

A Study of Trapezoidal Flume Models at San Dimas

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ABSTRACT: Presents rating curves applicable to small and large flume installations in which approach velocity permits a hydraulic control to exist. The accuracy to be expected from these curves is tabulated and plotted against field observations. The rating curves should be considered only indicative of the actual flow rates when applied to runoff containing appreciable debris quantities. Criteria are given for modifying field installations, without a hydraulic control at the flume inlet.

High-elevation watersheds ravaged by wildfire can become the scene of massive flood and erosion damage--unless steps can be taken to curb storm runoff and debris movement. After a wildfire struck the San Dimas Experimental Forest¹ northeast of Glendora, Cali-

fornia, in 1960, an emergency research program was started to test several treatments aimed at reducing damage to burned watersheds. To evaluate each mechanical and vegetative treatment, 36 trapezoidal flumes were built on the study watersheds to measure storm runoff.

As part of the post-fire research program, we conducted a model study of these flumes, in cooperation with the Los Angeles County Flood Control District.² The study sought to determine rating curves showing flow rates from runoff for typical flumes installed at the experimental forest. We studied models because of (a) discrepancies in computed discharges for individual flumes based on a theoretical rating curve of steady uniform flow at the water level recorder; (b) the impracticability of setting up a rating curve within a reasonable time for each individual flume; and (c) observations at some flumes showing that by making minor changes we might obtain improved relationships between stage at the recorder level and rate of discharge.

¹The San Dimas Experimental Forest is maintained by the U.S. Forest Service in cooperation with the California Division of Forestry.

²The authors gratefully acknowledge the use of the District's hydraulic laboratory, and the help of Maxwell F. Burke, hydraulic division engineer, for general direction, and J. H. Brown, assistant division engineer, for general supervision and guidance in preparation of the model-study report.

This paper describes the model study, and proposes rating curves that relate clear water flow rates to stage at the water level recorder. These rating curves apply to small and large flumes in which approach velocity permits hydraulic control at the upstream end of the flume during runoff. The rating curves are of limited use when flow contains appreciable amounts of debris. Field installations without hydraulic control at the flume inlet must be modified before a satisfactory rating can be obtained. The approach channel should be widened; the criteria for this procedure are included in this paper.

FIELD INSTALLATION OF FLUMES

FLUME CONSTRUCTION

Flume sites at San Dimas were selected so as to allow a free overfall at the lower end and thus eliminate any backwater effect at the measured cross section. Each flume is 30 feet long, 2 1/2 feet high, has 1.5:1 side slopes, and is set on about a 5 percent slope. Each is built of either reinforced gunite or reinforced soil cement. A water stage recorder stands about 26 feet downstream from the inlet (fig. 1). Large flumes, located on 11 watersheds, have an invert width of 2 feet. Small flumes, built on 25 watersheds, have an invert width of 0.5 feet.

Natural channel shape and stream bed slopes, upstream from the flumes, vary considerably. We added a rounded, quadrant-shaped soil cement transition to direct approaching flow into the flume when the cross sections of the natural channel exceeded that of the flume.

FLUME RATING

A control section at the flume inlet was necessary if the depth of flow at the recorder was to be a function solely of the flow rate and not be dependent on the upstream flow conditions. Thus, if a control was maintained at field installations, a single rating curve for each of the two flume sizes was adequate. Two models--one large and the other small--had to be built and tested.

