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Chapter A14

USE OF FLUMES IN MEASURING DISCHARGE

By F. A. Kilpatrick and V. R. Schneider

Book 3
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PREFACE

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SYMBOLS, DEFINITIONS, AND UNITS

Symbol	Definition	Unit
	GENERAL	
A	Cross-sectional area	ft^2
A_c	Cross-sectional area at critical depth section	ft^2
A_m	Cross-sectional area at measuring section	ft^2
CDL	Critical depth line	
D	Wall height	ft
d	Depth of flow	ft
d_c	Critical-flow depth	ft
d_m	Depth at the measuring section	ft
E	Specific energy	ft
EL	Energy line	
g	Gravitational constant (acceleration)	ft/s^2
H_T	Head measured in throat section	ft
h_e	Friction loss between two sections	ft
L_C	Axial length of flume-converging reach	ft
L_D	Axial length of flume-diverging reach	ft
L_T	Axial length of flume throat reach	ft
n	Manning roughness coefficient	$ft^{1/6}$
p	Drop from dike or gutter invert to flume floor for HS, H, HL flumes	ft
Q	Total discharge	ft^3/s
q	Unit discharge	ft^3/s
R	Hydraulic radius	ft
RP	Reference point	
r	Radius of flume entrance rounding	ft
S_c	Critical slope	
S_o	Bed slope	
T_c	Top width at the critical flow section	ft
T_m	Top width at the measuring section	ft
V	Velocity	ft/s
V_c	Critical velocity	ft/s
V_D	Mean vertical velocity at a distance from a vertical wall equal to the depth	
V_m	Velocity at the measuring section	ft/s
$V^2/2g$	Velocity head	ft
$\overline{W}$	Average width	ft
W_c	Flume width at the entrance to the contacted section	ft
W_D	Flume width at the exit of the diverging section	ft
W_T	Flume width in the throat section	ft
WS	Water surface	
Y	Elevation of flume floor above any arbitrary datum plane	ft
Z	Critical-section factor $=A_c\sqrt{A_c/T_c}$	$ft^{5/2}$
$>$	Greater than	
	SPECIFIC TO PARSHALL FLUMES	
C	Converging wall length	ft
H_c	Head measured in converging section at 2/3 the wall length, C, upstream of flume crest	ft
H_T	Head measured in throat section at a point a distance upstream of the exit of the throat section and b distance above lowest point in flume; used to determine submergence	ft
K	Amount of drop at exit of flume relative to flume datum	ft
k_s	Correction factor for submerged flow	ft^3/s
L	Distance from throat crest to upstream measuring section	ft
N	Amount of drop in throat floor relative to flume datum	ft
Q_c	Submergence discharge correction unadjusted for flume size	ft^3/s
Q_f	Discharge under free-flow conditions	ft^3/s
Q_o	Nondimensional discharge, $Q/g^{1/2}W_T^{5/2}$	
Q_s	Discharge under submergence conditions	ft^3/s
X_o	Nondimensional distance, L/W_T	ft^2
Y_o	Nondimensional depth, H_c/W_T	ft^2

UNIT CONVERSION

Multiply inch-pound unit	*By*	*To obtain SI unit*
	Length	
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785×10^{-3}	cubic meter (m^3)
cubic foot (ft^3)	0.0283	cubic meter (m^3)
	Volume per unit time	
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)
gallon per minute (gal/min)	6.309×10^{-5}	cubic meter per second (m^3/s)
	Weight	
1 pound (lb)	453.6	gram (g)

USE OF FLUMES IN MEASURING DISCHARGE

By F. A. Kilpatrick and V. R. Schneider

Abstract

Flumes for measuring discharge are usually of two general groups—critical-flow flumes and supercritical-flow flumes. In this chapter, the underlying design principles for each group are discussed; the most commonly used flumes are described and their discharge ratings presented. There is also discussion of considerations in choosing and fitting the appropriate flume for a given situation as well as flume construction techniques and operational experiences.

Introduction

The use of flumes in measuring open-channel flow began shortly after the turn of the century. Flumes have a limited but important use in such measurement. As with any other type of artificial control, such as weirs, flumes are built in streams whose channel characteristics are such that the natural stage-discharge relation is subject to shifting or is insensitive. Flumes are also built in small flashy streams where current-meter discharge measurements are impracticable because of the rapidity of changes in stage, and where the difficulty of anticipating stream rises makes it improbable that a streamgager will arrive at the site during high-water periods. Flumes commonly utilize a contraction in channel width and a drop or a steepening of bed slope to produce critical or supercritical flow in the throat (contracted section) of the flume. The relation between depth measured at some standard cross section and discharge is thus a function only of the configuration of the flume and the relation can therefore be determined prior to installation.

Purpose and scope

The purpose of this report is to describe the various types of flumes that are most commonly used in the United States, to present the principles that govern their design, to provide discharge ratings for each, and to discuss the general considerations involved in the selection and placement of the type of flume most suitable for any given set of conditions.

The eight flumes described are listed below; they are categorized with respect to the flow regime that principally controls the measured stage; that is, each flume is classed as either a critical-flow flume or a supercritical-flow flume.

- Critical-flow flumes:
  - Parshall
  - Portable Parshall
  - HS, H, and HL (these three flumes differ from each other, primarily, in dimension)
- Supercritical-flow flumes:
  - San Dimas
  - Modified San Dimas
  - Trapezoidal

Principles Governing the Design of Flumes

Hydraulic contractions and transitions may best be analyzed by the use of specific energy principles. The specific energy diagram of figure 1 defines, for a rectangular channel, the relationships between depth of flow, d, and specific energy, E, for various unit discharges, q. Specific energy is the energy level with reference to the streambed at a particular point. Thus a given increase in streambed elevation results in a decrease in specific energy of the same magnitude.

Specific energy is defined as

$$E=d+V^2/2g. \qquad (1)$$

Here V is the mean velocity and g is the gravitational constant. The term $V^2/2g$ is the velocity head. If unit discharge (the discharge per foot of width) is used, equation 1 becomes

$$E=d+q^2/2gd^2. \qquad (2)$$

Evaluation of this equation yields the family of constant q curves that are asymptotic to a 45° line. The points lying on these curves and representing the minimum specific energy for a rectangular channel are uniquely defined by the equation

$$d_c = \sqrt[3]{q^2g}\,. \qquad (3)$$

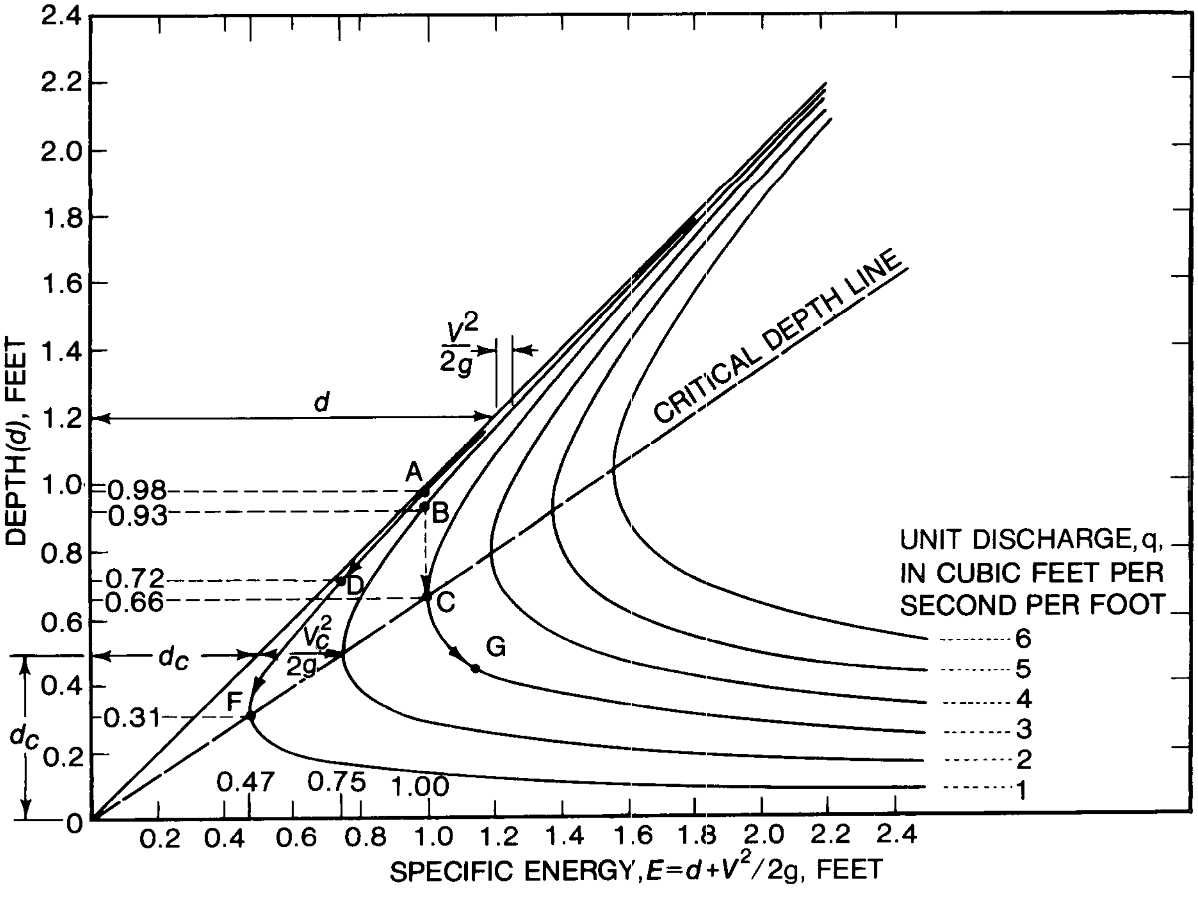


FIGURE 1.—Specific energy diagram for rectangular channel (all values are in units of feet except discharge).

