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CUTTHROAT FLUME DISCHARGE RELATIONS

Ray S. Bennett

Colorado State University

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CUSUS WASH

CUTTHROAT FLUME DISCHARGE RELATIONS

by Ray S. Bennett

COLORADO STATE UNIVERSITY
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The purpose of this study is to rate a group of cutthroat flumes which have the same geometric shape. Because of geometric similarity, the behavior of all flumes which are dimensionally similar to those tested should be capable of being predicted within a degree of accuracy suited for field use.

Twelve flumes were used in this study, all of which have the same shape. Three flume lengths were used, namely, 1.5 feet, 3 feet, and 4.5 feet, with four different throat widths for each length. In addition, the flume sizes were selected so as to permit correlation with the initial cutthroat flume studies (28), wherein a flume length of 9 feet, and throat widths varying from 1 foot to 6 feet, were studied.

From this study, it can be concluded that the cutthroat flume is an accurate open channel flow measuring device, which accuracy is satisfactory under both free flow and submerged flow conditions.

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College of Engineering
Colorado State University
Fort Collins, Colorado 80521

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ABSTRACT

CUTTHROAT FLUME DISCHARGE RELATIONS

The purpose of this study is to rate a group of cutthroat flumes which have the same geometric shape. Because of geometric similarity, the behavior of all flumes which are dimensionally similar to those tested should be capable of being predicted within a degree of accuracy suited for field use.

Twelve flumes were used in this study, all of which have the same shape. Three flume lengths were used, namely, 1.5 feet, 3 feet, and 4.5 feet, with four different throat widths for each length. In addition, the flume sizes were selected so as to permit correlation with the initial cutthroat flume studies (28), wherein a flume length of 9 feet, and throat widths varying from 1 foot to 6 feet, were studied.

The hydraulic data were collected under both free flow and submerged flow conditions. The method of submerged flow analysis reported by Skogerboe, Hyatt, and Eggleston (29) was utilized in developing the rating curves for the cutthroat flumes. This method of analysis was performed while the data were being collected.

An outstanding feature of the cutthroat flume is that generalized discharge rating curves can be easily developed.

This can be attributed to geometric simplicity of the structure. Consequently, it is possible for both free flow and submerged flow ratings to be developed for all intermediate flume sizes by merely interpolating on the appropriate graphs.

The flume is both simple and economical to construct. Now, based upon the results of this study, the range of sizes has been extended from a length of 9 feet to 18 inches, while throat widths varying from one or two inches to six feet can be used. However, scale effects resulting from curvilinear flow and non-hydrostatic pressure distribution become apparent in the small flume sizes. Therefore, based upon this study, flumes less than 3 feet in length are satisfactory for free flow operations, but are not recommended for submerged flow operation.

In order to obtain the best rating accuracy, it is recommended that flumes with throat width to length ratios between 0.1 and 0.4 be used. This range of throat width to flume length ratios corresponds to a range of constriction ratios (throat width divided by entrance, or exit, width, W/B) of 1/4 to 2/3.

Ray S. Bennett
Agricultural Engineering Department
Colorado State University
Fort Collins, Colorado 80521
March, 1972

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NOMENCLATURE

B = entrance and exit width for cutthroat flume, in feet

C = free flow coefficient

C_1 = submerged flow coefficient

h = upstream flow depth, in feet

h = downstream flow depth, in feet

Δh = difference in flow depth, $(h_a - h_b)$

K = free flow flume length coefficient

K_1 = submerged flow flume length coefficient

L = length of the cutthroat flume, in feet

L_a = length from the throat of the flume to the upstream measuring point, in feet

L_b = length from the throat of the flume to the downstream measuring point, in feet

L_1 = length of converging inlet section, in feet, $(L/3)$

L_2 = length of diverging outlet section, in feet, $(2L/3)$

M = constriction ratio for cutthroat flume (W/B)

n_1 = free flow exponent

n_2 = submerged flow exponent

Q = discharge through the flume, in cfs

S = submergence (h_b/h_a)

S_t = transition submergence

W = flume throat width, in feet

CHAPTER 1

INTRODUCTION

The problem of determining the flow rate in open channels is one which has been considered for many years. The rapidly increasing value of water is commanding new interest in the development of new open channel flow measuring devices. Water measuring devices are important for: (1) water conservation, (2) equitable distribution of water, (3) determining the amount of available water, (4) meeting legal requirements, and (5) successful management of the available supply.

There are many types of open channel flow measuring devices available. Of these, the flow measuring flumes are one of the most commonly used devices in irrigation systems. The favorable characteristics of the measuring flume are:

(1) They are self-cleaning due to the increase in velocities through the flume.

(2) There is sufficient accuracy over a large range of discharges.

(3) The structures are sturdy and relatively simple to construct.

(4) No moving parts are necessary, thereby reducing maintenance requirements.

(5) The energy head loss is low when compared to other open channel flow measuring structures, such as weirs.

(6) They are suitable for use as either stationary or portable structures, with the larger sizes and consequent increased weight being the only limitation on portability.

A water measuring flume consists of an open channel structure containing a constricted section. The constriction is formed by either raising the floor or by reducing the width between the sidewalls. The discharge characteristics are the same for both types; however, the raised floor is usually classified as a weir rather than a flume. Also, unless great care is taken in designing the raised floor section, some of the self cleaning properties may be lost.

Problem

Exhaustive laboratory studies have been conducted on certain types of water measuring flumes and these have gained great popularity in irrigation systems, especially in the western United States. These flumes, however, have the following restrictions:

(1) They require that a relatively large amount of head be lost in order to obtain reliable measurements.

(2) They are relatively difficult to construct.

(3) Some flumes use a sloping floor to assure that the flow will continue to accelerate throughout the length of the flume, which necessitates that the flume be installed at the time of construction if used in a lined channel.

(4) The flume sizes are not geometrically similar, which requires that each size be individually rated and discharge corrections are difficult to compute for construction errors in the dimensions of the flume.

Purpose

In view of the restrictions listed above, it would be desirable to develop a flow measuring flume which would eliminate these restrictions and still give satisfactory results. A device which shows great promise in accomplishing this is the cutthroat flume developed by Skogerboe, Hyatt, Anderson and Eggleston (31)* at Utah State University. While this device does not completely eliminate all of the restrictions mentioned, it does show much improvement in these areas.

The purpose of this study is to rate a group of cutthroat flumes which have the same geometric shape. Because

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*Numbers in parenthesis indicate references.

the flumes have the same geometric shape, the behavior of all flumes which are similar to those tested should be capable of being predicted within a degree of accuracy suitable for field use.

Scope

Twelve flumes were used in this study, all of which have the same geometric shape. Three flume lengths were used, namely 1.5 feet, 3 feet, and 4.5 feet with four different throat widths for each length. In addition, the flume sizes were selected so as to permit correlation with the initial cutthroat flume studies (28), wherein a flume length of 9 feet, and throat lengths varying from 1 foot to 6 feet, were studied. As a result, it would be possible to correlate both studies and expand the scope of this study greatly without requiring the recollection of the data used in the previous study.

The hydraulic data were collected under both free flow and submerged flow conditions. The method of submerged flow analysis reported by Skogerboe, Hyatt, and Eggleston (29) was utilized in developing the rating curves for the cutthroat flumes. This method of analysis was performed while the data was being collected. By doing this, it was possible to determine (1) if a mistake had been made in taking a reading, or (2) if sufficient data had been collected to define both the free flow and submerged flow ratings. These ratings were then compared with those obtained for the nine foot flumes (31) in order to develop generalized discharge characteristics for cutthroat flumes.

CHAPTER 2

HISTORICAL DEVELOPMENT OF FLOW MEASURING FLUMES

Introduction

Many devices have been developed for the measurement of water under field conditions. In early systems, most of these devices employed the principles of either the weir or the orifice. While these devices work very well under certain conditions, there were many systems in which they would not operate satisfactorily. As work continued on the development of field measuring devices, the following criteria were set down by Cone (5) for an ideal flow measuring structure: (1) it must be inexpensive to construct, (2) be simple to operate, (3) require little maintenance, (4) be free from working parts, (5) be accurate in its measurement, (6) be free from sand, silt or floating trash troubles, and (7) require but little head loss.

While weirs and orifices fulfilled many of the requirements, they had two serious drawbacks. First, they required a considerable head loss in order to function properly and secondly, they were very sensitive to sediment deposits, as well as requiring regular cleaning. Much work has been directed towards developing a measuring device which would fulfill as many of the criteria previously listed as possible. One such device which has received much attention is the measuring flume. There are many types of flumes which have been developed and the purpose of this chapter is to present a summary of the historical development of flow measuring flumes.

The use of flumes as open channel flow meters began shortly after the turn of the century. By constricting the area of the channel, small head losses were produced. By measuring this head loss, and knowing the characteristics of the flume, the flow rate could be determined within a certain range of accuracy.

Venturi Flume

One of the first men to work with a measuring flume was V. M. Cone. He developed what was called the Venturi flume and ran calibration tests on the flume in Fort Collins, Colorado. In 1917 his findings were published (5), of which the following is a summary.

The flume can be either rectangular or trapezoidal and consists of a converging section, a diverging section, and a short "throat" section between them (Figs. 1 and 2). The floor is level and is set at the elevation of the channel bed. Several experiments were made with various forms and shapes before deciding on the ones shown. By rounding the corners of the approach to the flume and lengthening the converging and diverging sections, a lower head loss can be achieved.

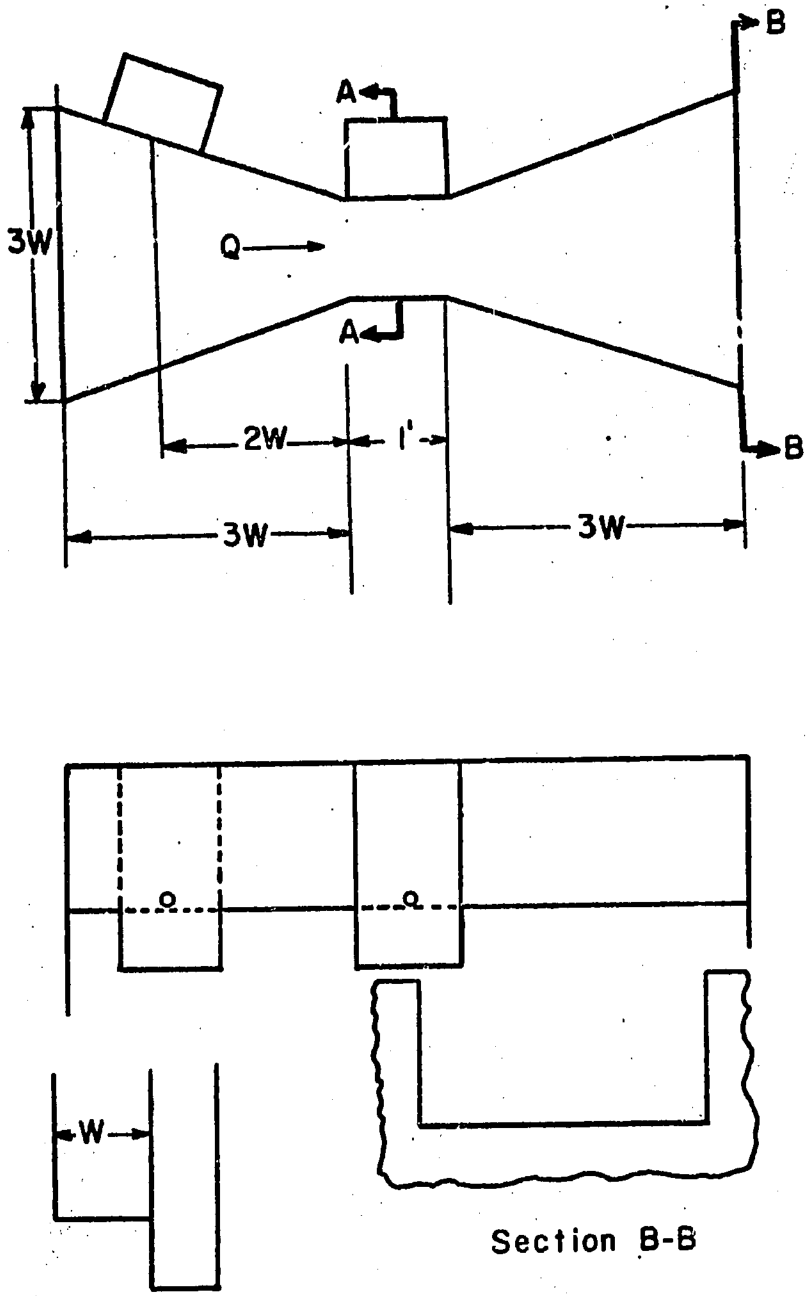


Figure 1. Typical rectangular Venturi flume (5).

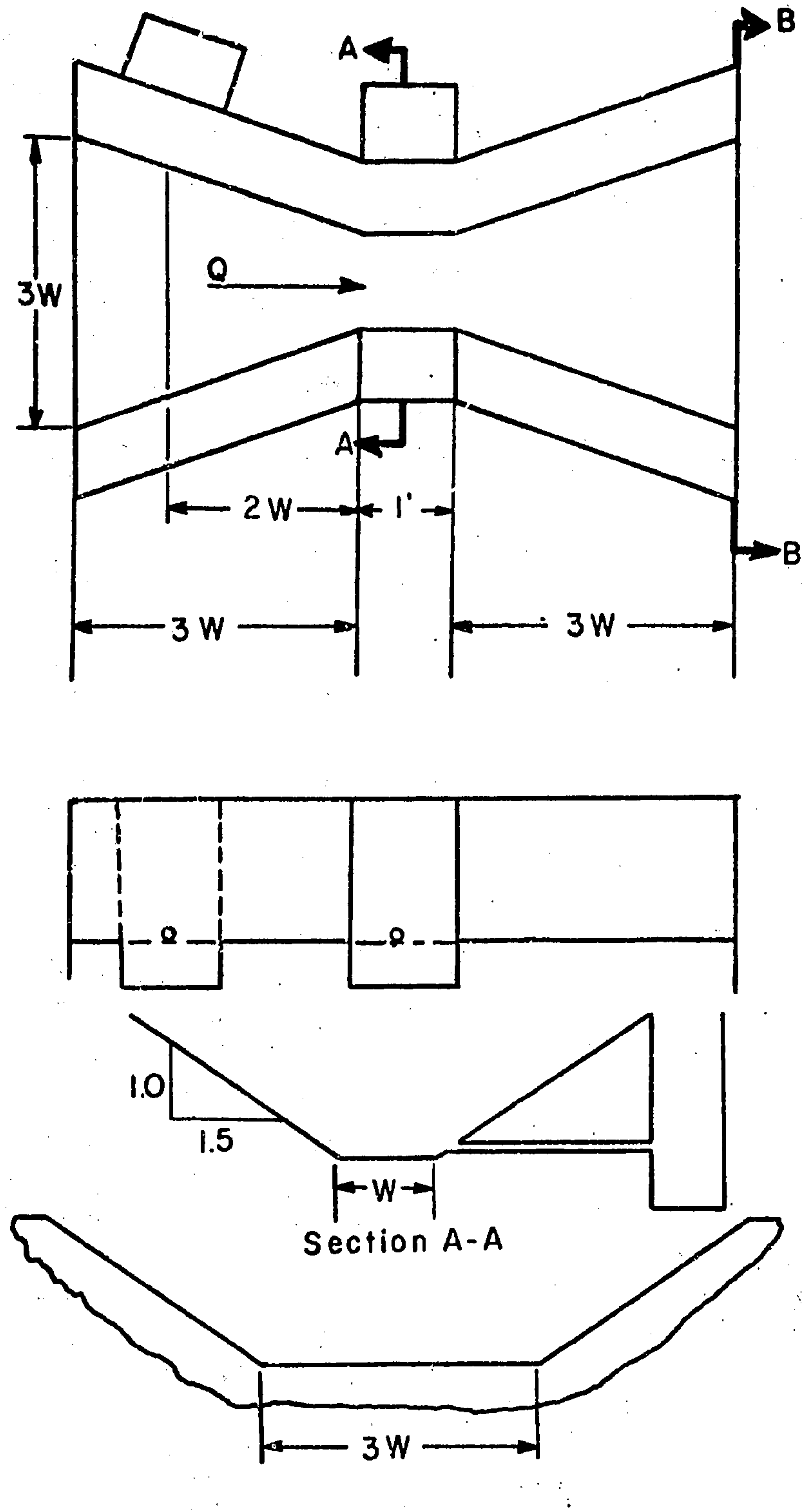


Figure 2. Typical trapezoidal Venturi flume (5).

This, however, increases construction costs. The sizes shown are a balance between costs and head loss. A V-Notch flume was also developed for use on very small flows (Fig. 3).

The action of this device depends upon an extension of Venturi's principle to the flow of a liquid in an open channel. As water passes through the flume there is a slight surface slope in the converging section, a sudden depression in the throat section and a rise in the diverging section. Because of this rise, the actual head loss is small - almost to the point of being negligible (5). The determination of the flow rate depends on the velocity and wetted cross-sectional area at two points in the flume, thus requiring two gage readings. (Note that because two readings are required, the flume is operating under submerged flow conditions at least part of the time.) One gage is arbitrarily located upstream from the throat section, a distance equal to 2/3 the converging section length. The other gage is located at the midpoint of the throat section. The zero of the gages were set at the elevation of the floor of the flume. The difference in these two readings is used to determine the flow rate. Because of the fluctuation in the level of the water surface, stilling wells should be used.

One strong advantage of the Venturi flume over other devices of the time was that it is self-cleaning. This self-

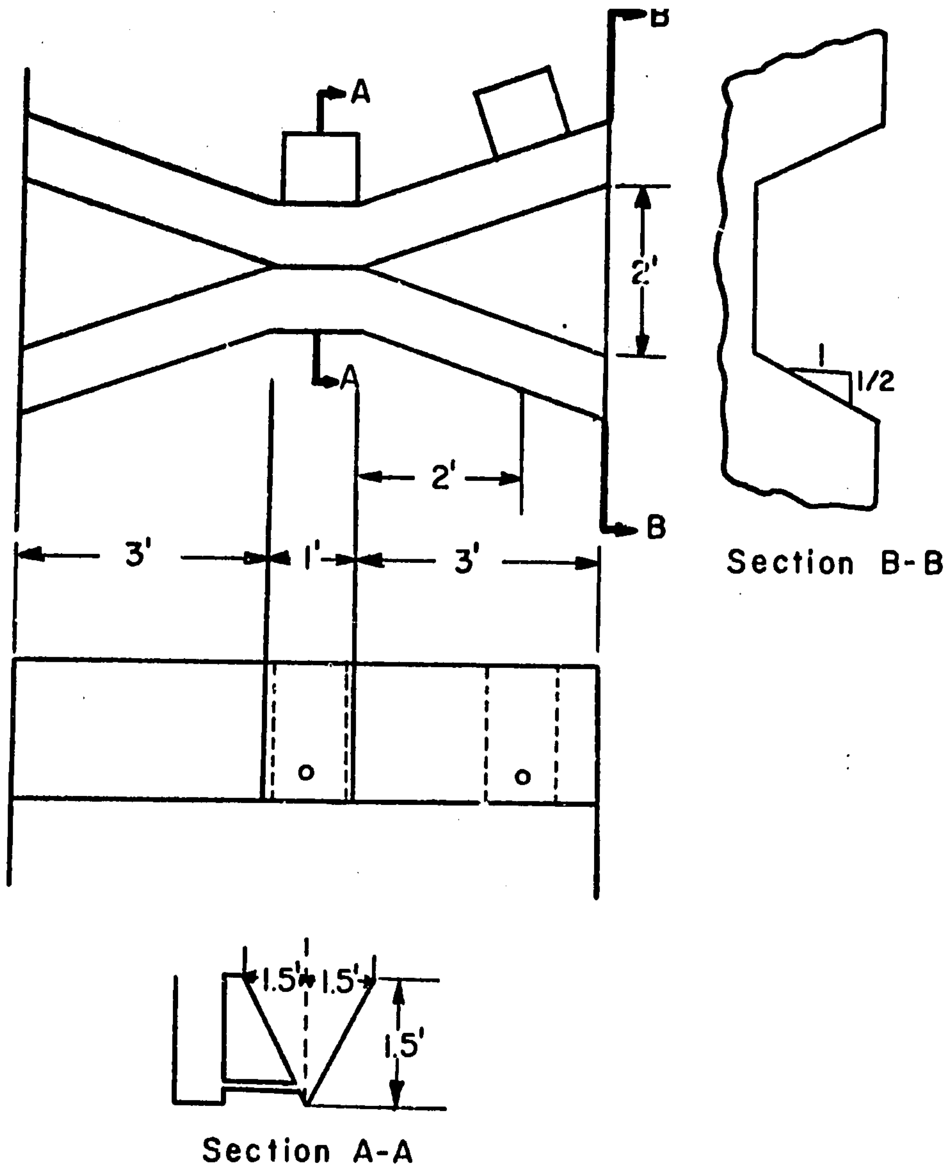


Figure 3. Typical V-shaped Venturi flume (5).

cleaning action is brought about by the increase in velocity through the flume. Therefore, material entering the flume is carried through the flume and is discharged downstream. The main drawback of the flume is that it is slightly less accurate than the weir type of measuring devices.

Due to the fact that the flume is operating under submerged flow conditions, and the lack of work done in this area at the time, the equations which Cone developed were extremely complicated. Rating tables were developed for use with the flumes which were developed.

Improved Venturi Flume

Much work was directed towards improving the design of the Venturi flume by Ralph L. Parshall. He realized some of the problems presented by the Venturi flume and worked towards solving them. In 1926, a paper was published by Parshall stating his findings (18).

Parshall used the same general structure (Fig. 4) that was used by Cone with the following modifications:

(1) The convergence of the inlet section was changed to one foot in five feet of length.

(2) The floor in the throat section slopes downward at the rate of nine inches in a horizontal distance of two feet.

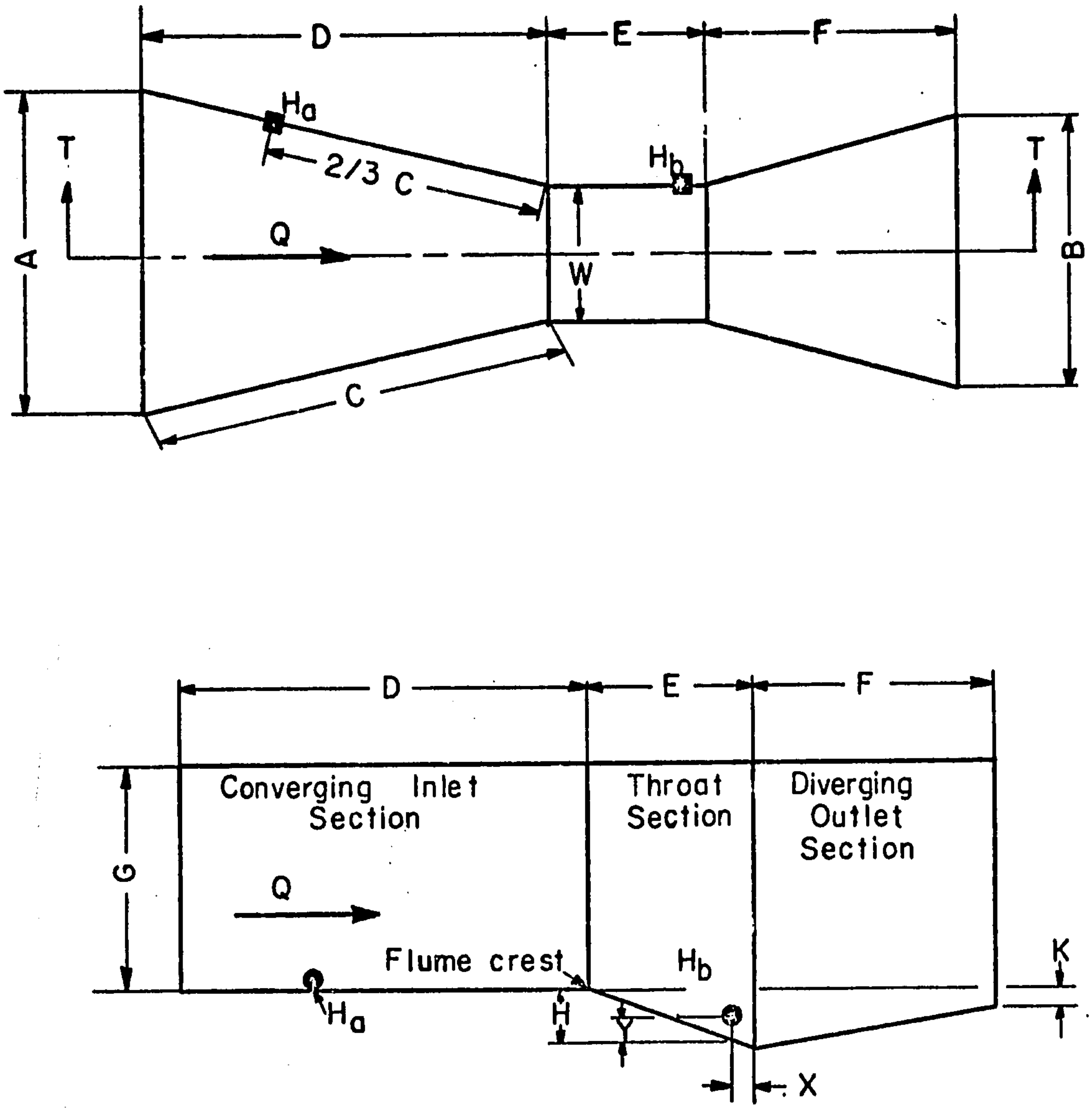


Figure 4. Typical Parshall measuring flume.

Table 1. Dimensions and capacities for Parshall flumes.

