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Techniques of Water-Resources Investigations of the United States Geological Survey

Chapter A8

DISCHARGE MEASUREMENTS AT GAGING STATIONS

By Thomas J. Buchanan and William P. Somers

Book 3

APPLICATIONS OF HYDRAULICS

3. Repeat velocity and depth observations at the same 10 sections with corresponding stages as often as possible throughout the period of the flood wave.
4. Develop stage-velocity and stage-area curves for each of the 10 sections.
5. Compute the discharge corresponding to selected stages by summation of the partial discharges from the curves thus defined.

Mean gage height of discharge measurements

The mean gage height of a discharge measurement represents the mean height of the stream during the period the measurement was made and is referred to the datum of the gaging station.

The mean gage height for a discharge measurement is one of the coordinates used in plotting the measurements to establish the stage-discharge relation, often called the rating curve. An accurate determination of the mean gage height is therefore as important as an accurate measurement of the discharge to define the stage-discharge relationship.

The computation of the mean gage height presents no problem when the change in stage is 0.1 foot or less, for then the mean may be obtained by inspection. However, measurements must sometimes be made during floods or regulation regardless of how rapidly stage changes.

To obtain an accurate mean gage height, the gage must be read before and after the discharge measurement, and the recorder chart must be read at breaks in the slope of the gage-height graph during the measurement. If the station is equipped with a digital recorder, the gage-height readings punched during the measurement are to be read. At nonrecording stations the only way to obtain intermediate readings is for the stream gager to stop during the measurement once or twice to read the gage, or to have someone else do this for him.

If the change in stage is greater than 0.1 foot, the mean is obtained by weighting the gage-height readings rather than by inspection of the available readings.

The mean gage heights during periods of constant slope of the gage-height graph and the corresponding measured partial discharges are used to compute the mean gage height of the measurement. The formula used is:

$$H=\frac{q_1h_1+q_2h_2+q_3h_3\,.\,.\,.\,.\,.\,.\,.\,.\,.\,+q_nh_n}{Q} \tag{5}$$

in which

H=mean gage height, in feet,
Q=total discharge measured, in cubic feet per second= $q_1+q_2+q_3\,.\,.\,.\,.\,.\,.\,+q_n$,
$q_1, q_2, q_3, \ldots q_n$=amount of discharged measured during time interval 1, 2, 3, . . . n, in cubic feet per second,
$h_1, h_2, h_3, \ldots h_n$=average gage height during time interval 1, 2, 3, . . . n, in feet.

Figure 67 shows the computation of a weighted mean gage height. The graph at the bottom is a reproduction of the gage-height graph during the discharge measurement. The discharges are taken from the current-meter measurement shown in figure 2. The upper computation of the mean gage height in figure 67 shows the computation using the given formula. The lower computation has been done by a shortcut method to eliminate the multiplication of large numbers. In this method, after the average gage height for each time interval has been computed, a base gage height, which is usually equal to the lowest average gage height, is chosen. Then, the difference between the base gage height and the average gage heights is used to weight the discharges. When the mean difference has been computed, the base gage height is added to it.

If a discharge measurement is made at a distance from the gage during a change in stage, the discharge passing the gage during the measurement will not be the same as the discharge at the measuring section because of the effects of channel storage between the measuring section and the gage.

Adjustment is made for channel storage by applying to the measured discharge a quantity obtained by multiplying the channel surface area by the average rate of change in stage in the reach. The formula is:

$$Q_G=Q_m\pm WL\frac{\Delta h}{\Delta t}, \tag{6}$$

Angle coefficient	Dist. from initial point ①	Width ②	Depth ③	Observation depth	Revolutions ④	Time in seconds	Velocity At point	Velocity Mean in vertical	Adjusted for hor. angle or	Area	Discharge
	Time	GHt.	Ave. GHt.		Q		③×④				
	1330	1.94	1.92		16.10		30.91				
	1345	1.90	1.70		24.31		41.33				
	1400	1.49	1.67		20.99		35.05				
	1415	1.85	1.88		14.97		28.14				
	1430	1.92									
			Total Q =		76.37	Total =	135.43				

$$M.G.H = \frac{\text{Total } ③\times④}{\text{Total } Q} = \frac{135.43}{76.37} = 1.77$$

