Water Measurement in Small Irrigation Channels Using Trapezoidal Flumes

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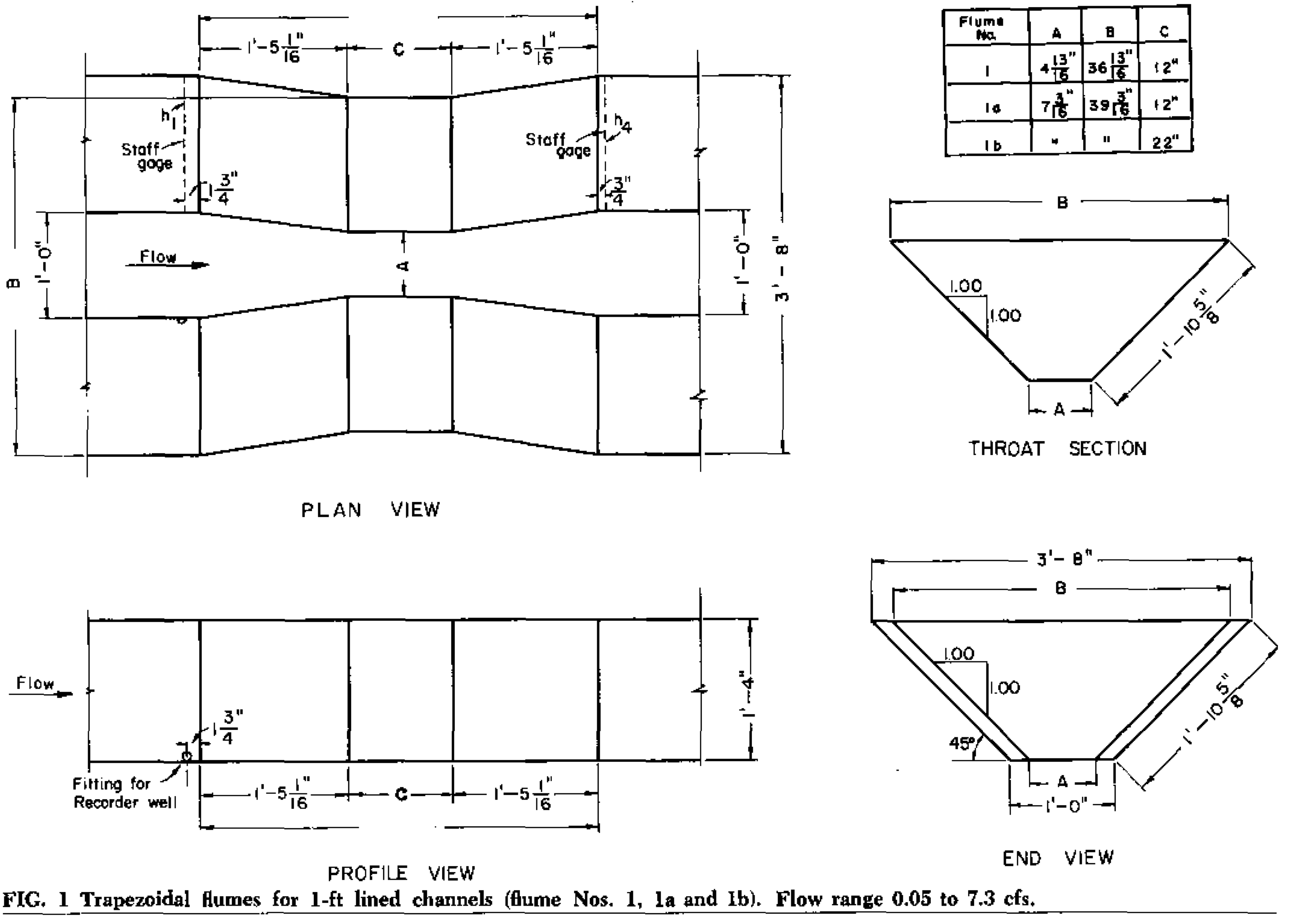
THE use of trapezoidal flumes for water measurement is increasing. Research and development has shown trapezoidal flumes in many cases to be more adaptable and more easily constructed than conventional rectangular flumes. Trapezoidal flumes are used to measure flows in natural streams and in irrigation canals and small furrows. Results of research on trapezoidal flumes at the Colorado State University hydraulics laboratory prior to 1959 have previously been published (5)*. This report presents the results of research on small trapezoidal flumes for irrigation channels.