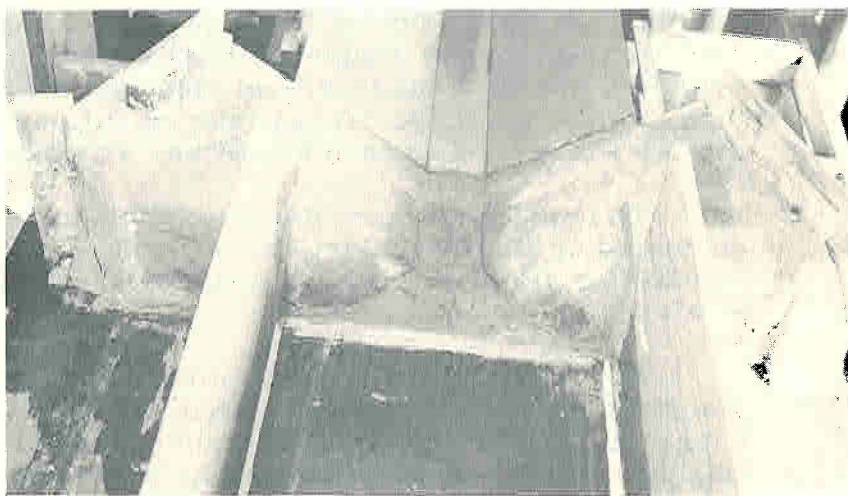
Flow approaching the flume can be either subcritical (velocity less than critical) or supercritical (velocity greater than critical). If the flow is subcritical, critical depth will occur at the flume inlet, thus becoming a hydraulic control. If the flow is supercritical, a control will result only if the energy content of the supercritical flow is less than the minimum energy level that can exist in the flume. Then the flow will be backed up by the flume until the energy in the approach equals the minimum allowable energy in the flume. This condition requires a hydraulic jump to form some distance upstream from the inlet. If the supercritical flow has more energy than the minimum level, the flow will shoot through the flume with the inlet depth less than critical--and no control exists.

Figure 1.--Typical large flume installation showing approach condition, instrumentation, construction, and free overfall.



Figure 2.--Typical model flume, with view looking upstream showing model construction and flow conditions in large flume.

Figure 3.--Typical transition section, with view looking downstream showing transition structure for large flume with 9.5-foot approach channel width.



SCALE MODELS

The two model flumes were built of plastic-coated plywood (fig. 2). We did not try to match the roughness values of the prototype because the effect of frictioned resistance in relatively short flumes can be considered minor. Roughness of natural approach channels was not known. Typical transitions were built of mortar (fig. 3). The approach channel was a plywood rectangular section which made easier any changes in slope and width of approach.

Scale ratios for both large and small flumes were governed by the space available and by the capacity of the recirculating system. The large flume was modeled on a 5:1 scale to obtain a maximum prototype flow of 100 c.f.s. The small flume was modeled on a 3.5:1 scale which gave 40 c.f.s. maximum flow. Relationships between model and prototype values were based on a Froude Model Law which considers the inertia and gravity forces to be dominant. All values quoted in this report are prototype values.

Models did not include prototype sediment samplers, witness gages, and recorder installations in the flume, nor a channel reach downstream from the flume.

We used a weir from the laboratory forebay tank to bring water to the models. A 55-foot adjustable slope approach channel was used to assure adequate length to develop approach conditions necessary for model tests. Free overflow from the flume was returned to the laboratory recirculating system.

THE MODEL PROGRAM

TEST CONDITIONS

The model tests on the large and small flumes used a control at the flume inlet and approach flow conditions that were varied. Conditions tested were: (a) a subcritical approach velocity considerably less than critical velocity; (b) a subcritical approach velocity near critical velocity; (c) a supercritical approach velocity near critical velocity; and (d) a supercritical approach velocity considerably greater than critical velocity. These four conditions were tested on each of the two flumes. For each condition, we obtained a rating curve.

The modification to the natural channel upstream from the flume consisted of a rectangular channel in the model. To insure hydraulic control for various approach velocities, we determined the minimum width of this channel.

Another modification was also tested. We constricted the flume transition to a section smaller than the flume section, and thereby caused a hydraulic control that otherwise did not exist. This constriction was tested independently of the approach channel modifications.

