were tested for the purpose of determining an accurate calibration of the 1.5 ft long flumes. The results obtained were:

Free flow: $Q = Ch_a^{2.0}$

where Q = the flow rate, in cfs;

h_a = is the head, measured at 2 inches from the beginning of the flume in ft;

$C = 6.4W^{1.025}$

and W = the throat width, in ft.

$$\text{or } Q = 6.4W^{1.025}h_a^{2.0} \quad \ldots\ldots\ldots\ldots \quad (3)$$

Submerged flow: $$Q = \frac{C_1 (h_a - h_b)^{2.0}}{(-\log S)^{1.6}}$$

where h_b = the head, measured at 2 inches from the end of the flume, in ft;

S = the ratio of h_b to h_a;

$C_1 = 3.75W^{1.025}$;

$$Q = \frac{3.75W^{1.025}(h_a - h_b)^{2.0}}{(-\log S)^{1.6}} \quad \ldots\ldots \quad (4)$$

and other terms are as defined previously.

The transition submergence was found to be roughly 50 percent.

This information was provided to the CSU Field Party in Pakistan and the Harza Engineering Company in Lahore during November, 1977.

Section 3

RECALIBRATION OF CUTTHROAT FLUMES

BY HARZA ENGINEERING COMPANY

During the winter months of 1977-78, G. Owens and C. Paskett of Harza Engineering Company utilized hydraulic facilities at the Irrigation Research Institute in Lahore, Pakistan to check the calibration of some Cutthroat flumes; namely, 8" x 18", 8" x 36" and 12" x 36". The results of their work indicated a substantial discrepancy from the earlier calibrations reported by the writer and others in CSU publications. The Paskett-Owens calibrations showed discharges much less than reported by CSU. Essentially, there is a difference of 15-20 percent between the CSU and Harza ratings for discharges commonly encountered in the watercourses in Pakistan.

Analysis by Trout

The Harza data was provided to the writer, as well as some data analysis by Mr. Tom Trout of CSU. The following material is quoted from the analysis by Trout (1978).

> Because of seeming inconsistencies in field data collected with the Cutthroat flumes during the 61 watercourse survey, a recalibration of the flumes was undertaken by Owens and Paskett of Harza Engineers. A dead level 80 x 80 cm flume at Irrigation Research Institute was used for the calibration work. The experimental setup is described in their report.
>
> I visited the laboratory during one day of data collection. I could find no faults with the equipment or procedure. The suppressed weir appeared to meet the standard specifications. They usually could maintain good control over their water flow and levels. The flume appeared to be constructed and installed

according to the instructions in "Selection and Installation of Cutthroat Flumes for Measuring Irrigation and Drainage Water," by Skogerboe, Bennett, and Walker [1973], hereafter referred to as the flume manual.

The main variation in the procedure from the original calibrations was the use of entrant sections. It was originally intended that the entrant conditions should have no effect on flume performance. Experience with the small 8" x 18" flume had indicated otherwise. (It was for this reason, the CSU project personnel in Pakistan had ceased to use the 8" x 18" flume.)

The main thrust of my efforts was to examine the collected data, check the calculations made and coefficients derived, and draw conclusions from the results.

First the data was reanalyzed, utilizing completely regression techniques rather than the graphical methods outlined in the flume manual, or the mixed graphical-regression method utilized by Paskett and Owens.

There are two basic measurements made with the Cutthroat flume, the upstream and downstream elevation head, h_a and h_b. Skogerboe used h_a to predict free flow and combined h_a and h_b into two multiplicative parameters $(h_a - h_b)$ and $(-\log h_b/h_a)$ to describe submerged flow. His exponent for the first submerged parameter was the same as derived for free flow. Both exponents were constant for flumes of the same length.

I found that the Master Planning data in which either no entrant section (MP_n) or only a hand (MP_h) was used, these exponents did tend to be equal for free and submerged flow, but the entrance sections seemed to change the flume characteristics sufficiently that significantly improved fits of the data were derived if the submerged exponent were allowed to vary from the free flow value.

Because some systematic residuals were found with the MP_e [full or pucca approach having entrance channel walls that corresponded with the entrance width, B, of the Cutthroat flume] submerged data, two other multiplicative variables were added to the correlation equation, h_a and h_b making the predictive equation:

$$Q = C_2(h_a - h_b)^{n_1}(-\log h_b/h_a)^{n_2} h_a^{n_3} h_b^{n_4} \quad . . . \quad [5]$$

Little additional accuracy could be developed with the added independent variables so they were dropped.

Most of the new coefficients generated by this method did not vary significantly from the Paskett-Owens coefficients. Exceptions include the 8" x 18" MP_h and MP_n coefficients and the before mentioned improvements from allowing the $(h_a - h_b)$ exponent to vary from the free flow exponent with MP_e data. A list of all derived coefficients are given in Table 1. The r^2 value is the average absolute variation of the data from the estimate, and net error is the average variation of the data from the estimate. The data was edited to remove sets in which the residual was greater than 10% of Q or 0.08 csc. This removed less than 10% of the data sets, except in the case of the 8" x 18" flume where much more variation was found. All correlations were multiple linear on the linearly transformed variables.

Although the addition of the entrant section improved somewhat the fit of the data (if n_1 is allowed to vary) in the 8" x 18" and 8" x 36" flumes, it often lead to non-random residuals which could not be removed even with the addition of variables. The increased accuracy is not very great, as can be seen in Table 1.

With the 36" flumes the MP_h and MP_n derived coefficients and curve fits are sufficiently similar to assume that the "hand" is not required. Even in the 8" x 18" data as shown, the variation in the predicted values is not great. The data indicates that no entrant section is required for 36" flumes.

The accuracy of the prediction of the equations for the 36" flumes averaged within 2% with less than 10% of the predictions varying from the weir measured flow by more than 5%.

From the 36" flume correlations, I would choose the following coefficients as most representative of the data for use under field conditions (with no entrant section):

8" x 36"	12" x 36"
$C_1 = 2.58$	$C_1 = 4.30$
$C_2 = 1.52$	$C_2 = 2.10$
$n_1 = 1.69$	$n_1 = 1.71$
$n_2 = 1.37$	$n_2 = 1.50$

Table 1. Derived coefficients for recalibration of Cutthroat flumes by Harza Engineering Co. (Trout, 1978)

Flume size	Entrance conditions	Method	C_1	C_2	n_1	n_2	r^2	Gross error (%)	Net error (%)
8 x 36	No (kacha)	Manual	2.97	1.70	1.84	1.48		7-14	0.3-12
		P-O	2.58	1.31	1.69	1.45		2.7	+1.4
		Trout I[1]		1.53	1.69	1.38	.9991	2.0	0.04
		Trout II[2]		1.54	1.68	1.36	.9973	2.0	0.04
		Trout F[3]	2.54		1.69		.9999		
	Hand	P-O	2.56	1.52	1.68	1.37		2.0	1.0
		Trout I		1.57	1.68	1.35	.9977	2.0	0.04
		Trout II		1.59	1.68	1.34	.9991	1.9	0.03
		Trout F	2.56		1.69		.9998	0.6	
	Full (pucca)	P-O	2.56	1.44	1.69	1.39		3.3	0.8
		Trout I		1.49	1.69	1.37	.9940	3.1	0.08
		Trout II		1.52	1.61	1.30	.9991	1.4	0.1
		Trout F	2.54		1.68		.9999		
12 x 36	No (kacha)	Manual	4.50	2.58	1.84	1.48		10-11	-(5-10)
		P-O	4.30	2.01	1.70	1.50		1.3	0.5
		Trout I		2.10	1.70	1.48	.9996	1.0	
		Trout II		2.10	1.68	1.47		0.9	0.1
		Trout F	4.29		1.69		.9999	0.5	
	Hand	P-O	4.37	2.02	1.74	1.54		1.5	0.1
		Trout I		2.12	1.74	1.51	.9993	1.3	0.01
		Trout II		2.10	1.72	1.50	.9995	1.3	0.1
		Trout F	4.37		1.74		.9995	1.0	
	Full (pucca)	P-O	3.83	1.98	1.60	1.39		1.5	0.7
		Trout I		1.90	1.60	1.40	.9990	1.2	0.01
		Trout II		1.95	1.55	1.35	.9999	0.4	
		Trout F	3.82		1.59		.9999	0.3	
8 x 10	No (kacha)	Manual	4.03	2.15	2.15	1.74		10-13	2.6
		P-O	3.23	1.95	1.63	1.37		18	18
		Trout I		1.65	1.63	1.37	.9941	3.9	0.1
		Trout II		1.65	1.63	1.37		3.9	0.2
		Trout F	3.14		1.65		.9923	4.9	0.2
	Hand	P-O	3.08	1.79	1.71	1.39		4.7	0.8
		Trout I		1.40	1.71	1.49	.9959	2.9	0.06
		Trout II		1.40	1.70	1.49	.9930	2.9	0.1
		Trout F	3.04		1.70		.9973	2.7	0.06
	Full (pucca)	P-O		1.48	1.72	1.46		2.7	0.06
		Trout I		1.47	1.72	1.46	.9954	2.7	0.06
		Trout II		1.47	1.67	1.41	.9962	1.4	0.1
		Trout F	2.87		1.70		.9995	0.8	

1/ $\dfrac{Q}{(h_a - h_b)^{n_1}} = C_2(-\log h_b/h_a)^{n_2}$

2/ $Q = C_2(h_a - h_b)^{n_1}(-\log h_b/h_a)^{n_2}$

3/ $Q = C_1 h_a^{n_1}$

No such generalization could be made for the 8" x 18" flume, since the entrant conditions are more important.

All coefficients derived from the Master Planning data vary significantly from the coefficients originally derived and even in the flume manual. Under most conditions at higher flow with all three flumes, the original coefficients predict significantly higher flows (up to 20%), although the maximum overestimate is usually between 10-15% within the recommended range of each flume. Figures [6] to [14] depict the predicted flows by the various formulas for free flow conditions and submergences (h_b/h_a) of 80% and 90%. For the 12" x 36" flume except under higher submergence conditions, the MP and original coefficients predict similar flows. The original coefficients predict less flow at 90% submergence at all flow levels.

With all three flumes, under all entrant conditions, the MP derived value for n_1 is less than the original value. This causes the original flow prediction to cross the new lines under most conditions, so at some value, both formulas predict the same flow, and at low values, the original equation predicts less flow than the MP derived one.

As a result of the above analysis, Trout (1978) presented the following conclusions:

1) The 8" x 18" flume is too short to follow the entrance characteristics ascribed to longer flumes in the flume manual.

2) The 8" x 18" flume is, even under controlled entrance conditions, less accurate than the longer flumes.

3) The best calibration for the 8" x 18" flume is the one which best describes the field conditions.

4) The 36" flumes can predict flows at submergences up to 90% with less than 2% average variation, if accurately installed.

5) The addition of a uniform entrance section tends to change the calibration and increase the gauge readings in flumes where the width-length ratio is large (i.e. the 8 x 18 and 12 x 36" flumes).

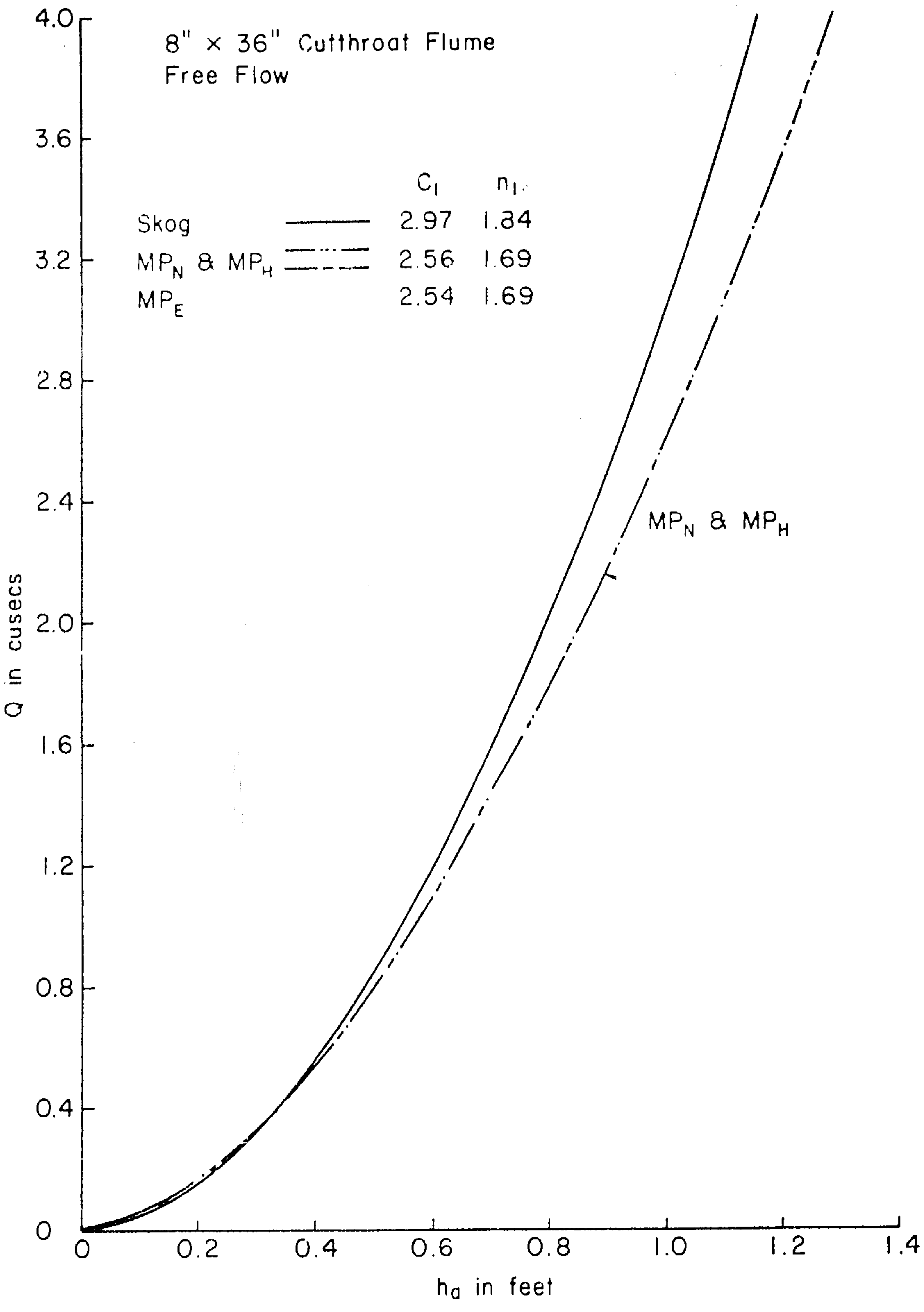


Figure 6. Comparison of free flow ratings for 8" x 36" Cutthroat flume.

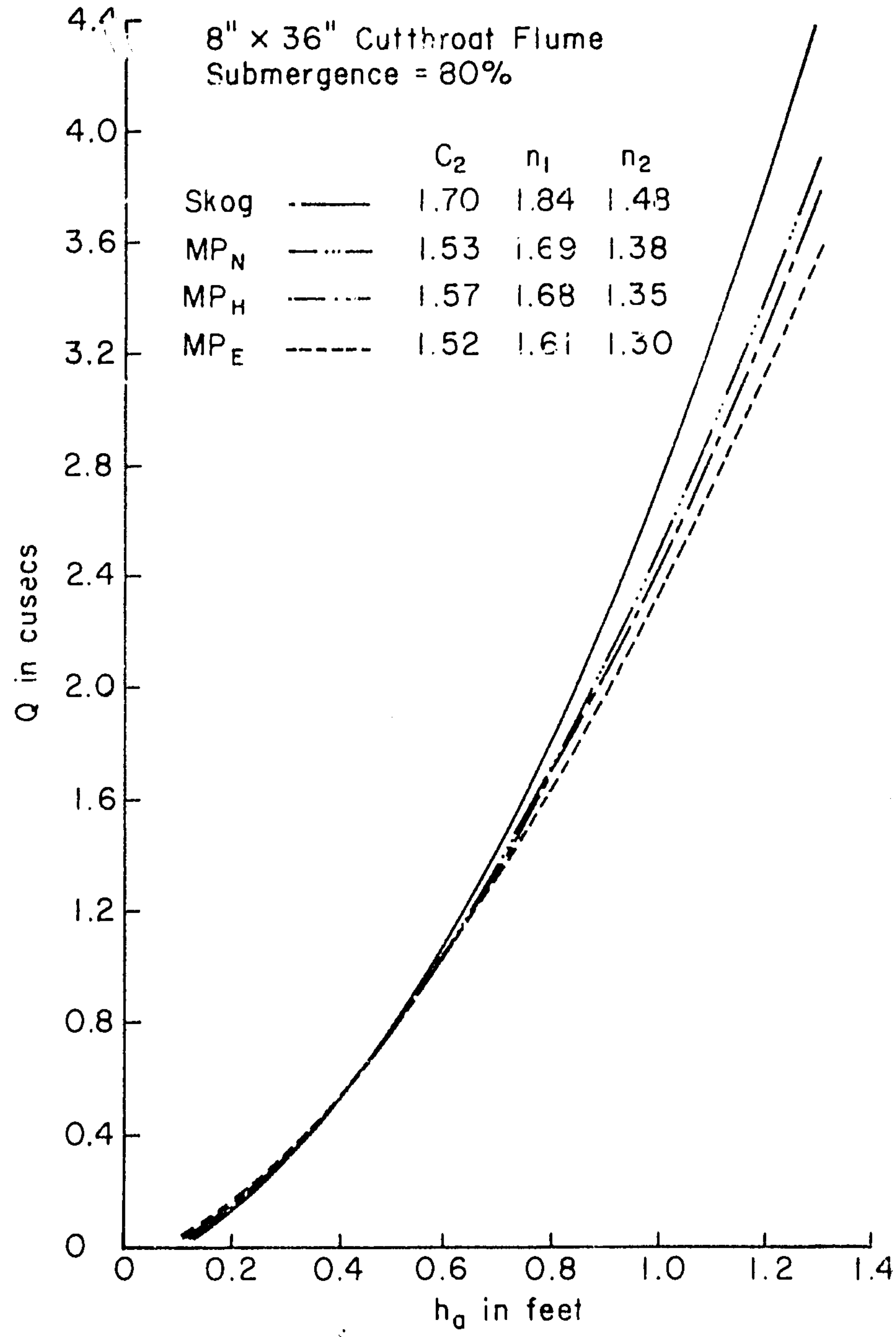


Figure 7. Comparison of submerged flow ratings at 80% submergence for 8" x 36" Cutthroat flume.