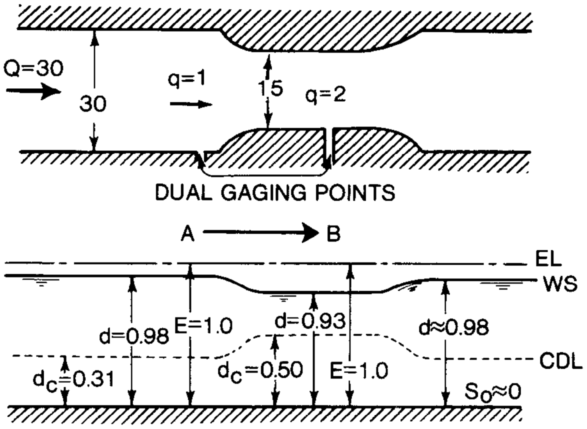
This equation defines the line of critical depths as shown in figure 1. At this critical depth, there is the unique relationship in which the velocity head is exactly half the depth of flow. Flow conditions more commonly found in rivers and streams are tranquil or subcritical and are represented by the curves above the line of critical depth. In this region depths are large, and velocities and velocity heads are relatively small. Conversely, in the supercritical flow region below the critical depth line, depths are small, and velocities and velocity heads quite large.

Six approaches employed in various flume designs, as illustrated in figures 2–7, will be discussed using the specific energy diagram of figure 1. Application of specific energy principles to abrupt contractions and short channels is not entirely correct due to accelerative and curvilinear flows. However, it is the concept that is of interest here and not an exact analysis.

Type I. Tranquil flow, small width reduction

The earliest measuring flumes are exemplified by figure 2, which shows subcritical flow entering a flume with zero bed slope, S_0, and side contractions. The side contractions reduce the width of the flume, resulting in an increase in unit discharge.

Because there is minor energy loss and no change in bed elevation, the specific energy in the throat is about the same as in the approach. With constant specific energy, the effect of a small width contraction is a lowering of the water surface in the throat. In the example shown in figure 2, the side contraction between point A and point B causes a change in the discharge per unit width. The transition is illustrated in figure 1, as the point A on the curve $q=1$ and the point B on the curve $q=2$. Owing to the small degree of contraction, critical depth is not accomplished (point C on curve $q=3$ in fig. 1). In this type of flume it is necessary to measure the head (vertical depth) in both the approach section and in the throat. For this reason, this type of flume, called a subcritical-flow meter, is seldom used today.



EXPLANATION OF TERMS AND UNITS

(For figures 2 through 7, units have been omitted and are in feet or as shown below)

CDL, Critical depth line
d, Depth in feet
d_c, Critical depth in feet
E, Specific energy in feet
Q, Discharge in ft^3/s
q, Unit discharge in $ft^3/s/ft$
S_c, Critical slope
S_0, Bed slope of flume
WS, Water surface

FIGURE 2.—Type I control: subcritical-flow contraction obtained by small width reduction, horizontal bed.

Type II. Critical flow, large width reduction

Further contraction of the throat width, as in type I, results in increasing the unit discharge until a critical width is reached (see fig. 3). This width corresponds to point C on figure 1 and represents the minimum specific energy that exists at the critical-flow depth. Earlier flume designs were based on measuring this depth in the throat because of the unique critical-depth discharge relationship of equation 3.

The discharge equations for flumes conform closely to this relationship, but it can be seen that depths in the vicinity of critical flow can change radically with little change in discharge. Thus, flow close to critical is very unstable, constantly attempting to become either subcritical or supercritical.

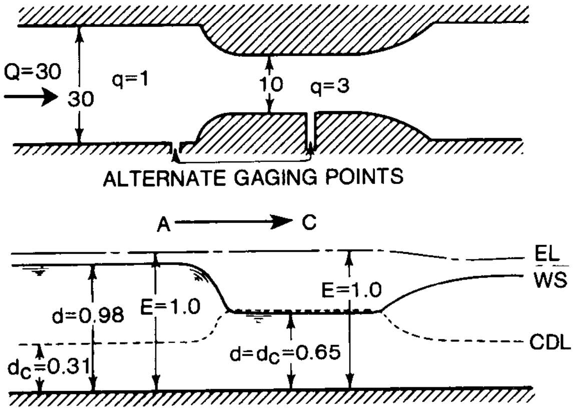


FIGURE 3.—Type II control: critical-flow contraction obtained by large width reduction, horizontal bed (for an explanation of symbols and units, see fig. 2).

In both type I and type II controls, the flume slope may be zero or nearly zero owing to the relatively small energy losses experienced.

In a type II control, head may be measured at either of two locations, in the immediate approach to the flume or in the throat. Measurement in the approach will yield a more sensitive head-discharge relation (discharge rating) because changes in discharge will result in greater changes in depth in subcritical flow than would like changes in discharges in critical flow. Unfortunately, the head-discharge relation in the approach may be unstable owing to approach conditions such as scour and fill. Consequently, head is usually measured in the throat to alleviate influence from either upstream or downstream. Approach conditions can have some influence on flow in the throat, but it is generally insignificant. The location at which critical depth is first reached may shift further downstream into the throat as a result of excessive deposition in the approach. For this reason and to avoid possible flow separations near the entrance, head measurements in the throat should not be too close to the entrance.

A type II control, called a critical-depth meter, has the advantage of requiring measurement of head at only one location; it has the disadvantage that free overfall is required to sustain flows at critical depths in the throat. Measurement of head upstream is not entirely satisfactory because of possible approach influences, nor is it satisfactory in the throat because of widely fluctuating water surfaces. As will be shown in the discussion of type IV and VI controls, much is to be gained by placing such a flume on a slope greater than critical.

Type III. Tranquil flow, small increase in bed elevation

Types I and II controls represent methods of obtaining measuring flumes by contracting the flow using width reductions. In these flumes, as can be seen on the specific energy diagram in figure 1, the specific energy, E, is constant from approach to throat. All changes in depths from the approach to the throat are accomplished by going to successively larger q curves.

Flow conditions similar to those produced by the side contractions, as in types I and II, can also be obtained by increasing the bed elevation. In the absence of side contractions, the unit discharges will not vary from approach to throat, but the specific energy, E, will change.

For a type III control with $E = 1.0$ in the approach and $q = 1.0$ throughout, the change in depth must be along a constant q curve. As illustrated in figure 4, this can only be effected by a reduction in specific energy. Hence, if the floor of the flume is arbitrarily raised 0.25 foot above the approach bed, the result is a direct reduction in E to 0.75 foot over the sill, point D on figure 1. This yields a depth of approximately 0.72 foot, which is still subcritical. Because q is the same in both approach and over the sill, d_c is 0.31 foot for both.

Raising the bed even more produces lower and lower depths across the sill until critical depth is reached, point F on figure 1. At this depth, the specific energy is minimal, $E = 0.47$ foot. Hence, a sill height of 0.53 foot is the

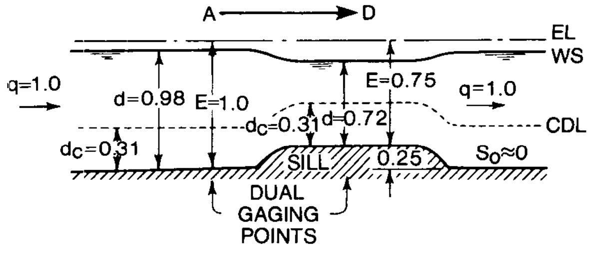


FIGURE 4.—Type III control: subcritical-flow contraction obtained by small increase in bed elevation, horizontal bed (for an explanation of symbols and units, see fig. 2).

critical height because a sill of greater height will produce increased stages upstream. A critical depth of 0.31 foot will exist at the sill.

Flumes that incorporate sills in their design are the least frequently used. This is so because one of the primary advantages of flumes as discharge meters is their self-cleaning characteristics; as might be expected, sills form a partial barrier to the approaching flow that encourages deposition. Therefore, there would appear to be no advantage to flume designs incorporating sills or raised floors.

Type IV. Supercritical flow, width reduction, steep slope

When flumes are on approximately zero slope, as in types I, II, and III, critical depth is the minimum depth possible in the flume. When the flow in the throat reaches the critical discharge, a critical contraction has been reached. Further contraction from the sides, the bottom, or both will not produce supercritical flow.

The design of a flume with supercritical flow in the throat can be accomplished only by increasing the available specific energy from the approach into the throat. Whereas a rise in the flume floor decreases the specific energy, a drop in the flume floor or an increase in flume slope serves to increase the specific energy. Type IV control in figure 5, therefore, is identical with type II, but has been placed on a slope to supply the required increase in specific energy to produce supercritical flow in the throat. Thus, for a particular discharge, the path A-B-C-G in figure 1 is followed.

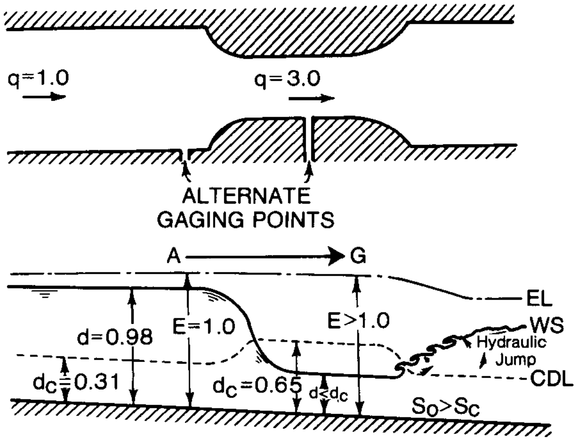


FIGURE 5.—Type IV control: supercritical-flow contraction obtained by width reduction and sloping bed (for an explanation of symbols and units, see fig. 2).

