Type II, critical-flow, large-width reduction flumes are illustrated in Figure 14 and differ from Type I flumes only in that the throat contraction is sufficient to ensure that critical flow is achieved. This gives the advantage of requiring measurement at only one location, which may be either in the immediate approach to the flume or in the throat. Measurement in the approach will yield a more sensitive stage-discharge relationship because changes in discharge will result in greater changes in depth in subcritical flow than would like changes in discharges in critical flow. Unfortunately, the stage-discharge relationship in the approach may be unstable due to approach conditions such as scour and fill. Consequently, stage is usually measured in the throat to alleviate influence from either upstream or downstream. Approach conditions can have some effect on flow in the throat, but it is generally insignificant. The site at which critical depth is first reached may shift further downstream into the throat as a result of excessive deposition in the approach. For this reason, and to avoid possible flow separations near the entrance, stage measurements in the throat should not be too close to the entrance. Flow close to critical is very unstable, constantly attempting to become either subcritical or supercritical. Therefore, this type of flume is seldom encountered in practice.

Type III, tranquil-flow, small-increase-in-bed elevation flumes are shown in Figure 15. Because of the requirement for dual gaging points and the partial barrier to the approaching flow, which will encourage deposition of suspended solids, such designs are not commonly used.

Type IV, supercritical-flow, width-reduction, steep-slope flumes are illustrated in Figure 16. For flumes that have bed slopes of near zero, critical depth is the minimum depth possible in the flume. Further contraction, either at the sides or bottom, will not produce supercritical flow. This can be accomplished only by increasing the available specific energy from the approach into the throat. For Type IV flumes, the bed is placed on a slope sufficient to cause the required increase in specific energy to produce supercritical flow in the throat. It may be thought of as a Type II flume tilted in the downstream direction. Only a single gaging point is required.

Type V, supercritical-flow, width-reduction, drop-in-bed flumes are depicted in Figure 17. Here the increase in specific energy required to achieve supercritical flow is provided by a sudden drop in the bed. Measurement of head is made either in the throat or the approach. A discharge rating based upon measurements in the region of supercritical flow, while not as sensitive as compared with measurements in subcritical flow, is the least influenced by disturbances either upstream or downstream, and hence is apt to be the most stable. Similarly, such flumes are the most capable of stable operation up to high submergences.

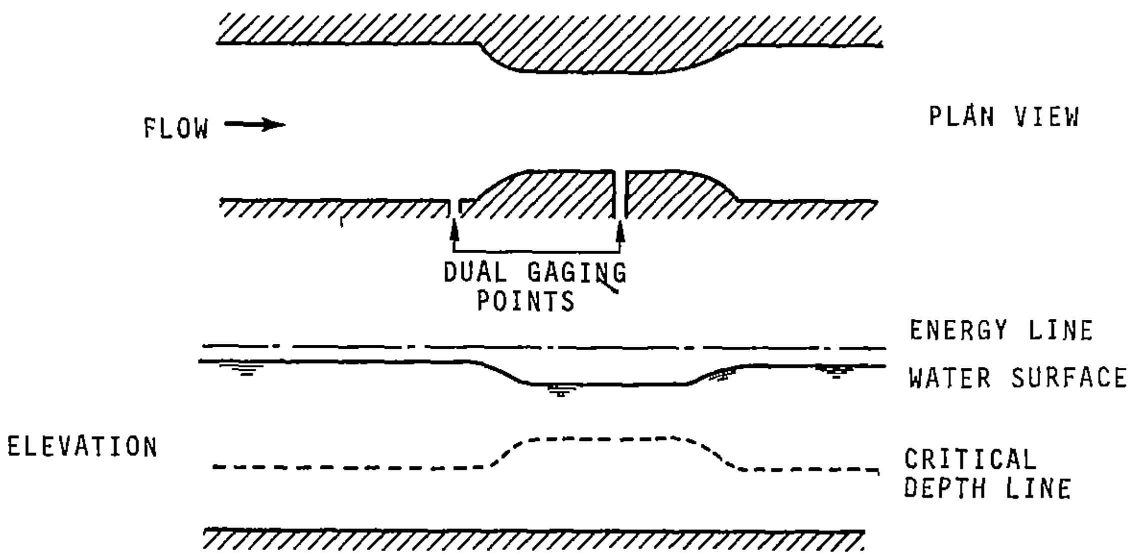


Figure 13. Type I Flume - Critical Flow Contraction Obtained by Small Width Reduction, Horizontal Bed

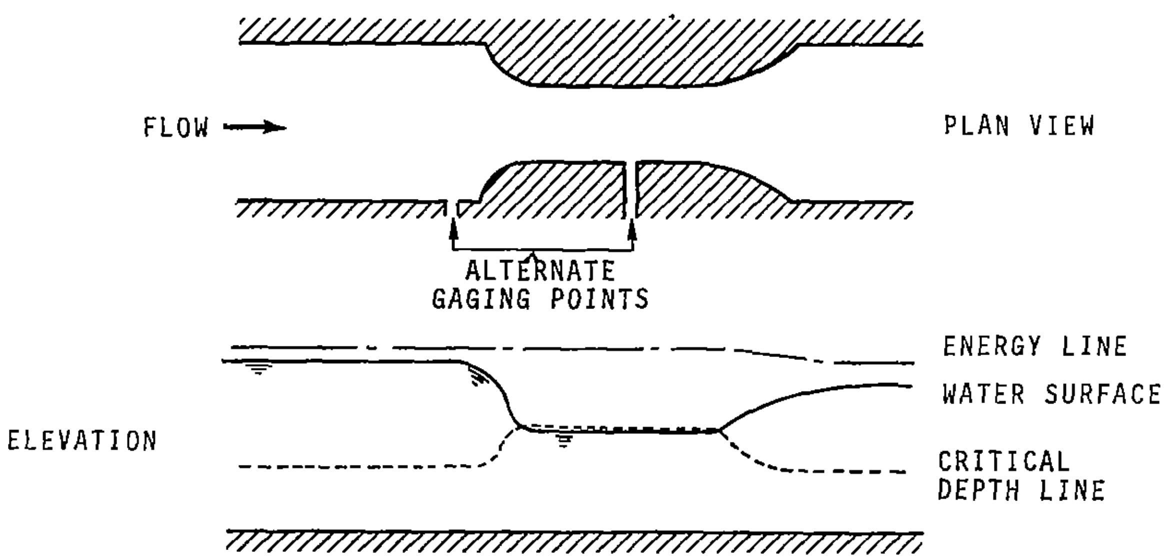


Figure 14. Type II Flume - Critical Flow Contraction Obtained by Large Width Reduction, Horizontal Bed

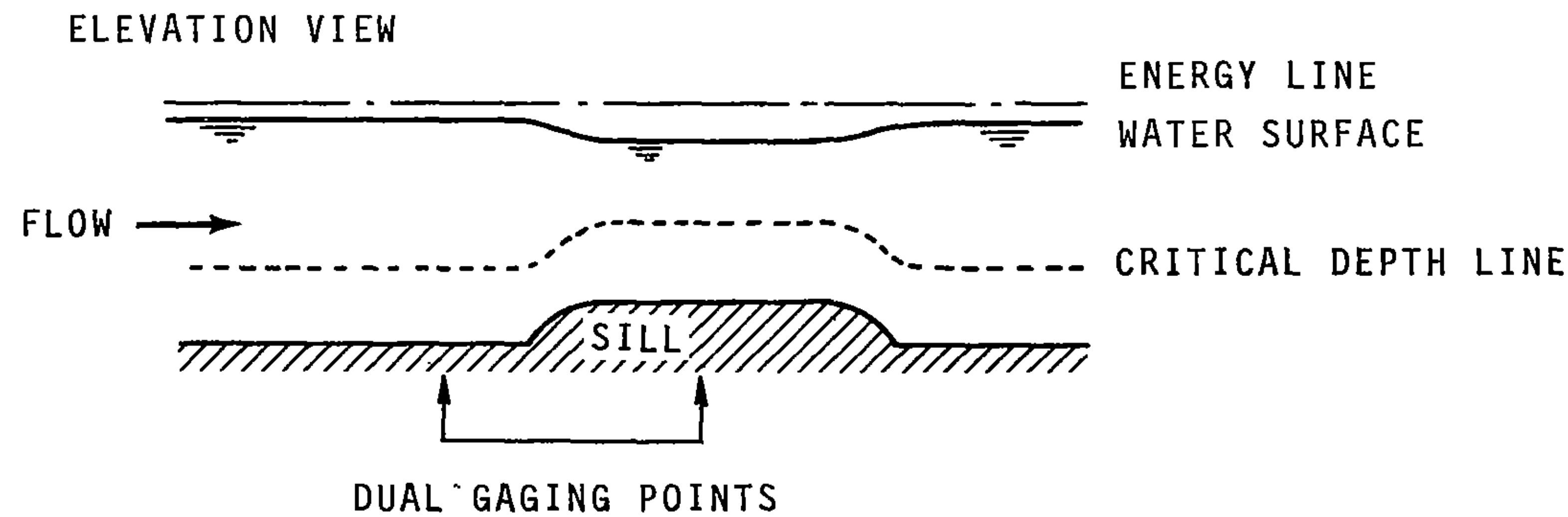


Figure 15. Type III Flume - Subcritical Flow Contraction Obtained By Small Increase In Bed Elevation, Horizontal Bed

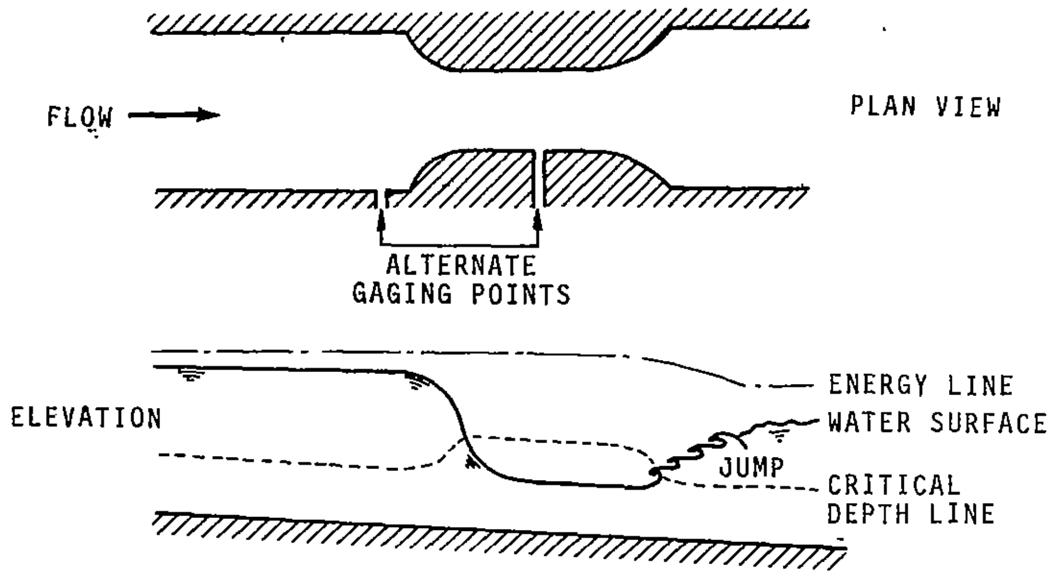


Figure 16. Type IV Flume - Supercritical Flow Contraction Obtained by Width Reduction and Sloping Bed

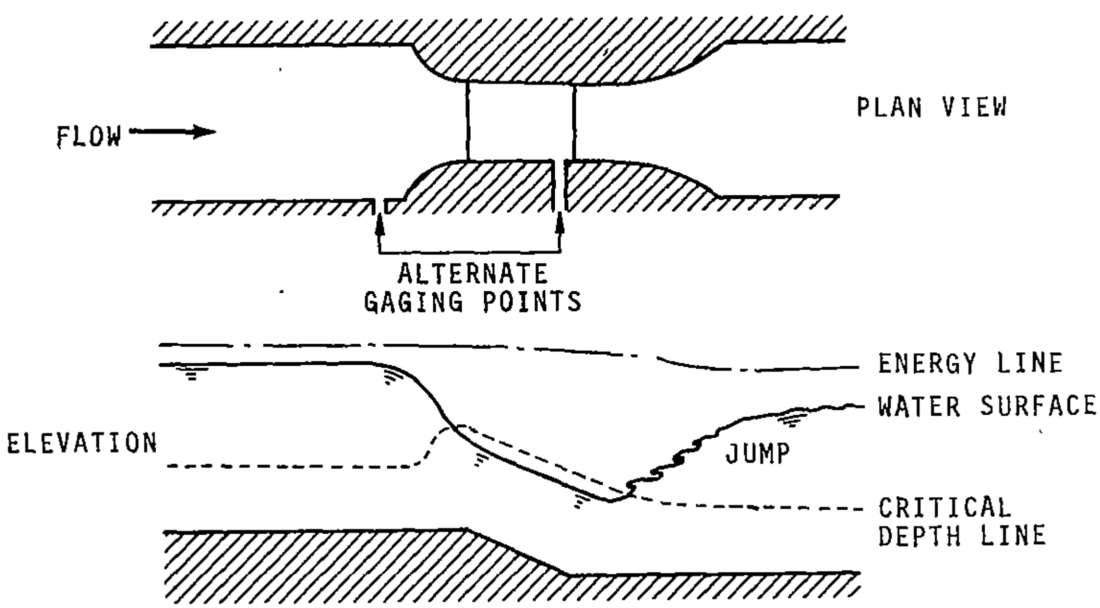


Figure 17. Type V Flume - Supercritical Flow Contraction Obtained by Width Reduction and Drop in Bed

Type VI, supercritical-flow, steep-slope flumes are illustrated in Figure 18. Here there is no contraction, the increase in specific energy necessary for achieving supercritical flow being produced simply by producing sufficient downstream slope. Although a slope of one degree is usually sufficient to produce critical depth in the vicinity of the upstream edge of the apron, waves and disturbances are apt to be numerous downstream. For this reason slopes on ordinary concrete aprons will more typically range from 2 to 5%.

Site Selection - A few recommendations for the selection of gaging sites apply in general to all types of commonly-encountered flumes. The flumes should be located in a straight section of channel without bends immediately upstream. The approaching flow should be well distributed across the channel, and relatively free of turbulence, eddies, and waves. Generally, a site with high velocity of approach should not be selected. But, if the water surface just upstream is smooth with no surface boils, waves, or high-velocity current concentrations, accuracy may not be greatly affected by velocity of approach.

Consideration should be given to the height of upstream banks, noting their ability to sustain the increased depth caused by the flume installation. Although less head is lost through flumes than over weirs, particularly if flat-bottomed flumes are used, losses may be significant with large installations. The possibility of submergence of the flume due to backwater from downstream must also be investigated, although the effect of submergence upon the accuracy of most flumes is much less than is the case with weirs.

Subcritical (Venturi) Flumes - Subcritical flumes are called true venturi type flumes by some researchers, e.g., Replogle (8), probably because of their requirement for the measurement of flow levels at two positions. The Type I and III flumes discussed earlier are examples of designs of such devices. Because of their advantage of requiring only a single measurement, supercritical flumes are generally preferred design approaches and, consequently, subcritical flumes are not often installed today. They are evaluated in Table 13.

Parshall Flume - The development of many early flumes arose from the need to measure irrigation flows, and the Parshall flume is no exception. The earlier designs were Types I, II, and III flumes, and the essential change introduced by Parshall was a drop in the floor which produced supercritical flow through the throat (Type V). Today the Parshall flume is the most widely used primary device in the head-area classification for the measurement of sewage and other wastewater. The configuration and standard nomenclature for Parshall flumes is given in Figure 19. For a given throat width (W), all other dimensions are rigidly prescribed. Since the rating tables for Parshall flumes are based upon extensive and meticulous research, faithful adherence to all dimensions is necessary to achieve accuracy.

