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Recommended Practice for the Use of Parshall Flumes and Palmer-Bowlus Flumes in Wastewater Treatment Plants

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RECOMMENDED PRACTICE FOR THE USE OF PARSHALL FLUMES AND PALMER-BOWLUS FLUMES IN WASTEWATER TREATMENT PLANTS

by

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16. ABSTRACT

Parshall and Palmer-Bowlus flumes are suitable for in-plant open channel flow measurement of raw wastewater and treated effluent as well as wastewater in intermediate stages of treatment.

Parshall flumes are empirical devices which must be fabricated and installed according to specific requirements in order to yield the "standard" values of discharge. The discharge of Palmer-Bowlus flumes can be determined analytically within specified error limits provided that described criteria for construction and installation are met.

The accuracy of a flume-based measuring system depends upon a combination of the accuracies of the flume itself and the secondary instrumentation. The basic uncertainty of properly constructed and installed flumes is about ± 3 percent. If this uncertainty is unacceptable to the user or if there are fabrication and installation conditions, as described in the report, for which additional errors cannot be estimated, a field calibration of the flume must be made. Suggested methods of calibrating and monitoring the performance of the flumes and secondary instruments are described.

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FOREWORD

The U. S. Environmental Protection Agency was created because of increasing public and Government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

Parshall and Palmer-Bowlus flumes are suitable for in-plant open channel flow measurement of raw wastewater and treated effluent as well as wastewater in intermediate stages of treatment.

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The accuracy of a flume-based measuring system depends upon a combination of the accuracies of the flume itself and the secondary instrumentation. The basic uncertainty of properly constructed and installed flumes is about $\pm$ 3 percent. If this uncertainty is unacceptable to the user or if there are fabrication and installation conditions, as described in the report, for which additional errors cannot be estimated, a field calibration of the flume must be made. Suggested methods of calibrating and monitoring the performance of the flumes and secondary instruments are described.

CONTENTS

1. SCOPE

1.1 This practice describes the use of Parshall and Palmer-Bowlus flumes in wastewater treatment plants and/or in the sewers leading to the plants. The flumes are the primary elements of measuring systems which must also include secondary instruments to measure depth.

1.2 This practice covers
- Specifications for the measuring system
- Recommendations for its installation
- Methods for calibrating the system
- Guidelines for its maintenance and performance monitoring.

2. NOMENCLATURE AND DEFINITIONS

2.1 Nomenclature. Terms are defined here and where they first appear in the text.

- b = width of throat in Palmer-Bowlus flume
- b_o = bottom width of trapezoidal throat
- b^1 = throat width at flow surface
- c = tracer concentration, in flow measurement by dilution
- f = friction factor
- g = acceleration due to gravity
- Δh = depth lag in stilling well, equation [8]
- ℓ = length of stilling well pipe
- m = side slope of trapezoidal throat
- n = exponent in Parshall flume equation
- q = tracer injection rate, in flow measurement by dilution
- w = fluid weight per unit volume
- y = depth of flow
- A = area of flow cross section
- A_w = area of stilling well, equation [8]
- A_p = area of connector pipe, equation [8]
- C = coefficient in Parshall flume equation
- C' = coefficient in equation [8]
- C_d = discharge coefficient
- C_v = velocity of approach factor
- D = float diameter
- E_1 = specific energy above crest of Palmer-Bowlus flume
- F = force required to move float
- H_a = depth, for flowrate determination in Parshall flume
- H_b = depth, for submerged flowrate in Parshall flume
- H_c = depth, for submerged flowrate in Parshall flume
- H_1 = upstream depth over crest of Palmer-Bowlus flume
- L = throat length, Palmer-Bowlus flume
- Q = flowrate
- V = velocity of flow
- W = throat width, Parshall flume
- Δ = float lag

2.2 Definitions

2.2.1 Accuracy -- The closeness of a measured result to an accepted "true" value.

2.2.2 Boundary layer -- In a flow that is otherwise essentially frictionless, a (usually relatively thin) zone of wall influence in which the velocity decreases to zero at the boundary.

2.2.3 Critical flow -- A minimum specific-energy condition for a given open channel flowrate, wherein the average velocity is equal to the velocity of shallow-water waves in that depth; see also Froude number, Subcritical flow, Supercritical flow.

2.2.4 Flume -- In this context, a device that constricts an open channel flow in such a way that the volumetric flowrate is determinable as a function of a measured depth or depths.

2.2.5 Free flow -- In this context, a condition in which the flow depth downstream of the flume is not high enough to affect the flow over the flume and the flowrate can be determined from a single upstream depth measurement. See also Submerged flow.

2.2.6 Froude number -- A dimensionless number equal to the velocity divided by the square root of the product of the depth of flow and the acceleration due to gravity. A Froude number of unity corresponds to critical flow. See also Critical flow, Subcritical flow, Supercritical flow.

2.2.7 Head -- In this context, a height of liquid above a specific elevation, e.g., the flume crest.

2.2.8 Hydraulic jump -- A discontinuous transition from supercritical to subcritical flow usually accompanied by considerable turbulence and/or gravity waves.

2.2.9 Invert -- The inside bottom of a conduit.

2.2.10 Precision -- A measure of the reproducibility or repeatability of a measurement.

2.2.11 Primary element -- The device (in this case a flume) which creates a hydrodynamic condition that is sensed by the secondary element.

2.2.12 Repeatability -- See Precision.

2.2.13 Scow float -- An in-stream float, usually mounted on a hinged cantilever.

2.2.14 Secondary instrument -- A device (in this case for depth measurement) which senses a measurable parameter characteristic of the flow pattern created by the primary (flume). The secondary instrument often converts the measured depth to a flowrate readout.

2.2.15 Specific energy -- The energy of an open channel flow referenced to the channel bottom; in a rectilinear flow, this is the sum of the depth and velocity head.

2.2.16 Stilling well -- A small reservoir connected through a constricted passage to the main channel so that the depth measurement can be made under quiescent conditions.

2.2.17 Subcritical flow -- Free surface flows with Froude number less than 1.0; disturbances can travel upstream, so that downstream conditions can affect upstream flows.

2.2.18 Submerged flow -- A condition in which the flow depth downstream of the flume is high enough to affect the flow over the flume (by partially "submerging" the overfall from the flume crest). In this case both downstream and upstream depth measurements are needed to determine the flowrate.

2.2.19 Supercritical flow -- Free surface flows with Froude number larger than 1.0; disturbances cannot travel upstream so downstream conditions do not affect the flow. For a given discharge, supercritical flow features lower depths and higher velocities than subcritical flow.

2.2.20 Velocity head -- A measure of the kinetic energy of the flow and equal to the square of the average velocity divided by twice the acceleration due to gravity.

3. PRINCIPLES OF OPERATION

3.1 Parshall Flume

3.1.1 The general shape of the flume is seen in figure 1. Upon entering the flume the incoming flow passes through a section of lateral convergence and, when under "free flow" conditions, passes through a critical flow condition when it drops over the crest formed by the steeply sloped throat.