Type V. Supercritical flow, width reduction, drop in bed elevation

Supercritical flow may also be obtained by abruptly dropping the bed as in type V (see fig. 6). As with type IV, the path A-B-C-G in figure 1 is followed: A represents flow in the approach; movement from A to C from one *q* curve to successively higher ones results from the side contraction; and movement from C to G is caused by the increased specific energy provided by the drop but no further contraction.

Types IV and V flumes are called supercritical-flow meters. As in the critical-flow meters, measurement of head is made either in the throat or the approach. The advantages and disadvantages of measuring in the approach have already been discussed. As previously emphasized, measurement of head in critical flow, as at point C, is undesirable since there may be large fluctuations in depth with little or no change in discharge. Therefore, head is customarily measured downstream of the point of critical depth in the region of supercritical flow. Measurement of head here may be difficult owing to the high velocities encountered under such conditions. As can be seen in figure 1, a particular

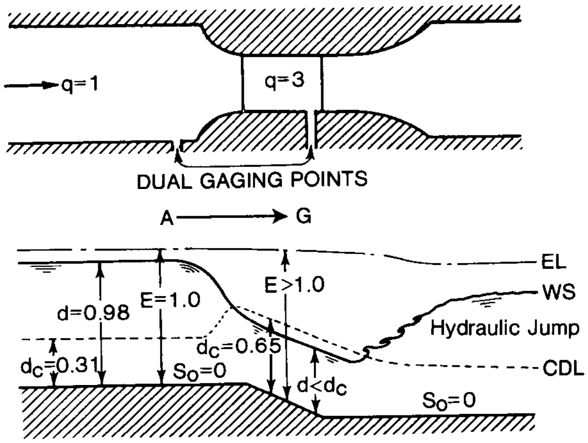


FIGURE 6.—Type V control: supercritical-flow contraction obtained by width reduction and drop in bed (for an explanation of symbols and units, see fig. 2).

disadvantage of measuring head in this region is the lack of rating sensitivity compared with measurements in subcritical flow. The primary advantage of a supercritical-flow flume is that it has optimum self-cleaning and scouring characteristics. A head-discharge relation (discharge rating) based on head measurements in the region of supercritical flow is the least influenced by disturbances either upstream or downstream and hence is apt to be the most stable. By the same token, such flumes are the most capable of stable operation with high submergences.

Type VI. Supercritical flow, steep slope

Contraction and increase in specific energy are not necessary for supercritical flow to occur. A sufficient increase in specific energy alone can produce supercritical flow. In an ordinary stream-gaging control, this flow is obtained simply by the drop created by the physical presence of the control.

As can be seen in figure 7, flow at supercritical depths can also be produced over a broad crest by simply giving it sufficient downstream slope.

A slope of 1 degree is usually sufficient to produce critical depth in the vicinity of the upstream edge of the apron, but waves and disturbances are apt to be numerous downstream. Such wave disturbances occur when flow across the apron is too close to critical and not well within the supercritical-flow range. On ordinary concrete aprons, slopes from 2 1/2 to 5 percent have been found to yield depths well within the supercritical-flow range.

For a type VI control, if approach conditions were not subject to change, a stable discharge rating could be expected to exist by measuring head in the subcritical region upstream. If accurate head measurements could be made in the region of supercritical flow down on the sloping crest, a stable discharge rating would be obtained regardless of upstream or downstream disturbances. However, such a rating would be very insensitive. The addition of side contractions improves the rating sensitivity. Thus, the ideal flume is basically a sloping broad-crested weir with side contractions.

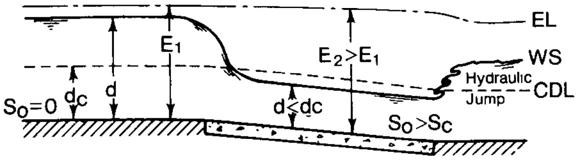


FIGURE 7.—Type VI control: supercritical flow obtained by steepening slope (for an explanation of symbols and units, see fig. 2).

Parshall Flume

Development

The development of measuring flumes was stimulated primarily by the need for simple and accurate devices for metering irrigation flows. Prior to 1920 the devices used were either weirs or flumes of the Venturi type; each had its disadvantages. Head loss and backwater caused by a weir set high in a canal was intolerable if the canal banks were low; when the weir crest was set at a lower elevation, the weir often operated at a degree of submergence for which discharges could be computed with less reliability. The Venturi flume, which is, in essence, a short stabilized reach of channel that includes a width-contracted section, usually operates more satisfactorily than a weir with regard to head loss and submergence effect. However, this flume requires the measurement of head both in the contracted section and in the upstream approach reach. The Venturi flume, developed by V. M. Cone (1917), was the forerunner of the Parshall flume. R. L. Parshall (1926) proposed changes in the design of the Venturi flume, the most important of which was a sharp drop in the slope of the floor through the throat. The break in floor slope at the entrance to the throat causes critical depth to occur there, thus providing a control that commonly requires only a single head measurement in the approach reach for a determination of discharge.

The throat width of the earlier Parshall flumes ranged from 3 to 8 feet. Flumes with throat widths of 10 to 50 feet were later built and field calibrated by Parshall (1953). More recently Parshall flumes with throat widths of 1 and 2 inches were calibrated by Robinson

(1957). Head-discharge relations are thus available for a wide range of throat widths.

Although the Parshall flume was developed for use in irrigation systems, it has also been used as a gaging-station control in natural streams. It will pass small- to medium-sized sediment without the rating being affected. Poor channel alinement and uneven distribution of flows in the approach may affect the discharge ratings. The flume is insensitive at low flows because of its rectangular cross section. During low-flow periods of the year, to obtain the required sensitiveness the flume is sometimes operated with a temporary V-notch weir installed at the entrance to the throat. Each flume size is limited in the range of discharge it can measure and thus is better suited to irrigation canals and other manmade systems.

Configuration

The general design of the Parshall flume is shown in figure 8. The dimensions, corresponding to the letters in figure 8 for various sizes of flumes, are given in table 1. The flumes are designated by the width, W_T, of the throat. Flumes with throat widths from 3 inches to 8 feet have a rounded entrance whose floor slope is 25 percent. The smaller and larger flumes do not have this feature, but it is doubtful whether the performance of any of the flumes is significantly affected by the presence or absence of the entrance feature as long as approach conditions are satisfactory.

The Parshall flume is a type V control with supercritical flow existing in the throat section, but because head is measured upstream of critical depth, it is classified here as a critical-depth meter. Head is measured downstream to indicate when submerged-flow conditions exist. The datum for both upstream and downstream gages is the level floor in the approach. The sloping floor, length L_D in figure 8, in the downstream diverging section, is designed to reduce scour downstream and to produce more consistent head-discharge relations under conditions of

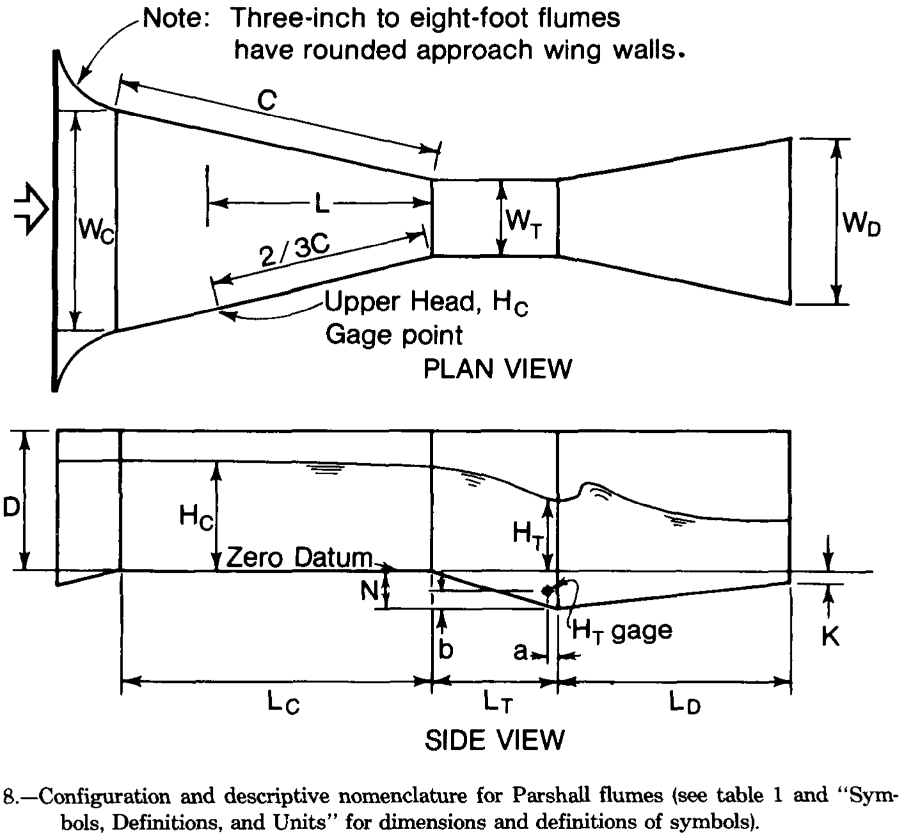


FIGURE 8.—Configuration and descriptive nomenclature for Parshall flumes (see table 1 and "Symbols, Definitions, and Units" for dimensions and definitions of symbols).