REVIEW OF RESEARCH

Increased interest in the use of trapezoidal flumes is evident by research projects in progress in the U.S. Bureau of Reclamation hydraulic laboratory at Denver, Colo., and hydraulic laboratories at Colorado State University, Utah State University, Washington State University, Israel Institute of Technology, Hydraulics Research Station, Wallingford, England, and the Snake River Conservation Research Center at Twin Falls, Ida. ARS, USDA has been developing trapezoidal measuring flumes for stream flow measurement at Stillwater, Okla., (3) and at Washington State University, Pullman, Wash. A trapezoidal flume was developed at Colorado State University (6) for U.S. Forest Service use in measuring flow in steep mountain streams.

Recently P. Ackers and A. J. M. Harrison reported on the development of trapezoidal flumes at the hydraulics research station, Wallingford, England (1). They showed that a theoretical calibration curve can be determined with sufficient accuracy using the boundary layer concept and a drag coefficient, C_f. As an alternate method, the Darcy-Weisbach friction factor f was used to determine friction losses within the flume as a function of Reynolds Number $4vR/\nu$ and relative roughness. Their analyses showed that the boundary layer method gave slightly more accurate results than the method using frictional flow factors. Design procedures for determining flume dimensions and calibrations for a particular situation were presented. A useful feature of their development was that the sidewall slope can be fixed, if the situation demands, or varied to fit a required range of discharge stages.

Trapezoidal flumes have been used extensively for measuring irrigation water on large plantations in Hawaii. Although no references are available,



Flume No.	A	B	C
1	4 13/16"	36 13/16"	12"
1a	7 3/16"	39 3/16"	12"
1b	"	"	22"

FIG. 1 Trapezoidal flumes for 1-ft lined channels (flume Nos. 1, 1a and 1b). Flow range 0.05 to 7.3 cfs.

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* Numbers in parentheses refer to the appended references.

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communications with personnel of the American Factor's, Ltd. and the Lihue Plantation Co., Ltd., indicate extensive use of flumes of the type developed by Chamberlain (2) and those described in this report. In each case it was reported that trapezoidal flumes were superior in operation to rectangular flumes.

A recent report by Kruse (4) summarizes a continuation of the phase of study being covered in this report. In addition to flumes for the standard shape of slipform ditch, another was developed for sidewall slope of ½ to 1. Length of the throat section was varied for each of the two sizes studied.

DESIGN AND TEST DATA

One major advantage of trapezoidal-shaped flumes is that the cross-section corresponds in shape to the common irrigation channel or ditch. For this reason, the flumes can be constructed without extensive use of complicated transition sections. The flumes can be constructed of metal, precast using plastic or concrete or poured and formed in place as an integral part of a lined channel. Several of the flumes discussed in this report have the same sidewall slope as the 1- and 2-ft bottom width standard slipform concrete ditch. For lined sections, flumes made of metal, plastics or fiberglass can be inserted in the channel and made to seal to the lining. In this manner they are semiportable and can be moved to other locations within the lined section.

The flume sizes studied, together with flow ranges and general dimensions, are given in Table 1. Since this report is intended as a guide to field use of the flumes, only design information and calibration tables are given. Development and presentation of theory can be found in the publications of Robinson and Chamberlain (5) and Ackers and Harrison (1). The effect of degree of contraction, degree of submergence and field setting and use will be presented.

The flumes were constructed, tested and calibrated in test channels where flow depths and quantities could be determined accurately. Flume No. 1 (Table 1) was installed in a channel 4 ft wide with a 16-ft approach section of the same cross-sectional shape upstream and an 8-ft section installed downstream from the flume. Discharges were measured by a volumetrically calibrated pipe orifice. Low flows were also checked using a 90-deg weir. Flume No. 2 was installed in a large outdoor test channel using a 16-ft approach channel of similar shape. The discharges were measured over precise rectangular weirs. Flume No. 3 was set in a 4-ft channel for flows up to 6 cfs and reset in the larger outdoor channel for higher flows. This flume was calibrated without the approach channel since it is primarily intended for flow measurement in earth canals. A bulkhead was used with the horizontal bottom set 4 in. above the test channel floor. In all cases the flumes were leveled both laterally and longitudinally.

