H-FLUMES FOR MEASUREMENT OF FLOWS OF WATER CONTAINING HIGH CONCENTRATIONS OF SUSPENDED SEDIMENT

JUNE 1970 ARS 41-163
Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE

ACKNOWLEDGMENTS

The authors express appreciation to B. R. Carroll, soil scientist, USDA Sedimentation Laboratory, Oxford, Miss., for performing the mechanical analysis on the sediment used in this study, and to W. O. Ree and Wendell R. Gwinn, Agricultural Research Service, USDA, Stillwater, Okla., for their suggestions, computations, and review of the material presented here.

SUMMARY

A 2-foot H-flume was constructed to standard dimensions and calibrated volumetrically in the hydraulics laboratory. Suspended sediment (98 percent of particles smaller than 0.05 mm.) concentrations in the water used for calibration ranged from 0 to 62,200 p.p.m. Stage-discharge relations at the high sediment concentrations were compared with those obtained using clear water.

Laboratory measurements showed no effect of suspended sediment on the stage-discharge relation at discharges of less than 3 c.f.s. At higher stages (1.1 to 1.5 feet), discharges with suspended sediment were as much as 2 percent lower than corresponding discharges with clear water. This difference, however, is within the accuracy range of the H-flume.

Pressure transducer indications of stage were greater than hook or staff gage measurements for high sediment concentrations. Corrections would be needed for suspended sediment concentrations greater than 60,000 p.p.m. to keep stage determinations accurate to within 2 percent when using a pressure-type indicator. High sediment concentrations in the flume stilling well did not cause significant changes in the flotation line of a water stage recorder float 5 inches in diameter.

At high sediment concentrations, deposits did form in the upstream sections of the H-flume, but no measurable change in the stage-discharge relation was associated with such deposits.

H-FLUMES FOR MEASUREMENT OF FLOWS OF WATER CONTAINING HIGH CONCENTRATIONS OF SUSPENDED SEDIMENT[1]

E. Gordon Kruse and Frank J. Dragoun[2]

In many hydrologic studies, H-, HS-, or HL-flumes are used to measure surface runoff from watersheds. These flumes have the advantages of simple construction, a high degree of accuracy over a wide range of flows, and standard calibrations for the sizes now available.[3] Flume sizes are available to measure discharge rates from 0.0002 to 117 cubic feet per second.

Runoff from watersheds where conservation practices have not been applied may contain large quantities of sediment, either as bed or suspended load. Both forms of transported sediment may affect the accuracy of flow measurement by flumes. Bed, or suspended load, or both, may deposit on the floor of the flume, decreasing the cross section of flow, adding to boundary resistance, and increasing the effective floor slope. Suspended sediment may change the density or viscosity of the flowing fluid, affecting the flume rating directly or indirectly through its pressure effects at the fluid surface in the stilling well. Hermsmeier and Young[4] have studied the effects of suspended sand and sandy loam (particles larger than 0.05 mm.) on flow measured by a 0.6-foot HS-flume.

The studies reported here were intended to determine the effect of suspended fine sediments on H-flume ratings. At the Central Great Plains Experimental Watershed near Hastings, Nebr., experiments were conducted with many H-flumes, on runoff containing sediment particles of silt and clay in concentrations greater than 100,000 p.p.m. If these high sediment concentrations affect H-flume ratings, then using standard, clear-water calibrations will result in errors in runoff measurement.

To measure the effects of suspended sediment on the flume ratings, a 2-foot H-flume was installed in the hydraulics laboratory at Colorado State University, and was calibrated volumetrically with water containing suspended sediment concentrations of as much as 62,000 p.p.m. We wanted to determine the effects of sediment on the stage-discharge relation for the flume, and to measure sediment effects on stage as indicated by staff gages, water stage recorders, and other indicators.

EQUIPMENT AND PROCEDURE

Apparatus

The 2-foot H-flume used in the tests was constructed of 1/2-inch acrylic sheet. Its inside dimensions (fig. 1) are the same as the standard dimensions for this flume,[5] and supports were used to prevent the side walls from bowing or spreading.

The cross section of the stilling well measured 0.236 square foot. Hydraulic connection to the H-flume was made through a vertical row of 1/4-inch-diameter holes drilled at 5/8-inch intervals along the full depth of the flume (fig. 1).

The H-flume was mounted at the downstream end of the test channel, which was similar to a field installation. After the test channel floor had been set at a 2-percent slope, the floor of the H-flume was leveled carefully in all directions. A false floor was fitted flush with the H-flume floor and extended 8 feet upstream in the test channel.

The H-flume studied did not have the cross-sloping false floor often used in the field to concentrate very low flows along the stilling well side. Nor was there any abrupt drop in the approach to the flume, as is often constructed in field installations.

Water and water-sediment mixtures were circulated from the sump pit through the test channel and H-flume by a centrifugal pump that produced discharges ranging from 0.04 to 6 c.f.s. Figure 2 shows the complete laboratory test apparatus.

Discharge from the H-flume dropped into a splitter that normally guided the flow back to the sump pit.

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[1] Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture; Colorado Agricultural Experiment Station cooperating.

[2] Agricultural engineer and hydraulic engineer, USDA, Ft. Collins, Colo., and Coshocton, Ohio, (formerly Hastings, Nebr.), respectively.

[3] Agricultural Research Service, Field manual for research in agricultural hydrology, U.S. Dept. Agr. Agr. Handb. No. 224, pp. 22-23. 1962.

[4] Hermsmeier, L. F., and Young, R. A. Effect of sediment load on the rating curve of 0.6-foot HS-flume, U.S. Dept. Agr., Agr. Res. Serv., ARS 41-142 10 pp. 1968.

[5] See footnote 3.