TABLE 1.—*Dimensions and capacities of standard Parshall flumes*

Widths			Axial lengths			Wall Depth in Converging Section	Vertical distance below crest		Converging wall length	Gage Points			Free-flow Capacities, in cubic feet per second	
Throat W_T	Upstream end W_C	Downstream end W_D	Converging section L_C	Throat section L_T	Diverging section L_D	D	Dip at Throat N	Lower end of flume K	C*	H_C, wall length upstream of crest**	H_T		Minimum	Maximum
											a	b		
Inches	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*		
1	0.549	0.305	1.17	0.250	0.67	0.5-0.75	0.094	0.062	1.19	0.79	0.026	0.042	0.005	0.15
2	.700	.443	1.33	.375	.83	0.50-0.83	.141	.073	1.36	.91	.052	.083	.01	.30
3	.849	.583	1.50	.500	1.00	1.00-2.00	.188	.083	1.53	1.02	.083	.125	.03	1.90
6	1.30	1.29	2.00	1.00	2.00	2.0	.375	.25	2.36	1.36	.167	.25	.05	3.90
9	1.88	1.25	2.83	1.00	1.50	2.5	.375	.25	2.88	1.93	.167	.25	.09	8.90
Feet														
1.0	2.77	2.00	4.41	2.0	3.0	3.0	.75	.25	4.50	3.00	.167	.25	.11	16.1
1.5	3.36	2.50	4.66	2.0	3.0	3.0	.75	.25	4.75	3.17	.167	.25	.15	24.6
2.0	3.96	3.00	4.91	2.0	3.0	3.0	.75	.25	5.00	3.33	.167	.25	.42	33.1
3.0	5.16	4.00	5.40	2.0	3.0	3.0	.75	.25	5.50	3.67	.167	.25	.61	50.4
4.0	6.35	5.00	5.88	2.0	3.0	3.0	.75	.25	6.00	4.00	.167	.25	1.30	67.9
5.0	7.55	6.00	6.38	2.0	3.0	3.0	.75	.25	6.50	4.33	.167	.25	1.60	85.6
6.0	8.75	7.00	6.86	2.0	3.0	3.0	.75	.25	7.0	4.67	.167	.25	2.60	103.5
7.0	9.95	8.00	7.35	2.0	3.0	3.0	.75	.25	7.5	5.0	.167	.25	3.00	121.4
8.0	11.15	9.00	7.84	2.0	3.0	3.0	.75	.25	8.0	5.33	.167	.25	3.50	139.5
10	15.60	12.00	14.0	3.0	6.0	4.0	1.12	.50	9.0	6.00			6	300
12	18.40	14.67	16.0	3.0	8.0	5.0	1.12	.50	10.0	6.67			8	520
15	25.0	18.33	25.0	4.0	10.0	6.0	1.50	.75	11.5	7.67			8	900
20	30.0	24.00	25.0	6.0	12.0	7.0	2.25	1.00	14.0	9.33			10	1340
25	35.0	29.33	25.0	6.0	13.0	7.0	2.25	1.00	16.5	11.00			15	1660
30	40.4	34.67	26.0	6.0	14.0	7.0	2.25	1.00	19.0	12.67			15	1990
40	50.8	45.33	27.0	6.0	16.0	7.0	2.25	1.00	24.0	16.00			20	2640
50	60.8	56.67	27.0	6.0	20.0	7.0	2.25	1.00	29.0	19.33			25	3280

*For sizes 1 to 8 feet, $C=W_T/2+4$ feet.

**H_C located ⅔ C distance from crest for all sizes; distance is wall length, not axial.

Note: Flume sizes 3 inches through 8 feet have approach aprons rising at 25 percent slope and the following entrance roundings: 3 through 9 inches, radius=1.33 feet; 1 through 3 feet, radius=1.67 feet; 4 through 8 feet, radius=2.00 feet.

submergence. The percentage of submergence for Parshall flumes is computed by the formula

$$(H_T/H_C)\times 100 \qquad (4)$$

where H_C is the head in the converging section and H_T is the head in the throat section. Where free-flow conditions exist for all flows, the downstream gage, H_T, may be omitted and the entire diverging reach may be dispensed with if desired. That simplification has been used in the design of small portable Parshall measuring flumes.

Head-discharge relations

Tables 2 and 3 summarize the discharge ratings at H_C under conditions of free flow for flumes of various sizes. Although the free-flow head-discharge relations for the various flumes were derived experimentally, all relations can be expressed closely by the following equation (Davis, 1963):

$$Y_o+\frac{Q_o^2}{2Y_o^2\,(1+0.4X_o)^2}=1.351Q_o^{0.645}, \qquad (5)$$

in which Y_o = nondimensional depth, H_C/W_T,
Q_o = nondimensional discharge, $Q/g^{1/2}W_T^{5/2}$,
X_o = nondimensional distance, L/W_T,
H_C = head at measuring section, in feet,
W_T = channel width at throat, in feet,
Q = discharge, in cubic feet per second,
g = acceleration of gravity, in feet per second squared, and
L = distance from throat crest to measuring section, in feet.

For flumes with throat widths no greater than 6 feet, the following simplified form of the above equation (Dodge, 1963) can be used:

$$Y_o=1.190Q_o^{0.645}X_o^{0.0494}. \qquad (6)$$

These equations may be helpful in developing discharge ratings for Parshall flumes of nonstandard dimensions or for those having finished dimensions differing from the standard.

When the head at H_T is relatively high, the free-flow discharge corresponding to any given value of H_C is reduced. The percentage of submergence, or value of $(H_T/H_C)\times 100$, at which the free-flow discharge is first affected, varies with the size of the flume. For flumes whose throat width is less than 1 foot, the submergence must exceed 50 percent before there is any backwater effect from downstream;

TABLE 2.—*Discharge ratings for 2- to 9-inch Parshall flumes under free-flow conditions*

H_C (feet)	Flume size			
	2 inches (ft^3/s)	3 inches (ft^3/s)	6 inches (ft^3/s)	9 inches (ft^3/s)
0.1	0.02	0.03	0.05	0.09
.2	.06	.08	.16	.26
.3	.11	.15	.31	.49
.4	.17	.24	.48	.76
.5	.24	.34	.69	1.06
.6	.31	.45	.92	1.40
.7	.40	.57	1.17	1.78
.8		.70	1.45	2.18
.9		.84	1.74	2.61
1.0		.89	2.06	3.07
1.1			2.40	3.55
1.2			2.75	4.06
1.3			3.12	4.59
1.4			3.51	5.14
1.5				5.71
1.6				6.31
1.7				6.92
1.8				7.54
1.9				8.20

TABLE 3.—*Discharge ratings for 1- to 50-foot Parshall flumes under free-flow conditions*

H_c	1 foot	1.5 feet	2 feet	3 feet	4 feet	5 feet	6 feet	7 feet	8 feet
feet	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs
0.10	0.11	0.15							
.15	.20	.30	0.42	0.61					
.20	.35	.51	.66	.97	1.26	1.55			
.25	.49	.71	.93	1.37	1.80	2.22	2.63	3.02	3.46
.30	.64	.94	1.24	1.82	2.39	2.96	3.52	4.08	4.62
.4	.99	1.47	1.93	2.86	3.77	4.68	5.57	6.46	7.34
.5	1.39	2.06	2.73	4.05	5.36	6.66	7.94	9.23	10.5
.6	1.84	2.73	3.62	5.39	7.15	8.89	10.6	12.4	14.1
.7	2.33	3.46	4.60	6.86	9.11	11.4	13.6	15.8	18.0
.8	2.85	4.26	5.66	8.46	11.3	14.0	16.8	19.6	22.4
.9	3.41	5.10	6.80	10.2	13.6	16.9	20.3	23.7	27.0
1.0	4.00	6.00	8.00	12.0	16.0	20.0	24.0	28.0	32.0
1.2	5.28	7.94	10.6	16.0	21.3	26.7	32.1	37.5	42.9
1.4	6.68	10.1	13.5	20.3	27.2	34.1	41.1	48.0	55.0
1.6	8.18	12.4	16.6	25.1	33.6	42.2	50.8	59.4	68.1
1.8	9.79	14.8	19.9	30.1	40.5	50.8	61.3	71.8	82.3
2.0	11.5	17.4	23.4	35.5	47.8	60.1	72.5	84.9	97.5
2.2	13.3	20.2	27.2	41.3	55.5	69.9	84.4	98.9	113.6
2.4	15.2	23.0	31.1	47.3	63.7	80.3	97.0	113.7	130.7