Time ①	G Ht ②	Ave GHt ③	Ave GHt minus base ④	Q ⑤	④×⑤
1330	1.94	1.92	.25	16.10	4.02
1345	1.90	1.70	.03	24.31	.73
1400	1.49	1.67	.00	20.99	.00
1415	1.85	1.88	.21	14.97	3.14
1430	1.92				
Base	1.67		Total Q =	76.37	Total 7.89

$$MGH = \text{Base} + \frac{\text{Total } ④\times⑤}{\text{Total } Q} = 1.67 + \frac{7.89}{76.37} = 1.67 + .10 = 1.77$$

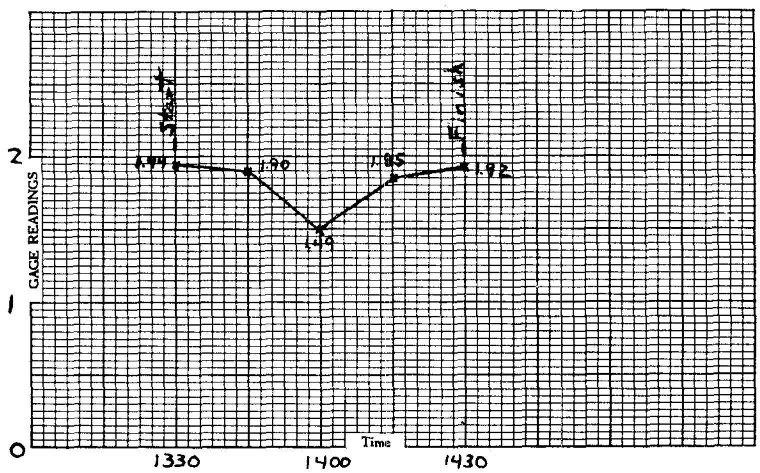

Figure 67.—Computation of weighted mean gage height.

in which

Q_G=discharge going over the control, in cubic feet per second,

Q_m=measured discharge, in cubic feet per second,

W=average width of stream between measuring section and control, in feet,

L=length of reach between measuring section and control, in feet,

Δh=average change in stage in the reach L during the measurement, in feet, and

Δt=elapsed time during measurement, in seconds.

A reference point (RP) or a temporary gage is set at the measuring section if channel storage might be significant. The water-surface elevation at the section is determined before and after the measurement to compute Δh. If the measurement is made above the control, the adjustment will be plus for falling stages and minus for rising stages; if made below the control, it will be minus for falling stages and plus for rising stages.

Figure 68 shows the front sheet of a measurement that has been made at a distance from the control during a period of changing stage. The computation of the adjustment for storage for the measurement shown in figure 68 follows:

Adjustment for measurement 264 on Big Creek near Dogwood, Va.

Measurement made 0.6 mile upstream =3,170 feet.

Average width between measuring section and control=150 feet.

Change in stage at control, 5.84–6.74 feet= ~~+0.09~~ foot. +.90

Change in stage at measuring section, 12.72–13.74 feet=+1.02 feet. Readings taken at measuring section from a reference point before and after measurement.

Average change in stage=(0.90+1.02) ÷2=0.96 foot.

9-275-F
Jan. 1966

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

Meas. No. 264
Comp. by TJB
Checked by

DISCHARGE MEASUREMENT NOTES

Sta. No. 1-9946.5
Big Creek near Dogwood, Va.
Date Mar. 26, 1962 Party T. J. Buchanan
Width 140 Area 1,040 Vel. 8.07 G. H. 6.29 Disch.* 8,390
Method 2-.8 No. secs. 30 G. H. change +.90 in 1¼ hrs. Susp. 15C
Method coef. 1 Hor. angle coef. Varies Susp. coef. 1.00 Meter No. 3684

EST Time	El. T	Recorder	T Inside	Outside
1415	5.54	5.54	5.54	5.52
1440	Start	5.84		
1500		6.08		
1530		6.44		
1555	Finish	6.74		
1630	7.16	7.16	7.16	7.14
Weighted M. G. H.				
G. H. correction				
Correct M. G. H.				