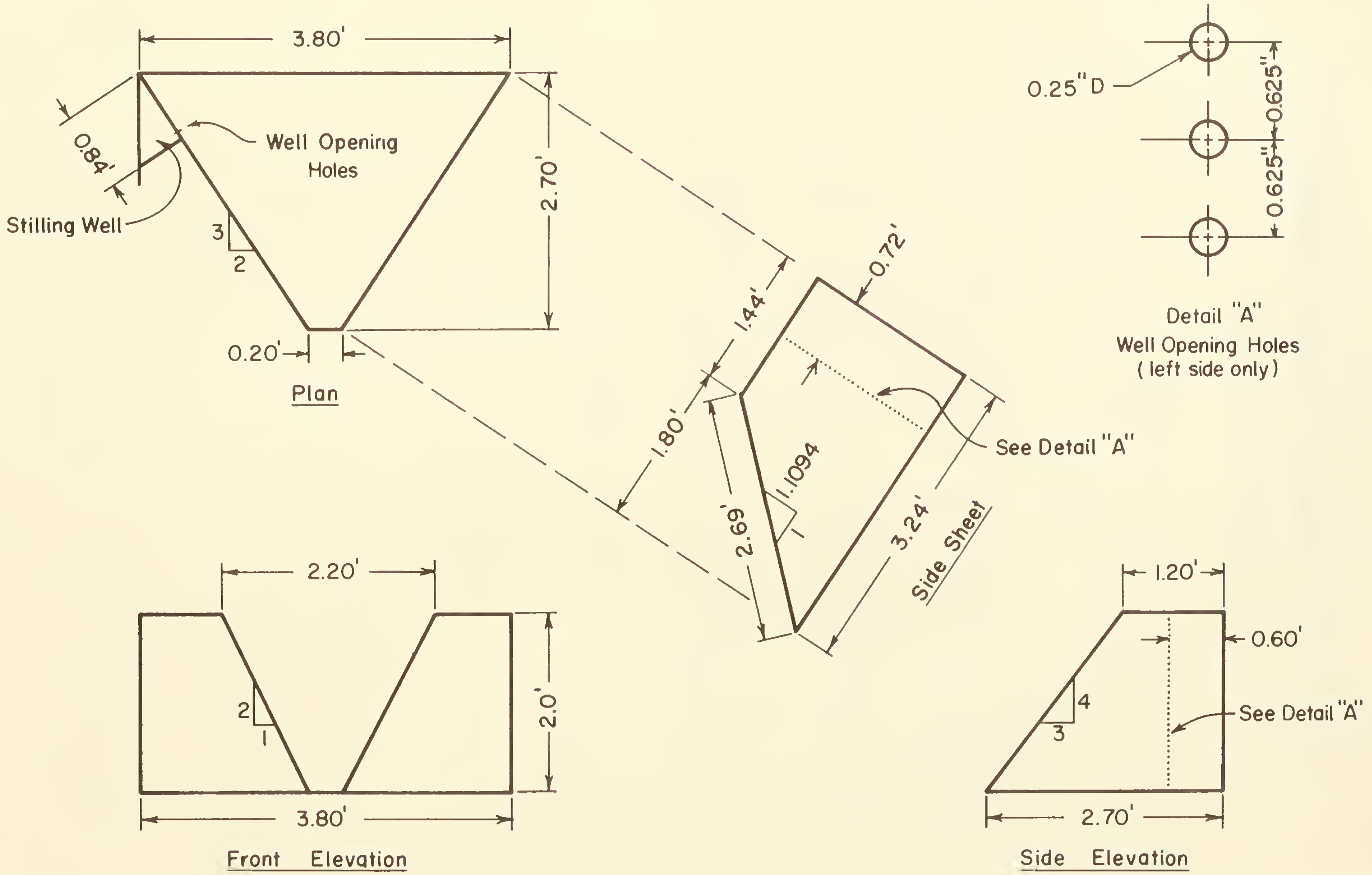

Figure 1.– Dimensions of 2-foot H-flume.

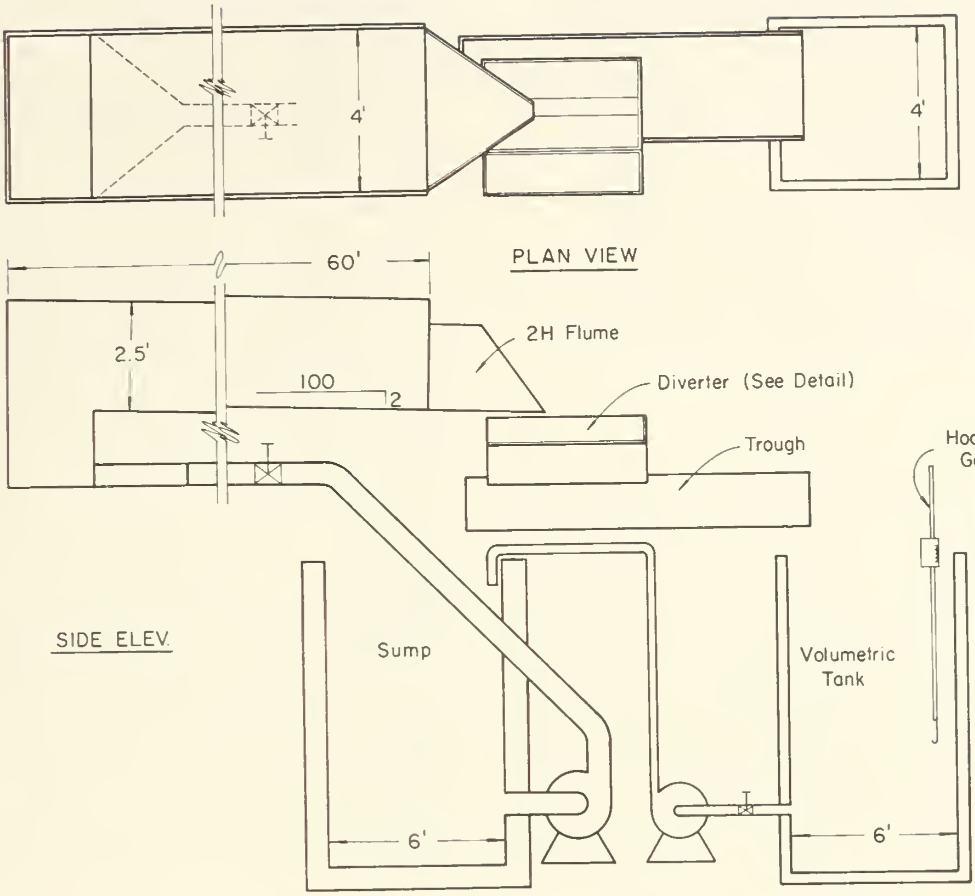

Figure 2.–Laboratory test apparatus.