3.1.2 Depth-Discharge Relations.

3.1.2.1 With free flow as depicted in figure 1, the flowrate is related to the depth measured at a specified location by an equation of the form

$$Q = CH_a^n \qquad [1]$$

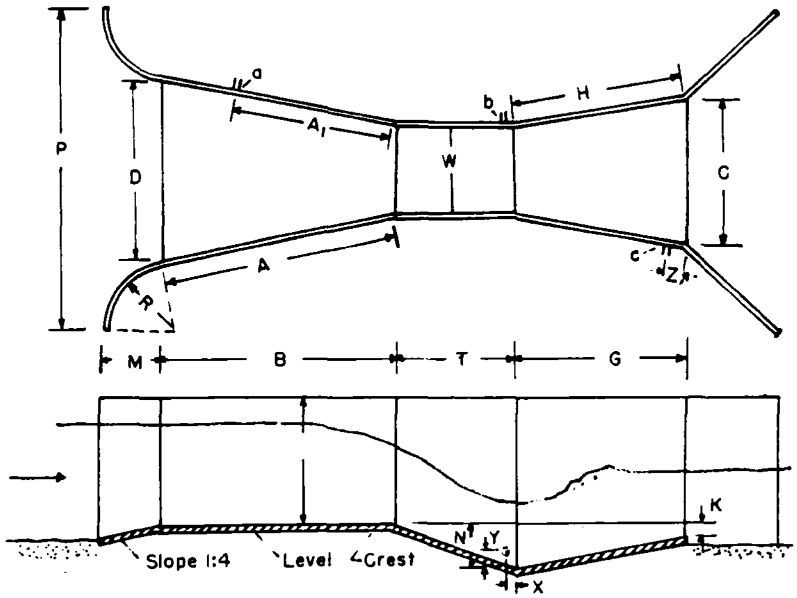
where Q is the flowrate, H_a is the depth measured as indicated in paragraph 4.3.1, and C and n are empirical constants which vary with flume size and are given in Table 1 of section 4.3.

3.1.2.2 The flume can also operate in a "submerged flow" mode, which occurs when the downstream depth becomes so high that the break in the floor slope of the flume can no longer be a complete control point for the flow. In submerged flow, two depths must be measured in order to determine the flowrate. Therefore, it is highly desirable that the installation be designed for free flow, for which limiting submergence conditions are given in section 4.4.2.

3.1.3 Advantages of the Parshall flume include a relatively small head loss and a capability for self-cleansing. A disadvantage is its empirical basis, which makes it difficult to adjust analytically for non-standard geometries.

3.2 Palmer-Bowlus Flumes

3.2.1 The Palmer-Bowlus flume differs from the Parshall flume in that it is a form of long-throated flume in which the channel width is constricted and/or the floor is raised to cause critical flow in a prismatic throat, as in figure 2. The flowrate then is a function of the upstream depth.



W FT	W IN	A FT	A IN	A1 FT	A1 IN	B FT	B IN	C FT	C IN	D FT	D IN	E FT	E IN	T FT	T IN	G FT	G IN	H FT	H IN	K FT	K IN	M FT	M IN	N FT	N IN	P FT	P IN	R FT	R IN	X FT	X IN	Y FT	Y IN	Z FT	Z IN
0	1	1	2 9/32	0	9 17/32	1	2	0	3 21/32	0	6 19/32	0	6 to 9	0	3	0	8	0	8 1/8	0	3/4	–	–	0	1 1/8		–	–		0	5/16	0	1/2	0	1/8
	2	1	4 5/16		10 7/8	1	4		5 5/16		8 13/32		6 to 10		4 1/2		10		10 1/8		7/8		–		1 11/16		–	–			5/8		1		1/4
	3	1	6 3/8	1	1/4	1	6		7		10 3/16	1 to 1 1/2			6	1	0	1	5/32		1	–			2 1/4		–	–			1		1 1/2		1/2
0	6	2	7/16	1	4 5/16	2	0	1	3 1/2	1	3 5/8	2	0	1	0	2	0	–		0	3	1	0	0	4 1/2	2	11 1/2	1	4	0	2	0	3	–	
	9	2	10 5/8	1	11 1/8	2	10	1	3	1	10 5/8	2	6	1	0	1	6	–			3	1	0		4 1/2	3	6 1/2	1	4		2		3	–	
1	0	4	6	3	0	4	4 7/8	2	0	2	9 1/4	3	0	2	0	3	0	–			3	1	3		9	4	10 3/4	1	8		2		3	–	
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2	0	5	0	3	4	4	10 7/8	3	0	3	11 1/2	3	0	2	0	3	0	–			3	1	3		9	6	1	1	8		2		3	–	
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4	0	6	0	4	0	5	10 5/8	5	0	6	4 1/4	3	0	2	0	3	0	–			3	1	6		9	8	10 3/4	2	0		2		3	–	
5	0	6	6	4	4	6	4 1/2	6	0	7	6 5/8	3	0	2	0	3	0	–			3	1	6		9	10	1 1/4	2	0		2		3	–	
6	0	7	0	4	8	6	10 3/8	7	0	8	9	3	0	2	0	3	0	–			3	1	6		9	11	3 1/2	2	0		2		3	–	
7	0	7	6	5	0	7	4 1/4	8	0	9	11 3/8	3	0	2	0	3	0	–			3	1	6		9	12	6	2	0		2		3	–	
8	0	8	0	5	4	7	10 1/8	9	0	11	1 3/4	3	0	2	0	3	0	–			3	1	6		9	13	8 1/4	2	0		2		3	–	
10	0	–		6	0	14	0	12	0	15	7 1/4	4	0	3	0	6	0	–		0	6	–		1	1 1/2	–		–		1	0	0	9	–	
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25	0	–		11	0	25	0	29	4	35	0	7	0	6	0	13	0	–		1	0	–		2	3	–		–		1	0		9	–	
30	0	–		12	8	26	0	34	8	40	4 3/4	7	0	6	0	14	0	–		1	0	–		2	3	–		–		1	0		9	–	
40	0	–		16	0	27	0	45	4	50	9 1/2	7	0	6	0	16	0	–		1	0	–		2	3	–		–		1	0		9	–	
50	0	–		19	4	27	0	56	8	60	9 1/2	7	0	6	0	20	0	–		1	0	–		2	3	–		–		1	0		9	–	

Figure 1. Parshall-flume dimensions.

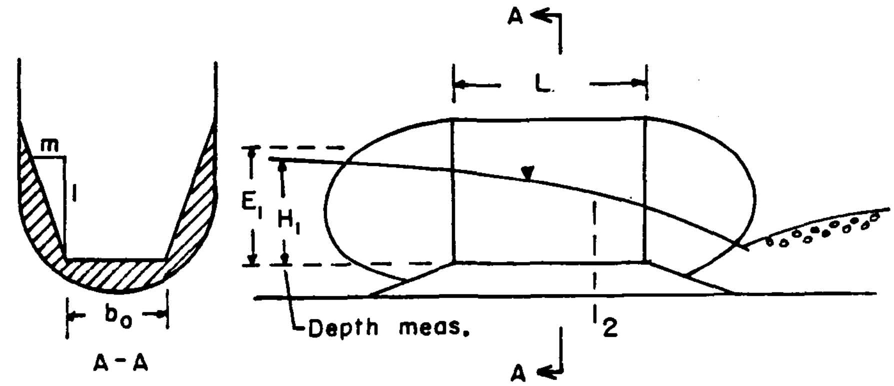

Figure 2. Example of Palmer-Bowlus flume.