Date rated 2-16-62 Used rating for rod ✓ susp. Meter 1.0 ft. above bottom of wt. Tags checked Yes
Spin before meas. 2:55 after 2:50
Meas. plots % diff. from rating
Wading, cable, ice, boat, upstr., downstr., side bridge 0.6 feet, mile, above, below gage, and
Check-bar, chain found
changed to at
Correct
Levels obtained

Measurement rated excellent (2%), good (5%), fair (8%), poor (over 8%), based on following conditions: Cross section Fairly even; stone and gravel bottom.
Flow Good distribution; some Weather Raining
Other debris flowing. Air 44 °F@ 1635
Gage OK Water 38 °F@ 1635
Record removed Yes Intake flushed
Observer Talked with
Control Clear
Remarks * Discharge adjusted for storage effect.
Qm = 8,494
G. H. of zero flow ft. Elev. RP = 30.00
RP to WS @ 1440 = 17.28; 30.00 − 17.28 = 12.72
RP to WS @ 1555 = 16.26; 30.00 − 16.26 = 13.74

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Figure 68.—Discharge measurement notes with discharge adjusted for channel storage effect.

Elapsed time during measurement=$1\frac{1}{4}$ hours=4,500 seconds.

Measured discharge=8,494 cfs (cubic feet per second).

$$Q_G = 8{,}494 - 150\ (3{,}170)\ \frac{0.96}{4{,}500}$$
$$= 8{,}494 - 101 = 8{,}393 \text{ cfs. Use } 8{,}390 \text{ cfs.}$$

It is also possible to approximate the effect of storage by computing the time of travel of the flood wave between the measuring section and the control and then adjusting the gage height for the traveltime to correspond to the measured discharge. The flood-wave velocity is generally assumed to be 1.3 times the mean velocity for the measurement.

The traveltime is computed by the following formula:

$$t = \frac{L}{1.3V}, \qquad (7)$$

in which

t=time of travel of the flood wave between the measuring section and the control, in seconds,

L=length of reach between measuring section and control in feet and

V=mean velocity of measurement, in feet per second.

In applying the time adjustment, the time-of-travel adjustment is subtracted from the observed time at the ~~gage if the measurement is made either below the gage on a rising stage, or above the gage on a falling stage, and the time-of-travel adjustment is added to the observed time at the gage if the measurement is either below the gage on a falling stage, or above the gage on a rising stage.~~

cor-rec-tion

Figure 69 shows the front sheet for the same measurement used in figure 68, but this time the storage adjustment has been made by adjusting the gage height. The computation of the traveltime is shown on the bottom of the front sheet. Figure 70 is an expanded plot of the gage-height graph during the time of the measurement. By applying the traveltime to the starting and finishing times of the measurement, the adjusted gage heights of 5.90 feet and 6.80 feet are obtained from figure 70. The mean gage height is obtained by weighting as described previously.

The relationship between mean velocity and the velocity of the flood wave is uncertain in many instances. For this reason the adjustment method using change in channel storage is usually preferred.

The proper coordination of the gage height and the discharge because of the amount of change in stage is a separate and distinct problem from that of making adjustments owing to variable slopes caused by changing discharge. Therefore the relation of stage to discharge at the time a measurement is made should be determined before adjustments owing to variable slopes are made.

Portable Weir Plates

Current-meter measurements made in shallow depths and low velocities are usually inaccurate, if not impossible to obtain. Under these conditions a portable weir plate is a useful device for measuring the discharge.

A 90° V-notch weir is suitable because of its favorable accuracy at low flows. A weir made of 10- to 16-gage galvanized sheet iron will produce a free-flowing nappe having the effect of a sharp-crested weir and will give satisfactory performance. The thickness of the plate should vary with the size of the weir. Refer to figure 71 for recommended proportions. Decreasing the plate thickness on larger weirs will help maintain portability. The notch is cut, without sharpening, leaving a flat, even edge. Framing, in the form of small angle irons, is required for medium and large sizes. Canvas attached on the downstream or upstream side prevents leakage under or around the weir. Eyebolts, properly placed, will secure rods driven in earth channels to stabilize the plate.