During measurements, manually activated pneumatic cylinders shifted the splitter to divert the discharge into a trough leading to a volumetric tank. The motion of the splitter along its path automatically activated a microswitch that started and stopped an electric timer, giving a measurement of the time of diversion precise to within 0.01 second. A hook gage, with vernier reading to 0.001 foot, was used to measure the depth of fluid in the volumetric tank before and after diversions.

Depths of flow in the H-flume and the depth of fluid in the stilling well were measured with point and hook gages, respectively, mounted on a carriage on the test channel and zeroed to the H-flume floor elevation.

The total pressure head in the flume and in the well was measured by a pressure transducer-recorder system, connected to small piezometers in the wall of the flume and in the well. Only one transducer, connected through a manifold, was used to monitor all of the piezometers. To calibrate the transducer, we connected it to a cylinder filled with clear water and read water surface elevations with the hook gage. Transducer outputs at two water levels were used to determine a linear equation zeroed to the floor of the H-flume. The calibration was rechecked several times each day.

Sediment

To form the sediment-water mixture, we added a pulverized Hastings silt loam soil to the water in the sump pit and pumped the fluid through the system until it was mixed well. A particle size analysis indicated that the soil is composed entirely of silt and clay (table 1). At higher concentrations, we added about 500 p.p.m. of sodium hexametaphosphate to the fluid to keep the necessary amounts of sediment in suspension.

In spite of all efforts, however, sediment deposited in the approach to the H-flume and downstream to about midway through the flume. We measured the thickness of these deposits periodically.

TABLE 1.–Particle size analysis of Hastings silt loam soil[1]

Particle size range (mm.)	Percentage by weight
Greater than 0.050	1.5
0.050 - 0.005	40.8
0.005 - 0.002	9.0
Less than 0.002	48.6

[1]Size analyses performed at USDA Sedimentation Laboratory, Oxford, Miss.

Procedure

During a typical sequence of measurements, we established a flow of fluid at the approximate rate and sediment concentration desired and continued it until we could detect no change in stage in the H-flume.

Flow depths in the flume and stilling well were measured with the point and hook gage, respectively, and the measurements were averaged. At steady state the flow was diverted to the volumetric tank while transducer readings of stilling levels were recorded. Water levels in the volumetric tank were measured immediately before and after a diversion. Immediately after the flow was switched out of the volumetric tank, a sample of fluid was taken from the throat of the H-flume with a US DH-48 hand sampler.[6] These specimens were then weighed and dried to determine suspended sediment concentration.

At low discharge rates, sampling time was adequate to divert at least 48 cubic feet of fluid to the volumetric tank, producing a 2-foot change in depth. At high discharges, the pump lowered the water level rapidly in the sump pit when water was being diverted to the volumetric tank. The total pumping head thus increased, decreasing the pump discharge. Storage in the test channel caused a lag of several seconds before this decrease in discharge could be noted at the H-flume. Sampling times were limited to about 10 seconds at the highest discharges, so that sampling could be completed before flow changed at the H-flume.

The effects of suspended sediment in a stilling well on water stage recorder readings were determined in the laboratory. A tank of water was located so that a point gage and a water stage recorder with a 5-inch-diameter float could be mounted over the water surface. Recorder and hook gage readings were first taken with clear water in the tank, and then a large concentration of sediment was thoroughly mixed into the clear water and the readings were repeated and compared. At the time of each reading, a hydrometer was used to measure the sediment concentration at the surface of the tank, and samples were collected and dried to check this measurement.

RESULTS

Clear Water Rating

The 2-foot H-flume was first rated with clear water after it had been installed in the test channel. Figure 3 shows the results of this clear water calibration. The solid line represents the standard rating,[7] and the data points show laboratory measurements with the plastic flume. Hook gage readings in the stilling well were used to obtain stage values. At the high rates of flow, the measured discharge is 3 percent less than the standard rating, but it is closer to the standard rating at lower flow rates. The ratings were identical at discharges lower than 3.5 c.f.s. Table 2 presents the data for flows with no sediment.

Flows With Suspended Sediment

The stage-discharge relation for flows with suspended sediment concentrations of as much as 50,000 p.p.m. agrees with the standard rating curve at the lower end of the discharge range (fig. 4). The curves begin to diverge at discharges greater than 3 c.f.s.

At a stage of 1.5 feet, the discharge with sediment in suspension is about 5 percent less than the standard clear water rating, and about 2 percent less than the clear water rating obtained with the laboratory flume.

Extent of Sediment Deposits

Figure 5 shows the depths of deposited sediment in the H-flume and in the approach channel. A hydraulic jump occurred at some point upstream of station 52.2. The supercritical flow upstream of the jump kept that part of the channel sediment free, and increasing effluent velocities near the throat of the flume also

[6]Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation. Operating instructions for US DH-48 suspended-sediment hand sampler, Report J. St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minn. 3 pp. 1958.

[7]See footnote 3.