Throat Width W	Dimensions in Feet and Inches												Free Flow Capacities	
ft. in.	A	B	C	2/3 C or 2/3(W/2+4)	D	E	F	G	H	K	X	Y	Min. cfs	Max. cfs
12"	2' 9 1/4"	2' 0"	4' 6"	3' 0"	4' 4 7/8"	2' 0"	3' 0"	3' 0"	0' 9"	0' 3"	0' 2"	0' 3"	0.4	16.0
18"	3' 4 3/8"	2' 6"	4' 9"	3' 2"	4' 7 7/8"	2' 0"	3' 0"	3' 0"	0' 9"	0' 3"	0' 2"	0' 3"	0.5	24.0
24"	3' 11 1/2"	3' 0"	5' 0"	3' 4"	4' 10 7/8"	2' 0"	3' 0"	3' 0"	0' 9"	0' 3"	0' 2"	0' 3"	0.7	33.0
30"	4' 6 3/4"	3' 6"	5' 4 1/4"	3' 6 3/4"	5' 3"	2' 0"	3' 0"	3' 0"	0' 9"	0' 3"	0' 2"	0' 3"	0.8	41.0
3' 0"	5' 1 7/8"	4' 0"	5' 6"	3' 8"	5' 4 3/4"	2' 0"	3' 0"	3' 0"	0' 9"	0' 3"	0' 2"	0' 3"	1.0	50.0
4' 0"	6' 4 1/4"	5' 0"	6' 0"	4' 0"	5' 10 5/8"	2' 0"	3' 0"	3' 0"	0' 9"	0' 3"	0' 2"	0' 3"	1.3	68.0
5' 0"	7' 6 5/8"	6' 0"	6' 6"	4' 4"	6' 4 1/2"	2' 0"	3' 0"	3' 0"	0' 9"	0' 3"	0' 2"	0' 3"	2.2	86.0
6' 0"	8' 9"	7' 0"	7' 0"	4' 8"	6' 10 3/8"	2' 0"	3' 0"	3' 0"	0' 9"	0' 3"	0' 2"	0' 3"	2.6	104.0
7' 0"	9' 11 3/8"	8' 0"	7' 6"	5' 0"	7' 4 1/4"	2' 0"	3' 0"	3' 0"	0' 9"	0' 3"	0' 2"	0' 3"	4.1	121.0
8' 0"	11' 1 3/4"	9' 0"	8' 0"	5' 4"	7' 10 1/8"	2' 0"	3' 0"	3' 0"	0' 9"	0' 3"	0' 2"	0' 3"	4.6	140.0
10' 0"	15' 7 1/4"	12' 0"	14' 3 1/4"	6' 0"	14' 0"	3' 0"	6' 0"	4' 0"	1' 1 1/2"	0' 6"	1' 0"	0' 9"	6.0	200.0

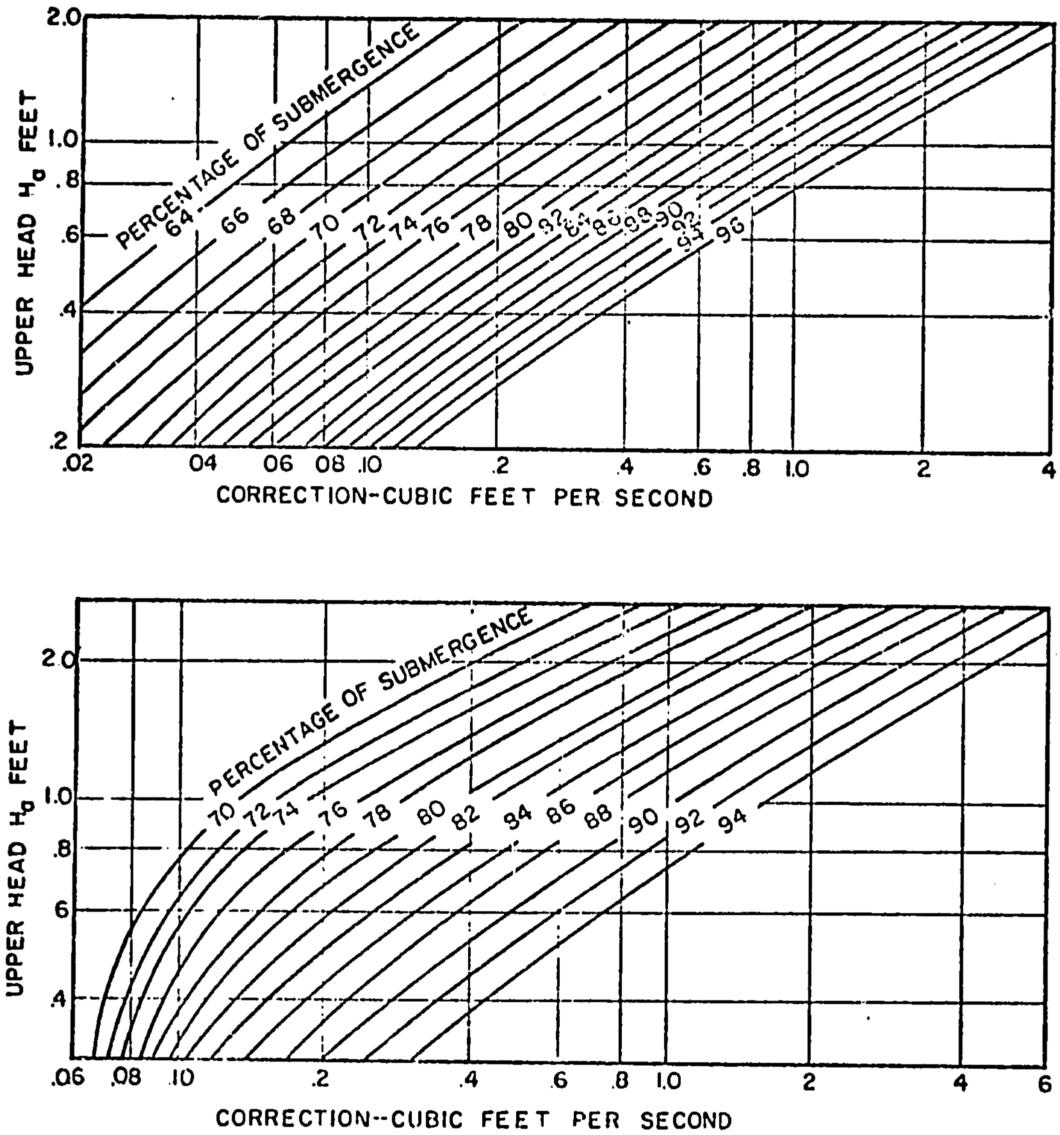


Figure 5. Typical submerged flow ratings for Parshall flumes (19).

(3) The outlet floor slopes upward at the rate of six inches in three feet.

(4) The divergence of the outlet is one foot in six feet of length.

(5) All flumes had vertical sides.

Because of these modifications, Parshall referred to this flume as "The Improved Venturi Flume." Later, the name of this type of flow measuring flume was changed to "Parshall Flume" by action of the American Society of Civil Engineers.

The lengths of the throat and the outlet of the flume were two and three feet, respectively for all flumes having a throat width between one and eight feet, inclusive. The side of the inlet was made longer as the width of the flume increases according to the empirical rule, $W/2 + 4$, in which W is the throat width, in feet.

Parshall recognized that there were two general conditions of flow, namely, "free flow" when the elevation of the water surface upstream is unaffected by fluctuations downstream; and "submerged flow" when the elevation of the water at the throat gage is greater than approximately 0.7 H_a. The upper head H_a was measured at a point 2/3 the distance from the throat section to the inlet along the wall, whereas H_b, the throat head, is measured at a point three inches vertically and two inches horizontally upstream from the lowest point in the floor. Both H_a and H_b are referred to the elevation of the flume crest as a datum. Therefore, H_b may be negative under certain free flow conditions.

Laboratory tests were performed on flumes having a throat width of 1, 2, 3, 4, 6, and 8 feet. The flow rates were varied from 0.3 cfs to 62.5 cfs for the various flumes. It was found that when H_b did not exceed 0.70 H_a, the flow rate could be determined using only one depth reading, H_a. Under this condition, the flow rate could be obtained by the following formula (18):

$$Q = 4\, W^{1.026}\, H_a^{1.522} \qquad (1)$$

where Q = discharge, in cfs
W = width of throat, in feet
H_a = flow depth in inlet, in feet

The accuracy of this device using this formula is believed to be sufficient for most field applications.

Parshall made the following observations and comments concerning the improved Venturi flume (18):

(1) The increased velocity of the water in the throat section, together with the depressed floor, causes a hydraulic jump to occur for values of H_b/H_a up to 0.70.

(2) It is recommended that the flume be operated under conditions where H_b/H_a does not exceed 0.70, thereby necessitating only one flow depth reading, H_a.

(3) For submergence values greater than 70 - 75 percent, the discharge is a function of H_a and H_b.

(4) Under conditions where sand and silt occur, there will be little problem of silting if a minimum difference in head of 0.05 - 0.10 feet is maintained.

(5) The velocity of approach seems to have little effect on the rate of discharge.

The improved Venturi flume, later called the Parshall flume, has become the most popular irrigation flow measuring device in the western United States. Because of its relatively low cost, ease of operation, high accuracy, and long life, it is especially suited for use by non-technical personnel usually encountered in the irrigation districts of the west.

Further studies on the Parshall flume (19) resulted in the final design standards shown in Table 1. A rating system was developed for use in the submerged flow range and graphs prepared of the findings. A sample of these graphs are shown in Fig. 5. To determine the flow rate under submerged flow conditions for flumes larger than one foot in width, the correction is determined by multiplying the correction for the one foot flume by the appropriate factor shown below (19).

Size of Flume, W_f, in feet	Multiplying Factor
1	1.0
1.5	1.4
2	1.8
3	2.4
4	3.1
6	4.3
8	5.4

Design criteria for flumes larger than eight feet in width were developed by Parshall and reported in 1953 (22). No change in formula is reported, but many rating tables are presented which are beyond the scope of this paper.

Standing Wave Flume

At approximately the same time that Parshall was developing an improved Venturi flume, work was being conducted on a type of measuring flume in Bombay and the Punjab of India by Inglis (12). This flume employed a contraction of the side walls sometimes coupled with a smooth hump in the floor to cause the flow velocity to exceed critical velocity. The walls were then diverged and the floor lowered back to the level of the downstream channel. This caused a standing wave, or hydraulic jump, to occur, thus recovering a high percentage of the original head (12). The formation of the standing wave (hydraulic jump) prompted the name of "Standing Wave Flume" for the device. Because of the raised floor, this structure is a combination of a weir (floor constriction) and a flume (side constriction).

A general definition sketch of the flume is given in Fig. 6. It is noted that because of the low head available and the lower cost of labor in this area (India), that the flume consists of a warped transition thereby reducing the head loss.

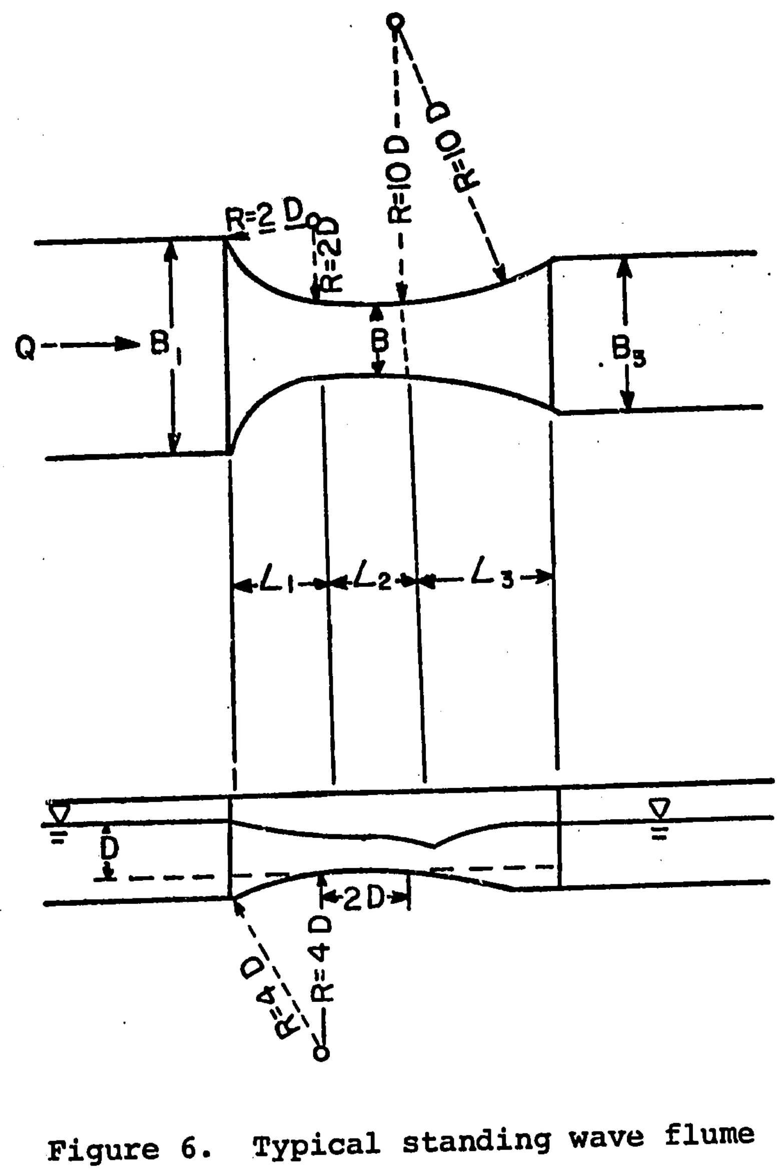


Figure 6. Typical standing wave flume (12).

The Standing Wave Flume consists of about the same sections as the Venturi Flume; namely, a converging section, a throat section, and a diverging section. The hump in the floor accomplishes the same purpose as the drop in the improved Venturi flume (Parshall flume). One main advantage of the Standing Wave flume over the Parshall flume is that only one gage reading is required for submergences of at least 80 percent and in some cases, as high as 94 percent if long gently curving sides are used (12). The depth gage is located on the upstream face of the flume entrance and referenced to the flume floor in the throat section. All calibrations performed by Inglis were in the free flow range of the flume; the reason being that the theory of the flume is not applicable if a standing wave does not occur.

The flume was first developed and operated using a purely mathematical approach. The equation of flow for vertical walls and neglecting friction is (12):

$$Q = 3.088 \; B \; D^{3/2} \qquad (2)$$

where Q = flowrate in cubic feet per second
B = width of throat section
D = effective depth of water (upstream)
or $D_1 + h$ = Depth + Entrance velocity head

Later, it was found that friction losses did have an appreciable effect on the results and the formula was modified to (12):

$$Q = 3.088 \; C_1 \; B \; D^{3/2} \qquad (3)$$

with C_1 being a varying coefficient according to the following schedule:

For narrow flumes 6 inches wide	C = 0.96	
For flumes one foot wide	C = 0.97	Flumes
For flumes 4 feet wide	C = 0.98	cement
For flumes 10 feet wide	C = 0.99	plastered

These equations hold only for flumes in which $B = D^{1.5}$. The coefficient, C, also varies with the rate of discharge, there fore making it necessary to rate every flume geometry for the range of desired discharge. This would appear to make the use of these flumes quite dependent on exact geometries and the availability of rating tables. When properly designed, installed, and operated it is possible to obtain accuracies of 2 percent over the full range of discharges (12).

Some work was done on a flume having a triangular throat section to accomodate low flows. The equation developed by Inglis (12) for this type of flume is

$$Q = 2.3\ s\ D^{2.5} \qquad (4)$$

where s is the side slope ratio of horizontal to vertical.

Many different types of flumes were developed by Inglis and reported in his paper (12). In general, it could be said that the Standing Wave Flume is an accurate measuring device, well suited for making flow measurements under field conditions.

Curved Entrance Venturi Flumes

One of the prime criteria for a flow measuring device is to keep the head loss through the device to a minimum. One method of lowering the head loss is to round the corners of the structure. A study using various types of smooth flumes was conducted by Anwar Khafagi (11). In this study, he used various flumes with different degrees of rounding in the entrance section. As can be seen from Fig. 7, there was a definite attempt to duplicate the geometry of the Venturi meter. From this study, the following equation was obtained (13):

$$Q = K\, b_1\, h_1\, b_2\, h_2 \sqrt{\frac{2g\ (h_1 - h_2)}{(b_1\ h_1)^2 - (b_2\ h_2)^2}} \quad \ldots. \quad (5)$$

where Q = flow rate
K = geometric constant
h_1 = upstream depth
b_1 = upstream width
h_2 = downstream depth
b_2 = downstream width
g = acceleration due to gravity

The work by Khafagi was very accurate and precise for the geometries studied (2).

Simple Side Constrictions

Further work on measuring flumes was performed by A. Balloffet and a report describing his work was published in 1955 (2). Balloffet reviewed and commented on the work of previous authors and also developed two additional geometries (Fig. 8). In this work, it was decided to eliminate the

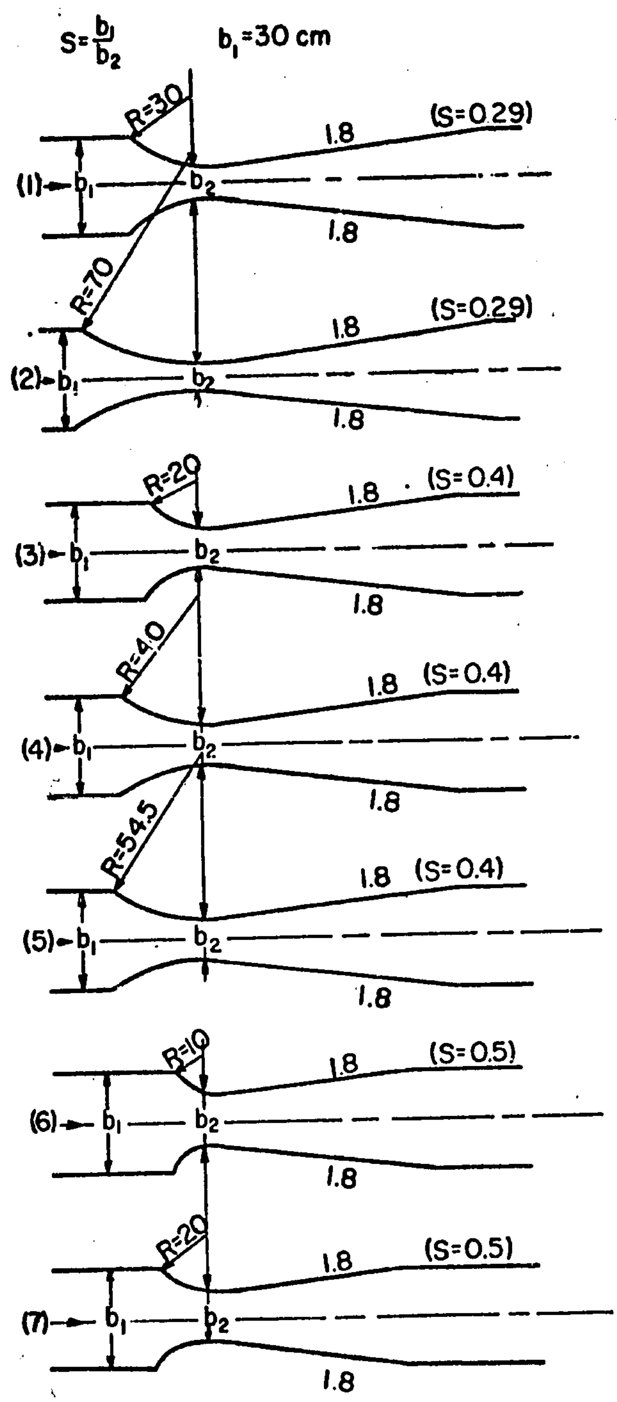


Figure 7. Geometries investigated by Khafagi in 1942 (13).

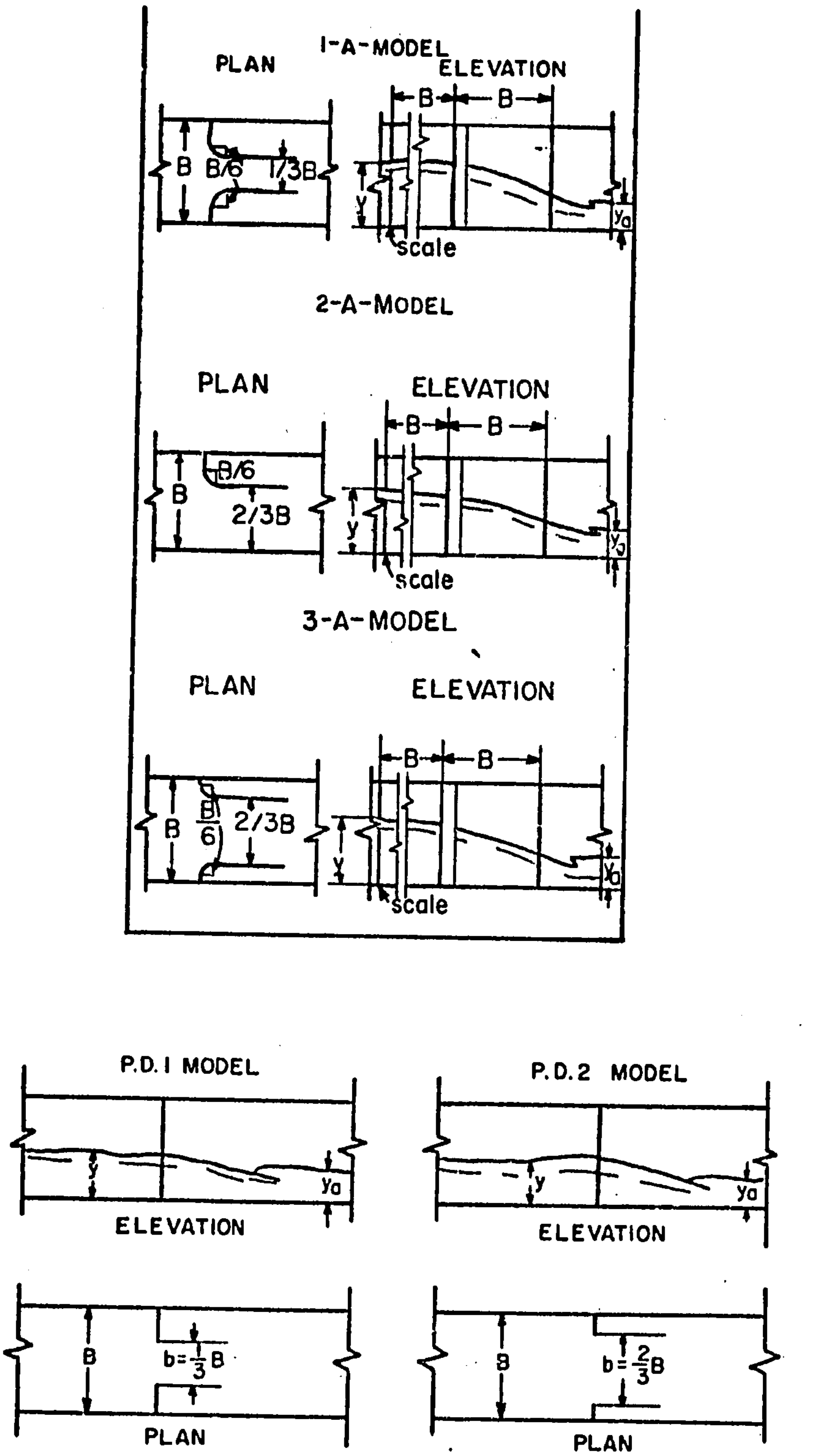


Figure 8. Geometries investigated by Balloffet (2).

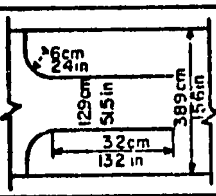
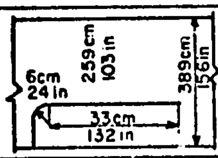
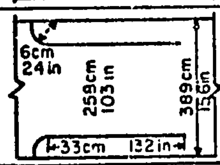
downstream diverging section from the flume, since it was felt that the exit section has little effect, under free flow conditions, on the flume's operation (2). The results for these geometries are shown in Fig. 9.

Balloffet determined that the values for C in the equations could be determined within 1 percent and that the flow rates could be determined within 2 percent. The submergence can be approximately equal to 85 percent with only a moderate error in flow rate (2).

The second geometry studied (Fig. 8) consisted of a thin plate constriction formed by two vertical plates placed perpendicular to the flow. This geometry was studied mainly because of the ease of construction and the results are shown in Fig. 9. However, the results obtained are not conclusive and require more experimentation before using (1). The work accomplished by Balloffet is helpful but not conclusive. The description of the procedure and locations at which measurements were collected are also lacking.

Broken Plane Transitions

The question of effects of transition types, or geometry, on the head losses occurring through the measuring structure were further studied by Otto Haszpra and reported in two papers (8,9). In these studies, the so-called broken plane transition (Fig. 10) was compared with the warped transition.

Model	Sketch plan	r = Channel / throat	μ	Qt	Material		Number of Observations	Coefficient of Discharge		Q actual	Submergence limit S_L
					bottom	throat walls		Mean value	Deviation from Mean		
				cfs					per cent	cfs	
1A		0.332	0.397	3.18 by$^{3/2}$	Concrete	Concrete	64	0.948	0.62	3.01 by$^{3/2}$	0.80
1B		0.334	0.39	3.20 by$^{3/2}$	Concrete (smoothed)	lucite	42	0.95	0.42	3.04 by$^{3/2}$	0.82
2A		0.666	0.435	3.48 by$^{3/2}$	Concrete	Concrete	19	0.962	0.5	3.34 by$^{3/2}$	0.90
3A		0.663	0.432	3.46 by$^{3/2}$	Concrete	Concrete	37	0.956	0.7	3.32 by$^{3/2}$	0.85

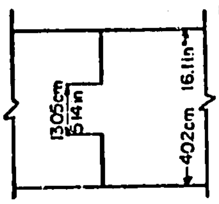
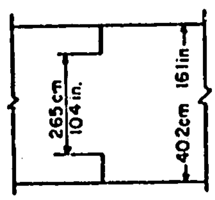
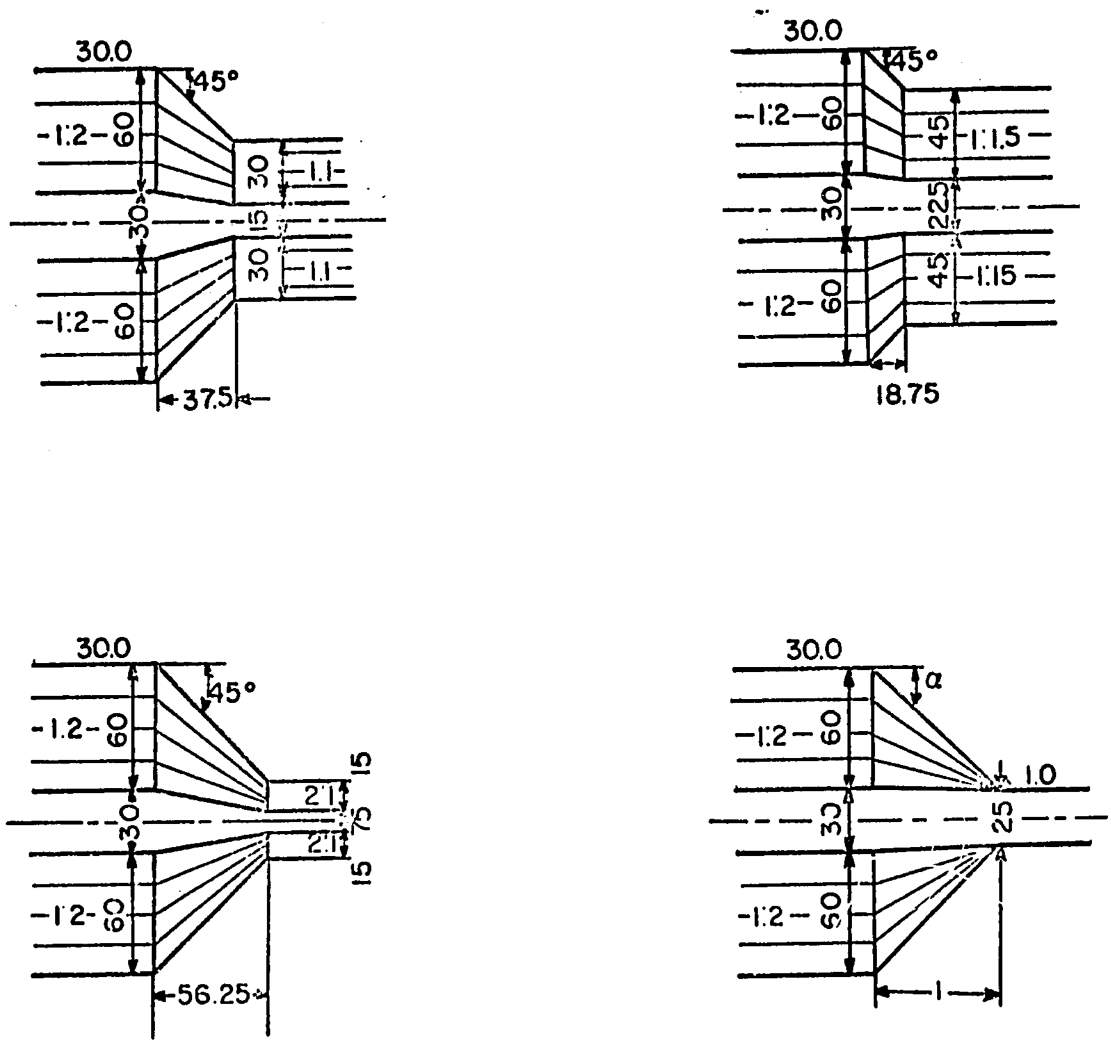
Model	Sketch plan	r = Channel / throat	μ	Qt	Material		Number of Observations	Coefficient of Discharge			Q actual		Submergence limit S_L
					bottom	throat walls		Mean	Deviation from Mean	$C = Ay^n$	Mean C	$C = Ay^n$	
				cfs									
PD1		0.325	0.396	3.17 by$^{3/2}$	Concrete	lucite sheets	111	0.98	1.2	$1.04y^{0.105}$	3.11 by$^{3/2}$	3.30 by$^{1.57}$	0.52
PD2		0.659	0.426	3.42 by$^{3/2}$	Concrete	lucite sheets	32	0.92	2.2	$1.06y^{0.179}$	3.15 by$^{3/2}$	3.63 by$^{1.58}$	0.75

Figure 9. Results reported by Balloffet (2).



Note: all dimensions in centimeters

Figure 10. Examples of broken plane transitions (8).

