TRAPEZOIDAL FLUMES FOR MEASURING FLOW IN IRRIGATION CHANNELS

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CONTENTS

TRAPEZOIDAL FLUMES FOR MEASURING FLOW IN IRRIGATION CHANNELS[1]

By A. R. Robinson[2]

INTRODUCTION

Experience and research have shown that, in many respects, trapezoidal flumes are superior to the rectangular or Parshall-type flumes, particularly for measuring smaller flows. The shape conforms to the normal shape of ditches, particularly those that are lined. This minimizes the amount of transition section needed as compared to that required when changing from a trapezoidal shape to a rectangular one and back to the trapezoidal. The trapezoidal shape is also desirable since the sidewalls expand as the depth increases. This means that one structure can convey a larger range of flow. Also, the entire range of depth for a given range of discharge is smaller.

Operational characteristics of trapezoidal flumes are also superior. Generally, less backwater will result and a shallower section will be required than for a rectangular shape. Another desirable feature of the trapezoidal flume is the flat bottom throughout rather than a dropped section such as with the Parshall flume. No particular advantage of a crest section with a drop in the floor such as that in the Parshall flume has been found.

The trapezoidal flume will operate under a higher degree of submergence than the Parshall flume without corrections being necessary. The loss in head, i.e., total-head loss, through the trapezoidal structure, may be less for comparable discharges.

FLUME DESIGN

Since the trapezoidal flume cross section corresponds to the shape of common irrigation channels or ditches, the flumes can be adapted to standard trapezoidal, lined ditches. A standard size, concrete-lined ditch has a 1-foot bottom width, 1:1 sidewall slope, and is usually from 15 to 18 inches deep. A larger size has a 2-foot bottom width and a 1.25:1 sidewall slope. The two trapezoidal flumes presented herein for 1-foot and 2-foot irrigation channels were designed with similar dimensions in order that they may be made an integral part of lined canals. The flumes may also be used in unlined ditches with cutoff walls attached to each end. The flumes can be constructed of metal, fiberglass, precast from concrete, or poured and formed in place as an integral part of a lined channel. Techniques have also been developed for casting the flume within an existing lined canal utilizing a portable form. In this case the canal lining acts as the outer form. Figure 1 shows the flumes in use.

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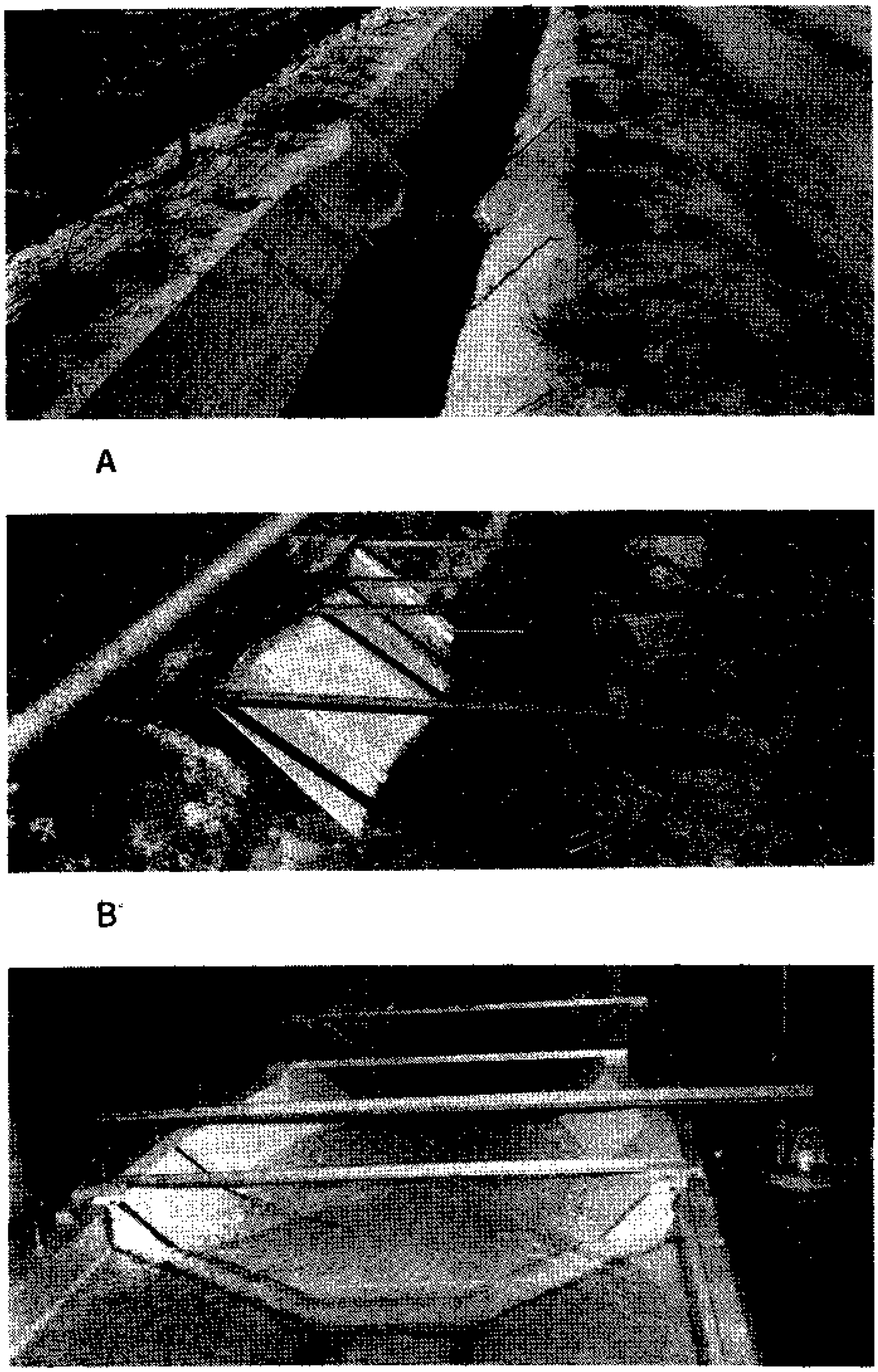
[1] Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Idaho Agriculture Experiment Station.