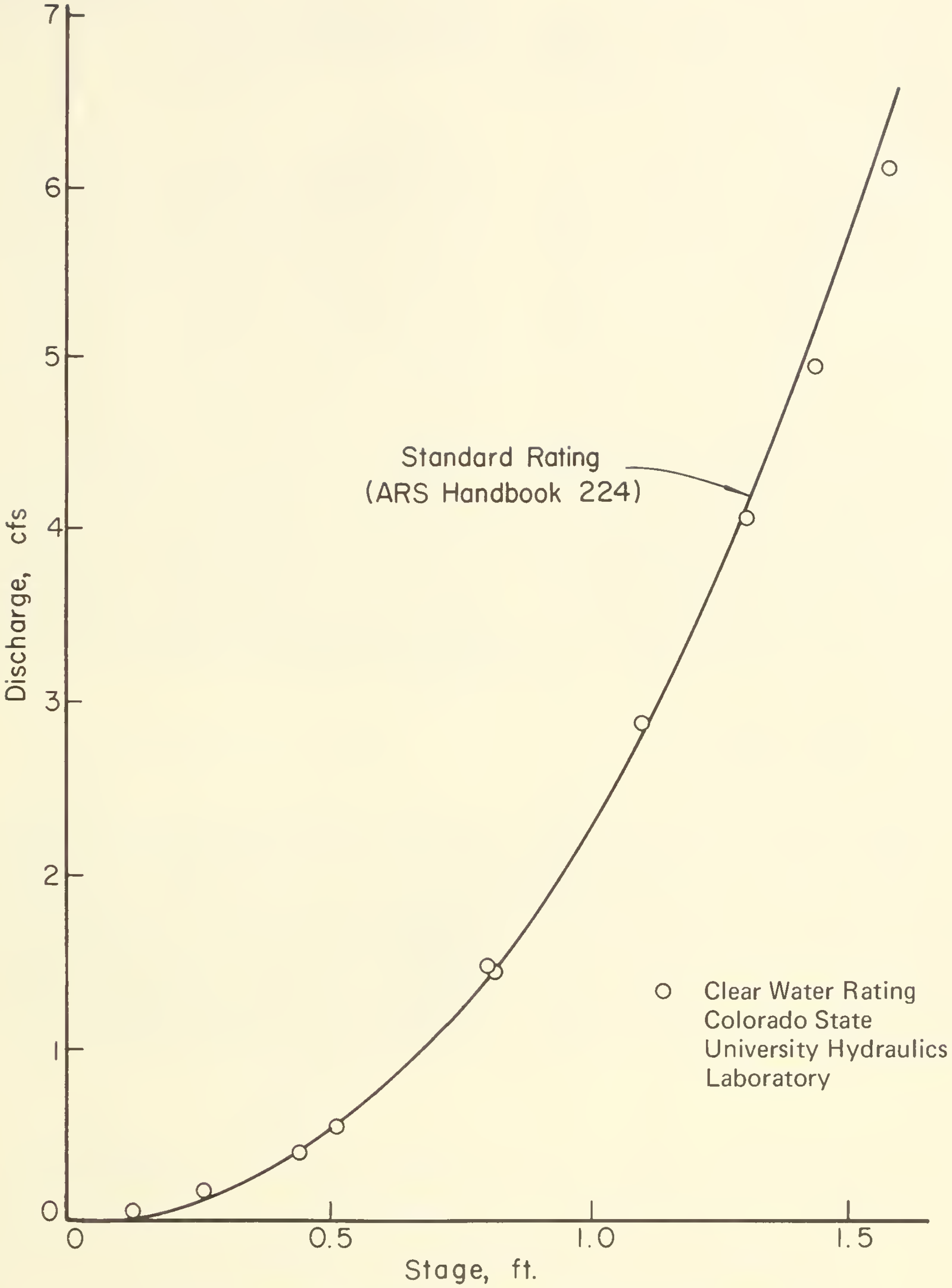

Figure 3.–Rating of 2-foot acrylic H-flume using sump water with no sediment.

TABLE 2.–Rating of 2-foot flume with clear sump water

Run No.	Date	Discharge	Stage	
			Hook gage	Pressure transducer
	6/67	*C.f.s.*	*Feet*	*Feet*
2	14	0.0405	0.131	–
3	14	.401	.447	–
4	14	.148	.267	--
5	14	.556	.521	.525
6	14	1.455	.827	.830
7	14	1.470	.829	.836
8	15	2.887	1.118	1.119
9	15	4.944	1.431	1.432
10	15	4.066	1.304	1.300
11	15	6.081	1.576	1.573
12	15	1.286	–	.771

prevented deposits on much of the floor of the H-flume. The deposits noted for run 21 (fig. 5) penetrated as far into the flume as any noted during the tests.

All deposited sediment was removed twice from the flume and from the approach channel during the series of tests. The times of removal are noted in the log of tests (table 3). The approach channel floor was essentially clear for one or two runs following sediment removal, but then sediment deposits reappeared.

Effect of Sediment Deposits on Flume Rating

The final test of the series was designed to isolate the effects of sediment deposited on the floor of the H-flume during the runs with the highest suspended sediment concentrations. Before the last test, the sump pit was drained and refilled with relatively clear water. The resulting suspended sediment concentration measured 5,700 p.p.m.–much less than for the preceding runs. Deposits in the approach channel were similar to those shown for run 21 (fig. 5). The stage at a discharge of 1.2 c.f.s. under these conditions was exactly the same as the earlier clear water flows, with no deposited sediment in the flume. The sediment deposits apparently did not occur near enough to the throat of the flume to affect the stage-discharge relation.

Stage Indicators

Water stage in the stilling well could be measured with a hook gage, a staff gage, or a diaphragm-type pressure transducer hydraulically connected to the well. Hook and staff gages directly indicated depth of fluid in the well, whereas the pressure transducer was calibrated to indicate equivalent depth of clear water. During each run, the stage was measured with the transducer plus either the hook or staff gage. These readings are compared in figure 6. Positive variation on the abscissa indicates the stage measured with the transducer was greater than that measured with the hook or staff gage.

Sediment suspensions in the stilling well had little effect on water stage recorder readings. For a sediment concentration of 100,000 p.p.m., the recorder indicated a water surface elevation only 0.002 foot higher than would exist with clear water. With a sediment concentration of 23,500 p.p.m., the recorder registered 0.001 foot higher. (In field practice, water levels are generally measured only to the nearest 0.01 foot.)

Viscosity of Water-Sediment Mixture

Suspended sediment in water flowing through an H-flume could affect the flume rating by changing the density or the viscosity of the fluid. A revolving cylinder viscosimeter was used to measure the viscosities of distilled water, the sump water with which the H-flume was rated, and the sump water with sediment concentrations varying between 20,000 and 40,000 p.p.m. Table 4 shows each viscosity and sediment concentration value as the average of two measurements.