3.2.2 If it is assumed that an essentially rectilinear flow exists in the throat, a one-dimensional treatment of the energy balance between an upstream section and a critical-flow section in the throat will yield a theoretical expression for flowrate in terms of upstream head. Corrections for friction effects can also be added.

3.2.3 The main advantages of Palmer-Bowlus flumes are their amenability to theoretical analysis and their adaptability for insertion into circular sewers at manholes.

4. SPECIFICATIONS FOR PARSHALL FLUMES

4.1 Dimensions

4.1.1 Parshall flumes are identified by throat width, e.g., a 1-foot (0.305m) flume; specifying the throat size fixes all other dimensions of the flume in accordance with figure 1 (reference 12.1).

4.1.2 Because exponents and coefficients for equation [1] have been experimentally determined using flumes with the dimensions in figure 1, it is imperative that installed flumes exactly match those specified dimensions. Limited exceptions are cited in the following.

4.1.2.1 The upstream wingwalls are sometimes eliminated, particularly in sewage flows. Possible effects on accuracy are covered in section 9.2.2.1.

4.1.2.2 If the flume operates in the free-flow mode, small deviations in the dimensions of the diverging section downstream of the throat are unlikely to introduce errors.

4.2 Depth Measurement

4.2.1 The depth H_a must be measured at location "a" in figure 1. However, there are cases where measurement at the corresponding longitudinal position along the flume centerline will not introduce significant errors. See section 9.2.2.1.

4.2.2 If a second depth measurement is needed for submerged flow, it must be made at location "b" in figure 1; but for 1, 2, and 3-inch flumes, this measurement is made at location "c". See figure A.4 for relationship between H_b and H_c.

4.2.3 A stilling well (not shown in figure 1) is usually desirable or necessary to accomplish the depth measurement. Sometimes the stilling well is furnished as a structurally integral part of a commercial flume. In that case the stilling well must conform to the specifications given in section 8.2.3.

4.2.4 The hole or slot in the sidewall, which connects to a stilling well or secondary device either directly or through a short pipe, must

- Have a projection-free and perpendicular junction with the inside wall, which should be smooth in the vicinity of the hole; see also section 8.2.4.

- Be located as low as possible along the wall consistent with the avoidance of sediment or sludge layers, but certainly below the minimum anticipated surface elevation. See figure 1 for H_b hole.

4.2.5 Depth-measuring devices are covered in section 8.

4.3 Depth-Discharge Relations for Free Flow

4.3.1 Values of C and n for use in equation [1] are given Table 1, along with the maximum flowrate for each size of flume. This table is based on H_a measured in feet and Q in cubic feet per second. Depth-discharge data developed from Table 1 and equation [1] are given in tabular form in Table A.1 in the Appendix for flume sizes to 8 feet.

4.3.2 Values of C and n for metric units (Q in cubic meters per second) are given in table A.2 in the Appendix. English units have been given precedence in this report mainly because they are still commonly found in field practice among Parshall flume users.

4.3.3 The estimated accuracy of the depth-discharge relations for free flow in properly installed and operated Parshall flumes is $\pm$ 3 percent.

4.3.4 The permissible depth range for each flume can be noted in Table A.1 in the Appendix.

4.4 Limiting Conditions for Free Flow

4.4.1 The limiting condition for free flow is expressed in terms of the submergence ratio, H_a/H_b, where H_a and H_b are the depths measured at points "a" and "b," respectively (figure 1). Both are referenced to the crest elevation.

4.4.2 The maximum submergence ratios for free flow are:

$H_b/H_a < 0.5$ for 1-in, 2-in and 3-in flumes;

$H_b/H_a < 0.6$ for 6-in and 9-in flumes;

$H_b/H_a < 0.7$ for 1-ft to 8-ft flumes; and

$H_b/H_a < 0.8$ for 10-ft to 50-ft flumes.

4.5 Depth-Discharge Relations for Submerged Flow

4.5.1 Parshall flume installations for sewage treatment plants should be designed for free flow (section 5.3) because free-flow secondary instrumentation is much simpler. Also, the basic accuracy of the free-flow head-discharge relations is higher than those for submerged flow. However, in the event that a flume is found to be submerged, curves are presented in figures A.1 through A.8 in the

TABLE 1

FREE FLOW VALUES OF C AND n FOR PARSHALL FLUMES (EQUATION [1])

Throat Width W	C	n	Max. Q cfs	Max. Q mgd
1 in	0.338	1.55	0.2	0.13
2 in	0.676	1.55	0.5	0.32
3 in	0.992	1.55	1.1	0.71
6 in	2.06	1.58	3.9	2.52
9 in	3.07	1.53	8.9	5.75
1 ft	4.00	1.522	16.1	10.4
1.5 ft	6.00	1.538	24.6	15.9
2 ft	8.00	1.550	33.1	21.4
3 ft	12.00	1.566	50.4	32.6
4 ft	16.00	1.578	67.9	43.9
5 ft	20.00	1.587	85.6	55.4
6 ft	24.00	1.595	103.5	66.9
7 ft	28.00	1.601	121.4	78.5
8 ft	32.00	1.607	139.5	90.2
10 ft	39.38	1.6	200	
12 ft	46.75	1.6	350	
15 ft	57.81	1.6	600	
20 ft	76.25	1.6	1000	
25 ft	94.69	1.6	1200	
30 ft	113.13	1.6	1500	
40 ft	150.00	1.6	2000	
50 ft	186.88	1.6	3000	

Appendix for determining flowrate based on H_a and a manually measured H_b until repairs can be made or until submerged-flow secondary instrumentation can be installed. Submergence ratios higher than 95 percent are not permitted in any case.

4.6 Materials

4.6.1 The roughness of the flume surface shall not be greater than that corresponding to a smooth concrete finish.

4.6.2 Flume and stilling-well surfaces shall have appropriate corrosion resistance for the flowing liquid.

5. INSTALLATION REQUIREMENTS FOR PARSHALL FLUMES

5.1 General

5.1.1 The objective of the installation requirements is to insure that the flow entering the flume is tranquil and uniformly distributed, and simulates as closely as possible the conditions under which the "standard" depth-discharge relations (Table 1) were originally obtained.

5.1.2 Owing in part to the empirical nature of the flume equations, it is often difficult to quantify the errors introduced by poor installation practices. Available information is detailed in section 9.

5.2 Slopes

5.2.1 The flume must be constructed or installed so that the floor of the converging section (figure 1) is level longitudinally and laterally consistent with careful field measurement of level. See also section 9.2.3.

5.2.2 Permissible slope upstream of the flume is governed in part by the requirements of section 5.4.2.

5.3 Satisfying the Requirements for Free Flow

5.3.1 In cases where the downstream depth makes flume submergence a possibility, free-flow performance can be insured at the design stage by following a procedure that is best illustrated by using a design example. More detailed design examples for various flume sizes are given in reference 12.1.

5.3.1.1 Consider a case in which the maximum anticipated flowrate is 10 ft^3/s (0.283 m^3/s) and the maximum expected downstream depth is 1.80 ft (0.548 m). A 1-ft (0.305 m) flume is the minimum size for this discharge (Table 1). From section 4.4.1, the maximum permissible submergence is 70 percent. From Table A.1, H_a is 1.825 ft (0.566 m) so H_b cannot exceed 0.70 x 1.825 $\cong$ 1.278 ft (0.390m). At the free-flow limit for this flume size the water surface elevation at H_b is, for practical purposes, the same as the downstream elevation (figure 3)(12.1). Therefore, the flume crest should be set above the bottom of the downstream channel by at least (1.80-1.28) = 0.52 ft (0.158 m).