H_c	10 feet	12 feet	15 feet	20 feet	25 feet	30 feet	40 feet	50 feet
feet	cfs	cfs	cfs	cfs	cfs	cfs	cfs	cfs
0.30	5.75	6.75	8.4	11.1	13.8	16.5	21.8	27.3
0.4	9.05	10.85	13.3	17.7	21.8	26.1	34.6	43.2
0.5	13.1	15.4	19.1	25.1	31.2	37.2	49.5	61.8
0.6	17.5	20.6	25.5	33.7	41.8	50.0	66.2	82.6
0.7	22.2	26.2	32.7	43.1	53.4	64.0	84.8	105.5
0.8	27.5	32.7	40.4	53.4	66.3	79.2	105	131
0.9	33.3	39.4	48.9	64.3	80.1	95.5	127	158
1.0	39.4	46.8	57.9	76.3	94.8	113.2	150	187
1.2	53.7	62.6	77.3	102.0	127.0	152	201	250
1.4	67.4	80.1	99.0	130.5	162	194	257	320
1.6	83.5	99.1	122.8	162	201	240	318	396
1.8	103.4	119.8	148.0	195	243	290	384	479
2.0	119.4	141.8	175.3	232	287	343	454	567
2.2	139.0	165.0	204	269	334	400	530	660
2.4	164.6	189.8	235	310	384	459	609	758
2.6	181.7	215.7	267	352	437	522	692	864
3.0	228.4	271.2	335	442	549	656	870	1084
3.5	294	347	429	566	703	840	1113	1387
4.0	363	430	531	700	870	1040	1379	1717
4.5	437	518	641	846	1051	1255	1664	2073
5.0	517	614	759	1002	1244	1486	1970	2453
5.5			885	1166	1448	1730	2295	2860
6.0			1016	1340	1664	1988	2638	3285

Note. Available data indicates that extension of the above ratings to greater heads is reliable for flumes with throat width from 1 to 8 feet, the threshold submergence is 70 percent; for flumes with throat width greater than 10 feet, the threshold submergence is 80 percent. Figure 9 shows the discharge ratings for Parshall flumes, from 2 to 9 inches, under both free-flow and submergence conditions. Figure 10 shows the correction in discharge for flumes that have

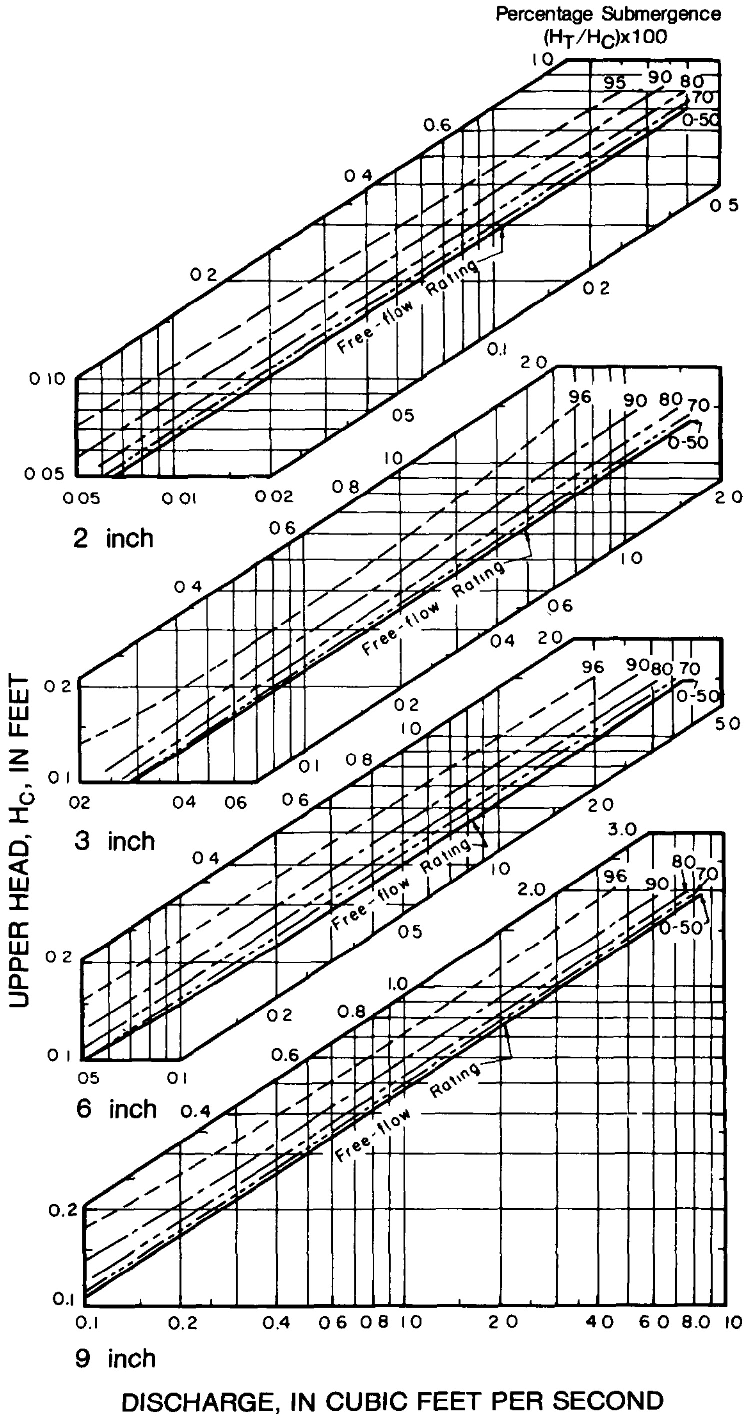


FIGURE 9.—Discharge ratings for "inch" Parshall flumes for both free-flow and submergence conditions.

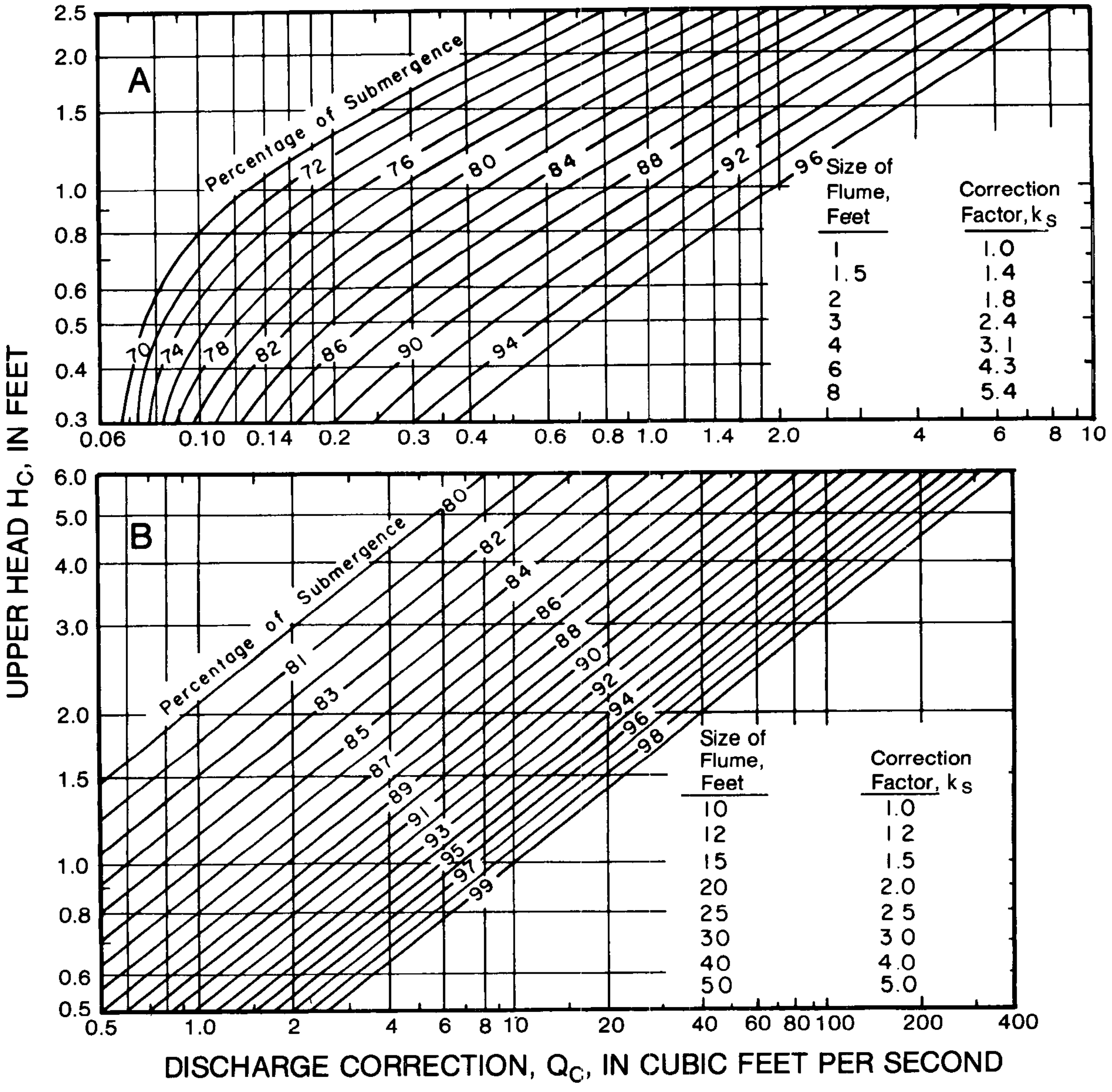
throat widths between 1 and 50 feet. The correction is always negative and is applied to the free-flow discharges. The appropriate correction factor (k_s) for a flume size is applied to the discharge corrections read from the graphs (fig. 10). In other words,

$$Q_s=Q_f-k_sQ_c, \tag{7}$$

where Q_s = discharge under submergence conditions,

Q_f = discharge under free-flow conditions, and

Q_c = discharge correction unadjusted for flume size.



Size of Flume, Feet	Correction Factor, k_s
1	1.0
1.5	1.4
2	1.8
3	2.4
4	3.1
6	4.3
8	5.4

Size of Flume, Feet	Correction Factor, k_s
10	1.0
12	1 2
15	1.5
20	2.0
25	2 5
30	3 0
40	4.0
50	5.0

FIGURE 10.—Correction factors for submerged flow through A, 1- to 8-foot, and B, 10- to 50-foot Parshall flumes.