Haszpra found that the broken plane transition was superior in every way to the warped transition. Not only is there less head loss, but the broken plane transition can also be constructed more accurately. The transitions were compared using the following equation (8,9):

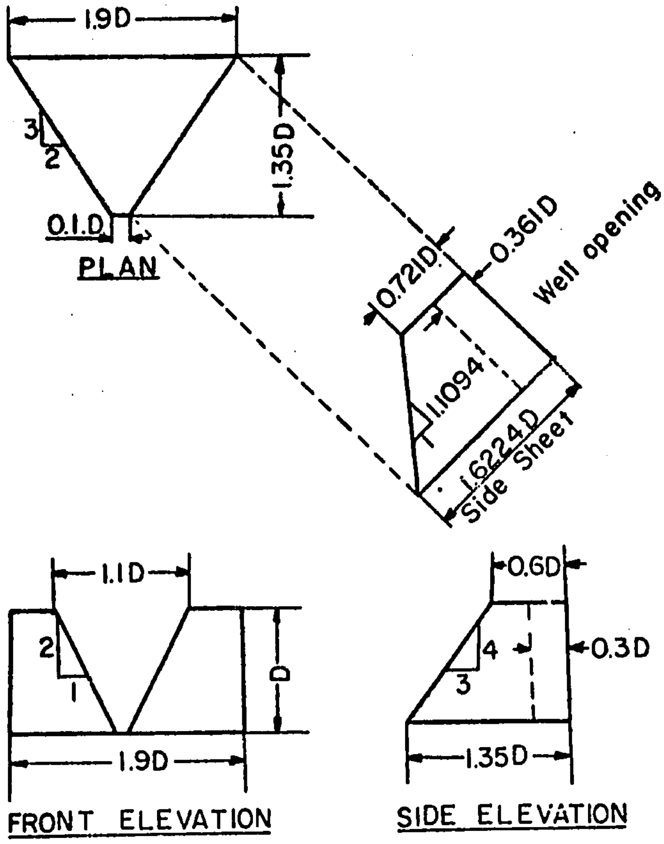
$$h_f - h_a = C_f Q^p h_a^n \qquad (6)$$

where h_a = tailwater depth
h_f = head water depth
C_f = head loss coefficient
Q = discharge
p and n = characteristic constants

Thus, the headloss for any particular structure is proportional to the head loss coefficient, C_f. The head losses in Venturi flumes having broken plane transitions were found to decrease by 15-35 percent as compared to those encountered with warped transitions. While these studies do not present any new types of measuring flumes, they do present information showing that the head loss in present measuring flumes may not be improved by using curved entrance or exit sections. Also, if any modifications were made on existing flumes, they would have to be recalibrated.

H-Flume

Another type of flume which is widely used, especially on natural drainage channels, is the so-called H-Flume (Fig. 11). Much work on the development and calibration of this flume has been carried out under the direction of the Agricultural Research Service (ARS) and has been reported by



PROPORTION OF THE TYPE H FLUME

APPROXIMATE	CAPACITIES
DEPTH-D	CAPACITY
Feet	C.f.s.
0.5	0.3+
0.75	[illegible]
1.0	2
1.5	5+
2.0	11
2.5	19
3.0	30

Note: For flumes less than 1 foot deep, the length of flume is made greater than 1.35 D so that the float may be attached.

Figure 11. Geometry of H-flume (10).

Holtan, Minshall and Harrold (10). While this flume operates much like a weir, it is classified as a flume because the control section contracts solely from the sides.

The main advantages of the H-Flume according to the ARS (10) are: (1) wide ranges of flow can be handled, (2) ease of construction, (3) easy to install and operate, and (4) a high degree of accuracy. By sloping the floor toward the well openings and varying the dimensions of the flume, flow rates from 0.0002 cfs to 30 cfs can be measured quite accurately using this device. Also, because the width of the opening increases with depth, each size of flume can handle a large range of discharges. This is very important when gaging uncontrolled natural streams. The ability of this flume to provide accurate flow measurements even when the flow contains a large amount of suspended material also adds to the desirability for its use on natural streams. Kruse and Dragoun (15) found that with sediment loads of up to 50,000 PPM, the flow rate readings were within 2 percent of the clear water readings. With clear water, the accuracy of the device should be within 3 percent.

From the work performed by the ARS, the following equation for flow rates was obtained (15):

$$Q = \tfrac{1}{2}\, C_d\, W\, H^{3/2} \quad \text{.....................} \quad (7)$$

where Q = discharge in cfs
C_d = discharge coefficient
W = the width of the flume throat at a state = H in feet
H = head in the flume at the measuring section in feet

There have been various modifications of the H-Flume to fit specific requirements. Specifications for other sizes of flumes tested, along with calibration tables for all sizes, are given in ARS publications (10).

The H-Flume seems to be a good measuring device and is used widely in small natural streams. However, it has found little use in irrigation systems. The H-Flume is used strictly as a free flow measuring device.

Large Critical Depth Flumes

Another type of measuring flume has been developed by the ARS for use on natural channels. This particular flume was developed to handle the flash-flood types of flow which occur in the southwestern United States. Because of its large size, the structure is referred to as a large critical depth flume (17). No attempt has been made to standardize the geometries of the flumes because of the large variety of conditions encountered. Instead, model studies were made on each proposed location.

A typical geometry is shown in Fig. 12, while the following description is given by the ARS (17). The critical depth flumes are designed with a broad entrance section approximately

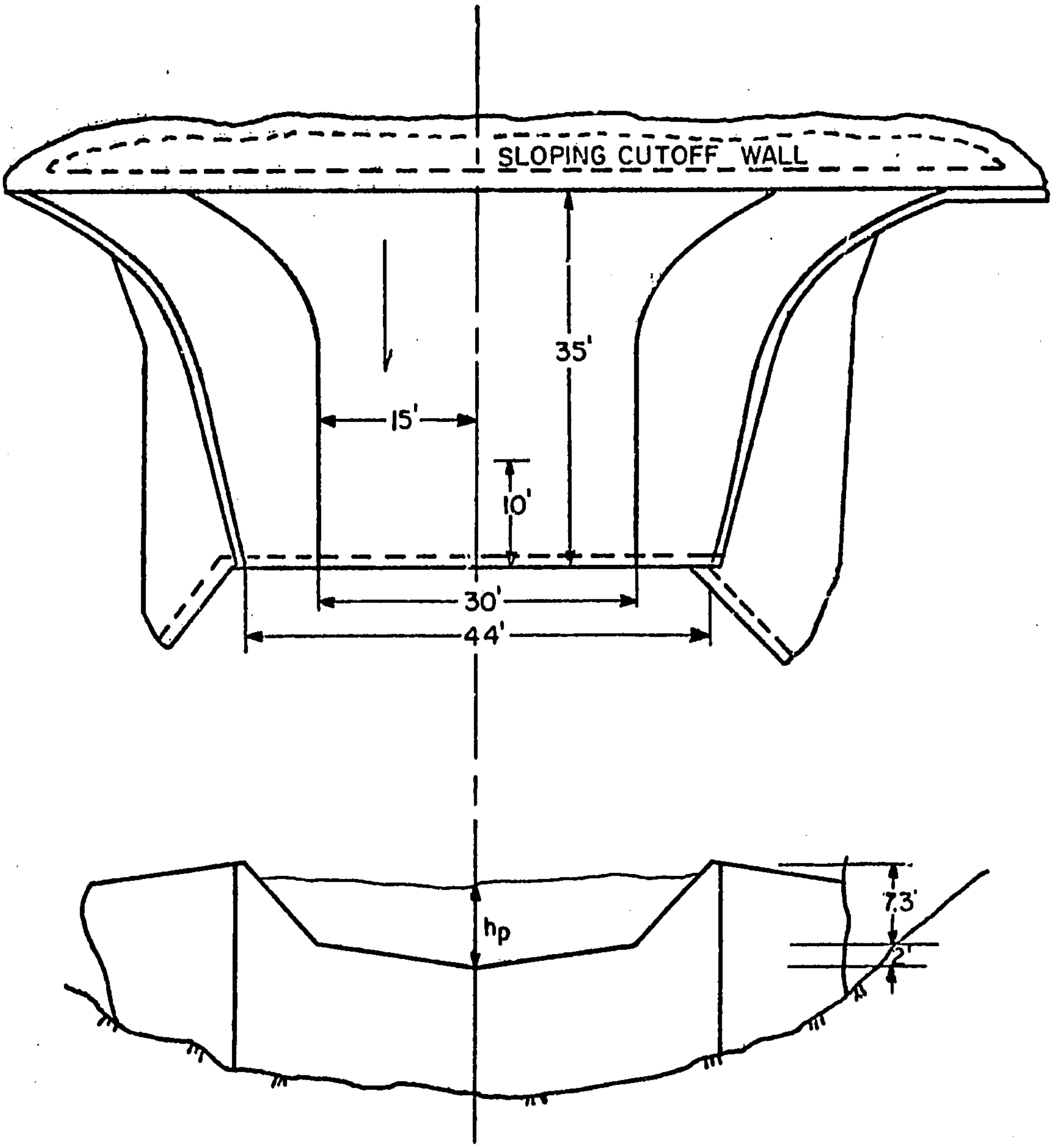


Figure 12. Example of large critical depth flume (17).

the size of the original channel section, a 15-foot long contracting reach with warped sidewalls to force the flow thru critical depth, and a 20-foot straight reach. The water level gaging station is located in the middle of the straight reach. A bottom slope of 3 percent keeps the flow accelerating throughout the length of the flume and eliminates deposition of sediment in the flume.

The flow rates encountered by these flumes range from 0 to 18,000 cfs. To handle the low flows, a V-notch weir plate can be added and calibrated. However, this aggravates the sedimentation problems.

Because of the large size of these flumes and the varying conditions of use, no formula for discharge is presented. Instead, each flume is rated using model studies. However, as a guideline for design purposes, the following formula can be used with a maximum error of 5 percent (6):

$$Q = C_d \; t/2 \sqrt{2g} \;\; h_p^{3/2} \quad \text{.............} \quad (8)$$

where Q = discharge in cfs
C_d = discharge coefficient
t = width in the measuring section at elevation h_p above the flume zero
g = acceleration due to gravity
h_p = piezometric head above the flume zero, the bottom of the V-notch at the measuring section

Swiss Channel Type

Several different geometries of flumes have been developed for use in Switzerland which are patterned after the large critical depth flumes discussed previously (25). Each of these flumes are designed especially for the flow conditions encountered. Therefore, there is little similarity between structures.

Basically, each flume consists of a small, flat-bottomed, rectangular or trapezoidal critical depth flume built into the floor of a larger flume. This gives the structure a much larger range of flow rates that can be handled accurately. To eliminate the deposition of sediment, the floor of the structures are placed on a 0.5 percent slope. This causes the water to accelerate through the flume, thereby eliminating the sedimentation problem (25).

Due to the fact that the structure is designed especially for each gaging station, no work has been performed to determine a general discharge equation. Instead, each structure is rated using a current meter. In general, the devices were found to give satisfactory results over the range of flows encountered. Sediment was found to cause little problem with the operation (25).

Trapezoidal Flumes

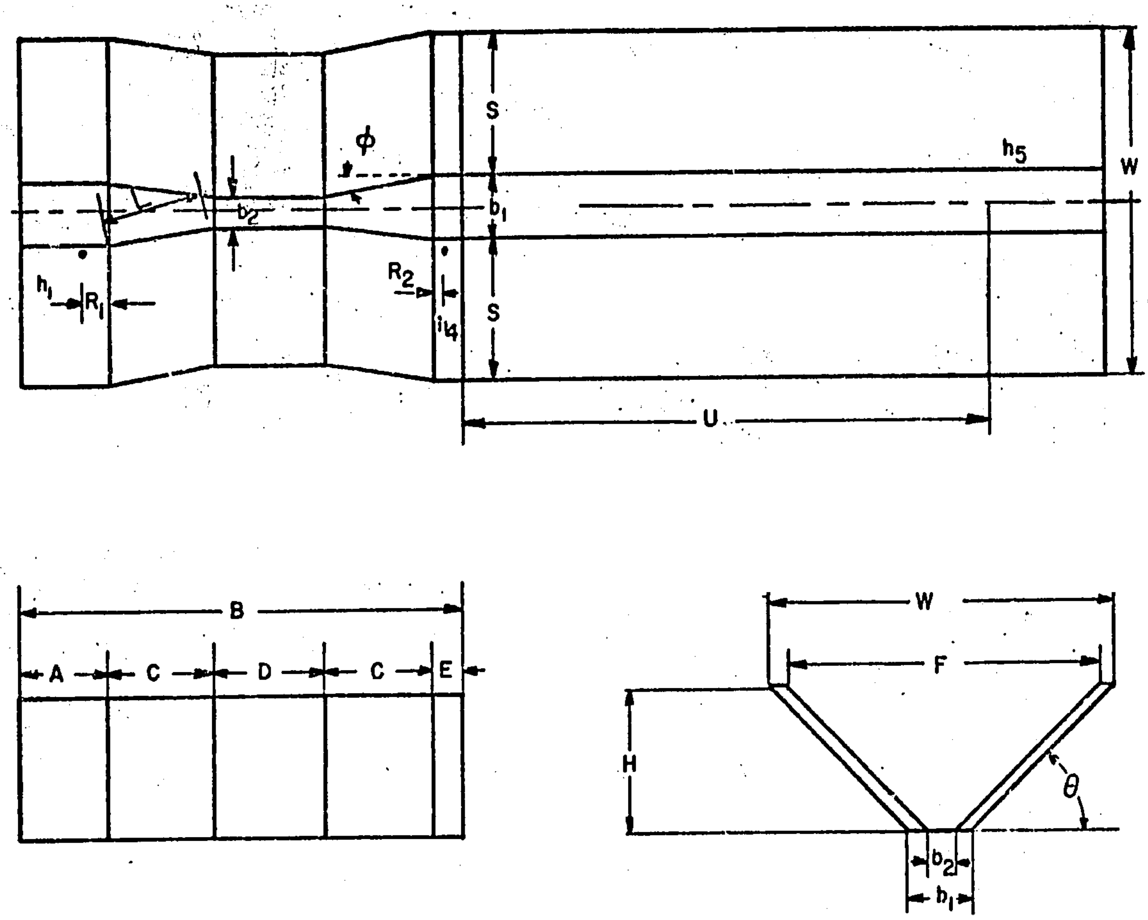
The trapezoidal flume is one type of measuring device which is gaining much popularity. A trapezoidal flat-bottomed flume was first developed around the turn of the century (5), but was not widely used at that time. Much work has been performed with the trapezoidal flume more recently by A. R. Robinson and A. R. Chamberlain (4, 26, 27) and Kruse (14). The following is a summary of their work. The main advantages of the trapezoidal flume are: (1) large ranges of discharge handled accurately, (2) can be constructed in existing trapezoidal channels, (3) low head loss coefficients, and (4) operates under submerged flow conditions. The trapezoidal flume (Fig. 13) consists of a flat-floored trapezoidal-shaped section with converging, throat, and diverging sections much the same as the Venturi flume.

In their work, Chamberlain and Robinson found that the trapezoidal flume would operate as a free flow measuring device at higher submergence values than the rectangular flumes. From their studies, it was found that the transition submergence for the trapezoidal flume ranged from 80 - 85 percent. This would eliminate the need for submerged flow ratings at many installations.

Because of the more complicated geometry of the trapezoidal section, the equation for discharge becomes more complicated. A general equation developed by Robinson (27), which closely approximates the flow is:

$$Q = C_a\, h_1^{2.5} + C_b h_1^{1.5} + C_c \qquad (9)$$

where Q = discharge in cfs
C_a, C_b, C_c = coefficients determined experimentally
h_1 = upstream head in feet (measured vertically)



Flume No	Description	b_1	b_2	Λ	L	C	D	E	F	H	B	R_1	R_2	S	U	W	θ	φ
1	45°- 12"	12	$4\frac{3}{16}$	12	$17\frac{7}{16}$	$17\frac{1}{16}$	22	6	$36\frac{13}{16}$	16	$64\frac{1}{8}$	$1\frac{3}{4}$	$\frac{3}{4}$	16	72	44	45°	11.9°
2	45°-22"	12	$4\frac{13}{16}$	12	$17\frac{7}{16}$	$17\frac{1}{16}$	22	6	$36\frac{13}{16}$	16	$74\frac{1}{8}$	1	$\frac{3}{4}$	16	60	44	45°	11.9°
3	0.6'-1:2	18	$7\frac{3}{16}$	12	$17\frac{29}{32}$	$17\frac{1}{16}$	22	6	24	$16\frac{13}{32}$	$74\frac{1}{8}$	1	1	$8\frac{13}{32}$	60	$34\frac{13}{16}$	63.43°	17.6°
4	0.9'-1:2	18	$10\frac{13}{16}$	12	$17\frac{7}{16}$	$17\frac{1}{16}$	22	6	$27\frac{5}{8}$	$16\frac{13}{32}$	$74\frac{1}{8}$	$1\frac{1}{2}$	1	$8\frac{13}{32}$	60	$34\frac{13}{16}$	63.43°	11.9°

Figure 13. Geometry and dimensions for some trapezoidal flumes (14).

While this equation is not exact, it is within the limits of field measurements. In lined canals, the trapezoidal flume can be designed with the same floor width and side slope as the canal.

In recent years (3) much work has been performed on methods of slip forming trapezoidal flumes in lined canals. This process has been found to work very efficiently and is more economical than other widely used measuring devices.

In general, the trapezoidal flume is a reasonable accurate measuring device, which is particularly adapted to lined trapezoidal channels frequently encountered in irrigation systems.

Modified Venturi Section

The modified Venturi section was developed many years ago by the U. S. Bureau of Reclamation (USBR) in 1915. Additional work on developing design criteria and discharge ratings was performed by J. E. Ferguson and J. E. Garton in 1949. Their work was accomplished under the direction of J. E. Christiansen (24). The following is a summary of the findings of these investigators.

The modified Venturi section is formed by introducing a curved cover over a rectangular channel as shown in Fig. 14. The closed section thus formed becomes a modified Venturi tube with a rectangular throat section. The throat section size

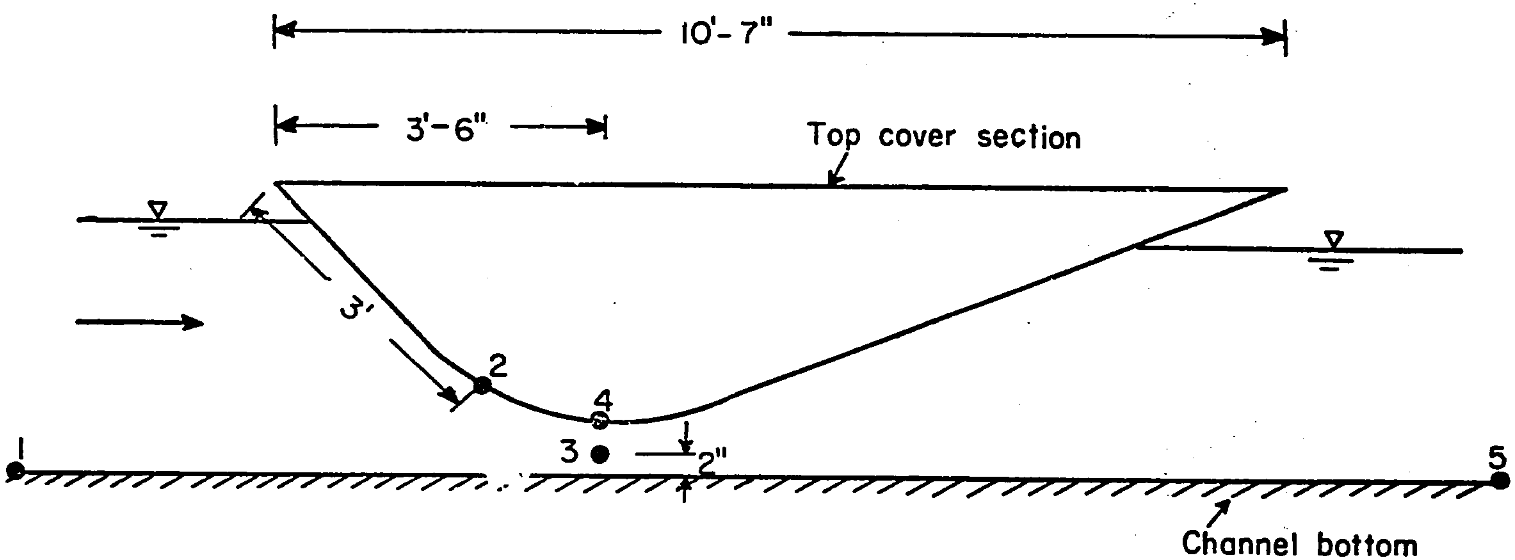


Figure 14. Modified Venturi (Gate) section (24).

may be fixed or varied by raising or lowering the cover. Thus this flow measuring device is somewhat like a gate structure, where the gate (or in this case, the curved cover) can be raised or lowered. This ability to adapt to different ranges of discharge is one of the strong advantages of this device. The flow rate through the structure has been related to pressure taps located in the cover at points 2 and 4. The following formula was presented by Ferguson and Garton (6) for design purposes:

$$Q = K\,H \qquad (10)$$

where Q = discharge in cfs
K = a constant
H = difference in head between the two piezometers.

This equation was valid only for a fixed throat area, since K varied for each throat size. No values for K were presented in this publication (6).

Further work was done by Rasheed in 1968 (24) with the geometry shown in Fig. 14. He presented the following formula for determining discharge:

$$Q = C_d\,A_t\,\sqrt{2g\Delta h} \qquad (11)$$

where Q = flowrate in cfs
C_d = coefficient of discharge
A_t = area of throat section
Δh = difference in head between points one and three

Values of C_d ranged from approximately 0.80 to 0.95. Due to the fact that the area of the throat section can be varied, head loss values can be minimized.

This device seems to be quite accurate and usable, but has found little popularity as a field measuring device.

Weir Flumes

The Neyrpic Company of France has developed a portable measuring flume using a broad crested weir to provide the constriction (Fig. 15). While this technically is not a flume, it has some of the advantages of the flume and does constrict the flow vertically in most cases. The main advantage of this device is that it has made the weir portable. The following equation is given for determining discharge (16):

$$Q = M\, l \sqrt{2g}\, H^{3/2} \qquad (12)$$

where Q = discharge
l = width of weir
M = discharge coefficient
g = acceleration due to gravity
H = height of water above sill

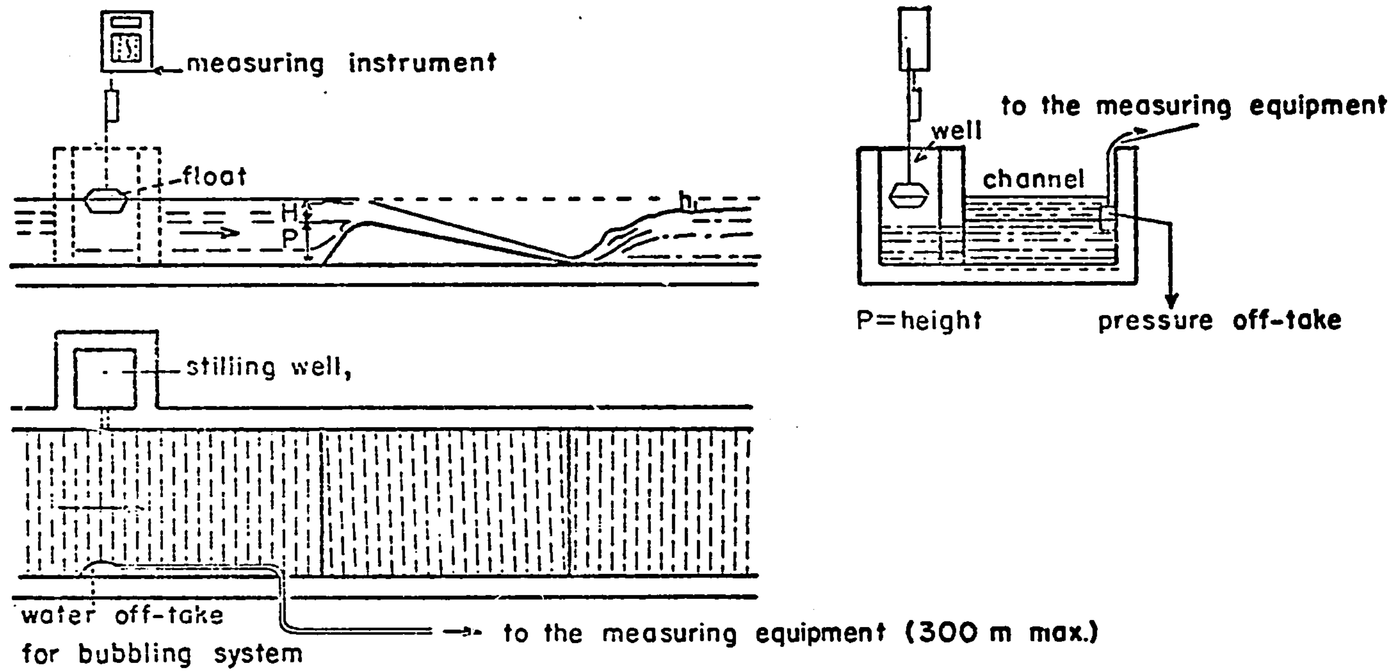


Figure 15. Example of portable weir flume (16).

CHAPTER 3

DEVELOPMENT OF THE CUTTHROAT FLUME

From the preceeding chapter it can be seen that a large number of different geometries for measuring flumes are in use today. The suitability of these flumes under various conditions along with the complexity of design varies greatly. In a recent publication (31), yet another geometry is presented. This flow measuring flume, while having some features similar to other flumes in use today, has a few unique characteristics. This flume has a horizontal floor, with an entrance section and an exit section but no throat length (Fig. 16). Hence, this flume has been called a cutthroat flume by its developers.

Previous studies by Robinson, Chamberlain (26) and Hyatt (11, 31) indicate that a flume having a flat-bottom will operate satisfactorily under both free flow and submerged flow conditions. The advantages of a level flume floor as opposed to those having an inclined floor are:

(1) It is easier to construct.

(2) It can be placed inside an existing concrete lined channel.

(3) It can be placed directly on the channel bed.

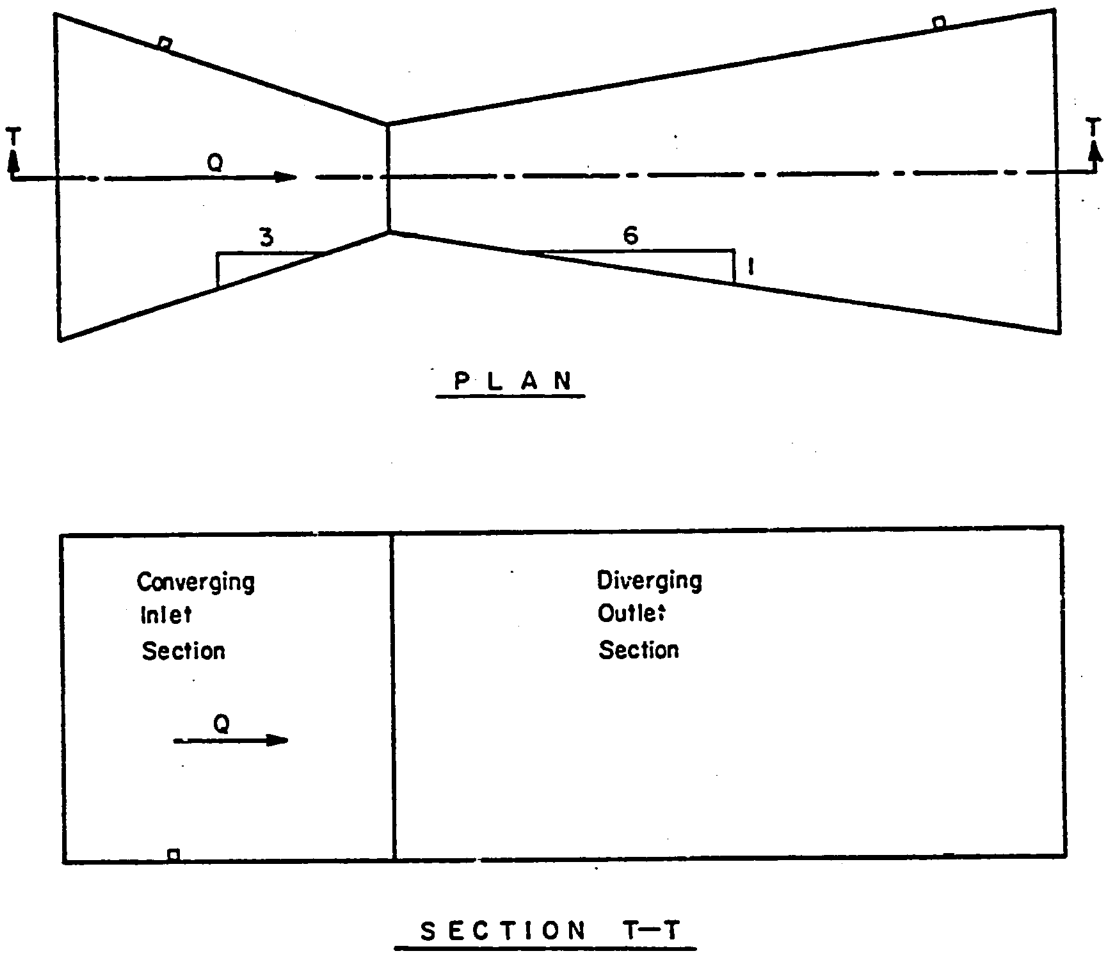


Figure 16. General sketch of cutthroat flume.