[2] Research agricultural engineer, Kimberly, Idaho.



A

B

C

Figure 1--Trapezoidal flumes installed for flow measurement: A, concrete; B, steel; C, fiberglass.

The design and dimensions of the two flumes are given in figures 2 (flume No. 1) and 3 (flume No. 2). Essentially, these designs involve a simple contraction from the standard ditch dimension with all surfaces plane and flat for simplified construction. Flume No. 1 has a flow range from 0.16 to 7.1 c.f.s. and flume No. 2, 0.67 to 53.2 c.f.s. Although the two flumes discussed in this publication cover the most usable range of discharges, many other sizes and designs of small trapezoidal flumes have been developed.[3,4,5]

Two positions for measuring flow depth through the flumes are used. The standard upstream location is h_1, where a staff gage is mounted. A fitting can be provided for use with a stilling well and recorder. Normally, the h_1 depth is all that is required. The h_4 depth is used only for correcting the indicated discharge for submergence.

OPERATION

Free Flow

The simplest and most accurate flow measurement using trapezoidal flumes is obtainable under "free-flow" conditions. Free flow occurs when the flow passes through critical depth (flow at minimum specific energy) in the throat section. With free flow, a unique relationship exists between the depth at an upstream point, designated as h_1 in figures 2 and 3, and the discharge. For this condition and a particular design and size of flume, the h_1 scale can be graduated in flow units. The discharge is then read directly from the scale.

For free flow, the relationship between depth and discharge is expressed by the following equations:

Flume No. 1

$$Q = 3.23\,h_1^{2.5} + 0.63\,h_1^{1.5} + 0.05 \quad (1)$$

Flume No. 2

$$Q = 4.27\,h_1^{2.5} + 1.67\,h_1^{1.5} + 0.19 \quad (2)$$

where Q is the discharge in cubic feet per second and h_1 is the upstream vertical depth in feet as shown in figures 2 and 3. These relationships are tabulated in tables 1 and 3 for vertical depth and in tables 2 and 4 for depths along the sloping sidewall. Both discharge equations were determined from laboratory calibrations where the discharge was measured through standard Venturi meters, Gentile flow tubes, and precise weirs. The data were analyzed by means of a digital computer by the method of least squares.

Recent tests were made utilizing a fiberglass trapezoidal flume (No. 1) to determine the effect of upstream conditions on the free-flow calibrations. For one condition, the flume was installed as an integral part of a lined ditch (fig. 1,A). The other condition was similar to that in figure 1,C where there was a sharp corner entrance. The flume bottom was 4 inches above the bottom of the channel. The ratings for the two conditions were identical.

It is usually neither possible nor desirable to maintain a low water depth downstream from the flume such as that shown in figure 4 as condition a. With this condition an excessive energy loss occurs when the kinetic energy (velocity head) is converted back to potential energy (water depth). Because of this energy dissipation, channel protection may be needed to prevent erosion. Maximum water depth downstream with free-flow conditions maintained is desired. If the downstream depth is too large, the flow does not go through critical depth. In this case the upstream depth is greater than normal for the free-flow discharge. This is the submerged flow condition, and corrections are necessary to determine the correct discharge.

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[3]Chamberlain, A. R. Measuring water in small channels with the WSC flume. Wash. Agr. Expt. Sta. Cir. 200, 12 pp. 1952.

[4]Robinson, A. R. Water measurement in small irrigation channels using trapezoidal flumes. Amer. Soc. Agr. Engin. Trans. 9(3): 382-385, 388. 1966.

[5]Robinson, A. R., and Chamberlain, A. R. Trapezoidal measuring flumes for open-channel flow measurement. Amer. Soc. Agr. Engin. Trans. 3(2): 120-124, 128. 1960.