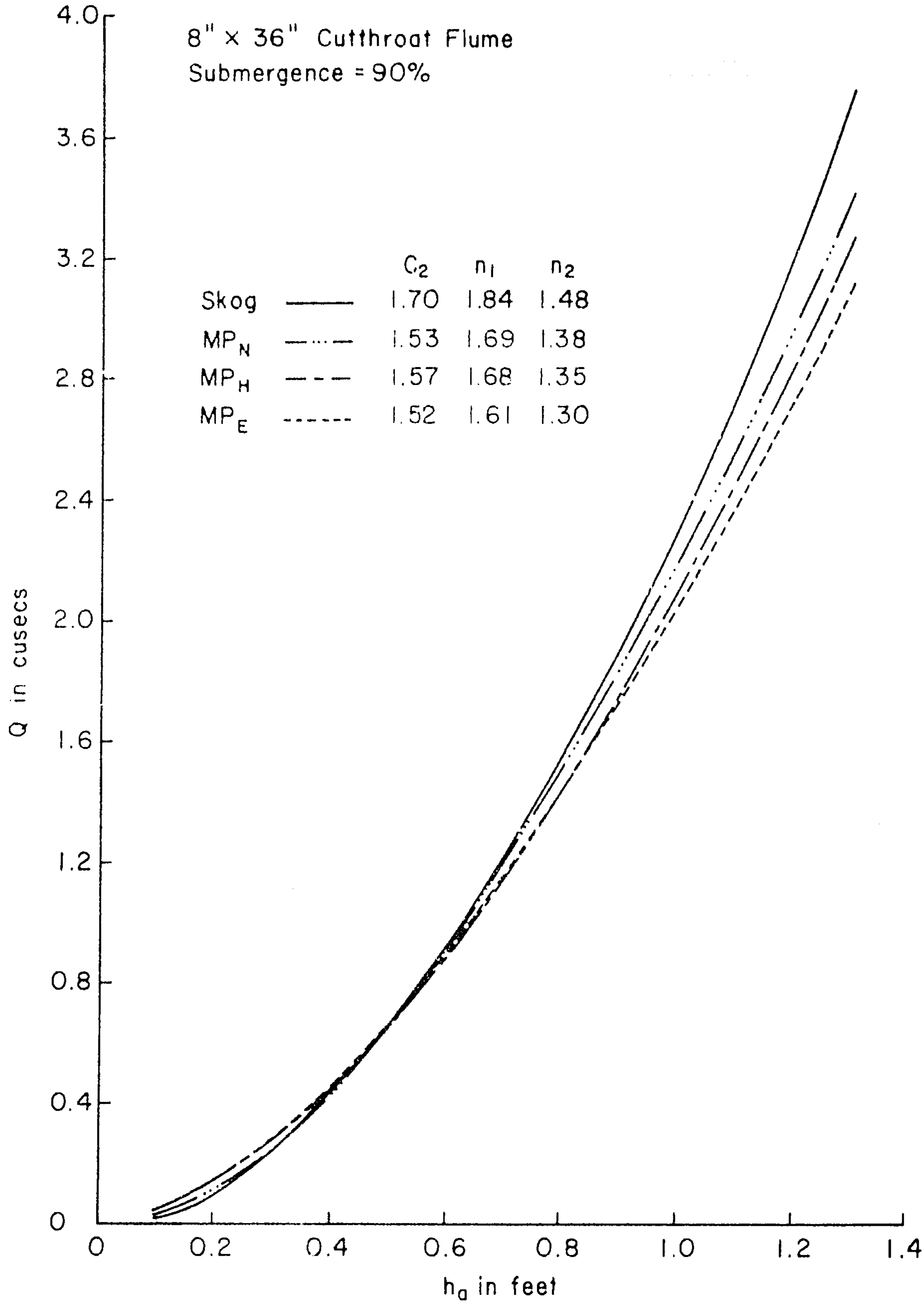


Figure 8. Comparison of submerged flow ratings at 90% submergence for 8" x 36" Cutthroat flume.

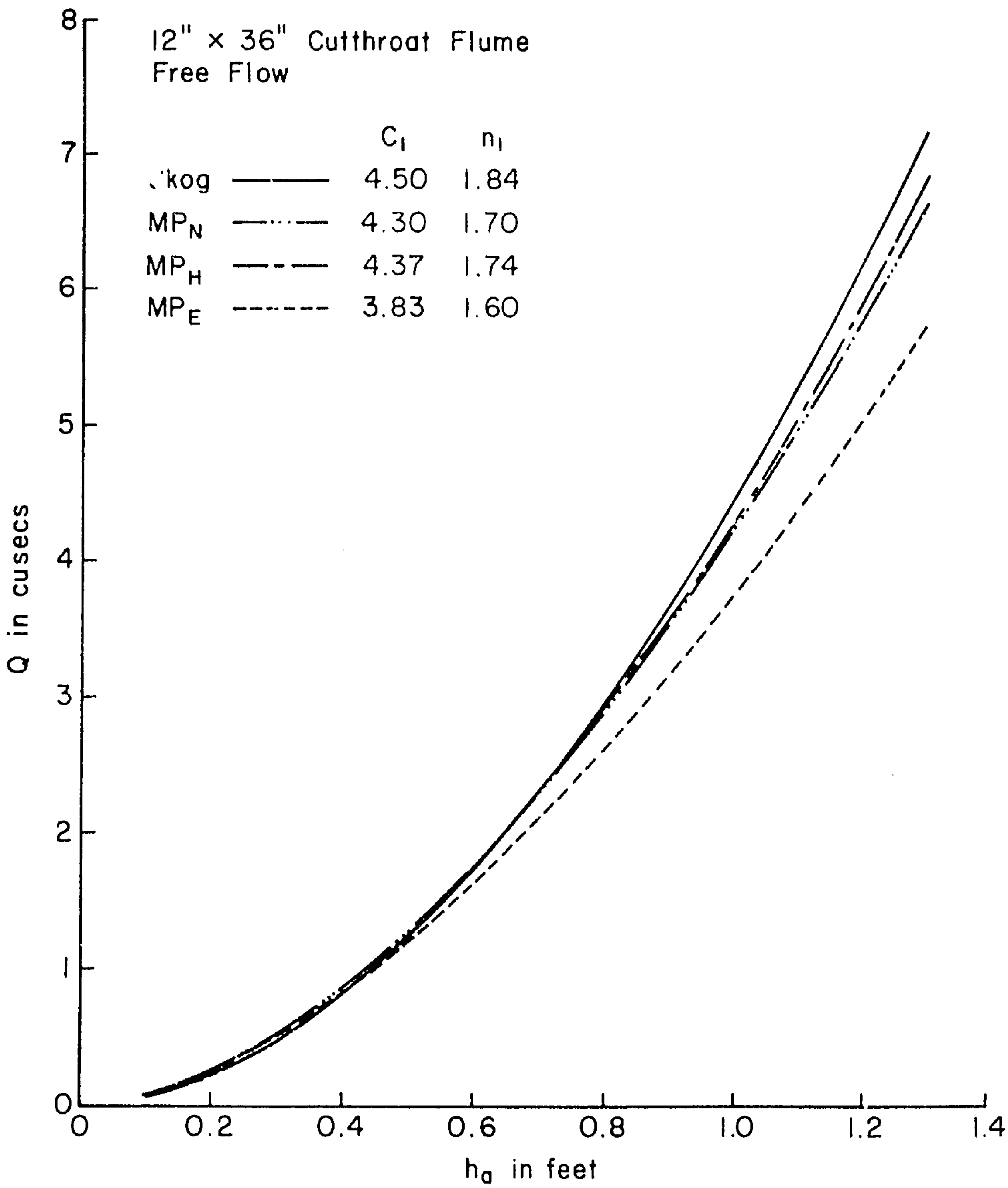


Figure 9. Comparison of free flow ratings for 12" x 36" Cutthroat flume.

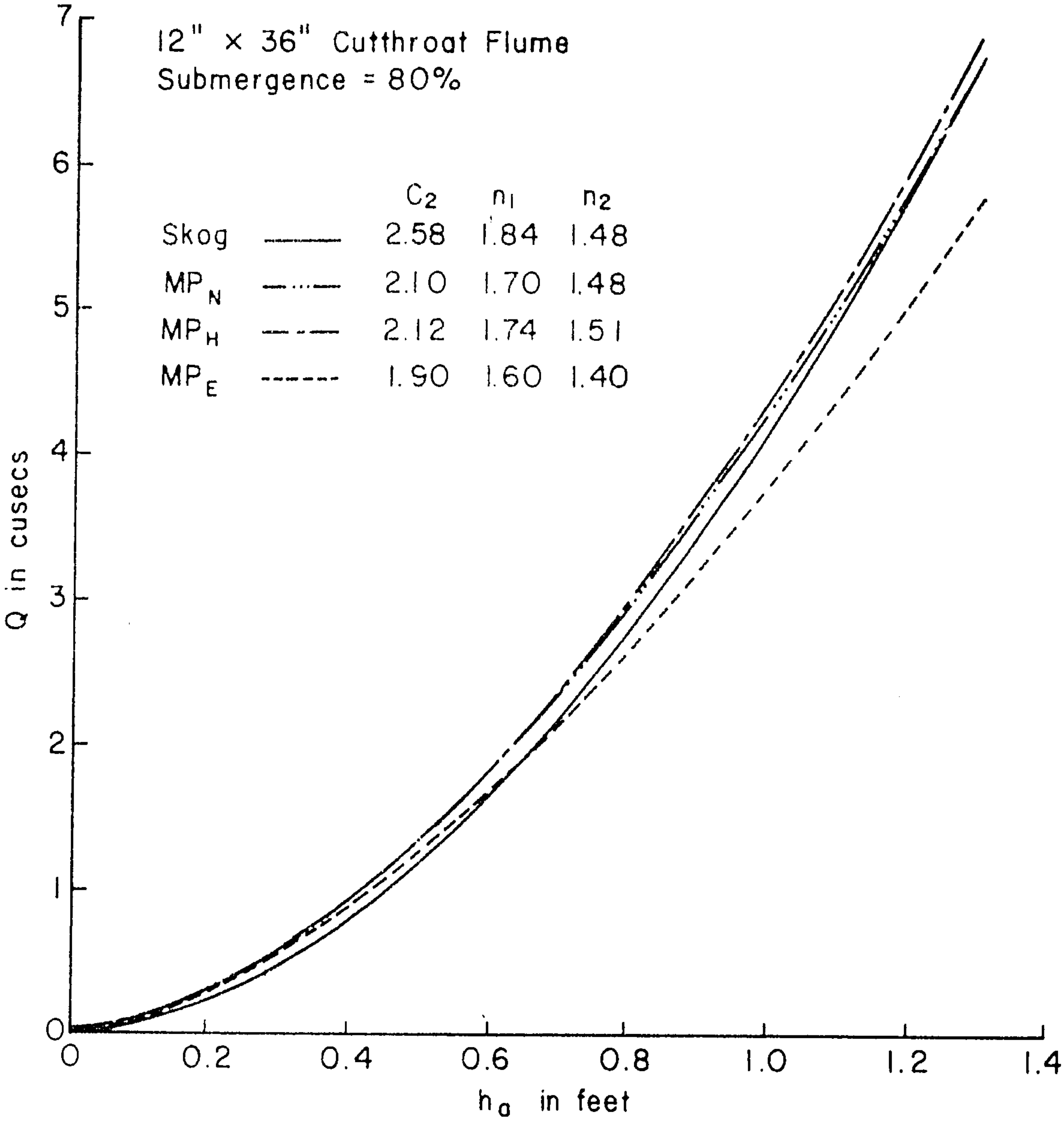


Figure 10. Comparison of submerged flow ratings at 80% submergence for 12" x 36" Cutthroat flume.

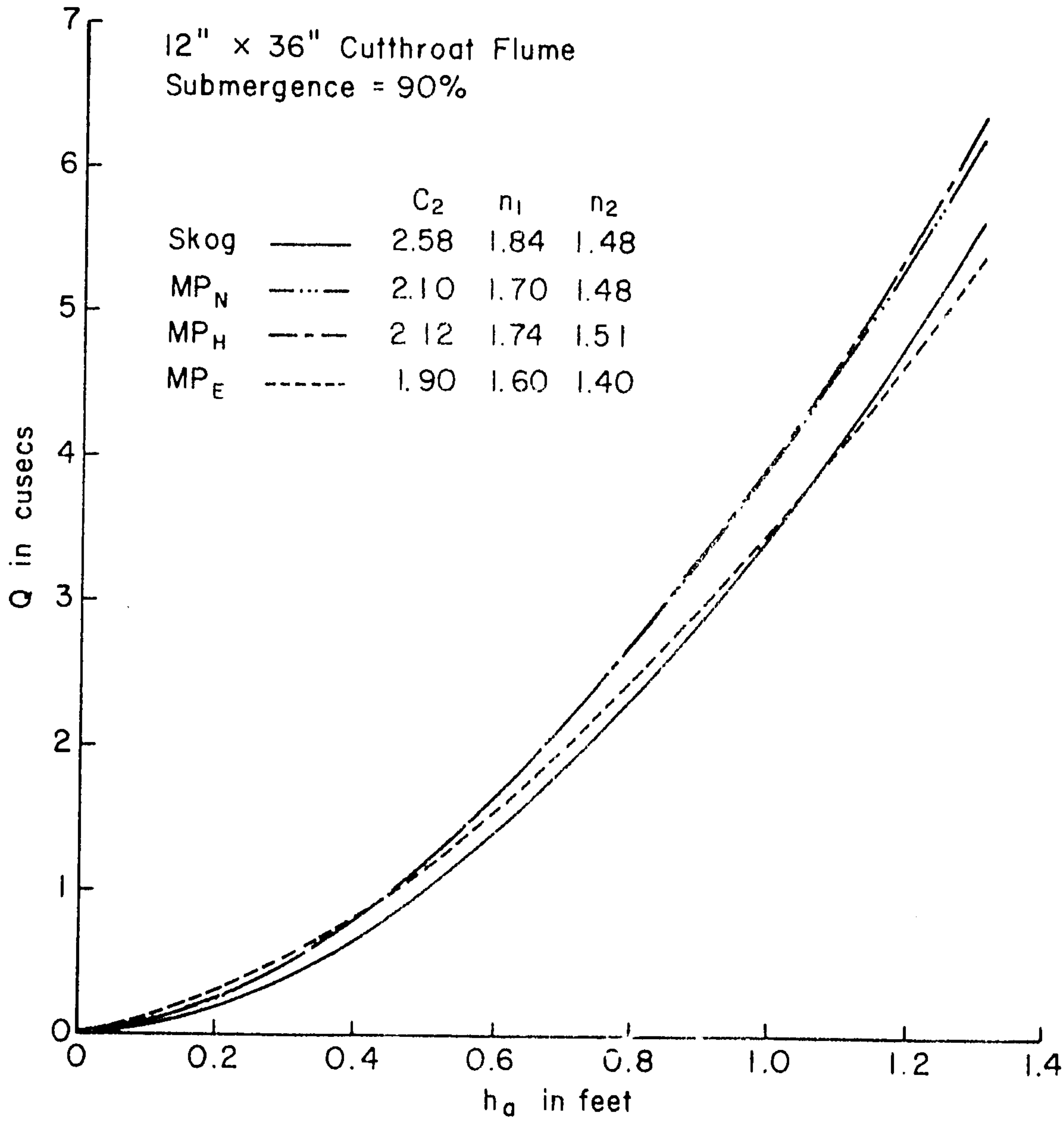


Figure 11. Comparison of submerged flow ratings at 90% submergence for 12" x 36" Cutthroat flume.

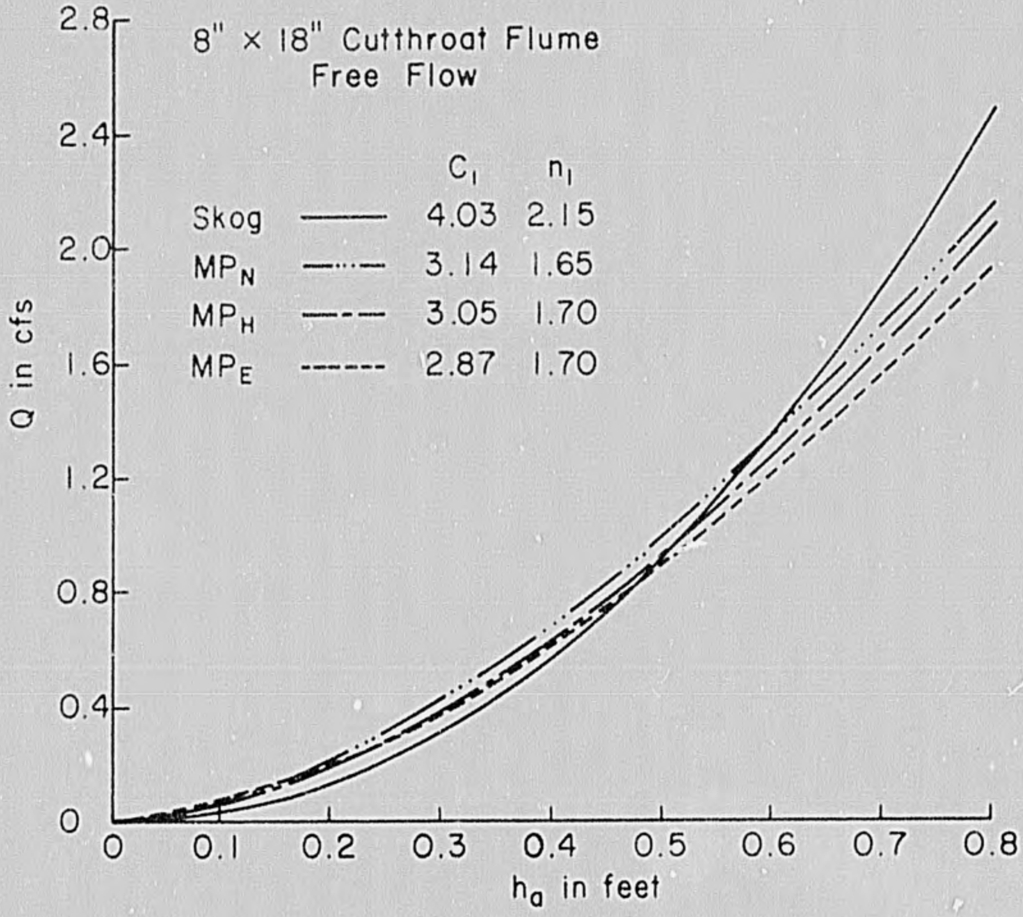


Figure 12. Comparison of free flow ratings for 8" x 18" Cutthroat flume.