A staff gage should be placed far enough upstream from the weir opening so that it is not in the drawdown region and it should be related to the weir gage by means of a carpenter's level. At a distance greater than twice the head, the drawdown effect is negligible. The staff gage is used to obtain head on the weir.

Flows from 0.02 to 2.0 cfs are measured with the large weir of figure 71. Discharges can be measured within 3 percent accuracy if the weir

measurement section if the measurement is made below the gage and is added if the meas. is made above the gage. The resulting adjusted time is used to look up the corresponding gage height to plot vs. Qm.

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(August 1949)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

Meas. No. 264
Comp. by TJB
Checked by

DISCHARGE MEASUREMENT NOTES

Big Creek near Dogwood, Va.

Date Mar. 26, 1962 Party T. J. Buchanan
Width 140 Area 1,040 Vel. 8.16 G. H.* 6.35 Disch. 8,490
Method 2+.8 No. secs. 30 G. H. change +.90 in 1¼ hrs. Susp. 75C
Method coef. 1 Hor. angle coef. Varies Susp. coef. 1.00 Meter No. 3684

EST	GAGE READINGS			
Time	El. T	Recorder	T Inside	Outside
1415	5.54	5.54	5.54	5.52
1440	Start	5.90*		
1500		6.14*		
1530		6.50*		
1555	Finish	6.80*		
1630	7.16	7.16	7.16	7.14
Weighted M. G. H.		6.35		
G. H. correction				
Correct M. G. H.				

Date rated 2-16-62 Used rating
for rod ✓ susp. Meter 1.0 ft.
above bottom of wt. Tags checked
Spin before meas. 2:55 after 2:50
Meas. plots % diff. from rating
Wading, cable, ice, boat, upstr., downstr.,
side bridge 0.6 feet, mile, above,
below gage, and
Check-bar, chain found
changed to at
Correct
Levels obtained

Measurement rated excellent (2%), good (5%), fair (8%), poor (over 8%), based on following conditions: Cross section Fairly even; stone + gravel bottom
Flow Good distribution; some Weather Raining
Other debris flowing Air 44 °F. @ 1635
Gage OK Water 38 °F. @ 1635

Record removed Yes Intake flushed { U. / L.

Observer Talked with

Control Clear

Remarks * Gage height adjusted for time of travel of flood wave.

G. H. of zero flow ft. Sheet No. 1 of 4 sheets.

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$$t = \frac{L}{1.3V} = \frac{3170}{1.3(8.16)} = 299 \text{ secs.} = 5 \text{ min.}$$

Figure 69.—Discharge measurement notes with mean gage height adjusted for time of travel of flood wave.

is not submerged. A weir is not submerged when there is free circulation of air on all sides of the nappe.

The general equation for flow over a sharp-edged triangular weir with a 90° notch is

$$Q = Ch^{5/2}, \tag{8}$$

where Q is the discharge, h is the static head, and C is the coefficient of discharge. Each weir should be rated by determining the flow volumetrically. In the absence of such a rating a value of C of 2.47 may be used.

To place the plate in a sand or silt channel, the only tools required are a carpenter's level and a shovel. The level is used to make the top of the plate horizontal and the plate plumb. Another way to level the plate is by fastening a staff gage or level bubble to each end of the weir. The staff gages are set at the same