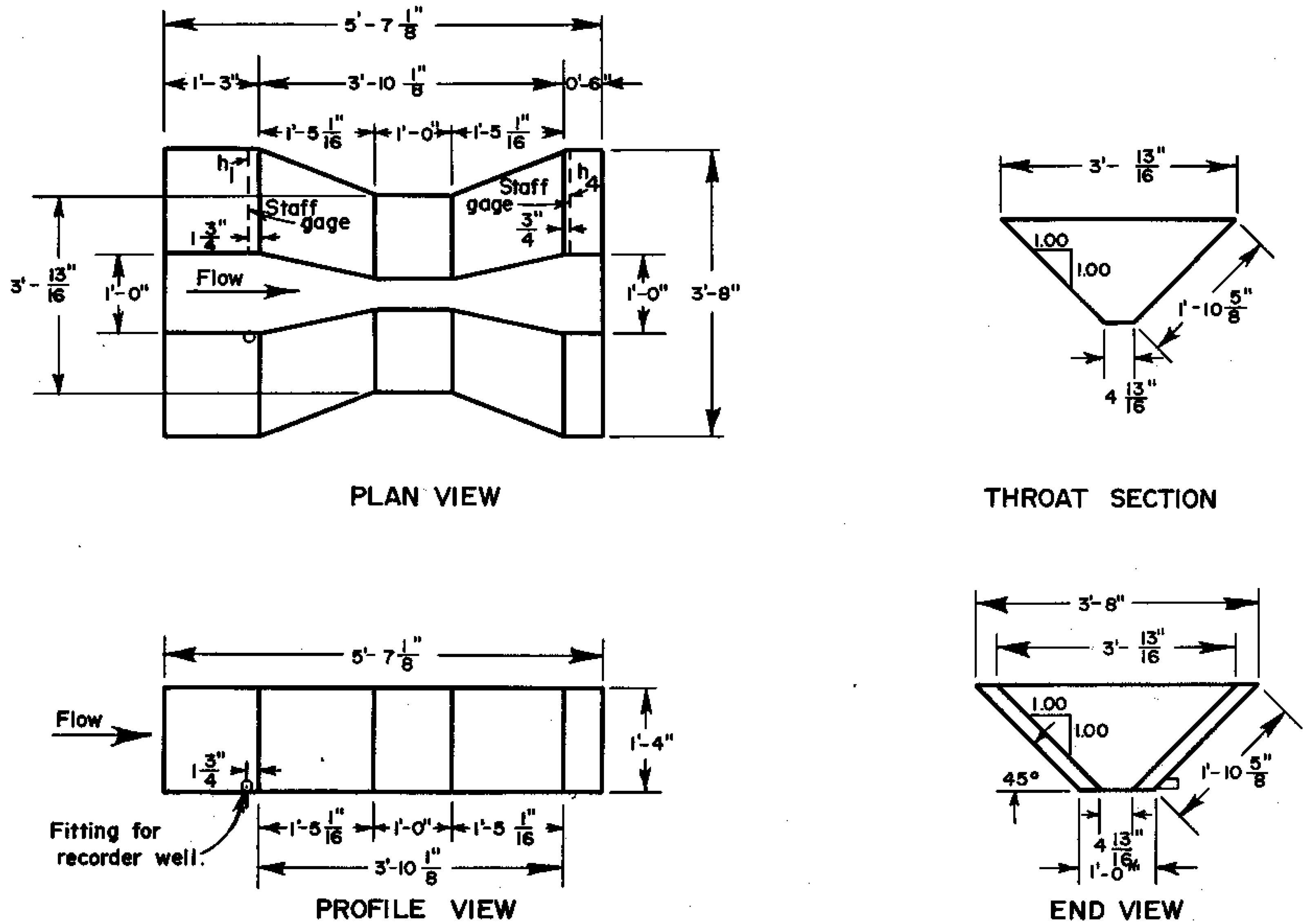

Figure 2.--Trapezoidal flume for 1-foot irrigation channels (flume No. 1).

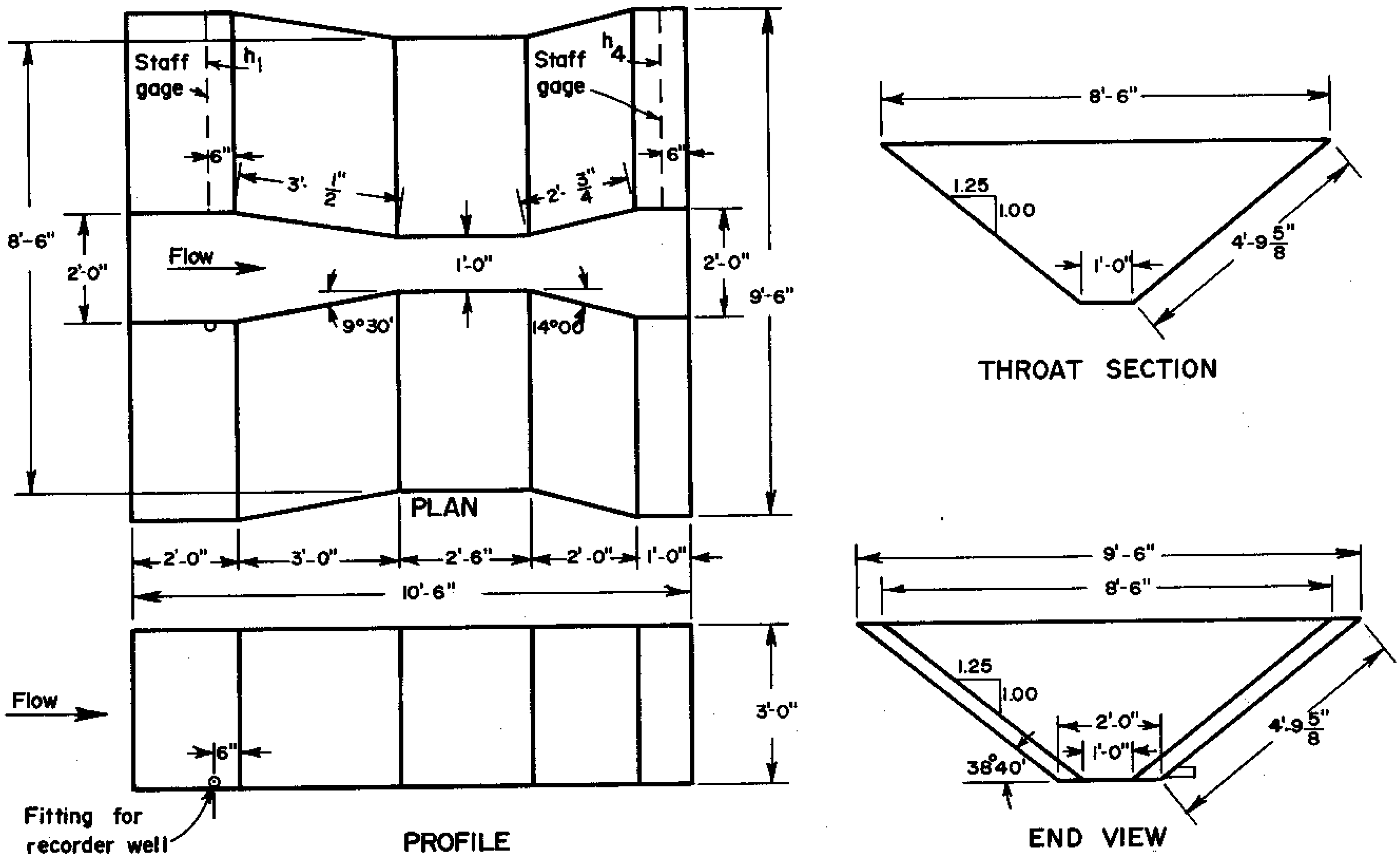

Figure 3.--Trapezoidal flume for 2-foot irrigation channels (flume No. 2).