Portable Parshall Flume

Configuration

The portable Parshall flume is a device for determining discharge when depths are too shallow and velocities too low for a current-meter measurement of discharge; it is not used as a gaging-station control. The portable flume used by the Geological Survey is a modified form of the standard Parshall flume, with a 3-inch throat. The modification consists, primarily, of the removal of the downstream diverging section of the standard flume. The purpose of the modification is to reduce the weight of the flume and to make it easier to install. Because the portable Parshall flume has no downstream diverging section, it cannot be used for measuring flows when the submergence ratio exceeds 0.6. The submergence ratio is the ratio of the downstream head to the upstream head (see equation 4). Although a submergence ratio of 0.6 can be tolerated without affecting the rating of the portable flume, in practice the flume is usually installed so that the flow passing the throat has virtually free fall. This may be accomplished by building up the streambed a couple of inches under the level converging floor of the flume (see fig. 4).

Figure 11 shows the plan and side views of the portable Parshall flume. Upstream head may be measured by a recorder placed on the small stilling well that is hydraulically connected to the flow by a 3/8-inch hole. The discharge rating (head-discharge relation) for the flume is given in table 4; the discharge corresponding to a given head is slightly greater for the portable flume than it is for the standard Parshall flume, with a 3-inch throat.

Installation and operation

When installing the flume in a channel, care must be taken to level the floor of the converging section both laterally and along its longitudinal axis. The level bubble that is attached to one of the braces (fig. 11) may not be sufficient unless its correctness is confirmed by comparing with a carpenter's level placed in the actual floor of the flume. Soil or streambed material is then packed around the flume to prevent leakage under and around it. Figure 12 shows a typical field installation. After the flume is installed, water will pool upstream from the structure. Head readings should be observed until they indicate the pool has stabilized; readings should then be taken at half-minute intervals for about 3 minutes. The mean value of those readings is the head used in table 4 to obtain the discharge.

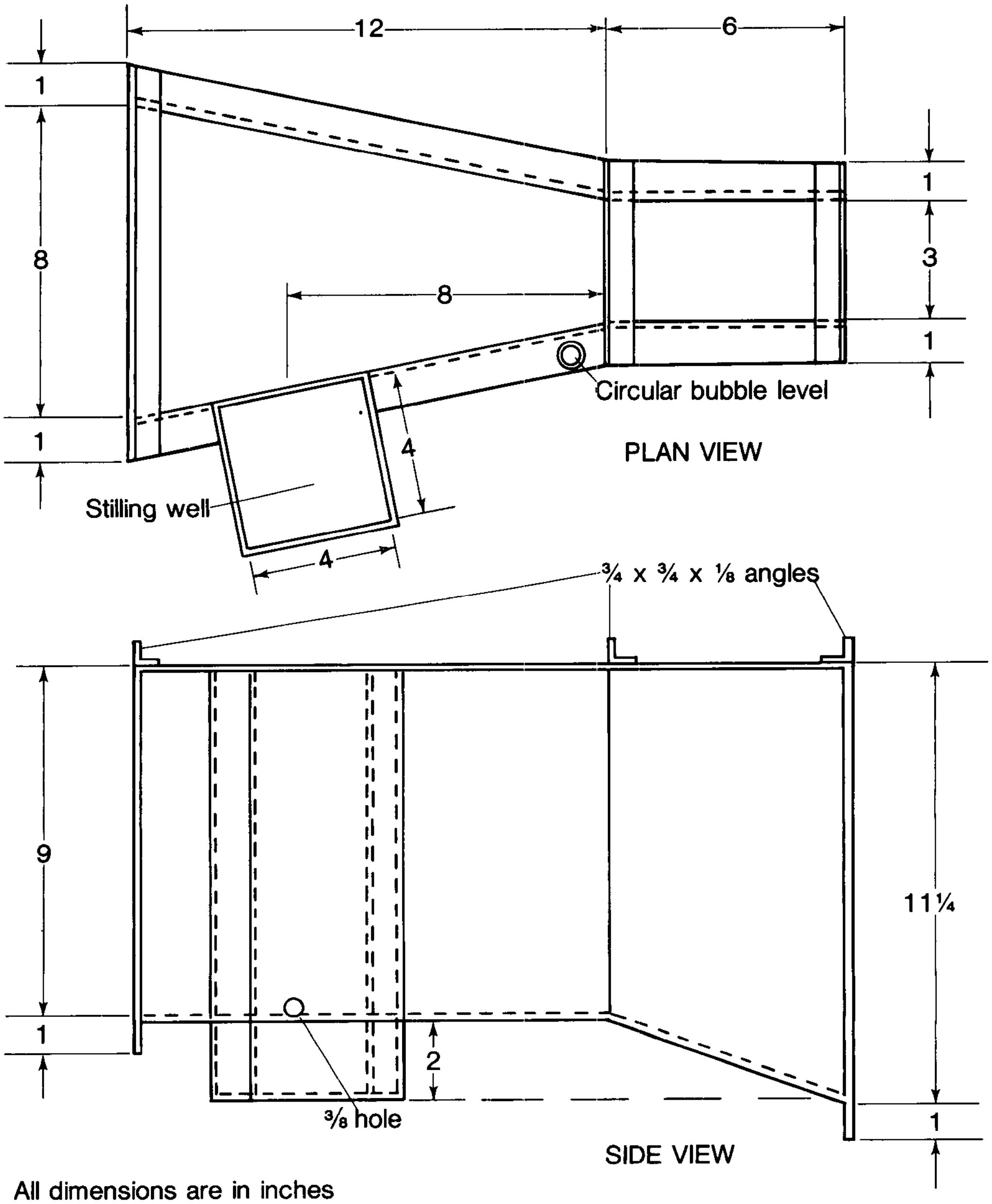
Calibration tests by the authors for 11 of the 3-inch modified Parshall Flumes indicated rather sizable differences between the discharge rating supplied here and that measured in the laboratory. Typically, especially at low heads, measured flows were about 7 percent greater than given in table 4. Some of the differences were attributed to poor dimensional control, especially where welded construction may have caused warping. Given these measurement differences, consideration should be given to calibrating each flume, either in a laboratory or in the field if other independent and accurate means of discharge measurement can be devised. In many instances, for the lower discharges, volumetric measurements can be made just downstream of the flume for confirmation or adjustment of the standard rating.

HS, H, and HL Flumes

Configuration

The U.S. Soil Conservation Service (U.S. Agricultural Research Service, 1962) has developed flumes, designated HS, H, and HL, for use on small watersheds. The configuration and proportional dimensions of the three flumes are shown in figure 13, where all dimensions are expressed in terms of the height of a given flume, D. A flume of the HS, H, or HL type is trapezoidal in cross section, and the side walls converge in the downstream direction to promote self-cleaning of the flume floor. The level floor of the flume becomes extremely narrow at its downstream end, providing greater sensitiveness to the discharge rating. In essence these flumes are quasi-weirs since they have zero bottom contraction. Critical flow is established at the downstream end of the flume by a free fall. The flume is intended to operate under free-fall conditions, but submergences up to 50 percent have no significant effect on the head-discharge relation. The head (vertical depth) is measured in the converging approach reach, upstream from the end of the flume.

The three flumes differ relatively little in general configuration, but the differences in proportional dimensions give the HL flume (L for large) the greatest capacity of the three flumes and the HS flume (S for small) the smallest capacity of the three. This is borne out by table 5, which gives the discharge ratings for the various sizes of HS, H, and HL flumes.



All dimensions are in inches
Material: ⅛ inch sheet aluminum
Welded or bolted construction
Note: This stilling well can accommodate a 3-inch float if used with a stage recorder for continuous measurement.

FIGURE 11.—Working drawing of modified 3-inch Parshall flume.

TABLE 4.—*Discharge ratings for 3-inch modified Parshall flumes*

Head (feet)	Discharge (ft^3/s)	Head (feet)	Discharge (ft^3/s)	Head (feet)	Discharge (ft^3/s)
0.01	0.0008	0.21	0.097	0.41	0.280
.02	.0024	.22	.104	.42	.290
.03	.0045	.23	.111	.43	.301
.04	.0070	.24	.119	.44	.312
.05	.010	.25	.127	.45	.323
.06	.013	.26	.135	.46	.334
.07	.017	.27	.144	.47	.345
.08	.021	.28	.153	.48	.357
.09	.025	.29	.162	.49	.368
.10	.030	.30	.170	.50	.380
.11	.035	.31	.179	.51	.392
.12	.040	.32	.188	.52	.404
.13	.045	.33	.198	.53	.417
.14	.051	.34	.208	.54	.430
.15	.057	.35	.218	.55	.443
.16	.063	.36	.228	.56	.456
.17	.069	.37	.238	.57	.470
.18	.076	.38	.248	.58	.483
.19	.083	.39	.259	.59	.497
.20	.090	.40	.269		

FIGURE 12.—Modified 3-inch Parshall flume installed for measuring discharge.

Construction and Installation

The HS, H, and HL flumes have the advantage of simplicity of design and construction. The three plane surfaces that comprise the flume are usually made of metal plates and can be prefabricated for assembly in the field. The flumes are usually mounted or cast into a concrete headwall. In many installations, lightweight sheet piling can be quickly driven to form both headwall and cutoff for the flumes.

Installation of the flumes should, wherever possible, be made with approach boxes depressed below the natural ground surface, as shown in figure 14. Where the watershed is small and the flow is dispersed, it may be necessary to use gutters to collect the run-off at the bottom of the slope and channel it into the approach box. The flume floor must be level. If silting is a problem, a 1-on-8 sloping false floor (fig. 14) can be installed to concentrate low flows and thereby reduce silting. The difference in calibration of a flume installation with a flat floor and one with a sloping false floor is less than 1 percent (U.S. Agricultural Research Service, 1962).