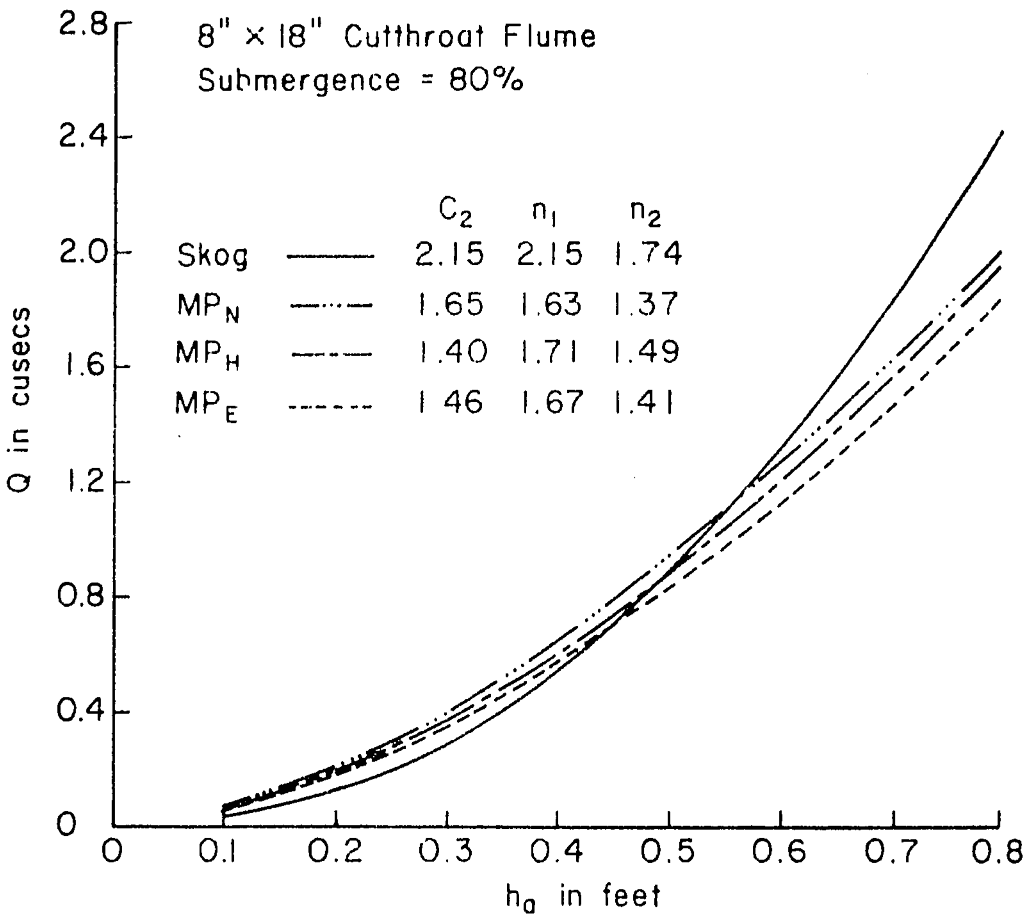


Figure 13. Comparison of submerged flow ratings at 80% submergence for 8" x 18" Cutthroat flume.

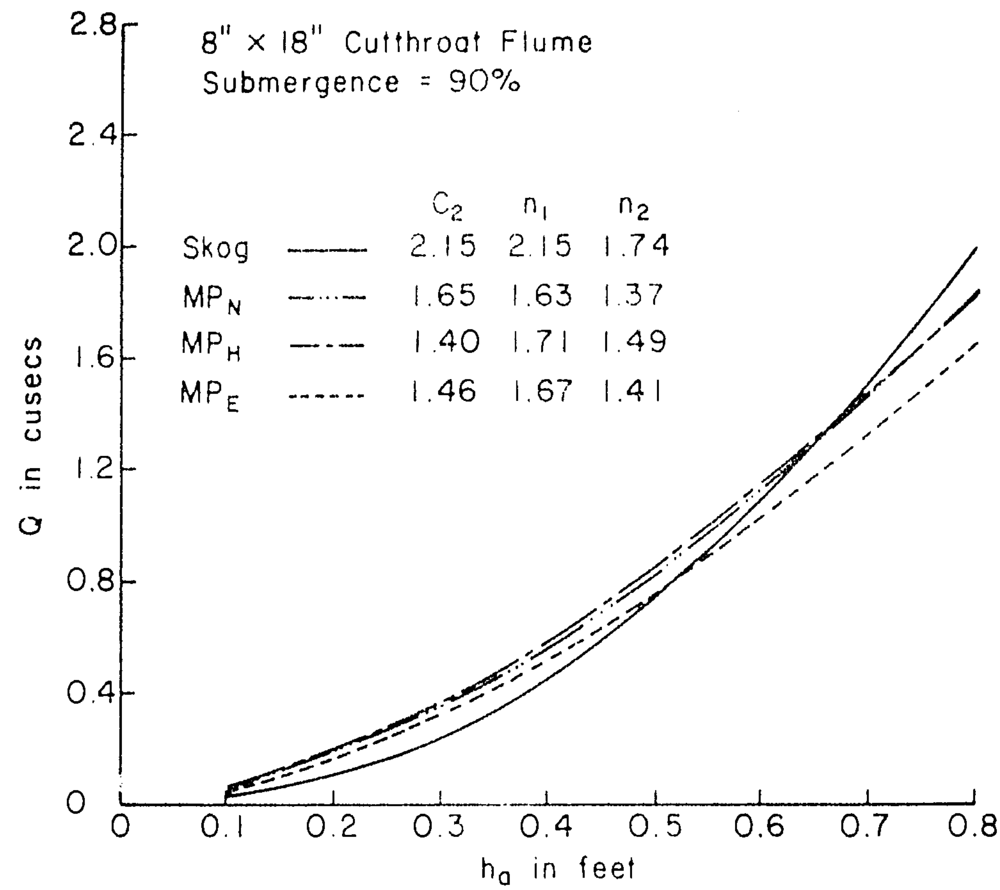


Figure 14. Comparison of submerged flow ratings at 90% submergence for 8" x 18" Cutthroat flume.

6) The variation in predicted flow between the newly derived and original equations is significant.

7) The reasons for this variation could not be determined.

Trout (1979) presented the following recommendations:

1) Cutthroat flumes can be used to measure flow.

2) The 8" x 18" flume should not be used.

3) For higher flows (above 4 csc) longer flumes (i.e. 54") will increase accuracy.

4) The original flume development [developer ?] should carry out a recalibration of the flumes to explain the differences between the two sets of data.

Analysis by Paskett and Owens

The laboratory data collected by Paskett and Owens (1978) was provided to the writer, along with some of their analysis and conclusions. The results of their analysis are summarized in Table 2. For the 8" x 18" Cutthroat flume, Skog 1 means the use of Equation 1 for free flow, while Skog 2 utilizes Equations 3 and 4. One of the major difficulties in Paskett and Owens accepting the recalibration ratings for the 8" x 18" Cutthroat flume (Equations 3 and 4) was that there was an even greater discrepancy with their laboratory data as compared with the original rating (Equation 1).

Some of the written comments by Paskett and Owens (1978) are quoted below because they provide some valuable insight:

> Skog ratings estimated water at mogha about 9% low (with 12" x 36" flumes).
>
> Skog ratings estimated downstream water from 2% low to 19% high depending on flume used.
>
> This indicates the following errors for the flumes normally used for the field measurements.

Table 2. Summary of Cutthroat flume rating curves with error estimates (Paskett and Owens, 1978).

	C_1	C_2	n_1	n_2	S_t	Net error %	Gross error %
8"x18"							
Skog 1 (pacca approach data)[1]	4.026	2.145	2.150	1.740	0.60	+8	16
Skog 1 (hand approach data)[2]	4.026	2.145	2.150	1.740	0.60	-2	11
Skog 2 (pacca approach data)	4.267	2.500	2.000	1.600	0.50	+19	20
Skog 2 (hand approach data)	4.267	2.500	2.000	1.600	0.50	+14	15
Paskett-Owens (pacca approach)	2.912	1.484	1.716	1.461	0.75	+1	2
Paskett-Owens (hand approach(ff))	2.973	-	1.691	-	-	+1	3
Paskett-Owens (hand approach (comp))	3.075	1.787	1.706	1.385	0.90	+3	4
8"x36"							
Skog (pacca approach data)	2.970	1.703	1.840	1.475	0.65	+11	14
Skog (hand approach data)	2.970	1.703	1.840	1.475	0.65	+8	9
Paskett-Owens (pacca approach)	2.549	1.440	1.694	1.390	0.71	-	2
Paskett-Owens (hand approach)	2.556	1.518	1.684	1.369	0.72	-	1
12"x36"							
Skog (pacca approach data)	4.500	2.580	1.840	1.475	0.65	-1	10
Skog (hand approach data)	4.500	2.580	1.840	1.475	0.65	-9	9
Paskett-Owens (pacca approach)	3.828	1.977	1.595	1.386	0.68	-	1
Paskett-Owens (hand approach)	4.373	2.016	1.740	1.535	0.72	-	1

1/With ideal approach having straight uniform stream lines.
2/Irregular approach with a wooden valve placed upstream to help straighten out the stream lines.

A. Discharge from mogha will be estimated lower than actual by about 9%.

B. Application (water turned into fields) will be estimated high by about 5% (this must await an analysis of data to determine downstream flume usage).

C. Loss rates will be estimated high by about 5-10%. Even more if recommended Skog 2 rating curves had been used.

Flume rating by Paskett-Owens (as previously described) contains two sources of error, both very small, which together account for most of the differences between measured Q and Q estimated from the derived formulae.

1. S_t as determined by mathematics is some sort of average of various transition submergences which actually exist for various Q's flowing through the flume. For example, actual transition submergence ranges from 0.5 at 3.17 cusecs to 0.85 at .28 cusecs for the 8" x 36" Cutthroat flume. S_t derived mathematically (wherein both free-flow and submerged flow formulae predict the same Q) is .71.

2. Observational error

   a. Misreading of vernier scale. Most such errors were on the order of less than .001 ft - judgmental errors. Others were ordinary errors which were mostly eliminated before final calculations by visual examination of observations or by plotting of data and deletion of outfliers.
   b. Undue haste in recording observations before water level in stilling well had adjusted. This eventually was recognized from the beginning and minimized by use of point gauge and watching for movement of light reflected by water in the stilling well. (The slightest movement of water in stilling well can be detected by noting changes in reflected overhead lights.) Again, most significant errors were eliminated by examination and plotting of data.

Kaccha and hand approach conditions resulted in significant variance in observations. This could not be termed error but it explains the difference in accuracy of the pacca, hand and kaccha formulae.

Under pacca approach conditions, water flows smoothly through the flume whereas under hand and particularly kaccha approach conditions, the water surface is uneven and unstable. The stilling wells "averaged out" most of this variation and, of course, resulted in different rating curves for different approach conditions.

Analysis by Wei

Harza Engineering Company had a consultant, Dr. C. Y. Wei, analyze the laboratory data collected by Paskett and Owens. The results of this analysis are summarized in a memorandum dated March 17, 1978, which is quoted below.

> As requested by J. C. Ringenoldus and M. M. Qureshi, we have reviewed the data and computations of HARZINT's [Harza International] calibration of Cutthroat flumes used in the 61 watercourse survey. The flumes were rated first by Colorado State University and the resulting rating curves differ significantly from those developed by HARZINT personnel. C. Paskett was HARZINT's principal investigator in the calibration work done in Lahore. Three sizes of flumes were tested. They were 8"x18", 8"x36", and 12"x36". As requested, the following comments are referred to HARZINT calibration.
>
> The entire series of calibrations were made based on the flow rates measured with a suppressed rectangular weir located near the inlet of the test channel. Francis weir flow formula,
>
> $$q = 3.33H^{1.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [6]$$
>
> was used to calculate the flow rates. When compared with the Rehbock formula,
>
> $$q = \left[3.237+0.428\ \frac{H}{P} + \frac{0.0175)}{H}\right] H^{1.5} \quad \ldots\ldots \quad [7]$$
>
> which includes approach and surface-tension effects, the flow rates calculated from Francis formula can be 1 to 3 percent too low for flows less than 2 cfs as shown in Table [3]. Therefore, we recommend that the weir (as installed for HARZINT's tests) be calibrated with weighing tanks.
>
> The general procedures used to calculate the constants of the free flow and submerged flow equations

Table 3. Francis formula vs. Rehbock formula.

H	P	H/P	Q_R (cfs)	Q_F (cfs)	$(Q_R-Q_F)/Q_r$ %
0.08	2.50	0.032	0.200	0.192	4.01
0.10	2.50	0.040	0.276	0.269	2.50
0.15	2.50	0.060	0.501	0.493	1.50
0.20	2.50	0.080	0.766	0.760	0.80
0.25	2.50	0.100	1.068	1.061	0.56
0.30	2.50	0.120	1.402	1.395	0.49
0.35	2.50	0.140	1.767	1.758	0.50
0.40	2.50	0.160	2.160	2.148	0.56

Note: H = head (ft.), P = weir height (ft.), Q_R = calculated from Rehbock formula, and Q_F = Q calculated from Francis formula.

appears proper. However, the regression analyses (using a programmable hand calculator) performed to finalize the parameters were based on selected samples of measured data. It is possible that somewhat different set of parameters may be derived by using different samples of data. Since time did not allow us to demonstrate this, we plotted all the 8"x18" flume data points necessary for defining the 0.80 and 0.90 submergence curves on a log-log paper to approximate a total data regression analysis. This approximate result shows that the flow rates calculated from HARZINT's submerged flow equation are probably 4 to 10 percent lower than the total data indicates. Therefore, we recommend that the entire set of data except some obvious outliers be included in the regression analyses. If necessary this could be done using a digital computer.

Figure 1 [not provided] shows the hand plotted rating curves for 8"x18" Cutthroat flume with paced approach. Table [4] shows flows calculated from Figure 1 (as Q_1) and from HARZINT's curves (as Q_2) and their differences.

In general, the converging section of the 8"x18" flume appears to be too short to maintain consistent flow pattern in the flume, and the degree of contraction of flow at the flume entrance is greater than the 8"x36" flume. Furthermore, the side wall effect is more pronounced in 8"x18" flume. Hence, the approach condition near the entrance can have greater influence on the flow through an 8"x18" flume. Therefore, it is important, when using an 8"x18" flume, that the approach condition and the installation procedure used in the calibration be precisely duplicated. We recommend that HARZINT's laboratory test procedure and set up be checked thoroughly against CSU's.

Table 4. Comparison of Harza and CSU submerged flow data for 8"x18" Cutthroat flume (Wei, 1978).

$H_a - H_b$ (feet)	H_b/H_a	Q_1 (cfs)	Q_2 (cfs)	$Q_1 - Q_2$ (cfs)	$(Q_1 - Q_2)/Q_1$ %
0.07	0.80	0.50	0.472	0.028	5.7
0.15	0.80	1.83	1.744	0.086	4.7
0.035	0.80	0.154	0.144	0.010	6.8
0.080	0.90	1.80	1.685	0.115	6.4
0.04	0.90	0.569	0.513	0.056	9.9
0.02	0.90	0.175	0.156	0.019	10.8

Also, we recommend that 8"x18" flume be replaced by 8"x36" flume whenever possible, since 8"x36" flume has longer converging section and less contraction at the entrance, and the flow through the flume is more stable.

Section 4

CALIBRATION OF
RECTANGULAR SUPPRESSED WEIR

The Paskett-Owens data was compared with the original Cutthroat flume data collected under the supervision of the writer using weighing tanks. Two weighing tanks had been used with each tank having been individually calibrated, which showed an accuracy of 1/4 of 1 percent for one of the tanks and 1/2 of 1 percent for the other tank. In addition, the writer had additional laboratory ratings on the 18-inch long Cutthroat flumes performed during the summer of 1977 by Mr. Abbas Ali Fiuzat. The individual data points were compared with the Owens-Paskett data for the 8" x 18" and 8" x 36" flumes (the 12" x 36" Cutthroat flume had never been calibrated in the laboratory and the reported rating has been interpolated from the ratings for the 8" x 36" and 16" x 36" Cutthroat flumes). This comparison verified that a major discrepancy in the two sets of data did exist.

Volumetric Channel Rating

Since the data collected by Owens and Paskett showed fairly good consistency, the most obvious question became the discharge rating for the rectangular suppressed weir used as the primary flow measuring device in the Harza calibrations. This particular weir was not calibrated by Owens-Paskett. Instead, they used the standard Francis formula for a rectangular suppressed weir:

$$Q = 3.33LH^{3/2} \quad . . . . (8)$$

With the cooperation of the Irrigation Research Institute and the assistance of Mr. Zahid Saeed Khan and Mr. Abdul Khaliq, an effort was made by the writer on May 22, 1978 to calibrate the rectangular suppressed weir by taking volumetric measurements. The flume channel downstream from the weir plate was converted into a volumetric tank by constructing a water-tight bulkhead near the downstream end of the hydraulic flume channel. Water passing over the weir plate would enter the volumetric tank where it could be discharged only by the use of siphons (or overflowing the walls of the hydraulic flume channel). A steady-state condition was established between the discharge passing over the weir plate and the discharge by the siphons; then, the siphons would be quickly lifted and the rise of water level in the volumetric tank (hydraulic flume channel) would be timed. Numerous length and width measurements had provided sufficient data to convert the rate of water level rise into the discharge passing over the weir. A summary of this data is listed in Table 5.

Table 5. Volumetric rating of rectangular suppressed weir.

Discharge Q, cfs	Weir head H, ft
0.16	0.063
0.23	0.077
0.88	0.198
1.01	0.225
1.44	0.290

This data has been plotted in Figure 15 where it can be compared with the standard Francis formula. The final point

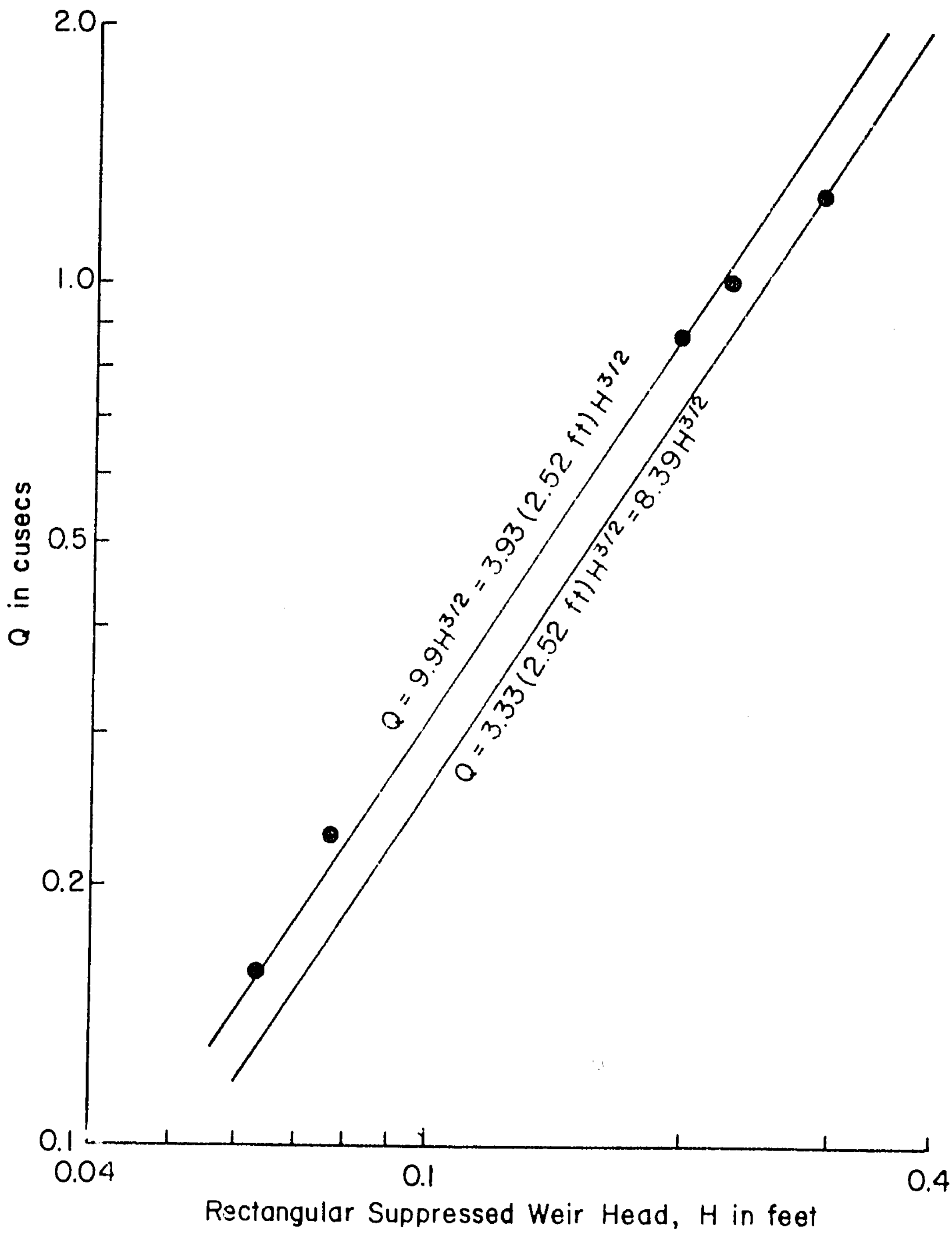


Figure 15. Comparison of volumetric data with Francis formula for rectangular suppressed weir.