To accomplish the objectives of the model tests, we had to: (a) adjust approach channel slope and width to establish the desired approach velocity; (b) set the discharge to be tested, and (c) measure the velocity in the approach channel and water surface level along the flume. Approach channel slopes and width to be tested for each approach condition were established from the desired approach velocity at the maximum flow rate. For supercritical approach conditions, the slope and width at the maximum discharge was set to position the hydraulic jump as near the flume as possible without causing wave action in the flume. When positioned in this manner the hydraulic jump indicated minimum width and length of approach channel required to assure formation of a satisfactory jump.

RESULTS OF MODEL TESTS

Four rating curves based on the depth at the right wall (station 0 + 26 feet) were obtained for the four approach conditions for each flume (fig. 4). These curves were in relatively close agreement with no consistent variation between supercritical and subcritical approaches. Any variation between the curves can be attributed to standing wave patterns which are inherent in supercritical flow. Generally, these waves start at the transition structure. Figure 5 illustrates a typical water surface profile exhibiting these standing waves.

The water surface profiles show a general increase in wave amplitude with increased discharge. The location of the wave from the recorder position (station 0 + 26 feet), however, is not constant. In some cases, the trough of the wave is at the recorder; in others the crest exists at the wall for the same discharge. This variation will result in a range of recorded depths for a given discharge. The water surface profiles also show that the flow accelerates throughout the flume, except at some low flows where the normal flow depth is obtained. The localized drawdown at the end of the flume from the free overfall did not extend upstream far enough to influence flow conditions at the recorder.

To construct the final rating curve, we used two methods to account for the standing wave patterns:

1. Use the average depth of flow at the recorder location (0 + 26) as the representative stage. This average was computed from three measured depths across the flow section for each of the four approach conditions. Thus the final representative stage for each discharge was the average of 12 depth measurements. This method was based on the assumption that some flumes will have a wave crest at the recorder, while others a wave trough. The average depth was then used to construct an average rating curve to be used for all flumes.

2. Use the midpoint of the maximum possible range of depths at the recorder wall. This maximum possible range was determined by drawing envelope curves of the crests and troughs along the flume for each run. The range of the two envelope curves at the recorder location was the maximum possible range desired. This assumed that wave crests and troughs may occur at different locations along the flume because of varying approach conditions (fig. 5).