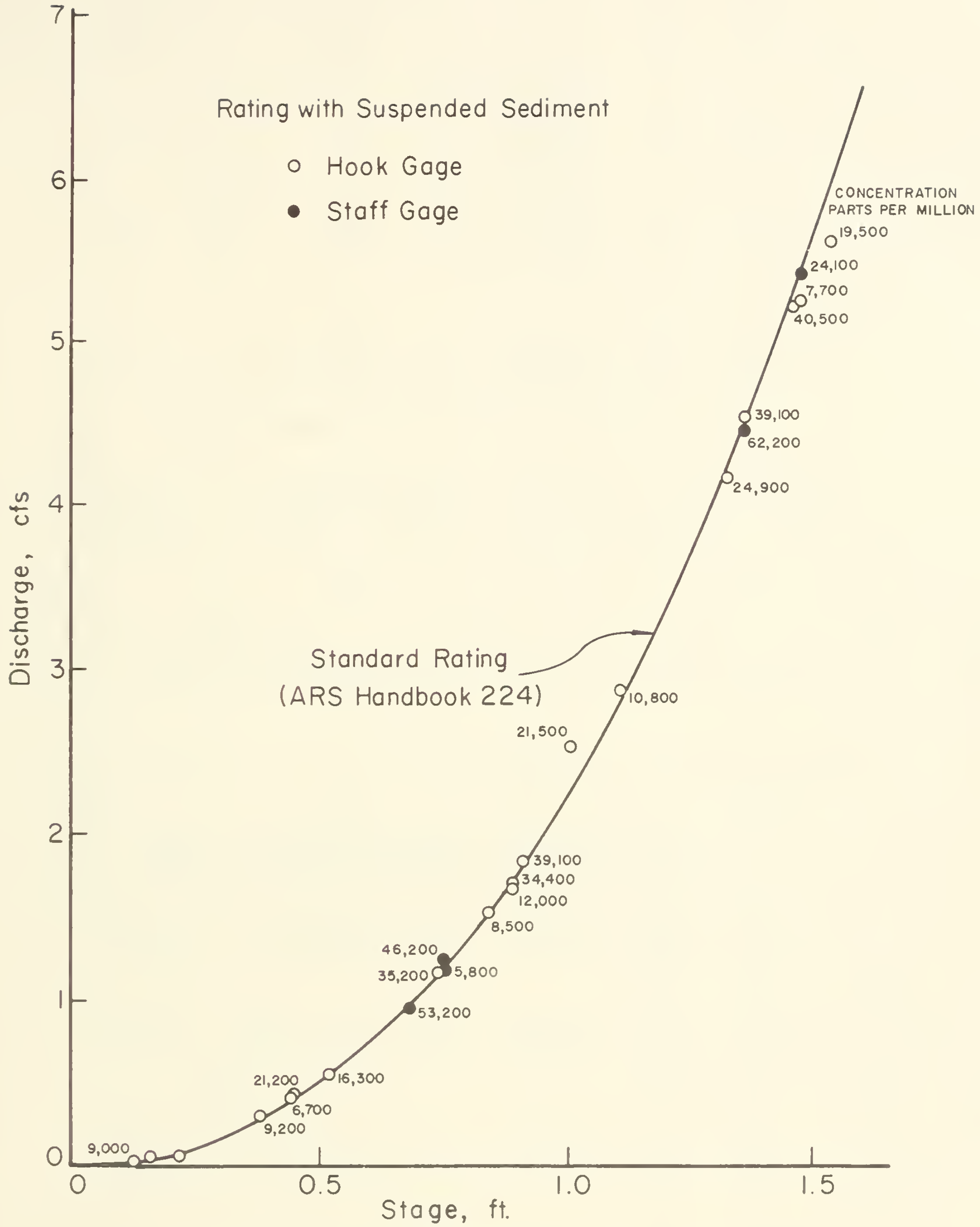

Figure 4.–Rating of 2-foot acrylic H-flume using water with suspended sediment.

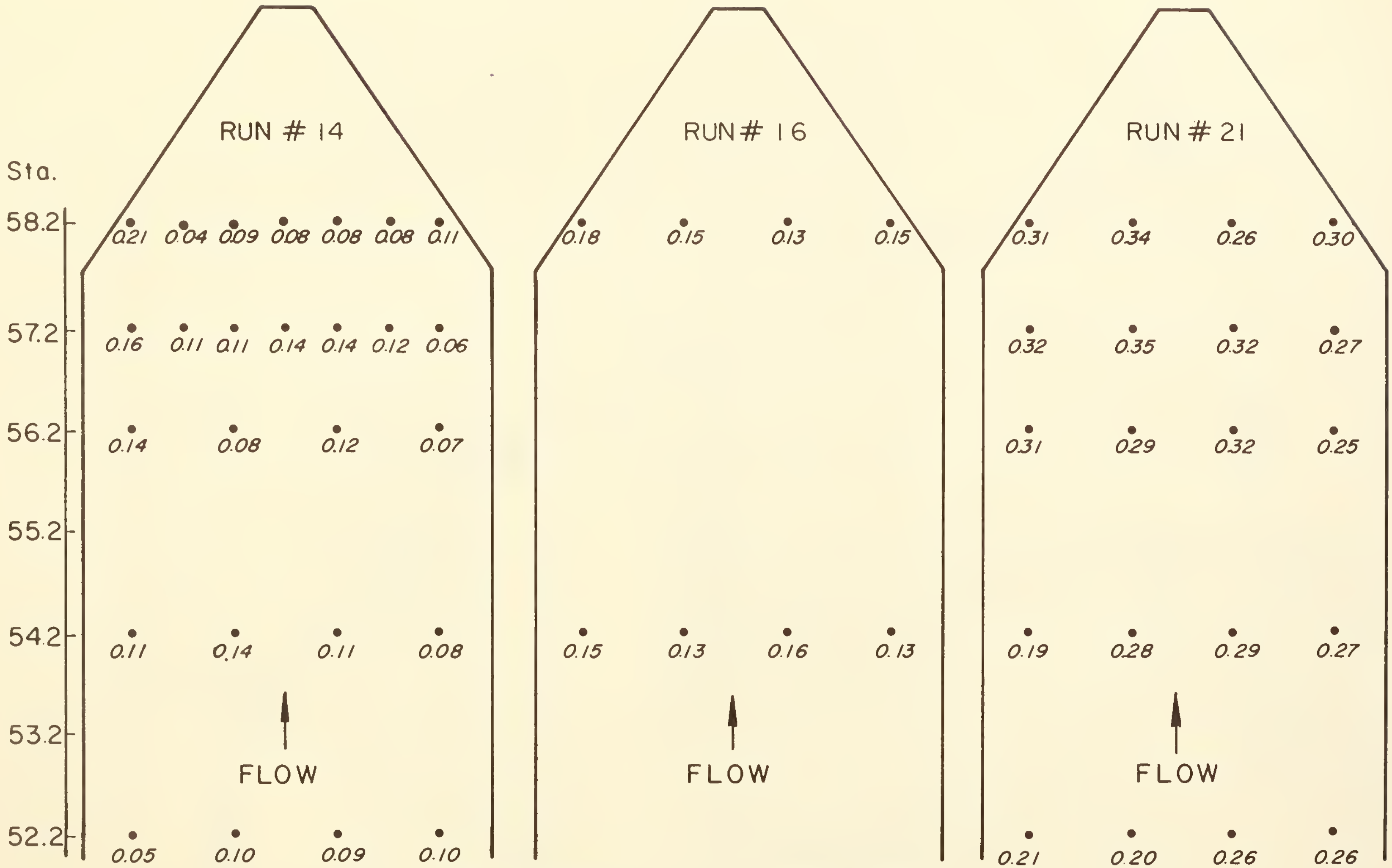

Figure 5.—Depth of sediment deposits upstream of H-flume.