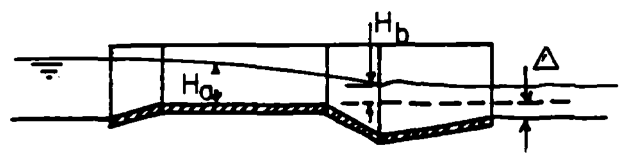

Figure 3. Setting flume elevation.

5.3.2 In principle a flume which operates submerged can be repaired by inserting a higher floor (while retaining the overall bottom shape), provided that upstream conditions and deposition considerations permit this.

5.4 Approach Channel

5.4.1 Quantitative standards or specifications do not exist for the length of the approach channel to the flume. It must be straight and smooth for a long enough distance to provide a "uniform" velocity distribution and a tranquil water surface at the wingwall entrance. For this purpose, "uniform" velocity distribution is defined as (at least) that associated with fully developed flow in a long straight concrete channel of good surface quality. A laterally symmetrical distribution in which the maximum velocity occurs above mid-depth at or near the vertical axis and does not exceed about 20-25 percent of the average velocity could be considered to satisfy this requirement.

5.4.1.1 The approach lengths cited for long-throated flumes in section 7.1 can serve as conservative requirements for the Parshall flume.

5.4.1.2 The adequacy of the entrance flow can also be demonstrated by experimental techniques such as velocity traverses with current meters or by other techniques provided their adequacy for this purpose is demonstrable.

5.4.2 If the flow in the upstream channel is supercritical, a hydraulic jump should be forced to occur at least 30 H_a upstream of the flume.

5.4.3 See section 9.2.4 for effects of departures from these conditions.

5.5 Secondary Instruments

5.5.1 Requirements for secondary-instrument installation are covered in section 8. See also section 4.2 for depth measurement locations and stilling-well requirements.

6. SPECIFICATIONS FOR PALMER-BOWLUS FLUMES

6.1 Geometry (Figure 2)

6.1.1 Throat.

6.1.1.1 The throat of the Palmer-Bowlus flume must be prismatic. Within this constraint the throat cross-section can have any reasonable shape, e.g., rectangular, trapezoidal, that can be formed by a bottom rise and/or sidewall constriction in the channel. It must be sufficiently constrictive to produce critical flow.

6.1.1.2 The length, L, of the throat should preferably be about 1.5 times the maximum anticipated upstream specific energy (referenced to the throat elevation). In sewers, this length should be at least equal to the pipe diameter.

6.1.2 The entrance and exit transition slopes upstream and downstream of the throat should be the same and must be no steeper than 1 on 3, and preferably 1 on 4.

6.1.3 Depth Measurement.

6.1.3.1 The depth-measurement location shall be one to two times the maximum depth (referenced to throat elevation) upstream of the flume entrance.

6.1.3.2 Other depth stations closer to the flume can be used provided that a rating equation for the selected location is furnished with the flume or alternatively it can be shown that there is no significant surface drawdown at that location.

6.1.3.3 If a stilling well is used, see sections 4.2, 8.2.3 and 8.2.4.

6.2 Depth-Discharge Relations for Free Flow

6.2.1 An energy balance between the depth station (subscript 1) and the throat (subscript 2) states that

$$E_1 = y_2 + V_2^2/2g = y_2 + Q^2/2g\,A_2^2 \qquad [2]$$

where E_1 is the specific energy (depth plus velocity head) referenced to the throat elevation and is for the moment considered constant along a frictionless flume; y_2 is flow depth; g is the acceleration due to gravity; and V_2 is the uniform velocity in a cross-section of area A. The flow at section 2 is critical, so that for minimum specific energy

$$dE/dy = 1 - (Q^2/gA^3)\ dA/dy = 0 \qquad [3a]$$

and

$$Q^2 b_c^1/gA_c^3 = 1 \qquad [3b]$$

where b^1 is the throat width at the flow surface; and the subscript c denotes the critical flow condition. For a given throat geometry, equations [2] and [3b] can be combined into an expression for Q in terms of E_1, as given in the following examples.

6.2.1.1 For <u>rectangular</u> throats,

$$Q = C_d\ (2/3)^{3/2}\ b\ g^{1/2}\ E_1^{3/2} \qquad [4]$$

where b is the throat width. Here a discharge coefficient, C_d, has been applied to take into account boundary-layer growth along the throat and other hydrodynamic effects.

6.2.1.2 For <u>trapezoidal</u> throats, equation [2] becomes

$$Q = C_d\ (b_o y_c/E_1^2 + m y_c^2/E_1^2)(1 - y_c/E_1)^{1/2}\ (2g)^{1/2}\ E_1^{5/2} \qquad [5]$$

where b_o is the width of the throat bottom and m is the horizontal-to-vertical sidewall slope. Equation [5] is used in conjunction with Table 2 (reference 12.2).

6.2.1.3 Equations [4] and [5] are expressed in terms of E_1, but the head H_1 is the parameter that is actually measured (figure 2). Therefore, these equations can be used directly only when $V_1^2/2g$ is negligible relative to H; otherwise, they are modified as follows:

- For <u>rectangular</u> throats it is convenient to incorporate this approach velocity effect in a coefficient C_v, so that equation [4] becomes

$$Q = C_v\ C_d\ (2/3)^{3/2}\ g^{1/2}\ b\ H_1^{3/2} \qquad [6]$$

with

$$C_v = (1 + Q^2/2gA_1^2 H_1)^{3/2} \qquad [6a]$$

and C_v is determinable by a trial procedure.

- For <u>trapezoidal</u> throats the approach-velocity effect cannot so conveniently be lumped into a C_v term, but equation [5] can be solved iteratively starting with the measured H_1 in place of E_1 and correcting with the computed $V_1^2/2g$.

TABLE 2

Y_c/E_1 AS A FUNCTION OF m AND E_1/b_o FOR TRAPEZOIDAL SECTIONS (REFERENCE 12.2)

E_1/b_o	Throat side slopes, horizontal to vertical 1/2:1	1:1	1 1/2:1	2:1	3:1	4:1
0	.667	.667	.667	.667	.667	.667
.02	.668	.670	.671	.672	.675	.678
.04	.670	.672	.675	.677	.683	.687
.06	.671	.675	.679	.683	.690	.696
.08	.672	.678	.683	.687	.696	.703
.10	.674	.680	.686	.692	.701	.709
.12	.675	.684	.690	.696	.706	.715
.14	.676	.686	.693	.699	.711	.720
.16	.678	.687	.696	.703	.715	.725
.18	.679	.690	.698	.706	.719	.729
.20	.680	.692	.701	.709	.723	.733
.22	.681	.694	.704	.712	.726	.736
.24	.683	.696	.706	.715	.729	.739
.26	.684	.698	.709	.718	.732	.742
.28	.685	.699	.711	.720	.734	.744
.30	.686	.701	.713	.723	.737	.747
.32	.687	.703	.715	.725	.739	.749
.34	.689	.705	.717	.727	.741	.751
.36	.690	.706	.719	.729	.743	.752
.38	.691	.708	.721	.731	.745	.754
.40	.692	.709	.723	.733	.747	.756
.50	.697	.717	.730	.740	.754	.762
.60	.701	.723	.737	.747	.759	.767
.70	.706	.728	.742	.752	.764	.771
.80	.709	.732	.746	.756	.767	.774
.90	.713	.737	.750	.759	.770	.776
1.00	.717	.740	.754	.762	.773	.778
1.20	.723	.747	.759	.767	.776	.782
1.40	.729	.752	.764	.771	.779	.784
1.60	.733	.756	.767	.774	.781	.786
1.80	.737	.759	.770	.776	.783	.787
2	.740	.762	.773	.778	.785	.788
3	.753	.773	.781	.785	.790	.792
4	.762	.778	.785	.788	.792	.794
5	.768	.782	.788	.791	.794	.795
10	.782	.791	.794	.795	.797	.798
∞	.800	.800	.800	.800	.800	.800