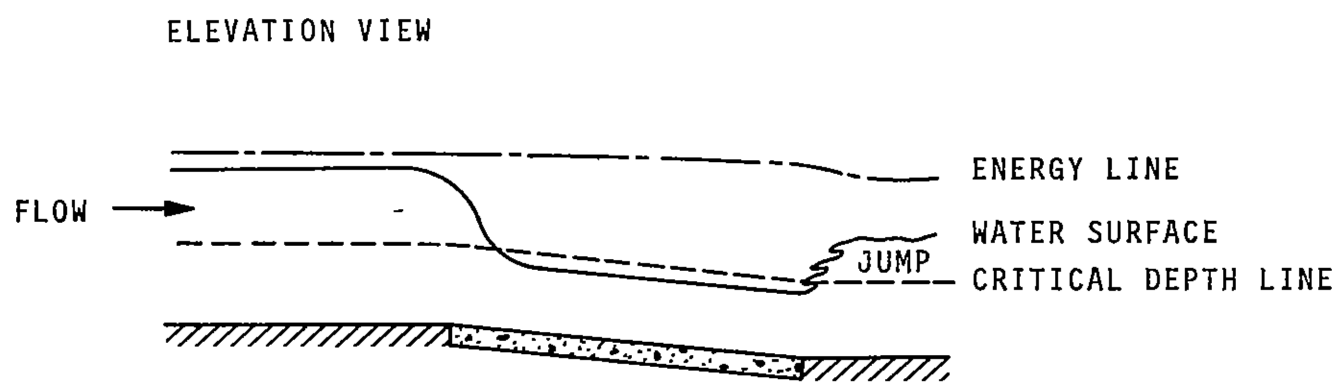
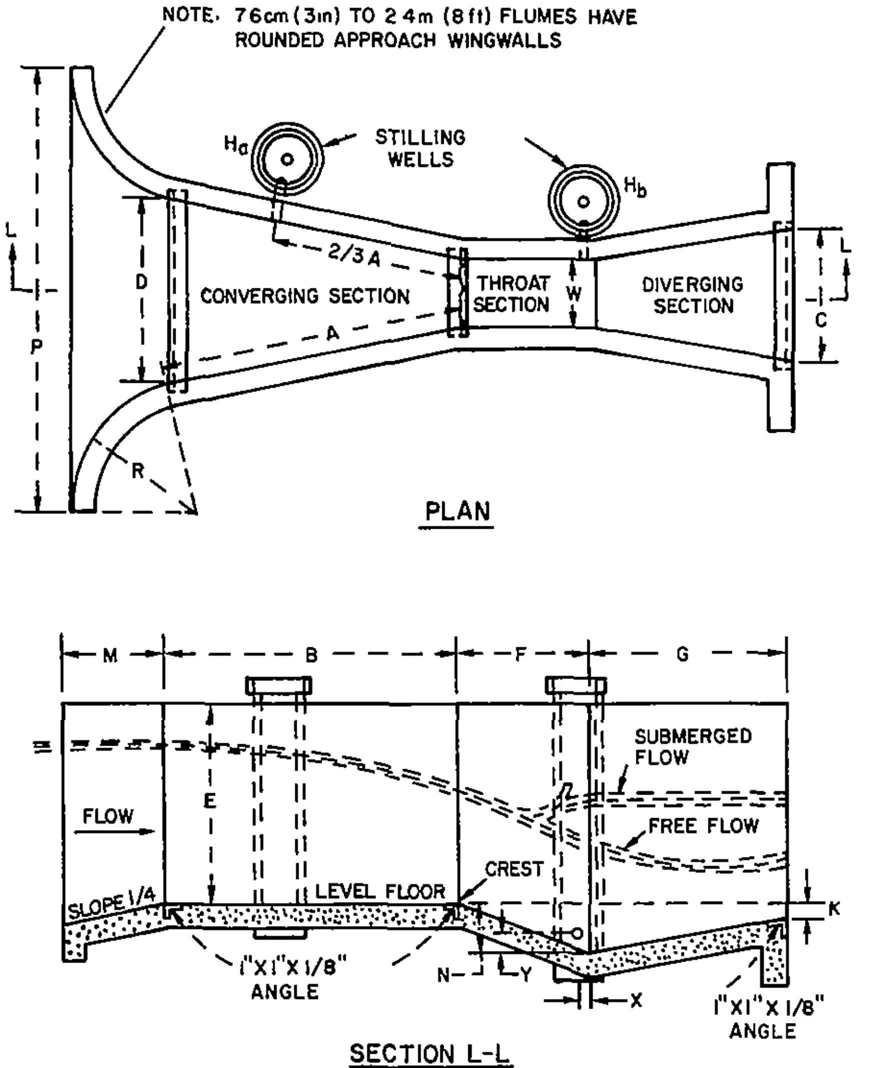


Figure 18. Type VI Flume - Supercritical Flow Contraction Obtained By Steepening Slope

TABLE 13. SUBCRITICAL (VENTURI) FLUME EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☒ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☒ Medium	☐ Low
25	Portability	☒ No		☐ Yes



LEGEND:

W	Size of flume, in inches or feet.
A	Length of side wall of converging section.
2/3A	Distance back from end of crest to gage point.
B	Axial length of converging section.
C	Width of downstream end of flume.
D	Width of upstream end of flume.
E	Depth of flume.
F	Length of throat.
G	Length of diverging section.
K	Difference in elevation between lower end of flume and crest.
N	Depth of depression in throat below crest.
R	Radius of curved wing wall.
M	Length of approach floor.
P	Width between ends of curved wing walls.
X	Horizontal distance to H_b gage point from low point in throat.
Y	Vertical distance to H_b gage point from low point in throat.

Figure 19. Configuration and Standard Nomenclature for Parshall Flumes

The earlier Parshall flumes were developed in sizes (throat widths) ranging from 7.6 cm (3 in.) to 2.4m (8 ft). More recently, Robinson (29) has calibrated Parshall flumes of 2.5 cm (1 in.) and 5.1 cm (2 in.) in size. Flumes with throat widths of 3 to 15m (10 to 50 ft) have been constructed and field calibrated. Head-discharge ratings are thus available for a large range in throat width. Table 14 is presented to give the reader a "feel" for the dimensions and capacities of all sizes of standard Parshall flumes.

Flow through a Parshall flume may be either free or submerged. In free flow, only the upstream head (Ha) need be measured, and this condition is favored for accurate measurement. Where free-fall conditions exist for all flows, the downstream (Hb) may be omitted and the entire diverging section left off if desired, assuming channel erosion is no problem. This simplification has been used in the design of small portable Parshall flumes.

Submerged flow exists when the water surface elevation downstream of the flume is high enough to affect the head and retard the rate of discharge. The degree of submergence is indicated by the ratio of the downstream head to the upstream head (Hb/Ha). If the ratio is greater than 0.6 for flumes under 0.3m (1 ft) or 0.7 for flumes in the 0.3 to 2.4m (1 to 8 ft) range, flow must be considered to be submerged and corrections must be made according to the degree of submergence. A complete treatment of the subject is given by Skogerboe, et al (30, 31).

Small solids in suspension are readily carried through Parshall flumes and do not affect the measurement accuracy, which should range between 1.5 percent (virtually the best obtainable) to 5 percent (more typical of good field installations). Errors greater than this are frequently found, the chief causes being either dimensional inaccuracies or improper flow conditions. Although Parshall flumes are self-cleaning, large rocks and other debris in the flow may cause problems. Kilpatrick (28) notes that, "*its use on flashy, cobble-strewn streams has been relatively unsuccessful.*" Another problem with the use of a Parshall flume in measuring dirty flows such as sewage is that sometimes the installation must differ from the standard so as to prevent deposition of material upstream from the flume. Such non-standard entrance transitions can result in discharges that are quite different from standard values as pointed out by Chen, et al (32).

The head loss required for flow measurement with a Parshall flume is quite small. There must be a way to achieve the required drop in the floor, however, and this will eliminate some sites from consideration. Parshall flumes are evaluated in Table 15.

Palmer-Bowlus Flume - Flumes of the type first suggested and developed by Palmer and Bowlus (27) are a form of Type IV flume, being dependent

TABLE 14. STANDARD PARSHALL FLUME DIMENSIONS AND CAPACITIES

Size, Throat Width	Widths: Up-stream End	Widths: Down-stream End	Axial Lengths: Con-verging Section	Axial Lengths: Throat Section	Axial Lengths: Diverging Section	Wall Depth in Con-verging Section	Vertical Distance Below Crest: Dip at Throat	Vertical Distance Below Crest: Lower End of Flume	Con-verging Wall Length	Gage Points: Ha, Dist Upstream of Crest**	Gage Points: Hb x	Gage Points: Hb y	Free Flow Capacities: Min	Free Flow Capacities: Max
W	D	C	B	F	G	E	N	K	A*		x	y		
Inches	Feet	Feet	Feet	Feet	Feet	Feet	Feet	Feet	Feet	Feet	Feet	Feet	cfs	cfs
1	0.549	0.305	1.17	0.250	0.67	0.5-0.75	0.094	0 062	1.19	0.79	0 026	0.042	0.005	0.15
2	.700	.443	1.33	375	83	0.50-0.83	.141	.073	1.36	.91	.052	.083	.07	.30
3	.849	583	1.50	.500	1.00	1 00-2.00	.188	.083	1.53	1.02	.083	.126	.03	1.90
6	1.30	1.29	2.00	1 00	2.00	2.0	.375	.25	2.36	1.36	.167	.25	05	3.90
9	1.88	1 25	2 83	1.00	1 50	2.5	.375	.25	2.88	1.93	.167	.25	.09	8.90
Feet	.													
1.0	2.77	2.00	4.41	2.0	3.0	3.0	75	.25	4.50	3.00	.167	25	.11	16.1
1 5	3 36	2.50	4.66	2.0	3.0	3.0	.75	.25	4.75	3.17	.167	.25	.15	24.6
2.0	3.96	3.00	4.91	2.0	3.0	3.0	.75	.25	5.00	3.33	.167	25	.42	33.1
3.0	5.16	4.00	5.40	2.0	3 0	3.0	.75	.25	5.50	3.67	.167	.25	.61	50.4
4.0	6.35	5 00	5.88	2 0	3.0	3.0	.75	.25	6.00	4.00	167	.25	1.30	67.9
5.0	7.55	6.00	6.38	2.0	3 0	3.0	.75	.25	6.50	4.33	.167	.25	1.60	85 6
6.0	8.75	7.00	6.86	2.0	3.0	3.0	.75	.25	7.0	4.67	167	.25	2.60	103.5
7.0	9.95	8.00	7.35	2.0	3.0	3.0	.75	.25	7.5	5.0	.167	.25	3.00	121.4
8.0	11.15	9.00	7.84	2.0	3.0	3.0	.75	25	8.0	5.33	.167	.25	3.50	139.5
10	15.60	12.00	14.0	3.0	6.0	4 0	1.12	.50	9.0	6.00			6	300
12	18.40	14.67	16 0	3.0	8.0	5.0	1.12	.50	10.0	6.67			8	520
15	25.0	18 33	25.0	4.0	10.0	6.0	1.50	.75	11.5	7.67			8	900
20	30.0	24.00	25.0	6.0	12 0	7.0	2.25	1.00	14.0	9.33			10	1340
25	35.0	29.33	25.0	6.0	13.0	7.0	2 25	1.00	16.5	11.00			15	1660
30	40.4	34.67	26.0	6.0	14.0	7.0	2.25	1.00	19.0	12.67			15	-1990
40	50.8	45.33	27.0	6.0	16.0	7.0	2.25	1.00	24.0	16.00			20	2640
50	60.8	56.67	27.0	6.0	20 0	7.0	2.25	1.00	29.0	19.33			25	3280

* For sizes 1' to 8', A = W/2 + 4

** Ha located 2/3 A distance from crest for all sizes; distance is wall length, not axial.

Notes: 1. Flume sizes 3 inches through 8 feet have approach aprons rising at a 1:4 slope and the following entrance roundings: 3 through 9 inches, radius = 1.33 feet, 1 through 3 feet, radius = 1.67 feet; 4 through 8 feet, radius = 2 00 feet.

2. To maximize clarity, equivalent SI units are not given.

3. Table prepared by Kilpatrick (28).

TABLE 15. PARSHALL FLUME EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☐ Fair	☒ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☒ Moderate	☐ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☒ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☒ Medium	☐ Low
25	Portability	☐ No		☒ Yes

upon existing conduit slope and a channel contraction (provided by the flume) to produce supercritical flow. Ludwig and Ludwig (33) and Wells and Gotaas (34) have discussed various design aspects of such flumes. Such flumes arose out of a desire to have a measurement device that could be inserted into an existing conduit with minimal site requirements other than sufficient slope. A number of different cross-section shapes have been used over the years. Typical shapes for round and rectangular conduits are depicted in Figure 20. A proprietary flume, the Leopold-Lagco, which was introduced in 1965, is a Palmer-Bowlus type flume with a rectangular cross-section and is designed for use with circular pipes.

In the detailed laboratory studies conducted by Wells and Gotaas (34), they found that accuracies within ±3% of the theoretical rating curve could be obtained at depths as great as 90% of the pipe diameter. No effect of downstream depth on calibration was found for submergence ratios less than 0.85. Various geometric effects were investigated, and it was found that a minimum throat length of at least 60 percent of the pipe diameter was required, that the base height and exit transitions had no effect on the calibration, that a variation of entrance transition slope from 1:3 to 1:2 had a negligible effect, and that the point of upstream depth measurement should be no more than half of the pipe diameter upstream from the entrance to the flume.

In some designs, e.g., Figure 20c, the bottom slab or base is omitted entirely. It is more often included, however, both to help distribute the overall channel contraction and to provide structural integrity, an important feature for portable devices especially.

The chief advantage of Palmer-Bowlus flumes over Parshall flumes is their ease of installation in existing conduits. They may also offer somewhat lower head loss. They share all of the benefits listed in the discussion of Parshall flumes. In ordinary designs operating under low flow conditions, the bottom slab acts as a broad-crested weir, whose characteristics were discussed earlier. A disadvantage of Palmer-Bowlus flumes is that they have a smaller range, with 20:1 being seldom exceeded. Standard Palmer-Bowlus flumes are available to fit pipe sizes from 15.2 cm (6 in.) to 2.4m (8 ft). Palmer-Bowlus flumes are evaluated in Table 16.

As stated by Palmer and Bowlus (27), "*The important factor in the construction and installation of any form of venturi device is that a constriction of some sort be placed in the channel to produce critical velocity with the least loss of energy, and that the shape, size, and dimensions of the device are important only insofar as they meet the specific problem at hand in a practical manner.*" Diskin (35) has introduced an unconventional sort of a Palmer-Bowlus flume, Figure 21. He achieved channel contraction by wedging a pier-shaped element in

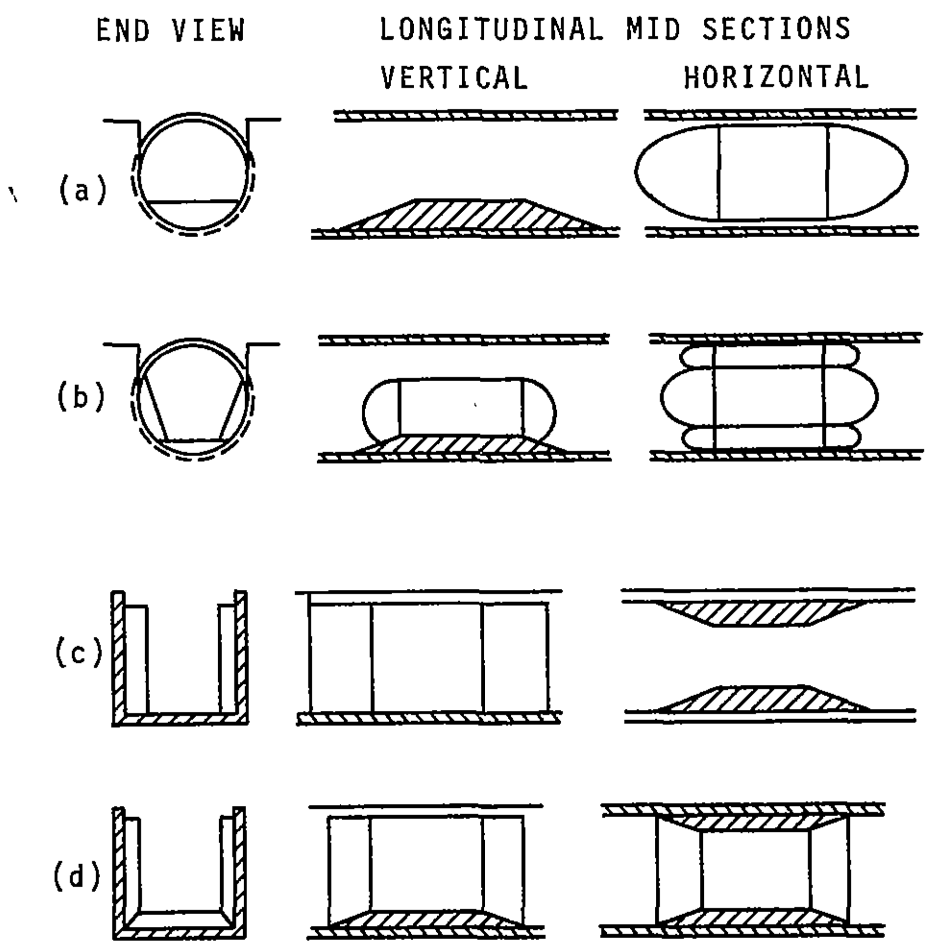


Figure 20. Various Cross-Section Shapes of Palmer-Bowlus Flumes

TABLE 16. PALMER-BOWLUS FLUME EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☒ Moderate	☐ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☐ Fair	☒ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☐ No		☒ Yes

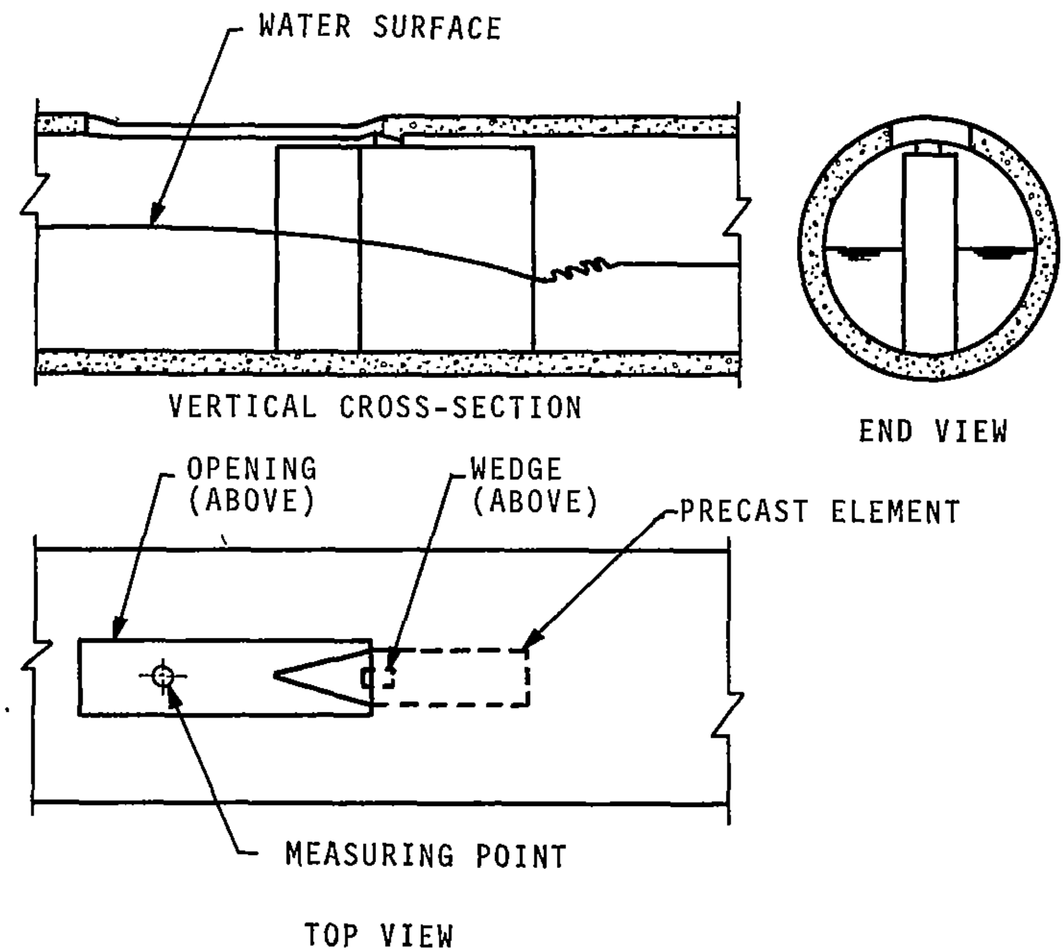


Figure 21. Diskin Measuring Device

the pipe between the crown and the invert. Experimental observations confirmed the theoretical rating curve determined under the same assumptions as for a standard Palmer-Bowlus flume. Limiting submergence was found to be between 0.75 and 0.85.