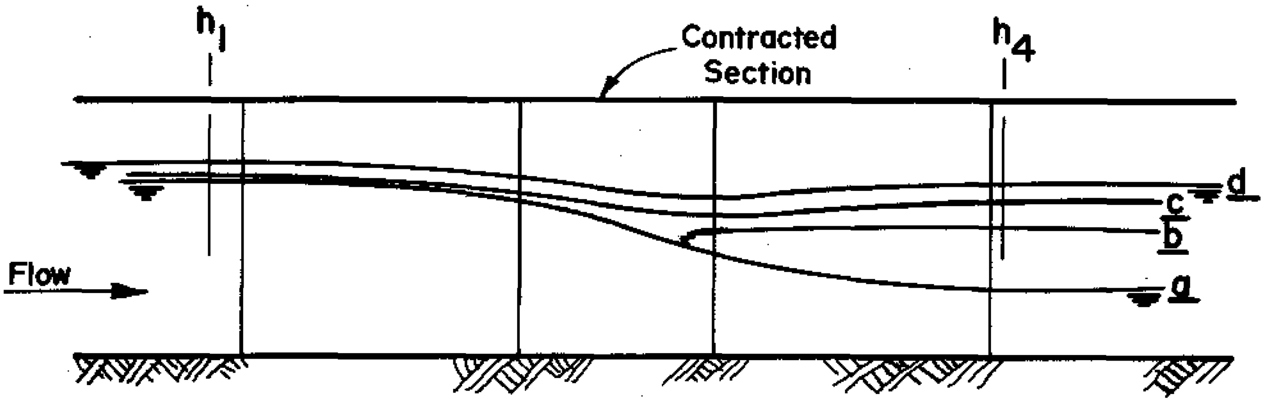

Figure 4.--Flow regimes through trapezoidal flumes (a and b are free flow, c and d are submerged flow).

Submerged Flow

Submerged flow is defined as the condition where the flow in the control section does not go through critical depth, i.e., the downstream depth is great enough that the flow throughout the flume is subcritical. For a given discharge, the depth upstream at the h_1 measuring point is increased so that the free-flow relationship does not apply. An accurate measurement with the flume is still possible but now two depth readings are needed, h_1 and h_4 (fig. 2 and 3). By use of the two depths, corrections can be made to determine the correct flow.

The flow profiles shown in figure 4 for a constant discharge illustrate free and submerged flow. Water surface profiles a and b are free flow, whereas c and d represent submerged flow. Profile a represents a low tailwater condition with a high-velocity jet of water emerging from the flume. Profile b represents a condition where the downstream depth is approaching the point where submergence must be considered in determining the correct discharge. Degree of submergence is expressed as the ratio of depth at the downstream point to that at the upstream gage point, i.e., h_4/h_1. Between profiles a and b there is a wide range of downstream conditions where free flow occurs. The water surface profiles c and d represent submerged flow conditions, with profile c having a submergence slightly greater than 75 percent, and d much greater. At flow conditions c and d, the upstream depth at the h_1 location has increased.

The effect of submergence and the correction factors necessary for determining the actual discharge for the two flumes are given in figure 5. This figure shows the effect of downstream water depth, h_4, on the head-discharge relationship determined under free-flow conditions. Recent tests have shown that the submergence effect is essentially the same for both flumes. Submergence begins to become a significant factor as h_4/h_1 exceeds 75 percent. The ordinate of figure 5 is a ratio of the actual discharge, Q, to observed discharge, Q_o, for the h_1 depth which has been increased owing to submergence. The use of this increased depth and the rating table for free flow, results in a determination of discharge (Q_o) which is greater than actual. The ratio Q/Q_o is a correction factor and can be used for determining the actual discharge.

Example:

For flume No. 2

Given: $h_1 = 1.61$ ft.

$h_4 = 1.43$ ft.

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

$$= 89 \text{ percent}$$

From table 3, the observed discharge for $h_1 = 1.61$ ft. is 17.63 c.f.s.

From figure 5:

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

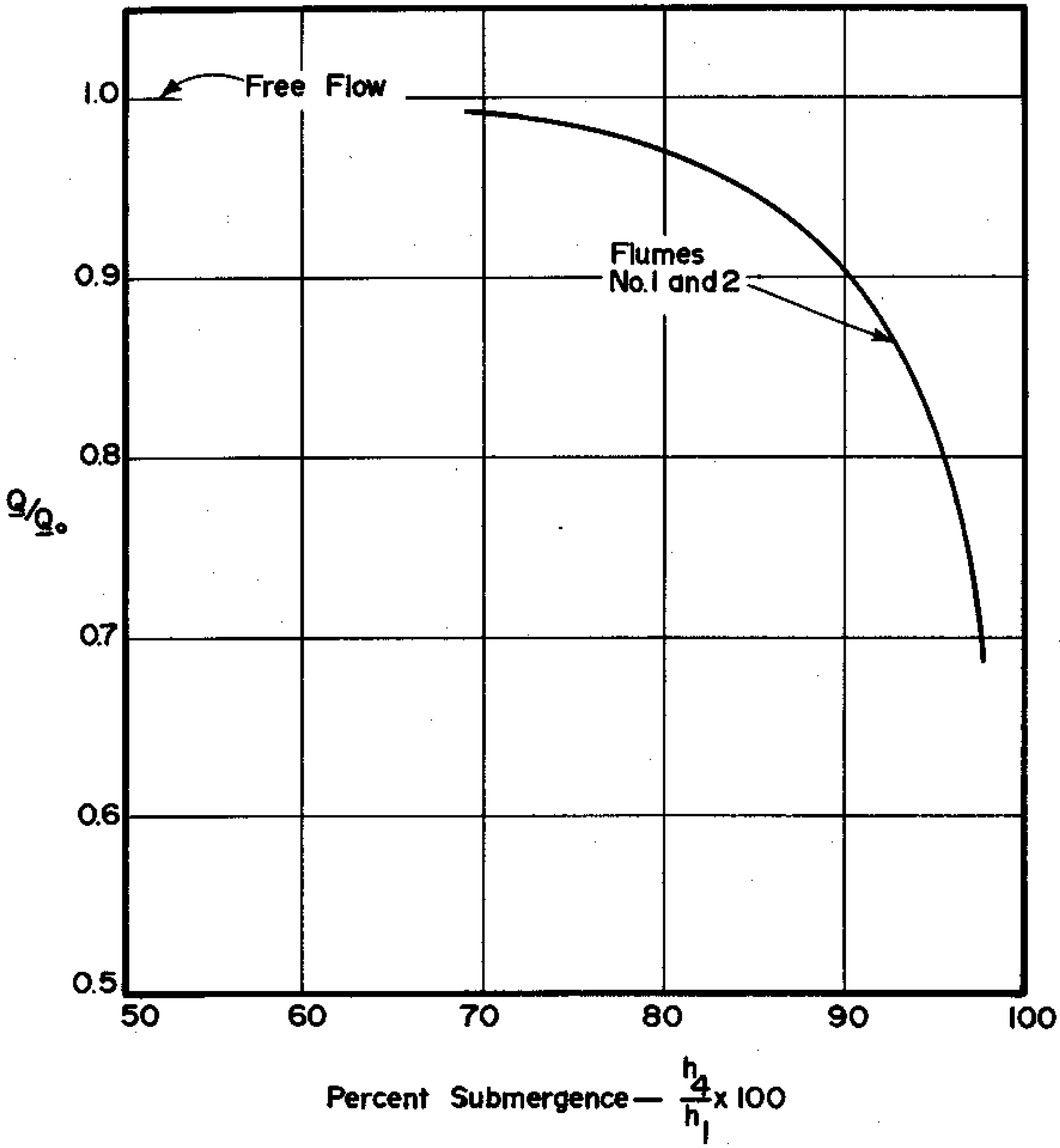

Figure 5.--Effect of submergence on discharge, flumes Nos. 1 and 2.

therefore, the actual discharge under submerged conditions is

$$Q = 0.92 \times 17.63 = 16.2 \text{ c.f.s.}$$

Although submergence actually begins to affect the head-discharge relationship when h_4/h_1 exceeds 70 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.

ACCURACY OF MEASUREMENT

As with most measuring devices, the accuracy of measurement depends to a great extent on the precision of construction, flume setting, and determining depths of flow. Using a device under conditions different from those under which it was calibrated results in errors.

The flumes must be constructed to the dimensions shown in figures 2 and 3. After construction, all dimensions should be checked to see that lengths and widths are correct and the staff gages are located in the proper position. The throat section is the control section and, therefore, the dimensions in this area are very important. If this section deviates from exact dimensions, then the discharge will also deviate from the standard. The equation of continuity applies, and the discharge is directly proportional to the area. For example, if the area is 3 percent smaller than standard in the throat section, then the discharge is also 3 percent less for the h_1 depth.

Flumes should normally be installed horizontally but may be installed on slopes within the determined limits if cast within concrete ditches. For those with bottom slope, the staff gages must be installed with the zero referenced to the elevation of the center of the throat section. It is important that the flumes be leveled transversely so that the staff gages are on the exact side slope specified for the flume.

The reading of depth is important since the accuracy of reading may determine the accuracy of the device. During calibration tests of flume No. 1 over the entire range of discharge, more than 80 individual readings were made both with staff gages mounted on the flume and with a hook gage in a stilling well. The staff gage differed from the hook gage readings by an average of ± 0.004 foot and had a standard deviation of 0.004 foot. An error of ± 0.01 foot in reading the staff gage would result in an error of ± 4.3 percent in discharge for low flows and ± 2.0 percent for high flows through flume No. 1.

CONSTRUCTION

Materials

The flumes can be constructed of different materials. Flume No. 1 has been constructed of concrete, sheet metal, and fiberglass as shown in figure 1. Because of its larger size, flume No. 2 should generally be constructed of concrete. Since both flumes conform to the dimensions of standard concrete ditches, the flumes can be cast in an existing ditch by the use of a portable form as shown in figure 6. For temporary installations the flumes could be constructed of plywood.

Flume Setting

The flumes should normally be set so that they operate in the free-flow range. The flume invert elevation relative to the natural bed level can be important. Flumes No. 1 and 2 were basically designed to become an integral part of a lined channel, and if there is sufficient slope, the bottom of the flumes corresponds to the elevation of the channel bottom and there is no step. For this situation, the slope of the channel and the corresponding normal depth determine the degree of submergence that may be encountered.

There is a lower limit to channel slope where flume submergence might exceed 80 percent. As an example, consider flume No. 1 at approximately maximum flow.

Assume: $Q = 5.98$ c.f.s.

$h_1 = 1.20$ ft. (table 1)

For 80-percent submergence, normal depth in the downstream section of a standard slipform, concrete ditch should be

$h_n \approx h_4 = 0.80 \times 1.20 = 0.96$ ft.

$A_4 = 1.88$ ft.^{2} (area)

$P_4 = 3.72$ ft. (wetted perimeter)

$R_4 = 0.505$ ft. (hydraulic radius)

$V_4 = Q/A_4 = 3.18$ f.p.s. (mean velocity)

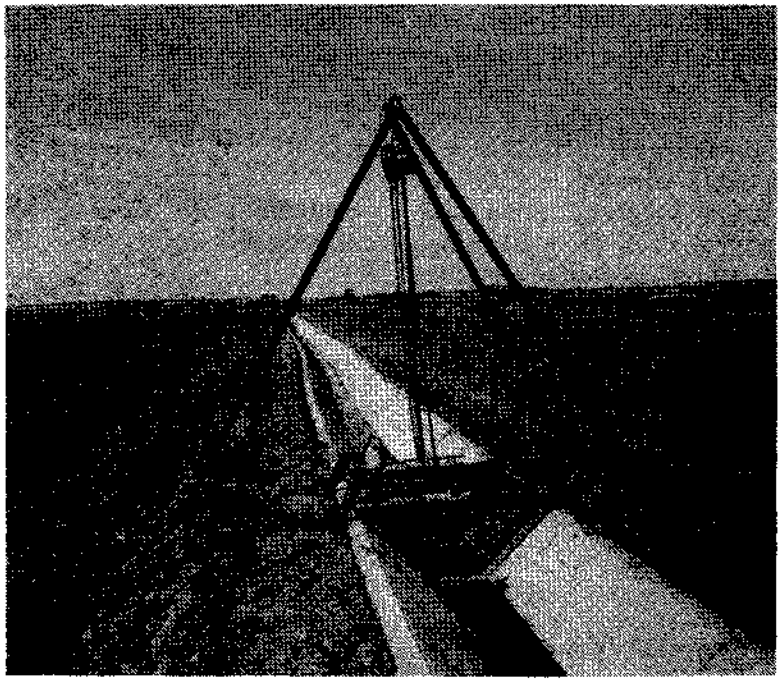

Figure 6.--Portable form used to pour trapezoidal flumes in concrete ditches

Assume: $\underline{n} = 0.015$ (Manning coefficient for concrete channel)