(Q = 1.44 cfs) cannot be considered very accurate because there was considerable difficulty in reaching a steady-state condition for this high discharge, and then only about 15 seconds was required to fill the volumetric tank. There was a fairly good capability of the hydraulic system to provide accurate volumetric measurements at discharges below 1 cfs.

The two lines shown in Figure 15 represent a difference of 18 percent in the discharge ratings. This difference easily accounts for the discrepancies encountered by Owens and Paskett in recalibrating the Cutthroat flumes.

Other smaller discrepancies were found by the writer when analyzing the Harza data. However, each of these discrepancies would account for only 1-3 percent. However, the writer recognizes that the hydraulic data collected by Owens and Paskett still provides some useful insight into the problems inherent in using the small Cutthroat flumes of 18-inch length.

Unfortunately, the failure to calibrate the primary flow measuring device (rectangular suppressed weir) used in their experiments means that the data cannot be used until an accurate calibration is undertaken. The volumetric tank measurements reported herein provide sufficient data to show that the standard Francis formula is not an accurate calibration of the rectangular suppressed weir used by Paskett and Owens. However, a primary flow measuring device should be rated to an accuracy within one percent. This will require a more elaborate volumetric tank setup in order to obtain readings for discharges as high as 2.5 or 3.0 cfs.

Based upon this review of the data reported by Harza Engineering Company and the analysis reported by Tom Trout, the writer made the following recommendations prior to his departure from Pakistan during late May of 1978.

1. Cutthroat flumes having a length of 18 inches are affected by entrance conditions, so they should only be used for small discharges (less than one cusec). The earlier CSU manuals stated that h_a should not exceed 0.6 feet for flume lengths of 18 inches. The writer has continually advocated the use of 36-inch flume lengths (or longer) in Pakistan.

2. The data collected by Owens and Paskett does not warrant changing the Cutthroat flume calibrations reported by CSU.

3. The general discharge equation that should be used for Cutthroat flumes having a length of 18 inches is:

$$Q = 6.40W^{1.025}h_a{}^{2.00}$$

where W is the throat width in feet and h_a is the flow depth in feet measured in the flume inlet (h_a should not exceed 0.6 feet).

4. In order to utilize the data collected by Owens and Paskett to quantify various entrance effects upon 18-inch flume lengths, the rectangular suppressed weir must be accurately calibrated; the volumetric measurements reported herein serve to show that the Francis formula does not accurately describe the weir rating. A more elaborate hydraulic setup is

required to obtain a weir rating accurate within one percent, which is the accuracy expected of a primary flow measuring device.

Later, upon return to campus, the data listed in Table 5 was combined with the weighing tank free flow data reported by Bennett (1972) to show the discrepancy in the actual rating for the rectangular suppressed weir as compared with the Francis formula. The results are shown in Figure 16. For each set of weighing tank data (Q and h_a), the value of h_a was placed into the Paskett-Owens rating curve (Table 2) and Q computed. This value of Q was placed in the Francis formula (Equation 8) to determine the head, H, on the rectangular suppressed weir. This value of H was then plotted against the weighing tank Q in Figure 16. This data would indicate that the correct rating for the rectangular suppressed weir would deviate from the Francis formula less than 18 percent. Although this analysis is not conclusive regarding the true discharge rating for the weir, it does corroborate the findings from the volumetric tank data.

Volumetric Tank Rating

In the mean time, as a result of the findings cited above, the Irrigation Research Institute, Lahore used a volumetric tank arrangement to check the calibration of the rectangular suppressed weir. Their results are summarized in a memorandum dated August 8, 1978 from the Chief Engineer of the Irrigation Research Institute, Lahore to the Director General of Master Planning in WAPDA. These results are quoted below.

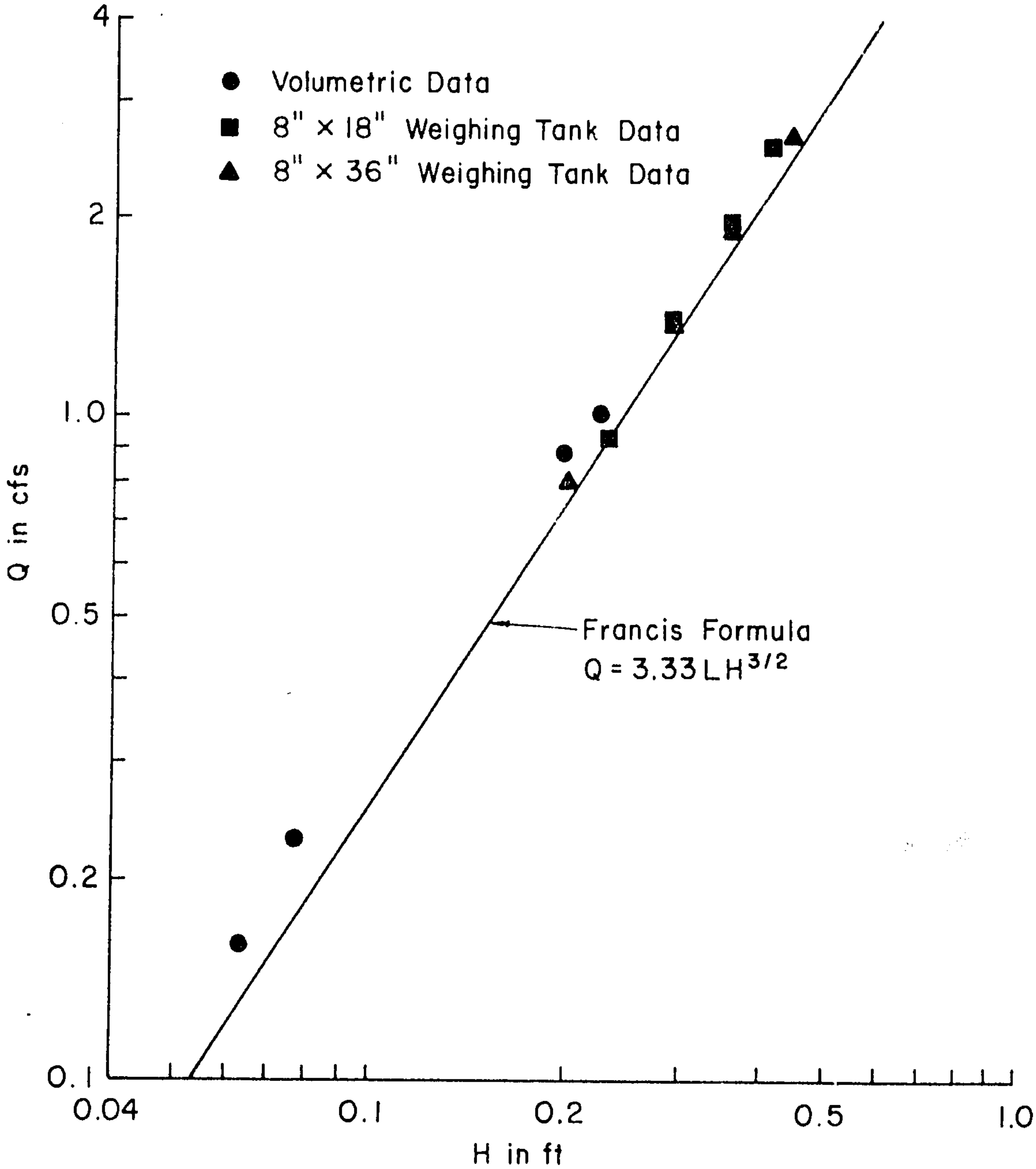


Figure 16. Comparison of volumetric and weighing tank data with the Francis formula for the rectangular suppressed weir.

M/S G. Owens and C. Paskett of Harza Engineering Company recalibrated the Cutthroat flumes, namely 8" x 18", 8" x 36" and 12" x 36" at the Irrigation Research Institute, Lahore during winter months of 1977-78. The data collected by Owens and Paskett showed fairly good consistency and indicated substantial discrepancy from the earlier calibrations reported in C.S.U. publications. There was a difference of 15 to 20% between the C.S.U. and Harza ratings for discharges commonly encountered in the watercourses of Pakistan.

Mr. G. V. Skogerboe commented on the Hydraulic facilities and data analysis. He commented that the suppressed rectangular weir used as the primary flow measuring device in the Harza calibrations was not calibrated by Owens-Paskett. They used standard Francis Formula for the standard suppressed rectangular weir.

Mr. Skogerboe visited the Irrigation Research Institute on May 22, 1978 and made an effort to calibrate the rectangular suppressed weir by taking volumetric measurements, utilizing the flume channel downstream of the weir plate as a volumetric tank by making it water tight at its downstream end. The incoming flow was syphoned out of the flume to attain steady state conditions. From the five measurements he has taken, he has concluded that his measurements present a difference of 18 percent in his discharge ratings and the Francis formula. So, he explains the discrepancy encountered by Harza and C.S.U. calibration of the Cutthroat flumes. Mr. Skogerboe has questioned the primary flow measuring device used by Harza in their calibration of the Cutthroat flumes.

The Irrigation Research Institute Hydraulic Laboratory has a facility of Rating Circular Tank built right underneath the Laboratory. This Rating Tank is used for calibrating all the measuring devices in the laboratory flumes. The Rating Tank has an average diameter of 13.58 ft. and 13 ft. depth.

The laboratory flume was directly connected to the Rating Tank. For each specific head over the suppressed rectangular weir the discharge collected for a specific time was observed with the help of a standard float gauge. The error due to switch off and on of the connecting pipe of the flume was eliminated.

The data of ten measurements is given in the attached table [Table 6] and compared with Francis

Table 6. Calibration of 2.53' sharp crested weir installed on 2.5' wide glass sided flume.

Head in ft.	Disch Gauge	Initial W. L.	Final W. L.	Time Min-Sec	Depth in ft.	Total Volume in rating well cft.	Disch/sec (Observed) Cs.	Theoretical Rehbock Formula	Discharge Francis Formula	% Rehbock Formula	Difference from Francis Formula
.067	1.745	3.600	5.600	30-25	2.000	287.912	.15776	0.1551	0.1462	+1.67	+7.900
.082	1.760	1.200	3.800	30-9.5	2.600	374.2856	.2068	0.2066	0.1980	+0.096	+4.440
.117	1.795	1.100	4.600	24-3.5	3.500	503.846	.3490	0.3452	0.3375	+1.100	+3.400
.177	1.855	5.100	10.317	19-36	5.217	751.018	.6386	0.6339	0.6279	+0.741	+1.700
.256	1.934	1.200	4.380	7-00	3.180	457.780	1.08995	1.0964	1.09125	-0.592	-0.120
.317	1.995	2.900	7.400	7-9.5	4.500	647.802	1.5083	1.5094	1.5036	-0.072	+0.313
.346	2.024	1.800	6.800	7-30	5.000	719.780	1.7016	1.7214	1.7147	-1.150	-0.770
.429	2.107	3.000	8.200	5-19	5.200	748.5712	2.34662	2.37958	2.36729	-1.380	-0.870
.461	2.139	0.900	8.120	6-34.75	7.220	1039.362	2.63296	2.6528	2.6394	-0.748	-0.243

Average diameter of rating tank = 13.538'

Area of rating tank = 143.956 sq. ft.

i) Rehbock Formula: $Q = \frac{2}{3}\sqrt{2g}\ BH^{3/2}\left(0.605 + \frac{1}{320H-3} + \frac{0.08H}{P}\right)$

ii) Francis Formula: $Q = 3.33\ BH^{3/2}$

Formula is fair for heads above 0.17 ft. where as the percentage error for head below 0.17 ft. increased with the lowering of head and the maximum error is of the order of 7.9 percentage at a head of 0.067 ft.

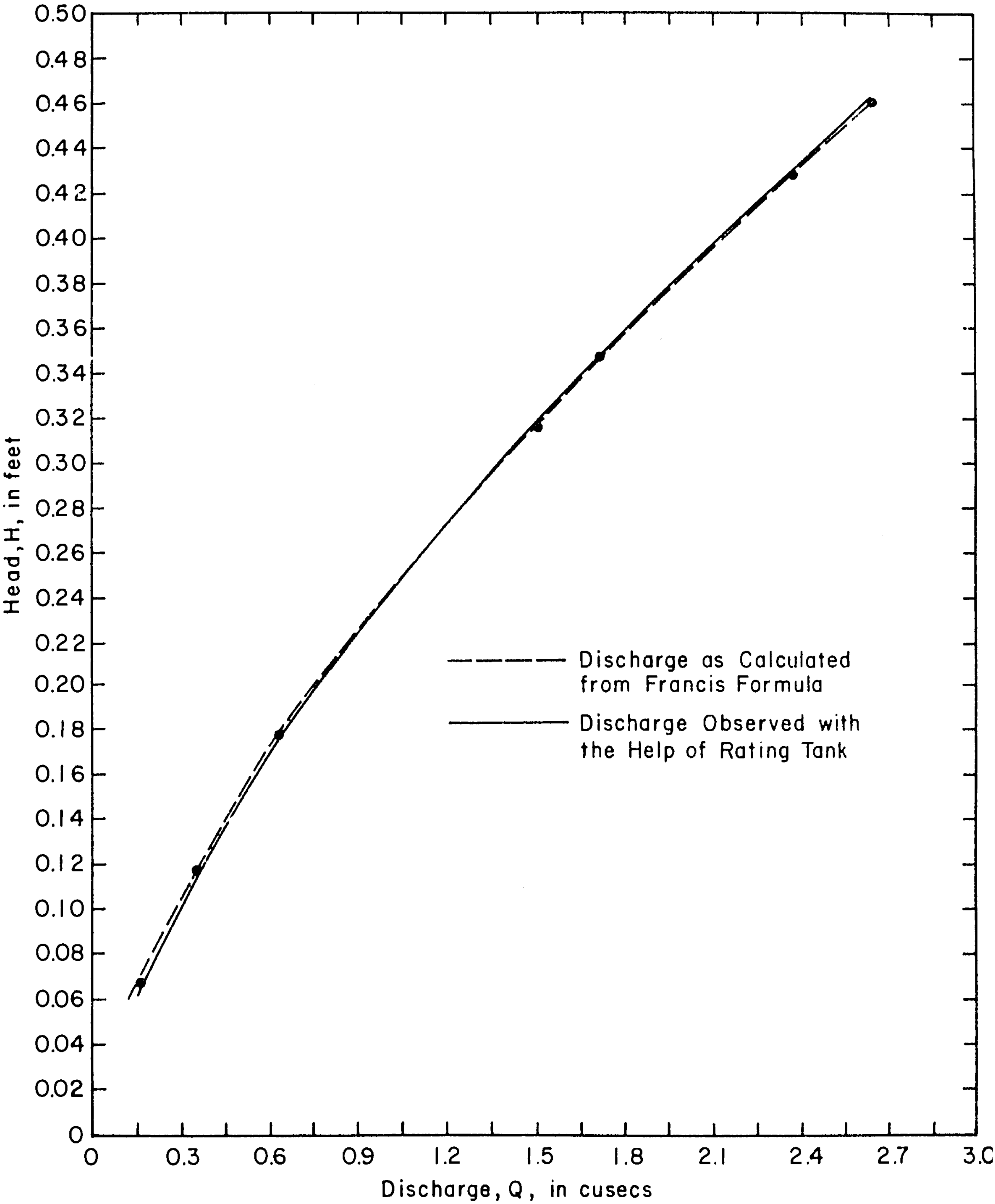
The percentage difference in the calibration and Rehbock formula is better than that of Francis Formula and the difference is not more than 1.67 percentage.

It is suggested that the Owens-Paskett data may the reprocessed with the calibration curves of suppressed rectangular weir given in the attached figure [Figure 17].

V-Notch Weir Rating

In March and April of 1979, the writer was again in Pakistan, with a portion of the assignment being to answer any remaining questions regarding the calibration of the 8" x 18" Cutthroat flume. In this section, additional laboratory work performed in cooperation with the Irrigation Research Institute (IRI), Lahore regarding the calibration of the rectangular suppressed weir will be discussed, while the last sub-section in Section 5 of this work will discuss the additional laboratory tests conducted with the 8" x 18" Cutthroat flume.

In personal discussions with Professor Carl Kindsvater (1978), who is a highly respected authority on hydraulic research and is presently with the U.S. Geological Survey, but for many years was on the faculty at Georgia Tech University, he advised that I use a 90° V-notch weir as a standard for accurate discharge calibration work when volumetric or weighing tanks are not available. As a consequence, a V-notch weir was constructed by the staff at IRI, which had a central angle of 91° 01' 34", which hereafter will be referred to as a



gure 17. Calibration of 2.53 rectangular suppressed sharp crested weir.

91° V-notch weir. This weir was installed in the hydraulic channel downstream from the rectangular suppressed weir.

Although discharge equations are available for V-notch weirs (Shen, 1959), it was deemed desirable to check the rating using a volumetric pan. So, a volumetric pan having dimensions of four-feet long, two-feet wide and one-foot deep was fabricated. This pan was calibrated by placing known volumes of water in the pan and then recording the water depth for each known volume. The results of this calibration are presented in Figure 18, which shows a very accurate linear relationship between water depth and volume.