6.2.2 It is sometimes possible to estimate C_d from boundary-layer equations. However, in view of uncertainties in this computation it is reasonable to use average values of C_d that have been accumulated from experiments. These are shown in figure 4.

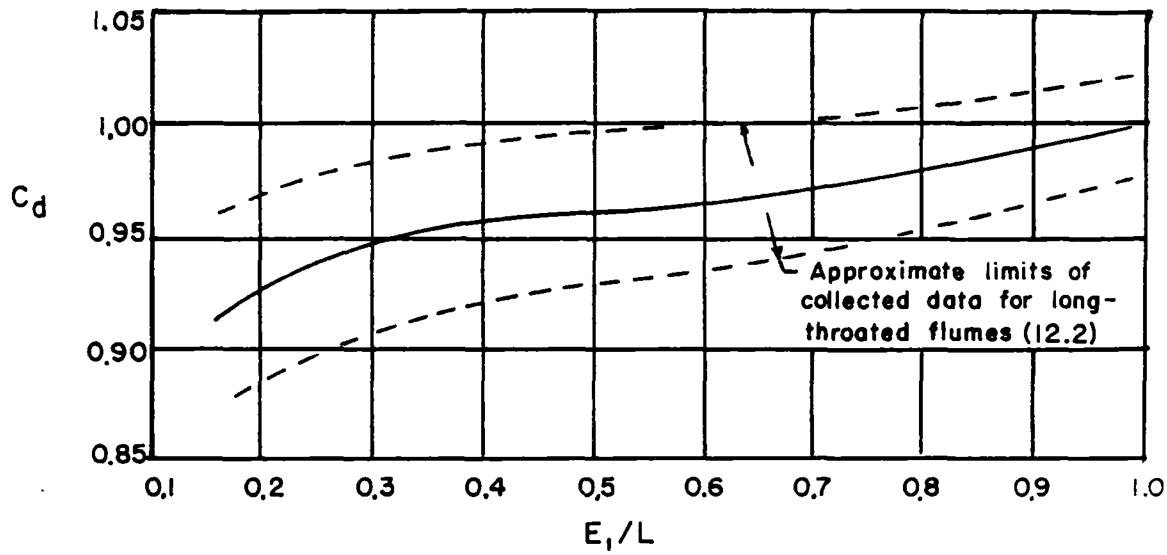

Figure 4. C_d values for long-throated flumes.

6.2.3 Depth-discharge relations furnished by the manufacturer can be used in place of the foregoing equations (see section 6.2.6).

6.2.4 Limiting Conditions.

6.2.4.1 At minimum flow H_1 should not be less than the larger of 0.1 L or 0.2 ft (0.06m). At maximum flow H_1 should preferably not exceed about 0.6 L.

6.2.4.2 The width of a rectangular throat (or the average width of a trapezoidal throat) should preferably be larger than 0.33 ft (0.10 m).

6.2.5 Accuracy.

6.2.5.1 The accuracy of these depth-discharge relations is estimated to vary from $\pm$ 3 percent at large H_1/L to $\pm$ 5 to 6 percent at low H_1/L. The decrease in accuracy reflects the increased importance and uncertainty of C_d at low flows.

6.2.6 Ratings Furnished by Manufacturer.

6.2.6.1 The manufacturer of a prefabricated flume should provide the user with the head-discharge relation (equation, table or curve) for the flume even if the flume is of standard geometry and even if the secondary instrumentation is an integral part of the flume.

6.2.6.2 If the prefabricated flume is non-standard in any way, the manufacturer should also provide analytical or experimental information on how the head-discharge relation was developed and an accuracy estimate.

6.3 Limiting Submergence

6.3.1 Free flow will prevail if the downstream surface elevation (referenced to the throat floor) is less than the throat critical depth, y_c. This provides a conservative limit for design. Slightly higher downstream depth limits may occur depending on the energy-recovery of the downstream transition slopes.

6.4 Materials

6.4.1 The roughness of the flume surface shall not be greater than that corresponding to a smooth concrete finish.

6.4.2 Flume and stilling well surfaces shall have appropriate corrosion resistance for the flowing fluid.

7. INSTALLATION REQUIREMENTS FOR PALMER-BOWLUS FLUMES

7.1 Approach Channel

7.1.1 The objective of the upstream channel requirements is to insure that a uniformly distributed flow with a tranquil surface approaches the flume. A "uniform" distribution in this context is described in section 5.4.1.

7.1.2 The approach channel shall be straight, free of projections and relatively smooth for the distances given below.

7.1.2.1 If the throat width is less than half the width of the approach channel, the straight upstream length shall be the larger of 20 throat widths or 10 H_1.

7.1.2.2 If the throat width is larger than half the width of the approach channel, the required straight approach length is increased to 10 approach channel widths.

7.1.2.3 Specifications 7.1.2.1 and 7.1.2.2 assume that no extreme conditions exist at the inlet to the specified approach length. For example, if a small diameter pipe discharges a high velocity flow into the channel a longer approach would probably be needed to dissipate the jet.

7.1.2.4 If the foregoing approach conditions are not met, the adequacy of the entrance flow can still be demonstrated as in section 5.4.1.2.

7.1.3 If flow in the upstream channel is supercritical, a hydraulic jump should be forced to occur at least 30 H_1 upstream of the flume.

7.1.4 See section 9.3.2 for effects of departures from these conditions.

7.2 Slopes

7.2.1 The Palmer-Bowlus flume must be installed so that the throat floor is level longitudinally and transversely consistent with careful field level measurement.

7.2.2 Maximum upstream slopes are governed in part by section 7.1.3.

7.3 Other Requirements

7.3.1 Flume inserts must be installed so that all of the flow enters the throat, that is, there must be no leakage between the entrance transition and the channel walls.

7.3.2 The flume must be installed so that it operates in a free flow mode.

7.4 Secondary Instruments

7.4.1 Requirements for installation of secondary instruments are covered in section 8.

7.4.2 See section 6.1.3 for depth-measurement locations.

8. SECONDARY INSTRUMENTS

8.1 Components of the Secondary Instrumentation

8.1.1 In cases where a continuous record of flow is required, the minimum secondary system must contain a depth measuring device and a recorder. The user then must manually convert the depth record to flowrates using either the equations of sections 4 and 6 or depth-discharge ratings supplied by the manufacturer.