TABLE 3.–Rating of 2-foot H-flume with suspended sediment

Run No.	Date in June 1967	Discharge[1]	Stage				Suspended sediment concentration	Temperature	Remarks
			Point gage	Hook gage	Staff gage	Pressure transducer			
		C.f.s.	*Feet*	*Feet*	*Feet*	*Feet*	*P.p.m.*	°*F.*	
1	16	0.083	--	0.215	–	0.196	–	--	
2	16	3.118	1.160	1.164	–	1.167	10,900	64	
3	16	.395	.444	.444	–	443	6,700	65	
4	16	1.538	.838	.842	–	.844	8,500	63	
5	17	5.240	1.476	1.480	–	1.496	7,700	71	
6	17	.038	--	.122	--	.124	9,000	72	
7	17	.293	.383	.384	.384	.383	9,200	72	
8	17	1.685	.875	.879	--	.863	12,000	72	
9	17	5.603	1.539	1.540	1.50	1.532	13,500	72	Measured sediment deposits
10	17	.039	.143	.150	.123	.185	–	--	Sediment deposits removed after run 10.
11	17	.547	.523	.523	.520	.521	16,300	72.5	
12	17	2.526	1.050	1.054	1.050	1.062	21,500	72.5	15 lb. buffered sodium hexametaphosphate added to water-sediment mixture after run 13.
13	17	4.183	1.329	1.338	1.340	1.344	24,900	73	
14	19	1.84	.912	.913	.915	.912	26,000	70	
15	19	.399	.443	.448	.450	.447	21,200	70	
16	19	4.55	1.360	1.368	1.365	1.383	39,100	71	
17	19	1.709	.883	.891	.890	.893	34,400	71	
18	19	5.203	1.460	1.469	1.460	1.458	40,500	72	
19	19	1.164	.740	.742	.745	.747	35,300	–	
20	19	5.414	--	–	1.485	1.491	24,100	–	
21	19	1.236	--	–	.760	.771	46,200	72.5	
22	20	4.462	--	--	1.37	1.432	62,200	73	Sediment deposits removed after run 21.
23	20	.991	--	–	.695	.706	53,200	73	
24	20	1.201	--	–	.750	.745	5,800	73.5	

[1] Some of sample was lost during flows in excess of about 4 c.f.s.

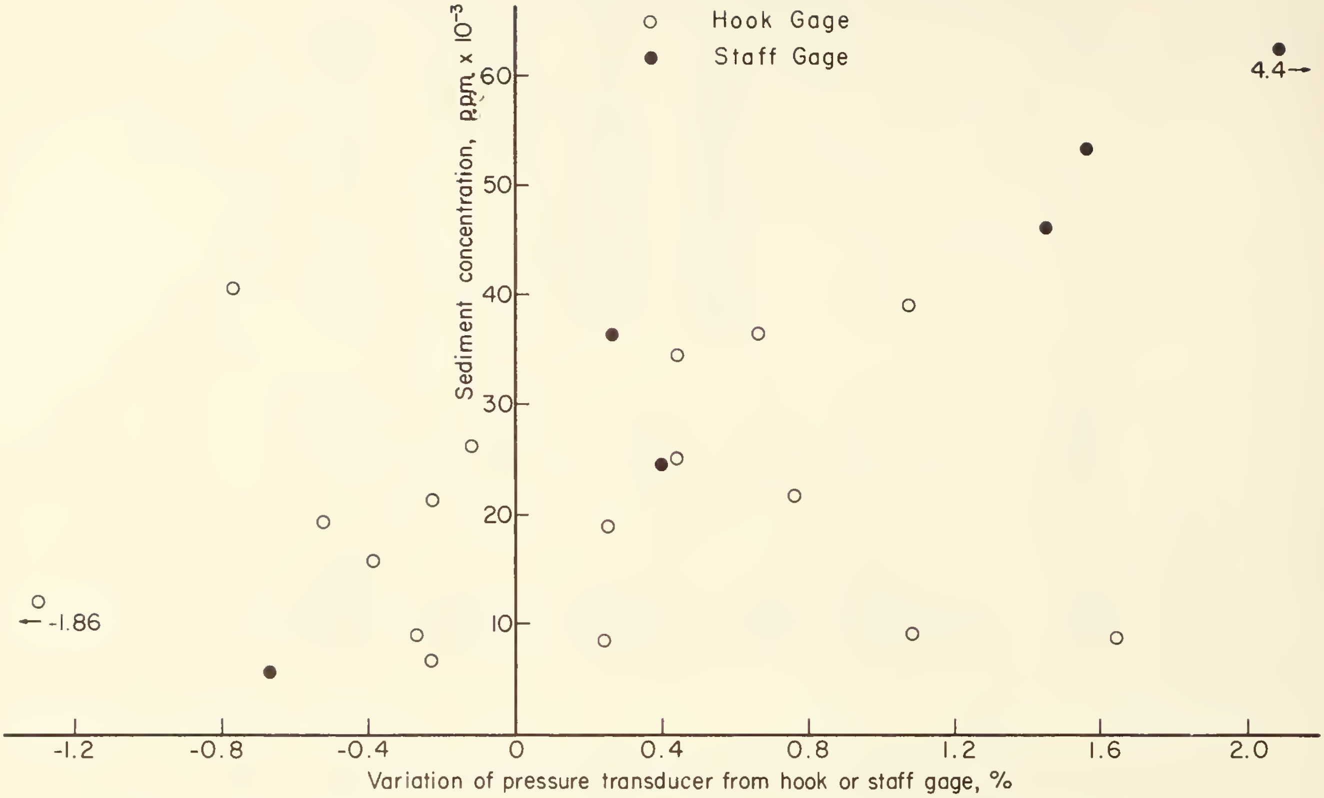

Figure 6.–Comparison of water stage readings with pressure transducer and with hook or staff gage readings in stilling well.