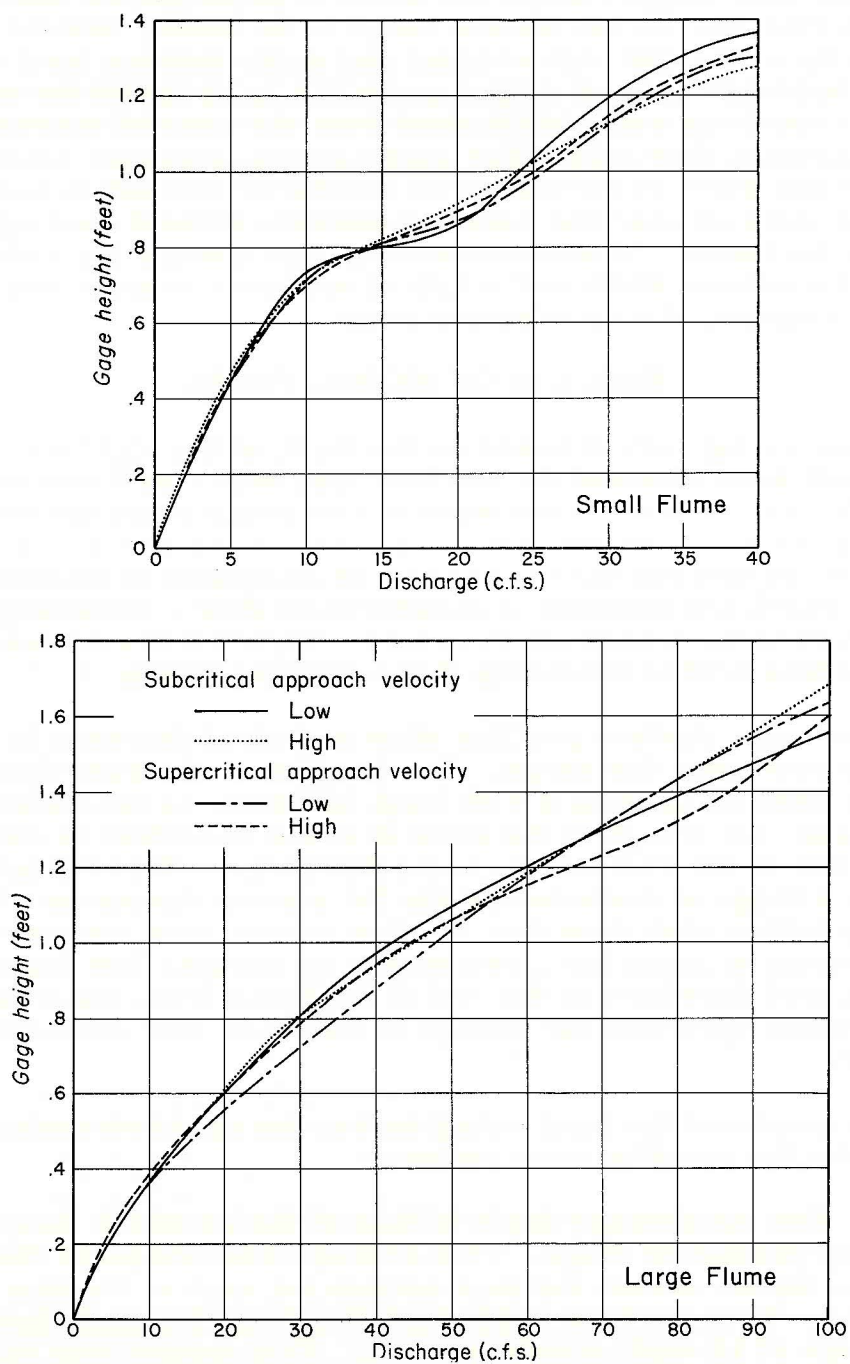


Figure 4.--Rating curves for small and large flumes plotted from basic test data.

Use of the two methods yielded almost identical rating curves. We concluded that ratings determined by the second would be most applicable to prototypes under a variety of approach conditions (fig. 6). Rating accuracy to be expected was computed from the range of discharge possible for a given recorder stage (table 1). The higher stages in the large flume tended to be more accurate than the lower stages.