The chief drawback to such a metering device is that it poses a severe obstruction to the flow and, if applied to trashy or debris-laden flows, it almost surely invites, in time, either its own destruction or blockage of the conduit. As a portable device, however, it can be installed quickly and may have some use. The Diskin device is evaluated in Table 17.

Cutthroat Flume - The cutthroat flume was developed for use in flat gradient channels where a flume which could operate satisfactorily under both free (critical) flow and submerged flow conditions might be desired. It operates as either a Type I or Type II flume. The advantages of a flume with a level floor are that it is easy to construct and can be placed inside an existing channel without requiring excavation, simply by placing it on the channel bed. Studies reported by Skogerboe, et al (30) showed that flow depths measured in the exit section of the flume resulted in more accurate submerged flow calibration curves than calibrations employing flow depths measured in the throat section. Since the upstream depth measurement is made near the entrance, there is no need for a throat section in such a flume; in fact, removing the throat section was found to improve flow conditions in the exit section. Skogerboe, et al (36), who performed the development work on these flumes, have given the name "Cutthroat" to any such flume that has no throat section (i.e., zero throat length). A rectangular cutthroat flume is illustrated in Figure 22.

One of the benefits of a cutthroat flume is economy, since fabrication is facilitated by the flat bottom and removal of the throat section. Another fabrication advantage is that every flume size has the same wall lengths, which allows the same forms or patterns to be used for every flume size. Rectangular cutthroat flume sizes of 0.3, 0.6, 0.9, 1.2, and 1.8m (1, 2, 3, 4, and 6 ft) have been studied extensively by Skogerboe, et al (36). Transition submergences were found to vary smoothly from 79% to 88% over this range. Above these values, the flow is subcritical (submerged) and the submerged flow calibration curves must be used.

Similar cutthroat flumes of a trapezoidal shape with sides sloping outward at 45 degrees were also investigated by Skogerboe, et al (36) in small sizes, i.e., throat widths of 0, 15, and 30 cm (0, 6, and 12 in.). Development of intermediate and larger sizes was not attempted because of the variety of possible geometries that could be used. Cutthroat flumes are evaluated in Table 18.

TABLE 17. DISKIN DEVICE EVALUATION

Evaluation Parameter		Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☒ Moderate	☐ Low
6	Effect of Solids Movement	☐ High	☒ Moderate	☐ Slight
7	Flow Obstruction	☒ High	☐ Moderate	☐ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☐ Fair	☒ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☒ No		☐ Yes
15	Maintenance Requirements	☒ High	☐ Medium	☐ Low
16	Adverse Ambient Effects	☒ High	☐ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☒ Fair	☐ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☐ No		☒ Yes

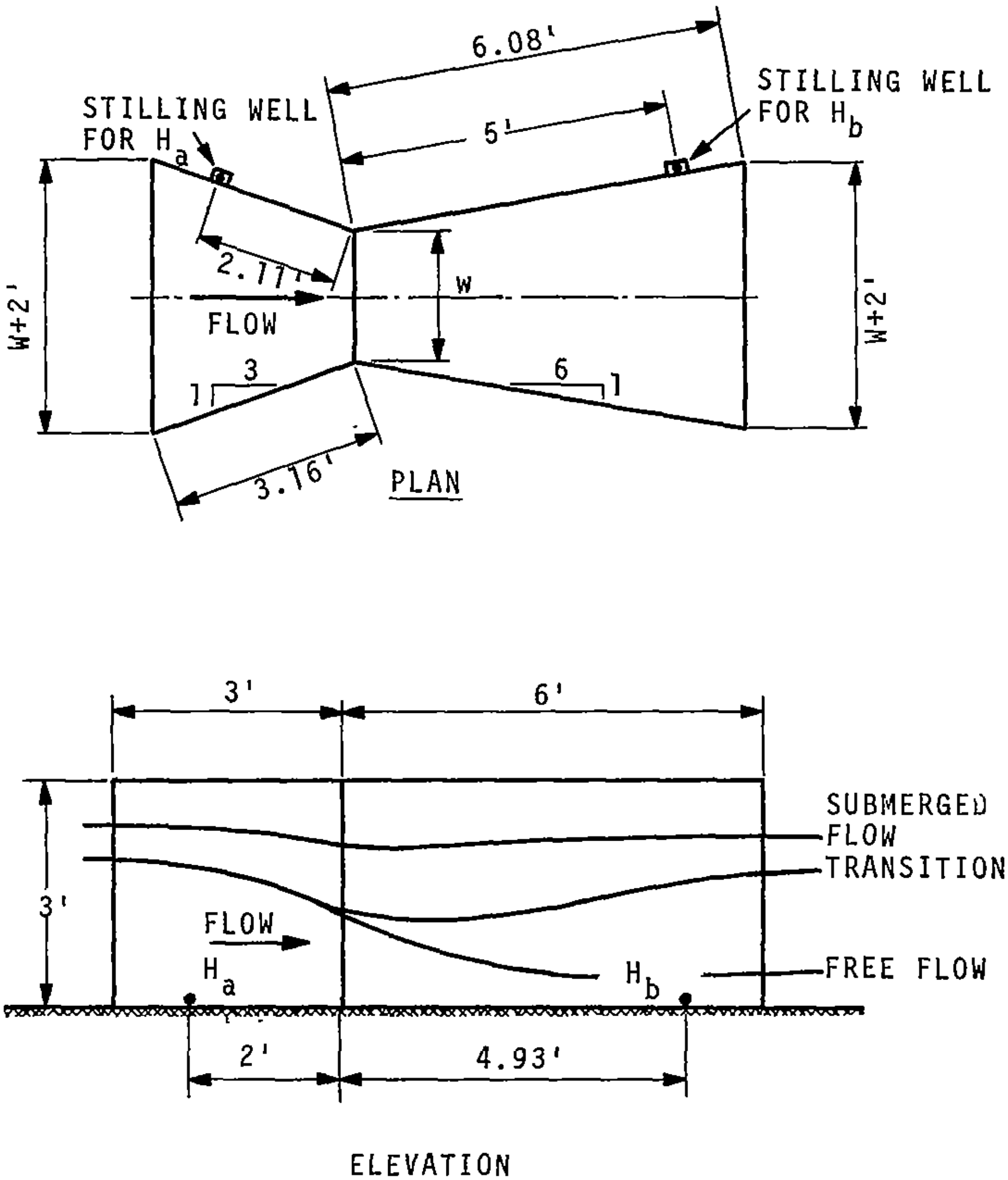


Figure 22. Rectangular Cutthroat Flume

TABLE 18. CUTTHROAT FLUME EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☐ Fair	☒ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☒ No		☐ Yes

Other Flumes - Several other flume designs have been used to solve specific problems. These flumes may: (a) be easier to construct for certain types of sites; (b) pass sediment-laden flows more readily; (c) handle a wider range of flows under certain conditions; (d) have increased sensitivity in a particular flow range; etc. As a general rule, they have not been as extensively investigated as the Parshall or Palmer-Bowlus flumes, and less is known about their behavior over a wide range of conditions.

San Dimas Flumes - As an example, the San Dimas flume was developed to measure debris-laden flows in the San Dimas Experimental forest in 1938. It is a modified Type IV flume in that it uses lateral contraction plus a 3% slope in its floor to create a supercritical flow. In the entry, the floor rises quickly to the crest, after which it falls as indicated in Figure 23a. Because head measurements are made in supercritical flow in the throat and critical depth occurs upstream, the discharge ratings should be independent of upstream and downstream distubances. Variation in approach conditions also should have little effect on the ratings. Because of its rectangular cross-section, the San Dimas flume is not sensitive or accurate at low flows. Results of tests on modified San Dimas flumes were reported by Bermel (37), who reduced the degree of contraction of the flume relative to the natural channel, provided a less abrupt entrance, and measured the head at the midpoint of the flume regardless of length. The modified San Dimas flume is depicted in Figure 23b. San Dimas flumes are evaluated in Table 19.

Trapezoidal Flumes - In attempts to obtain wider ranges of discharge than those that can be obtained with Parshall or San Dimas flumes, several investigators have considered supercritical trapezoidal flumes. These generally operate as Type IV flumes. The outward sloping of the flume walls provides increased sensitivity to lower discharge rates for a given size and, hence, increased range. The possible elements of a trapezoidal flume are indicated in the isometric sketch in Figure 24. All of these elements need not be included in a particular design, however. In the trapezoidal cutthroat flume discussed earlier, for example, the throat section is absent. Other designs eliminate the diverging and exit sections where channel erosion is not a problem, and so on.

Serious investigations of trapezoidal flumes began to be reported in increasing numbers in the late 1950s. Geometric variations are so numerous that no attempt will be made here to describe them all. Robinson (38) has extensively investigated a trapezoidal flume with a flat floor throughout the flume that conforms to the general slope of the channel. Other designs, such as the one reported by Gwinn (39), have the floor sloping slightly towards the center to form a very shallow "V".

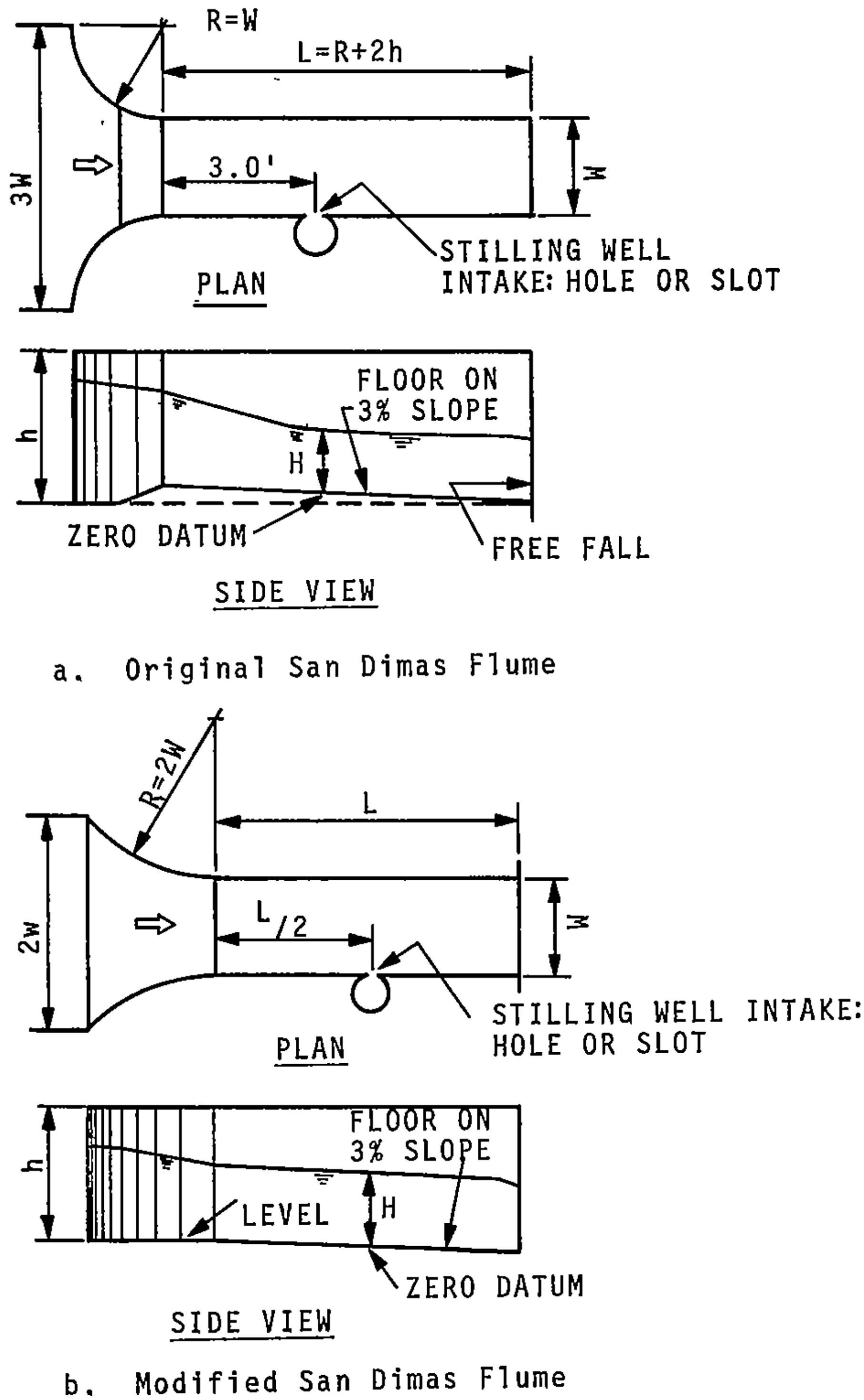


Figure 23. San Dimas Flumes

TABLE 19. SAN DIMAS FLUME EVALUATION

Evaluation Parameter		Scale		
1	Range	☐ Poor	☐ Fair	☒ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☒ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☒ No		☐ Yes

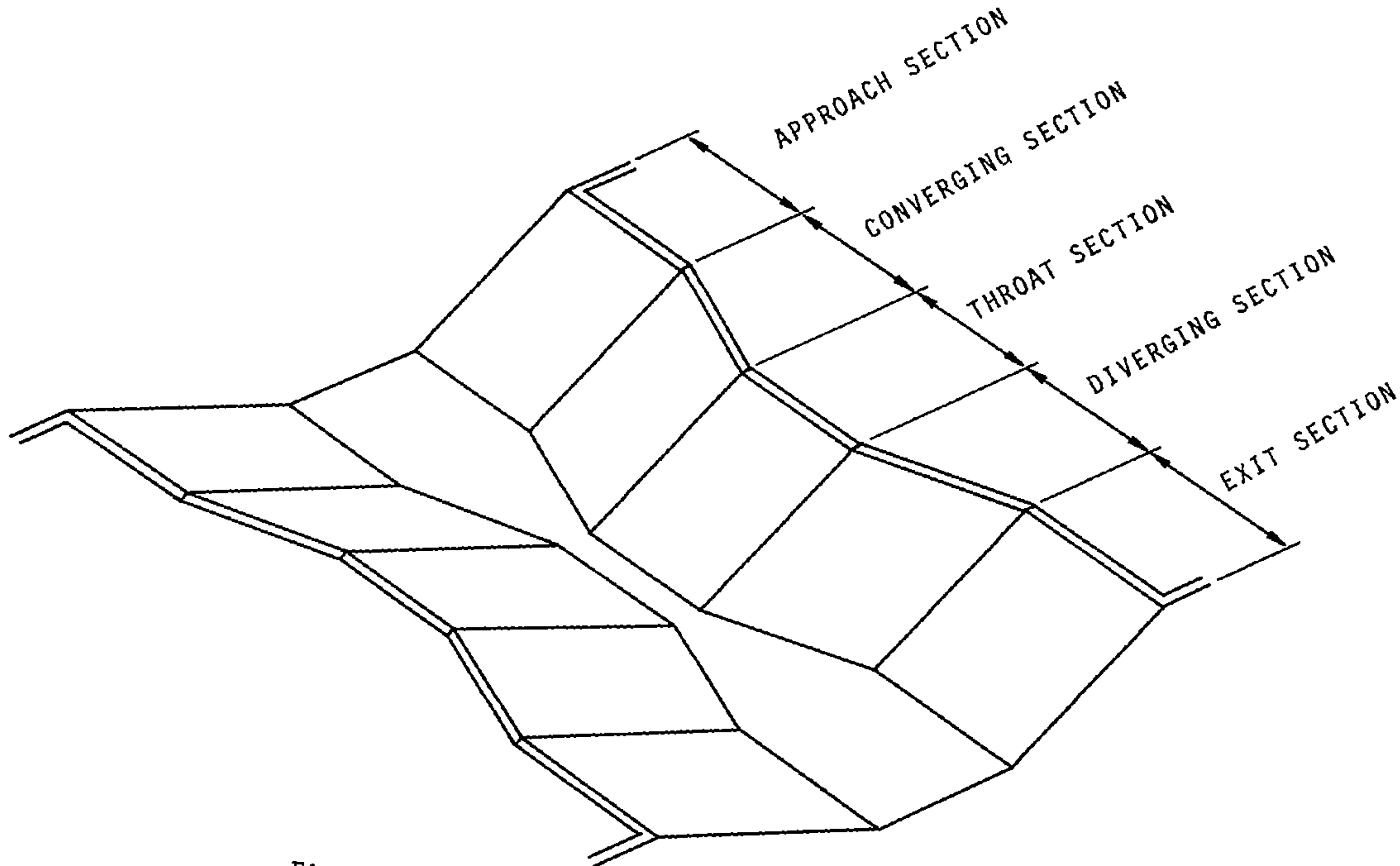


Figure 24. Elements of a Trapezoidal Supercritical Flow Flume

Sizes and maximum discharge capacities for trapezoidal flumes vary widely. Some are capable of measuring flows under 28 ℓ/s (1 cfs), while one of the largest known to the writers (located near Tombstone, Arizona) has a throat width of 36.6m (120 ft) and is rated to a maximum discharge of 736,000 ℓ/s (26,000 cfs).

When the throat width is reduced to zero, such flumes are more properly termed triangular flumes. Distinct advantages of a triangular flume are its ability to measure accurately over a wide range of flows and its high tolerance for submergence. Some designs can tolerate submergences as high as 90%, as opposed to the 60% noted earlier for the Parshall flume. Trapezoidal flumes will lie between these two values depending on their individual geometries. Trapezoidal flumes, including triangular, are evaluated in Table 20.

Type HS, H, and HL Flumes - The U.S. Department of Agriculture (USDA) Soil Conservation Service has HS, H, and HL type flumes in use in many small watersheds. These USDA (40) flumes are illustrated in Figures 25 and 26. It is pointed out that all dimensions are proportional to the total depth (height) of a given flume. These flumes have the advantage of simple construction and reasonably good accuracy over a wide range of flows. A variety of sizes are available to measure flows ranging from 0.006 ℓ/s (0.0002 cfs) to 3,400 ℓ/s (120 cfs).