Design dimensions for three flumes for 1-ft bottom slipform ditches are given in Fig. 1. Essentially, these designs involve a simple contraction from the standard concrete ditch section. For simplified construction, all surfaces are plane. Two positions for measuring depths are shown, the standard upstream position, h_1, and immediately downstream from the diverging section, h_4. The depth at h_4 is used for correcting the indicated discharge for submergence and will be discussed in a later section. Flume No. 1 has a bottom contraction of 1 ft to 0.4 ft whereas flume No. 1*a* has a ratio of 1 to 0.6. Discharge equations, which were determined by fitting a curve to the experimental data, are presented in Table 2.

The relationship of depth at h_1 to discharge for the flume with the greatness degree of contraction (1 − 0.4), flume No. 1, is given in Table 2. With less contraction (1 − 0.6), flume No. 1*a*, a larger flow can be passed through the structure at comparable depth. There are advantages in using flume No. 1*a* since a smaller amount of backwater is created and a shallower depth of section is needed. However, an incremental difference in depth represents a larger quantity of flow than for flume No. 1, thereby decreasing the sensitivity and possible accuracy of the flume. Some of the data obtained at lower discharges (< 0.20 cfs) indicated that the flow was not passing through critical depth for the free-flow condition. A third design utilizing a longer throat length is shown as No. 1*b* in Fig. 1. A discharge equation is not given for this design but some of