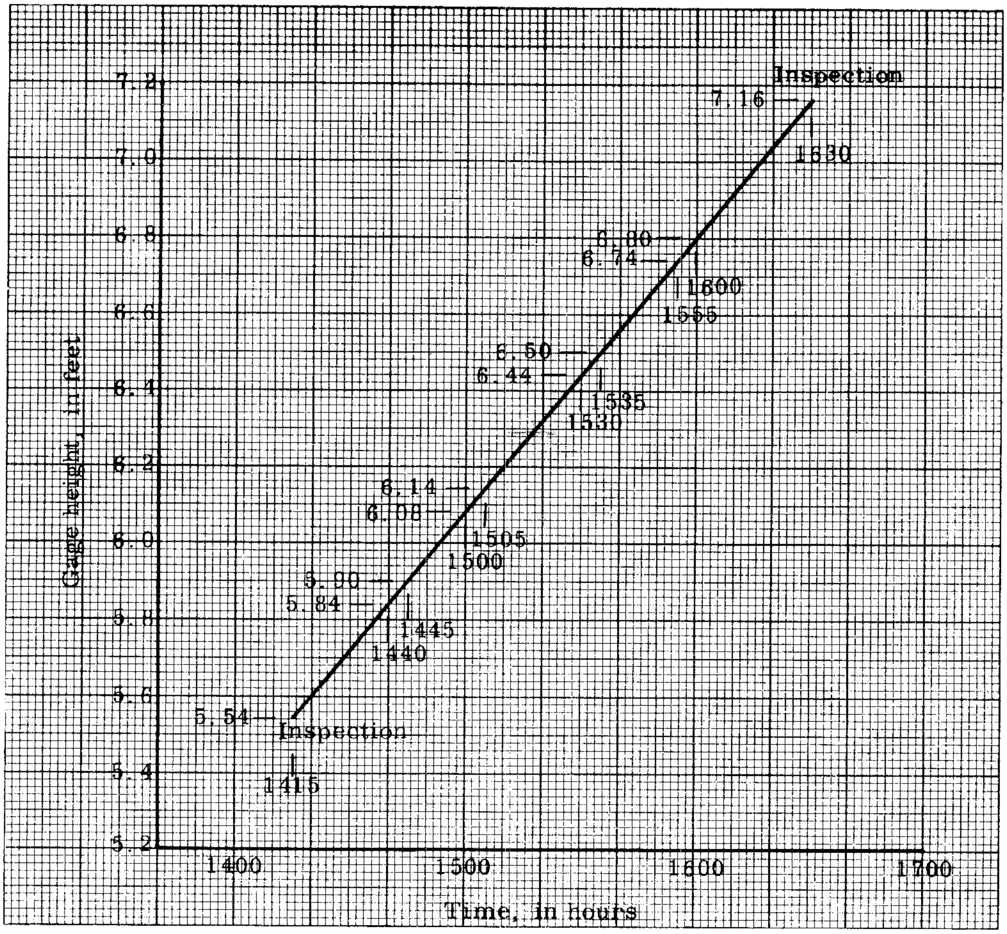


Figure 70.—Expanded plot of gage-height graph during measurement 264 at Big Creek near Dogwood, Va., March 26, 1962.

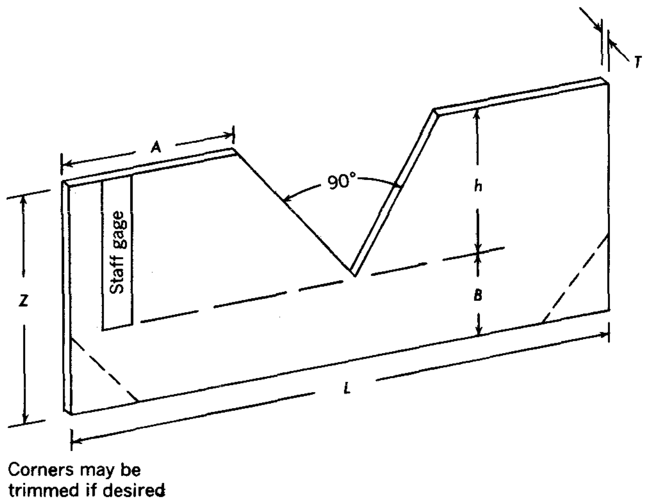
elevation. The plate is leveled by making the staff-gage readings identical or by using the level bubbles. The flow should be allowed to stabilize before making a measurement. The gage height should be read five or six times during a 3-minute interval and a mean value should be used. Ordinarily a lone man can measure with a weir of this type.

Portable Parshall Flumes, Description and Theory

A portable Parshall measuring flume is useful for measuring discharge when the depths are shallow and the velocities are low. The flume has a converging section, a throat, and a diverging section. The floor of the converging, or upstream section is level both longitudinally and transversely when in place. The floor of the throat section slopes downward and the floor of the diverging or downstream section slopes upward.