These flumes differ from the flume types discussed earlier because they are, in fact, more weir than flume. They are more properly termed open channel flow nozzles but are included here because of historical precedent. Their design attempts to combine the sensitivity and accuracy of the sharp-crested weir and the self-cleaning features of the flume. The result is a compromise in both. The flat, unobstructed bottom allows the passing of silt better than a weir. Like the weir, flow control is achieved by discharging through a sharp-edged opening. However, the flow is contracted gently from the sides only, much like the converging section of ordinary flumes. The plane of the exit tilts backward toward the incoming flow. Like weirs, these flumes should be used in free outfall situations, and the minimum head loss will be the measured head. Head is measured upstream in subcritical but accelerating flow, and critical flow occurs over the crest as with an ordinary weir.

These devices are capable of measuring quite wide ranges of flow in some instances. For example, Soil Conservation Service rating tables for H flumes indicate possible ranges of 175:1 for a 0.15m (0.5 ft) flume and 5633:1 for a 1.38m (4.5 ft) flume. Type HS, H, and HL flumes are evaluated as a group in Table 21.

Open Flow Nozzles

As mentioned in the discussion of Type HS, H, and HL flumes, the open (channel) flow nozzle is a combination of flume and sharp-crested weir.

TABLE 20. TRAPEZOIDAL FLUME EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☐ Fair	☒ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☒ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☒ No		☐ Yes

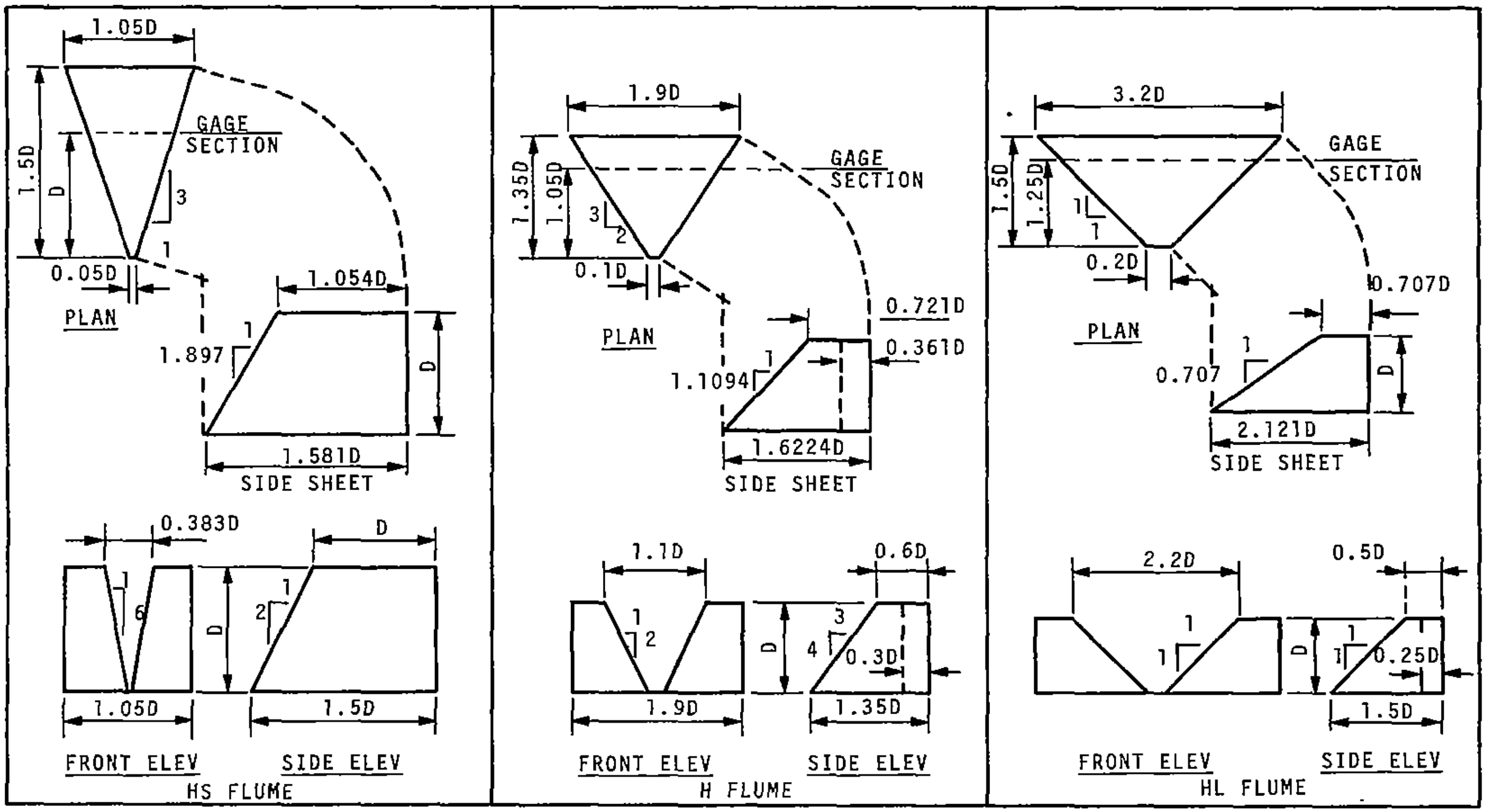
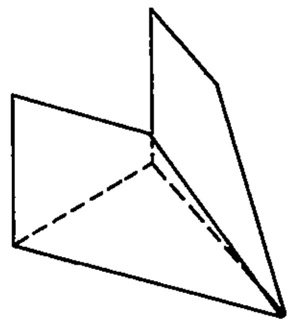
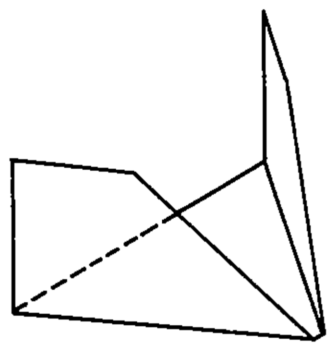


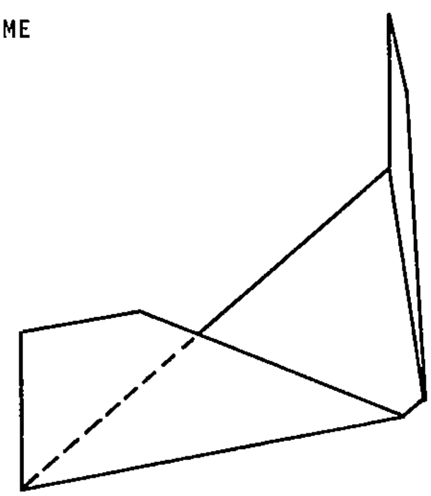
Figure 25. Type HS, H, and HL Flumes



HS FLUME



H FLUME



HL FLUME

Figure 26. Isometric View of Type HS, H, and HL Flumes

TABLE 21. TYPE HS, H, AND HL FLUME EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☐ Fair	☒ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☒ High	☐ Moderate	☐ Low
6	Effect of Solids Movement	☐ High	☒ Moderate	☐ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☒ High	☐ Medium	☐ Low
9	Manhole Operation	☐ Poor	☐ Fair	☒ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☐ No		☒ Yes

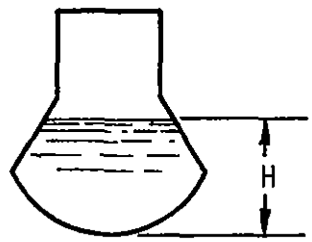
Unlike the conventional weir, it can handle suspended solids rather effectively, as a self-scouring action exists, and relatively large solids will pass without clogging. Use of open flow nozzles for heavy sludge, however, is not recommended unless calibration is for such use. Any deposition will alter the contour of the nozzle and, hence, its flow characteristics. For this reason the top of the nozzle is open in most designs to allow for ready inspection and cleaning.

Conversely, the open flow nozzle does not have the good head recovery characteristics of the flume. The loss of head through the device will be at least one pipe diameter. Open flow nozzles are designed to be attached to the end of a conduit flowing partially full and must discharge to a free fall.

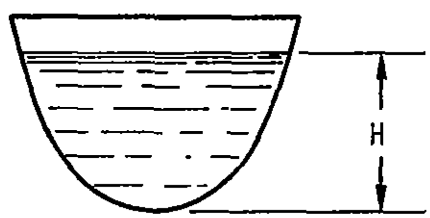
As with all head-area meters, the design is such that a predetermined relationship exists between the depth of the liquid within the nozzle and the rate of flow. In one design (the Kennison nozzle), the cross-section is shaped so that this relationship is linear. In another design (the parabolic nozzle), the relationship is a parabola so that each unit increase in flow produces a smaller incremental increase in head. The discharge profiles of these two nozzles are depicted in Figure 27.

Open flow nozzles are factory calibrated and offer reasonable accuracy (often better than ±5% of the reading) even under rather severe field conditions. Standard sizes are available from 15 to 91 cm (6 to 36 in.) in diameter, with maximum capacities up to 850 ℓ/s (30 cfs). These devices are capable of ranges of 20:1 or better and, for a given site, will exceed the range of either a Parshall flume or a sharp-crested weir. Parabolic nozzle lengths are roughly four times the diameter, while Kennison nozzle lengths are twice the diameter. Open flow nozzoles require a length of straight pipe immediately upstream of the nozzle, and the slope of the approach pipe must not exceed certain limits (depending upon nozzle size and profile) or else the calibration will be in error. Open flow nozzles are evaluated in Table 22.

The open flow nozzles discussed above were characterized by a cross-sectional profile shaped to give a better depth-discharge relationship than the ordinary circular pipe cross-section. The latter can be used for indicating flow, but high accuracies are not normally achieved, ±10% or worse being typical. The method, developed by Vanleer (41), is commonly referred to as the California pipe method, and uses as the primary device a straight, level (zero slope) section of pipe at least six diameters in length (see Figure 28a). The pipe, which cannot be flowing full, must be located so that there is free fall for the liquid at its exit, i.e., it must discharge freely into air. Also the velocity of approach must be at a minimum. The measurement taken is the distance from the crown of the pipe to the free water surface at the exit. An empirically-developed rating formula (or set of tables) is used, knowing



a. Linear (Kennison) Nozzle Profile ($Q \propto H$)

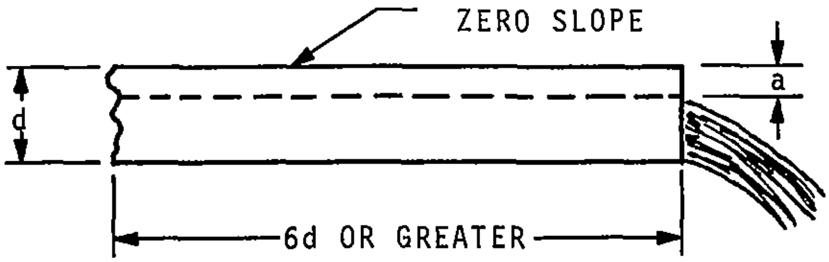


b. Parabolic Nozzle Profile ($Q \propto H^2$)

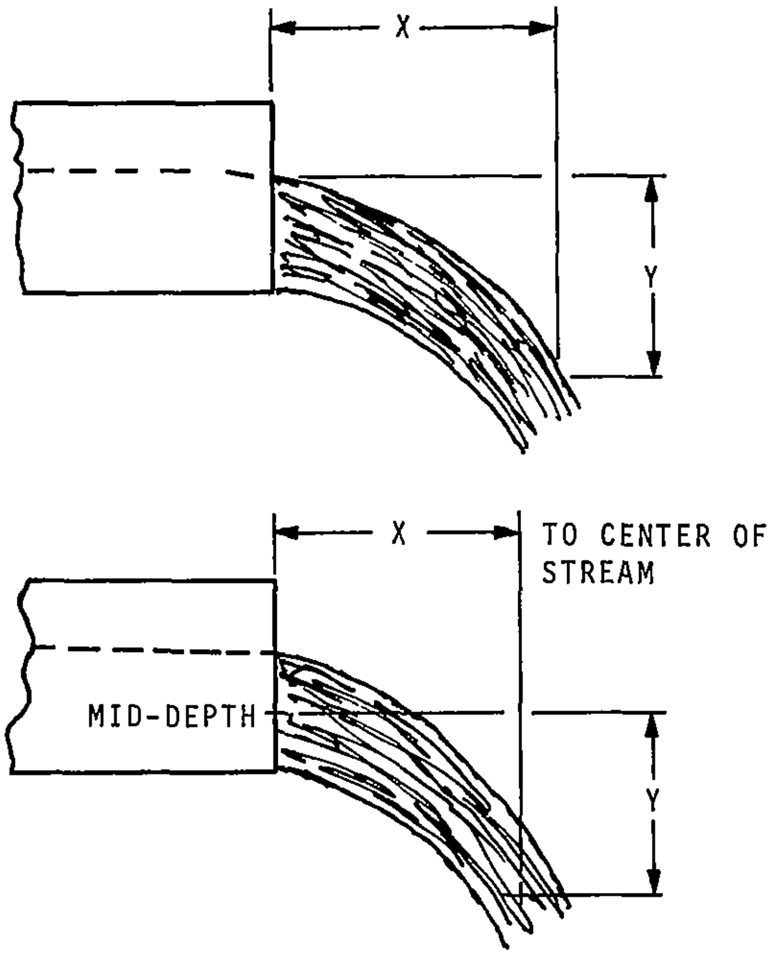
Figure 27. Open Flow Nozzle Discharge Profiles

TABLE 22. OPEN FLOW NOZZLE EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☐ Fair	☒ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☒ High	☐ Moderate	☐ Low
6	Effect of Solids Movement	☐ High	☒ Moderate	☐ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☒ High	☐ Medium	☐ Low
9	Manhole Operation	☐ Poor	☐ Fair	☒ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☐ No		☒ Yes



a. CALIFORNIA PIPE METHOD



b. TRAJECTORY METHODS

Figure 28. California Pipe and Trajectory Methods

the pipe diameter, to convert this distance (pipe diameter minus water depth at the exit) to discharge. The experimental data used to develop the formula were obtained on steel pipes from 7.6 to 25.4 cm (3 to 10 in.) in diameter, but tables can be found extending up to 0.9m (3 ft) diameter pipes. It has also been observed that, for depths greater than half the diameter, discharges do not necessarily follow the Vanleer formula. Except for its poorer accuracy, the California pipe method exhibits similar characteristics to the other open flow nozzles and, consequently, will not be separately evaluated.

Trajectory Methods

The California pipe method, although discussed under open flow nozzles, may also be considered as a trajectory method. Trajectory methods are not true head-area methods, but appear to fit in the discussion at this point. There are a number of techniques, both theoretically and empirically derived, but all share in common the taking of two measurements, one in the vertical (Y) and one in the line of the pipe axis (X) as indicated in Figure 28b. Like the California pipe method they should be viewed as methods for producing flow estimates rather than accurate measurements. The theoretically based methods generally ignore resistance effects and thereby arrive at a parabolic contour for the center line issuing stream. These measurements, as indicated in the second sketch of Figure 28b, should preferably be used when applying theoretical methods as opposed to those indicated in the first sketch of Figure 28b, but field conditions and operator experience play a much greater role in improving the discharge estimate.

When the mid-depth value of Y has been set at one foot (Figure 28b) and the pipe is horizontal but not flowing full, the discharge in gallons per minute is approximated by 1,800 times the product of the cross-sectional area of the issuing stream and the value of X measured in feet. Other empirically developed coordinate or trajectory methods (e.g., the Purdue method) have been put forth over the years in the form of equations, tables, and curves, but little comparative work has been performed. Because of the lack of accuracy of such techniques and the infrequent occurrence of suitable freely discharging pipes in storm and combined sewers, trajectory and other free overfall methods will not be evaluated or discussed further.

FLOW VELOCITY

The flow rate of a stream can be expressed as the product of the mean flow velocity across a cross-section and the flow area at that point. In open channel flow, this will generally require two separate measurements, one to determine mean velocity and the other to determine flow depth. Under pressurized flow conditions, the conduit cross-section is the area, and only the velocity need be measured. A complication in this seemingly simple procedure is that the velocity profile of a flow is dependent upon many factors, and frequently a series of velocity measurements will be necessary in order to arrive at the average velocity across a section. The following quotation from the USDI Bureau of Reclamation (10) is given to illustrate some of the vagaries and methods for implementation: "*The following methods are used to determine mean velocities in a vertical line with a current meter:*

(1) Two-point method.

(2) Six-tenths-depth method.

(3) Vertical velocity-curve method.

(4) Subsurface method.

(5) Integration method.

(6) Two-tenths method.

(7) Three-point method.

(8) One-point continuous method.

The two-point method consists of measuring the velocity at 0.2 and then at 0.8 of the depth from the water surface, and using the average of the two measurements. The accuracy obtainable with this method is high and its use is recommended. The method should not be used where the depth is less than 2 feet.

The six-tenths-depth method consists of measuring the velocity at 0.6 of the depth from the water surface, and is generally used for shallow flows where the two-point method is not applicable. The method gives fairly satisfactory results.

The vertical velocity-curve method consists of measuring the velocities at equal vertical intervals of 0.5 foot or more and calculating their arithmetical mean, or finding the mean value from a curve obtained by plotting the measurements on cross-section paper. The method is very accurate, but is time consuming and costly.

The subsurface method involves measuring the velocity near the water surface and then multiplying it by a coefficient ranging from 0.85 to 0.95, depending on the depth of water, the velocity, and the nature of the stream or canal bed. The difficulty of determining the exact coefficient limits the usefulness and accuracy of this method.

The integration method is performed by observing the velocity along a vertical line by slowly and uniformly lowering and raising the meter throughout the range of water depth two or more times. The method is not accurate and should be used only for comparisons or quick rough checks.

The two-tenths, three-point, and one-point continuous methods are special procedures based on a relationship - previously established for the section - between the true discharge and the velocities observed by these methods. These methods are generally reliable for sections which undergo no serious changes because of erosion, sedimentation, or other deformation."

For conduits flowing full and under pressure, the velocity profile will be a function of the Reynolds number, the cross-sectional shape, and the wall roughness, among other factors. As in the case for open channel flow, some prior knowledge of the flow characteristics is necessary in order to use a single velocity reading to compute discharge.

In the following discussion it is generally assumed that such knowledge exists, having been obtained by calibration (or other measurements) at the site or from other empirical work. Methods for measuring the stage for determining flow area in open channel flow are also assumed and will not be addressed here. It is common practice to refer to devices in this category as velocity meters when they are normally applied to pressurized flow and as current meters when they are normally applied to open channel flow, but no real distinction should be attached to the terms. A good review of velocity measuring devices has been recently prepared by Smoot (42), and liberal use has been made of some of his comments in the following paragraphs.