In developing the cutthroat flume, an attempt was made to overcome some of the shortcomings of other flow measuring devices which are commonly used. This was accomplished in the following areas:

(1) Submerged flow operations. The cutthroat flume operates well under submerged flow conditions. This will be shown in later chapters.

(2) Low head loss requirement. This is due mainly to the level floor which eliminates the head loss due to elevation difference. Since the flume can be operated under submerged flow conditions, the head loss can be further reduced.

(3) Same geometric shape. Since the angles of convergence and divergence remain the same for all flumes, the flume size is changed by merely moving the walls in or out (sideways). Therefore, ratings for intermediate sized flumes can be developed from the ratings available. This is extremely helpful when flume sizes other than those having a rating are required or a mistake is made in the construction of the throat width.

Ackers and Harrison (1) recommend a maximum convergence of 3:1 for a flume inlet section. The experimental work which led to the development of the cutthroat flume (31) indicated that such a convergence provided satisfactory hydraulic performance. Therefore, a 3:1 convergence (Fig. 16) is used in the entrance section of the cutthroat flume.

Earlier studies by Hyatt (31) indicated that when the divergence of the flume exit exceeded 6:1, flow separation would occur and a major portion of the flow would adhere to one of the side walls. Although numerous divergences and lengths of exit section were tested during the development of the cutthroat flume, the 6:1 divergence (Fig. 16) proved most satisfactory as a balance between flow separation and fabrication costs (31).

Studies regarding the length of the throat section (29), showed that the flow depths measured in the exit section of the flume resulted in more accurate submerged flow calibration curves than ratings employing flow depths measured in the throat section. The water surface profile changes rapidly in the throat section as compared with the exit section where the water surface profile is nearly horizontal. Thus, there appeared to be no apparent advantage in having a throat section. Also, flow conditions in the exit section were improved by removing the throat section (31).

The most obvious advantage of a cutthroat flume is economy, since fabrication is facilitated by a flat-bottom (horizontal floor) and removal of the throat section. The initial investigations were confined to a flume length, L, of 9 feet with throat widths, W, varying from 1 foot to six feet.

CHAPTER 4

METHOD OF FLOW ANALYSIS

As stated earlier, the cutthroat flume can be used to measure flow rates under two different flow conditions; namely, free flow and submerged flow. The flow equation and the method of flow analysis is different for each type of flow.

Free Flow

Under free flow conditions, critical depth occurs in the vicinity of flume neck. This critical depth makes it possible to determine the flow rate knowing only the upstream depth, h_a. This is possible because whenever critical depth occurs in the flume the upstream depth, h_a is not affected by changes in the downstream depth, h_b, as shown in Fig. 17, thereby resulting in a unique relation between discharge, Q, and upstream flow depth, h_a.

For free flow operation a plot is made of flow rate, Q, against upstream depth, H_a, with Q as the ordinate and h_a as the abscissa. When these two variables are plotted on logarithmic paper, all of the points will fall on a straight line as shown in Fig. 18. The equation for this free flow rating can be written as:

$$Q = C\ h_a^{n_1} \qquad (13)$$

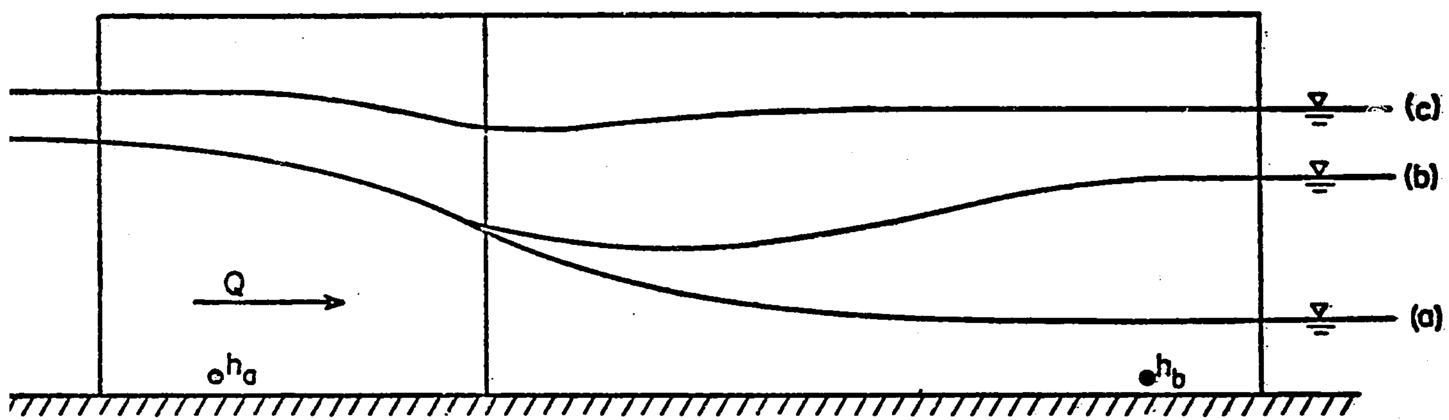


Figure 17. Illustration of flow conditions in a cutthroat flume.

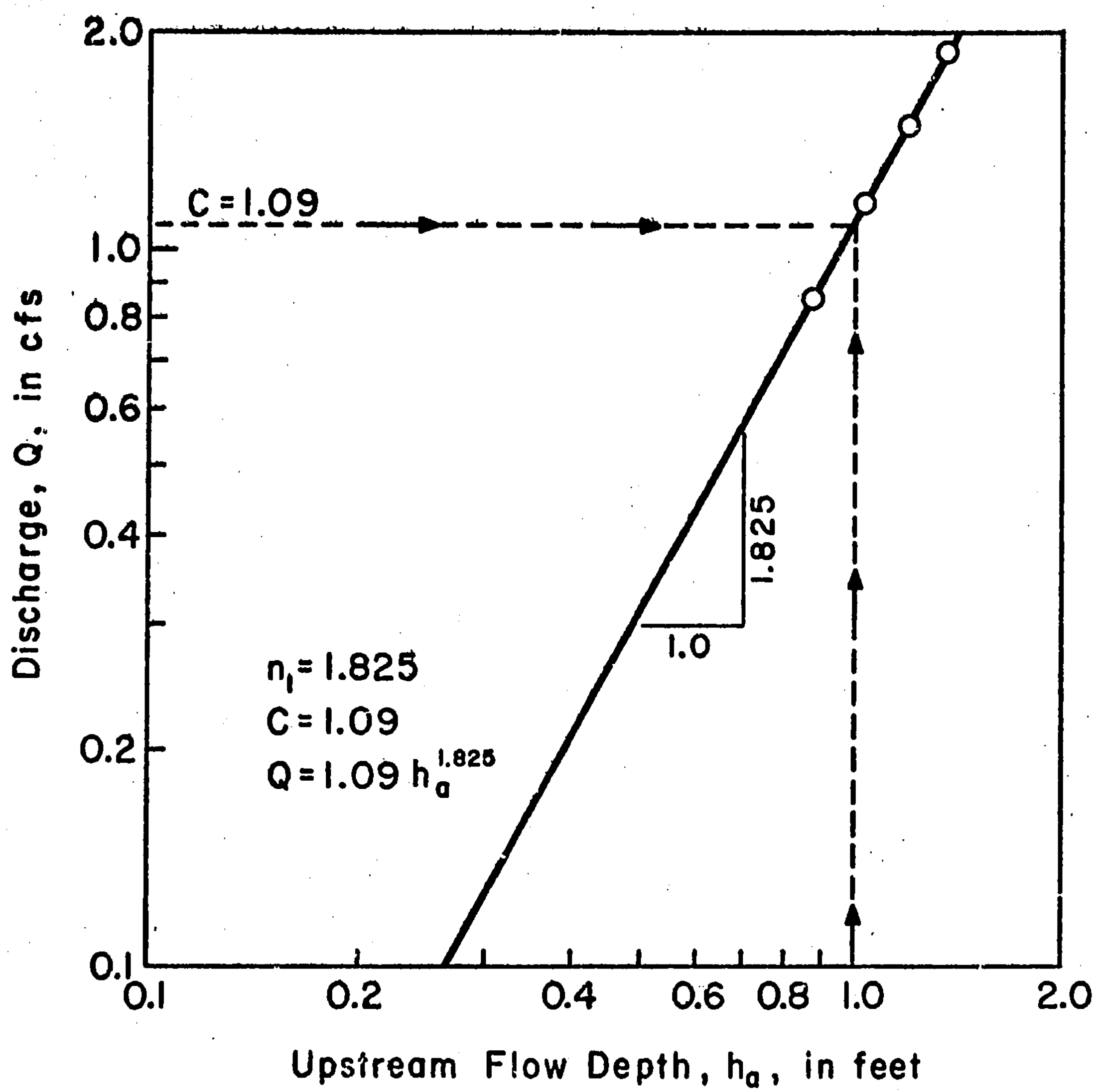


Figure 18. Typical free flow rating curve showing actual data points and development of free flow equation.

where Q = flow rate, in cubic feet per second
C = free flow coefficient which is the value of Q when h_a is 1.0 feet
h_a = upstream flow depth, in feet
n_1 = free flow exponent, which is the slope of the free flow rating when plotted on logarithmic paper.

In previous studies, the free flow plots were drawn by hand and the best fit line determined by sight. In this study, the values of the free flow coefficient, C, and the free flow exponent, n_1, were determined with the help of a digital computer program. The values of Q and h_a were read into the computer and the best fit rating curve determined using a mathematical regression. The values of n_1 and C were then calculated and printed out by the computer. The values were then plotted by hand and compared with the values obtained for the other flumes used in the study. By using the computer, more accurate values for the coefficients could be obtained.

Submerged Flow

When the flow conditions are such that the downstream flow depth, h_b, is raised to the extent that the flow depths at every point through the structure become greater than critical depth, resulting in a change in the upstream depth, then the flume is operating under submerged flow conditions as shown in Fig. 17. A flume operating under submerged flow conditions requires that two flow depths be measured, one upstream (h_a) and one downstream (h_b) from the flume neck. The definition given to submergence, shown as S, is the ratio, often expressed as a percentage, of the downstream depth to the upstream depth:

$$S = h_b/h_a \qquad (14)$$

Submerged flow calibration curves are determined for the cutthroat flume by preparing three dimensional plots of the parameters describing submerged flow. The data is plotted on logarithmic paper with the discharge, Q, as the ordinate; difference in upstream and downstream depths of flow, h_a-h_b, as the abscissa; and the submergence, h_b/h_a, as the varying parameter. Lines are then drawn connecting points of equal submergence. These are straight lines having a slope identical to the slope of the free flow rating curve (which is n_1) for the same geometry.

From the submerged flow plots, an equation has been developed (29) which describes the flow rate through the cutthroat flume. The equation is:

$$Q = \frac{C_1 \ (h_a - h_b)^{n_1}}{\left[-\log(S + C_2)\right]^{n_2}} \qquad (15)$$

where Q = flow rate, in cfs
h_a = upstream flow depth, in ft.
h_b = downstream flow depth, in ft.
C_1 = submerged flow coefficient
n_1 = free flow exponent
C_2 = a constant for the approximate submerged flow distribution
n_2 = submerged flow exponent
S = submergence (h_b/h_a)

For the case of the cutthroat flume, C_2 can be chosen as being equal to zero. Therefore, Equation 15 can be reduced to:

$$Q = \frac{C_1 \ (h_a - h_b)^{n_1}}{(-\log S)^{\ n_2}} \ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

In order to obtain values for n_2 and C_1 for the cutthroat flume, the following steps were taken:

(1) The submerged flow rating plots were drawn for the flume.

(2) The lines of constant submergence were extended until they crossed the abscissa at $h_a - h_b = 1.0$, where the corresponding ordinate value of Q, designated as $Q_{\Delta h\ =\ 1.0}$ is noted (Fig. 19).

(3) A plot is then prepared on logarithmic paper with $Q_{\Delta h\ =\ 1.0}$ plotted on the ordinate and -log S plotted along the abscissa (Fig. 20). A single straight line having a negative slope will result from plotting the data. The general format of the equation describing this relationship is:

$$Q_{\Delta h\ =\ 1} = C_1 (-\log S)^{-n_2} \ldots\ldots\ldots\ldots \quad (17)$$

(4) The submerged flow coefficient, C_1, is the value of $Q_{\Delta h\ =\ 1.0}$ when -log S = 1.0, as illustrated by Fig. 20.

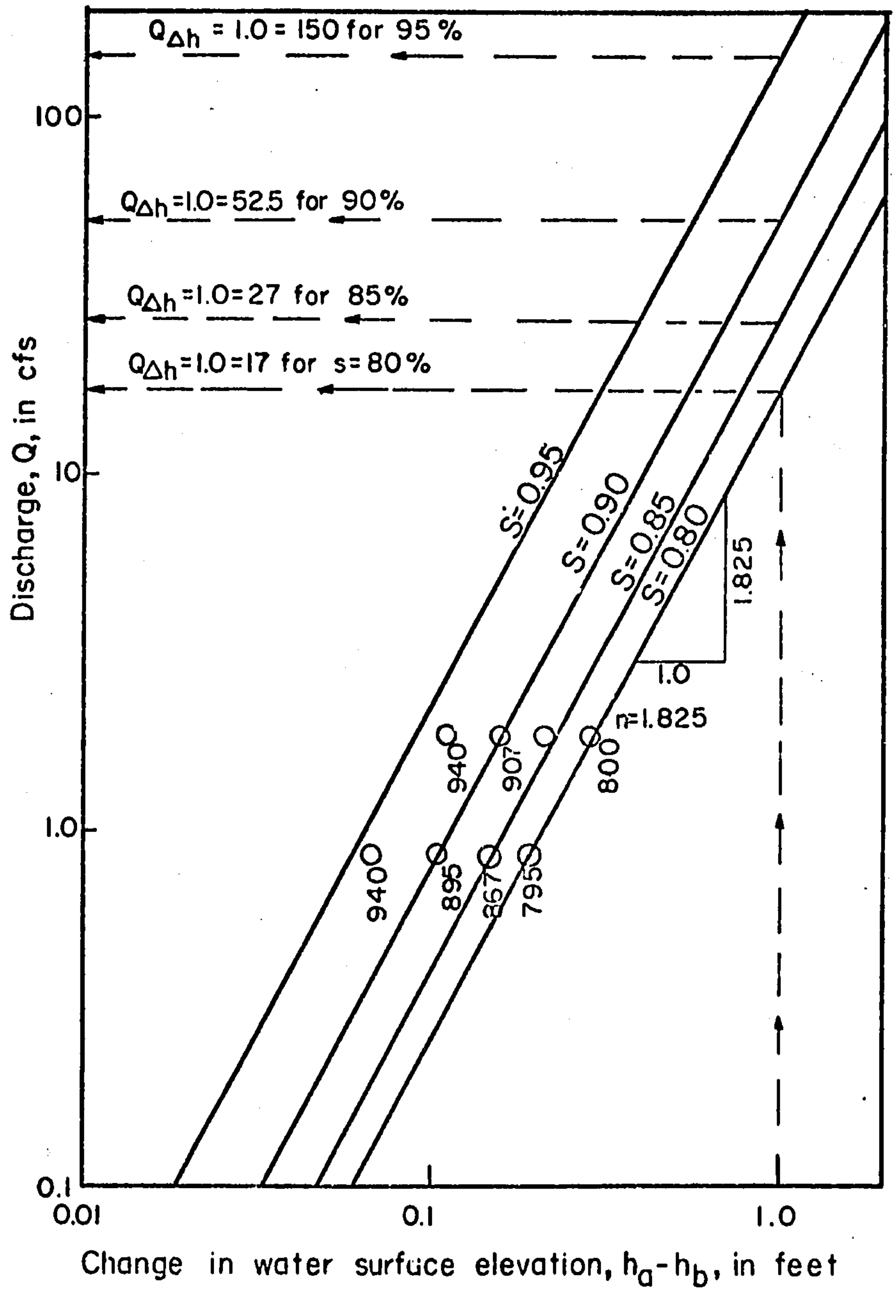


Figure 19. Typical submerged flow rating curve.

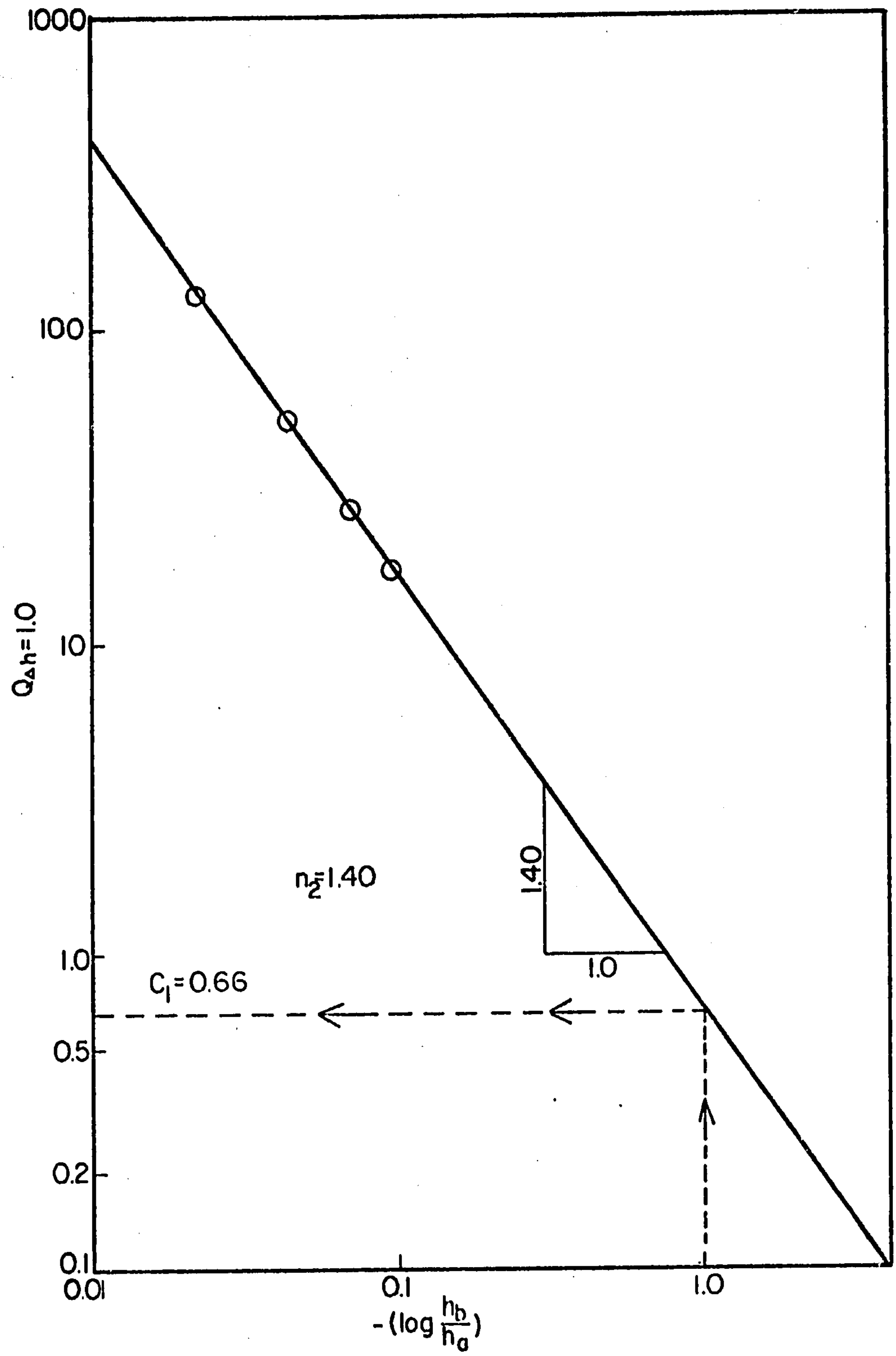


Figure 20. Typical plot for developing submerged flow coefficient, C_1, and submerged flow exponent, n_2.

(5) The submerged flow exponent, n_2 is the slope of the straight-line relationship illustrated in Fig. 20.

The preceeding procedure can be carried out by hand, but for this study it was accomplished using a digital computer. Having determined the values of the constants in the submerged flow equation, it is now possible to evaluate the flow rate for any combination of upstream and downstream flow depth that might be encountered.

The transition submergence, S_t, is the value of submergence at which the discharge passes from free flow to submerged flow, or vice versa (Fig. 17). Under this unique condition, both the free flow equation and the submerged flow equation will predict the same value of discharge.

To determine the transition submergence (S_t), the free flow and submergenced flow equations are set equal to one another.

$$Ch_a^{n_1} = \frac{C_1 \ (h_a - h_b)^{n_1}}{-\log \ (h_b/h_a)^{n_2}} \ \ldots\ldots\ldots\ldots \quad (18)$$

Dividing both sides of Equation 18 by $h_a^{n_1}$ in order to obtain an expression containing only the submergence and known values of coefficients and exponents, and then recognizing that the submergence is really the transition submergence, Equation 18 can be reduced to:

$$-\log \ (S_t)^{n_2} = (C_1 \ / \ C)(1-S_t)^{n_1} \ \ldots\ldots \quad (19)$$

Equation 19 can be solved by trial and error to obtain a value of the transition submergence.

In order to determine whether free flow or submerged flow conditions exist in a cutthroat flume, or any flow measuring flume, it is necessary to calculate the submergence, which is then compared with the transition submergence to determine which flow equation should be used. If the submergence is less than the transition submergence, then free flow conditions exist; but the flume is operating under submerged flow conditions if the submergence is greater than the transition submergence.

CHAPTER 5

EXPERIMENTAL DESIGN

The geometry of the cutthroat flume is extremely simple. The only independent dimensions are flume length, L, and flume width, W (Fig. 21). For any given flume length, the size of flume is changed by simply moving the walls of the flume, which changes the flume width. All dimensions except those dealing with the width of the flume remain constant for any given flume length (Fig. 21).

Because of the simplicity in geometric design for cutthroat flumes, it is possible to develop laboratory discharge ratings for a few sizes and then prepare the ratings for intermediate sizes by interpolation. Thus, in order to develop generalized discharge relationships for cutthroat flumes it is only necessary to rate some flumes which cover the desired range of flume length and throat width.

In choosing the flumes for this study, it was decided to use three flume lengths; namely, 1.5 feet, 3.0 feet, and 4.5 feet. In addition to these lengths, it was possible to use the results of the initial studies in which a flume length, L, of 9.0 feet was used (31). The throat widths selected were based on four width to length (W/L) ratios; namely, 1/18, 1/9, 2/9, and 4/9 (Fig. 22 and 23). The range of these width to

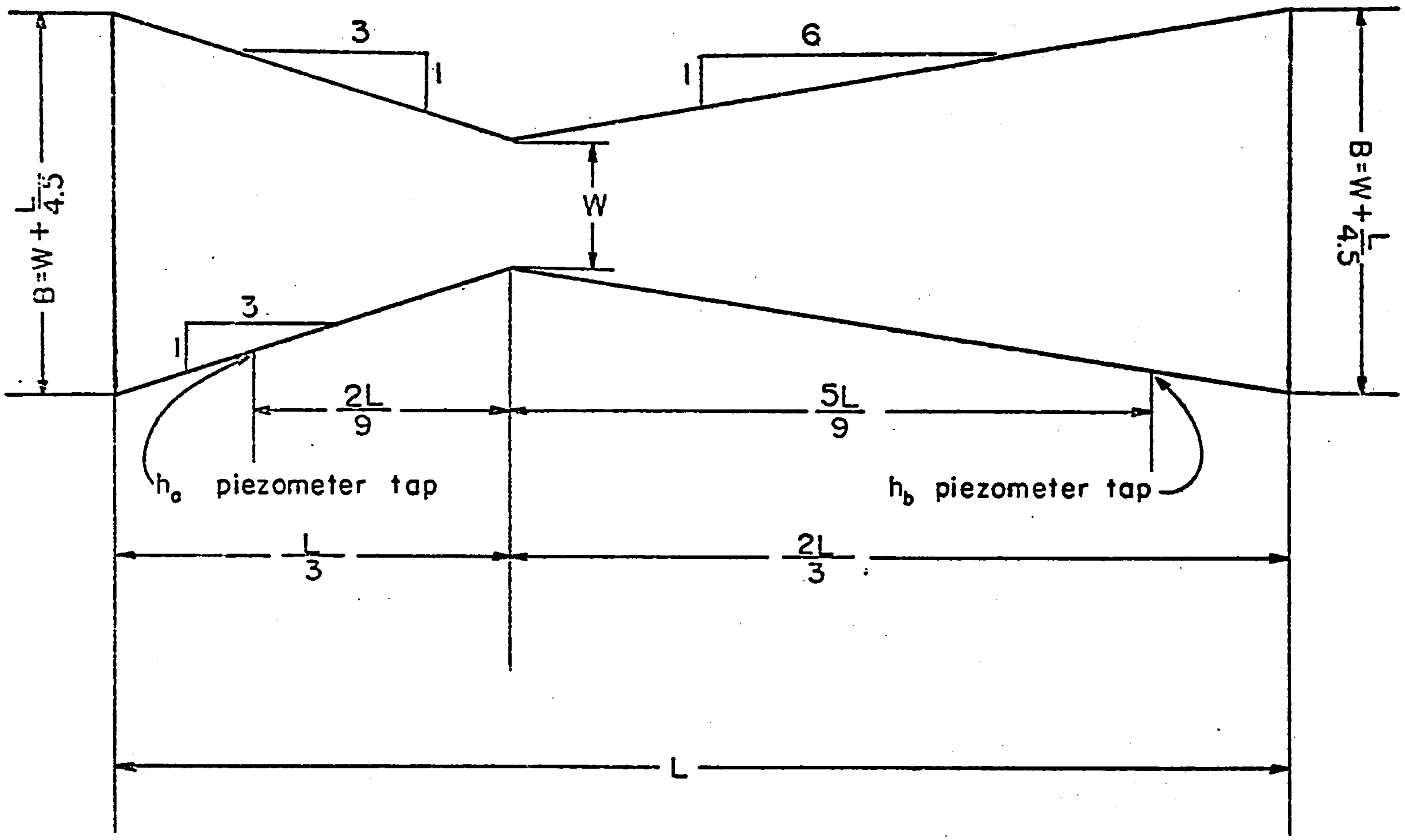


Figure 21. Definition sketch of cutthroat flume.