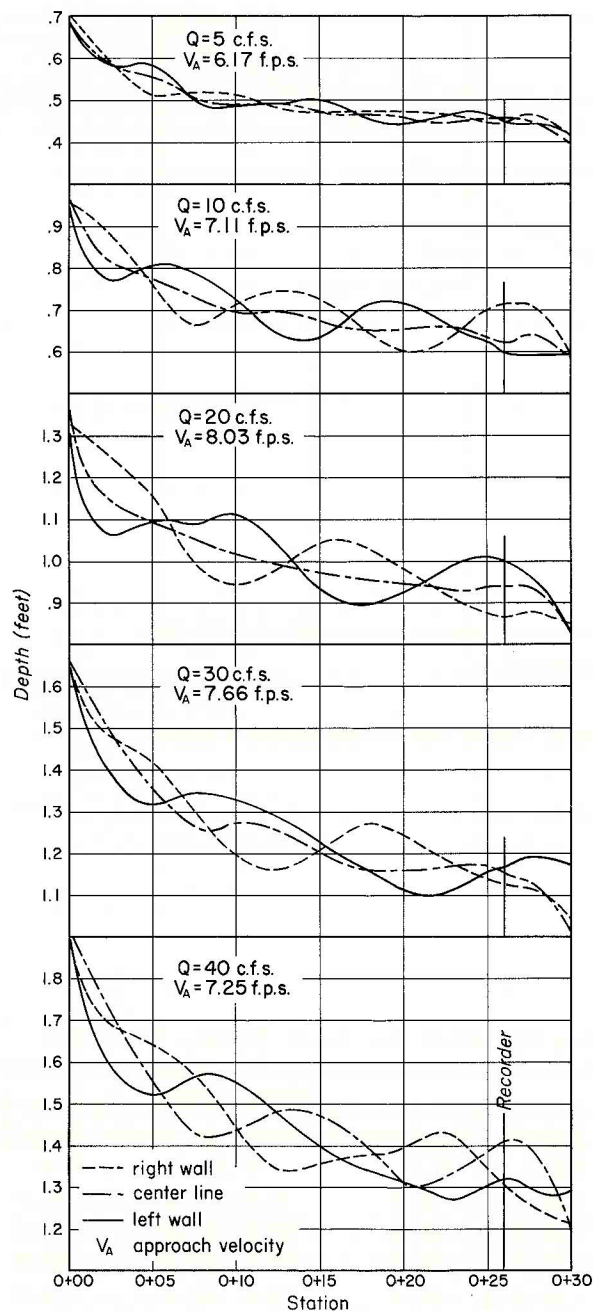


Figure 5.--Water surface profiles in small flume of low supercritical approach velocity.

CHANGES IN FIELD INSTALLATIONS

From these model tests, we found that certain changes in flume installations were called for. Approach channel sections extending upstream from the transition at the flume inlet should be widened. Curves in figure 6 indicate requirements for a hydraulic control at typical large and small flumes in terms of approach channel velocity and width. Channel widths above those indicated by the curves should result in a control. Widening the approach channel would not effect control at velocities greater

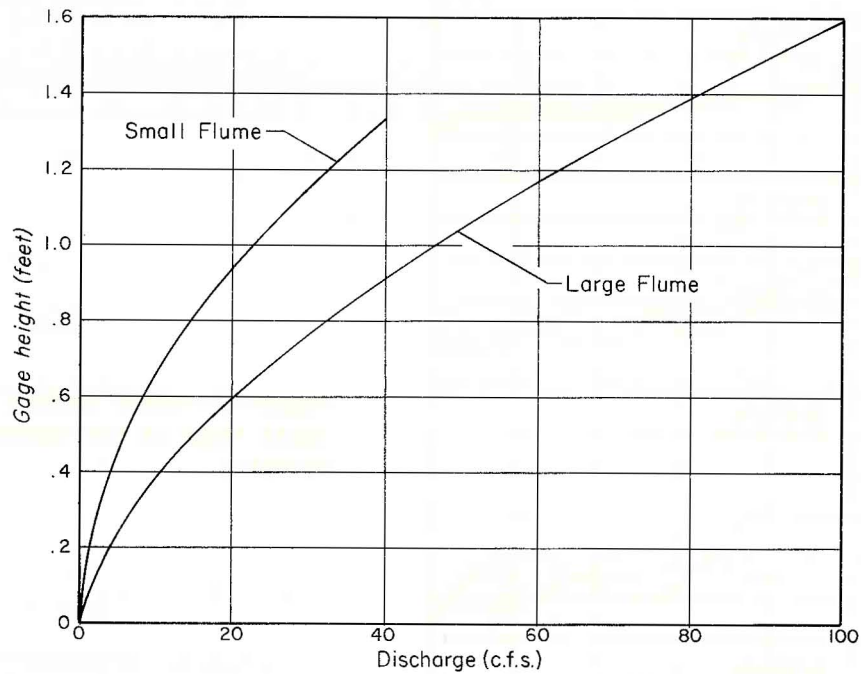


Figure 6.--Recommended rating curve for trapezoidal flumes.