The stilling well for the stage recorder is usually made of sheet metal and attached to the flume wall. Openings to the flume are provided for ready exchange of water between the flume and the stilling well.

San Dimas Flume

Configuration

A flume for measuring the discharge of streams heavily laden with coarse debris was developed for use in the San Dimas Experimental Forest in southern California. Although

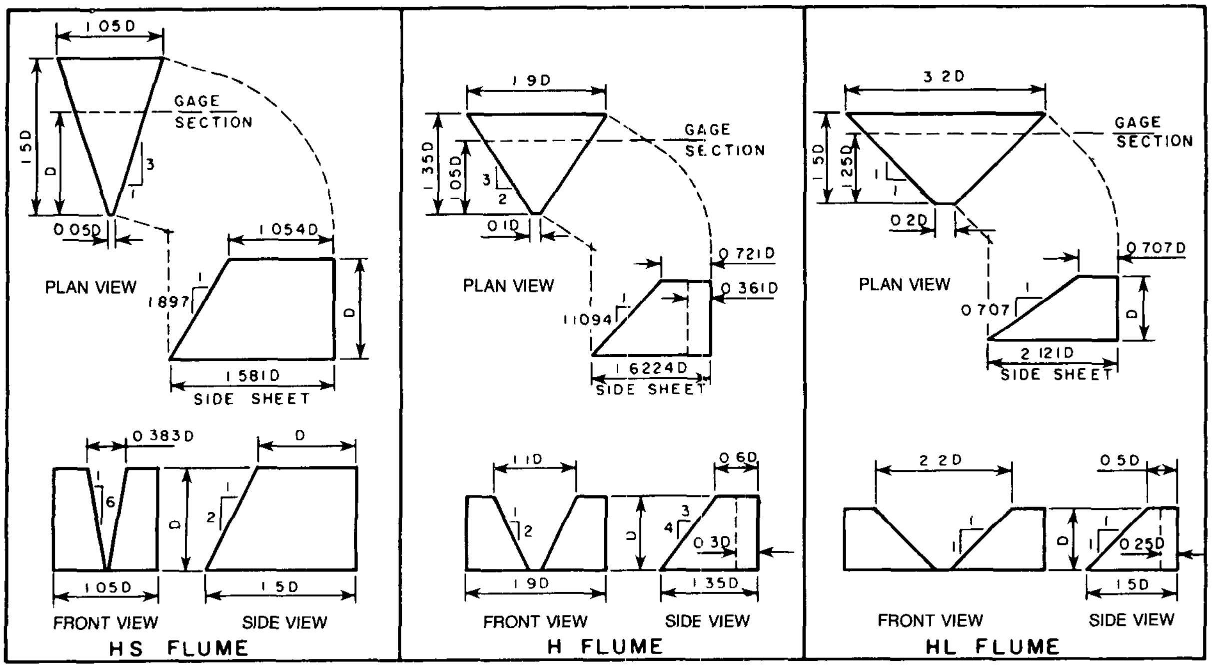
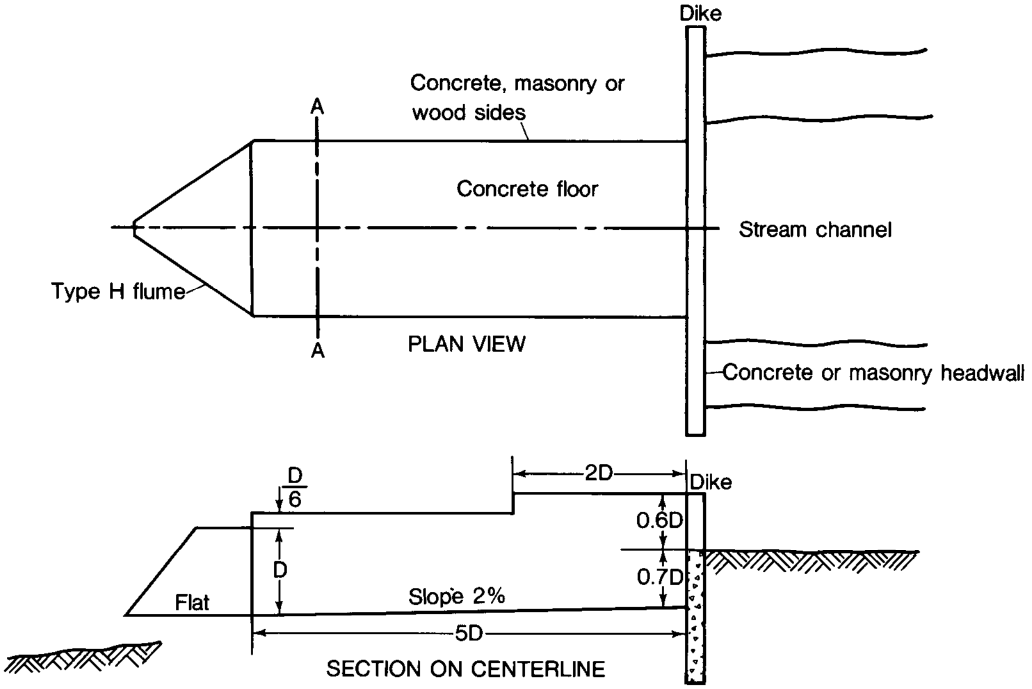


FIGURE 13.—Configuration and proportions of type HS, H, and HL flumes.

TABLE 5.—*Discharge ratings for various sizes of HS, H, and HL flumes*

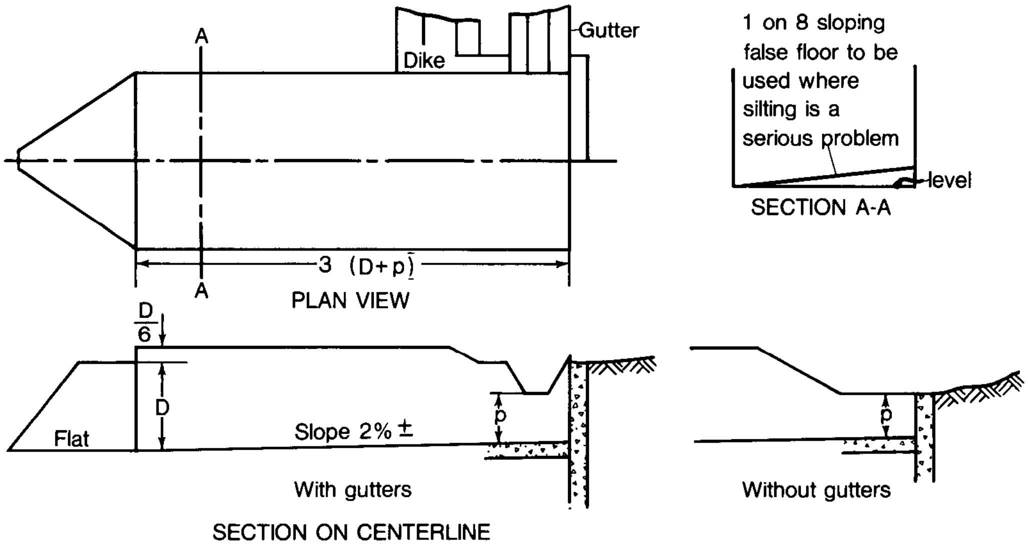
Flume size D in feet	Head in feet																		
	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.80	1.00	1.2	1.4	1.6	1.8	2.0	2.5	3.0	3.5	4.0	4.5
	HS Flume																		
0.04	0.0010	0.004	0.018	0.044	0.085														
.6	.0014	.005	.021	.049	.092	0.15	0.23												
.8	.0017	.006	.024	.054	.10	.16	.24	0.47											
1.0	.0021	.007	.027	.060	.11	.18	.26	.50	0.82										
	H Flume																		
0.5	0.002	0.010	0.04	0.11	0.20	0.35													
.75	.003	.013	.05	.12	.22	.37	0.57												
1.0	.004	.015	.06	.13	.24	.40	.60	1.16	1.96										
1.5	.006	.020	.07	.16	.28	.45	.67	1.27	2.09	3.20	4.60								
2.0	.007	.025	.08	.18	.32	.51	.74	1.38	2.25	3.38	4.82	6.58	8.67	11.1					
2.5	.009	.030	.10	.21	.36	.56	.82	1.49	2.41	3.59	5.06	6.84	8.98	11.5	19.4				
3.0	.010	.035	.11	.23	.40	.62	.89	1.60	2.57	3.80	5.33	7.16	9.33	11.9	19.9	31.0			
4.5	.015	.050	.16	.31	.52	.78	1.11	1.94	3.04	4.42	6.11	8.12	10.50	13.2	21.6	32.7	46.8	63.9	84.5
	HL Flume																		
4.0	0.03	0.09	0.28	0.56	0.94	1.42	2.01	3.53	5.56	8.06	11.2	14.9	19.2	24.3	39.9	60.3	85.9	117	

Note.—Ratings are in cubic feet per second and are derived from tests made by the Soil Conservation Service at Washington, D.C., and Minneapolis, Minn.