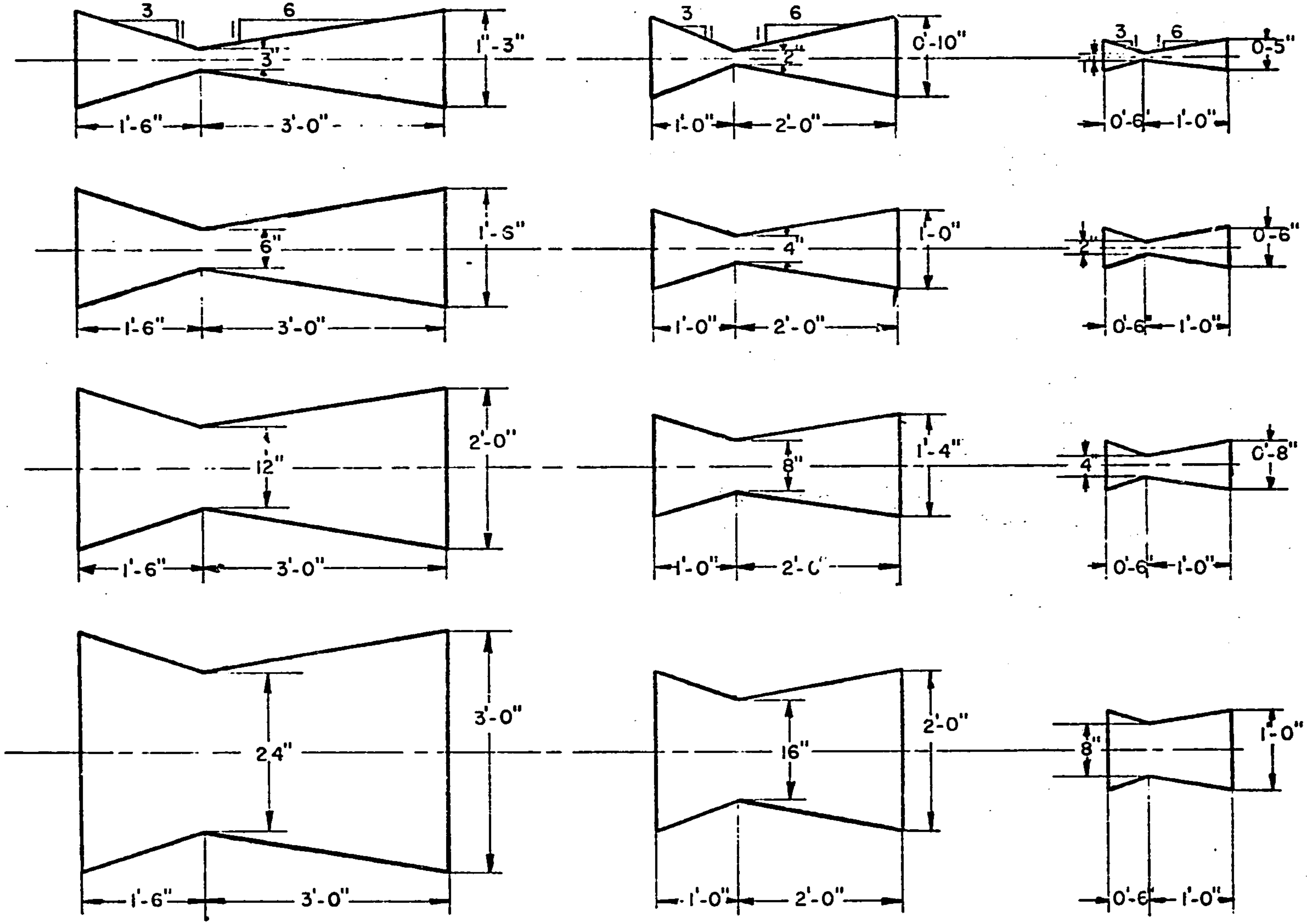
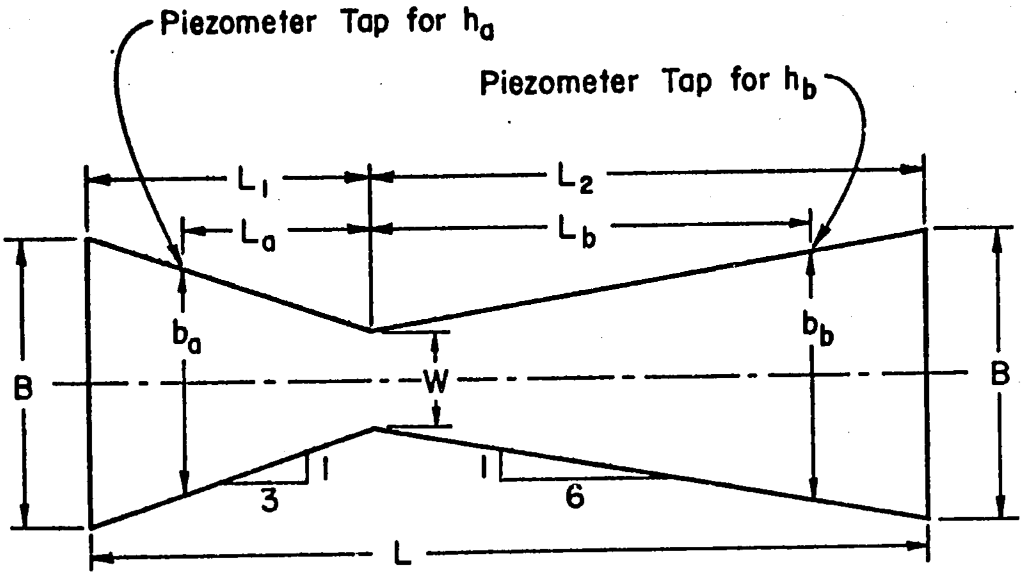


Figure 22. Cutthroat flumes used in experimental design.

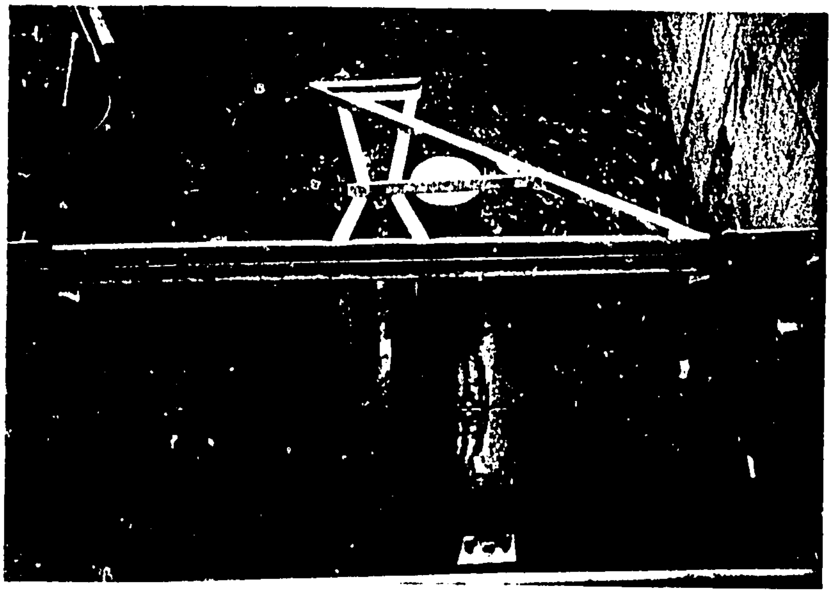


$$B = W + \frac{2}{3} L_1 = W + \frac{1}{3} L_2$$

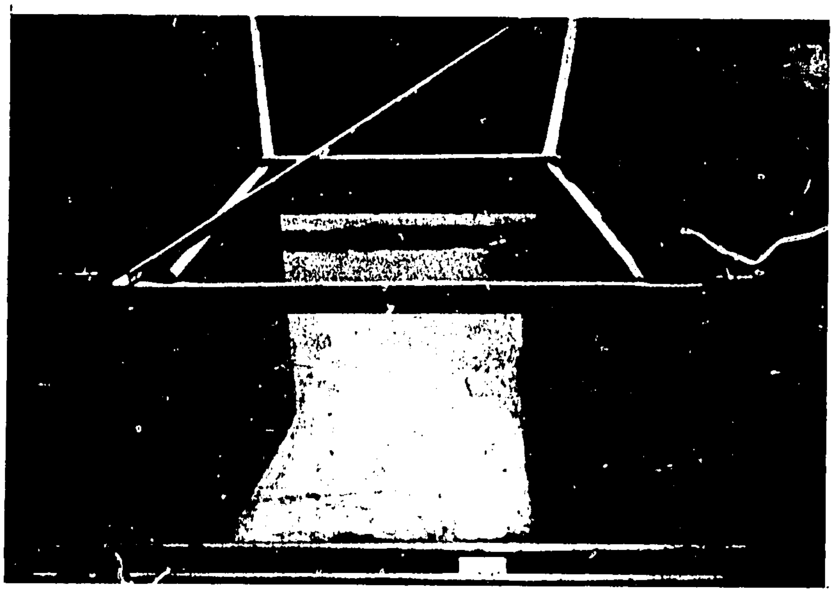
Flume	W	L_1	L_2	L_a	L_b	L	B
3"x4.5'	3"	1'-6"	3'-0"	1'-0"	2'-5½"	4.5'	1'-3"
6"x4.5'	6"	1'-6"	3'-0"	1'-0"	2'-5½"	4.5'	1'-6"
12"x4.5'	12"	1'-6"	3'-0"	1'-0"	2'-5½"	4.5'	2'-0"
24"x4.5'	24"	1'-6"	3'-0"	1'-0"	2'-5½"	4.5'	3'-0"
2"x3.0'	2"	1'-0"	2'-0"	0'-8"	1'-7⅝"	3.0'	0'-10"
4"x3.0'	4"	1'-0"	2'-0"	0'-8"	1'-7⅝"	3.0'	1'-0"
8"x3.0'	8"	1'-0"	2'-0"	0'-8"	1'-7⅝"	3.0'	1'-4"
16"x3.0'	16"	1'-0"	2'-0"	0'-8"	1'-7⅝"	3.0'	2'-0"
1"x1.5'	1"	0'-6"	1'-0"	0'-4"	0'-9⅞"	1.5'	0'-5"
2"x1.5'	2"	0'-6"	1'-0"	0'-4"	0'-9⅞"	1.5'	0'-6"
4"x1.5'	4"	0'-6"	1'-0"	0'-4"	0'-9⅞"	1.5'	0'-8"
8"x1.5'	8"	0'-6"	1'-0"	0'-4"	0'-9⅞"	1.5'	1'-0"

Figure 23. Dimensions of cutthroat flumes used in experimental design.

length ratios is illustrated in Fig. 24 which shows a 1 in. by 1.5 ft. and a 24 in. by 4.5 ft. flume installed in the laboratory flume. By selecting the four width to length ratios, the throat widths of the flumes for any one length vary from each other by a factor of two. Also, the flumes of a given width to length ratio are scale models of each other with a scale factor of two. In addition, the small flumes are scale models of all the larger flumes having the same width to length ratio. For example, the 2 in. by 1.5 ft. flume is a 1/2 model of the 4 in. by 3 ft. flume; a 1/3 model of the 6 in. by 4.5 ft. flume; and a 1/6 model of the 12 in. by 9 ft. flume (Fig. 25). By designing the flumes using these criteria, a two way comparative analysis can be made. That is, it can be determined what effect doubling the flume width has on the flow coefficients while the length of the flume remains constant. Secondly, a model analysis can be made using the Froude number with scale ratios of 1/2, 1/3, and 1/6. Having a two way check on the results makes it possible to further refine the development of generalized flow coefficients and exponents.



(a) Cutthroat flume having 1 inch throat width and 18 inch flume length.



(b) Cutthroat flume having 24 inch throat width and 54 inch flume length.

Figure 24. Comparison of a small and large cutthroat flume installed in laboratory test channel.

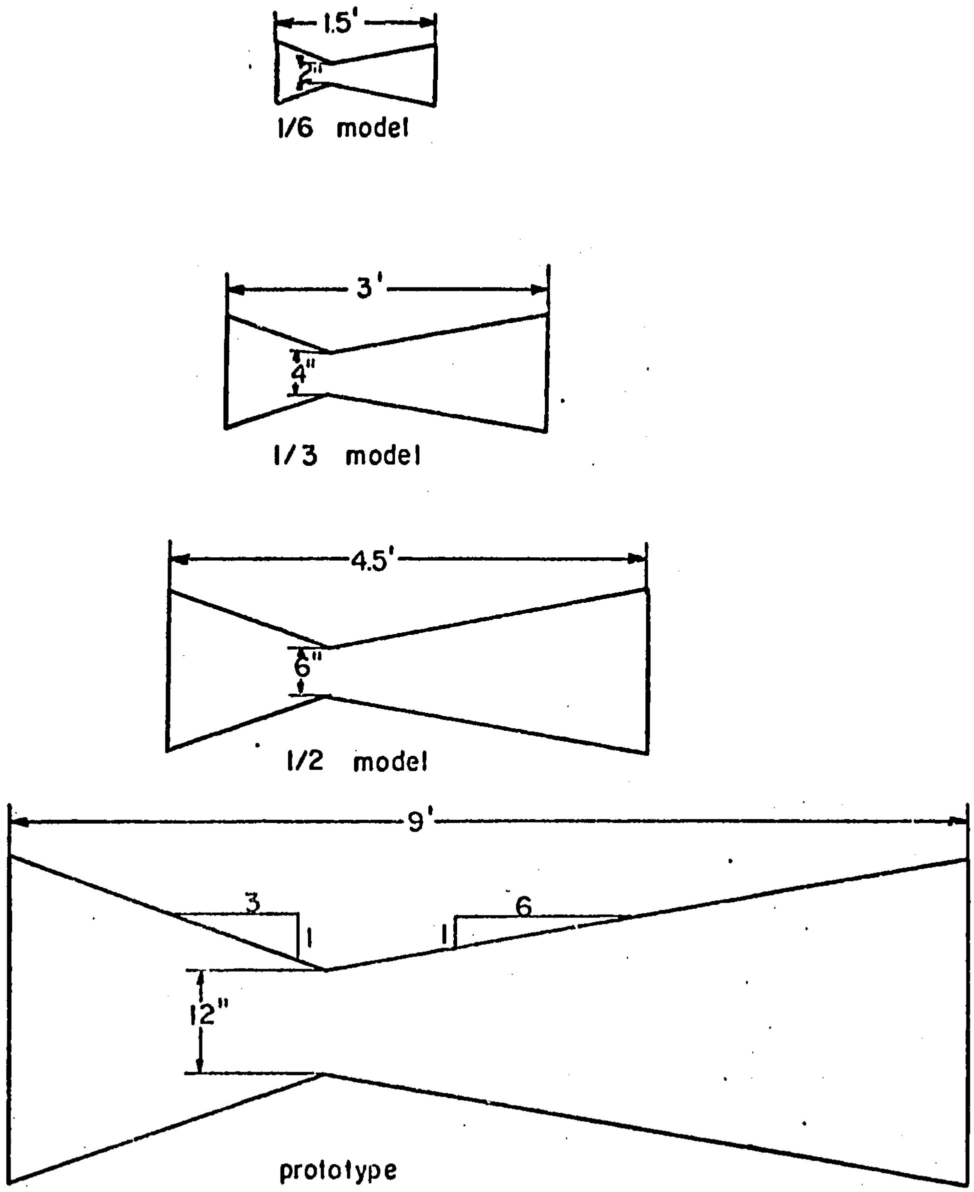


Figure 25. Schematic representation of scale model ratios.

CHAPTER 6

EXPERIMENTAL FACILITIES

The data for this study were collected using a test channel located in the Fluid Mechanics Laboratory of the Engineering and Physical Science Building at Utah State University, Logan, Utah (Fig. 26). The test channel is 5 feet wide, 5 feet deep and 100 feet long. The water is supplied from a sump located under the building and is circulated by four deep well turbine pumps and one propeller pump. Each pump can be operated individually or in parallel, which allows for a fairly large range of flow rates. The discharge from the pumps varies only slightly with head, which minimized fluctuations in the flow rate due to the water level in the sump.

The water is transported from the pumps to the head of the test channel by a 12 in. diameter pipeline which is located along the ceiling of the laboratory. The flow is then dropped vertically in the pipeline into the test channel. Therefore, once a flow rate is set, the level of water in the test channel has no effect on the flow rate because there is a constant head on the pumps caused by the vertical lift to the pipeline which is constant. Also, the headloss through the pipeline is constant for a given flow rate.

Figure 26. Experimental facility with recessed test channel.

The water is very turbulent when it emerges from the pipe, which could cause large fluctuations in flow depth throughout the length of the channel. This turbulence is removed by installing a wire basket filled with gravel across the test channel, just below the pipeline outlet.

One of the foremost problems in installing small test structures into a channel is assuring a leak proof seal around the test structure. The test channel used in this study has a unistrut located at a point 1/3 of the channel length from the inlet. This unistrut is 1 inch wide, 1½ inches deep and goes around the perimeter of the test channel as can be seen in Fig. 27. A headwall was fitted into the unistrut, a strip of rubber sealer was attached to the headwall and then wedged tightly into the unistrut to provide a watertight seal. The headwall was constructed in such a manner to allow easy installation and removal of the flumes by connecting the headwall with the cutoff wall attached to each flume.

The flumes used in this study were constructed of medium gauge galvanized steel. This provided a sturdy structure that was light weight for easy handling. Galvanized steel is an ideal material for laboratory work because it can be fastened to make watertight joints and also is resistant to dimension or roughness changes due to the repeated wetting and drying required to collect the needed hydraulic data. The upstream end of each flume was constructed with a cutoff wall which was matched to a cutoff wall installed in a unistrut located in

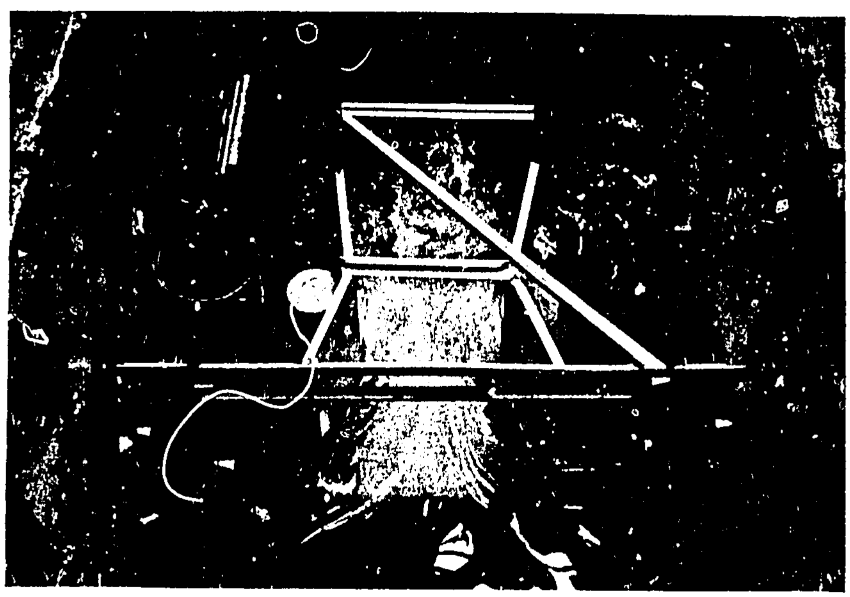


Figure 27. Installation of cutthroat flume in test channel.

the laboratory test channel. Rubber gasket was placed around the periphery of each cutoff wall. This provided a water tight seal, while allowing for easy installation of the flumes.

The flumes were each equipped with piezometer taps located at the bottom of the flume wall as shown in Fig. 21. These piezometer taps were connected by means of rubber hose to stilling wells, which were used to measure the flow depths, h_a and h_b, in each flume.

Each stilling well was one foot in diameter. The piezometer taps on the flume were 1/2 inch in diameter and provided satisfactory damping of the water level fluctuations in the stilling well. The water level in the stilling wells was measured using a hook gage equipped with a vernier which could be read to an accuracy of 0.001 ft.

The test channel was fitted with an adjustable overflow structure near the downstream end (Fig. 28). This consisted of a gate fastened to the channel floor with a hinge. The gate was raised using a winch and could be set at any level desired. By varying the height of this gate, the submergence on the cutthroat flume could be varied over the desired range of interest for this study.

The water, after passing through the test channel, is directed into one of two weighing tanks. Each of these tanks has a capacity of 26,000 pounds and the scale is accurate to the nearest 5 pounds. The time required to fill the tank was

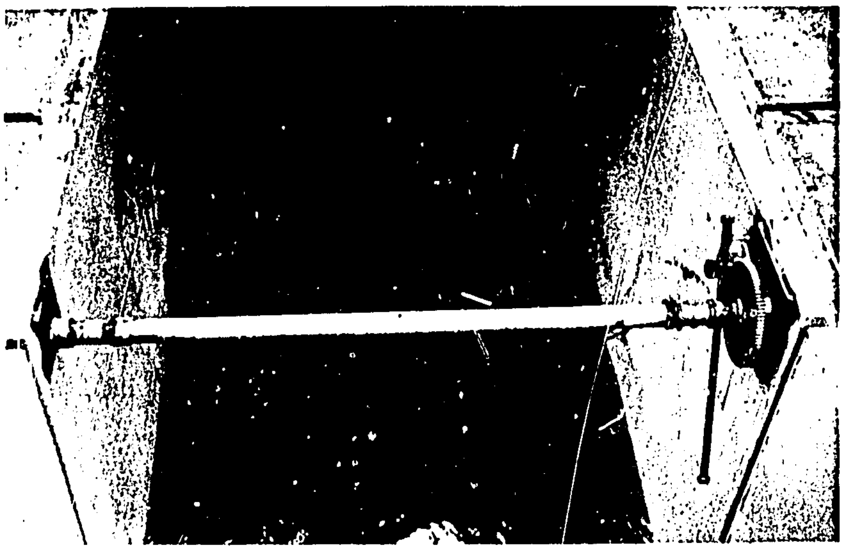


Figure 28. Overflow structure used to control downstream flow depths.

determined using a stop watch. Five readings were taken and the times averaged. The flow rate was then calculated to the nearest 0.01 cfs. It was felt that with this facility and using reasonable care it was possible to obtain very accurate data.

CHAPTER 7

RESULTS

The main purpose of this study has been to explore the possibility of developing a general method for describing the discharge characteristics of cutthroat flumes. With generalized discharge ratings, both the free flow and submerged flow equations can be computed for any size of cutthroat flume without having to physically rate the flume. The experimental design covers a range of flume length, L, from 18 inches to 9 feet, while the throat width, W, was varied from 1 inch to 6 feet. The ratios of throat width to flume length (W/L) used in the analysis varied from 1/18 to 4/9.

Generalized discharge relations are especially valuable when an installation requires an unusual flume size, or when errors are made in constructing the structure. An example of this would be in setting the forms for a concrete flume wherein the throat width turned out to be 12 1/2 inches when a 12 inch width was desired. By using the findings of this study, a rating could be computed for a 12 1/2 inch cutthroat flume.

In order to develop generalized discharge ratings, there must be a consistant and identifiable relationship between the ratings for dimensionally similar flumes. This required that some small adjustments be made to the rating curves for some of the flumes. It should be noted, however, that these adjustments are small and that all data points on the graphs that follow are actual data. The lines drawn through the points are positioned such that a consistent relationship exists for all flumes studied.

Free Flow Discharge Relations

When critical depth occurs in a flow measuring flume, the flume is considered to be operating under free flow conditions. Under this condition, the upstream flow depth is unaffected by changes in the downstream flow conditions. Therefore, the flow rate through the flume can be determined using only the upstream depth.

As was shown in Chapter 4, the free flow rating curve is developed for a measuring flume by plotting flow rate, Q, against upstream flow depth, h_a, with Q as the ordinate and h_a as the abscissa. When plotted on logarithmic paper, the points will fall on a straight line. Therefore, the first step in the free flow analysis is to plot the data as described above. For comparison purposes, two methods of grouping the data were tried; namely, grouping by flume length, L, and by throat width, W. It was found that with small corrections, the slope, n_1, of the free flow curve was a constant for all flumes of equal length. Therefore, n_1 is dependent only on the length of the flume.

The next step in the analysis was to determine if there was a consistant relationship among the values of the free flow coefficient, C, for the various flumes. A plot was made on logarithmic paper of C against W, with C as the ordinate and W as the abscissa. It was found that the points plotted as a straight line for flumes of equal length. Furthermore, with small changes, the lines for all four flume lengths were parallel. This adjustment was made and a new free flow rating curve prepared for each flume using the adjusted C and n_1 values. The new graphs were then compared with the original data. The entire process was repeated until the difference between the original plots and the corrected plots was minimized.

It was found that values of n_1 and C are not independent for each flume size. Therefore, if the value of n_1 or C is changed for one flume size, the values are also changed for all other sizes of flumes. The values for n_1 and C for a given flume size are therefore unique.

As a further check, the free flow plots for the nine foot cutthroat flumes reported by Skogerboe, Hyatt, Anderson, and Eggleston (31) were also compared with those obtained in this study.

The final free flow rating curves for flume lengths of 1.5, 3.0, and 4.5 feet are shown in Figs. 29, 30 and 31, respectively. The data points shown on the graphs are original

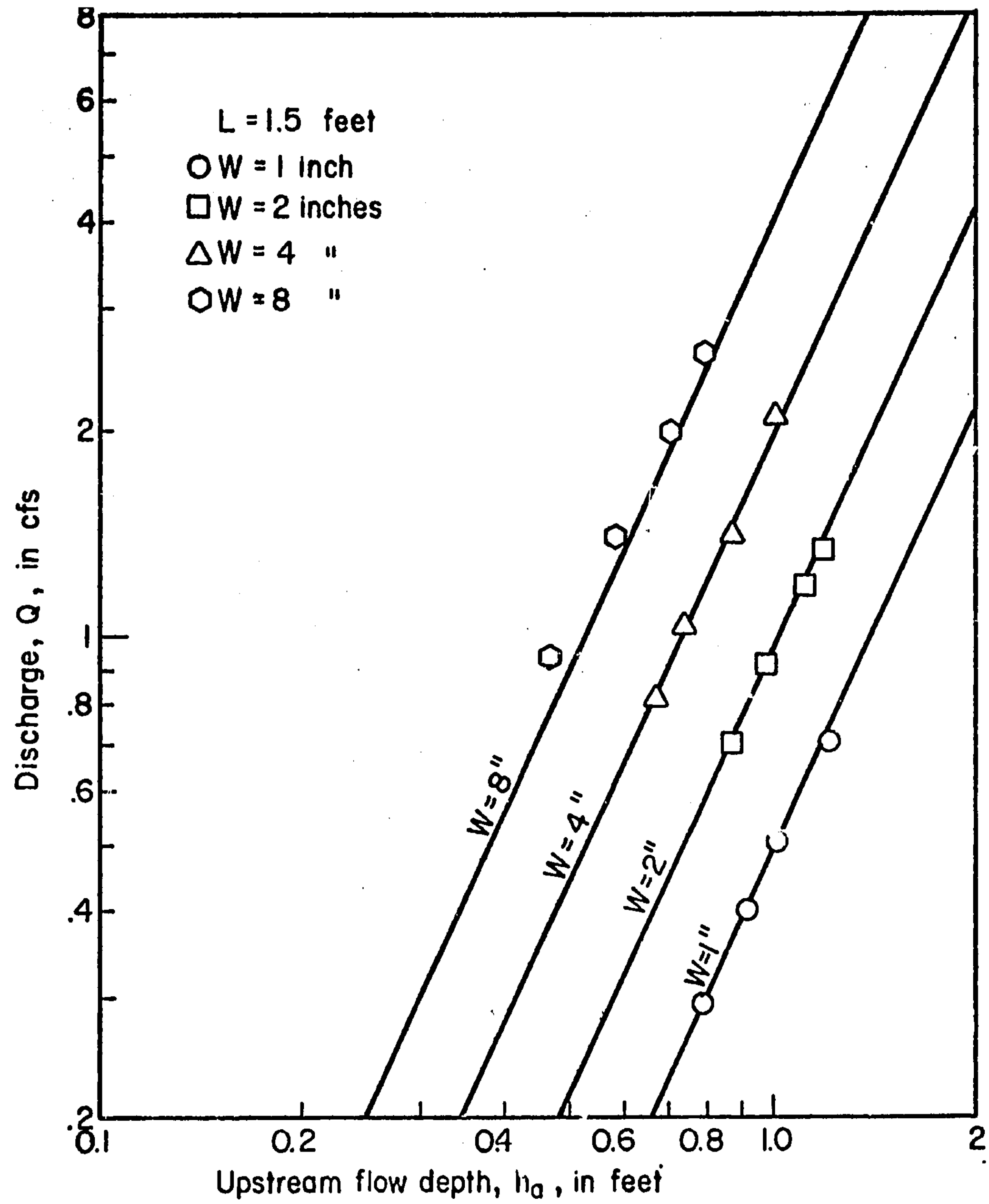


Figure 29. Free flow discharge ratings for flume length of 1.5 feet.