A series of hydraulic tests were conducted wherein the discharge was measured using the volumetric pan in conjunction with measuring the hydraulic head for the V-notch weir and the rectangular suppressed weir. The discharge rating for the 91° V-notch weir is given in Figure 19, which shows that the data points define very accurately the following relationship,

$$Q = 2.50 h_e^{5/2} \qquad (9)$$

where h_e is the effective hydraulic head defined as the measured hydraulic head plus a correction of 0.003 feet to compensate for the combined effects of viscosity and surface tension (Shen, 1959).

The volumetric pan data is also plotted in Figure 20 as a check on the discharge rating for the rectangular suppressed weir. In addition, there was an 8" x 18" Cutthroat flume also located in the hydraulic channel, so that the corrected

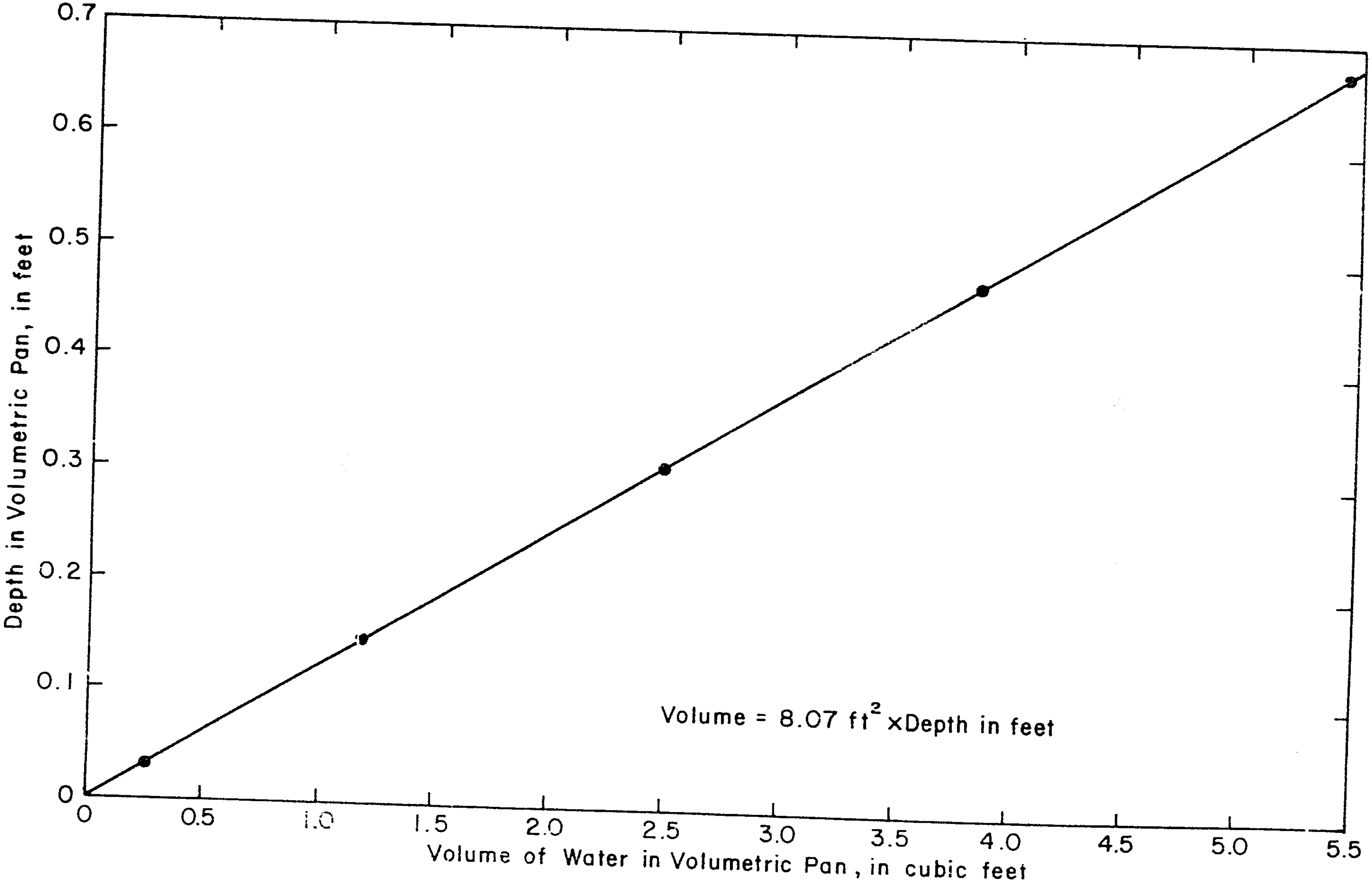


Figure 18. Calibration of volumetric pan.

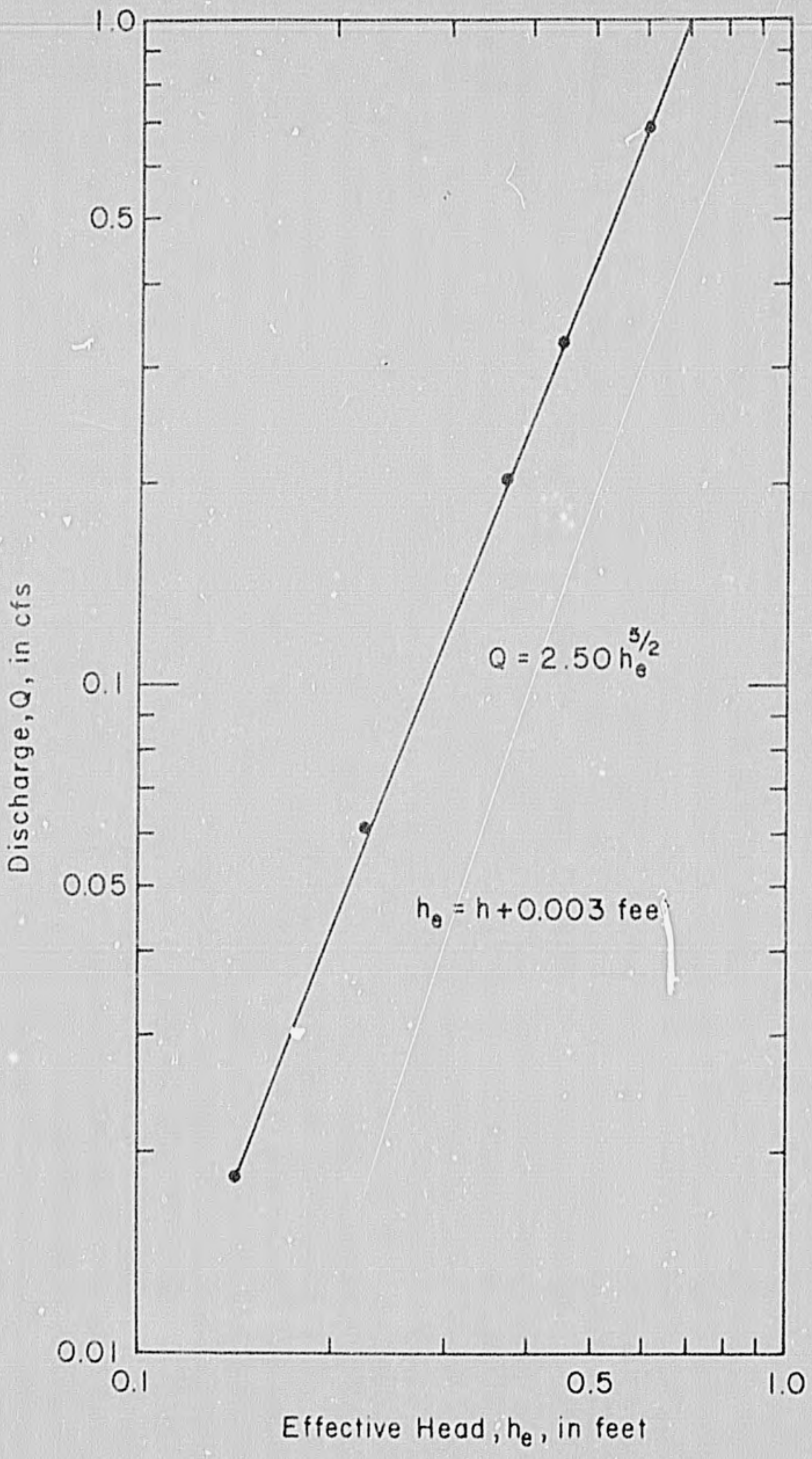


Figure 19. Discharge rating for 91° V-notch weir.

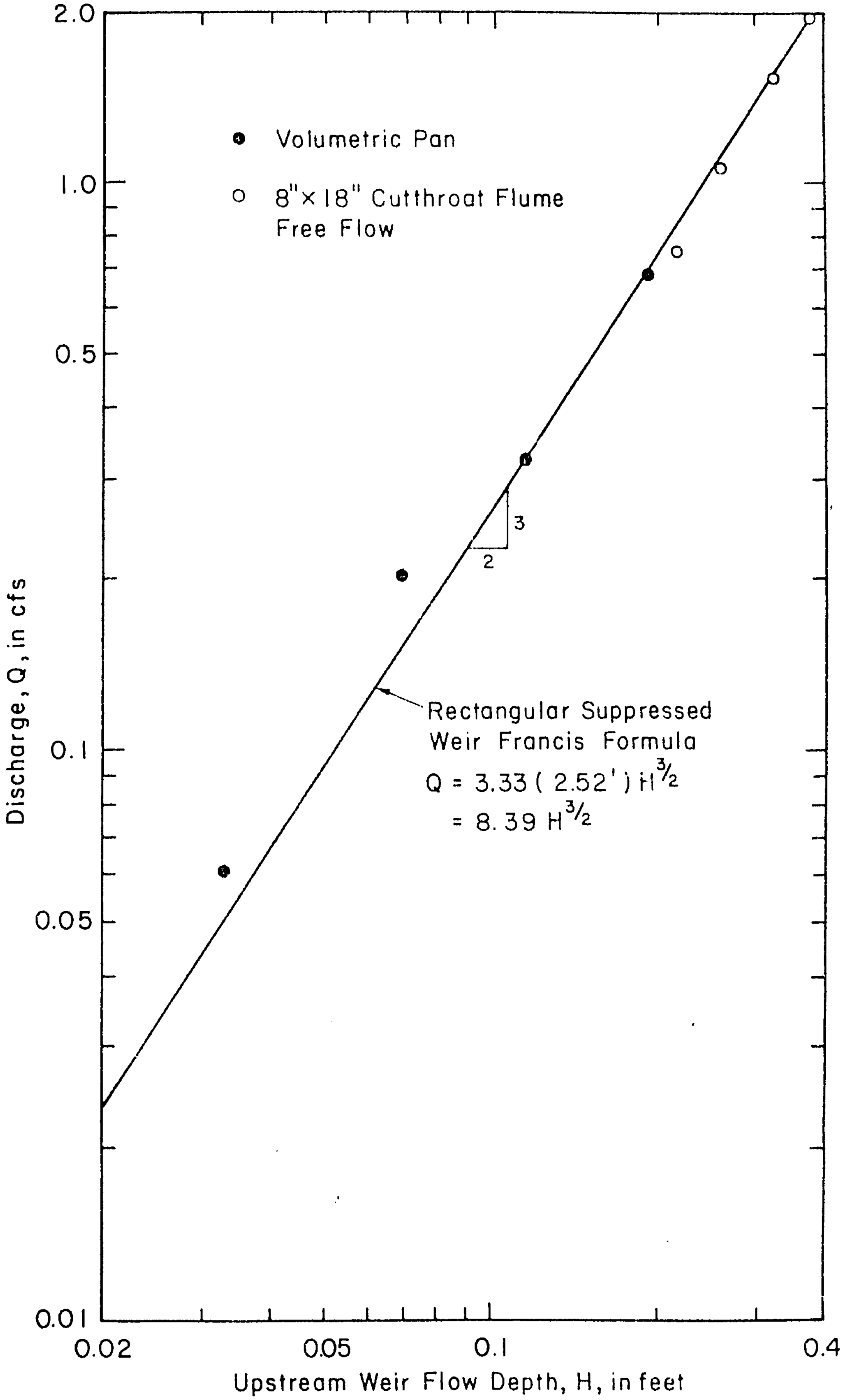


Figure 20. Comparison of volumetric pan and 8" × 18" Cutthroat flume data with the Francis formula for the rectangular suppressed weir.

discharge rating reported in Section 5 of this report could be used for higher discharges. This data is also plotted in Figure 20. In contrast with the discharge rating for the 91° V-notch weir (Figure 19), the discharge data for the rectangular suppressed weir shows considerable more scatter. This scatter in data is not explained by the Francis formula alone. After observing the performance of the rectangular suppressed weir more closely in March and April of 1979, the writer is of the opinion that much of this scatter is the result of the nappe clinging to the downstream face of the weir plate at low heads. Then, as the discharge is increased, the nappe springs free from the weir crest and is aerated by a small diameter pipeline located just below the downstream edge of the weir crest. The V-notch weir has certain advantages over rectangular weirs, such as the discharge ratings being less affected by entrance conditions (Kindsvater, 1978), along with no difficulties in keeping the nappe aerated, as well as providing more accurate discharge measurements at low heads.

Section 5

ADDITIONAL CSU LABORATORY ANALYSIS

As stated earlier, the 12" x 36" Cutthroat flume had never been calibrated in the laboratory by the writer. Instead, the rating for this flume had been interpolated from the laboratory calibrations for the 8" x 36" and 16" x 36" Cutthroat flumes. Consequently, it was deemed desirable to construct a 12" x 36" Cutthroat flume and develop a laboratory calibration. At the same time, it was felt that the discharge rating for the 8" x 36" Cutthroat flume should be checked. The additional laboratory work performed in 1977 for the 8" x 18" Cutthroat flume was considered sufficient.

Experimental Procedure

The flume calibration tests were conducted in the Hydraulics Research Laboratory of the Engineering Research Center at Colorado State University. The tests were run in a flow channel two feet wide and 60 feet long. The channel had a recirculating pump and was equipped with a segmental orifice plate for flow measurement. However, the orifice was not considered to be accurate enough for flow measurement and therefore an 8" x 36" Cutthroat flume was installed in the channel for this purpose. It was found later that the orifice was accurate for flow rates above one cfs but not accurate enough for smaller flow rates. The channel was capable of carrying 9 cfs. The flow channel had a slope which helped prevent any interference between the primary flow measurement flume and the test flume. The steep slope was also advantageous in attaining rapid establishment of steady flow in the channel.

The Cutthroat flumes were set absolutely level in the channel. They were surveyed with a surveyor's level and a rod graduated to 1/100 of an inch. The zero points on the hook gages were also established using the same surveying equipment. Depths of water in the flumes were measured in stilling wells 4 inches in diameter. Hook gages graduated to 1/1000 of a foot were used to measure depths of water in the stilling wells. At least 15 minutes were allowed between every two readings of data to assure the establishment of steady flow in the channel, although it had been found that within less than 10 minutes steady flow was established in the hydraulic channel.

The entrance conditions of the flumes were an abrupt contraction of flow from the channel into the flume. The flow measuring flume was set six inches above the channel bed to assure free flow through it and hence accurate flow measurement. For the test flume, to obtain the desired level of submergence, a finger gate was installed at the downstream end of the channel. Accurate control of water level downstream of the test flume was possible using the finger gate.

During data collection careful observation was made to detect any fluctuations or surges in the flow, which proved to be non-existent. Every time one set of data were recorded, the test flume as well as the measuring flume and the orifice manometer readings were recorded to make sure any possible changes in flow rate were measured. This proved to be useful since at higher levels of submergence the flow rate did decrease slightly due to a drop in the sump water level.

For free flow analysis, nine flow rates were tested, covering practically all the range of possible flow rates through each flume. For submerged flow analysis, the downstream depth of water was gradually increased until a rise in the upstream depth reading was noticed. From that point on, the downstream depth was increased at small increments, and an entire range of submerged flow data were collected, covering up to 99% submergence.

In the case of the 8" x 18" flume, additional free flow data were collected using two special approach conditions. In the "hand approach" one hand was placed in the water, flush with the converging flume side where the piezometer tap was located. In the "board" approach, two boards of 3½ inches width were placed in water flush with the converging sides of the flume.

<u>Laboratory Results</u>

A basic assumption is that the weighing tank data collected by Bennett (1972) is correct. The writer went to great lengths in checking the calibration of the two weighing tanks to insure a high degree of accuracy. The calibration for one of the weighing tanks showed an accuracy of one-fourth of one percent, while the other weighing tank had an accuracy of one-half of one percent.

Some orifice meters were used in the more recent CSU laboratory studies as another check on the discharge measurements. These orifice meters had been rated on the hydraulic calibration stand located at the Engineering Research Center of the CSU foothills campus. The experimental techniques utilized in these additional studies did not provide any basis for refuting the accuracy of the weighing tank measurements. Consequently, the collection of additional laboratory data was undertaken primarily to extend the range of the discharge ratings for the 8" x 36" Cutthroat flume, along with providing data for the 12" x 36" Cutthroat flume (which had never been rated in the laboratory).