Floats

In the float method of determining flow velocity, one or more floats are placed in the stream and their time to travel a measured distance is determined. The simple use of surface floats, floats immersed less than one fourth of the flow depth, is the least desirable of all as they may be subjected to wind effects in addition to current effects. Since the surface velocity is greater than the mean velocity, a correction must be applied. For reasonably smooth flows in regular conduits, the correction factors range from around 0.7 to 0.9 depending upon flow depth, conduit shape, and other factors.

Another method makes use of oranges, which float mostly submerged and work fairly well in the shallow flows found in many sewers. Somewhat more sophisticated are the rod floats, which consist of a square or round rod (usually wooden); the rod is designed with a weighted end so that it will float in a vertical position with the length of the immersed portion approximately 0.9 times the depth of the flow. The reasoning here is that the velocity of a rod float which extends from the water surface almost to the bottom will be very nearly the same as the mean velocity of the flow.

A further improvement in accuracy is known as the integrating float method, which is discussed by Lin (43). Here, buoyant spheres are released from the channel floor and are displaced downstream as they rise to the surface. The time from the moment of release to the moment of surfacing is measured as is the distance traveled downstream. The proper selection of size and specific gravity of the spheres for a particular flow depth minimizes the error caused by initial ascent acceleration and permits a flow measurement method that automatically compensates for velocity distributions in a channel. The method is best suited for fairly low velocities.

These methods should only be used for making rough estimates and are not well suited for many storm or combined sewer applications, especially the integrating floats. They are evaluated in Table 23.

Tracers

In an attempt to improve upon the accuracy of float velocity methods, many investigators turned to the use of liquid tracers to measure velocity. Dye, salt, and radioactive tracer substances have been used. In principle, a slug of tracer is instantaneously introduced into the flow at an upstream station, and the time of travel to a downstream station a known distance away is measured. The technique should not be confused with dilution techniques which will be discussed later.

When dyes are used, the technique is sometimes referred to as the color-velocity method. Potassium permanganate, fluorescein, uranine, sodium dichromate, and rhodamine dyes have been commonly used. In application, the downstream time should be noted when the center of the mass of colored liquid passes. Considerable judgment is required to determine the center of mass of the dye pattern and, consequently, the accuracy of timing is limited. In actuality, the peak concentration is often used. In high velocity flows, air entrained near the surface and spray above the surface can further degrade the measurement. Also, it may be uncertain whether the observed dyecloud velocity is the mean velocity of the stream or just the velocity of the surface. Careful use of a fluorometer can help eliminate part of the uncertainties, but high accuracies should not be expected as a rule.

A more precise method uses salt as the tracer and is often referred to as the Allen salt velocity method. It is based on the fact that salt in solution increases the electrical conductivity of water. In application, a quantity of salt solution is forced into the stream under pressure through quick-closing valves. In determining the average velocity of the salt solution, two pairs of electrodes are installed in the stream a known distance apart. The electrodes are energized by an electrical current, and the resistivity of the water path is measured. The greater conductivity of the salt solution will appear as a decrease in resistance and, hence, an increase in current flow. If the electrodes are connected to a control recording galvanometer, the graph of

TABLE 23. FLOAT VELOCITY EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☐ Fair	☒ Good
2	Accuracy	☒ Poor	☐ Fair	☐ Good
3	Flow Effects on Accuracy	☒ High	☐ Moderate	☐ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☐ Fair	☒ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☒ No		☐ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☒ High	☐ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☒ No		☐ Yes
20	Precalibration	☐ No		☐ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☐ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☐ No		☒ Yes

current strength will have two humps that indicate the passing of the salt slug past each pair of electrodes. The distance on the chart between these two humps (or peaks) is a measure of the time of travel, and from this and the electrode spacing the flow velocity can be obtained. Salt-velocity methods are more amenable to automation than color-velocity methods. However, this requires rather special equipment not familiar to average personnel, and its use is relatively expensive. With care, accuracies of better than ±2% can be achieved. This method is sometimes used to calibrate other flow measurement devices in place.

Radioisotopes can also be used as velocity tracers much as in the salt-velocity method. The sensors here are scintillation counters or geiger counters, but the application is essentially as described above. The requirements for Federal licensing, expensive equipment, and highly trained personnel together with the reluctance on the part of the public to accept deliberate introduction of radioactive substances into their water tend to limit the application of this technique. Tracer velocity methods as a group are evaluated in Table 24.

<u>Vortex</u>

There are two major sub-types of vortex meters, the difference being in whether vortex rotation or vortex generation is measured.

<u>Vortex-Velocity</u> - The vortex-velocity meter has been discussed by Henke (44) and McVeigh (45). It is designed to be used in pipes flowing full and under pressure. Essentially the meter is a conduit having a bulge on one side. Flow through the conduit results in a vortex pool in the enlarged section of the conduit. A vortex cage located in the pool counts its revolutions, which are related to the flow velocity. These meters can be quite accurate (to ±0.5% of the reading) in certain flows and have a usual rangeability of around 10:1. They are sensitive and have very low pressure loss. However, solids in the flow and potential fouling problems make the device appear generally unsuitable for sewage applications. Vortex-velocity meters are evaluated in Table 25.

Closely related to the operating principle of the vortex-velocity meter is a rotorless current meter developed in Russia. As described by Replogle (8): "*The meter consists of a tube which is shaped into a closed, race-track-shaped oval with two parallel lengths. In one of the straight lengths, several slots parallel to the axis are cut through the tube. A ball whose density is equal to that of the gaged fluid is enclosed in the tube. The meter is placed in the stream so that the direction of the slots coincides with the direction of the current. The fluid in the tube is set in motion by the viscous force transmitted through the slots, and the ball moves around the closed oval at a rate depending on the stream velocity. Advantages claimed for the meter are*

TABLE 24. TRACER VELOCITY EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☒ Moderate	☐ Slight
4	Gravity & Pressurized Flow Operation	☐ No		☒ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☐ Fair	☒ Good
10	Power Requirements	☐ High	☒ Medium	☐ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☐ Moderate	☒ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☒ No		☐ Yes
20	Precalibration	☒ No		☐ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☐ No		☒ Yes

TABLE 25. VORTEX-VELOCITY METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☒ High	☐ Moderate	☐ Slight
7	Flow Obstruction	☒ High	☐ Moderate	☐ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☒ High	☐ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☒ High	☐ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☒ High	☐ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☐ Moderate	☒ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☒ Poor	☐ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☒ Fair	☐ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

simplicity, low cost, light weight, and ability to operate at low velocities and depths as small as one inch." Such a device would not seem well suited for dirty flows such as sewage because of fouling problems.

Eddy-Shedding - In these devices, which can be used in open channel as well as pressurized flow, the measure is the count of the frequency of the vortex street formed behind a strut in the flow. This phenomenon is well treated by Schlitchting (46). This shedding frequency is directly proportional to the flow velocity and the Strouhal number and inversely proportional to the diameter of the strut. Typical lower threshold values are around 0.03 to 0.06 m/s (0.1 to 0.2 fps). Various means of detecting the eddies have been tried, including acoustic sensors and pressure transducers downstream from the strut and a variable reluctance transducer attached to the strut to measure its vibration. Problems have been met, many of them doubtless arising from the complications in the uniform pattern of the eddies caused by natural turbulence in the flow. Of course, any collection of debris on the strut will cause serious errors. Accuracies as high as ±1% have been achieved under ideal conditions, and ranges of 50:1 are commonplace. Eddy-shedding meters are evaluated in Table 26.

Turbine Meters

The turbine meter uses a turbine (which rotates about a horizontal axis) with many small blades of slight curvature to measure flow velocity. The turbine meter, discussed by Artz (47) and Yard (48), is probably available in more variations than any other mechanical meter. They are chiefly used in measuring flows in pipes that are flowing full and under pressure. Turbine meters can be quite accurate (±0.5% of reading) if properly calibrated, and their repeatability is often better than ±0.1%. Linear operation over a 15:1 range is not uncommon. There is some pressure loss associated with turbine meters, and they are not well suited for liquids containing suspended solids, entrained air, or trash and debris. Turbine meters are evaluated in Table 27.

Rotating-Element Meters

Essential features of these meters are a wheel (primary device), which rotates when immersed in the flow, and a provision (secondary device) for determining either the number of turns of the wheel or its rate of rotation. Rotating-element flowmeters may be grouped into one of two sub-types, depending upon whether their axis of rotation is horizontal or vertical. Some writers refer to them as propeller meters (horizontal-axis) or cup-type meters (vertical-axis). Strictly speaking, the turbine meter would fall in the horizontal-axis class but, because of its greater limitations, it was addressed separately. There has been a long-standing debate on which of the two classes of rotating-element current meters is better, and the issue will not be belabored here.

TABLE 26. EDDY-SHEDDING METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☐ No		☒ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☒ Moderate	☐ Slight
7	Flow Obstruction	☐ High	☒ Moderate	☐ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☐ Fair	☒ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☐ Moderate	☒ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☒ Medium	☐ Low
25	Portability	☐ No		☒ Yes

TABLE 27. TURBINE METER EVALUATION

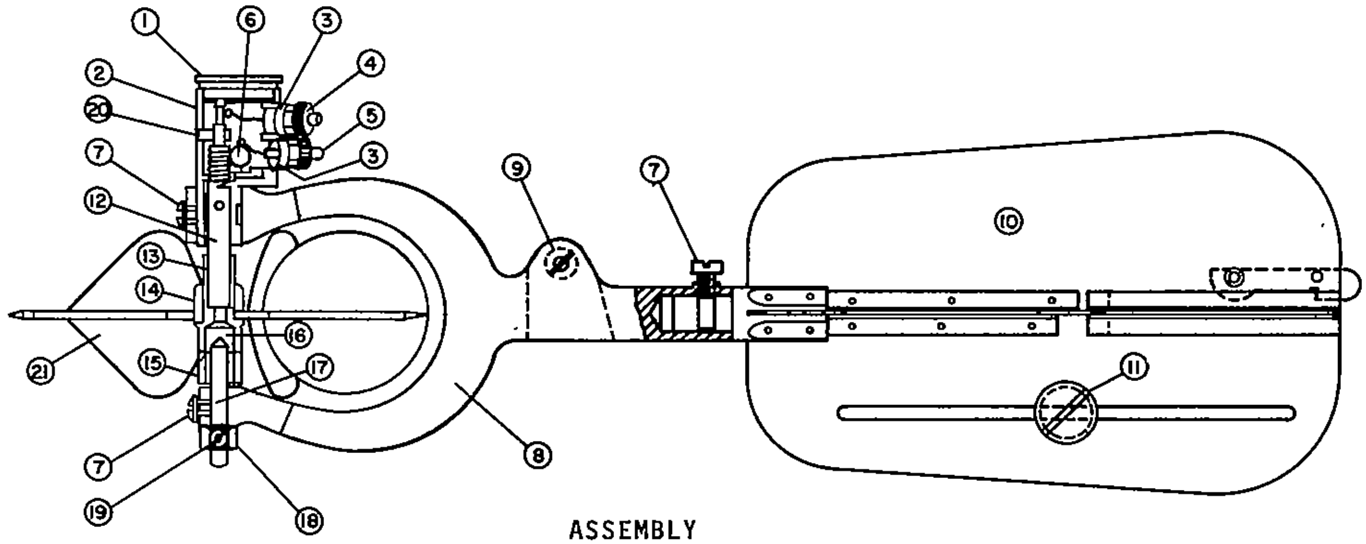
Evaluation Parameter		Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☒ High	☐ Moderate	☐ Slight
7	Flow Obstruction	☒ High	☐ Moderate	☐ Slight
8	Head Loss	☐ High	☒ Medium	☐ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☒ High	☐ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☒ High	☐ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☐ Moderate	☒ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

Both have proper applications with both advantages and disadvantages. Horizontal-axis meters have found wide use in pipe lines, water mains, and high-flow applications that require a low permanent pressure drop. They can handle higher flow rates than volumetric (positive displacement) flowmeters, but not as high as turbine meters. Along with vertical-axis meters, they are also used to measure open channel flows. A thorough treatment of the use of current meters for open channel flow measurement is given by Buchanan and Somers (49) and the USDI Bureau of Reclamation (10).

Vertical-Axis Meters - The most common vertical-axis meters are those with either the S-shaped (or Savonius) rotor or with a bucket wheel made up of a number of conical or hemispherical cups. In general, the bearing systems in the vertical-axis meters are simpler in design, more rugged, better protected from silty water, and consequently, easier to maintain than those of horizontal-axis meters. Bearing adjustment is usually less sensitive, and their calibration at lower velocities (where frictional effects are higher) is more stable. Vertical-axis meters operate in lower velocities than horizontal-axis meters, generally having lower threshold velocities of around 0.03 meters per second (0.1 fps) or less. Finally, a single cup rotor serves for the entire range of velocities, and the rotor is repairable in the field without adversely affecting the rating.

The type AA Price current meter is probably the most common type of vertical-axis meter. This device has a rotor 12.7 cm (5 in.) in diameter and 5 cm (2 in.) high with six cone-shaped cups mounted on a stainless steel shaft. It also has a vane to keep the rotor headed into the flow, an electrical device to signal the number of revolutions, and provisions for handling the meter. An assembly drawing of a Price type AA current meter is given in Figure 29. There is also a Price type BTA current meter which differs from the type AA only in its mounting yoke, contact chamber, and the absence of the tailpiece. For smaller flows there is a pygmy meter that is similar to the Price meter but only about two-fifths its size. The rotational speed of the pygmy rotor is more than twice that of the Price meters, and consequently its use is limited to velocities up to 0.9 or 1.2 m/s (3 or 4 fps).

Horizontal-axis meters - This class of current meter is less sensitive to vertical velocity components than is the vertical-axis meter, which will over-register in most such instances. Vertical-axis meters cannot correct for oblique flow, whereas some of the helical rotors of horizontal-axis meters are designed to act as nearly perfect cosine meters. The horizontal-axis rotor disturbs the flow less because of its axial symmetry with flow direction. They also present a clearer view to the flow than vertical-axis meters and, consequently, are slightly less susceptible to fouling. Bearing friction, especially at higher velocities, is less than for vertical-axis meters because bending



ASSEMBLY

LIST OF PARTS

1. CAP FOR CONTACT CHAMBER
2. CONTACT CHAMBER
3. INSULATING BUSHING FOR CONTACT BINDING POST
4. SINGLE-CONTACT BINDING POST
5. PENTA-CONTACT BINDING POST
6. PENTA GEAR
7. SET SCREWS
8. YOKE
9. HOLE FOR HANGER SCREW
10. TAILPIECE
11. BALANCE WEIGHT
12. SHAFT
13. BUCKET-WHEEL HUB
14. BUCKET-WHEEL HUB NUT
15. RAISING NUT
16. PIVOT BEARING
17. PIVOT
18. PIVOT ADJUSTING NUT
19. KEEPER SCREW FOR PIVOT ADJUSTING NUT
20. BEARING LUG
21. BUCKET WHEEL

Figure 29. Assembly Drawing of a Price Type AA Current Meter

moments on the shaft are eliminated. Finally, although the horizontal-axis meter has a higher velocity threshold of around 0.08 m/s (0.25 fps), it is capable of measuring higher flow velocities, with some designs capable of measuring in excess of 9 m/s (30 fps).

The types of horizontal-axis meters in common use today are the Ott, Neyrpic (Dumas), Haskell, and Hoff. The Ott meter was developed in Germany, the Neyrpic meter in France, and the Haskell and Hoff in the United States. All are precision instruments that can cover a wide range of flow velocities by using propellers with a variety of screw pitches.

Townsend and Blust (50) give a comparison of stream velocity meters, and the reader who is further interested is referred to their discussion. No rotating-element current meter is ideal for any extended period of unattended operation, but they can be used to give excellent results in the hands of a skilled operator. Generally they are inexpensive, simple in design, and rugged in construction. A major shortcoming of all rotating-element current meters is that their accuracy is so closely coupled with the operator. In general, it requires much experience and great care to select gaging sites and apply techniques in such a way as to obtain results that approach the basic accuracy of the instrument itself (often ±1%). Typically, it is difficult to achieve better than ±2 or 3% accuracy in the field. Carter and Anderson (51) and Smoot and Novak (52) discuss accuracy of current meter measurements further. Their obstruction to the flow and susceptibility to fouling limit their use in storm and combined sewers. Rotating-element velocity meters are evaluated in Table 28.

Other Devices

Other devices are available to measure the velocity of open channel flow at a point within the stream. They include pitot tube, electromagnetic, venturi, thermal, optical, and other fundamental principles. They are discussed in the subsections of this report that address their particular principles of operation, and will not be covered again here. In this use (as current meters) they all require attended operation. Otherwise they function as described in their individual discussions.

FORCE-DISPLACEMENT

This class of flowmeters is related to the variable area class discussed earlier in that both operate by a force due to the flow displacing an obstruction (primary element) that is immersed in the fluid. In effect, the drag of the obstruction is being measured, and this is related to the square of the fluid velocity, among other parameters which include the drag coefficient. Being proportional to the velocity squared means that force-displacement meters will tend to be insensitive at very low

TABLE 28. ROTATING-ELEMENT METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☐ No		☒ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☒ High	☐ Moderate	☐ Slight
7	Flow Obstruction	☐ High	☒ Moderate	☐ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☒ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☒ No		☐ Yes
15	Maintenance Requirements	☒ High	☐ Medium	☐ Low
16	Adverse Ambient Effects	☒ High	☐ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☒ No		☐ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☐ No		☒ Yes

velocities. The dependency on drag coefficient means that calibration will shift if the primary element becomes fouled by buildup or debris. The secondary device measures the displacement of the primary element and converts this into velocity or actual discharge.

Vane Meters

The vane meter is simply a vane hinged along either a vertical or horizontal axis and placed in the flow (Figure 30). The flowing fluid produces an angular displacement which is related to velocity and read by the secondary element.

The vertical-axis vane meter is one of the most common. As indicated in Figure 30a, the vane may be quite short as compared with the flow depth or, for flows whose levels do not change greatly, the vane may extend over almost the entire flow depth in an attempt to average the velocity. The advantages of the vertical axis arrangement are that the counterbalancing weight can be easily changed to alter flow ranges; it can be made to integrate velocities over a great portion of the vertical; and its mechanical output can be recorded and indicated visually. Its disadvantages include its tendency to collect debris; the high degree of bearing friction (resulting from its typically heavy weight) that adds to the low flow insensitivity problem of this class; and the fact that removal for service or repair is difficult.