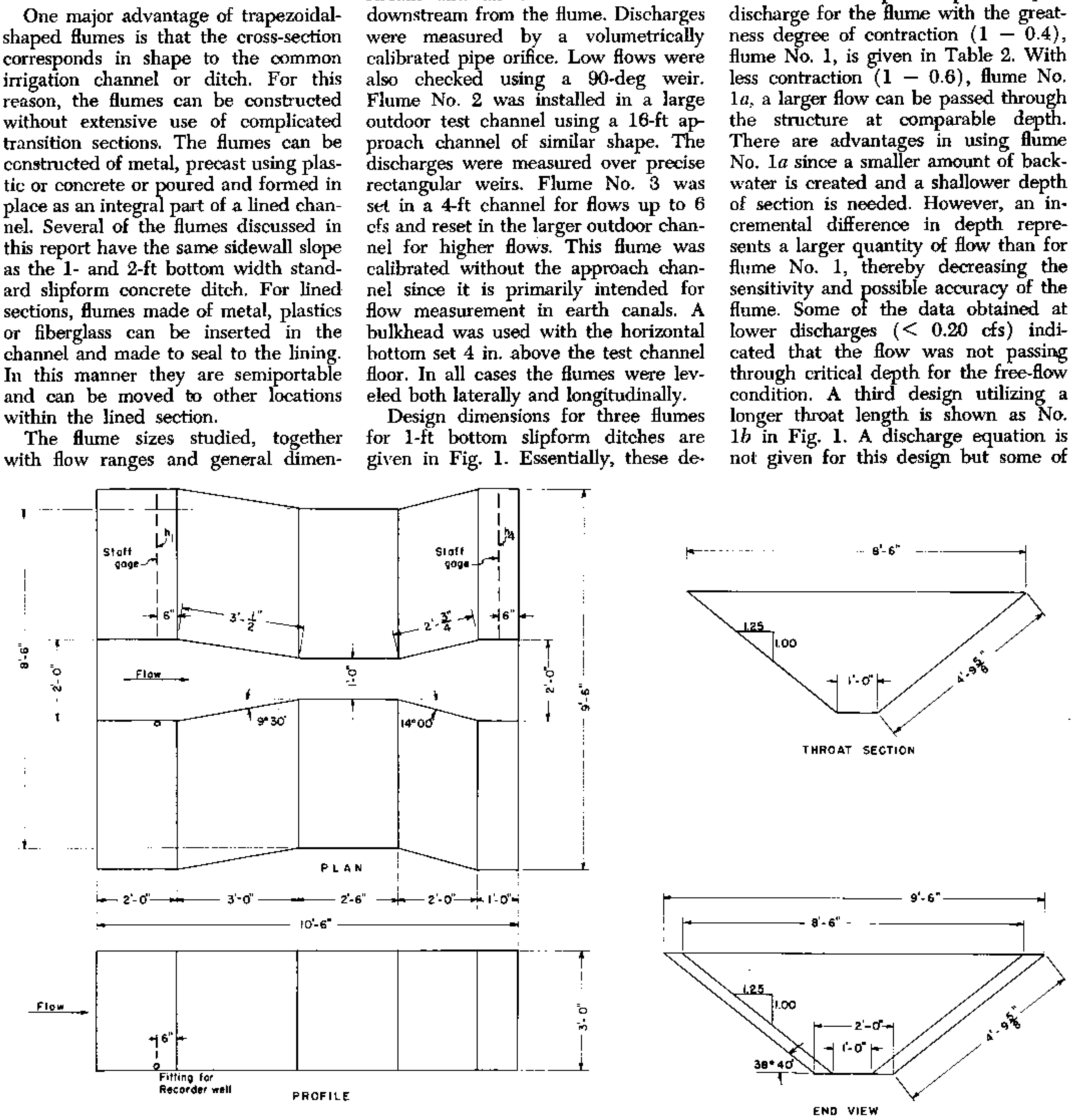

FIG. 2 Trapezoidal flume for 2-ft lined channel (flume No. 2). Flow range, 0.51-61.0 cfs.

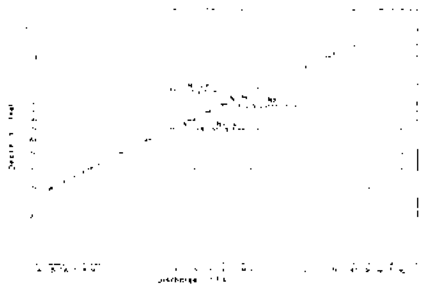

FIG. 3 Rating curves for flumes Nos. 2, 2a and 2b.

the operating characteristics are presented in following sections.

The design data for flume No. 2 for the larger size (2-ft bottom) slipform ditch are given in Fig. 2. The flume has a contraction of 1 to 0.5 and was also designed to become an integral part of the lined channel. The location of points h_1 and h_4 used for measuring flow depths is shown. A staff gage mounted on the sloping wall and marked to read depths in the vertical can be used, or a stilling well with intake as indicated in Fig. 2 can be used for continuous recording. The discharge equation for flume No. 2 is given in Table 2 for a flow range of 0.54 to 58.8 cfs.

In order to extend the usefulness of the larger flume, two additional channel widths were used. These flumes are listed as 2*a* and 2*b* in Table 1 and are identical in dimension to that shown in Fig. 2 with the exception of bottom width of approach channel. The length of converging section remained the same, which resulted in greater amounts of convergence with increasing upstream widths.

Rating curves for the three flumes (Nos. 2, 2*a* and 2*b*) are given in Fig. 3. With the least contraction, greater flow is passed through the flume for a given head. This is due, in part, to a decrease in loss of energy for changing flow direction. For all designs of the No. 2 flume, calibrations were made with 16-ft of approach channel with the same shape as the entrance section of the flume.

Flume No. 3 was designed primarily for use in earth channels and for situations where a greater accuracy of measurement is required. Because of the steeper sidewall slope (0.58 to 1) a unit change in discharge results in a larger change in depth h_1. The design of this flume is given in Fig. 4 and a field installation is shown in Fig. 5. For the calibration setting there was a 4-in. rise from the invert of the approach channel to the horizontal floor of flume 3. As with the other flumes, h_1 is measured either with a staff gage or stilling well as indicated in Fig. 4 and the depth at h_4 may be required to determine the submergence effects. The discharge equation for flume No. 3 is given in Table 2.