The results for the free flow calibration of the 12" x 36" Cutthroat flume is shown in Figure 21. The original free flow rating for this flume was reported as

$$Q = 4.50\ h_a^{1.84} \quad \ldots\ldots\ldots\ldots \quad (10)$$

The rating curve drawn in Figure 21 fits the equation

$$Q = 4.41\ h_a^{1.84} \quad \ldots\ldots\ldots\ldots \quad (11)$$

At the same time, a regression analysis of the data shown in Figure 21 gives the best fit rating as

$$Q = 4.29\ h_a^{1.79} \quad \ldots\ldots\ldots\ldots \quad (12)$$

The reason that Equation 11 is being recommended as the free flow rating for the 12" x 36" Cutthroat flume, rather than Equation 12, is that additional analysis of the other Cutthroat flumes having a length of 36 inches does not provide any basis

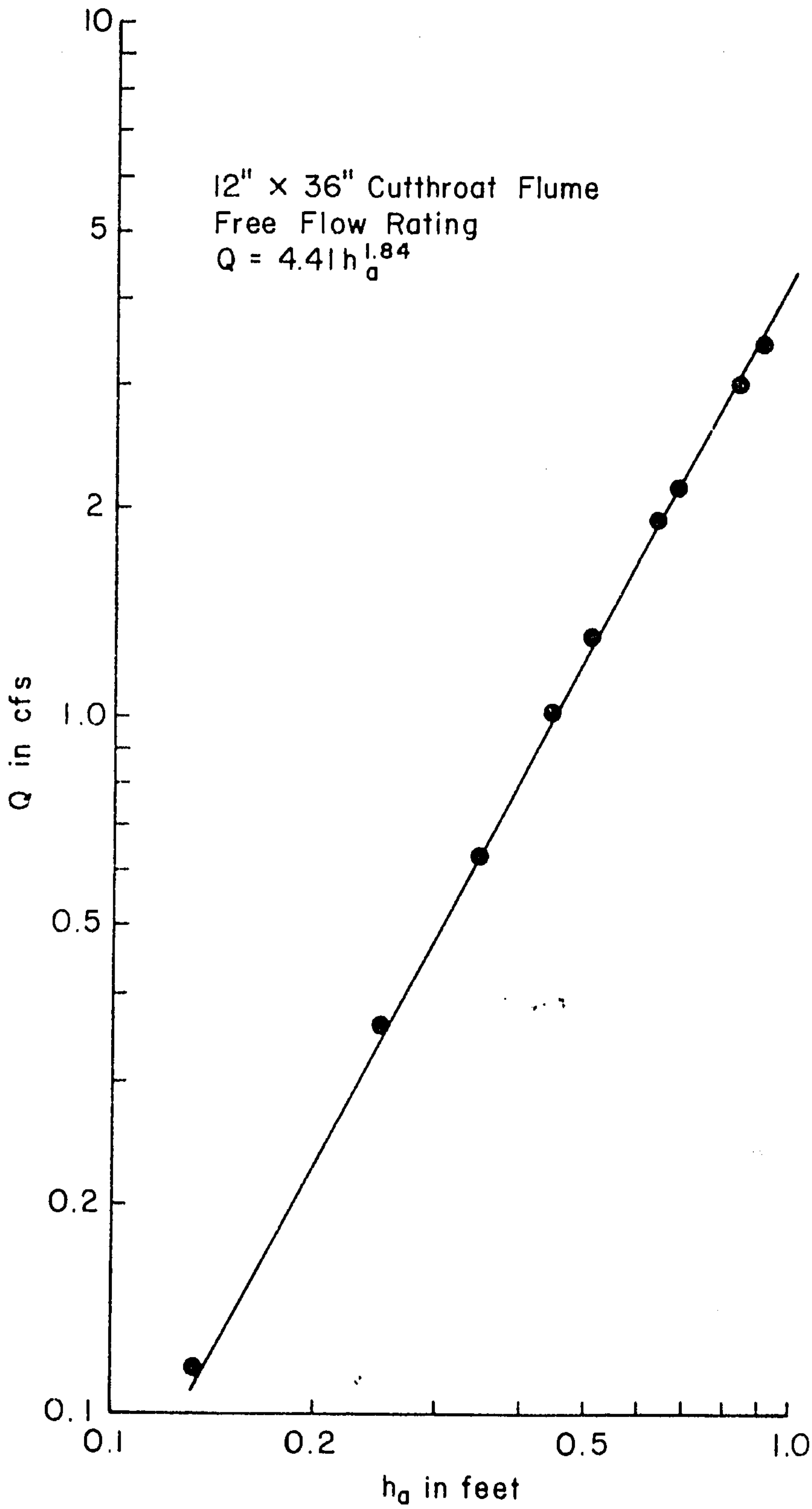


Figure 21. Free flow rating for 12" x 36" Cutthroat flume.

for changing the free flow exponent to any other value than 1.84. In other words, the free flow exponent, n_1, does not show any consistent variation with increasing throat width, W. This result is similar to the free flow analysis of the 18-inch length Cutthroat flumes shown in Figure 4.

The results of the additional laboratory data collection and analysis for the 8" x 36" Cutthroat flume is shown in Figure 22. The original free flow rating equation was

$$Q = 2.97\ h_a^{1.84} \quad \ldots\ldots\ldots\ldots\ldots (13)$$

The free flow rating drawn in Figure 22 is

$$Q = 2.93\ h_a^{1.84} \quad \ldots\ldots\ldots\ldots\ldots (14)$$

which is not much different from the original free flow rating.

The results of the additional data analysis for the 8" x 18" Cutthroat flume is shown in Figure 23. Based upon Equation 3, the free flow rating provided in November, 1977 was

$$Q = 4.226\, h_a^{2.00} \quad \ldots\ldots\ldots\ldots\ldots (15)$$

The free flow rating drawn in Figure 23 fits the equation

$$Q = 4.10\ h_a^{2.00} \quad \ldots\ldots\ldots\ldots\ldots (16)$$

The selection of the free flow coefficient as 4.10 is based upon additional analysis of other flume sizes that results in overall best fits to the free flow data.

The results of this additional laboratory analysis is summarized in Table 7. For the three sizes of Cutthroat flumes investigated in this study, the free flow ratings have all been

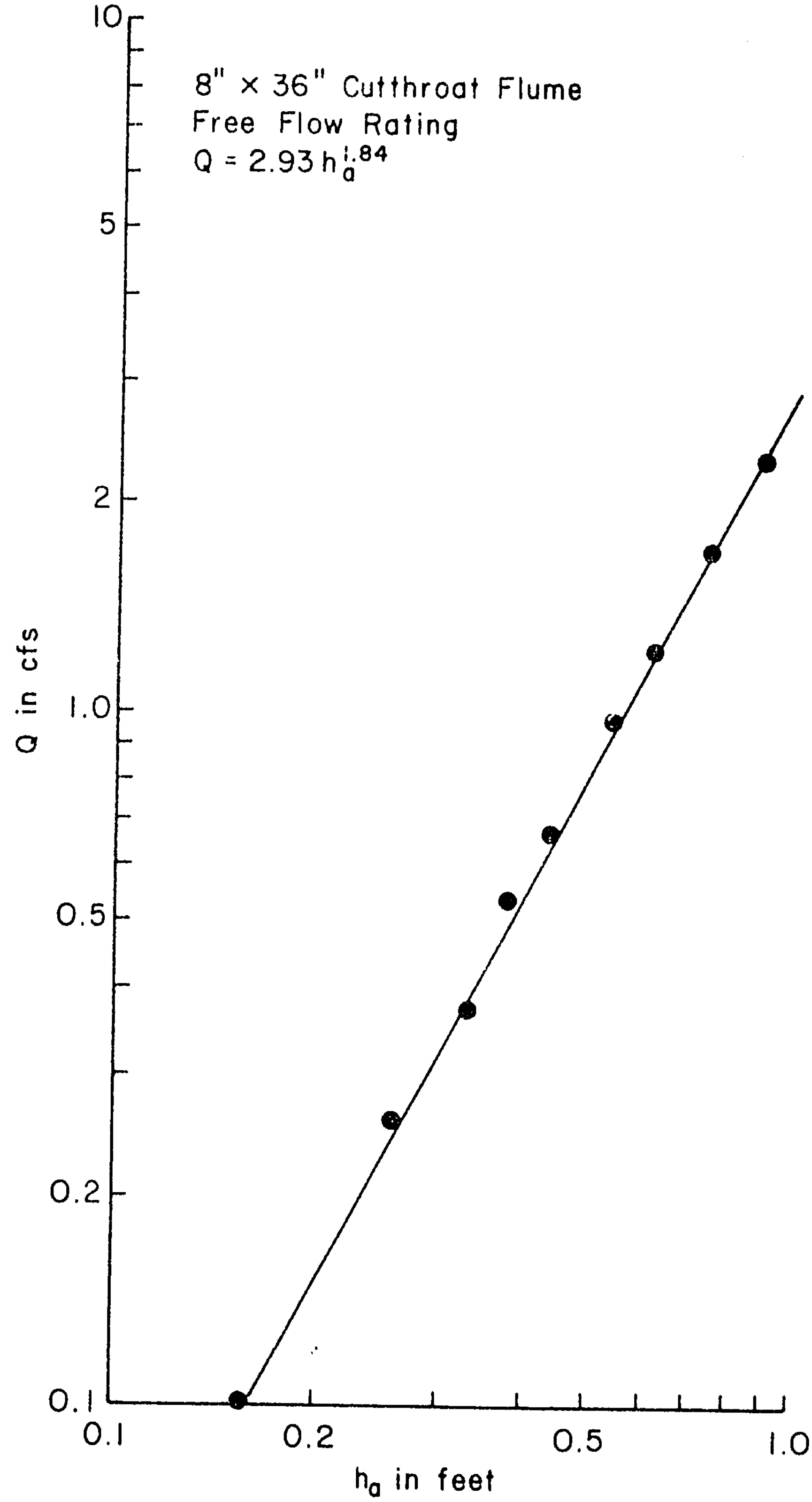


Figure 22. Recalibration of 8" x 36" Cutthroat flume using flow rate found from 8" x 18" Cutthroat flume formula $Q = 4.10\ h_a^{2.00}$.

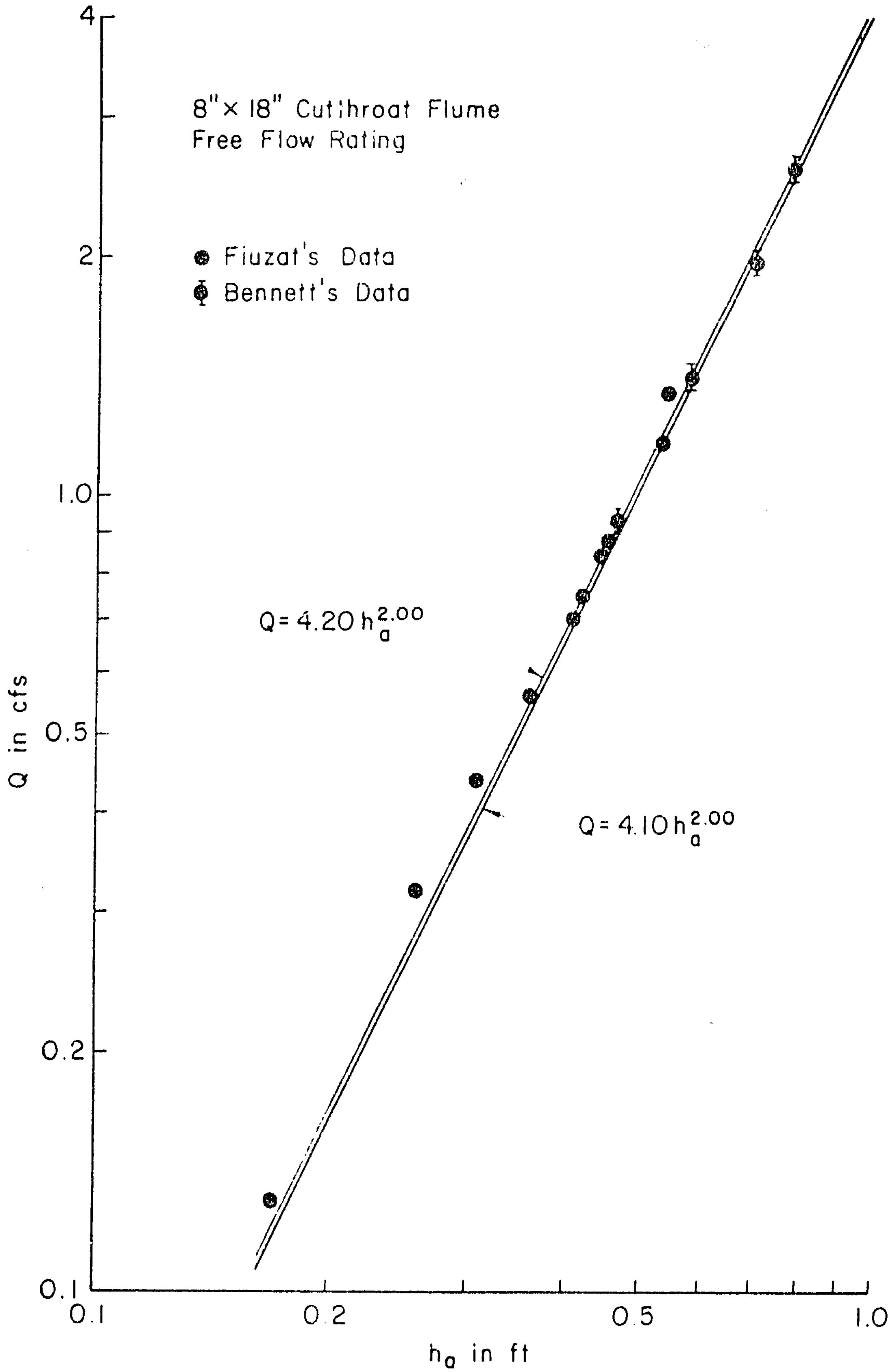


Figure 23. Free flow discharge rating for 8" x 18" Cutthroat flume.

Table 7. Summary of free flow analysis for selected Cutthroat flumes.

Cutthroat Flume Size	Free Flow Coefficient		
	Original	Revised	Percent difference
8" x 18"	4.226	4.10	-3.0
8" x 36"	2.97	2.93	-1.3
12" x 36"	4.50	4.41	-2.0

Note: The free flow exponents, n_1, were not changed.

revised so that the discharge will be reduced. The greatest difference in free flow ratings is for the 8" x 18" Cutthroat flume, where the discharge readings would be reduced by 3 percent. The reductions in discharge ratings for the 36-inch flume lengths are roughly 1-2 percent.

In the standard method of measuring h_a, flow enters the flume with an abrupt contraction from the sides and the bottom. In the "2-board" method of measuring h_a, two boards of 3½ inches wide were placed beside the 8" x 18" Cutthroat flume at the entrance in such a way that the boards were flush with the converging sides of the flume. At a constant flow rate, the 2-board reading of h_a is higher than the standard reading, the reason being that as the flow contracts into the flume, it forms a depression close to the h_a piezometer tap. Placing the board removes this effect, causing higher readings of h_a. As expected, this effect is very small at small flow rates (less than about 0.6 cfs) as shown by the plotted data points in Figure 24. The increase in h_a due to the two boards is from 3 percent at smaller flow rates to 10 percent at higher

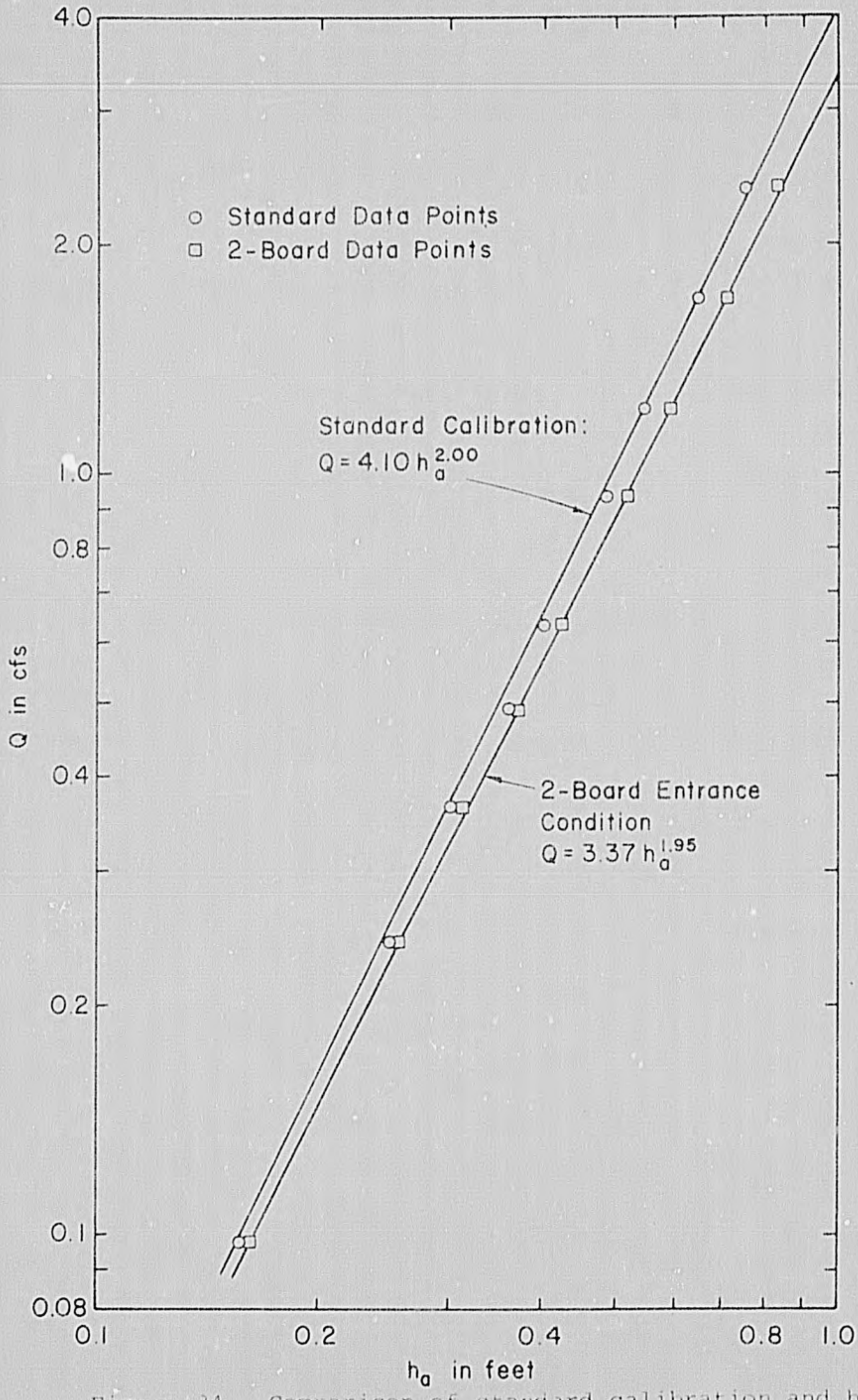


Figure 24. Comparison of standard calibration and board entrance condition for free flow discharge rating of 8" x 18" Cutthroat flume.

flow rates. One example will show the percent change in flow rate measurement. Referring to Figure 24, if the flow rate is 1.70 cfs, using the 2-board method, h_a will be measured as 0.703 feet (instead of the standard 0.644 feet). Using 0.703 feet for h_a in the standard calibration will give a flow rate equal to 2.05 cfs, or a 20 percent overestimation of the flow rate.

Piezometer Taps

During discussions with some staff members of Master Planning, WAPDA in March 1979, the writer came to the conclusion that the only remaining question regarding the Cutthroat flumes that were used in their 61 watercourse survey was the use of three piezometer taps at h_a and h_b rather than the single piezometer tap used in the original laboratory calibrations. The three Cutthroat flumes investigated by Owens and Paskett at the Irrigation Research Institute also employed three piezometer taps at both h_a and h_b.

As described above, the 8" x 18" Cutthroat flume is affected by entrance conditions at values of discharge commonly measured in the watercourses of Pakistan. This implies that non-hydrostatic pressure conditions might exist at the piezometer tap for h_a. Consequently, for the laboratory calibrations to be valid in the field, the same entrance conditions are required in the field as used in the laboratory. Also, since a single piezometer tap (located with its centerline one-half inch above the flume floor) was used in the laboratory calibrations, it would be necessary for the field flumes to also have only a single piezometer tap at the same location as employed in the laboratory.

An 8" x 18" Cutthroat flume was installed in the hydraulic test channel at the Irrigation Research Institute, which had previously been used by Owens and Paskett, as well as the writer. The purpose of these hydraulic tests was to quantitatively evaluate the effects of having three piezometer taps at both h_a and h_b as compared with a single piezometer tap at both h_a and h_b. The three piezometer taps were located 5/8-inch, 4 inches and 7 1/8-inches above the flume floor. Each of the six piezometer taps had a diameter of 1/4-inch.