The flume may be operated as a free-flow, single-head measuring device, or operated under submerged-flow conditions where two heads are measured. The head in the converging section and the head near the downstream end of the throat section are read on staff gages or in stilling wells. Both gages have their datum at the elevation of the floor of the converging section.

Free flow occurs when the ratio of the lower gage reading to the upper gage is less than 0.6. The discharge under this condition depends only on the length of crest (width of throat



Weir	*Z*	*h*	*B*	*L*	*A*	*T*	Weight (lb)
Large	1.75	1.00	0.75	4.0	1.0	16 ga.	24
Medium	1.25	.80	.45	3.0	.7	14 ga.	17
Small	.75	.47	.28	2.0	.53	10 ga.	8

Figure 71.—Portable weir plate sizes.

section) and depth of water at the upper gage. Submerged flow occurs when the ratio of the lower gage reading to the upper gage reading exceeds 0.6. When this occurs, a reduction adjustment to the free-flow rating of the flume is needed.

A flume that is properly constructed has an accuracy of 2–3 percent under free-flow conditions, but is less accurate during submerged flow.

A modified Parshall flume was designed by C. A. Taylor and H. C. Troxell in 1931 (fig. 72) and is virtually the same as the Parshall flume

Figure 72.—Modified 3-inch Parshall flume made of sheet iron.

except that it does not have a diverging section and is used only under free-flow conditions. The plans are shown in figure 73 and the rating is given in table 8.

The modified Parshall flume is recommended for general use because of its simplicity, light weight, and ease of installation. However, the regular Parshall flume is also satisfactory.

The flume is installed by placing it in a hole dug in the channel and by filling in around it to prevent any water from bypassing it. A carpenter's level is used to set the floor of the converging section level. Some flumes are equipped with levels attached to the braces on the flume. After the flume is in place, the streamflow is allowed to stabilize before reading the gages. Gage readings indicate flow conditions. The discharge is determined by means of the flume rating.

Volumetric Measurements

The most accurate method of measuring small discharges is by observing the time required to fill a container of known capacity, or the time required to partly fill a calibrated container to a known volume. The basic equipment needed is a calibrated container and a stopwatch.

Calibration is done by weighing the container with varying amounts of water in it,

Table 8.—Rating table for 3-inch modified Parshall flume as designed by C. A. Taylor and H. C. Troxell (1931)

Gage height (ft)	Discharge (cfs)	Gage height (ft)	Discharge (cfs)	Gage height (ft)	Discharge (cfs)
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		