Table 1. Computed accuracy of rating for small and large flumes, by stages

Stage	Small flume				Large flume		
	Discharge	Discharge range	Error±		Discharge	Discharge range	Error±
	Ft. C.f.s.	C.f.s.	Pct.		C.f.s.	C.f.s.	Pct.
0.25	2.1	2.4 - 1.8	14.3		5.5	6.6 - 4.4	20.0
.50	6.2	7.2 - 5.2	16.2		15.1	18.2 - 12.0	20.5
.75	12.9	15.5 - 10.3	20.0		29.3	34.4 - 24.2	17.4
1.00	23.0	26.8 - 19.2	16.5		46.5	53.4 - 39.5	14.8
1.25	36.2	41.2 - 31.2	13.7		67.0	76.0 - 58.0	13.4
1.50	--	-- --	--		90.6	100.6 - 80.6	11.0

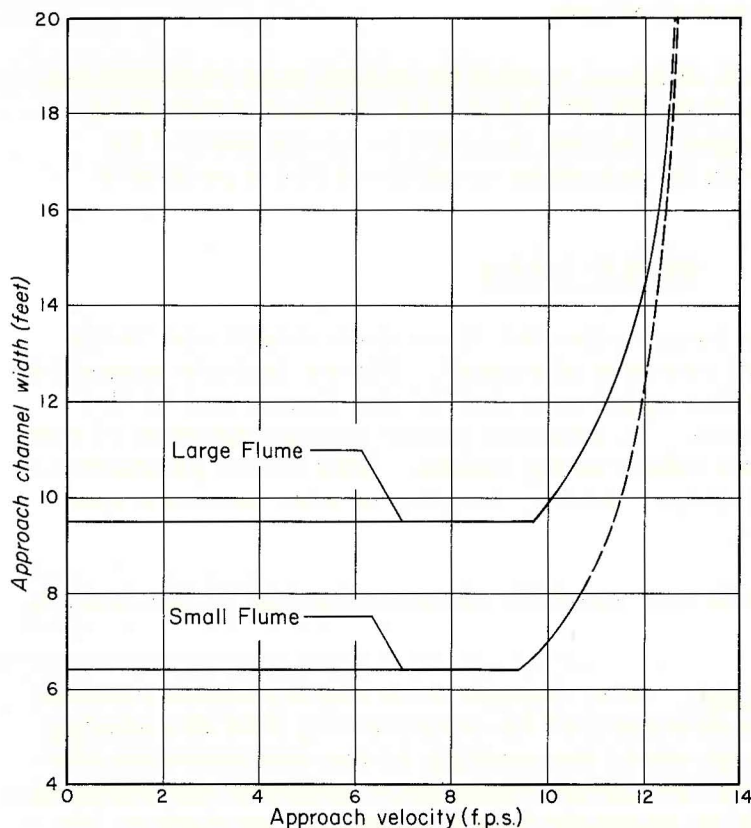


Figure 7.--Requirements for hydraulic control at flume inlet in terms of approach channel velocity and width.

than about 13 feet per second. These curves are applicable at maximum flow rates of 40 c.f.s. and 100 c.f.s. for the small and large flume, respectively. To minimize wave disturbances in the flume, the approach channel width should not be less than the top width of the flow cross-section in the trapezoidal flume at the inlet when a hydraulic control exists (fig. 7).

The length of any modified approach channel section required is governed primarily by the position of the hydraulic jump which in turn depends on the approach channel slope. The modified section should be extended upstream from the jump at enough distance to allow the flow from the natural channel to conform to the shape of the widened section. A criterion for minimum length of approach channel was not studied by model; however, for a modified approach channel section placed on a slope between 4.8 and 9.0 percent, a length of 15 to 20 feet and 35 to 40 feet would provide proper conditions for a hydraulic jump and control at the inlet of small and large flumes, respectively.

Constriction of the transition as an alternative to modifying the approach channel was tested on the small flume model. The transition was constricted to a trapezoidal section with a 1:1 side slope and a base width of 0.5 feet. The unconstricted transition was a trapezoidal section with 1.5:1 side slopes and 0.5-foot base width. Observations of the flow in the flume showed that standing waves were excessive for waves for comparable flow conditions without a constricted transition. Therefore,

constricting the transition did not appear satisfactory to effect a hydraulic control in field installations.