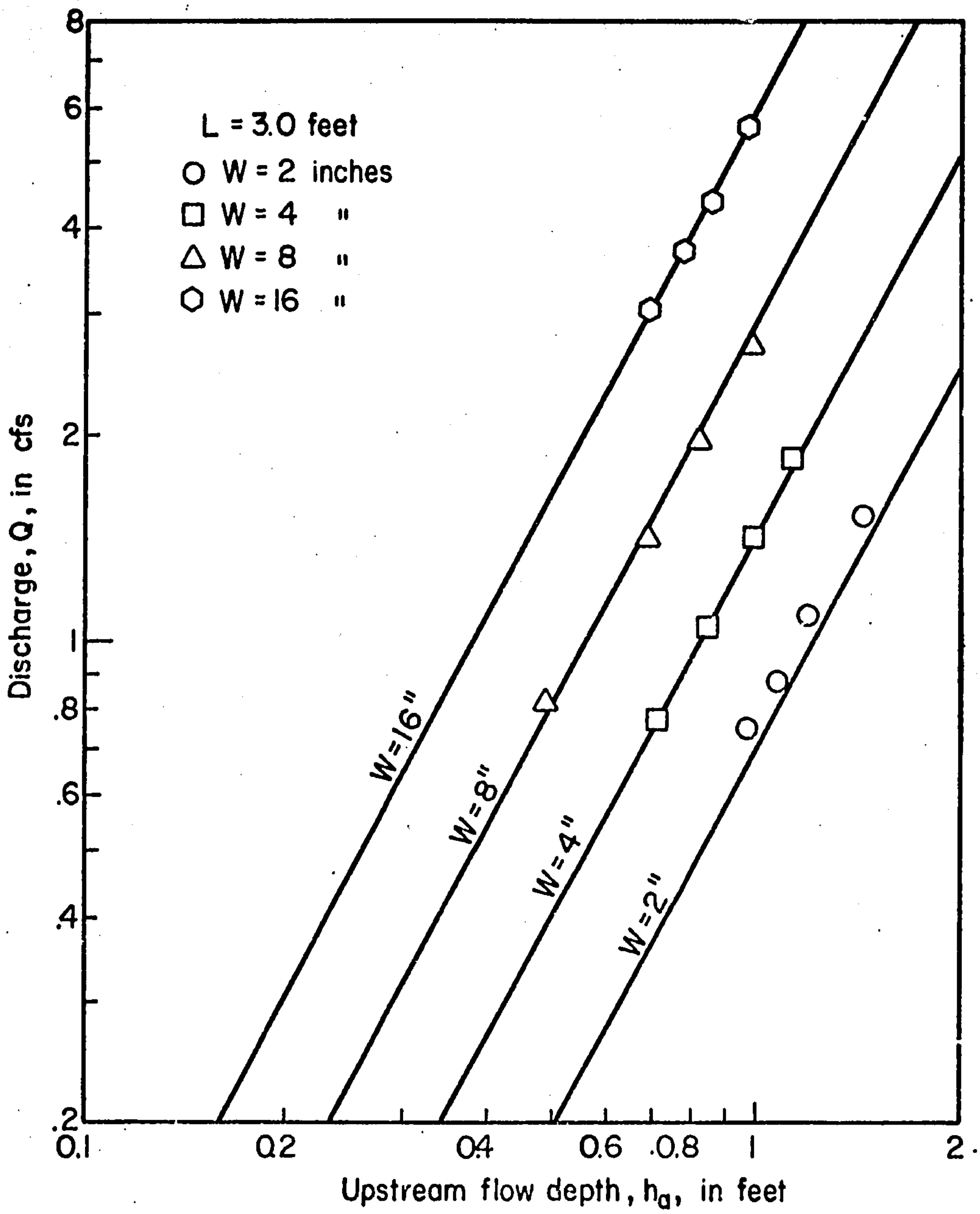


Figure 30. Free flow discharge ratings for flume length of 3 feet.

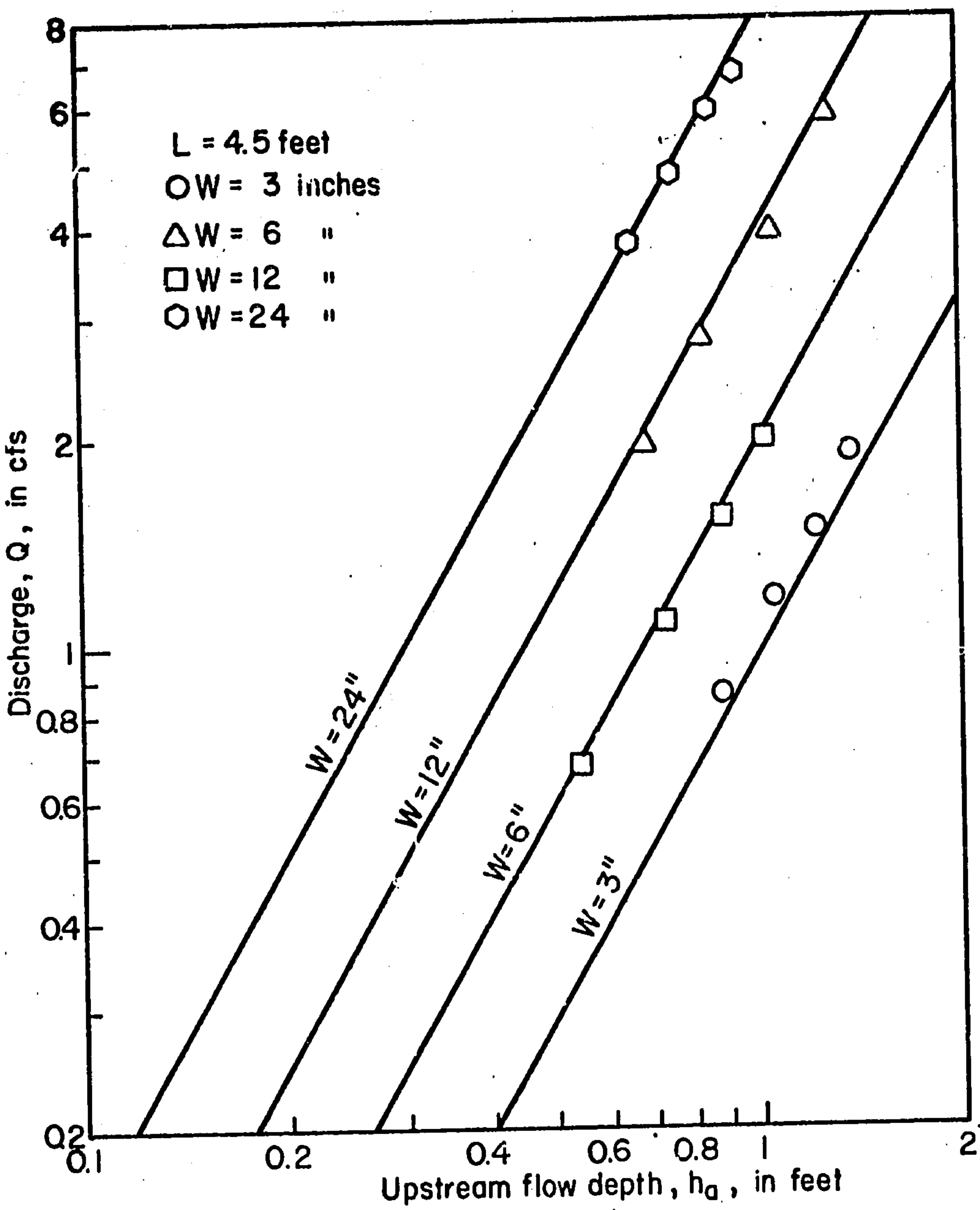


Figure 31. Free flow discharge ratings for flume length of 4.5 feet.

and unaltered and are shown for comparative purposes. The rating curves reported for the 9 foot flumes (29) are shown in Fig. 32.

The first time the lines were drawn on these plots, they were drawn as the best-fit line through the data points for each flume size. There was no attempt made to correlate the ratings between flume sizes. A comparison of the ratings disclosed that the ratings were at almost the same slope for identical flume lengths. Therefore, the lines were all adjusted to an average slope and spaced uniformly on the page for each flume length. As can be seen the error introduced by this procedure is small. For each flume length, there are three of the four flume widths for which the ratings fit the data points very closely, with one rating in each group having a larger error. However, this error is still small for all flumes and was attributed to scale effects resulting from very curvilinear flow and non-hydrostatic pressure distribution since it was most apparent in the small flumes.

The equation for the free flow rating can be written for each flume. In general form, the equation is as follows:

$$Q = C h_a^{n_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

where Q = flow rate, in cfs
C = free flow coefficient
h_a = upstream flow depth in feet
n_1 = free flow exponent

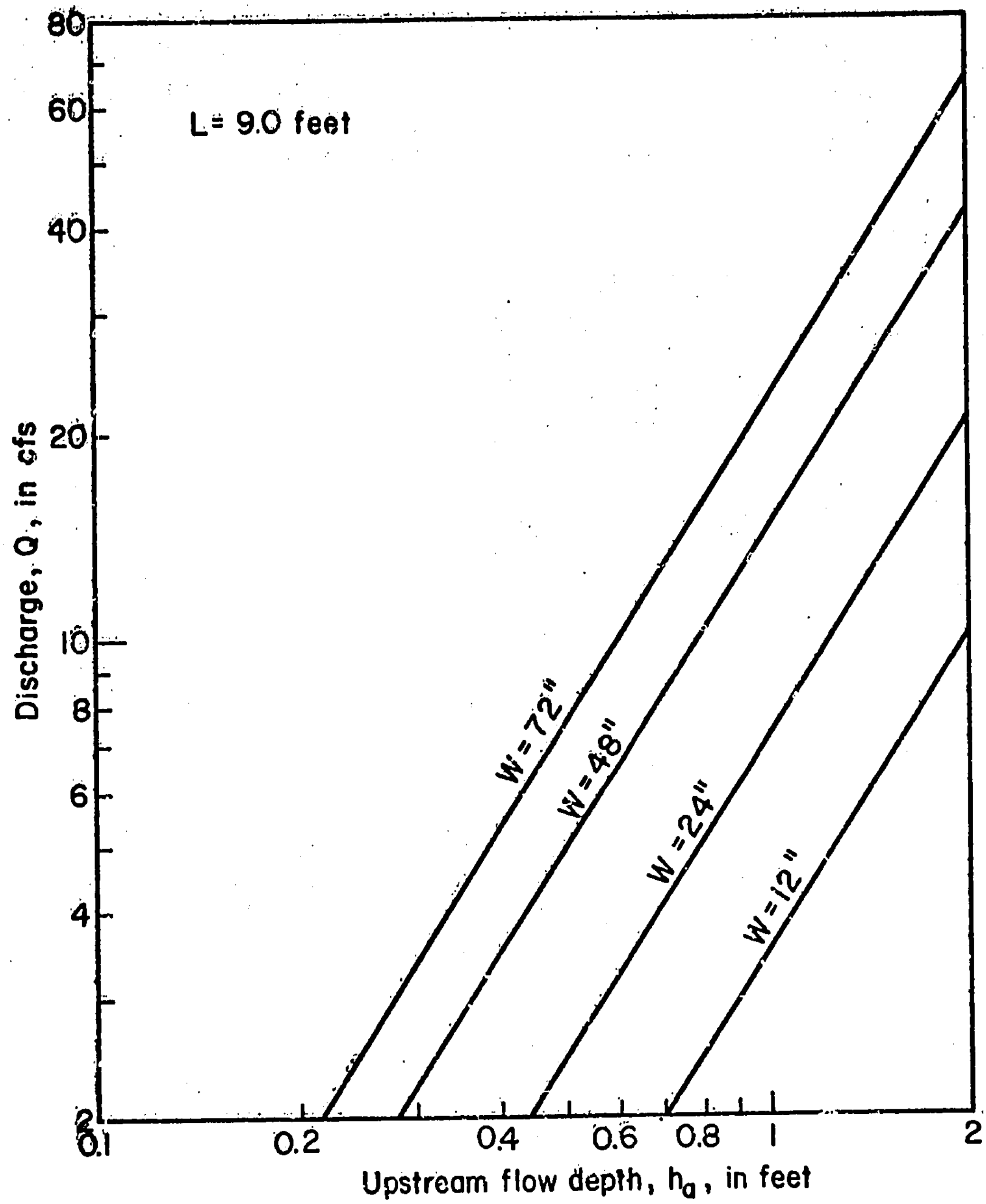


Figure 32. Free flow discharge ratings for flume length of 9 feet.

The values of n_1 and C for the various flumes tested are shown in Table 2.

The final adjusted curves showing the relationships between the free flow coefficient, C, and throat width, W, are shown in Fig. 33. From these curves, the equation for determining the value of C to be used for a given flume size can be written as follows:

$$C = KW^{1.025} \quad \text{.......................} \quad (20)$$

where C = free flow coefficient
K = free flow flume length coefficient
W = flume throat width in feet.

The value of K, which is a constant for any particular flume length, is listed in Table 2 for the flume lengths studied.

The free flow rating for any size of cutthroat flume can now be developed by interpolating to find the value of K for the desired flume throat width Fig. 34 and then using Equation 20 to calculate the free flow coefficient, C, for this flume. The value of the free flow exponent, n_1, can also be determined from Fig. 34 for any chosen flume length. These values of C and n_1 are then used in Equation 13 to calculate the flow rate through the flume for any given upstream flow depth, h_a.

Submerged Flow Discharge Relations

A flow measuring flume is operating under submerged flow conditions when the minimum flow depth occurring in the flume is greater than critical depth. Under these conditions, a

Table 2. Free flow coefficients and exponents for experimental cutthroat flumes.

Flume	12" x 9.0'	3" x 4.5'	2" x 3.0'	1" x 1.5'
C	3.50	0.960	0.719	0.494
n_1	1.560	1.720	1.840	2.150
K	3.500	3.980	4.500	6.100

Flume	24" x 9.0'	6" x 4.5'	4" x 3.0'	2" x 1.5'
C	7.11	1.960	1.459	0.974
n_1	1.560	1.720	1.840	2.150
K	3.500	3.980	4.500	6.100

Flume	48" x 9.0'	12" x 4.5'	8" x 3.0'	4" x 1.5'
C	14.49	3.980	2.970	1.975
n_1	1.560	1.720	1.840	2.150
K	3.500	3.980	4.500	6.100

Flume	72" x 9.0'	24" x 4.5'	16" x 3.0'	8" x 1.5'
C	22.0	8.010	6.040	4.030
n_1	1.560	1.720	1.840	2.150
K	3.500	3.980	4.500	6.100

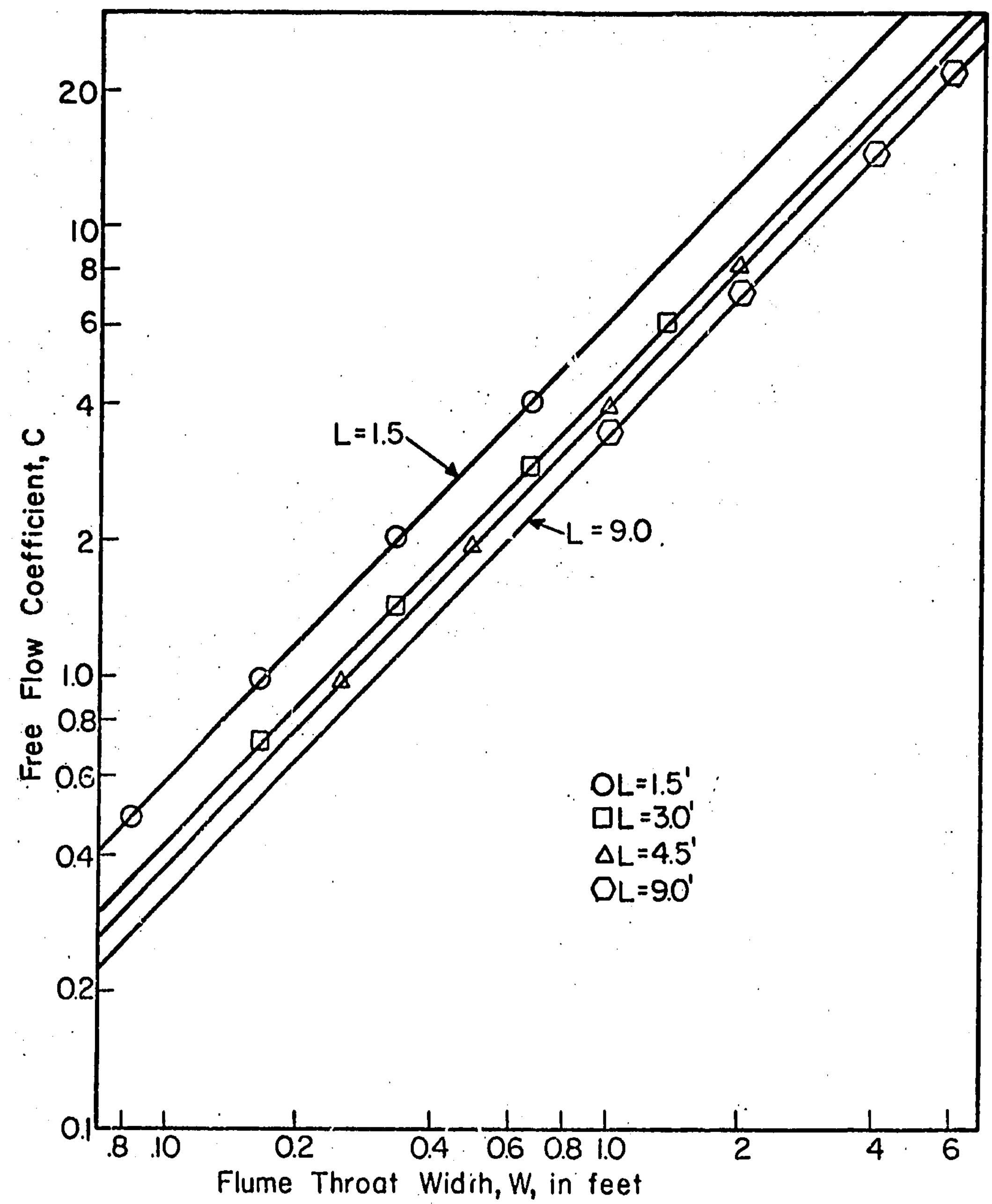


Figure 33. Free flow relationships between flume length, flume throat width, and free flow coefficients.

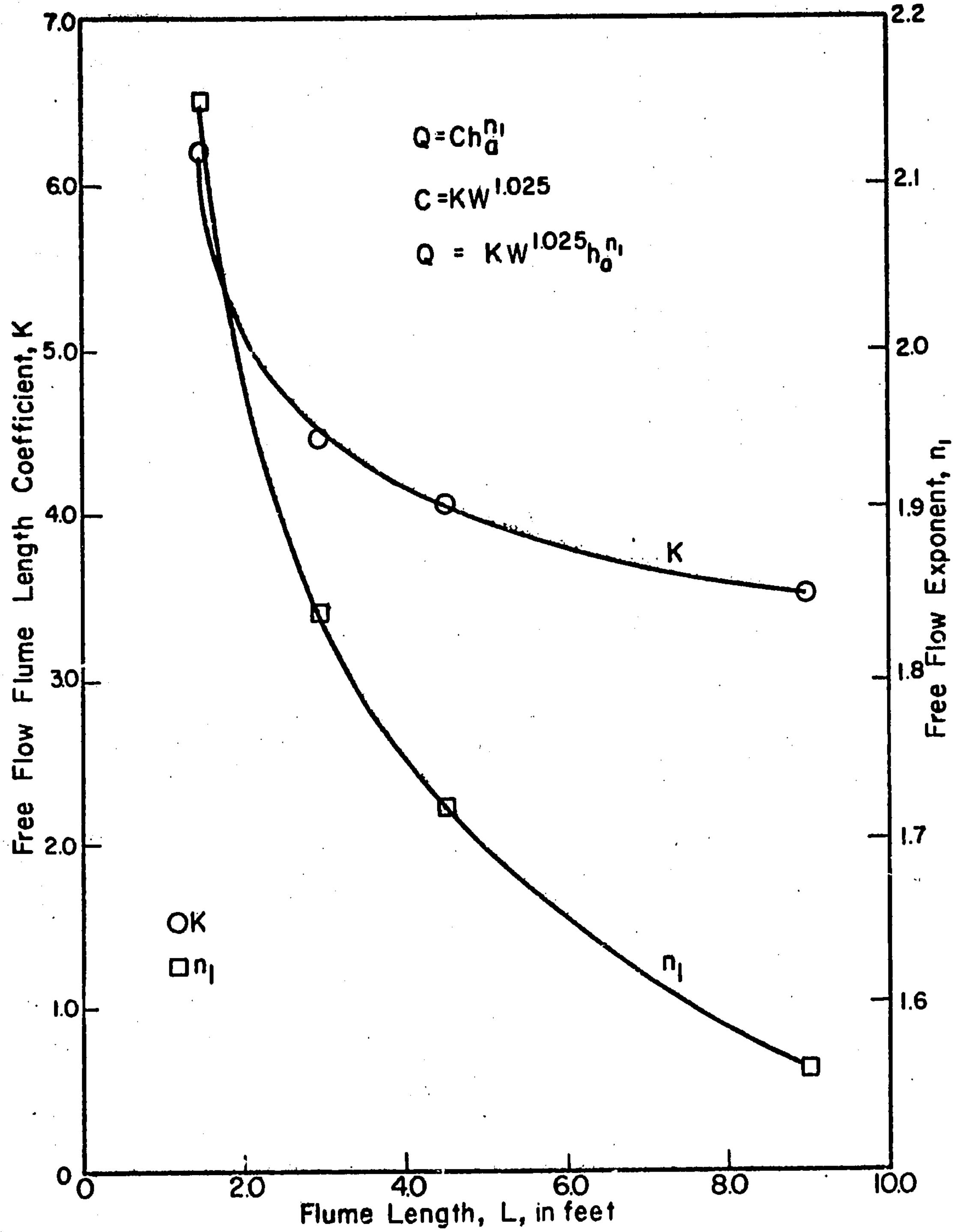


Figure 34. Generalized free flow ratings for cutthroat flumes.

rise in the downstream flow depth will cause the flow depth to rise at all points throughout the flume. In order to obtain an accurate discharge rating for the structure under these conditions, both the upstream, h_a, and downstream, h_b, flow depths must be measured.

The general method for developing a submerged flow rating for a measuring flume is presented in Chapter 4. This method was used to analyze the data collected in this study; however, certain refinements in the analysis were made possible by the use of a digital computer program to remove some of the error due to human judgement.

The first step in the analysis is to prepare a three dimensional plot of the submerged flow data with the flow rate, Q, as the ordinate, upstream depth minus downstream depth, Δh, as the abscissa, and submergence, S, as the varying parameter as illustrated in Fig. 19. When the data are plotted on logarithmic paper, a family of parallel lines can be drawn with each line representing a constant value of submergence. The slope of these lines is equal to n_1 for the given flume. This step in the procedure can be accomplished by hand and the best fit line assumed by sight. For this study, however, the digital computer was used and the best fit line was determined by a mathematical regression. This method provided more accurate and consistant results. This curve produces the entire rating necessary for a single flume size.

The general equation used for the submerged flow analysis is:

$$Q = \frac{C_1 \; (h_a - h_b)^{n_1}}{(-\log\; S)^{n_2}} \;\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

where Q = flowrate in cfs
C_1 = submerged flow coefficient
h_a = upstream flow depth
h_b = downstream flow depth
n_1 = free flow exponent
S = submergence, h_b/h_a
n_2 = submerged flow exponent

The value of n_1 has already been determined to be a constant with flume length based upon the free flow analysis in the previous section. The purpose of the submerged flow analysis is to first of all determine values of C_1 and n_2 for eacl experimental cutthroat flume; then, attempt to develop generalized relations for C_1 and n_2.

In order to investigate the possibility that a consistan relationship exists among the parameters in the submerged flo equation, plots yielding the value of n_2 and C_1 for each flum must be prepared based upon the submerged flow graphs describ ed immediately above. This procedure consists of plotting th value of Q at $\Delta h = 1.0$, which is designated by the symbol $Q_{\Delta h = 1.0}$ against -log S on logarithmic paper with $Q_{\Delta h = 1.0}$ as the ordinate and -log S as the abscissa. When the data are plotted on logarithmic paper, the data points will fall on a straight line with the slope equal to $-n_2$ and the value of $Q_{\Delta h = 1.0}$ at $-\log S = 1$ will be the submerged flow coefficient, C_1, for that particular flume size.

In the computer program, the preparation of submerged flow graphs relating Q, Δh, and S was bypassed. Since the value of n_1 was already known for each flume, the method of analysis was to write a simple equation for each data point having the form:

$$Q = Q_{\Delta h = 1.0} (\Delta h)^{n_1} \ldots\ldots\ldots\ldots\ldots \quad (21)$$

With Q, Δh, and n_1 known, a value of $Q_{\Delta h = 1.0}$ can be computed for the data point. Knowing $Q_{\Delta h = 1.0}$ the value of $-\log S$ can be computed knowing S, and the data point can be represented on a plot containing the two variables. This procedure can be repeated for each data point, thereby producing the straight-line relationship between the two variables, which allows a determination to be made of the value of both n_2 and C_1.

When the n_2&C_1 relationships for all flumes of the same length were plotted on one sheet, it was found that n_2 was very nearly a constant for all lines (Figs. 35, 36, and 37). Therefore, it was assumed that n_2 was also a constant with flume length.

A plot was then made on logarithmic paper between the submerged flow coefficient, C_1, and the flume throat width, W, with C_1 as the ordinate and W as the abscissa. The best fit straight line was drawn through the points and the value of C_1 redetermined for each flume. The n_2-C_1 relationship plot was again prepared using the new value of C_1, which required computing n_2. This plot was then compared with the original one. The process was repeated until the discrepancy between the two types of plots was minimized. The final n_2&C_1 relationship plots are shown for the 1.5-, 3.0-, and 4.5-, foot flumes in Figs. 35, 36, and 37, respectively, while the n_2&C_1 relations for the 9-ft. flume length is shown in Fig. 38. The final relationship between C_1 and W is shown in Fig. 39.

The values of n_2 and C_1 were found not to be independent for each flume size. If the values of n_2 and C_1 are changed for one flume size, then they must be changed for all flume sizes. The values of n_2 and C_1 for a given flume size are therefore unique.

A summary of the values of n_2 and C_1 determined for each flume is listed in Table 3. The points shown on the plots are the original data. As a further check, this same analysis was performed on the data reported by Skogerboe, Hyatt, Anderson and Eggleston (31) for the 9-ft. flume length. The results for this flume length is shown in Fig. 38.