Then:
$$\underline{s}_o = \frac{\underline{V}_4^2 n^2}{(2.22)\,(\underline{R}_4)^{4/3}} = \frac{(3.18)^2(0.015)^2}{2.22(0.505)^{1.33}}$$
$$= 0.0025 \text{ (channel slope)}$$

The following tabulation gives the minimum slopes for a range of roughness values $\underline{n}$ for the discharge limits in the standard 1-foot ditch.

Q c.f.s.	$\underline{n}$	$\underline{s}_o$
5.98	0.015	0.0025
5.98	.018	.0034
.54	.015	.0013
.54	.018	.0019

The values of $\underline{n}$ represent those for smooth (0.015) to rough (0.018) concrete surfaces.

Slipform concrete ditches are generally placed on slopes ranging from 0.00075 to 0.0015. It would be necessary to require a slope of 0.0025 for the smooth ditch or else make submergence corrections at the higher flows. The foregoing procedure can be used to determine the minimum slope requirements for other channels in order to insure free-flow conditions through the flume.

There is also an upper limit on the slope of a concrete ditch for placing a trapezoidal flume. Since the flume is a critical depth device, flow approaching the structure must be at subcritical velocity. Critical slope can be determined for a channel of given size with a particular roughness coefficient. The upper limit of discharge gives the upper limit of slope. The following tabulation gives the upper critical slopes for ditches conforming in shape to each of the measuring flumes:

	Critical slope	
$\underline{n}$	Flume No. 1	Flume No. 2
0.015	0.0053	0.0040
.018	.0076	.0057

The invert height above channel bed level can be chosen arbitarily, although it must be kept in mind that the higher the invert, the higher will be the upstream water level and, therefore, the higher the ditchbanks that will be required. For earth ditches, the flumes should always be placed higher than the ditch bottom. When a concrete ditch has a flat slope so that the flume would operate more than 80 percent submerged most of the time, then the flume should be raised above the bottom.

Figures 7 and 8 can be used to determine the head loss through the flumes and also to give an approximate elevation for setting the flume above the natural bed to insure that the flow will generally be free. If the canal slope is very flat, i.e., below the slopes determined in the previous section, then the setting of the flume can be determined. For flume No. 1 assume the maximum flow is

$$Q = 4.98 \text{ c.f.s.},$$

$$h_1 = 1.11 \text{ ft. (table 1)}$$

and maximum submergence is to be 80 percent. From figure 7

$$h_L = 0.22 \text{ ft.}$$

and the flume bottom should be raised 0.22 foot above the canal invert.

Figures 7 and 8 can also be used to determine the drop in water surface through the structures for design or operational needs. For a flow of 6 c.f.s. at 80-percent submergence, the head loss for flume No. 1 is 0.24 foot. For the same conditions, the loss through flume No. 2 is 0.20 foot (fig. 8).