Although the approach channel tested by model was rectangular, the shape of a modified section would depend on channel conditions. Any modified approach channel section subject to scour should be lined with gunite or concrete to maintain conditions for a properly positioned hydraulic jump.

FIELD DATA

Some field data have been collected from both small and large flumes during the few brief periods of runoff. These include measurements of water depth near the upstream end of the flume and at the water level recorder location. In addition some measurements of the water surface velocity were taken using floats. The exact geometry of each flume (slope, side slope, width, length) is also known from surveys after construction.

To convert these depth and velocity measurements to discharge, we used two methods:

Energy balance method. -- For flumes with depth measurements only, the discharge can be determined by considering that the energy at the upstream station must equal the energy at the downstream station, plus the energy lost to frictional resistance between the stations. Using the Manning formula to compute this frictional resistance, we developed an equation for the discharge:

$$Q = \sqrt{\frac{\Delta t + d_1 - d_2}{\frac{1}{2g} \left(\frac{1}{A_2^2} - \frac{1}{A_1^2} \right) + \frac{1}{2} L \left(\frac{1}{C_1^2} + \frac{1}{C_2^2} \right)}}$$

in which $C_1 = \frac{1.486 R_1^{2/3} A_1}{n}$, $C_2 = \frac{1.486 R_2^{2/3} A_2}{n}$

$$R_1 = \frac{A_1}{P_1}, \quad R_2 = \frac{A_2}{P_2}$$

Q - discharge - cfs.

Δt - difference in elevation of flume invert between measuring stations - ft

d_1, d_2 - water depths at upstream and downstream stations, respectively - ft

A_1, A_2 - cross sectional area of water prism at measuring stations - ft²

L - length between stations - ft

P_1, P_2 - wetted perimeter of flume across section at measuring stations - ft

g - acceleration of gravity = 32.16 ft/sec²

n - Manning roughness coefficient

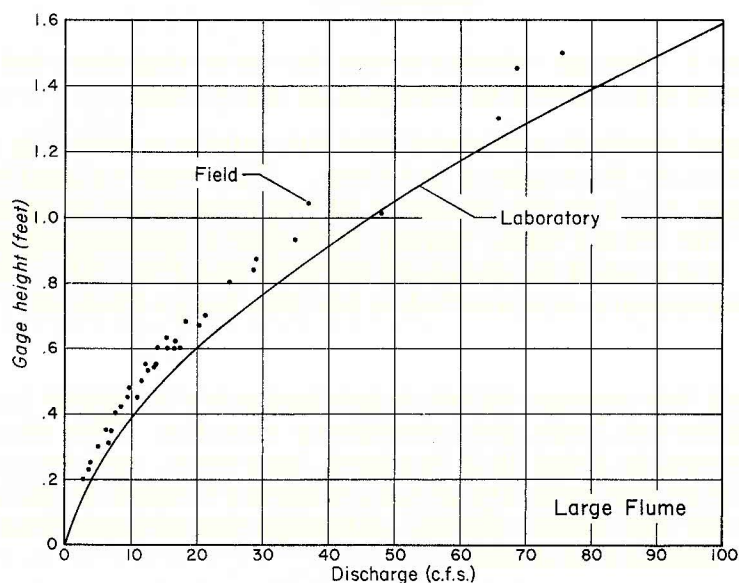
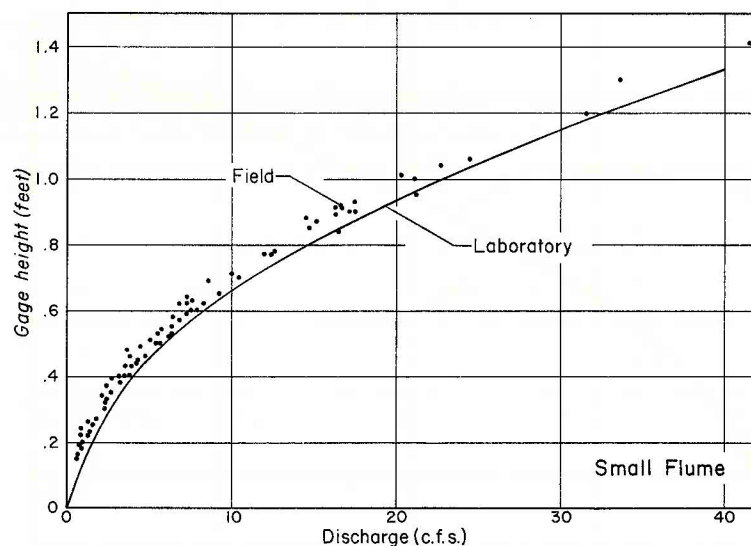