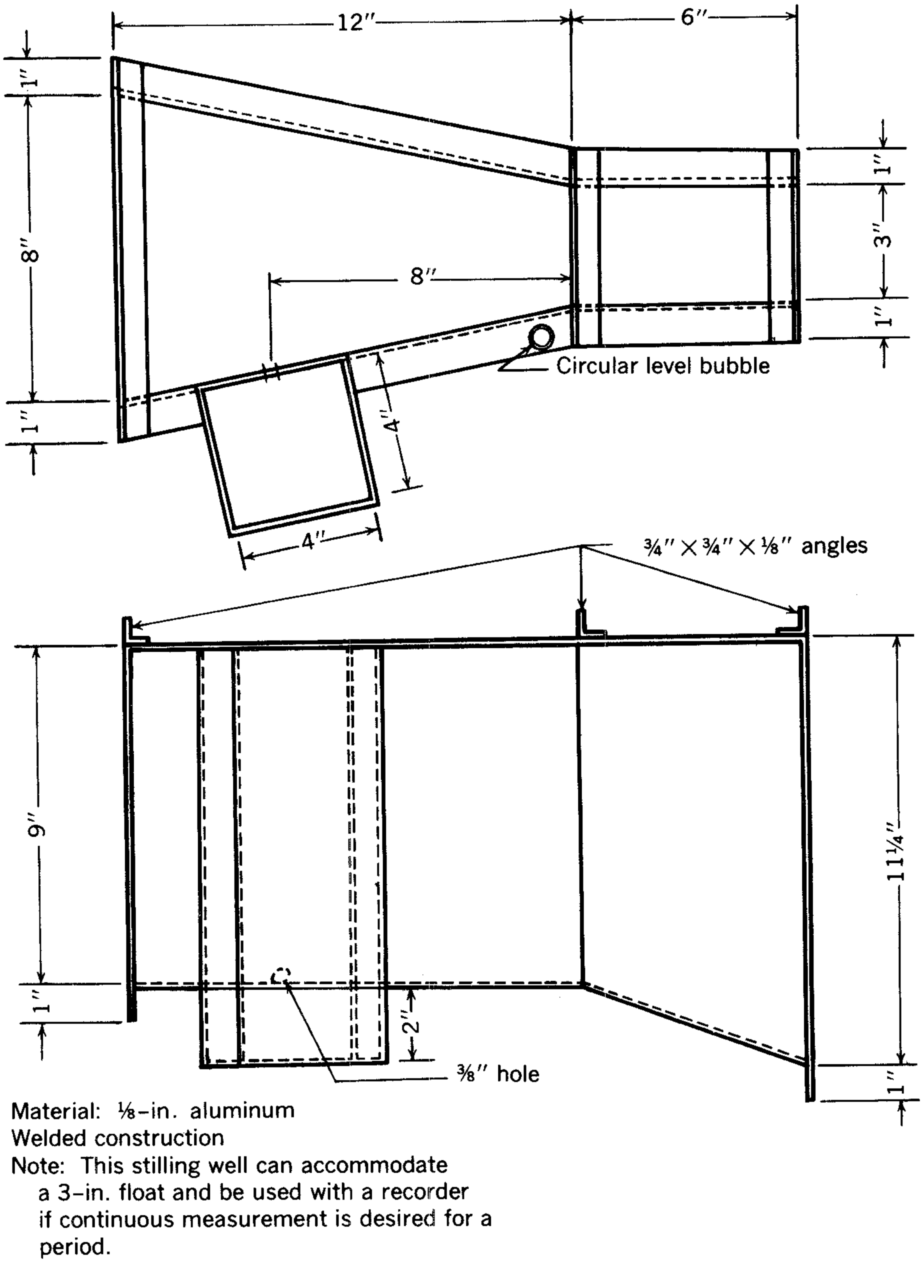


Figure 73.—Working drawing of modified 3-inch Parshall flume.

noting the depth of water in the container, and then using the following formula:

$$V=\frac{W_2-W_1}{w}, \quad (9)$$

in which

V=volume of water in container, in cubic feet,

W_2=weight of container with water, in pounds,

W_1=weight of container empty, in pounds,

w=unit weight of water, 62.4 lb per cu ft (pounds per cubic foot).

Another way to calibrate a container is to add known volumes of water by increments and note the depth of water in the container.

Volumetric measurements are made under two types of conditions:

1. When the flow is concentrated or can be concentrated so that all of it may be diverted into a container.
2. When the depth of water flowing over broad-crested weirs and dams is small and volumetric-increment samples can be obtained.

Measurements are made under the first condition at V-notch weirs, at artificial controls where all the flow is in a notch or catenary, and at places where an earth dam can be built and all the water can be diverted through a pipe of small diameter. Sometimes it is necessary to place a trough against the artificial control to carry the water from the control to the calibrated container. If a small dam is built, the stage behind the dam is allowed to stabilize before the measurement is begun. The measurement is made three or four times to be certain no errors have been made and to be sure the results are consistent.

Volumetric measurements are made under the second condition by catching a segment of the streamflow with a container having a known width of opening. Samples are taken at a number of locations across the dam or weir similar to procedures used for current-meter measurements. The flow rate of each sample is increased by the ratio of the subsection width to the sampled width to obtain a discharge rate for each subsection. The total discharge of the stream is the summation of the discharge rates of each subsection.

Floats

Floats have very limited use in stream gaging, but there are two occasions when they prove useful. A float can be used where the velocity is too low to obtain reliable measurements with the current meter. They are also used where flood measurements are needed and the measuring structure has been destroyed or it is impossible to use a meter.

Both surface floats and rod floats are used. Surface floats may be almost anything that floats, such as wooden disks, bottles partly filled, or oranges. Rod floats are wooden rods weighted on one end so they will float upright in the stream. Rod floats must not touch the streambed. Floating debris or ice cakes may serve as natural floats.