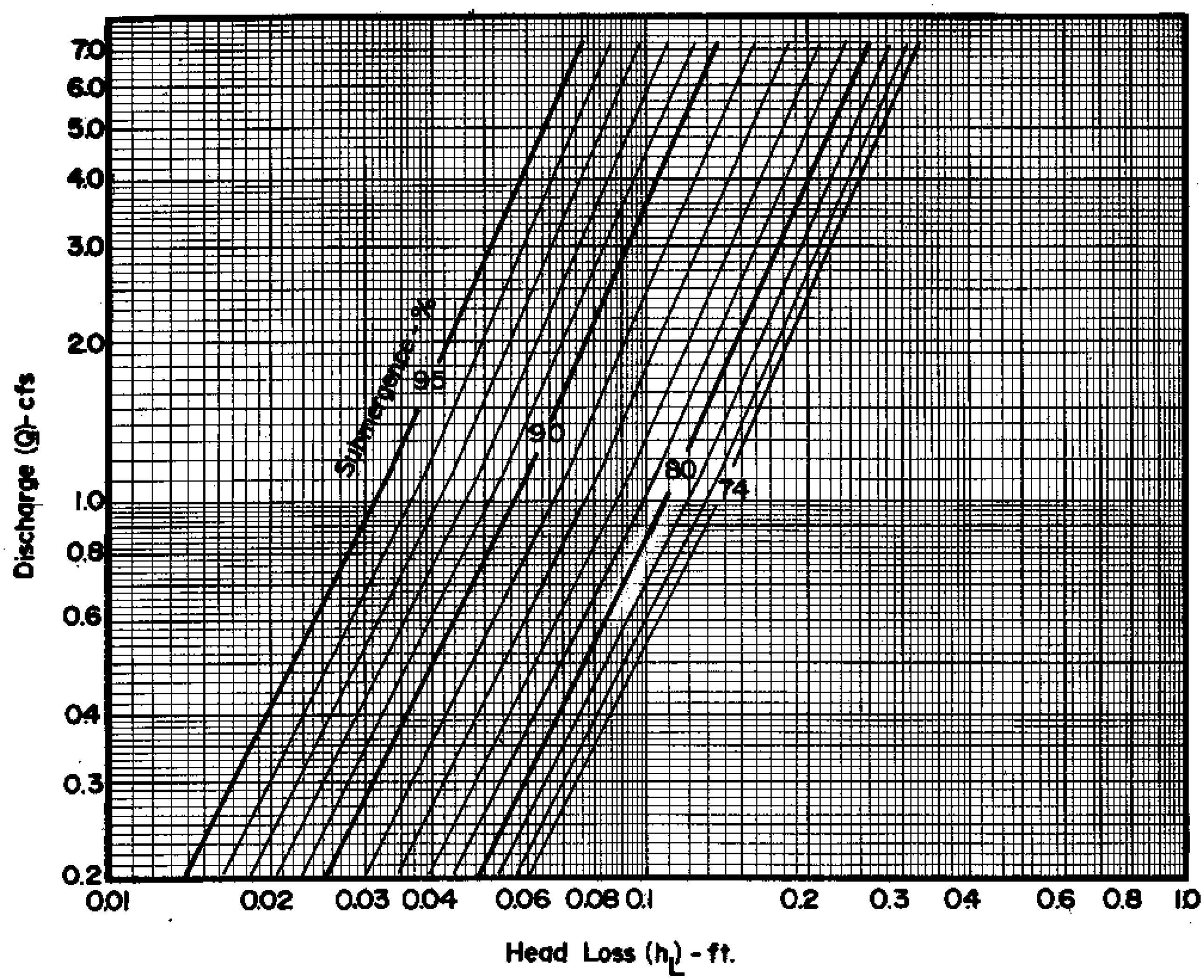

Figure 7.—Head loss through trapezoidal flume No. 1.

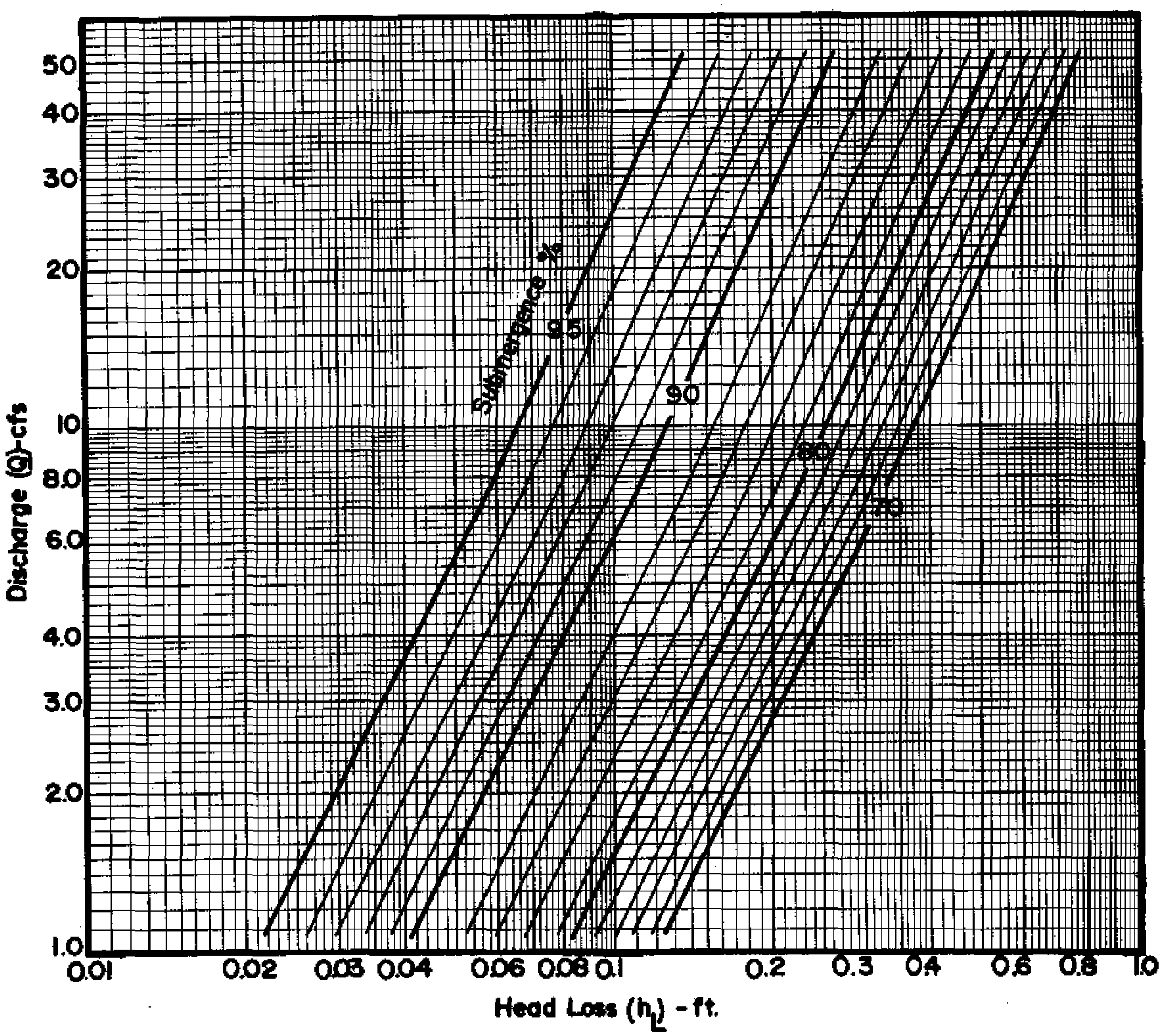

Figure 8.--Head loss through trapezoidal flume No. 2.

SUMMARY

Trapezoidal flumes can be constructed as an integral part of a lined canal or made of metal, fiberglass, or wood and installed in the channel. The flumes can be used where head loss must be kept to a minimum. Submergence to a maximum of 80 percent can be allowed before corrections are necessary. For flows with submergence in excess of 80 percent, flow corrections can easily be made.