Figure 8.--Energy balance method for converting depth and velocity measurements to discharge in small and large flumes.

In this method, the only unknown quantity, besides the discharge, is the value of n . This was assumed to be 0.016, which is reasonable for rough finished gunite. The values of d_1 and d_2 were the observed data. The discharges were plotted against d_2 small and large flumes (fig. 8).

Average velocity method. --For flumes with both depth measurements and water surface velocity measurements discharge can be computed by a continuity relation:

$$Q = \frac{1}{2} (A_1 + A_2) V$$

in which V is the average surface velocity, and other symbols as previously defined.

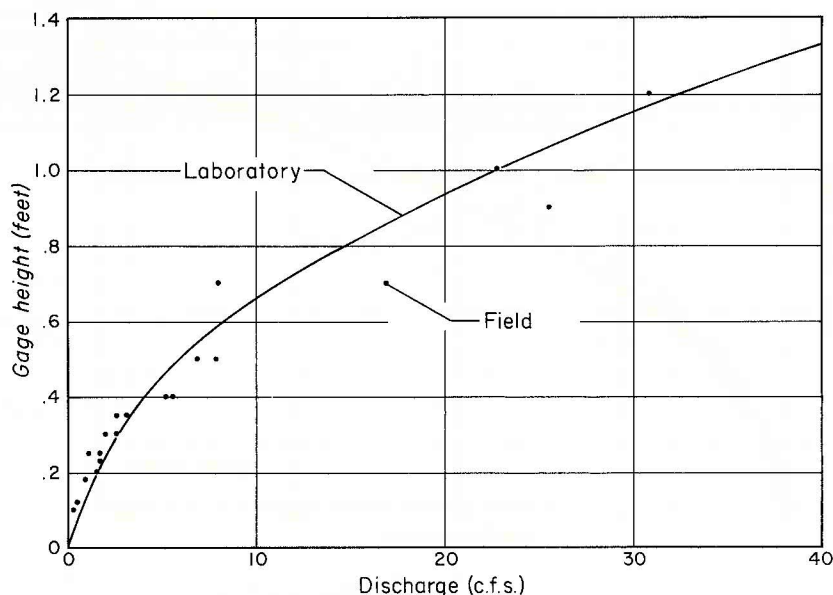


Figure 9.--Average velocity method for converting depth and velocity measurements to discharge in small flume.

The second method assumes that the surface velocity represents the average velocity throughout the flow. This approximation probably does not warrant refinement because of uncertainties in collecting this type of data. The flume data, which included a measurement of the surface velocity, were used to compute discharges (fig. 9). Only a few velocity measurements are available for the large flumes. They are not shown.

In general the energy balance method gave a rating curve which was slightly different from the laboratory results. The somewhat consistent rating results from this method, however, are encouraging. The data based on average velocity measurements tended to follow the laboratory curve for the small flume, although the scatter was greater than for the energy balance method.

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