8.1.2 Commercial secondary devices frequently incorporate internal conversion of the measured depth to a recorded flowrate. The equation used for this conversion shall be made known to the user.

8.1.3 Transmission of the signal to a central control console or computer may be required. See section 8.3. In this case a visual readout at the flume site shall be provided in addition.

8.2 The Depth Measurement

8.2.1 Continuous measurements of the water depth above the flume crest can be made with several types of sensor including, but not restricted to, the following:
- Floats, cylindrical and scow-type;
- Pressure sensors, e.g., bubble tubes, diaphragm gages;
- Acoustic gages;
- Electrical gages, e.g., resistance, capacitance, oscillating probes.

8.2.2 Under emergency conditions, frequent manual readings with staff gage or point gage can approximate a continous record. However, for the purposes of this practice, manual readings are used only for calibration and performance monitoring of automatic on-line devices.

8.2.3 Stilling Wells.

8.2.3.1 A stilling well is required in cases where a wire-supported cylindrical float is used for depth measurement and in any situation where the water surface in the flume is ruffled or wavy.

8.2.3.2 The stilling well must extend vertically far enough to cover the full range of depth, without risk of a float resting on the bottom at low flow or protruding beyond the top of the well at high flow.

8.2.3.3 The diameter (or area) of the stilling well is governed by the following requirements:

- If a float is used, there must be a clearance of at least 0.1 ft (0.030 m) between the float and the wall of the stilling well. This clearance should be increased to 0.25 ft (0.076 m) if the well is constructed of concrete or other rough material. The diameter of the float itself may be governed in part by permissible float-lag error (section 9.4.3).
- The maximum stilling well size must be selected with a view toward possible response lag (section 9.4).
- Depth measuring devices other than the float may impose size requirements on the stilling well. For example, acoustic depth gages require a large enough well to avoid interference from wall reflections. Manufacturers shall inform the user about special stilling-well requirements for their sensors.

8.2.3.4 The construction of the stilling well must be watertight so that the only communication with the flume is through the connecting hole or pipe.

8.2.3.5 Provision must be made for cleaning the stilling well or flushing for removal of accumulated solids.

8.2.4 Connector Between Stilling Well and Flume.

8.2.4.1 The hole, slot or pipe connecting the stilling well to the flume must be small enough to accomplish its basic purpose of damping wave and surge effects. Yet it must be large enough to stay open and also avoid introducing a lag in the stilling well response to changing flows in the main channel (see section 9.4.3). A hole or pipe having a cross-sectional area about 1/1000th of the stilling well area or a diameter of about 1/2 in (13 mm) is often adequate for this purpose.

8.2.4.2 When a connecting pipe is used, it is recommended that a valve be installed in the line so that the stilling well can be isolated for cleaning or servicing.

8.2.4.3 If the flow contains solids or other contaminants, it is recommended that a small purge flow of tap water be added to the stilling well to aid in keeping the connector clean. This water should be added at a low enough rate to cause an imperceptible depth increase in the stilling well. For example, if the head difference due to purge flow is not to exceed 0.001 ft (0.3 mm) and the connector is effectively a very short 1/2-inch diameter pipe, the flow must be less than about 0.13 gpm (0.8 cc/s).

8.2.4.4 See section 4.2.4 for conditions on the flume tap.

8.3 Transmission

8.3.1 Transmission of measurements to a central location can be done either by electrical or pneumatic means, but pneumatic transmission should be limited to distances shorter than 1000 ft or 300 meters.

8.3.2 The signal shall be transmittable in computer-compatible form or be capable of future conversion to that form.

8.4 Accuracy

8.4.1 In a system that records depth only, the accuracy of the depth registered at the indicator/transmitter shall be within 1 percent of the maximum depth to be measured, with repeatability within 1/2 percent.

8.4.2 In a system that records flowrate, the accuracy of the flowrate registered at the indicator/transmitter shall be within 2 percent at the maximum flowrate to be measured and within 3 percent at one-half of the maximum flowrate, with repeatability within 1/2 percent.

8.4.3 The receiver/recorder accuracy, or the difference between the on-site indicator and control-room chart, shall be within 1 percent of the maximum reading.

8.4.4 The foregoing accuracy requirements are expressed in terms of maximum depth or flow and may have to be converted to terms of full scale in order to conform to the accuracy statements of many commercial devices. It is clearly important to avoid selecting devices that will be operating at small fractions of their capacity.

8.4.5 Errors in depth measurement other than those due to internal inaccuracies in the secondary instruments are covered in section 9.

8.5 Other Requirements

8.5.1 The stilling well and secondary equipment must be protected against freezing where necessary.

8.5.2 Manufacturers shall furnish installation, maintenance, repair and operation information on the secondary instruments in user manuals.

8.5.3 Manufacturers shall furnish to the users all available information relevant to the accuracy and precision, of the instruments such as any known temperature, pressure or humidity dependence, as well as interferences and limitations in their use.

9. ERROR SOURCES

9.1 Introduction

9.1.1 Section 9.2 describes effects of commonly found departures from standard conditions for Parshall flumes; section 9.3 does the same for Palmer-Bowlus flumes. Most errors in depth measurement are common to both types of flumes and are covered in section 9.4.

9.1.2 See section 10.2 for methods of estimating total system error.

9.2 Parshall Flume Error Sources

9.2.1 Depth-Discharge Relations.

9.2.1.1 The free-flow depth-discharge data given in section 4.3 should be considered to introduce errors in discharge of up to ± 3 percent. Errors for submerged flow are larger.

9.2.1.2 Any uncorrected errors introduced by the following sources will add to the basic 3 percent error.

9.2.2 Flume Geometry.

9.2.2.1 The curved wingwalls and entrance ramp (figure 1) are sometimes eliminated, particularly in sewage flows where it is desirable to maintain upstream velocities high enough to avoid deposition. This change has these possible effects of unknown magnitude: first, the capability (provided by the "nozzle effect" of the wingwalls and ramp) for flattening the incoming velocity distribution is lost; second, the sudden change in direction of the sidewall from the straight channel to the converging wall of the flume causes lateral curvature in the entrance flow. The first effect may not have a discernible effect on the performance if the approach flow is essentially uniform to start with and if the flume is small (see section 9.2.4.1). Any error from this source is in the direction of underestimating the flowrate, i.e., the measured depth is too low for a given flowrate. The second effect may be noticeable in large flumes, where the abrupt change in direction could result in an incorrect reading at the depth station.

9.2.2.2 If the throat width deviates from the prescribed width by a small amount (a few percent), the standard discharge can be corrected by multiplying it by the width ratio, in the case of 1 to 3-inch flumes (reference 12.1). In the absence of data on larger flumes such adjustments should probably be restricted to changes smaller than 1 percent.

9.2.3 Slope.

9.2.3.1 If the flume floor (section 5.2.1) slopes downward in the direction of flow, use of the measured depth in the standard rating equation will result in a computed flowrate less than the actual. In a given flume this error increases as the discharge decreases. Laboratory experiments on a 3-inch flume at a 0.01 slope showed a discharge error of 3 percent at H_a = 0.5 ft (0.15 m) increasing to about 10 percent at $H_a \cong$ 0.15 ft (0.046 m).