OPERATIONAL CHARACTERISTICS

Submerged Flow

Measuring flumes should operate under free flow wherever possible. Free flow occurs when the flow passes through critical depth, *i.e.*, flow at minimum specific energy, in the throat section. With free flow, unique relationships exist between upstream depth and discharge as given in Table 2. Although this is the ideal situation, it is sometimes not obtainable nor desirable. In order to convert kinetic energy (velocity head) back to potential energy (depth), with the least amount of provision for energy dissipation, it is desirable to maintain as great a depth of water downstream as possible. If the downstream depth is great enough, the flow does not go through critical depth and the upstream depth is increased above normal for free-flow discharge. This condition is called submerged flow and corrections are necessary to determine the correct flow.

The effect of submergence and correction factors necessary for determining the exact discharge for the different flumes are given in Figs. 6, 7, and 8. These figures show the effect of the depth of downstream water surface h_4 on the head-discharge relationship determined under free-flow conditions for the entire discharge range. Degree of submergence is defined as the ratio of depth at the downstream point to that at the upstream gage point, *i.e.*, h_4/h_1 in percent. The location of points h_4 and h_1 are indicated in Figs. 1, 2, and 4 for the different designs. As the depth at h_4 increases above a certain point, the depth at h_1 also increases. This changes the free-flow relationship and corrections are necessary. Using Fig. 7 as an example, submergence begins to become a significant factor at approximately 70 percent. The ordinate of Fig. 7 is a ratio of the actual discharge Q to observed discharge Q_0 for the h_1 depth which has been increased due to submergence. Using this increased depth and the rating table for free flow results in a determination of discharge Q_0 which is greater than actual. The ratio Q/Q_0 is a correction factor and can be used for determining the actual discharge.

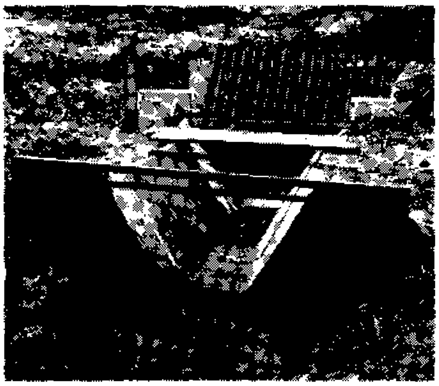

FIG. 5 Flume No. 3 installed in irrigation ditch. Structure downstream is intake for an underground pipe system.

Example:

Given: $h_1 = 1.61$ ft
$h_4 = 1.43$ ft

$$\text{Submergence} = \frac{h_4}{h_1} \times 100$$

$= 89$ percent

From Table 2, flume No. 2, the observed discharge is 17.85 cfs.

From Fig. 7,

$$\frac{Q}{Q_0} = 0.92$$

$$Q = 0.92 \times 17.85 = 16.42 \text{ cfs}$$

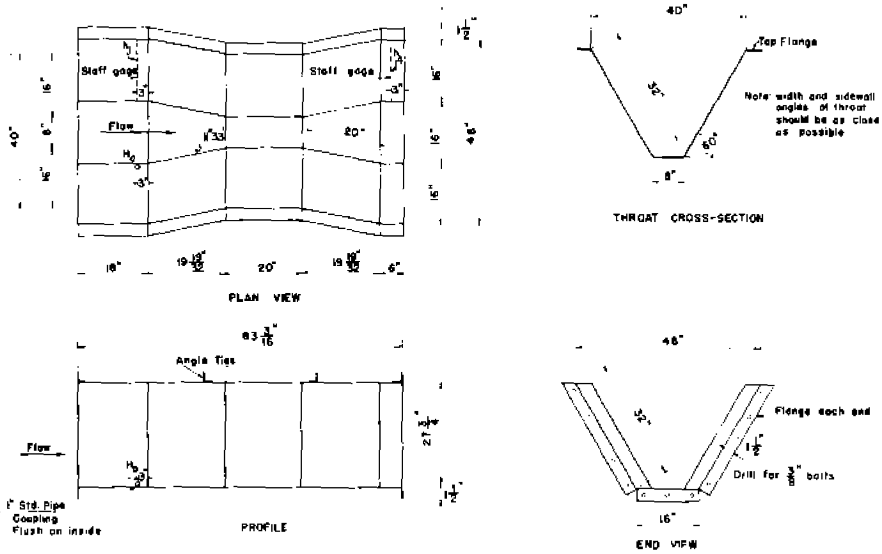

FIG. 4 Trapezoidal flume for variable-width channels (flume No. 3). Flow range, 0.24-17.4 cfs.