TABLE 4.–Viscosities of suspension of Hastings silt loam soil in water

Sediment concentration, p.p.m. (in sump water)	Viscosity, relative to distilled water[1]
0	1.028
21,600	1.028
21,800	1.023
30,600	1.039
39,500	1.057

[1]Temperature of fluid–25° C. for all measurements.

DISCUSSION

Sediment Concentration in Stilling Well

A theoretical development of the relation between stage and volumetric rate of discharge through a critical depth measuring flume would indicate that fluid density or viscosity changes have no effect on the relation.[8] However, the effects of higher fluid density on various stage-measuring devices may influence the indicated discharge. Also, flow measurement might be affected if the density of the fluid in the flume stilling well differed from that of the flowing water.

Sediment samples were taken from the surface of the stilling well and compared with the samples taken in the throat of the flume. The concentrations in the well were less than in the flowing water, because some sediment was deposited in the stilling well as soon as the fluid was abstracted from the turbulent flow in the flume. The

[8]Rouse, H. Fluid mechanics for hydraulic engineers. Engin. Soc. Monog., Dover (unabridged and corrected republication), 422 pp. 1961.

suspended concentration in the well probably would not decrease continuously because the multiple holes connecting the well to the flume allow some circulation between flume and well, even during periods of constant stage. Fluid density differences resulting from deposition of sediment in the well could cause such circulation.

Stage values obtained during the runs did not indicate any errors caused by density difference. The differences in the stage values were less than 0.01 foot, and errors in discharge determination caused by stage variations of this magnitude are negligible.

Stilling Well Intake Ports

When the flow is pulsating, as it seemed to be at the higher discharges, a bias can develop in the gage well level if the discharge coefficients of the orifices are not the same on both sides of the flume wall. If it is easier for the fluid to flow out of the well than in, the stage in the well would tend to be a little lower than in the flume. However, this was not considered to be a problem in this experiment.

Volumetric Measurements

Suspended sediment did not affect the flume rating curve for discharges below 3 c.f.s. At higher discharges, the rate of flow at a given head dropped as much as 5 percent below the standard value and 2 percent below the clear water laboratory rating. The deviation may not be significant, however, because the deviation of individual points does not seem to be related to the sediment concentration that they represent. For example, in figure 4, points that represent flows with relatively low sediment concentrations of 19,500 and 7,700 p.p.m. fall to the right of the clear water calibration, while those with concentrations of 39,100 and 62,200 p.p.m. fall on the line.

At high discharge rates, excessive splashing in the diversion trough caused some fluid to be lost between the splitter and the volumetric tank. Such errors tend to be systematic and should be of the same magnitude and direction for similar discharges—with and without sediment.

Discharge through H-flume can be represented by the equation:

$$Q = \tfrac{1}{2} CWH^{3/2}$$

where Q is the discharge in c.f.s.,
C is a discharge coefficient, and
W is the width of the flume throat at a stage equal to H, in feet, and H is the head in the flume at the measuring section (feet).

Gwinn[9] used standard rating tables to develop a coefficient curve for H-flumes by relating C to H/D, where D is the depth in feet of the H-flume. Except for low flows, Gwinn found C to be constant for any given H/D ratio, regardless of the size of the flume.

The C values corresponding to the respective H/D ratios for both the clear and sediment-laden water were computed from values in tables 2 and 3. For the clear water readings the hook gage values for the head were used. For the sediment data the point gage readings were used. We believed that the point gage data were closer to the true values for the sediment-laden flows because the sediment concentration in the well was less than that of the flow in the flume, and the fluid in the gage well tends to remain higher than in the flume. Because of the holes drilled all the way up the side of the flume, however, mixing would have taken place through the intake holes until the fluid levels stood at nearly the same elevation. The only difference would be in the part of the fluid in the well above the last hole submerged.

Figure 7 shows the computed points and the constant C curve. Assuming that the flume was dimensionally precise, we can draw these conclusions from this figure: the sediment in the water does not affect the discharge rating; and the volumetric discharge measurements at the large flows ($H/D > 0.5$) were in error and on the low side.

Water Stage Readings

When comparing hook gage with pressure transducer measurements, one should remember that with high sediment concentrations, the specific gravity of the fluid in the stilling well will be greater than unity. The higher specific gravity will not affect hook or staff gage readings, but will affect the pressure transducer measurements. Figure 6 shows that the transducer readings tend to be greater than hook or staff gage readings at the higher sediment concentrations, indicating the greater fluid density at these concentrations. Other than experimental error, no explanation exists for the negative variation at low concentrations.

Hook gage readings of stage in the stilling well were higher than readings of stage in the flume. However, the magnitude of the difference in readings seemed to be random, being unrelated to the magnitude of the stage reading or to the suspended sediment concentration. The difference may be explained by errors in reading stage in the flume with the point gage because of waves on the water surface. The difference may also be explained by a slight superelevation of the water surface at the sides of

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[9]Gwinn, W. R., and Ree, W. O. (Personal Correspondence) Agricultural Research Service, USDA, Stillwater, Okla. 1968.