The hydraulic tests were conducted first for free flow conditions. A constant discharge was set for the hydraulic channel. After taking point gauge readings of h_a and h_b with all piezometer taps open, the upper two piezometer taps at both h_a and h_b would be sealed, and again point gauge readings would be taken in the stilling wells for h_a and h_b. Four free flow discharges were used. Later, a similar procedure was followed for submerged flow conditions, where two discharges were used. For submerged flow, a constant discharge would be set and then the downstream depth was increased in small increments by adjusting the tailgate located at the downstream end of the hydraulic channel.

For free flow conditions, there is a significant impact upon the h_a flow depth measured in the stilling well by employing three piezometer taps as compared with a single piezometer tap as shown in Figure 25. The h_a stilling well depth is greater with three taps as compared with a single tap. The

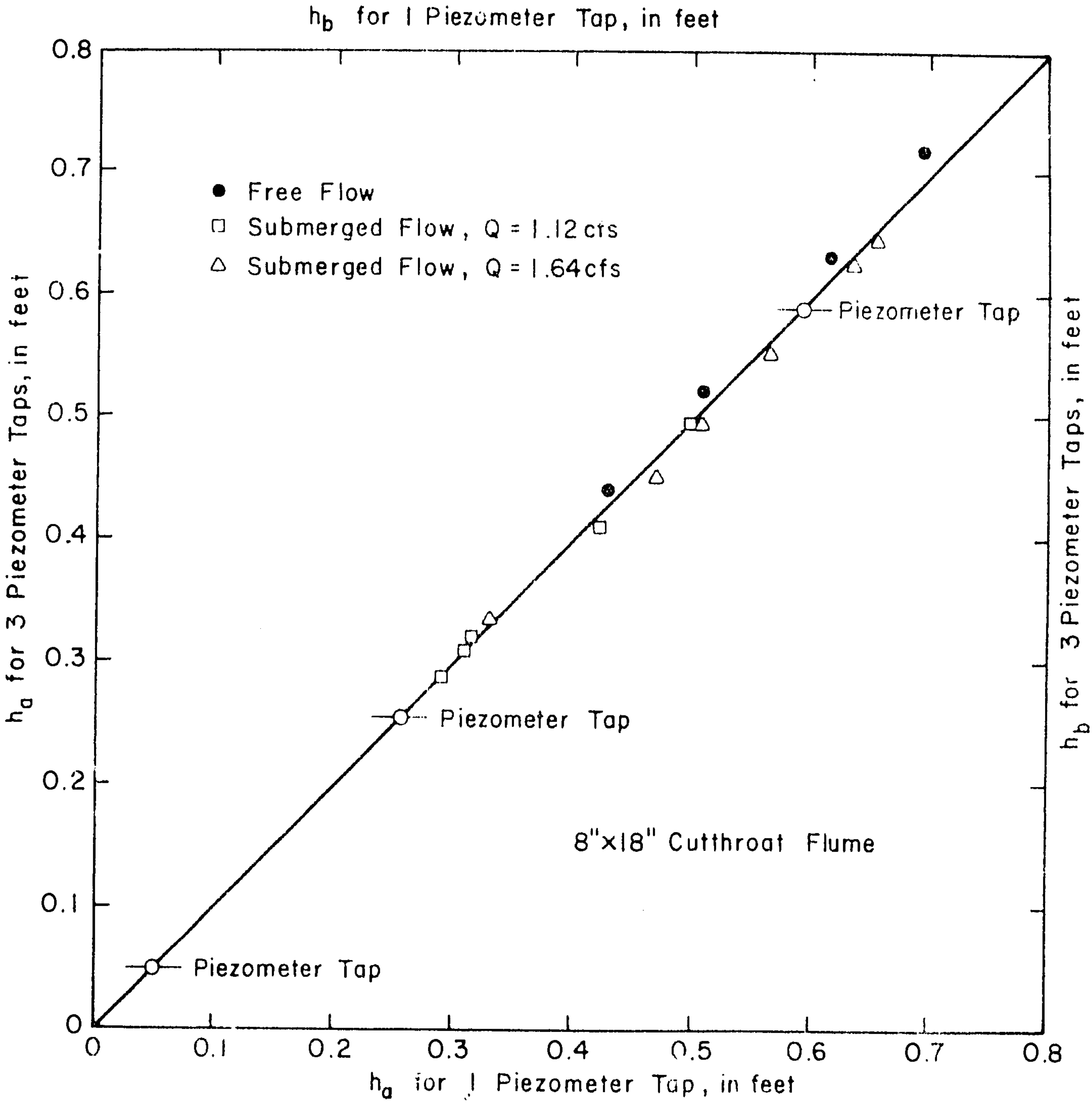


Figure 25. Comparison of h_a and h_b stilling well flow depths for 8" x 18" Cutthroat flume using three piezometer taps or a single tap.

h_b stilling well depth is not affected as much as h_a by the change in number of piezometer taps (Figure 25). Of particular interest is that h_b is affected in the opposite direction of h_a. Whereas the h_a readings were too high when three piezometer taps were employed, the h_b readings were too low. The four free flow discharge measurements using three piezometer taps are plotted in Figure 26, where a comparison with the original and free flow ratings for the 8" x 18" Cutthroat flume shows that these four measurements fall between the two ratings, but have a slope more nearly corresponding with the final free flow rating.

Unfortunately, with three piezometer taps, there are three separate free flow ratings corresponding with each combination of piezometer taps. The same situation would exist for the submerged flow ratings. Consequently, it becomes more desirable to correct the h_a and h_b readings so that they correspond with the single piezometer tap measurements, and then employ the correct ratings. Consequently, the writer recommended the following corrections to the h_a and h_b readings for the 8" x 18" Cutthroat flume having three piezometer taps:

For 0.25 ft $< h_a <$ 0.59 ft, reduce h_a by 0.01 ft. . (17)

For $h_a \geq$ 0.59 ft, reduce h_a by 0.02 ft. . . . . . . (18)

For $h_b \leq$ 0.40 ft, increase h_b by 0.01 ft. . . . . . (19)

The impact of adjusting h_a according to Equations 17 and 18 are illustrated in Table 8 which includes a comparison of the original free flow rating using the three piezometer h_a

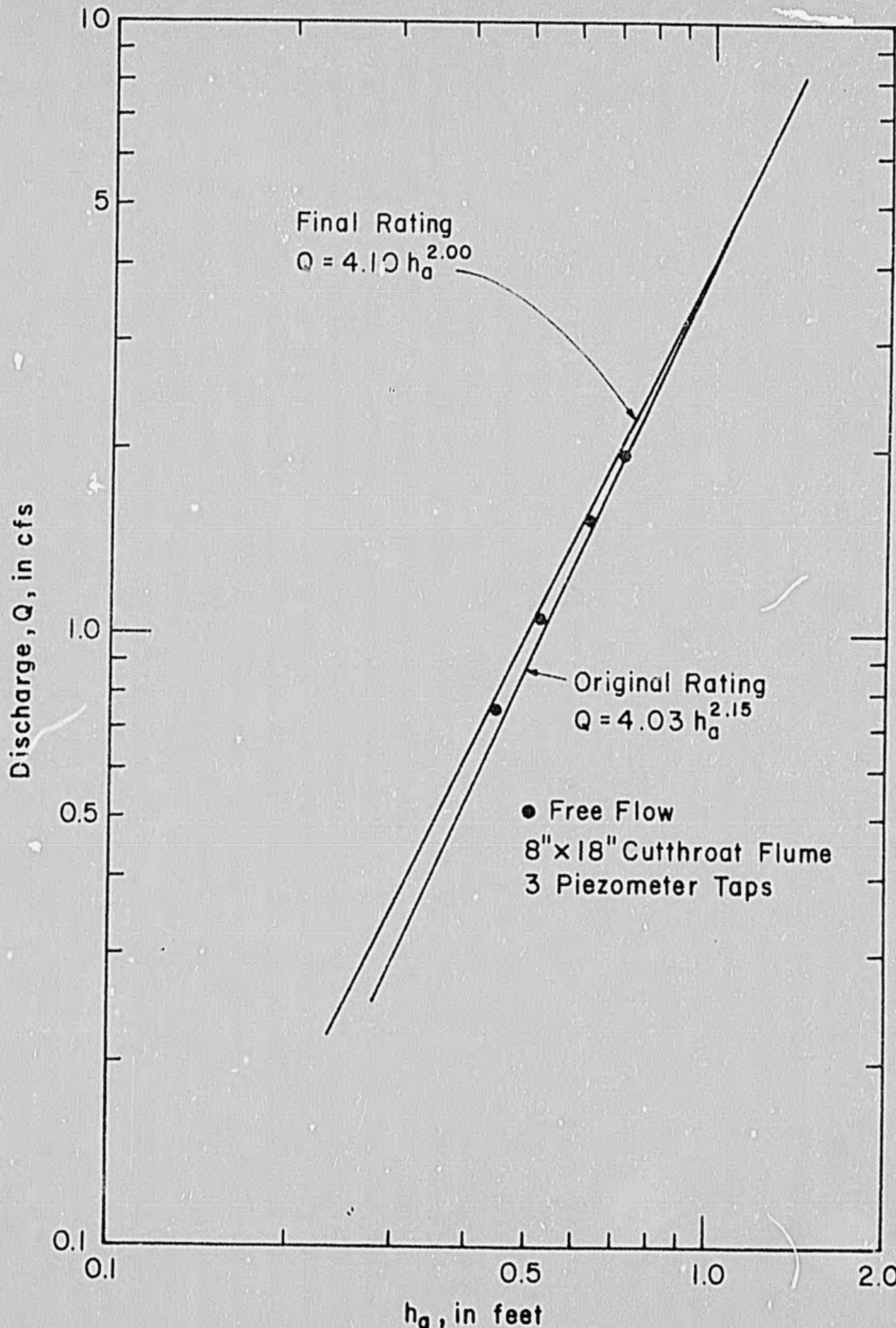


Figure 26. Comparison of original and final free flow ratings for 8" x 18" Cutthroat flume with h_a using three piezometer taps.

Table 8. Comparison of original free flow rating for 8" x 18" Cutthroat flume having three piezometer taps with final free flow rating adjusted to correspond with a single piezometer tap.

h_a ft.	Q_{fi} cfs	Adjusted h_a = (h_a) ft	Q_{ff} = cfs	Q_{ff}/Q_{fi}
0.40	0.562	0.39	0.624	1.110
0.45	0.724	0.44	0.794	1.097
0.50	0.908	0.49	0.984	1.084
0.55	1.115	0.54	1.196	1.072
0.60	1.344	0.58	1.379	1.026
0.65	1.596	0.63	1.627	1.020
0.70	1.872	0.68	1.896	1.013
0.75	2.171	0.73	2.185	1.006
0.80	2.494	0.78	2.494	1.000
0.85	2.842	0.83	2.824	0.994
0.90	3.213	0.88	3.175	0.988

For $0.25 < h_a < 0.59'$; $(h_a)_{adj} = h_a - 0.01$ ft.

For $h_a \geq 0.59'$; $(h_a)_{adj} = h_a - 0.02$ ft.

Original free flow rating; $Q_{fi} = 4.03 h_a^{2.15}$

Final adjusted free flow rating; $Q_{ff} = 4.10 (h_a)_{adj}^{2.00}$

field readings (Q_{fi}) with the final recommended free flow rating (Q_{ff}) wherein h_a is adjusted. The final column in Table 8 shows the ratio Q_{ff}/Q_{fi}, which is the factor that the present free flow measurements from the 61 watercourse survey should be multiplied to provide the correct free flow discharge. For all practical purposes, taking into account the difficulties in collecting accurate field measurements, the free flow discharge computations should only be corrected for values of h_a between 0.25 and 0.59 feet.

For submerged flow, the correction factors listed in Table 9 are recommended for the 8" x 18" Cutthroat flume. The adjusted submergence, S_{adj}, is computed using Equations 17, 18 and 19 to adjust h_a and h_b

$$S_{adj} = (h_b)_{adj}/(h_a)_{adj} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (20)$$

The coefficient, Q_s/Q_{ff}, is obtained from Table 9, where it can also be seen that, for all practical purposes, free flow exists when the adjusted submergence, S_{adj}, is less than 70 percent. The adjusted value of h_a is used in Equation 16 to calculate Q_{ff}, which is the final free flow rating for the 8" x 18" Cutthroat flume,

$$Q_{ff} = 4.10(h_a)^{2.00}_{adj} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (21)$$

For $S_{adj} \geq 0.70$, the submerged flow, Q_s, is computed from,

$$Q_s = Q_{ff}(Q_s/Q_{ff}) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (22)$$

Where Q_{ff} is calculated using Equation 21 and the ratio, Q_s/Q_{ff}, is obtained from Table 9.

Table 9. Submerged flow coefficients for 8" x 18" Cutthroat flume having three piezometer taps at both h_a and h_b.

S_{adj}	Qs/Qff
0.70	0.990
0.72	0.987
0.74	0.982
0.76	0.975
0.78	0.965
0.80	0.955
0.82	0.943
0.84	0.930
0.86	0.910
0.88	0.880
0.90	0.820

Free flow; $Q_{ff} = 4.10(h_a)_{adj}^{2.00}$

Submergence; $S_{adj} = (h_b)_{adj}/(h_a)_{adj}$

Submerged flow; $Q_s = Q_{ff}(Q_s/Q_{ff})$

For 0.25 ft $< h_a <$ 0.59 ft; $(h_a)_{adj} = h_a - 0.01$ ft

For $h_a \geq 0.59$ ft; $(h_a)_{adj} = h_a - 0.02$ ft

For $h_b \geq 0.40$ ft; $(h_b)_{adj} = h_b + 0.01$ ft

Section 6

RESPONSE TO OTHER CRITICISMS

Discharge Measurement Structures

After the first publication on Cutthroat flumes appeared in 1967 (Skogerboe, et al., 1967), the writer has had numerous conversations with other hydraulic researchers, as well as users of this flume, regarding questions on method of analysis, generalized discharge relations, field experiences, etc. Frequently, in recent years, the writer has been confronted by the discussion of Bos (1976) on Cutthroat flumes. This discussion has also been cited in Pakistan. Consequently, there is a need to respond to the questions raised in this publication, "Discharge Measurement Structures." The discussion by Bos (1976) is quoted below.

> The geometry of the throatless flume with broken plane transition was first developed in irrigation practice in the Punjab and as such is described by Harvey (1912). Later, Blau (1960) reports on two geometries of this flume type. Both sources relate discharge and modular limit to heads upstream and downstream of the flume, h_1 and h_2 respectively. Available data are not sufficient to warrant inclusion in this manual.
>
> Since 1967 Skogerboe et al. have published a number of papers on the same flume, referring to it as the "Cutthroat flume" In the Cutthroat flume, however, the flume discharge and modular limit are related to the piezometric heads at two points, in the converging section (h_a) and in the downstream expansion (h_b) as with the Parshall flume. Cutthroat flumes have been tested with a flat bottom only. A dimension sketch of this structure is shown in Figure [27].
>
> Because of gaps in the research performed on Cutthroat flumes, reliable head-discharge data are only available for one of the tested geometries (b = 0.305 m, overall length is 2.743 m). Because

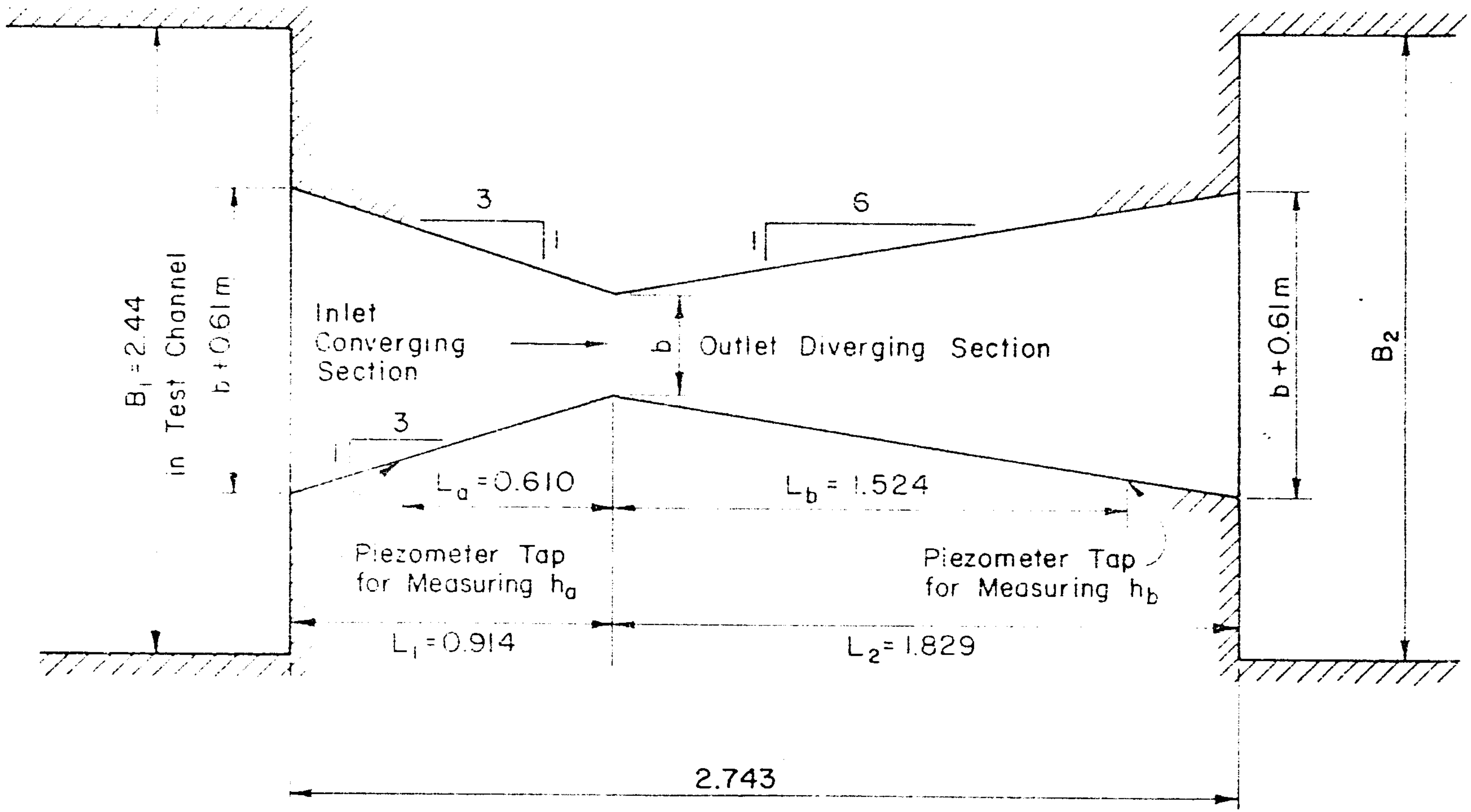


Figure 27. Cutthroat flume dimensions, after Skogerboe, et al., 1967 (Bos, 1978).

of the non-availability of discharge data as a function of h_1 and h_2 (or H_1 and H_2) the required loss of head over the flume to maintain modularity is difficult to determine.