The final plot of C_1 against W is shown in Fig. 39. From this figure, the general equation for C_1 can be written as follows:

$$C_1 = K_1 W^{1.025} \qquad (22)$$

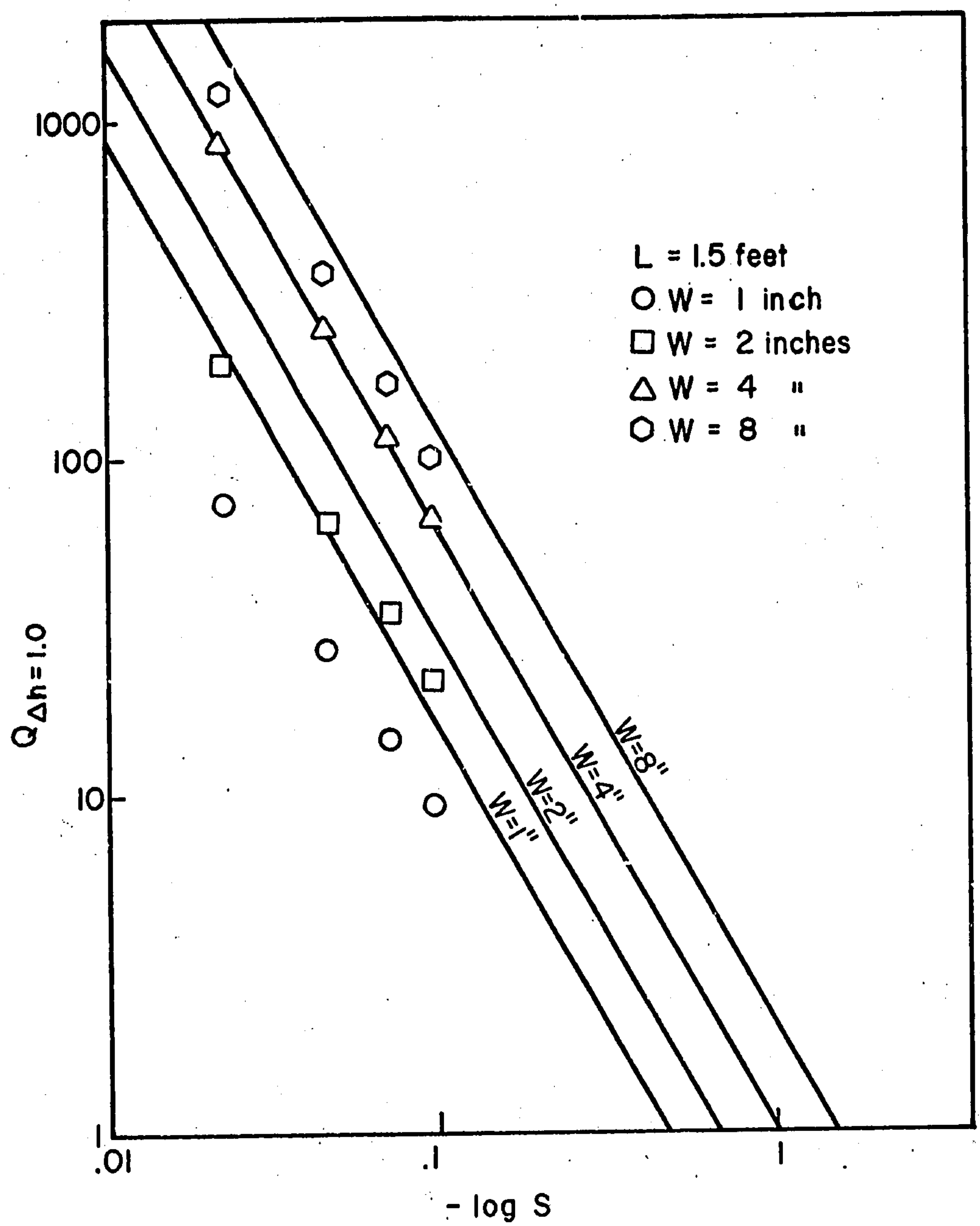


Figure 35. Development of submerged flow coefficient and exponent 1.5 foot cutthroat flume length.

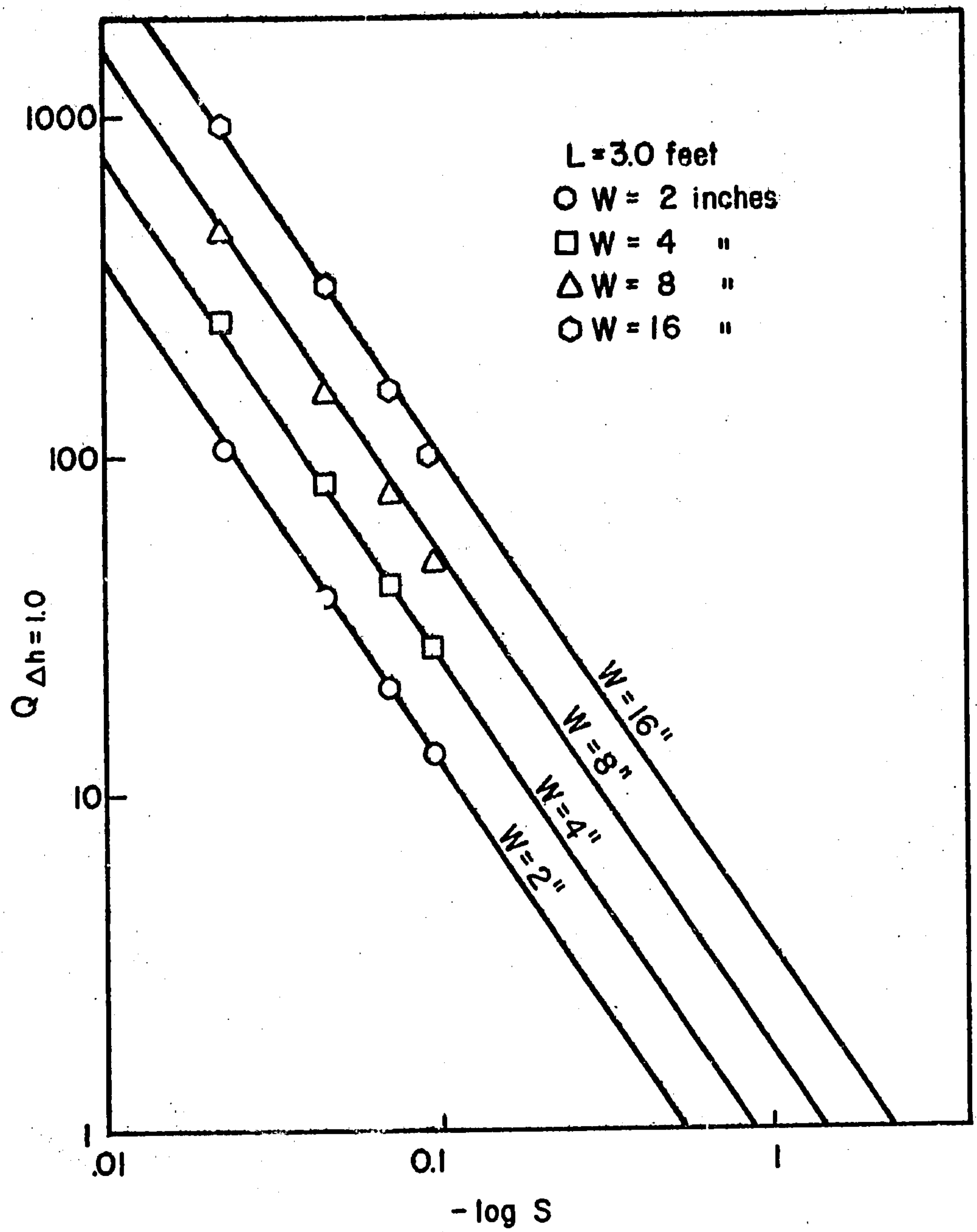


Figure 36. Development of submerged flow coefficient and exponent 3 foot cutthroat flume length.

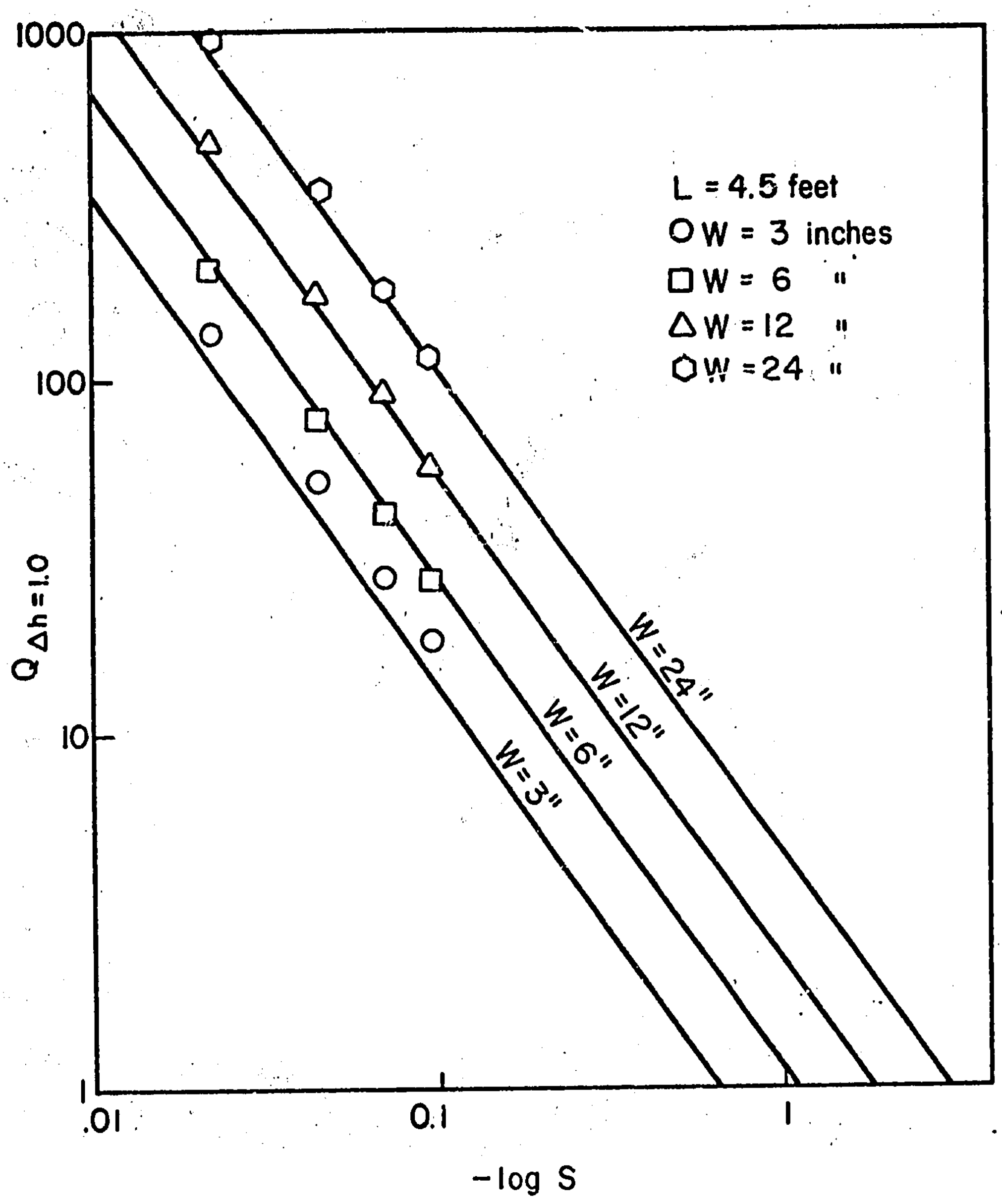


Figure 37. Development of submerged flow coefficient and exponent 4.5 foot cutthroat flume length.

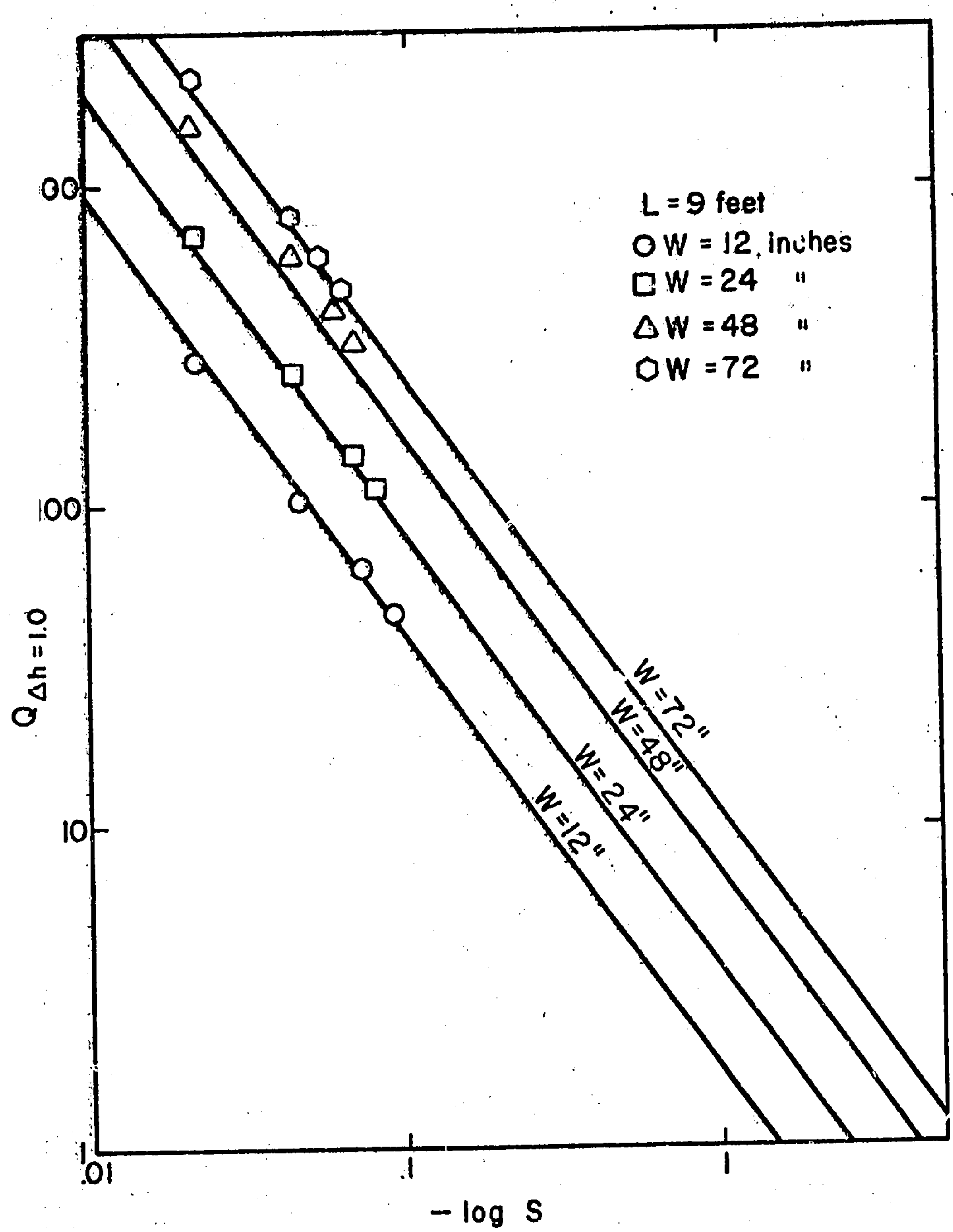


Figure 38. Development of submerged flow coefficient and exponent 9 foot cutthroat flume length.

Table 3. Submerged flow coefficients and exponents for experimental cutthroat flumes.

Flume	12" x 9.0'	3" x 4.5'	2" x 3.0'	1" x 1.5'
C_1	1.688	0.548	0.413	0.261
n_2	1.390	1.410	1.480	1.741
K_1	1.700	2.250	2.580	3.250
Flume	**24" x 9.0'**	**6" x 4.5'**	**4" x 3.0'**	**2" x 1.5'**
C_1	3.430	1.120	0.837	0.516
n_2	1.390	1.410	1.480	1.741
K_1	1.700	2.250	2.580	3.250
Flume	**48" x 9.0'**	**12" x 4.5'**	**8" x 3.0'**	**4" x 1.5'**
C_1	6.970	2.275	1.705	1.048
n_2	1.390	1.410	1.480	1.741
K_1	1.700	2.250	2.580	3.250
Flume	**72" x 9.0'**	**24" x 4.5'**	**16" x 3.0'**	**8" x 1.5'**
C_1	10.600	4.575	3.465	2.140
n_2	1.390	1.410	1.480	1.741
K_1	1.700	2.250	2.580	3.250

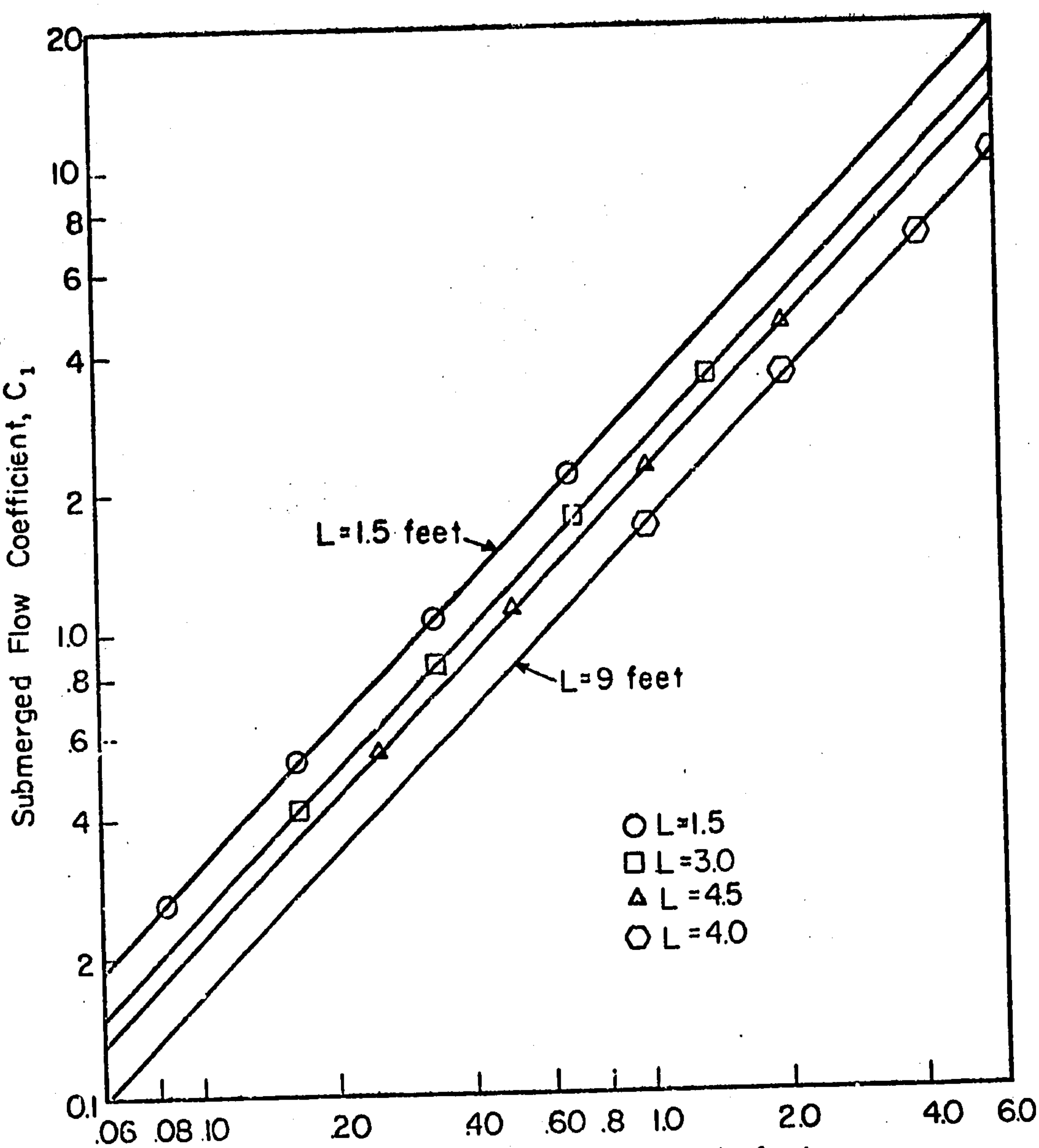


Figure 39. Submerged flow relationships between flume length, flume throat width, and submerged flow coefficient.

where C_1 = submerged flow coefficient
K_1 = submerged flow flume length coefficient
W = flume throat width, in feet

The value of K_1 for each experimental cutthroat flume is shown in Table 3.

The submerged flow rating curves can now be determined for any size of cutthroat flume ranging in length from 1.5 ft. to 9 ft. The value of n_1 is determined from the free flow analysis as shown in Fig. 34. The values of n_2 and K_1 can be obtained from Fig. 40. Thus, the value of C_1 can now be computed using Equation 22. Knowing n_1, n_2 and C_1, the discharge Q, can now be calculated for any combination of h_a and h_b using Equation 16.

Transition Submergence

The transition submergence, S_t, is the precise value of submergence, S, at which the flow conditions in a measuring flume change from free flow to submerged flow. At this point, both the free flow and the submerged flow equations will yield exactly the same value of discharge, Q. Therefore, the transition submergence for any particular flume geometry can be determined by setting the two flow equations equal to each other, which results in Equation 19.

$$-\log (S_t)^{n_2} = (C_1/C)(1-S_t)^{n_1} \quad \ldots\ldots\ldots \quad (19)$$

This equation is then solved for S_t by trial and error.

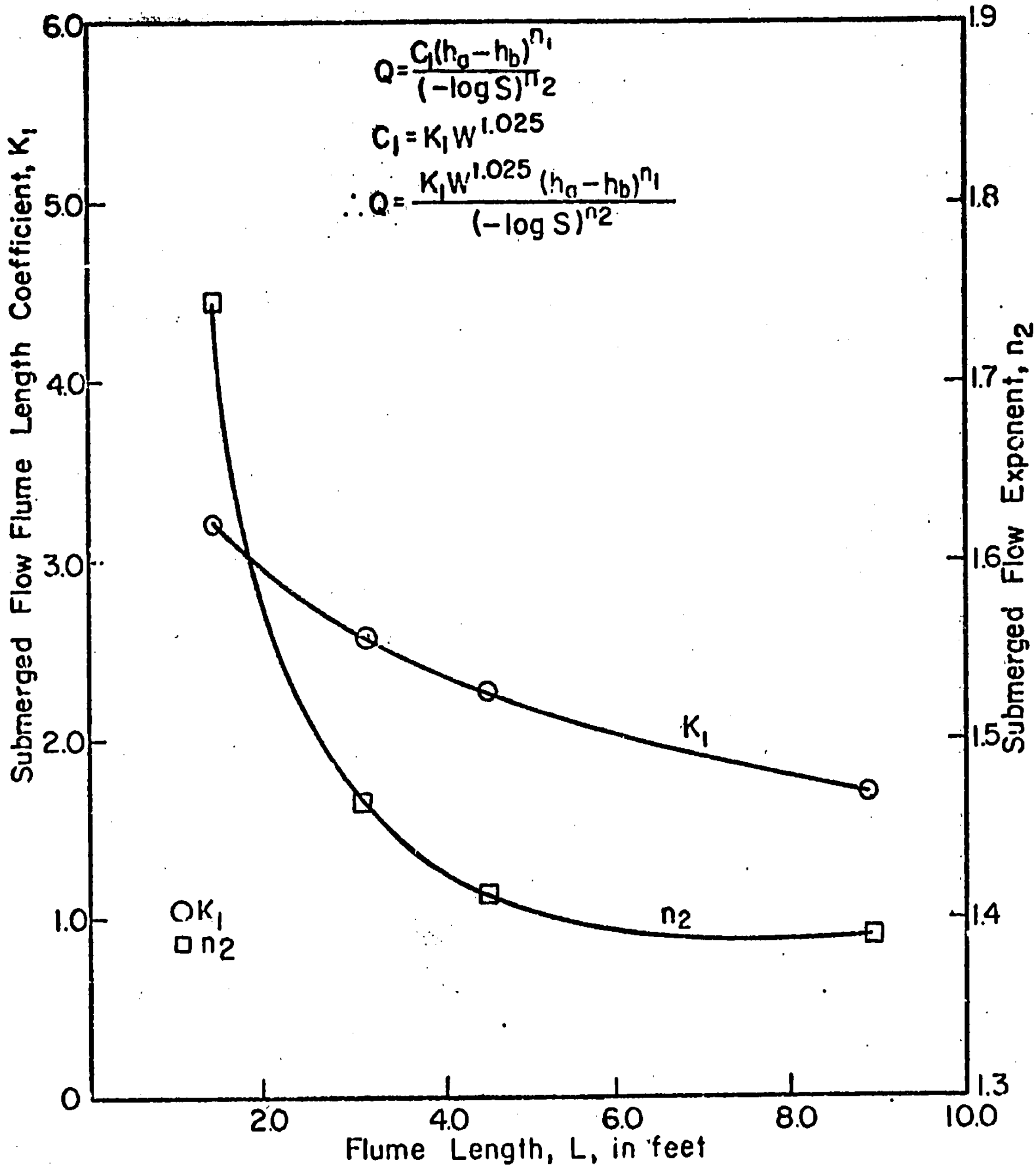


Figure 40. Generalized submerged flow ratings for cut-throat flumes.

In order to determine the values of S_t for the various experimental cutthroat flumes, a computer program was written which performed the trial and error solution. The value of S_t was found to be a constant for each flume length. The values of S_t are listed in Table 4 for all flumes tested.

Table 4. Transition submergence for experimental cutthroat flumes.

Flume	12" x 9.0'	3" x 4.5'	2" x 3.0'	1" x 1.5'
S_t	0.80	0.70	0.65	0.60
Flume	24" x 9.0'	6" x 4.5'	4" x 3.0'	2" x 1.5'
S_t	0.80	0.70	0.65	0.60
Flume	48" x 9.0'	12" x 4.5'	8" x 3.0'	4" x 1.5'
S_t	0.80	0.70	0.65	0.60
Flume	72" x 9.0'	24" x 4.5'	16" x 3.0'	8" x 1.5'
S_t	0.80	0.70	0.65	0.60

CHAPTER 8

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

The purpose of this study has been to develop general discharge ratings for a range of cutthroat flume sizes. As has been stated earlier, the cutthroat flume can operate under either free flow or submerged flow conditions.

The general equation used to determine the flow rate under free flow conditions is

$$Q = Ch_a^{n_1} \quad (20)$$

$$C = KW^{1.025} \quad (13)$$

or

$$Q = KW^{1.025}h_a^{n_1} \quad (23)$$

The general equation used to determine the flow rate under submerged flow conditions is

$$Q = \frac{C_1 \, (h_a - h_b)^{n_1}}{(-\log S)^{n_2}} \quad (16)$$

$$C_1 = K_1W^{1.025} \quad (22)$$

where Q = flow rate in cfs
C_1 = a submerged flow coefficient
h_a = upstream depth
h_b = downstream depth
n_1 = slope of the free flow rating line
S = submergence (h_b/h_a)
n_2 = a submerged flow exponent

or

$$Q = \frac{K_1 W^{1.025} (h_a - h_b)^{n_1}}{(-\log S)^{n_2}} \quad \ldots\ldots\ldots\ldots\ldots \quad (24)$$

For the 16 experimental cutthroat flumes, values of the free flow and submerged flow coefficients and exponents, along with the transition submergence are listed in Table 5. In Fig. 41 the generalized relationships for the coefficients and exponents in Equations 23 and 24 are shown. Also, the variation of transition submergence, S_t, with flume length is shown in Fig. 41.

Conclusions

From this study, it can be concluded that the cutthroat flume is an accurate open channel flow measuring device, which can be used either in the laboratory or in the field. The accuracy is satisfactory under both free flow and submerged flow conditions.

An outstanding feature of the cutthroat flume is that generalized discharge rating curves can be easily developed. This can be attributed to geometric simplicity of the structure, along with the same geometric shape among flume sizes. Consequently, it is possible for both free flow and submerged flow ratings to be developed for all intermediate flume sizes by merely interpolating on the appropriate graphs.

The flume is both simple and economical to construct. Now, based upon the results of this study, the range of sizes

Table 5. Summary of coefficients, exponents, and transition submergences for experimental cutthroat flumes.