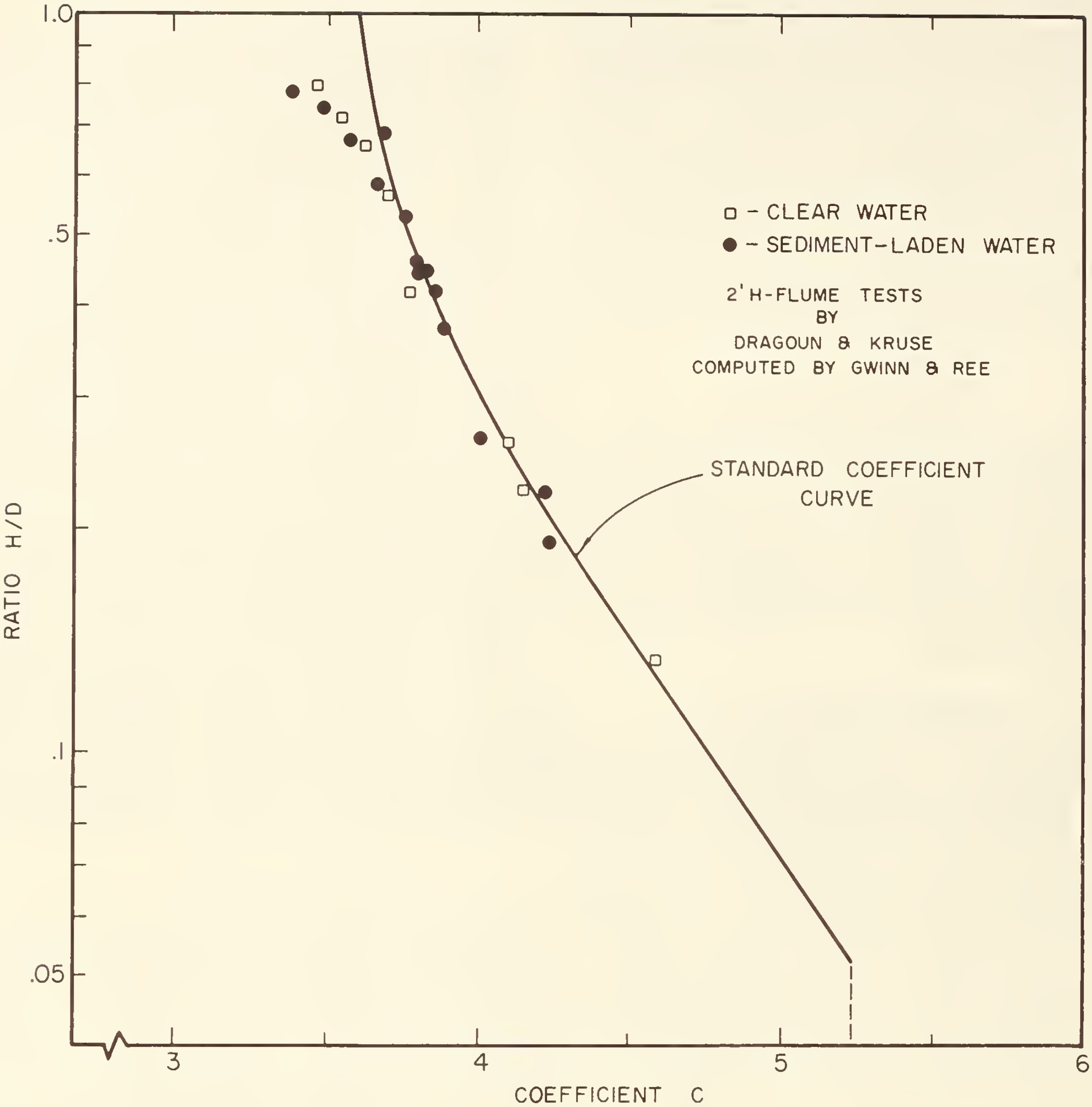

Figure 7.—Standard coefficient curve for H-flumes.

the flume as the flow is deflected toward the center. All hook gage readings in the stilling well were made under good lighting conditions.

For some flows, waves traveling the flume caused the water surface in the well to fluctuate 0.05 to 0.1 foot. Under such conditions, several readings were taken and averaged to obtain the water surface elevation. These values were used to plot the stage-discharge relations in figures 3 and 4.

Sediment Deposits

Effects of sediment deposits on flume ratings were determined by comparing runs with discharges of the same magnitudes and similar suspended sediment concentrations. The stage-discharge relations for one such pair of runs, No. 3 (with deposits) and No. 7 (without deposits), varied the same amount from the standard rating (table 5). The same was true for run 11 (without deposits) and run 15 (with deposits). After run 21, deposits were removed for 5 feet upstream from the lip of the flume. There was no difference in the stage-discharge relations for run 18 (with deposits, 40,500 p.p.m.) and run 22 (without deposits, 62,200 p.p.m.). The discharge from run 20, with deposits similar to those for run 18 but only 24,100 p.p.m. sediment, was slightly greater than the clear water rating.

Sediment deposits at low flows can cause considerable error in the field, as they did in this study. As

TABLE 5.–Effect of deposited sediment on rating curves

With Deposits			
Run	Discharge	Sediment Concentration	Deviation discharge from standard
	C.f.s.	*P.p.m.*	*Percent*
3	0.395	6,700	-1.25
15	.399	21,200	-2.68
18	5.203	40,500	-0.61
21	1.236	46,200	0

Without Deposits			
Run	Discharge	Sediment Concentration	Deviation discharge from standard
	C.f.s.	*P.p.m.*	*Percent*
7	0.293	9,200	-2.33
11	.547	16,300	-2.32
22	4.462	62,200	-1.55
23	.706	53,200	-2.94

indicated for run 10, table 3, the staff gage and pressure transducer show strange readings. This was caused by sediment deposits in the stilling well and in the flume. In the well, the buildup of sediment gave a false depth, and the flow in the flume was diverted away from the staff gage.

Hermsmeier and Young[10] indicated discharge errors of as much as 30 percent in an HS flume when large quantities of sand or sandy loam soil were being transported by the flow. In their study none of the transported material was smaller than 0.05 mm., whereas in our study only 1.5 percent was greater than 0.05 mm. They attributed the discharge errors to changes in effective slope and elevation of the flume floor caused by deposited sediment, rather than to the effects of suspended sediment. In our study, not enough sediment was deposited on the floor of the flume to cause such effects.

[10] See footnote 4.

Volume of Sediment

Although an H-flume or other flow-measuring device may be recording accurate discharge values, these values may not be an accurate measure of the volume of water. If, for example, the fluid being measured contained 100,000 p.p.m. of sediment, the liquid phase of the volume being measured would be only about 96 percent of the total. The other 4 percent would be solids. With higher concentrations of sediment, the percentage of water in the mixture would be even smaller. If the volume of solids were not considered, the output (runoff) on some field studies could exceed the input (rainfall).

Experimental Difficulties

Any further calibrations of this nature should incorporate a drop from the supply channel to the flume approach. High sediment loads could then be kept in suspension in the supercritical flow upstream of the drop. Turbulence should prevent the sediment from being deposited between the drop and the measuring flume.

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