Two cross sections are selected along a reach of straight channel for a float measurement. The cross sections should be far enough apart so that the time the float takes to pass from one cross section to the other can be measured accurately. A traveltime of at least 20 seconds is recommended, but a shorter time can be used on small streams with high velocities, where it is impossible to select an adequate length of straight channel.

The procedure for a float measurement is to distribute a number of floats uniformly over the stream width, noting the position of each. They should be allowed to reach a constant velocity before timing by stopwatch the interval each takes to travel between two cross sections. The distance of each float from the bank as it passes each cross section should also be noted.

The velocity of the float is equal to the distance between the cross sections divided by the time of travel. Care must be taken when measuring low velocities, that the floats are not being affected by wind. The mean velocity of flow in the vertical is equal to the float velocity multiplied by a coefficient which is based on the shape of the vertical-velocity profile and relative depth of immersion of the float. A coefficient of about 0.85 is commonly used to convert surface velocity to mean velocity. The coefficient for rod floats varies from 0.85 to 1.00 depending on the shape of the cross section and the velocity distribution.

The discharge in each partial section is computed by multiplying the average area of the partial section by the mean velocity in the vertical for that partial section. The total discharge is equal to the sum of the discharges for all the partial sections.

Float measurements can be made with an accuracy within 10 percent under good conditions and when a certain amount of care is exercised. If a poor reach is selected and not enough float runs are made, the results can be as much as 25 percent in error.

Indirect Discharge Measurements

During floods, it is frequently impossible or impractical to measure the peak discharges when they occur, because of conditions beyond control. Roads may be impassable; structures from which current-meter measurements might have been made may be nonexistent, not suitably located, or destroyed; knowledge of the flood rise may not be available sufficiently in advance to permit reaching the site near the time of the peak; the peak may be so sharp that a satisfactory current-meter measurement could not be made even with an engineer present at the time; the flow of debris or ice may be such as to prevent use of a current meter; or limitations of personnel might make it impossible to obtain direct measurements of high-stage discharge at numerous locations during a short flood period. Consequently, many peak discharges must be determined after the passage of the flood by indirect methods such as slope-area, contracted-opening, flow-over-dam, or flow-through-culvert, rather than by direct current-meter measurement.

Detailed descriptions of the procedures used in collecting field data and in computing the discharge are given in Benson and Dalrymple (1967), Dalrymple and Benson (1967), Bodhaine (1968), Matthai (1967), and Hulsing (1967), which are book 3, chapters A1–A5, of this series. The use of electronic computers in these computations is explained by Anderson and Anderson [1] and by Somers and Selner.[2]

Dye-Dilution Method of Measuring Discharge

Measurement of discharge by this method depends on determination of the degree of dilution of an added tracer solution by the flowing water. A solution of a stable or radioactive chemical is injected into the stream at either a constant rate or all at once. The solution becomes diluted by the discharge of the stream. Measurement of the rate of injection, the concentration of the tracer in the injected solution, and the concentration of the tracer at a cross section downstream from the injection point permits the computation of stream discharge. The accuracy of the method critically depends upon complete mixing of the injected solution through the stream cross section before the sampling station is reached and upon no adsorption of the tracer on stream-bottom materials. The method is recommended only for those sites where conventional methods cannot be employed owing to shallow depths, extremely high velocities, or excessive turbulence. A detailed description of the procedures and equipment used in measuring discharge by a dye-dilution method is given by Cobb and Bailey.[3]

[1] Anderson, D. B., and Anderson, W. L., Computation of water-surface profiles in open channels: U.S. Geol. Survey Techniques Water-Resources Inv., unpub. data.

[2] Somers, W. P., and Selner, G. I., Computation of stage-discharge relationships at culverts and Computer technique for slope-area measurements: U.S. Geol. Survey Techniques Water-Resources Inv., unpub. data.

[3] Cobb, E. D., and Bailey, J. F., Measurement of discharge by dye-dilution methods: U.S. Geol. Survey Techniques Water-Resources Inv., unpub. data.

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