9.2.3.2 It appears that if the slope does not exceed about 0.005, an approximate correction can be made by referencing the depth measurement to the elevation of the crest overfall. However, this correction, which has been extrapolated from unpublished experimental results on a 3-inch flume, can serve for information and estimating purposes only and cannot be employed as a standard except as agreed to in specific cases.

9.2.3.3 No experimental information is available on the effect of transverse slope on flow patterns in the flume. However, to minimize the error the user should check to see that the depth measurement is still referenced to the crest centerline and correct it if necessary.

9.2.4 Approach Channel.

9.2.4.1 If the approach channel is not long, straight and smooth enough to provide the approach flow described in section 5.4.1, the effects (if any) generally cannot be quantified. Certain qualitative judgments based on flume properties can be made as follows:

- Small flumes have (relatively) longer converging sections than the larger flumes and thus should be less sensitive to approach conditions;
- Uneven velocity distributions (but still symmetrical in plan view) tend to cause depth readings that err on the low side and therefore underestimate the discharge.

9.2.4.2 When a partly full circular pipe discharges into the rectangular approach channel of a Parshall flume, it is possible under certain conditions for a nominally subcritical pipe flow to be drawn down to a supercritical condition in the approach, particularly when the flume crest is at the same elevation as the pipe invert. Caution must be exercised during the design stage to avoid these situations.

9.2.4.3 Certain upstream conditions cause serious surface waves or surging which preclude good depth measurements. Apart from the obvious case of having a hydraulic jump too close to the flume, any full or nearly full pipe flow containing large amounts of entrained air can feature severe surging or instability at the outlet. Hydraulic jumps or drops in approach pipes can create these circumstances, which can be forestalled only by appropriate design.

9.2.5 Submergence.

9.2.5.1 Errors caused by ignoring the effect of downstream submergence can be computed from the information cited in section 4.4. An example of these errors is shown in figure 5 for a 1-ft flume as determined from figure A.7.

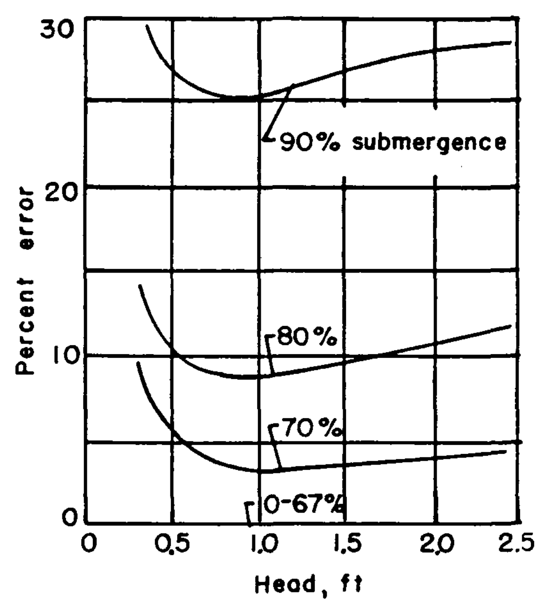

Figure 5. Errors in 1-ft Parshall flume discharge if uncorrected for submergence.

9.2.5.2 The submergence can be checked by manually measuring the depth at "b" and referencing it to the crest elevation. However, the existence of a hydraulic jump downstream of "b" can be taken as evidence of free flow.

9.3 Palmer-Bowlus Flume Error Sources

9.3.1 Depth-Discharge Relations.

9.3.1.1 The flume equations developed in section 6.2 should be considered to introduce errors in discharge of up to $\pm$ 3 percent at intermediate and high values of the head-to-throat length ratio.

9.3.1.2 Any uncorrected errors introduced by the following sources will add to the basic 3 percent error.

9.3.2 Flume Geometry.

9.3.2.1 If the throat dimensions of the installed flume differ, for whatever cause, from the nominal dimensions, corrections can be made by the methods of section 6.2 provided that the throat remains prismatic.

9.3.2.2 Excessive roughness of the flume surfaces will result in C_d values lower than the average values given in figure 4, owing to increased energy loss and boundary-layer thickness.

9.3.2.3 Deposits at the bottom of the approach to the flume due to low upstream velocities effectively form a change in geometry, for which the equations can be adjusted.

9.3.3 Slopes.

9.3.3.1 Downward slopes in the direction of flow will cause the control (critical) point to shift from the downstream to the upstream edge of the flume throat. This is a departure from the conditions for the derivations of equations [5] and [6] and can cause an error of unspecifiable magnitude in the discharge measurement. Small upward slopes can be corrected for by referencing the depth measurement to the downstream edge of the throat.

9.3.3.2 See section 9.2.3.3 for transverse slopes.

9.3.4 Approach Channel.

9.3.4.1 Approach conditions that cause non-uniform velocity distributions (but still symmetrical in plan view) will tend to result in upstream depth readings and computed discharges that are too low. The magnitude of this error increases as the ratio of upstream velocity head to depth increases. It is noted in this regard that excessive upstream roughness can increase the non-uniformity of the upstream velocity distribution.

9.3.4.2 Approach-channel Froude numbers larger than 0.6 will be conducive to the formation of standing waves, which will interfere with the depth measurement.

9.4 Errors Sources in Depth Measurement

9.4.1 General.

9.4.1.1 Errors described in section 9.4 must be combined with the flume errors of sections 9.2 and 9.3 as shown in section 10.2 to obtain an estimate of the total measurement error.

9.4.1.2 It is noted from sections 4 and 6 that flume discharge depends upon powers of measured depth of from 3/2 to 5/2, and that the system error is therefore particularly sensitive to errors in depth measurement.

9.4.1.3 Any error in referencing the zero depth to the elevation of the flume crest will introduce an error in it that is constant in magnitude over the flow range and therefore relatively more important at low flows.

9.4.2 Float Gage Error.

9.4.2.1 A float-lag error is developed because a small change in water level is necessary to develop the force needed to overcome internal friction in the float device, i.e., pulley, gears, etc. The <u>maximum</u> lag error, Δ, for a float and pulley can be shown to be, in compatible units,

$$\Delta = 8F/w\pi D^2 \qquad [7]$$

where F is the force required to move the mechanism, D is the cylindrical float diameter, and w is the weight per unit volume of the flowing liquid.

9.4.2.2 The manner in which this error is distributed during the flow cycle depends upon whether the readout or record is set to read correctly during the rising stage, falling stage or midway between. For example, a 6-inch (0.15 m) diameter float requiring 2 ounces (57 g) to move has a maximum (or potential) float lag error of 0.021 ft (0.64 cm), which can be halved by setting the index to a correct reading between the rising and falling stages.

9.4.2.3 Equation [7] shows that float-lag error can be reduced by minimizing the force needed to move the float and by using a large diameter float.

9.4.2.4 Pulley-type float gages are also subject to line-shift error because, as the float moves, a portion of the suspending line moves from one side of the pulley to the other. The potential error due to line shift can be computed from equation [7], in which F is now a force obtained by multiplying the weight of the line per unit length by the maximum float-elevation change. Unless an unusually heavy line is used, this error should be negligible for most flume installations, the depth ranges usually being relatively small.

9.4.2.5 It is preferable that the line-and-pulley arrangement be such that the counterweight is not submerged at higher stages. If submergence does occur, there is an apparently smaller pull on the float and the error again can be estimated from equation [7] using F as the buoyancy force on the counterweight. Particular care should be taken to keep the descending counterweight from landing on top of the rising float.