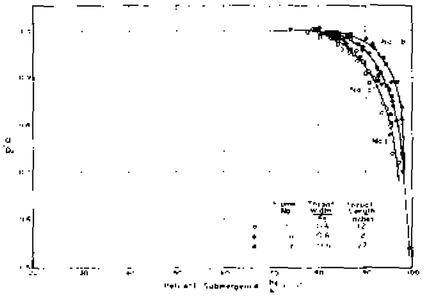

FIG. 6 Effect of submergence on the discharge relationship (flumes Nos. 1, 1a, 1b).

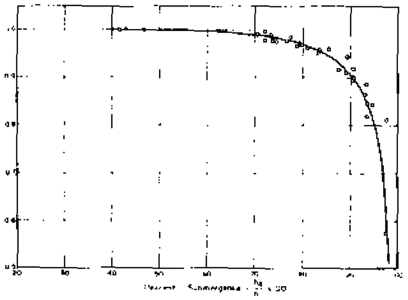

FIG. 7 Effect of submergence on the discharge relationship (flume No. 2).

Although submergence actually begins to change the discharge when values exceed 60 percent, there is only a 3 percent difference from the free-flow relationship at 80 percent. Since this deviation is within the usual expected error of measurement with a flume, a correction may not be necessary until submergence exceeds 80 percent.

A comparison of the relationships shown in Figs. 6, 7, and 8 reveal that submergence is a function of degree of contraction, sidewall slope, length of throat and possibly size of flume. For the smaller flumes (Fig. 6) and the least amount of contraction, flume 1*b*, submergence as great as 90 percent results in only a 2.5 percent change in discharge for the 22-in. throat length. For the same contraction and a shorter throat section (flume No. 1*a*) the discharge is reduced by 4 percent. One factor contributing to this difference is that the h_4 measuring point is further downstream from the control section in flume 1*b*. The conversion of kinetic energy to potential has been more complete at the measuring point than for the shorter flume.

The smallest submergence effect for most of the discharge range is noted for flume No. 3 (Fig. 8) which has the steepest sidewall slope. This flume is intermediate in size and flow range to the other designs. For the larger flume No. 2, at 90 percent submergence, there is a 9-percent change in discharge. In all cases, the effect of submergence is not as pronounced as with rectangular flumes.

Flume Setting

The elevation of the invert of the flume relative to the natural bed level can be important in the case of flumes used in an earth channel. Flumes Nos. 1 and 2 were designed to become an integral part of a lined channel and the bottom of the flumes corresponds to the elevation of the bottom of the channel and there is no step. For this situation, the slope of the channel and the corresponding normal depth determine the percent of submergence that may be encountered.

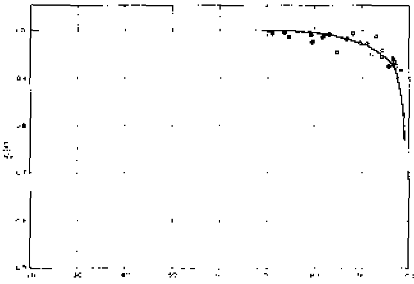

FIG. 8 Effect of submergence on the discharge relationship (flume No. 3).

Ackers and Harrison (1) state that "invert height above channel-bed level can be chosen arbitrarily, keeping in mind that the higher the invert, the smaller will be the available head on the flume and therefore a wider structure will be needed to pass a given discharge." For a structure of fixed dimensions, raising the structure will, in turn, raise the water level upstream and require higher banks. Ackers and Harrison were concerned with placing the flumes high enough so that submergence was not possible for the highest flows.