APPENDIX

TABLE 1.--Free-flow discharge, in cubic feet per second, through trapezoidal flume No. 1

[h_1 measured in vertical direction $Q = 3.23\ h_1^{2.5} + 0.63\ h_1^{1.5} + 0.05$]

h_1 (ft.)	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.20..........	0.16	0.18	0.19	0.20	0.22	0.23	0.24	0.26	0.28	0.30
.30..........	.31	.33	.35	.37	.39	.42	.44	.46	.48	.51
.40..........	.54	.56	.59	.62	.65	.68	.71	.74	.78	.81
.50..........	.84	.88	.92	.95	.99	1.03	1.07	1.11	1.16	1.20
.60..........	1.24	1.29	1.34	1.38	1.43	1.48	1.53	1.58	1.64	1.69
.70..........	1.74	1.80	1.86	1.92	1.97	2.03	2.10	2.16	2.22	2.29
.80..........	2.35	2.42	2.49	2.56	2.63	2.70	2.77	2.84	2.92	3.00
.90..........	3.07	3.15	3.23	3.31	3.39	3.48	3.56	3.65	3.74	3.82
1.00..........	3.91	4.00	4.10	4.19	4.28	4.38	4.48	4.58	4.68	4.78
1.10..........	4.88	4.98	5.09	5.20	5.30	5.41	5.52	5.63	5.75	5.86
1.20..........	5.98	6.10	6.21	6.33	6.46	6.58	6.70	6.83	6.96	7.08

TABLE 2.--Free-flow discharge, in cubic feet per second, through trapezoidal flume No. 1

[h_1 measured along sloping sidewall $Q = 1.36\ h_1^{2.5} + 0.37\ h_1 + 0.05$]

h_1 (ft.)	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.30..........	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.25	0.26	0.27
.40..........	.28	.29	.31	.32	.33	.35	.36	.38	.39	.41
.50..........	.42	.44	.46	.47	.49	.51	.52	.54	.56	.58
.60..........	.60	.62	.64	.66	.69	.71	.73	.76	.78	.80
.70..........	.83	.85	.88	.90	.93	.96	.98	1.01	1.04	1.07
.80..........	1.10	1.13	1.16	1.19	1.22	1.25	1.28	1.31	1.35	1.38
.90..........	1.41	1.45	1.48	1.52	1.56	1.59	1.63	1.67	1.71	1.74
1.00..........	1.78	1.82	1.86	1.91	1.95	1.99	2.03	2.08	2.12	2.16
1.10..........	2.21	2.25	2.30	2.35	2.40	2.44	2.49	2.54	2.59	2.64
1.20..........	2.69	2.74	2.79	2.84	2.90	2.95	3.00	3.06	3.11	3.17
1.30..........	3.23	3.28	3.34	3.40	3.46	3.52	3.58	3.64	3.70	3.76
1.40..........	3.82	3.89	3.95	4.02	4.08	4.15	4.22	4.28	4.35	4.42
1.50..........	4.49	4.56	4.63	4.70	4.77	4.84	4.92	4.99	5.06	5.14
1.60..........	5.21	5.29	5.37	5.44	5.52	5.60	5.68	5.76	5.84	5.92
1.70..........	6.01	6.09	6.17	6.26	6.34	6.43	6.52	6.60	6.69	6.78
1.80..........	6.87	6.96	7.05	7.14	7.23	7.33	7.42	7.51	7.61	7.70

TABLE 3.--Free-flow discharge, in cubic feet per second, through trapezoidal flume No. 2

[h_1 measured in vertical direction $Q = 4.27\ h_1^{2.5} + 1.67\ h_1^{1.5} + 0.19$]

h_1 (ft.)	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.30..........	0.67	0.70	0.74	0.77	0.81	0.84	0.88	0.92	0.96	1.00
.40..........	1.04	1.09	1.13	1.18	1.22	1.27	1.32	1.37	1.42	1.48
.50..........	1.53	1.59	1.65	1.70	1.76	1.83	1.89	1.95	2.02	2.09
.60..........	2.15	2.22	2.30	2.37	2.44	2.52	2.59	2.67	2.75	2.83
.70..........	2.92	3.00	3.09	3.17	3.26	3.35	3.44	3.54	3.63	3.73
.80..........	3.82	3.92	4.03	4.13	4.23	4.34	4.45	4.56	4.67	4.78
.90..........	4.89	5.01	5.12	5.24	5.36	5.49	5.61	5.74	5.86	5.99
1.00..........	6.12	6.26	6.39	6.53	6.66	6.80	6.95	7.09	7.23	7.38
1.10..........	7.53	7.68	7.83	7.98	8.14	8.30	8.46	8.62	8.78	8.95
1.20..........	9.11	9.28	9.45	9.62	9.80	9.98	10.15	10.33	10.52	10.70
1.30..........	10.88	11.07	11.26	11.45	11.65	11.84	12.04	12.24	12.44	12.64
1.40..........	12.85	13.06	13.26	13.48	13.69	13.90	14.12	14.34	14.56	14.79
1.50..........	15.01	15.24	15.47	15.70	15.94	16.17	16.41	16.65	16.89	17.14
1.60..........	17.38	17.63	17.88	18.13	18.39	18.65	18.91	19.17	19.43	19.70
1.70..........	19.96	20.24	20.51	20.78	21.06	21.34	21.62	21.90	22.19	22.48
1.80..........	22.76	23.06	23.35	23.65	23.95	24.25	24.55	24.86	25.17	25.48
1.90..........	25.79	26.10	26.42	26.74	27.06	27.39	27.71	28.04	28.37	28.71
2.00..........	29.04	29.38	29.72	30.07	30.41	30.76	31.11	31.46	31.82	32.17
2.10..........	32.53	32.90	33.26	33.63	34.00	34.37	34.74	35.12	35.50	35.88
2.20..........	36.26	36.65	37.04	37.43	37.82	38.22	38.62	39.02	39.42	39.83
2.30..........	40.24	40.65	41.06	41.48	41.90	42.32	42.74	43.17	43.60	44.03
2.40..........	44.46	44.90	45.34	45.78	46.23	46.67	47.12	47.58	48.03	48.49
2.50..........	48.95	49.41	49.87	50.34	50.81	51.28	51.76	52.24	52.72	53.20