The horizontal-axis vane meter (see Figure 30b) overcomes many of the disadvantages of the vertical-axis type. Among its advantages are the ease of changing the weight at the bottom in order to change ranges; its capability for being installed totally submerged to avoid fouling by floating debris; its light weight and simplified design to reduce bearing friction; and the fact that its output is usually electrical. On the other hand, despite its relatively small size and weight, it may not be convenient for some installations, and there is no visual readout of deflection. Both types of vane meters will be affected by wind on the exposed portion of the vane.

Robinson (53) has described a somewhat different form of the horizontal-axis vane meter that is sometimes referred to as the pendvane meter. It is designed for use in open channel flow, usually for small channels less than 0.9m (3 ft) deep and 1.8m (6 ft) wide. In the pendvane meter, the vane is shaped to match a particular channel cross-section so that its displacement is the same for a particular discharge rate irrespective of the velocity profile (within certain specified depth limits). Thus the pendvane meter indicates discharge rate directly. Errors of ±10% are possible, and flow range is low.

Two percent might be considered an accuracy limit for vane meters and accuracies of ±5% or more should be considered more typical. For a

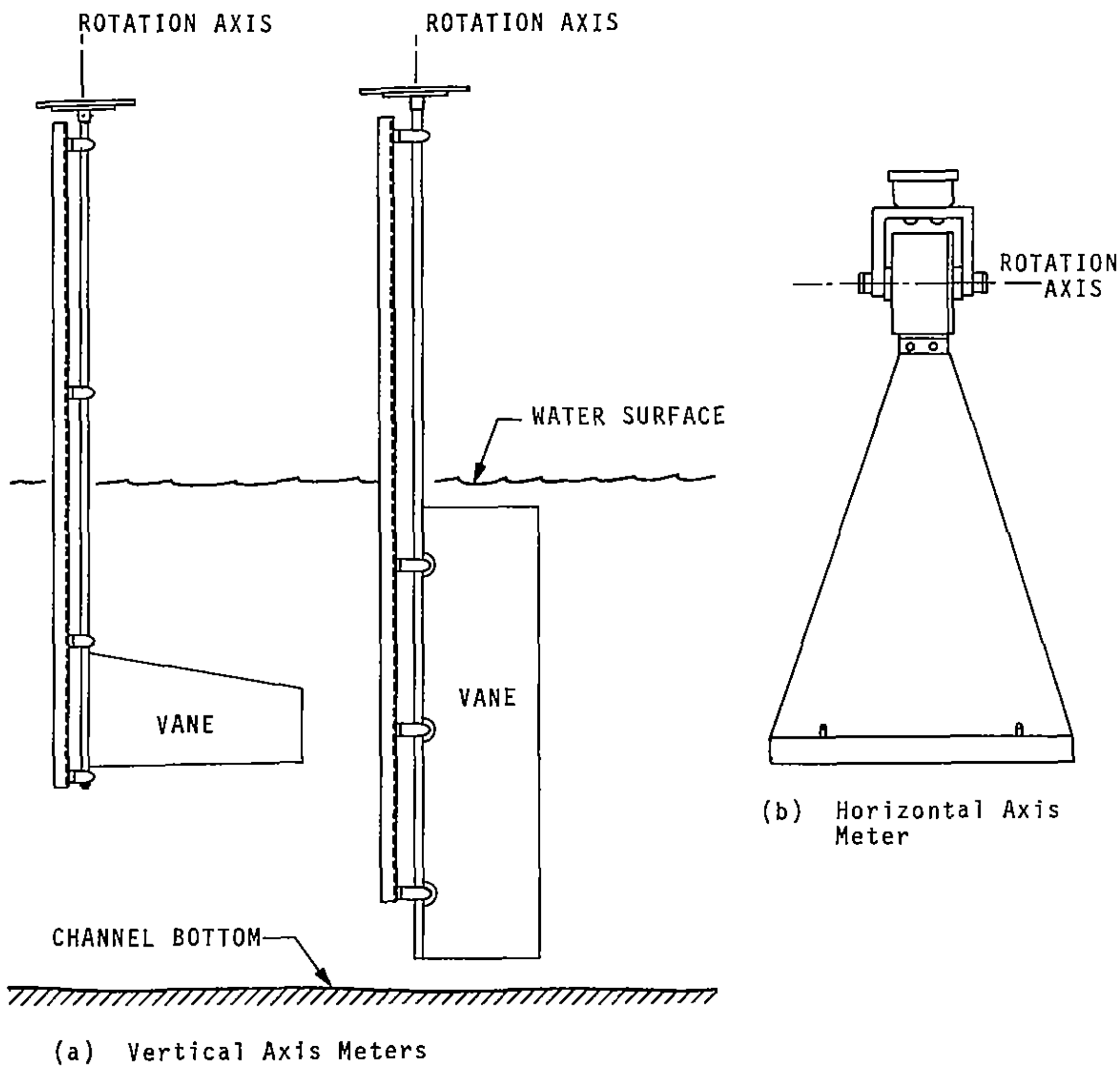


Figure 30. Vane Meters

given weight (i.e., range setting), 5:1 or so should be considered a typical flow range that these devices can handle. Vane meters are evaluated in Table 29.

Hydrometric Pendulum

The hydrometric pendulum is sometimes used in open channels as a current meter. In its most elemental form, it consists of a ball (heavier than the fluid) suspended by a string (or light cable). The angular deflection of the ball and string is proportional to the flow velocity in the vicinity of the ball. Accuracies are poor because stream fluctuations make determination of the deflection angle difficult. These are partly due to the vortex shedding phenomenon discussed earlier. Also, there is usually no method for recording the output, and the device must be manually operated. Accuracy is further degraded by the complex and somewhat uncertain corrections for drag on the line that are required. Drag on the line is increased greatly by floating debris, such as moss or grass, catching on it. Good features are that the drag element can be very easily changed to alter the ranges, and the line can easily be lengthened or shortened to measure velocity at various depths. The hydrometric pendulum is evaluated in Table 30.

Target Meter

The target meter, discussed by Stapler (54), is a more sophisticated force-displacement device for measuring flows. The primary element (or target) is shaped similarly to the sharp-edged annular orifice. It mounts on a support that passes through the conduit wall via a sealed, flexible closure, and the displacement of the primary device is measured by a strain gage or some other suitable displacement measuring secondary device (Figure 31). This meter has relatively high accuracies, approaching those of the orifice meter under certain conditions.

Strictly speaking, although the target meter is a point velocity measuring device, the point may be rather large so that an integrating effect is achieved. Replogle (55) reports that analytical and experimental studies have indicated that target meters can be designed for open channels of any cross-sectional shape and can indicate discharge rate directly to better than ±3%, independent of flow depth. Such meters are limited in discharge measurement primarily by the ability to predict the general type of velocity profile existing in the flow. Typical ranges are around 5:1. They do not appear especially suitable for use in flows containing suspended material such as sewage. Target meters are evaluated in Table 31.

Other

Brief mention will be made here of a few other force-displacement type flowmeters. They do not appear well suited for storm or combined sewer flow measurement at this time, but are included since special adaptations may be possible in some situations.

TABLE 29. VANE DEFLECTION METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☒ Moderate	☐ Slight
7	Flow Obstruction	☒ High	☐ Moderate	☐ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☒ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☒ Fair	☐ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☒ No		☐ Yes

TABLE 30. HYDROMETRIC PENDULUM EVALUATION

	Evaluation Parameter	Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☒ Poor	☐ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☒ Moderate	☐ Slight
7	Flow Obstruction	☐ High	☒ Moderate	☐ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☐ Fair	☒ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☒ No		☐ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☒ High	☐ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☒ No		☐ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☒ Fair	☐ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☐ No		☒ Yes

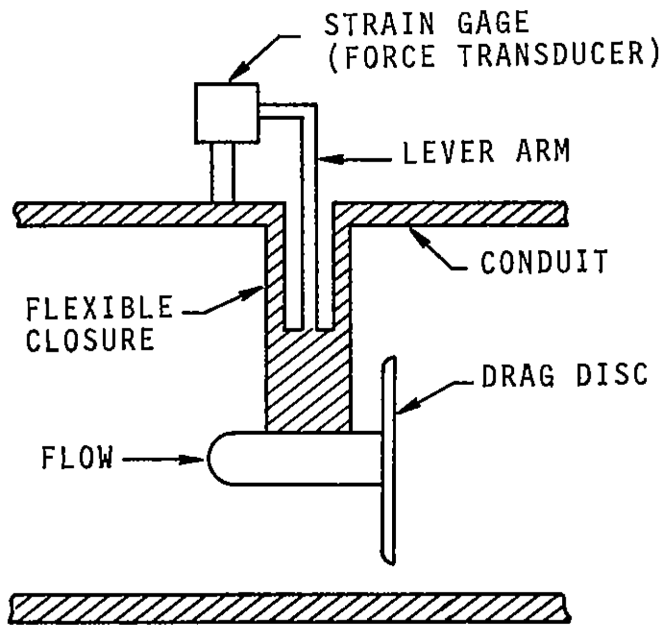


Figure 31. Target Meter

TABLE 31. TARGET METER EVALUATION

Evaluation Parameter		Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☒ Moderate	☐ Slight
7	Flow Obstruction	☒ High	☐ Moderate	☐ Slight
8	Head Loss	☐ High	☒ Medium	☐ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☒ Medium	☐ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☒ High	☐ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☐ Moderate	☒ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☒ Poor	☐ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

The jet deflection meter is a development reported by Stanney (56) in which a fluid jet is directed across the flow stream towards two impact tubes on the opposite side. The flow stream displaces the jet an amount proportional to the flow rate, thereby creating a differential pressure between the two impact tubes that is a linear function of the flow velocity of the measured fluid. Like many so-called fluidic devices for measuring flow, it is primarily suitable for gas flows. It has been used for clean water flow velocities from 0.03 to 0.3 m/s (0.1 to 1 fps). Accuracies of ±1% have been obtained over flow ranges of 5:1. The device does not appear at all suitable for dirty liquids and, consequently, will not be discussed further.

The ball and tube flowmeter consists of a tube (usually transparent) bent through 180 degrees into some shape of an arc, semicircular being the original design. The tube is placed in a vertical plane concave upward, and a ball (primary element) of density greater than the liquid and diameter smaller than the tube is placed inside. The flow creates drag forces on the ball, and it rises in the tube until they are balanced by the gravity forces; thus, the position of the ball along the tube is a measure of the flow rate. The device should not be confused with the rotameter which uses a taper so that the area varies as the float is displaced. Of course, ball and tube flowmeters are only suitable for pressurized flow. They are not obtainable commercially (to the writers' knowledge), but can be easily fabricated in the laboratory. Accuracies of around ±2-5% can be achieved over flow ranges of up to 5:1. When maximum design flow rates have been appreciably exceeded, the ball will be lost unless provision is made for capturing it at some point.

Another interesting force-displacement type of flowmeter utilizes a variable weight principle. It consists of a vertical section of pipe (usually transparent) containing a float of density slightly less than that of the fluid to be measured. A chain is fastened to the bottom of the float. The device operates under pressurized flow conditions with flow in the upward direction. As the flow rate increases, the float rises and in so doing picks up a larger portion of the chain, thus effectively varying its weight. The height of the float in the tube is a measure of the flow rate. This device is also not commercially available to the writers' knowledge.

FORCE - MOMENTUM

Force-momentum flowmeters measure the mass flow rate of the fluid as opposed to its volumetric flow rate. Several instruments for which the measured variable is directly related to mass flow will be discussed below. Those that add mechanical energy to the system, such as the transverse momentum devices, generally require a constant speed drive and rotating seals.

Axial Flow Mass Meter

The axial flow mass meter uses a turbine driven at constant speed to induce a constant angular velocity to the fluid and a complementary spring-retained rotor to measure the force required to overcome the angular momentum. The angular displacement of the retained rotor is directly related to the mass flow of the fluid. The axial-flow, transverse-momentum device is the most common of this type and is available in several configurations. They can be quite accurate (±0.5% of reading) over ranges, typically, of 10:1. They clearly are suited only for pressurized flows and clean fluids.

Radial Mass Meter

This device, often referred to as a Coriolis mass flowmeter, has a primary element resembling a centrifugal pump. The fluid is accelerated radially, and the torque required to accomplish this is proportional to the mass flow of the fluid. These devices have been discussed by Halsell (57). They produce a pressure rise, rather than drop, and have been successfully used with liquids, foams, and slurries. Accuracies of ±1% over of 10:1 range have been achieved.

Gyroscopic Mass Meter

This meter consists of a circular pipe loop, the fluid flowing through it constituting a gyroscope. If a gyroscope is rotated about a perpendicular axis, a torque is created due to precession effects. Like the other mass flowmeters, a constant-speed motor and rotating seals are required (in one design the gyro is vibrated rather than rotated, and flexible couplings replace the rotating seals). The meter is an unobstructed pipe so it is suitable for handling troublesome liquids and flows high in solids. Pressure losses are low, but external power is required and the meter is quite expensive. Its range and accuracy are similar to the other mass meters.

Magnus Effect Mass Meters

The Magnus effect, discussed by Schlitchting (46) and others, is the phenomenon that produces a differential force on a body spinning in a flow field. (It allows golfers to slice and baseball pitchers to throw curves, for example.) The force is proportional to the fluid velocity and density and to the surface speed of the rotating body among other factors. In the Magnus-effect mass meter, a rotating cylinder is immersed with its axis at right angles to the flowing stream. Since the cross-section of the conduit and the surface speed of the cylinder are constant, the mass flow is a direct function of the "lift" on the cylinder, which is measured with suitable transducers. Again, the meter requires a constant speed drive and rotating seals. The spinning cylinder poses a rather severe flow obstruction, and the device is not suitable for dirty flows.

Force-momentum meters as a group are evaluated in Table 32.

THERMAL

Thermal flowmeters were originally developed for the measurement of gas flows but have also found application in liquid flows in recent times. In view of the extremely rapid response times that are achievable with some designs, they have been especially useful in the study of turbulent boundary layer structures and the like. Fundamentally, they all work on the principle that heat transferred between a body and a flowing stream is related to the rate of flow.

Hot Tip Meters

When an electrically heated (bead, wire, film, etc.) is placed in a flowing fluid, heat will be transferred from the element to the fluid at a rate that is a function of: (a) the velocity of the flow; (b) the temperature, density, viscosity, and thermal conductivity of the fluid; and (c) the temperature, geometry, and properties of the element. If all but one of the fluid-flow and element variables are kept constant, the heated element is a transducer for measuring the remaining variable. A few typical hot-tip element configurations are depicted in Figure 32.

Two methods are used in flow measurement. The first technique employs a constant current passing through the sensing element. Variation in flow results in changed element temperature; hence, changed resistance, which thereby becomes a measure of flow. The major drawback of the constant current system is that the frequency response of a sensor depends not only on sensor characteristics, but also on flow characteristics. The response depends on both the thermal capacity of the sensor and the heat transfer coefficient between the sensor and its environment. Since the sensor response varies with changes in flow (changing the heat transfer coefficient), the frequency compensation of the amplifier must be readjusted whenever the mean flow changes.

The constant temperature type of compensating circuitry overcomes the primary disadvantage just mentioned in the constant current system by using a feedback loop. As the velocity past the sensor increases, the sensor will tend to cool with a resulting decrease in the resistance. This resistance decrease will cause the voltage to decrease, thus changing the input to the amplifier. The phase of the amplifier is such that this decrease in voltage will cause an increase in the output of the amplifier in order to increase the current through the sensor. The output of the constant temperature system is the voltage output of the amplifier, which in turn is the voltage required to drive the necessary current through the sensor.

TABLE 32. FORCE-MOMENTUM METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☐ Fair	☒ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☒ Moderate	☐ Slight
7	Flow Obstruction	☐ High	☒ Moderate	☐ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☒ High	☐ Medium	☐ Low
11	Site Requirements	☒ High	☐ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☒ High	☐ Moderate	☐ Slight
13	Simplicity and Reliability	☒ Poor	☐ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☒ High	☐ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☐ Moderate	☒ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☒ Poor	☐ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

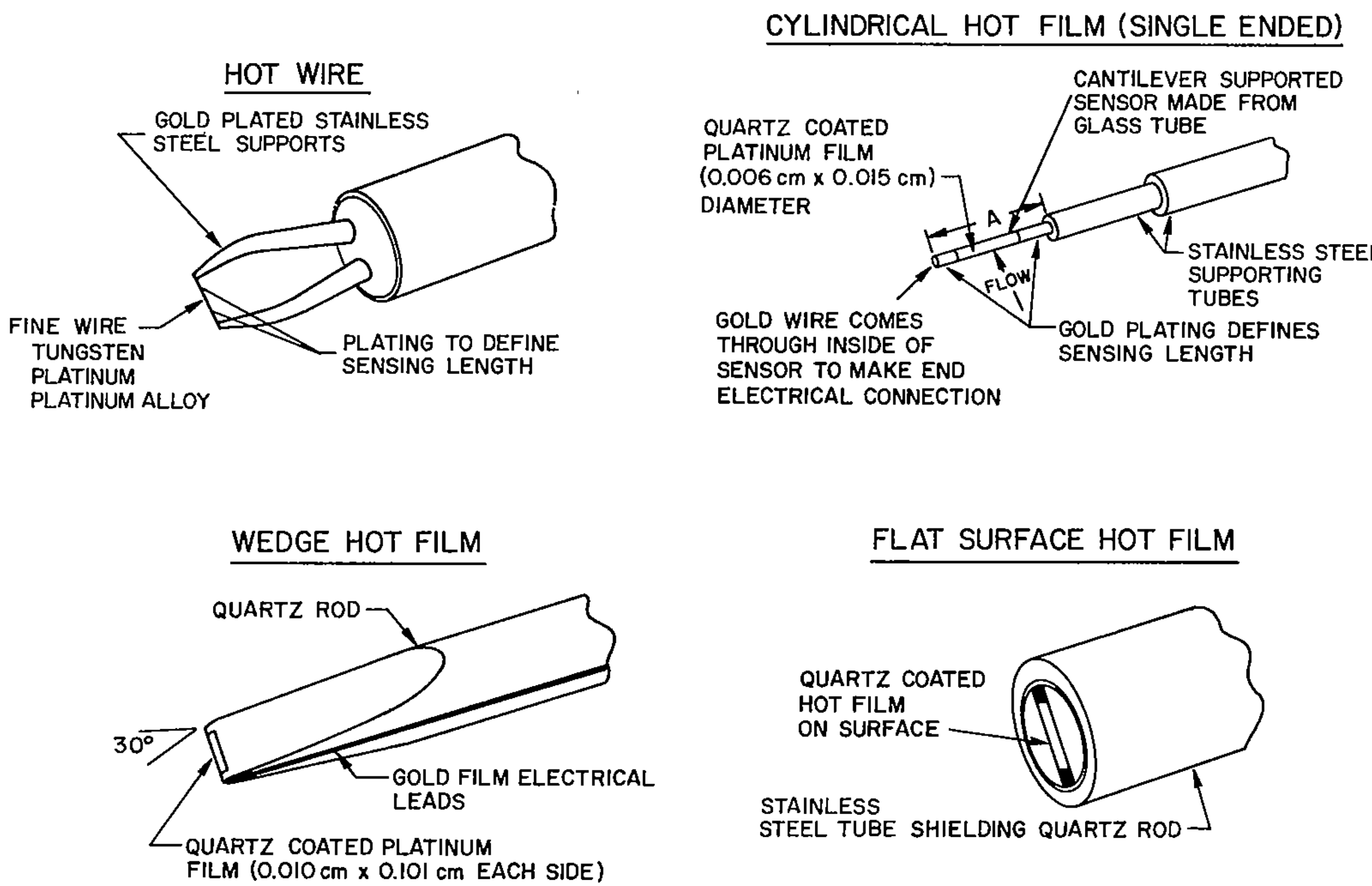


Figure 32. Typical Hot-Tip Element Configurations

Ling (58) introduced the hot-film probe for use in liquid flows in 1955. Since then, a number of investigations have been carried out in liquids with only a few being successful. In most of these, the film was placed away from the wall since its size can interfere with the detailed measurements required in the sub-layer region. Indeed, different configurations of film probes have produced very different results within the same experiment even for the simple case of measuring velocity profiles in turbulent flows. The one type of film probe that holds promise of being applied to sewer flow is the flush-mounted probe, because the backing material does not interfere with the flow field and has the best chances of physical survival in the sewer environment. Very little research has been done to determine the feasibility of using flush-mounted, hot-film sensors for quantitative measurements in water because the electrolysis problem has only recently been solved through the use of quartz coatings. Runstadler, et al (59) give a very concise summary of the factors that significantly affect the stable non-drift operation of hot-film probes in water. Hot-tip probes are evaluated in Table 33.