STRAIGHT HEADWALL INSTALLATION

(for use when flume is to be installed in a well-defined natural channel)



DROP BOX INSTALLATION

(for use when the runoff must be concentrated by gutters or dikes)

FIGURE 14.—Plans for straight headwall and drop-box installations of HS, H, and HL flumes (U.S. Agricultural Research Service, 1962, p. 31).

labeled a critical-flow flume by its designers (Wilm and others, 1938), the flume is a type IV, supercritical-flow flume in the terminology used here, because head (vertical depth) is measured in the supercritical-flow reach of the flume, 3 feet downstream from the critical-depth cross section. The configuration of the original San Dimas flume, including proportional dimensions for different sizes are shown in figure 15. The flume has a converging approach reach whose floor is flat, except for a hump at its downstream end which is the critical-depth cross section. The supercritical-flow reach is rectangular in cross section and has a slope of 3 percent. Because of this rectangular shape and the fact that supercritical depths are measured, the flume is extremely insensitive at low flows. For the accurate determination of low flows the San Dimas flume is generally operated in conjunction with sharp-crested weirs that can be bypassed when flows are high.

Head-discharge relations

Figure 15 also shows the head-discharge relations for various throat widths. The ratings for the 1-, 2-, and 3-foot flumes were determined from tests on structures of those sizes; the general equation developed from the ratings for the three flumes is also given in figure 15. That equation was found to be applicable for a 4-foot flume, but could not be extrapolated with great confidence to other throat widths. Therefore, figure 15 shows dashed-line discharge ratings, based on head-discharge measurements, for the 0.5- and 10-foot flumes.

Modified San Dimas Flume

Configuration

The San Dimas flume described on the preceding pages has been modified (Bermel,

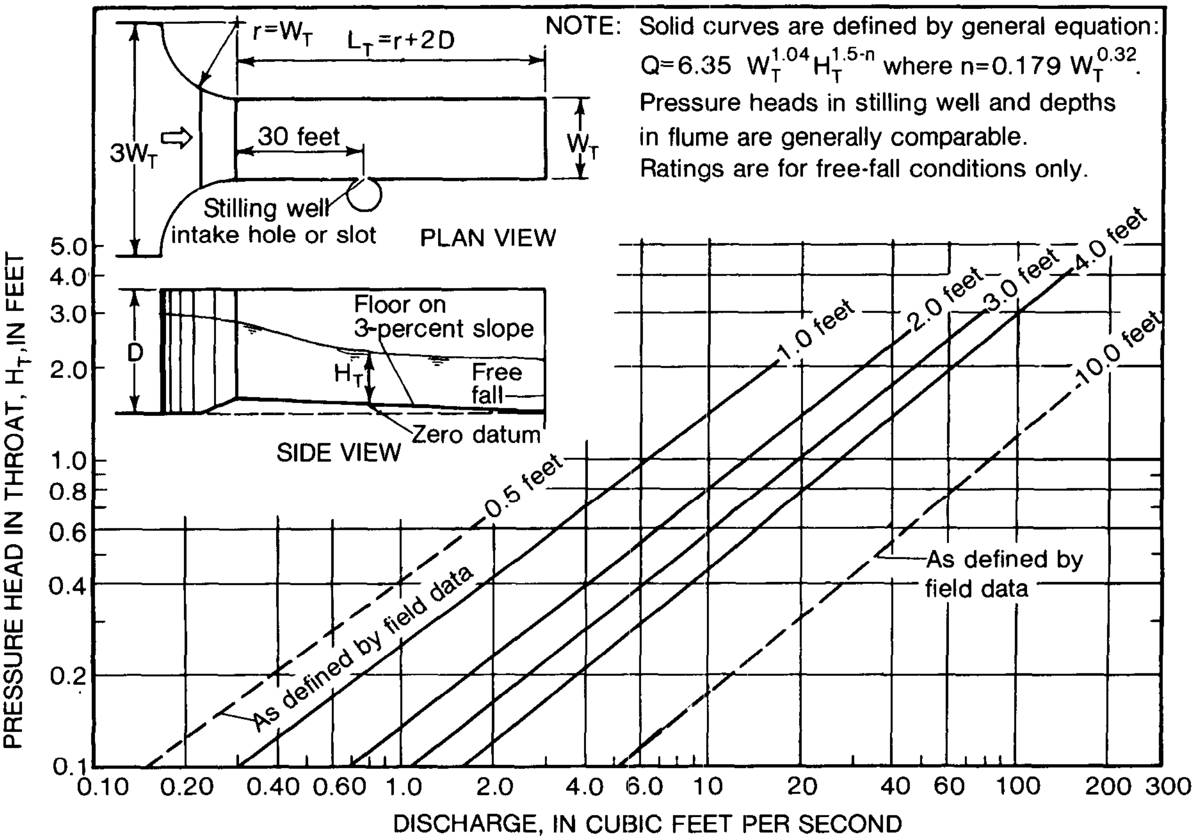
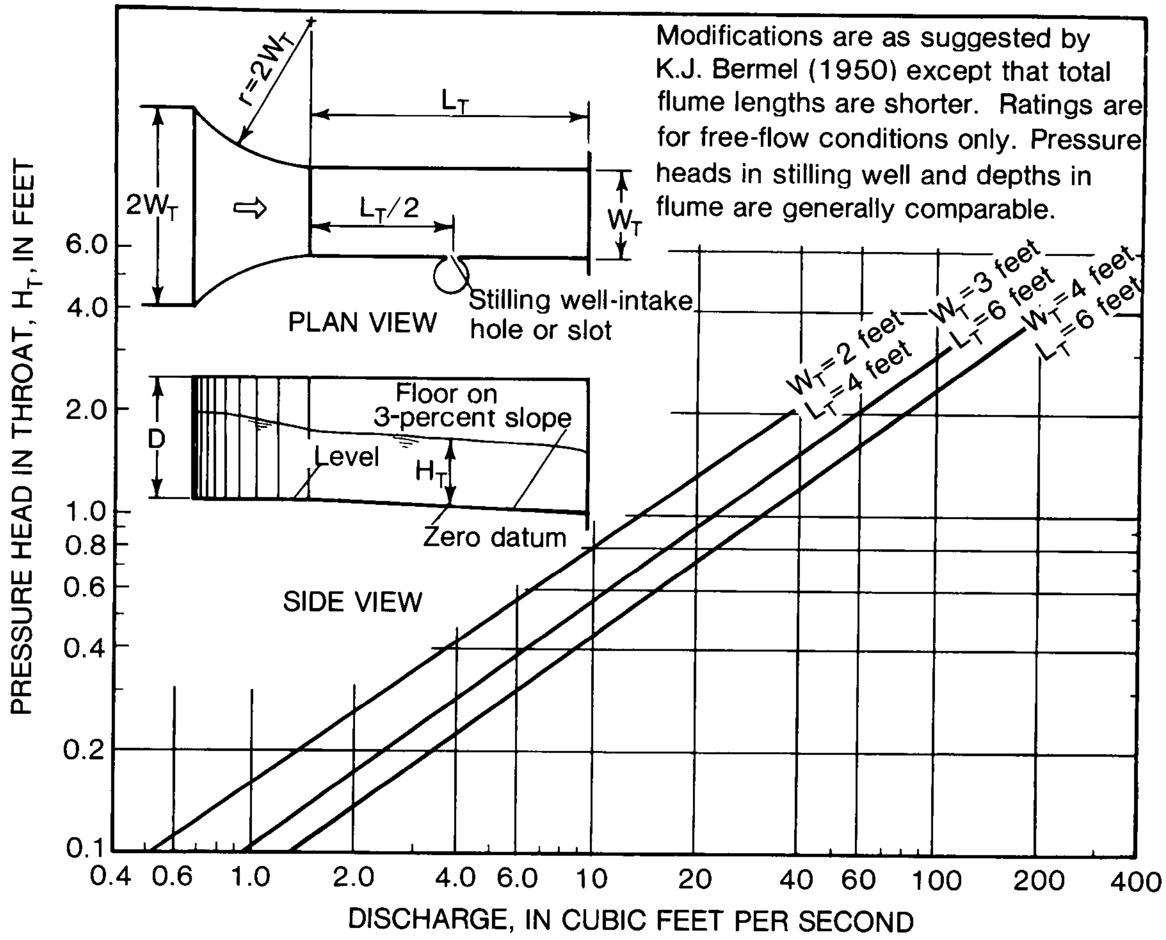


FIGURE 15.—Configuration and discharge ratings for different sizes of San Dimas flume as originally designed.



Modifications are as suggested by K.J. Bermel (1950) except that total flume lengths are shorter. Ratings are for free-flow conditions only. Pressure heads in stilling well and depths in flume are generally comparable.

FIGURE 16.—Configuration and discharge ratings for different sizes of the modified San Dimas flume.

1950); the configuration and proportional dimensions of the modified flume are shown in figure 16. The principal changes in the design can be seen by comparison of figures 15 and 16. In figure 16, the approach reach has been narrowed relative to the width of the throat, but the convergence of the side walls of the approach reach has been made less abrupt. The hump at the downstream end of the approach reach has been removed. This is because the hump added nothing to the effectiveness of the flume. With or without the hump, the entrance to the rectangular part of the flume is the critical-depth cross section; the hump has the disadvantage of being a potential sediment trap. Another change in design involves the site for measuring head. In the original San Dimas flume (fig. 15), head was measured 3 feet downstream in the throat section; in the modified version (fig. 16), head is measured at the mid-length of the throat section.

Head-discharge relations

The head-discharge relations for flumes of three different sizes are also shown in figure 16. Because the location of the head-measurement site varies with the length of the throat section, the discharge rating will vary with both width and length of the flume. Recorded head was found to be more accurate when a slot intake, rather than a circular intake, was used for the head-measurement stilling well.

Trapezoidal Supercritical-Flow Flume

General design

Supercritical-flow flumes with vertical side walls, such as the San Dimas flumes, have head-discharge relations that are insensitive at low