In the original Cutthroat flume design, various discharge capacities were obtained by simply changing the throat width b. Flumes with a throat width of 1, 2, 3, 4, 5, and 6 feet (1 ft = 0.3048 m) were tested for heads h_a ranging from 0.06 to 0.76 m. All flumes were placed in a rectangular channel 2.44 m wide. The upstream wingwall had an abrupt transition to this channel as shown in Figure [27].

Obviously, the flow pattern at the upstream piezometer tap is influenced by the ratio b/B_1. Eggleston (1967) reports on this influence for a 0.3048 m wide flume. A variation of discharge at constant h_a up to 2 percent was found. We expect, however, that this variation will increase with increasing width b and upstream head. Owing to the changing entrance conditions it even is possible that the piezometer tap for measuring h_a will be in a zone of flow separation. As already mentioned in [a previous section], the ratios b/B_2 and b/L_2 are also expected to influence the head-discharge relationship.

Bennett (1972) calibrated a number of Cutthroat flumes having other overall lengths than 2.743 m. He reported large-scale effects between geometrically identical Cutthroat flumes, each of them having sufficiently large dimensions (b ranged from 0.05 to 0.305 m). Those scale effects were also mentioned by Eggleston (1967), Skogerboe and Hyatt (1967), and Skogerboe, Bennett, and Walker (1972).

In all cases, however, the reported large-scale effects are attributed to the improper procedure of comparing measurements with extrapolated relations.

As a consequence of the foregoing, no head-discharge relations of Cutthroat flumes are given here. Because of their complex hydraulic behavior, the use of Cutthroat flumes is not recommended by the present writers.

These comments by Bos (1976) are primarily concerned with two basic issues. The first issue is the lack of exact head loss data for Cutthroat flumes, while the second issue is the complex hydraulic behavior of Cutthroat flumes.

When Bos (1976) states ..."reliable head-discharge data are only available for one of the tested geometries" and .... "the required loss of head over the flume to maintain modularity is difficult to determine".... he is referring to the desirability of having a structure as shown in Figure 27 in which the flow depths upstream and downstream from the flume would be known. This would require extending the length of the flume both upstream and downstream in order to maintain a rigid boundary that would produce unique head-discharge relations for each flume geometry. Actually, the head upstream from a Cutthroat flume can be calculated quite accurately based on the head-discharge relation at h_a since there is extensive hydraulic research that shows there is only a very small energy loss in a flume inlet section. Most of the energy loss occurs in the diverging outlet section of a flume. The energy loss in a Cutthroat flume is closely approximated by the difference in specific energies between h_a and h_b; however, there can be additional energy loss after the flow leaves the Cutthroat flume and this energy loss will be a function of the geometry of the downstream channel. This same situation would result for any flume even if the flow depth were measured downstream from the flume, unless the channel downstream from the flume has a rigid boundary geometry corresponding to the geometry utilized in the original calibration of the flume. Consequently, although the writer can appreciate having head-discharge relations upstream and downstream of each Cutthroat flume, as well as those already provided at h_a and

h_b, this certainly does not alter the validity of the head-discharge relations at h_a and h_b and the subsequent use of the Cutthroat flume as an accurate flow measuring device.

The second issue of complex hydraulic behavior is only true in the sense that it does not conform to simple theory. In most flumes, there exists a throat section having parallel walls, wherein the flow streamlines become parallel before leaving the throat section. Having parallel streamlines in the throat section allows many of the simplifying assumptions used in developing theoretical discharge equations for open channel constructions to be valid. In a Cutthroat flume, the streamlines passing through the throat section are curvilinear. The real advantage of curvilinear streamlines is that the flow passing through the outlet section will diverge more rapidly without flow separation occurring as compared with more traditional flow measuring flumes. The most serious disadvantage of having curvilinear flow is the difficulty in developing generalized discharge relations that would predict the discharge rating for any set of Cutthroat flume dimensions. To overcome this difficulty, the writer developed an experimental design utilizing flume lengths from 1.5-9 feet and throat widths from 1-inch to 6-feet. By developing discharge relations for many sizes of Cutthroat flumes, it was possible to develop generalized discharge relations (Skogerboe, Bennett and Walker, 1972) that would allow the interpolation of discharge ratings for intermediate sizes. In other words, the writer did not extrapolate these discharge relations to predict the rating for flume sizes larger or smaller than those calibrated in the laboratory.

Another aspect of the complex hydraulic behavior of Cutthroat flumes that has been bothersome to other researchers is that the free flow exponent, n_1, exceeds the theoretical value of 3/2 significantly. For example, the 9-foot length Cutthroat flumes have a free flow exponent of 1.56, for 3-foot lengths $n_1 = 1.84$, and for 18-inch lengths $n_1 = 2.00$. A.J.M. Harrison (1971) did considerable analysis of free flow in Cutthroat flumes to arrive at a generalized free flow discharge rating. His analysis is quoted below.

> All the 12 flumes tested had the same contraction and expansion angles and, I suppose, the same roughness. The geometry can therefore be defined simply by the overall length, L, and throat width, W. Assuming that the total head, H, is constant throughout the approach section (i.e. ignoring frictional effects) it can be shown by dimensional analysis that the dimensionless discharge coefficient, C, is given by:
>
> $$C = \frac{Q}{\sqrt{g} W H^{3/2}} = f\left(\frac{H}{W}, \frac{L}{W}\right)$$
>
> This was the basis of our first plot. It appeared to be generally true except for small values of W. The data suggested that an approximately constant correction of 0.02 ft had to be made to the value of the width, in the same way that our Crump weir data require a head correction to be made, these weir data fitting the equation
>
> $$\frac{Q}{\sqrt{g}\, W(H-0.001)^{3/2}} = 0.630$$
>
> with the head correction in ft.
>
> We then proceeded to try out various corrected coefficient formulae until we found one in which all data plotted on a single curve when C was plotted against H/W.

The final result is shown on the attached figure [Figure 28] in which the scatter of all the data appears to be no worse than the scatter of the data for individual flumes and the trend of each set of flume data follows the trend of the whole of the data. We originally plotted (C-0.545) against H/W because $\frac{2}{3}\sqrt{\frac{2}{3}} = 0.545$ and I expected the coefficient to be the same as that of a frictionless critical-depth flume at small values of H/W and L/H. In fact we found the best log-log relationship fitting the data to be given by

$$C - 0.505 = 0.12\ (H/W)^{0.755}$$

where

$$C = \frac{Q}{\sqrt{g}(W-0.02)(1+0.25W/L)\left\{\left[H-0.02L\right]\left[1+0.0002(L/H)^{3}\right]\right\}^{3/2}}$$

I am fairly sure that all Cutthroat flumes within the limitations W>1 inch, L/H<8, H/W<15, and L/W>2 should fall on this calibration line, but I should like to see data for a large flume tested over a wide range of H/W showing agreement before I should be fully convinced.

I must confess to being somewhat disappointed by the complicated nature and relatively large values of the corrections to W and H in the coefficient formula. However the structures we have investigated here - which we have found to have relatively simple discharge formulae - have had special characteristics e.g. geometrical similarity of flow at different heads (Crump weir, and flat-vee weir), or parallel flow (broad-crested weir and critical-depth flume). Despite its geometrical simplicity, the Cutthroat flume does not possess such characteristics.

I had thought that analysis of the data on the basis of total head would lead to a theoretically-based, simple formula which would fit all the experimental data. In the event so many empirical corrections have had to be added to the basic formula that one can have little confidence in its use outside the tested range. In that case one might as well produce an entirely empirical equation, as you did in your earlier paper, by correlating the measured head and discharge with the flume geometry.

Bos (1976) has also stated, "Owing to the changing entrance conditions it even is possible that the piezometer tap

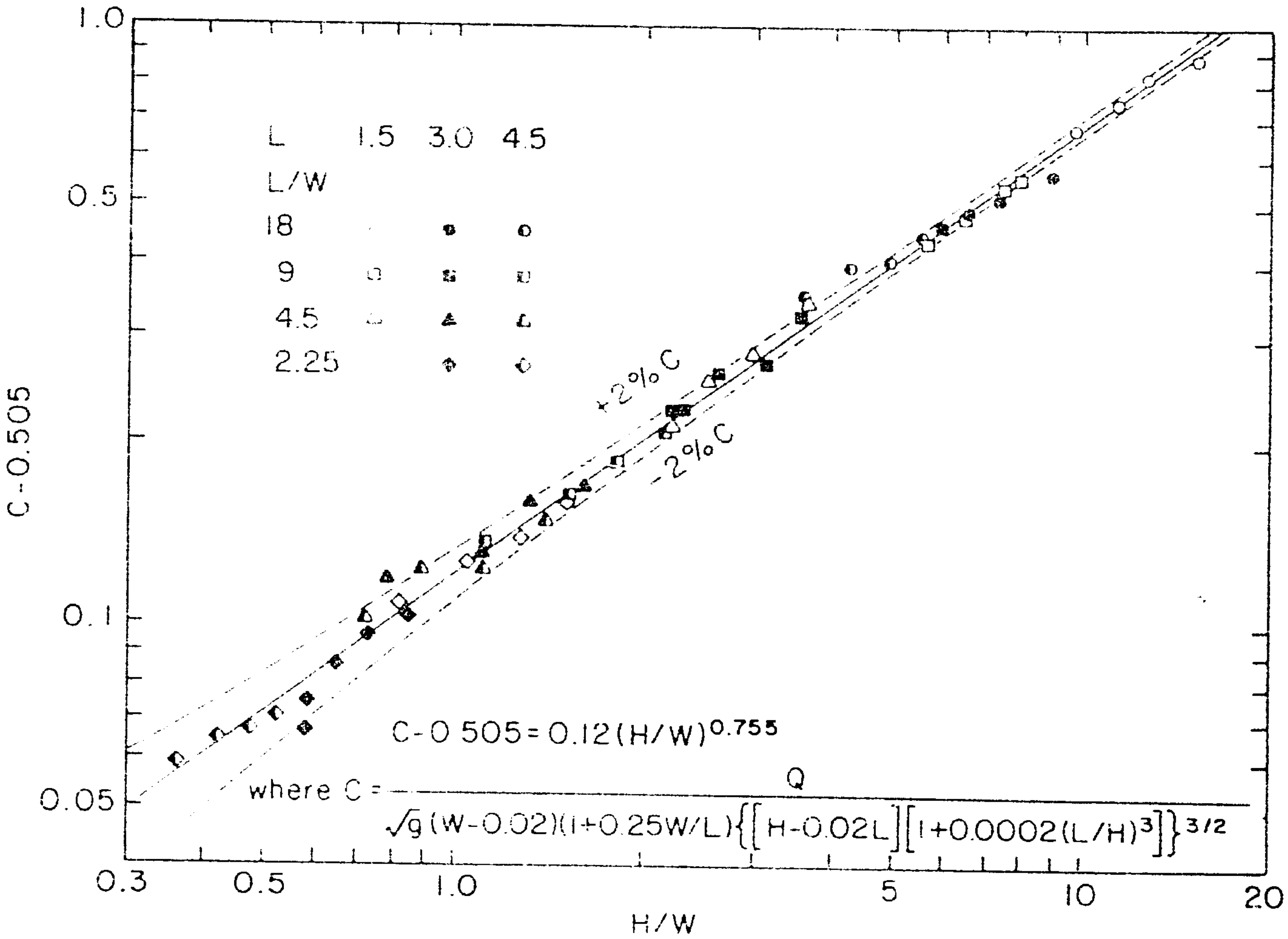


Figure 28. Generalized free flow discharge rating for Cutthroat flumes (Harrison, 1971).

for measuring h_a will be in a zone of flow separation." This is certainly true for the 18-inch length Cutthroat flumes, where as this is not the case for 3-foot lengths and longer. This does not preclude the development of a unique head-discharge (h_a - Q) relation for the 18-inch Cutthroat flumes. What it does mean is that the 18-inch length flumes are influenced by entrance conditions, so that the use of those flumes in the field has to correspond with the geometric setup used in the laboratory for developing the discharge ratings. Thus, for 18-inch flume lengths, piezometer taps located one-half inch above the flume floor (rather than multiple piezometer taps along the wall) and connected to stilling wells for reading h_a and h_b must be used rather than staff gages if accurate discharge measurements are to be obtained. In addition, the no (kaccha) entrance condition as shown in Figure 27 should be used.

Mogha Discharge Ratings

The writer has frequently been confronted while in Pakistan with the statement .... "there is something wrong with the Cutthroat flume because the discharge does not correspond with the authorized discharge for the mogha." This statement fits the frequent situation where a Cutthroat flume is installed in the watercourse at a short distance downstream from the mogha inlet to the watercourse. There are many reasons for this discrepancy, which will be discussed below. In fact, the probability of these two discharges being nearly equal (say within [illegible]) is very low.

Each mogha module was originally designed to provide a particular discharge based upon the cultural command area served by the mogha and watercourse. The geometry and elevation of the mogha module was constructed so as to provide this particular discharge corresponding to the normal water surface elevation in the distributary. First of all, there are many inherent reasons why the water surface elevation rarely corresponds with the water surface elevation used for designing the mogha. The discharge in the distributary, itself, is not constant throughout the year. Even if the flow rate in the distributary were held constant, the water surface elevation at the mogha would vary throughout the year as a result of aquatic and vegetative growth in the distributary. Sediment deposition in the distributary will affect water surface operating levels with time.

Another major reason why the measured discharge from a mogha module does not correspond with the authorized discharge for the watercourse is because the discharge rating for the mogha does not remain constant with time. In time, entrance conditions near the mogha change, the mortar covering the brick walls may chip away, and bricks may become dislodged. These factors could have a major effect on the discharge rating for the mogha module.

Section 7

CONCLUSIONS

1. Unfortunately, the failure to calibrate the primary flow measuring device (rectangular suppressed weir) used in the experiments by Paskett and Owens means that the data cannot be used until an accurate calibration is undertaken. The volumetric tank measurements reported herein provide sufficient data to show that the standard Francis formula is not an accurate calibration of the particular rectangular suppressed weir located at the Irrigation Research Institute (IRI) in Lahore, Pakistan. In fact, IRI has found that the Rehbock formula more accurately describes the correct rating for this weir. A primary flow measuring device should be rated to an accuracy within 1 percent. This will require a more elaborate volumetric tank setup in order to obtain readings for discharges as high as 2.5 or 3.0 cfs. In the meantime, the 91° V-notch weir now installed downstream from the rectangular suppressed weir could be utilized as a check on the discharge rating.

2. The data collected by Owens and Paskett does not warrant changing the Cutthroat flume calibrations reported by CSU.

3. The general discharge equation that should be used for Cutthroat flumes having a length of 18 inches is:

$$Q = 6.40\ W^{1.025} h_a^{\ 2.00}$$

where W is the throat width in feet and h_a is the flow depth in feet measured in the flume inlet (h_a should not exceed 0.6 feet).

4. Cutthroat flumes having a length of 18 inches are affected by entrance conditions, so they should only be used for small discharges. The earlier CSU manual stated that h_a should not exceed 0.6 feet for flume lengths of 18 inches. The writer has continually advocated the use of 36-inch flume lengths (or longer) in Pakistan. In addition, these ratings were developed using piezometer taps at h_a and h_b, which were connected to stilling wells, in order to obtain accurate discharge measurements.

5. The additional laboratory analyses conducted at CSU during 1977 and 1978 shows that the free flow discharge readings could be decreased slightly for the 8" x 18", 8" x 36", and 12" x 36" flumes. The recalibration work performed in the laboratory for these flumes, along with refinement of the data analyses, would indicate that the free flow ratings for the 8" x 18" Cutthroat flume would be reduced 3 percent, the free flow rating for the 8" x 36" Cutthroat flume would be reduced 1.3 percent, and the free flow rating for the 12" x 36" Cutthroat flume would be reduced 2 percent.

6. The recalibration and refinement of the laboratory data for the 8" x 18", 8" x 36", and 12" x 36" Cutthroat flumes indicates a change in discharge ratings that are <u>not</u> considered significant. Although the writer would recommend the use of these revised ratings, it is recommended that the

Master Planning Division of WAPDA, for the purposes of the watercourse survey, does not need to modify the previous reported ratings for the 36-inch length flumes. These small reductions in free flow ratings are insignificant compared with all of the other small errors that are inherent in field data collection programs.

7. The laboratory studies at IRI by Owens and Paksett, as well as the CSU studies, show that the 8" x 18" Cutthroat flume is affected by entrance conditions, particularly at values of discharge commonly encountered in the watercourses of Pakistan. Consequently, the use of three piezometer taps at both h_a and h_b, instead of the single piezometer tap located one-half inch above the floor as used in the CSU laboratory calibrations, has a significant impact upon the free flow and submerged flow ratings. The appropriate adjustments in h_a and h_b for the 8" x 18" Cutthroat flume are given in Equations 17, 18 and 19. The adjusted free flow rating is given by Equation 21, whereas the adjusted submerged flow rating is obtained from Table 9 and Equation 22.

8. The publication, "Discharge Measurement Structures," does not recommend the use of Cutthroat flumes because of the complex hydraulic behavior and the lack of head-discharge relations, which would provide exact information regarding the head loss across a Cutthroat flume. Although admittedly the Cutthroat flume does have complex hydraulic behavior, even hough the flume geometry is quite simple, the laboratory

ratings using weighing tanks combined with the readings of flow depth at h_a and h_b provide very accurate free flow and submerged flow ratings for those flume sizes calibrated in the laboratory. Also, the experimental design was such that the individual ratings for each flume size provided sufficient information that the discharge ratings for the intermediate flume sizes could be obtained by interpolation. The validity of this approach is evidenced by the free flow discharge rating reported herein for the 12" x 36" Cutthroat flume, which had not been previously calibrated in the laboratory, where the more recent laboratory data showed the predicted rating to be accurate within 2 percent.

9. A.J.M. Harrison has shown that although the hydraulic behavior in a Cutthroat flume is complex, it is possible to develop a single generalized discharge rating for all flume sizes, which is accurate within plus or minus 2 percent. This again shows the validity of the previous laboratory discharge ratings accomplished by using weighing tanks for obtaining accurate discharge measurements.

10. Individuals in Pakistan have frequently installed a Cutthroat flume immediately downstream from the mogha, only to find that the discharge reading from the Cutthroat flume did not correspond with the authorized discharge for the mogha. This is considered by some individuals as evidence that the discharge ratings for the Cutthroat flumes are not correct. However, the probability of the Cutthroat flume discharge reading being equal to the mogha authorized discharge is

extremely low because of two reasons: 1) the operating water surface levels in the distributary are not constant and change not only from day to day, but also over long periods of time such as years; 2) the rigid boundary geometry of the mogha does not remain constant with time, but is affected by the chipping away of mortar and the dislodging of bricks, as well as changing entrance and outlet conditions.

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