Cold-tip Meters

Harris (60) has described a sort of inverse of the hot-tip meters. The operating principle of his device involves the use of a thermoelectric cooling unit to provide a cold surface in contact with the stream flow. The temperature of the cold surface is then, of course, a function of stream velocity and the other factors noted in the discussion of hot-tip devices. This approach would offer advantages when applied to a fluid containing dissolved gases which tend to come out of solution when heated by a hot-tip type element. The temperature difference between the probe and the fluid must be even smaller than with the hot-tip devices, however, because most storm and combined sewer flows are closer to their freezing temperatures than their boiling points. The ice formations will affect calibration. Although interesting, it is not felt that cold-tip devices are ready, as yet, for application as sewage flow measuring devices. Most of the evaluation comments of Table 33 hold for cold-tip devices also.

Boundary Layer Meter

Laub (61, 62) and Barlow (63) describe a boundary layer meter wherein the heater and temperature measuring elements are on the outside of the conduit. With this design, only the layer of fluid immediately adjacent to the inner wall of the conduit is heated. Response times of under a second are possible as is temperature compensation. There is no obstruction to the flow in such a design, so the meter introduces no additional head loss. Errors can result from changes in fluid composition which would change the parameters affecting thermal devices (e.g., viscosity, specific heat, thermal conductivity, etc.). The device would appear to overcome many of the other objectionable features of the hot-tip designs, however. Good ranges (50:1) and accuracies (±1%) are achievable under ideal circumstances, but should not be expected in a sewage measurement application.

TABLE 33. HOT-TIP METER EVALUATION

Evaluation Parameter		Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☒ Poor	☐ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☐ No		☒ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☒ High	☐ Moderate	☐ Slight
7	Flow Obstruction	☐ High	☒ Moderate	☐ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☒ Fair	☐ Good
10	Power Requirements	☐ High	☒ Medium	☐ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☒ High	☐ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

As in the case of thermal probes, it is possible to locate a number of sensors along the vertical (here, around the periphery of the conduit if round) and thereby measure depth as well as velocity under open channel flow conditions. Such designs have recently become available, but experience with them is limited as yet.

Eshleman and Blase (64) describe a related device which is more properly termed a thermal time-of-flight flowmeter. It is actually a tracer technique, but here the tracer is energy in the form of heat. A heater element is used to introduce a slug of heat (a thermal wave) into the boundary layer flow. Temperature compensated thermistors, located a known distance downstream, were used to detect the heat pulse (extremely complex electronics were required) and its time of flight was determined. This velocity could be related, through calibration, to mean flow velocity, but accuracy and repeatibility were poor in the device as designed. Thermal boundary layer meters are evaluated in Table 34.

ELECTROMAGNETIC

In 1839, Michael Faraday attempted to measure flow by lowering large electrodes into the Thames River near the Waterloo bridge. This experiment did not succeed. Faraday's Law states that if a conductor (in this case the flowing fluid) is passed through a magnetic field, a voltage will be inducted across the conductor at right angles to both the lines of flux and the direction of motion and will be proportional to the velocity of the conductor and the strength of the magnetic field.

Today, there are a number of successful designs of electromagnetic flowmeters, all based upon Faraday's Law. All share the same fundamental components, but they differ in their design of implementation, ranging from meters for measuring pressurized flow in pipes to point velocity sensors. Their earliest successful adaptations were in sea-water applications such as oceanographic current meters and logs for indicating ships' speed. When applied to a pipe flowmeter, the fundamental components are a piece of straight pipe, electrical coils to produce a magnetic field perpendicular to the axis of the pipe, and a pair of diametrically-opposed electrodes orthogonal to the magnetic field and the pipe axis (Figure 33). For a velocity probe (Figure 34) the same fundamental components are involved, but they are in a sort of "inside out" arrangement as compared to the pipe meter. The theory of electromagnetic flow measurement is treated in the monograph by Shercliff (65).

There are a number of parameters of the flowing stream that must be considered in the application of electromagnetic flowmeters. These include: corrosion levels, abrasion levels, possible magnetic content, presence of entrained gases, and the ability to coat electrodes. The devices can tolerate low fluid conductivity, e.g., some work with distilled water, and design features can be incorporated to overcome most problems posed by undesirable fluid characteristics.

TABLE 34. THERMAL BOUNDARY LAYER METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☐ Fair	☒ Good
2	Accuracy	☐ Poor	☐ Fair	☒ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☐ No		☒ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☒ Medium	☐ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☐ Moderate	☒ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

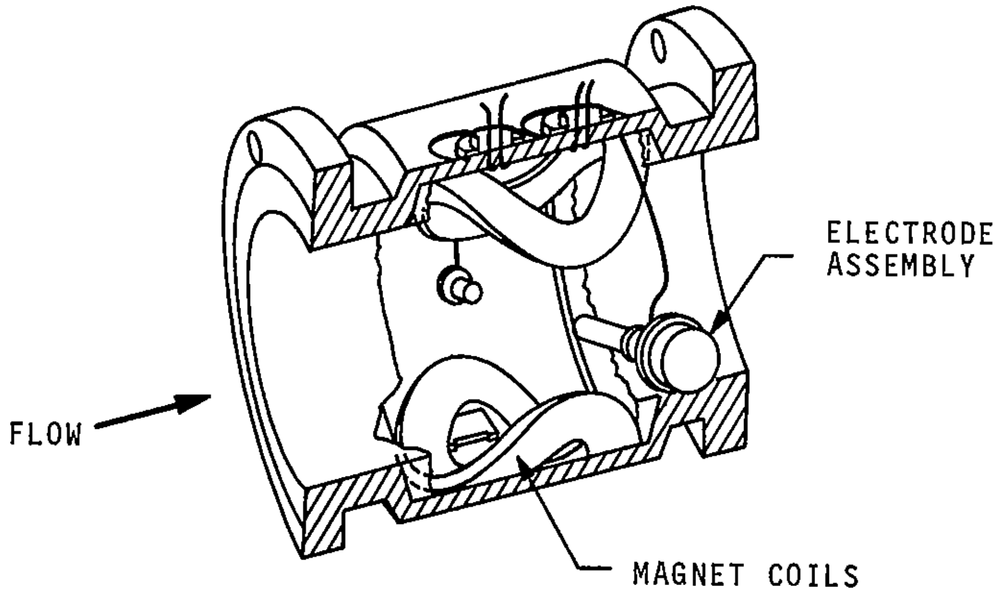


Figure 33. Components of an Electromagnetic Pipe Flowmeter

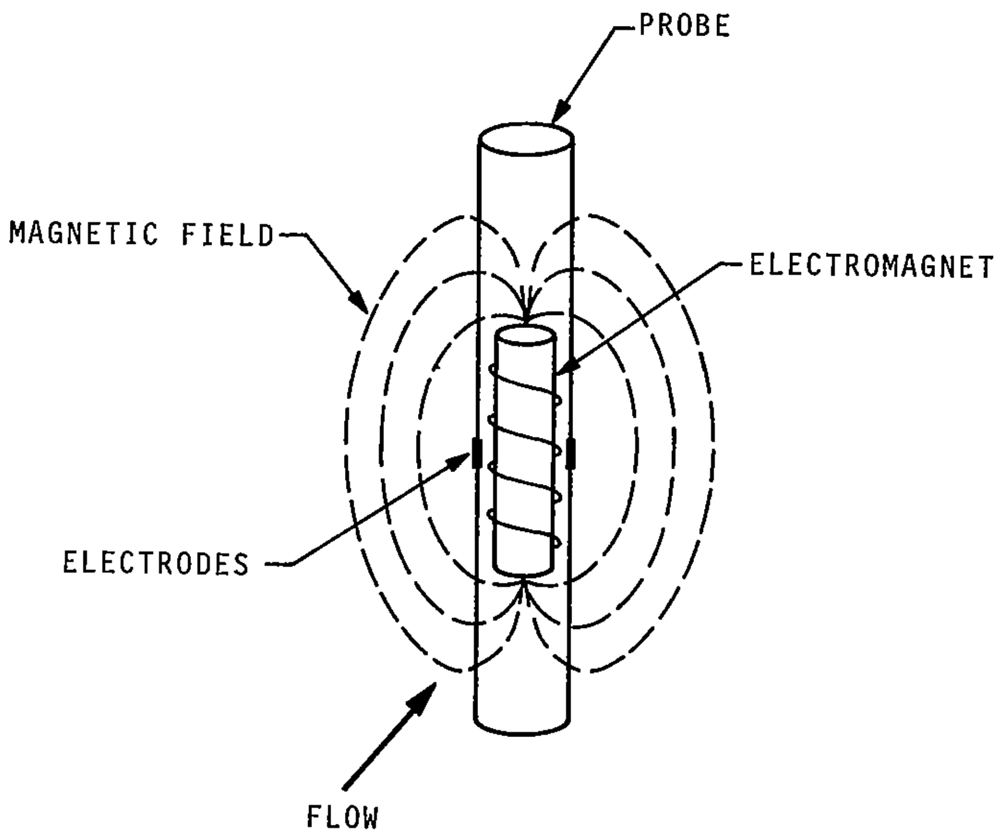


Figure 34. Components of an Electromagnetic Velocity Probe

An alternating polarity magnetic field (ordinarily or at near 60 Hz) is usually generated to avoid thermoelectric effects, electro-chemical effects, and DC detection problems. A difficulty is that the alternating magnetic field can cause a quadrature voltage (induced noise) problem resulting in an offset in the zero point (thus indicating flow when there is none). Quadrature is not constant, but can change due to electrode fouling (5-10 percent output zero shifts are not uncommon when electrode coating occurs). The problem is reduced by using self-cleaning electrodes and superimposing a signal equal in amplitude but 180 degrees out of phase (null adjustment). One design uses a quadrature rejection circuit to virtually eliminate zero shifts. Although normally used only under full pipe flow conditions, an electromagnetic pipe flowmeter will work if the pipe is less than full (e.g., down to about half), but an additional measurement, the fluid depth, is required to determine flow rate. It is also possible to mount a number of sensors up the wall of the conduit to measure both velocity and depth. Such an arrangement should be capable of measuring both open channel and pressurized flows. Except in attended use as a current meter, the probe configuration, because of its necessary obstruction to the flow, is not as desirable for measuring storm or combined sewer flows.

These devices have only relatively minor disadvantages (fouling of electrodes in some designs, susceptibility to the presence of stray electrical and magnetic fields) except for their relatively high power consumption, which makes battery operation for extended periods impractical. Electromagnetic flowmeters have a number of inherent advantages. They are capable of very high accuracies (better than ±1% of full scale) over fairly wide ranges (20:1 or more in many standard designs, and higher in configurations mentioned above) and can measure flow in either direction. They introduce very little pressure loss, have no moving parts, their response time is rapid (less than one second), and output is linear. The devices are fairly expensive, however. Electromagnetic flowmeters are evaluated in Table 35.

ACOUSTIC

The scientific use of acoustic principles in instrumentation today has its roots in the SOund Navigation And Ranging (SONAR) equipment developed during the Second World War. The fundamental principles were known, of course, before that time, and the depth of wells has long been measured by discharging a blank shell from a gun and using a stopwatch to determine the echo return time. Because most equipment in use today operates at frequencies above the audio range, the term ultrasonic is used by many writers when referring to this class of devices. A very recent article by Liptak and Kaminski (66) provides a comprehensive survey of the field.

Acoustic meters have two classes of application in flow measurement today; as secondary devices to continuously monitor liquid level (or stage) and as primary devices to measure actual flow velocity. Common

TABLE 35. ELECTROMAGNETIC FLOWMETER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☐ Poor	☐ Fair	☒ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☐ No		☒ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☒ High	☐ Medium	☐ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☐ Moderate	☒ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

to both is the measurement of the travel time of acoustic pulses between a transmitter and receiver. The two applications will be discussed in turn.

Continuous measurement of liquid depths is accomplished by measuring the time required for an acoustic pulse to travel to the liquid-air interface (where it is reflected) and return. The transmitter and receiver may be separate physical entities or may be combined. There are two fundamental physical arrangements as depicted in Figure 35. One uses air path measurement and the other uses liquid path measurement. Although better short-term accuracy can be achieved with liquid path arrangements, for wastewater applications the air path arrangement is more common since it simplifies installation, is independent of fluid velocity, and avoids any contact with the flow.

When flow (velocity) measurement is to be accomplished, it is not the velocity of sound that is measured but, rather, the differential velocity between travel in the upstream and downstream directions. Since the acoustic devices are actually velocity sensors, the area and vertical velocity profile across the flow must be known. For open-channel flow, the depth must also be determined and, understandably, manufacturers generally use acoustic level sensors for this purpose. For widely varying flow depths, sensor placement is critical, and more than one pair of sensors may be required.

As noted by Liptak and Kaminski (66), acoustic flow sensing or measuring equipment (like sonar) falls into one of two rather broad categories, passive and active. In passive operation, the transducer does not emit any acoustic energy but simply acts as a receiver. Flow switches (on/off state indicators) usually sense the noise generated by the flowing stream and provide indication that some predetermined threshold value has been exceeded. Passive flowmeters are either immersed in the flowing stream or, as in the case of open-channel flow, can be located in air. Fundamentally, they operate on the idea that, as the flow in the conduit increases, the sound level also increases in some direct and repeatable manner. Only two commercial firms offer such equipment, and considerable work would be required before they could be reliably used in a storm or combined sewer flow measurement application. This is discussed further in Section VIII.

There are a number of active acoustic flowmeter designs available today. They all use at least one pair of transducer sets (transmitter/receiver), so located that one operates against the direction of flow and the other operates with the flow. A few physical arrangements are indicated in Figure 36. Differences occur in the details of implementation; e.g., sensor geometry, sensors immersed in the flow or fastened to the outside of the conduit, sensors projecting into the flow, flush mounted, or recessed in wells, etc. There are also three fundamental approaches to determining the velocity of the flow in present equipment designs - differential time circuits, total travel time circuits, and "sing-around" circuits.