Figs. 6, 7, and 8 show that a submergence of 80 percent can be tolerated before corrections to the flow are necessary. Experience has shown that if flume No. 3 is set 3 to 4 in. above the natural channel bottom, submergence will rarely exceed 80 percent. Special precautions against erosion may be necessary downstream.

For flumes No. 1 and No. 2 there is a limit to channel slope where submergence might exceed 85 percent. As an example, consider flume No. 1 at the maximum flow.

Then

$Q_{\max} = 5.96$ cfs (Table 1)
$h_{1\max} = 1.20$ cfs (Table 2)

For 85-percent submergence, normal depth in the downstream section should be:

$h_n = h_4 = 0.85 \times 1.20 = 1.02$ ft
$A_4 = 2.06$ sq ft (area)
$P_4 = 3.88$ ft (wetted perimeter)
$R_4 = 0.531$ ft (hydraulic radius)
$V_4 = Q/A_4 = 2.89$ fps (mean velocity)

Assume

$n = 0.015$ (Manning coefficient for concrete channel)

Then

$$s_0 = \frac{V_4{}^2 n^2}{2.22 \times R_4{}^{4/3}} = \frac{(2.89)^2\ (.015)^2}{2.22(.531)^{1.33}} = 0.002 \text{ (channel slope)}$$

By comparison, for $Q = 0.549$, $n = 0.015$ and the same channel, $s_0 = 0.001$.

Slipform concrete ditches used as irrigation head ditches are generally placed on slopes ranging from 0.00075 to 0.0015. From this information it would be necessary to require a slope of 0.2/100 for the ditch or else make submergence corrections at the higher flows. The foregoing procedure can be used to determine the minimum slope requirements in order to insure free-flow conditions through the flume.

CONCLUSIONS AND OBSERVATIONS

The use of trapezoidal measuring flumes for irrigation ditches should result in easy, accurate measurements of a wide range of discharge. Trapezoidal flumes can be constructed as an integral part of a lined canal or made of metal, plastic or fiberglass and installed in the channel.

The flumes can be used with submergence up to 80 percent with no discharge correction and will be correct within 3 percent. For submergences in excess of 80 percent, corrections can easily be made by the use of plots contained in this report. Head loss through the flume can be held to a minimum by operating at a high degree of submergence.

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TABLE 1. SUMMARY OF BASIC DIMENSIONS AND FLOW RANGES
(Trapezoidal Flumes for Small Irrigation Channels)

Flume number	Description*	Approach channel, bottom width, ft	Throat bottom width, ft	Sidewall slope	Flume length, in.	Throat length, in.	Depth, in.	Calibrated flow range, cfs
1	1′(1-0.4)—1:1	1.0	0.4	1:1	46⅛	12	16	0.05-5.96
1a	1′(1-0.6)—1:1	1.0	0.6	1:1	46⅛	12	16	0.07-7.32
1b	1′(1-0.6)—1:1	1.0	0.6	1:1	56⅛	22	16	0.07-7.32
2	2′(1-0.5)—1.25:1	2.0	1.0	1.25:1	126	30	36	0.54-58.8
2a	2.5′(1-0.4)—1.25:1	2.5	1.0	1.25:1	126	30	36	0.50-60.0
2b	3′(1-0.33)—1.25:1	3.0	1.0	1.25:1	126	30	36	0.50-60.0
3	1.33′(1-0.5)—0.58:1	variable	0.67	0.58:1	83 3/16	20	27¾	0.24-17.4

* Description 1′(1.-0.4)—1:1 is a 1-ft channel width, 1.0-0.4 contraction ratio and 1:1 sidewall slope.

TABLE 2. SUMMARY OF EQUATIONS FOR DISCHARGE—TRAPEZOIDAL FLUMES

Flume number	Equation	h_1 range
1	$Q = 3.23h_1^{2.5} + 0.63h_1^{1.5} + 0.050$	0.20-1.20
1a	$Q = 3.53h_1^{2.5} + 1.25h_1^{1.5} + 0.045$	0.20-1.20
2	$Q = 4.14h_1^{2.5} + 2.07h_1^{1.5}$	0.30-2.70
3	$Q = 1.46h_1^{2.5} + 2.22h_1^{1.5}$	0.20-2.20