Flume	12" x 9.0'	3" x 4.5'	2" x 3.0'	1" x 1.5'
C	3.500	0.960	0.719	0.494
n_1	1.560	1.720	1.840	2.150
K	3.500	3.980	4.500	6.100
C_1	1.688	0.548	0.413	0.261
n_2	1.390	1.410	1.480	1.741
K_1	1.700	2.250	2.580	3.250
S_t	0.800	0.700	0.650	0.600

Flume	24" x 9.0'	6" x 4.5'	4" x 3.0'	2" x 1.5'
C	7.110	1.960	1.459	0.974
n_1	1.560	1.720	1.840	2.150
K	3.500	3.980	4.500	6.100
C_1	3.430	1.120	0.837	0.516
n_2	1.390	1.410	1.480	1.741
K_1	1.700	2.250	2.580	3.250
S_t	0.800	0.700	0.650	0.600

Flume	48" x 9.0'	12" x 4.5'	8" x 3.0'	4" x 1.5'
C	14.490	3.980	2.979	1.975
n_1	1.560	1.720	1.840	2.150
K	3.500	3.980	4.500	6.100
C_1	6.970	2.275	1.705	1.048
n_2	1.390	1.410	1.480	1.741
K_1	1.700	2.250	2.580	3.250
S_t	0.800	0.700	0.650	0.600

Flume	72" x 9.0'	24" x 4.5'	16" x 3.0'	8" x 1.5'
C	22.000	8.010	6.040	4.030
n_1	1.560	1.720	1.840	2.150
K	3.500	3.980	4.500	6.100
C_1	10.600	4.575	3.465	2.140
n_2	1.390	1.410	1.480	1.741
K_1	1.700	2.250	2.580	3.250
S_t	0.800	0.700	0.650	0.600

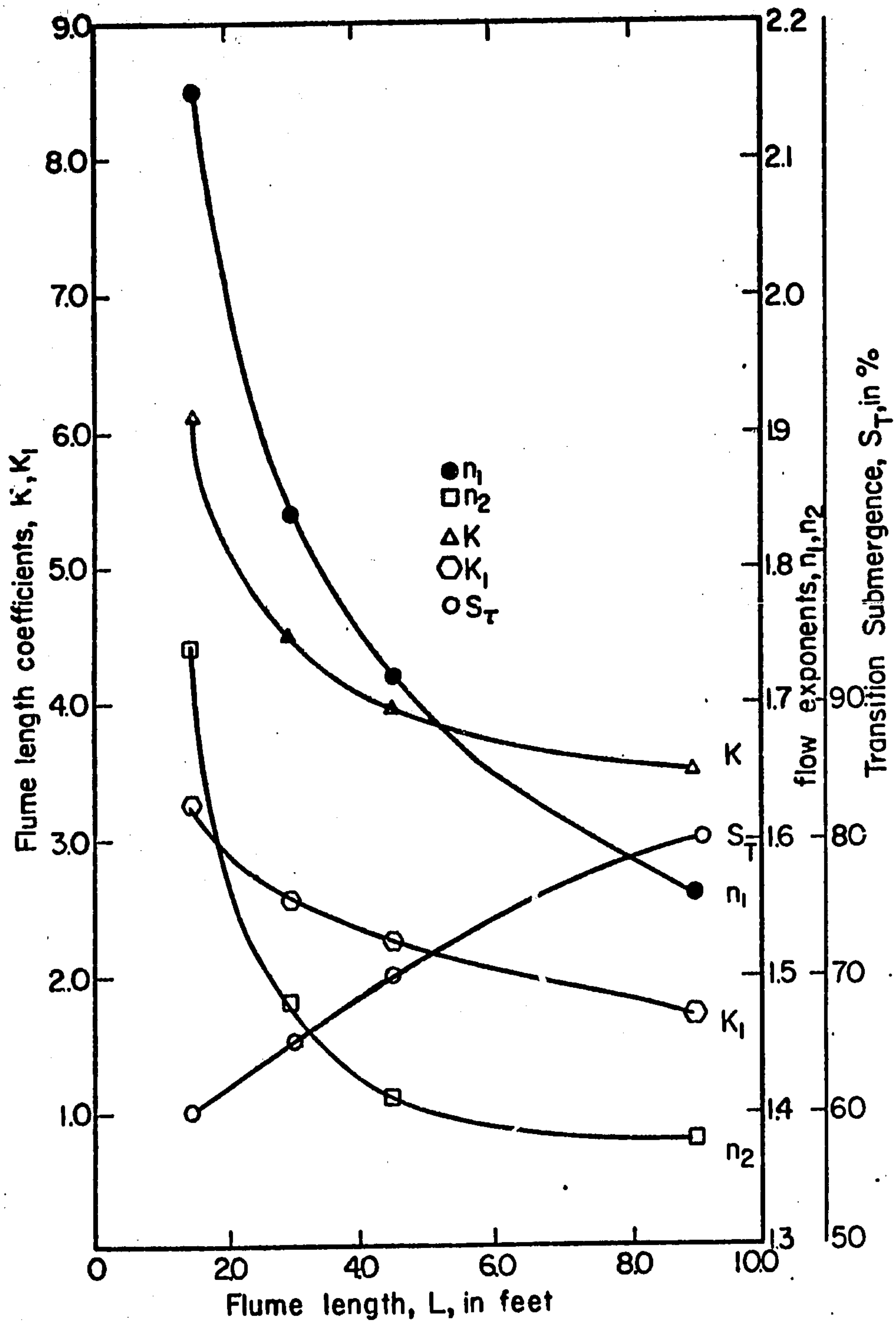


Figure 41. Generalized free flow and submerged flow coefficients and exponents and S_t for cutthroat flumes.

has been extended from a length of 9 feet to 18 inches, while throat widths varying from one or two inches to six feet can be used. However, scale effects resulting from curvilinear flow and non-hydrostatic pressure distribution become apparent in the small flume sizes. Therefore, based upon this study, flumes less than 3 feet in length are satisfactory for free flow operations, but are not recommended for submerged flow operation.

In order to obtain the best rating accuracy, it is recommended that flumes with throat width to length ratios between 0.1 and 0.4 be used. This range of throat width to flume length ratios corresponds to a range of constriction ratios (throat width divided by entrance, or exit, width, W/B) of 1/4 to 2/3.

Recommendations

Recommendations for further research are:

(1) Separate study be undertaken to evaluate short cutthroat flume lengths (less than three feet) with narrow throat widths (3 inches and less). Such a study should evaluate the problems of non-hydrostatic pressure distribution at piezometer taps, considerable flow curvature, and the possibility that the flow depth near the wall is less than that at the center line of the flume.

(2) A study of very large cutthroat flumes with throat widths of possibly 10, 20, 30, 40, and 50 feet and lengths of 20 to 100 feet should be undertaken. Such a study would not only provide free flow and submerged flow ratings for very large structures, but would also establish whether or not the present trends continue for the various flow parameters (coefficients, exponents, and transition submergence).

APPENDIX

HYDRAULIC LABORATORY DATA

Table 6. Hydraulic laboratory data for cutthroat flume with 1-inch throat width and 18-inch flume length.

Q, cfs	h_a ft.	h_b ft.
0.501	1.008	0.327
0.501	1.008	0.345
0.501	1.008	0.373
0.501	1.009	0.408
0.501	1.010	0.454
0.501	1.021	0.518
0.501	1.028	0.604
0.501	1.046	0.668
0.501	1.062	0.735
0.501	1.085	0.786
0.501	1.108	0.844
0.501	1.151	0.917
0.501	1.192	0.991
0.501	1.245	1.062
0.501	1.298	1.133
0.501	1.359	1.216
0.501	1.422	1.289
0.501	1.510	1.389
0.501	1.600	1.488
0.697	1.205	0.450
0.697	1.205	0.476
0.697	1.205	0.538
0.697	1.218	0.634
0.697	1.234	0.740
0.697	1.262	0.825
0.697	1.304	0.926
0.697	1.353	1.030
0.697	1.413	1.124
0.697	1.487	1.220
0.697	1.576	1.338
0.697	1.666	1.456
0.697	1.776	1.578
0.697	1.882	1.687
0.294	0.780	0.186
0.294	0.780	0.247
0.294	0.780	0.336
0.294	0.790	0.425
0.294	0.801	0.485
0.294	0.815	0.549
0.294	0.841	0.624
0.294	0.872	0.694
0.294	0.904	0.752
0.294	0.939	0.813
0.294	0.988	0.878
0.294	1.049	0.959
0.294	1.115	1.036
0.294	1.192	1.117
0.401	0.913	0.263
0.401	0.913	0.298
0.401	0.914	0.363
0.401	0.921	0.456
0.401	0.937	0.545
0.401	0.959	0.651
0.401	0.991	0.741
0.401	1.027	0.818
0.401	1.076	0.894
0.401	1.135	0.982
0.401	1.209	1.084
0.401	1.304	1.206
0.401	1.416	1.321

Table 7. Hydraulic laboratory data for cutthroat flume with 2-inch throat width and 18-inch flume length.

Q, cfs	h_a ft.	ft.
1.341	1.191	0.549
1.341	1.191	0.562
1.341	1.191	0.584
1.341	1.191	0.617
1.341	1.199	0.660
1.341	1.218	0.702
1.341	1.221	0.752
1.341	1.224	0.799
1.341	1.232	0.868
1.341	1.259	0.925
1.341	1.297	0.990
1.341	1.326	1.049
1.341	1.372	1.132
1.341	1.421	1.224
1.341	1.494	1.327
1.341	1.564	1.436
1.341	1.657	1.564
1.341	1.799	1.712
0.898	0.989	0.437
0.898	0.989	0.452
0.898	0.989	0.481
0.898	0.994	0.561
0.898	0.999	0.664
0.898	1.037	0.759
0.898	1.064	0.862
0.898	1.106	0.920
0.898	1.137	0.996
0.898	1.201	1.075
0.898	1.254	1.159
0.898	1.325	1.235
0.898	1.444	1.382

Q, cfs	h_a ft.	h_b ft.
1.185	1.121	0.529
1.185	1.121	0.555
1.185	1.129	0.602
1.185	1.132	0.685
1.185	1.180	0.772
1.185	1.207	0.862
1.185	1.234	0.957
1.185	1.279	1.055
1.185	1.343	1.142
1.185	1.397	1.237
1.185	1.465	1.332
1.185	1.549	1.425
1.185	1.677	1.587
0.703	0.878	0.381
0.703	0.878	0.394
0.703	0.881	0.435
0.703	0.886	0.518
0.703	0.914	0.597
0.703	0.929	0.696
0.703	0.965	0.780
0.703	1.009	0.855
0.703	1.056	0.942
0.703	1.105	1.025
0.703	1.184	1.109
0.703	1.264	1.207

Table 8. Hydraulic laboratory data for cutthroat flume with 4-inch throat width and 18-inch flume length.

Q, cfs	h_a ft.	h_b ft.	Q, cfs	h_a ft.	h_b ft.
1.034	0.740	0.353	0.809	0.668	0.301
1.034	0.740	0.373	0.809	0.668	0.323
1.034	0.743	0.421	0.809	0.668	0.380
1.034	0.755	0.480	0.809	0.677	0.474
1.034	0.769	0.550	0.809	0.674	0.424
1.034	0.788	0.632	0.809	0.688	0.525
1.034	0.840	0.712	0.809	0.713	0.575
1.034	0.871	0.789	0.809	0.733	0.629
1.034	0.858	0.750	0.809	0.760	0.674
1.034	0.906	0.838	0.809	0.785	0.720
1.034	0.991	0.930	0.809	0.817	0.764
1.034	1.061	1.035	0.809	0.850	0.807
1.034	1.015	0.980	0.809	0.884	0.849
1.034	0.986	0.942			
2.07	1.010	0.524	1.395	0.862	0.427
2.07	1.010	0.567	1.395	0.862	0.435
2.07	1.030	0.619	1.395	0.865	0.473
2.07	1.033	0.696	1.395	0.868	0.533
2.07	1.075	0.775	1.395	0.884	0.620
2.07	1.090	0.871	1.395	0.907	0.710
2.07	1.123	0.948	1.395	0.922	0.783
2.07	1.167	1.027	1.395	0.993	0.872
2.07	1.240	1.104	1.395	1.061	0.982
2.07	1.290	1.204	1.395	1.024	0.934
2.07	1.262	1.160	1.395	1.137	1.062
2.07	1.377	1.302	1.395	1.226	1.161
2.07	1.458	1.417	1.395	1.330	1.275

Table 9. Hydraulic laboratory data for cutthroat flume with 8-inch throat width and 18-inch flume length.

Q, cfs	h_a ft.	h_b ft.	Q, cfs	h_a ft.	h_b ft.
1.41	0.584	0.325	0.937	0.470	0.254
1.41	0.584	0.334	0.937	0.470	0.280
1.41	0.584	0.339	0.937	0.471	0.342
1.41	0.584	0.353	0.937	0.486	0.434
1.41	0.586	0.371	0.937	0.481	0.414
1.41	0.587	0.393	0.937	0.480	0.392
1.41	0.587	0.411	0.937	0.472	0.369
1.41	0.595	0.444	0.937	0.471	0.325
1.41	0.596	0.494	0.937	0.471	0.307
1.41	0.600	0.534	0.937	0.470	0.295
1.41	0.597	0.513	0.937	0.483	0.435
1.41	0.612	0.564	0.937	0.498	0.465
1.41	0.628	0.589	0.937	0.518	0.493
1.41	0.641	0.624			
1.41	0.635	0.608			
1.98	0.703	0.425	2.59	0.791	0.492
1.98	0.703	0.436	2.59	0.791	0.500
1.98	0.703	0.471	2.59	0.791	0.527
1.98	0.707	0.489	2.59	0.794	0.558
1.98	0.709	0.521	2.59	0.804	0.600
1.98	0.712	0.554	2.59	0.808	0.647
1.98	0.720	0.598	2.59	0.818	0.693
1.98	0.733	0.649	2.59	0.840	0.752
1.98	0.745	0.700	2.59	0.868	0.814
1.98	0.773	0.746	2.59	0.897	0.869
1.98	0.785	0.767	2.59	0.873	0.838
1.98	0.759	0.719			
1.98	0.752	0.695			

Table 10. Hydraulic laboratory data for cutthroat flume with 2-inch throat width and 3-foot flume length.

Q, cfs	h_a ft.	h_b ft.	Q, cfs	h_a ft.	h_b ft.
0.88	1.060	0.226	1.08	1.185	0.272
0.88	1.060	0.268	1.08	1.185	0.283
0.88	1.060	0.373	1.08	1.185	0.352
0.88	1.060	0.458	1.08	1.189	0.440
0.88	1.068	0.596	1.08	1.193	0.557
0.88	1.082	0.691	1.08	1.201	0.674
0.88	1.121	0.831	1.08	1.220	0.771
0.88	1.150	0.899	1.08	1.239	0.858
0.88	1.207	1.016	1.08	1.294	1.005
0.88	1.254	1.104	1.08	1.335	1.096
0.88	1.308	1.183	1.08	1.379	1.175
0.88	1.390	1.299	1.08	1.427	1.257
0.88	1.446	1.365	1.08	1.501	1.367
0.88	1.494	1.450	1.08	1.557	1.443
0.88	1.469	1.391	1.08	1.644	1.548
1.53	1.427	0.380	0.74	0.968	0.196
1.53	1.427	0.481	0.74	0.968	0.289
1.53	1.427	0.593	0.74	0.968	0.433
1.53	1.431	0.684	0.74	0.978	0.565
1.53	1.444	0.818	0.74	1.014	0.714
1.53	1.470	0.923	0.74	1.048	0.798
1.53	1.509	1.098	0.74	1.084	0.885
1.53	1.540	1.194	0.74	1.128	0.971
1.53	1.586	1.270	0.74	1.172	1.043
1.53	1.655	1.355	0.74	1.218	1.117
1.53	1.716	1.486	0.74	1.254	1.161
1.53	1.793	1.588	0.74	1.295	1.217
1.53	1.877	1.704	0.74	1.361	1.295
1.53	1.935	1.781	0.74	1.424	1.370
1.53	2.024	1.891			

Table 11. Hydraulic laboratory data for cutthroat flume with 4-inch throat width and 3-foot flume length.

Q, cfs	h_a ft.	h_b ft.	Q, cfs	h_a ft.	h_b ft.
1.38	0.987	0.289	1.83	1.119	0.351
1.38	0.987	0.296	1.83	1.119	0.383
1.38	0.987	0.361	1.83	1.119	0.449
1.38	0.987	0.441	1.83	1.119	0.538
1.38	0.989	0.513	1.83	1.122	0.629
1.38	0.995	0.603	1.83	1.131	0.708
1.38	1.004	0.682	1.83	1.142	0.790
1.38	1.024	0.755	1.83	1.161	0.859
1.38	1.049	0.826	1.83	1.195	0.945
1.38	1.079	0.895	1.83	1.223	1.014
1.38	1.114	0.964	1.83	1.261	1.085
1.38	1.155	1.032	1.83	1.298	1.152
1.38	1.197	1.102	1.83	1.339	1.213
1.38	1.241	1.165	1.83	1.382	1.271
1.38	1.291	1.226	1.83	1.478	1.393

Q, cfs	h_a ft.	h_b ft.	Q, cfs	h_a ft.	h_b ft.
1.04	0.834	0.226	0.76	0.707	0.175
1.04	0.834	0.302	0.76	0.707	0.309
1.04	0.834	0.389	0.82	0.747	0.490
1.04	0.836	0.463	0.82	0.758	0.561
1.04	0.839	0.532	0.82	0.781	0.623
1.04	0.850	0.593	0.82	0.813	0.690
1.04	0.869	0.657	0.82	0.859	0.757
1.04	0.898	0.717	0.82	0.886	0.803
1.04	0.928	0.782	0.82	0.929	0.872
1.04	0.958	0.840	0.82	0.979	0.936
1.04	0.993	0.900	0.82	1.034	1.001
1.04	1.039	0.965			
1.04	1.085	1.026			
1.04	1.137	1.090			

Table 12. Hydraulic laboratory data for cutthroat flume with 8-inch throat width and 3-foot flume length.

Q, cfs	h_a ft.	h_b ft.	Q, cfs	h_a ft.	h_b ft.
2.66	0.975	0.417	0.80	0.488	0.282
2.66	0.975	0.440	0.80	0.488	0.366
2.66	0.975	0.479	0.80	0.488	0.399
2.66	0.975	0.562	0.80	0.493	0.427
2.66	0.980	0.662	0.80	0.496	0.445
2.66	0.990	0.753	0.80	0.501	0.464
2.66	1.009	0.828	0.80	0.508	0.477
2.66	1.035	0.894	0.80	0.520	0.492
2.66	1.069	0.957	0.80	0.531	0.506
2.66	1.111	1.021	0.80	0.535	0.515
2.66	1.149	1.080	0.80	0.546	0.530
2.66	1.189	1.140			
2.66	1.235	1.198			
2.66	1.279	1.256			
1.39	0.682	0.273	1.91	0.803	0.319
1.39	0.682	0.365	1.91	0.803	0.357
1.39	0.682	0.408	1.91	0.803	0.427
1.39	0.683	0.485	1.91	0.806	0.513
1.39	0.688	0.538	1.91	0.810	0.600
1.39	0.697	0.592	1.91	0.825	0.668
1.39	0.719	0.642	1.91	0.843	0.716
1.39	0.738	0.677	1.91	0.869	0.766
1.39	0.756	0.710	1.91	0.890	0.814
1.39	0.778	0.741	1.91	0.920	0.860
1.39	0.812	0.782	1.91	0.950	0.903
1.39	0.846	0.824	1.91	0.984	0.947

Table 13. Hydraulic laboratory data for cutthroat flume with 16-inch throat width and 3-foot flume length.

Q, cfs	h_a ft.	h_b ft.	Q, cfs	h_a ft.	h_b ft.
5.53	0.957	0.465	4.38	0.839	0.411
5.53	0.957	0.474	4.38	0.839	0.421
5.53	0.957	0.491	4.38	0.845	0.446
5.53	0.967	0.561	4.38	0.855	0.486
5.53	0.994	0.662	4.38	0.859	0.555
5.53	0.976	0.673	4.38	0.869	0.674
5.53	1.002	0.767	4.38	0.878	0.789
5.53	0.990	0.799	4.38	0.872	0.732
5.53	1.007	0.833	4.38	0.864	0.615
5.53	1.010	0.856	4.38	0.874	0.763
5.53	1.020	0.896	4.38	0.900	0.834
5.53	1.030	0.937	4.38	0.885	0.815
5.53	1.046	0.982	4.38	0.905	0.855
5.53	1.023	0.964	4.38	0.920	0.873
5.53	1.051	1.002	4.38	0.951	0.914
5.53	1.060	1.013	4.38	0.982	0.956
5.53	1.038	0.995			
5.53	1.062	1.029			
5.53	1.068	1.037			
3.64	0.763	0.373	3.00	0.690	0.339
3.64	0.763	0.404	3.00	0.690	0.359
3.64	0.779	0.431	3.00	0.700	0.380
3.64	0.781	0.467	3.00	0.706	0.461
3.64	0.786	0.529	2.91	0.691	0.583
3.64	0.788	0.609	2.91	0.696	0.625
3.64	0.797	0.676	2.91	0.704	0.663
3.64	0.790	0.638	2.91	0.722	0.696
3.64	0.826	0.778	2.91	0.743	0.724
3.64	0.817	0.757	2.91	0.732	0.710
3.64	0.809	0.736	2.91	0.714	0.680
3.64	0.805	0.717	2.91	0.701	0.650
3.64	0.844	0.800	2.91	0.695	0.617
3.64	0.868	0.833	2.91	0.694	0.605
3.64	0.891	0.867			

Table 14. Hydraulic laboratory data for cutthroat flume with 3-inch throat width and 54-inch flume length.

Q, cfs	h_a ft.	h_b ft.	Q, cfs	h_a ft.	h_b ft.
1.491	1.201	0.246	1.885	1.352	0.291
1.491	1.201	0.267	1.885	1.352	0.355
1.491	1.201	0.368	1.885	1.352	0.477
1.491	1.201	0.455	1.885	1.354	0.598
1.491	1.201	0.557	1.885	1.358	0.625
1.491	1.202	0.664	1.885	1.372	0.834
1.491	1.210	0.740	1.885	1.400	0.950
1.491	1.223	0.813	1.885	1.434	1.045
1.491	1.249	0.892	1.885	1.476	1.142
1.491	1.275	0.963	1.885	1.518	1.225
1.491	1.305	1.029	1.885	1.564	1.308
1.491	1.339	1.109	1.885	1.614	1.396
1.491	1.387	1.196	1.885	1.660	1.474
1.491	1.439	1.281	1.885	1.714	1.554
1.491	1.500	1.369	1.885	1.777	1.633
1.491	1.563	1.446	1.885	1.857	1.745
1.170	1.039	0.205	0.855	0.880	0.183
1.170	1.039	0.251	0.855	0.880	0.316
1.170	1.039	0.363	0.855	0.880	0.459
1.170	1.039	0.439	0.855	0.883	0.551
1.170	1.039	0.550	0.855	0.891	0.613
1.170	1.044	0.634	0.855	0.912	0.683
1.170	1.057	0.707	0.855	0.940	0.747
1.170	1.076	0.775	0.855	0.974	0.812
1.170	1.103	0.846	0.855	1.012	0.878
1.170	1.134	0.913	0.855	1.053	0.945
1.170	1.169	0.981	0.855	1.101	1.013
1.170	1.207	1.049	0.855	1.143	1.077
1.170	1.248	1.117	0.855	1.200	1.141
1.170	1.301	1.181			
1.170	1.336	1.241			

Table 15. Hydraulic laboratory data for cutthroat flume with 6-inch throat width and 54-inch flume length.

Q, cfs	h_a ft.	h_b ft.	Q, cfs	h_a ft.	h_b ft.
1.991	1.030	0.263	1.497	0.881	0.222
1.991	1.030	0.324	1.497	0.881	0.321
1.991	1.030	0.435	1.497	0.881	0.394
1.991	1.030	0.527	1.497	0.881	0.485
1.991	1.033	0.623	1.497	0.881	0.575
1.991	1.038	0.709	1.497	0.885	0.636
1.991	1.061	0.776	1.497	0.899	0.709
1.991	1.070	0.837	1.497	0.925	0.768
1.991	1.101	0.897	1.497	0.965	0.831
1.991	1.146	0.966	1.497	0.991	0.885
1.991	1.169	1.029	1.497	1.032	0.943
1.991	1.205	1.087	1.497	1.070	1.001
1.991	1.253	1.146	1.497	1.114	1.058
1.991	1.293	1.204	1.497	1.167	1.120
1.991	1.339	1.260	1.497	1.224	1.183
1.991	1.389	1.324			
1.991	1.454	1.394			
1.075	0.727	0.206	0.665	0.540	0.247
1.075	0.727	0.328	0.665	0.540	0.375
1.075	0.727	0.442	0.665	0.540	0.418
1.075	0.728	0.533	0.665	0.546	0.464
1.075	0.743	0.605	0.665	0.561	0.500
1.075	0.766	0.661	0.665	0.577	0.528
1.075	0.795	0.708	0.665	0.597	0.555
1.075	0.824	0.750	0.665	0.619	0.584
1.075	0.857	0.795	0.665	0.651	0.621
1.075	0.886	0.830			
1.075	0.936	0.891			
1.075	0.980	0.939			
1.075	1.024	0.990			
1.075	1.070	1.038			

Table 16. Hydraulic laboratory data for cutthroat flume with 12-inch throat width and 54-inch flume length.

Q, cfs	h_a ft.	h_b ft.	Q, cfs	h_a ft.	h_b ft.
5.723	1.279	0.523	3.909	1.039	0.410
5.723	1.279	0.529	3.909	1.039	0.413
5.723	1.279	0.540	3.909	1.039	0.415
5.723	1.279	0.548	3.909	1.041	0.424
5.723	1.279	0.575	3.909	1.042	0.442
5.723	1.279	0.611	3.909	1.041	0.488
5.723	1.283	0.679	3.909	1.046	0.600
5.723	1.290	0.779	3.909	1.047	0.687
5.723	1.293	0.865	3.909	1.048	0.754
5.723	1.295	0.943	3.909	1.049	0.813
5.723	1.305	1.016	3.909	1.057	0.859
5.723	1.308	1.089	3.909	1.067	0.908
5.723	1.341	1.146	3.909	1.085	0.960
5.723	1.371	1.214	3.909	1.111	1.014
5.723	1.400	1.274	3.909	1.143	1.063
5.723	1.439	1.336	3.909	1.176	1.113
5.723	1.470	1.391	3.909	1.211	1.156
5.723	1.514	1.449			
2.739	0.831	0.320	1.919	0.677	0.251
2.739	0.831	0.322	1.919	0.677	0.259
2.739	0.831	0.323	1.919	0.677	0.276
2.739	0.831	0.333	1.919	0.678	0.311
2.739	0.835	0.374	1.919	0.680	0.373
2.739	0.836	0.448	1.919	0.681	0.426
2.739	0.837	0.509	1.919	0.682	0.483
2.739	0.838	0.575	1.919	0.683	0.532
2.739	0.839	0.621	1.919	0.684	0.574
2.739	0.840	0.677	1.919	0.687	0.610
2.739	0.846	0.725	1.919	0.693	0.636
2.739	0.859	0.771	1.919	0.706	0.660
2.739	0.881	0.811	1.919	0.721	0.681
2.739	0.903	0.850	1.919	0.743	0.714
2.739	0.938	0.894			

Table 17. Hydraulic laboratory data for cutthroat flume with 24-inch throat width and 54-inch flume length.

Q, cfs	h_a ft.	h_b ft.	Q, cfs	h_a ft.	h_b ft.
6.849	0.924	0.441	3.82	0.650	0.315
6.849	0.924	0.446	3.82	0.650	0.348
6.849	0.924	0.456	3.82	0.665	0.463
6.849	0.928	0.485	3.82	0.667	0.551
6.849	0.938	0.523	3.82	0.672	0.610
6.849	0.944	0.618	3.82	0.666	0.506
6.849	0.947	0.691	3.82	0.668	0.536
6.849	0.948	0.732	3.82	0.669	0.565
6.849	0.952	0.786	3.82	0.670	0.590
6.849	0.956	0.823	3.82	0.675	0.612
6.849	0.960	0.858	3.82	0.679	0.628
6.849	0.970	0.895	3.82	0.688	0.645
6.849	0.984	0.926	3.82	0.701	0.663
6.849	1.000	0.947	3.82	0.721	0.685
6.849	1.024	0.979	3.82	0.750	0.723
6.849	1.048	1.010			
4.827	0.749	0.368	5.892	0.846	0.409
4.827	0.749	0.382	5.892	0.846	0.417
4.827	0.759	0.422	5.892	0.855	0.441
4.827	0.764	0.515	5.892	0.864	0.491
4.827	0.769	0.567	5.892	0.865	0.595
4.827	0.784	0.640	5.892	0.868	0.710
4.827	0.772	0.608	5.892	0.866	0.664
4.827	0.776	0.687	5.892	0.872	0.750
4.827	0.783	0.720	5.892	0.875	0.755
4.827	0.798	0.748	5.892	0.882	0.810
4.827	0.815	0.770	5.892	0.876	0.785
4.827	0.833	0.795	5.892	0.898	0.838
4.827	0.781	0.709	5.892	0.911	0.863
4.827	0.774	0.680	5.892	0.933	0.888
4.827	0.772	0.651	5.892	0.956	0.914

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