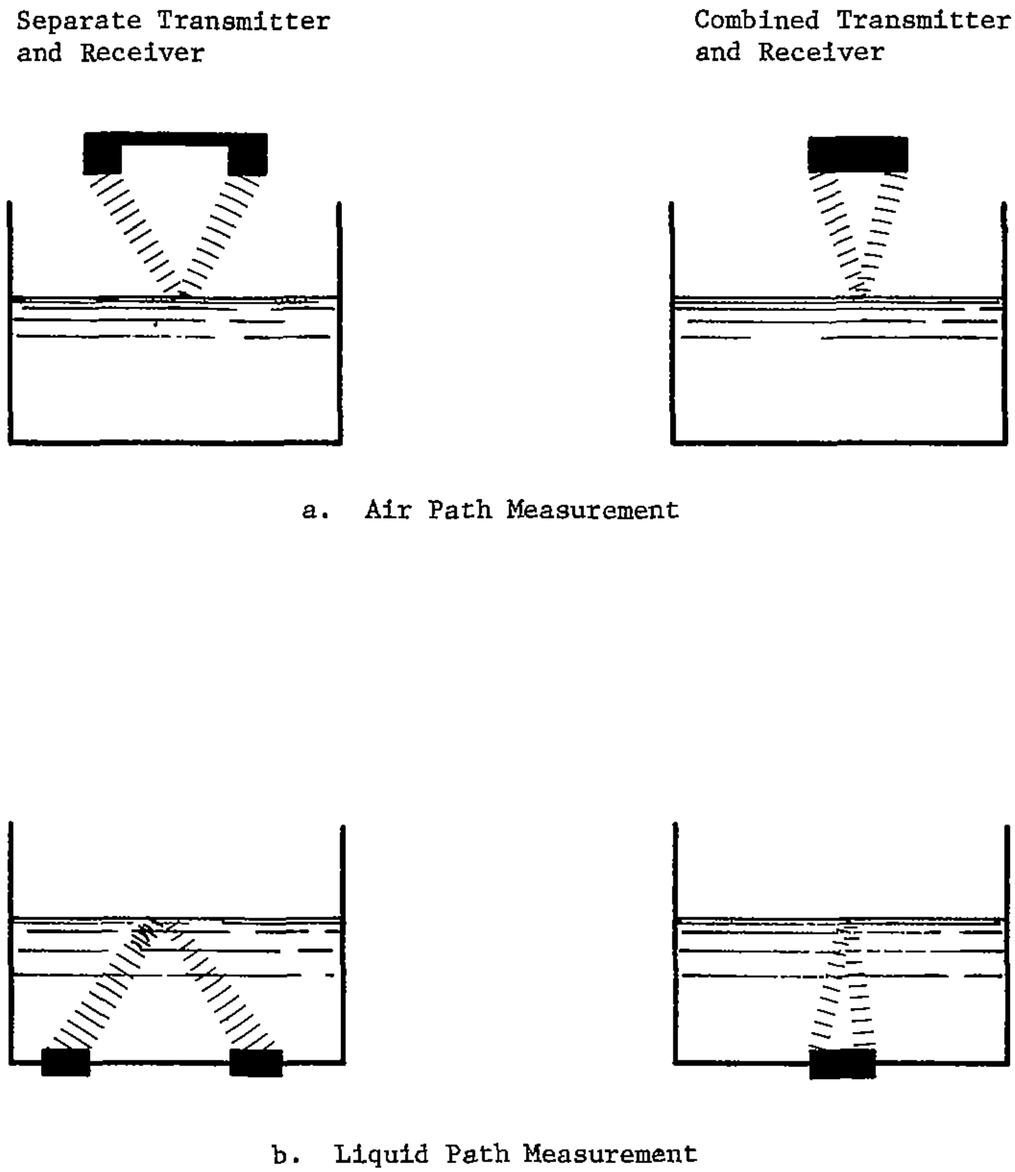
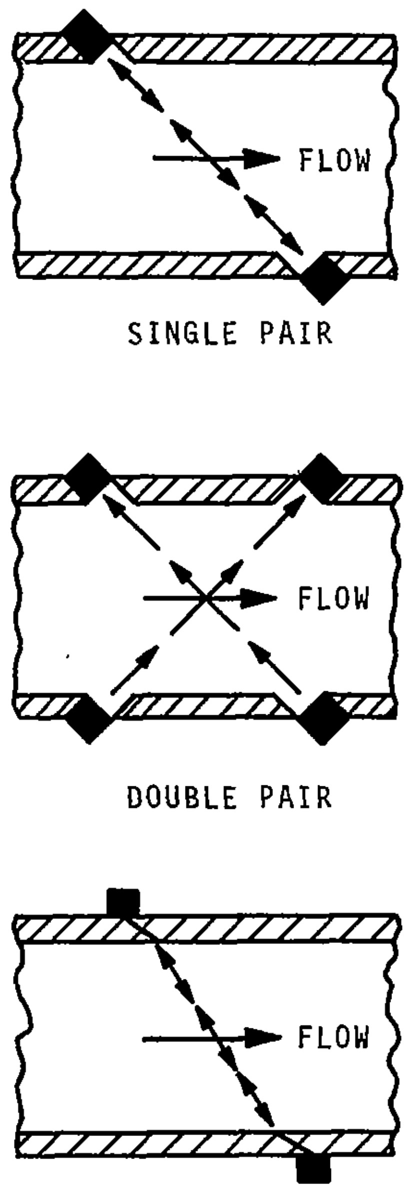


Figure 35. Physical Arrangements of Acoustic Depth Sensors



a. WETTED TRANSDUCERS

b. CLAMP-ON TRANSDUCERS

Figure 36. Physical Arrangements of Acoustic Velocity Sensors

In the differential time circuit, the difference in the time of arrival of acoustic pulses, which are triggered simultaneously at each end of a diagonal path across the stream, is measured directly. When the two transmitters send signals simultaneously toward each other, the flow of water will increase the effective speed of one and decrease that of the other. The signal transmitted in the downstream direction arrives first, and is used to start a timer, which runs until the signal transmitted in upstream direction arrives. This time increment is thus the differential between the total travel times involved and is linearly proportional to the fluid velocity. The average total travel time must also be recorded to compensate for changes in the speed of sound of the fluid. This technique is not well suited for small conduits with low velocities because the time differences may be on the order of nanoseconds.

In the total travel time circuit, the flow velocity is computed by resolving the velocity component in the flow direction as computed from the sequential travel times required for pulses to travel; e.g., first from the downstream sensor to the upstream sensor and then from the upstream sensor to the downstream sensor. Since the total travel times are used, changes in the speed of sound in the fluid are automatically compensated for. Errors in indicated velocity are a linear function of timing errors in either direction.

The sing-around circuit technique is sometimes referred to as a pulse-repetition frequency technique. In it, cumulative measurements of travel times are made by using the received pulse at the far end of an acoustic path to immediately trigger a second pulse from the originating transmitter. Arrival of the second pulse triggers a third, and so on. Either the total time required for completion of a fixed number of cycles is measured or the cycling rate is reduced to a continuous, pulse-repetition frequency. Where a single pair of transducers is employed, measurements are made in one direction for a given period and then in the other. Sometimes two pairs of transducers are used (tuned to different frequencies) and operated simultaneously. By using the difference in the upstream and downstream frequencies to determine the flow velocity, the dependence upon the sound velocity of the fluid is eliminated.

From the foregoing discussion it can be seen that one of the most important factors in any acoustic flow measuring device is the accurate measurement of time (or its inverse, frequency). As noted by Smoot (42), four different signal-recognition methods have been used in various designs on the market today - the leading-edge detection method; a method that utilizes the differential of the voltage time pulse train; the zero-crossover method; and the phase difference method. There are advantages and disadvantages to each, and competing claims have been made by proponents of one method or another.

In summary, acoustic liquid velocity sensors have not yet reached the state of the art where they can be considered as simple, off-the-shelf items for wastewater flow application. They offer many advantages, but tend to be relatively expensive for some installations and require highly trained technicians for their repair and maintenance. Accuracies to ±0.5% of full scale are achievable, but numbers as high as ±5% must often be considered more typical, especially for a wastewater application. Ranges from 20:1 to 1000:1 are possible, depending upon design details discussed earlier. Acoustic meters are evaluated in Table 36.

DILUTION

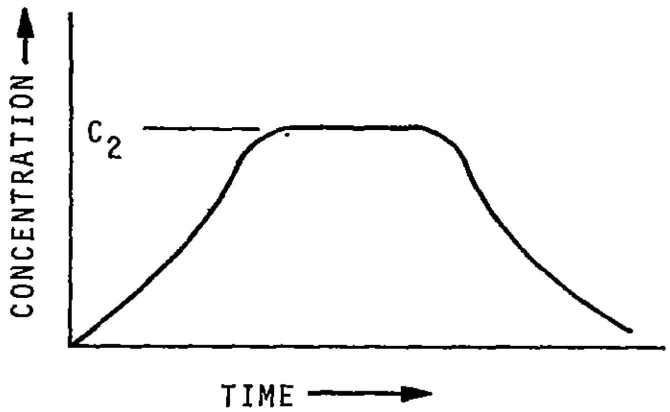
The dilution method can be used to measure discharge directly without experiencing many of the difficulties of other devices. It can be used in any shape of conduit flowing either partially full or under pressure and does not involve the stream dimensions or measurement of fluid properties such as pressure, temperature, or even level. It produces no pressure loss, requires no drop in hydraulic grade line, offers no obstruction to the flow, and indicates flow rate directly by simple theoretical formulas.

Basically, the measurement of discharge by dilution methods depends upon determining the degree of dilution of an added tracer solution by the flowing water. Spencer and Tudhope (67) have noted that dilution methods have been known since at least 1863. Although the earliest tracers were brine, radioactive and fluorescent dye tracers are more commonly used today. They have greatly reduced the quantities of tracer substance required and increased the accuracies achievable in many instances. For example, the fluorescent dye Rhodamine WT can be quantitatively detected with an accuracy of ±1% in concentrations of less than 10 parts per billion.

There are two general techniques used in dilution flow measurement: the constant-rate injection method and the total-recovery method (called the slug-injection method by some writers). These are depicted in Figure 37. As its name implies, the constant-rate injection method requires that the tracer solution be injected into the flow stream to be measured at a constant flow rate for a given period of time. The discharge is determined by the simple formula given in Figure 37a involving the background concentration in the stream (if any), the tracer concentration and injection rate (both presumably controlled and known), and the measured plateau of the concentration-time curve at the measurement site. In the total-recovery method, a known quantity of the tracer solution is introduced into the stream in any one of a number of ways, and a continuous sample is removed at a uniform rate for the entire time needed for the tracer wave to pass, in effect integrating the concentration-time curve. This integral is sometimes approximated by using a series of successive discrete samples. The discharge is simply related to the total quantity of tracer injected and the integral of the concentration-time curve as indicated in Figure 37b. This latter method requires that the total volume of the tracer be accounted for at the measurement site.

TABLE 36. ACOUSTIC METER EVALUATION

Evaluation Parameter		Scale		
1	Range	☐ Poor	☐ Fair	☒ Good
2	Accuracy	☐ Poor	☐ Fair	☒ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☐ No		☒ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☒ Moderate	☐ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☒ Fair	☐ Good
10	Power Requirements	☐ High	☒ Medium	☐ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☐ Moderate	☒ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes



a. CONCENTRATION-TIME CURVE FOR CONSTANT-RATE INJECTION METHOD.

$$Q = \left(\frac{C_1 - C_2}{C_2 - C_o}\right) q$$

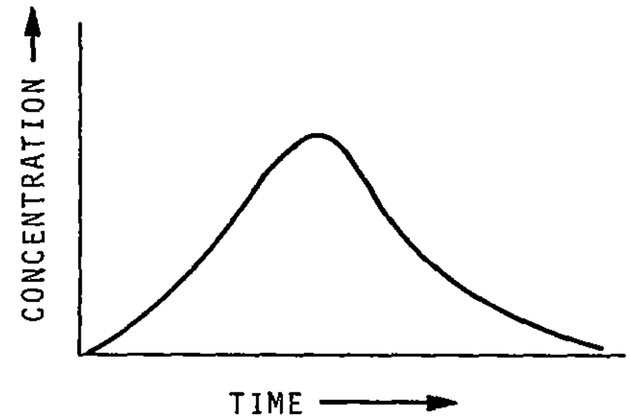
Q IS FLOW RATE OF STREAM

q IS FLOW RATE OF CHEMICAL

C_o IS BACKGROUND CONCENTRATION OF STREAM

C_1 IS CONCENTRATION OF CHEMICAL INJECTED

C_2 IS CONCENTRATION OF STREAM PLATEAU



b. CONCENTRATION-TIME CURVE FOR SLUG-INJECTION METHOD.

$$Q = \frac{v\ C_1}{\int_o^\infty (C - C_o)dt}$$

Q IS FLOW RATE OF STREAM

v IS VOLUME OF CHEMICAL INJECTED

C_o IS BACKGROUND CONCENTRATION OF STREAM

C_1 IS CONCENTRATION OF CHEMICAL INJECTED

C IS INSTANTANEOUS STREAM CONCENTRATION

Figure 37. Chemical Dilution Methods

Although each of these dilution methods has its advantages and limitations, they are basically similar. A fluorometer, geiger counter, or some other appropriate instrument is required for determining sample concentration, a method of extracting a sample for analysis is needed, and a device to either inject tracer at a steady known rate or withdraw sample at a steady (but not necessarily known) rate is required. Both methods require complete vertical and lateral mixing at the measurement site. Since vertical mixing usually occurs rather rapidly as compared to lateral mixing, the latter usually controls the distance required for complete mixing, and hence, the distance between the injection and measurement sites. Cobb and Bailey (68) provided a thorough discussion of dye-dilution methods, in which they recommend calibration of the measurement reach (the length between injection point and measurement point) to ascertain the required mixing length and to determine relative tracer losses (due to adsorption by pipe walls or solids for example).

The effect of inflow or outflow in the measurement reach will cause the point of flow determination to shift for a dilution-type measurement. Where there is no inflow or outflow in the measurement reach, the measured flow will be the flow occurring at any point in the reach. If there is inflow within the measurement reach and it is totally mixed with the stream at the measurement point, the flow measured will be that at the measurement point, not the injection point. If there is outflow from the measurement reach but after complete mixing of the tracer has occurred, the flow measured will be that at the injection point, not the measurement point.

Replogle, et al (69) report achieving accuracies of better than ±1% in laboratory flume measurements using dye dilution techniques and Kilpatrick (70), making dye-dilution discharge measurements on the Laramie River under total ice cover, obtained agreement of better than +2% (+0.6% in one case) as compared with current meter measurements. Shuster (71) reports obtaining accuracies better than ±3% using radioisotopes as a tracer. He found that, in the concrete-lined trapezoidal channel used in his study, the length required for almost complete mixing was 250 to 300 times the flow depth. Ranges of 1000:1 or better can be achieved. One popular use of the technique is to calibrate other primary devices. The main disadvantages of dilution techniques are the cost associated with the instrumentation required for determining tracer concentrations, the lack of ruggedness in some of their designs, and the required training for operator personnel. The dilution method is evaluated in Table 37.

OTHER

There are a number of less widely used flow measurements that do not fit well under any of the more traditional classifications discussed so far. They will be discussed here.

TABLE 37. DILUTION METHOD EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☐ Fair	☒ Good
2	Accuracy	☐ Poor	☐ Fair	☒ Good
3	Flow Effects on Accuracy	☐ High	☒ Moderate	☐ Slight
4	Gravity & Pressurized Flow Operation	☐ No		☒ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☐ Fair	☒ Good
10	Power Requirements	☐ High	☒ Medium	☐ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☐ Moderate	☒ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☒ No		☐ Yes
20	Precalibration	☒ No		☐ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☐ No		☒ Yes

Doppler

A fairly recent technique for measuring the velocity of flow in a liquid stream makes use of the doppler effect. Such devices, called scatter frequency shift devices by some writers, may utilize any one of a number of forms of radiated energy, including ultrasonic wavelengths, infrared, ultraviolet, laser, etc. They operate on the principle that when a beam of energy is projected into a nonhomogeneous liquid, it is scattered by suspended particulate matter in the fluid, and some of it is reflected back to a receiver. Owing to the doppler effect, the frequency of the return signal reflected from the scatterers in the fluid differs from that of the transmitted signal provided there is a net movement of the nonhomogeneities with respect to the transmitter or receiver. This frequency shift is directly related to the velocity of the scatterers (among other factors) and, if they are stationary with respect to the liquid, to the flow velocity itself. The scatterers can range from solid particles to gas bubbles, the only requirement being that they move at the same velocity as the flow transporting them.

It is pointed out that such devices usually sense velocity only in a very small region (where the transmitter and receiver signals cross) and, hence, knowledge about the velocity profile is normally necessary in order to infer total flow quantities. For example, at acoustic frequencies of 5-10 MHz, the reverberation volume is on the order of 0.003m (0.01 ft) in diameter. This has been used to advantage in laboratory studies of boundary layer development using laser-doppler devices.

Acoustic-doppler devices have been investigated by the U.S. Geological Survey over a period of several years. As noted by Smoot (42), their experience has been less than totally successful. Under good conditions, i.e., size and concentration of suspended particulate matter, the meter functions very well, but when concentrations are too low (or particle sizes too small) or too high, there is either sporadic or no signal return. A further limitation of such devices is the need for temperature and composition compensation. Under ideal conditions, Doppler meters can yield accuracies of ±0.5% over ranges of 10:1 or higher. They are expensive, however, and little applications data are available. Doppler meters are evaluated in Table 38.

Optical

The U.S. Geological Survey and the California Department of Water Resources have developed a meter which uses optical methods to determine surface velocities of streams; see Buchanan and Somers (49) or Smoot (42). The meter is a stroboscopic device and essentially

TABLE 38. DOPPLER METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☐ Fair	☒ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☐ No		☒ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☒ High	☐ Moderate	☐ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☒ Fair	☐ Good
10	Power Requirements	☐ High	☒ Medium	☐ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☐ Moderate	☒ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

consists of a low-power telescope, a set of mirrors on the periphery of a drum, a variable-speed motor that rotates the drum at precisely-controlled speeds, and a tachometer for determining drum rotational speed. Velocity measurements are made from an observation point above the stream. Light coming from the water surface is reflected by the mirrors into the lens system and eyepiece. By adjusting the rotational speed of the drum, the apparent motion of the water surface images reflected by the mirrors slows down and stops, appearing as if the surface of the water was being viewed while moving along exactly in pace with it. The velocity can be determined by knowing this "null" speed of rotation and the vertical distance from the water surface to the optical axis of the meter.

The meter is a light-weight, battery-powered unit that has no parts in contact with the flowing stream. It can be used for quite high velocity streams and for flows heavily laden with debris and sediment (it was developed for flood use). It is not useful for low-velocity, tranquil flows, but has been used successfully to measure velocities ranging from 1.5 to 15.2m/s (5 to 50 fps). The optical meter is evaluated in Table 39.

Electrostatic

A very recent development by Alger (72) is the electrostatic flow meter. The concept arose from the observation that a stream of water discharging from a pipe into air appeared to possess a surrounding electrical field or charge. Experimental tests have been run using water as the flowing medium. The voltage between two dissimilar metal pipe sections (electrically insulated from each other) was measured at different controlled rates of flow, most of which were within the laminar range.

It is well established that a potential difference exists between two different metals immersed in a fluid containing ions of the metals. This is observed in the experimental set-up just described when there is no flow. Increasing the flow rate was found to produce an immediate decrease in the voltage. Decreasing the flow rate, however, caused an increase in the voltage which required some time before it would steady out. The voltage levels were also functions of certain elements of the system geometry (e.g., length of insulation between the two pipe sections), the type of metal pipe sections (steel and copper were used), and perhaps of the nature of the fluid (e.g., conductivity) as well. The method at present requires that the pipe be flowing full and under pressure. It offers no obstruction to the flow, head loss, etc., and could be rather inexpensive if it utilizes the natural elements of a fluid-pipe system. It is presently the subject of continuing research and cannot be considered as fully understood or suitable for practical use at this time. Therefore, no further discussion will be given.

TABLE 39. OPTICAL METER EVALUATION

Evaluation Parameter		Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☒ Poor	☐ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☒ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☐ Moderate	☒ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☒ No		☐ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☒ High	☐ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☒ No		☐ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☐ No		☒ Yes