9.4.3 Stilling Well Lag.

9.4.3.1 For a constant rate of depth change, dH/dt, in the flume, the depth in the stilling well will lag by an amount,

$$\Delta h = (A_w/A_p)^2 \ (dH/dt)^2 \ (C'/2g) \qquad [8]$$

Here A_w is the sectional area of the stilling well, A_p is the effective area of the connecting orifice or pipe, and C' is a head loss coefficient given below.

- If the connector hole has a thick wall that makes it essentially a very short pipe, C' is 1.5.
- If there is a connector pipe, the additional friction loss in the pipe is taken into account by adding to the foregoing 1.5 the value of $f\ell/d$, where ℓ and d are the length and diameter of the pipe, and f is a friction factor that depends upon velocity through the pipe and on pipe roughness and is likely to be in the 0.05-0.10 range. See figure A.9 in the Appendix for estimating f.
- If there is a thin wall between flume and stilling well so that the connecting hole is effectively a sharp edged orifice, C' = 1 and, further, A_p should be taken as about 0.6 of the hole area to account for contraction.

This error is likely to be small in usual treatment plant situations where dH/dt is small.

9.4.4 Other Errors.

9.4.4.1 Humidity effects on recorder chart paper can introduce errors of about 1 percent.

9.4.4.2 Manufacturers must provide, as part of the requirements of section 8.5.3, enough information for users to estimate errors introduced by depth sensors and all other components of the secondary system. However, actual system errors can be determined only by comparison of in-place measurements with independently made measurements of known accuracy (section 10).

9.4.4.3 Some potential error sources are associated with specific types of secondary instruments. These errors usually cannot be quantified and only cautionary statements can be made. For example:

- Acoustic depth-measuring devices may incorrectly sense foamy surfaces. See also section 8.2.3.3.
- Bubbler-tube tips placed in a flowing liquid may be subject to errors due to dynamic pressures, unless properly shaped.
- Grease coatings may affect some types of wire probes.

10. PERFORMANCE CHECKS AND CALIBRATIONS

10.1 Introduction

10.1.1 Section 10 describes two types of performance checks or calibrations. The first covers only the secondary instruments, while the second covers the entire measuring system.

10.1.1.1 Calibrating only the secondary instrument is a sufficient procedure when one of the following conditions is met:

- The primary elements (flumes) meet all specifications and installation requirements of sections 4 and 5 (Parshall) or sections 6 and 7 (Palmer-Bowlus); and further, the basic accuracy of the primary (section 4.3.3 or 6.2.5) is satisfactory to the user.
- The flume and its installation do not satisfy all specifications, but the departures from standard conditions can either be corrected for analytically or be assigned quantitative error limits, and the resulting estimated accuracy is satisfactory to the user; or adequate depth-discharge data is furnished by the manufacturer.
- The user requires only precision or repeatibility rather than accuracy, and it can be shown that any departures from standard conditions for the primary will not affect the repeatibility.

10.1.1.2 A complete calibration of the entire system must be made when the conditions described in section 10.1.1.1 do not prevail. However, a calibration of the secondary system is still a necessary part of the complete calibration. In this way the performance of the primary device (flume) can be isolated and future checks need to include only the secondary instrument so long as flow and channel conditions remain the same.

10.1.2 The performance checks described here can be used for acceptance testing of recently installed equipment and for future routine performance monitoring as part of an operations and maintenance program.

10.2 Checking the Secondary System

10.2.1 Reference-Depth Measurement.

10.2.1.1 In order to check the secondary instrument it is necessary to make independent depth measurements and estimate their accuracy. These measurements will usually be made using a scale (staff gage) or preferably a point gage as described in the following sections.

10.2.1.2 Staff gage. A scale graduated at least to hundredths of feet (or to 0.005 m) should be mounted at the proper location along the sidewall or in a stilling well.

- This scale should be sufficiently thin and streamlined in section to permit an easily readable interface if it is placed in the main channel.
- The effective zero reading for this scale must be carefully determined by referencing it to the proper crest elevation. The specific manner in which this is done is left to the user and will depend upon such factors as whether the flow can be diverted around the flume, accessibility, etc. The accuracy of the selected procedure should be estimated for use in section 10.2.2.

10.2.1.3 Point gage. The use of a point gage instead of a staff gage is recommended, since more accurate readings are likely. The requirements for the establishment of the zero reading are the same as for the staff gage.

10.2.1.4 When the flow surface is disturbed it becomes more difficult to make accurate reference-depth readings with either a staff gage or point gage, although the latter can yield acceptable results in a ruffled surface if the point is carefully adjusted to be alternately immersed and free of the surface for equal amounts of time. In principle, these problems can be avoided by making the reference measurements in the stilling well. However, this recourse is often precluded by line-of-sight or accessibility problems, particularly when a float is in the well, unless an auxiliary well is used. No matter how the reference-depth measurement is made, an estimated error for it must be agreed upon (section 10.2.2).

10.2.1.5 It is recommended that the staff gage or point gage be left in place after the initial calibrations so that it can be used for future maintenance checks.

10.2.2 Reference-Depth Error.

10.2.2.1 In order to compare the secondary-instrument readings with the reference measurements in an equitable way, it is necessary to estimate the error in the latter.

10.2.2.2 The error in the measured reference head consists of a combination of the zero-setting error and the systematic and random reading errors. The random errors associated with an unsteady surface can be reduced by using the average of multiple readings. A systematic error (relative to a single observer) may result, for example, from the interpretation of the meniscus against the scale. As an example, suppose that it is estimated from consideration of the leveling method that the zero was set to within 0.003 ft (1 mm) and that the reading error for this field situation is 0.005 ft (1.5 mm). Then the combined error in the reference-depth measurement can be estimated as

$$[0.003)^2 + (0.005)^2]^{1/2} \cong \pm 0.006 \text{ ft } (1.9 \text{ mm})$$

10.2.3 Checking a Depth Measurement/Recording Instrument.

10.2.3.1 Section 10.2.3 pertains to instruments which record the depth only, as distinguished from those which record flowrate directly. If the secondary instrument is of the latter type, see section 10.2.5.

10.2.3.2 Check the manufacturer's literature to see that the instrument installation and operation are in accordance with recommended usage. Also check the instrument to see that a range has been selected to permit the largest available chart deflection at maximum depth.

10.2.3.3 At a convenient flowrate that is steady enough to permit reliable readings, observe the reference depth (section 10.2.1) and the recorder or readout depth for the same time and compute the difference, ΔH.

10.2.3.4 Repeat step 10.2.3.3 at several depths covering the anticipated flow range, in such a way that an indication of instrument repeatability is obtained.

- As an absolute minimum, three such points should be obtained, i.e., corresponding to a low, medium and high flow; but it must be noted that this procedure gives no indication of instrument repeatability and is correspondingly less authoritative for instrument evaluation.
- If the flow is cyclic, points should be obtained for both the rising and falling stages so that errors due to float lag or gearing backlash will be visible.

- In order to accumulate numerous points in a reasonable time, it may be necessary to create depth changes artificially; for example, by manually backing up the flow or by changing stilling-well levels independently of the flume. In many cases such artifices are acceptable (always provided that reference-depth measurements and corresponding error estimates can be made), since only the secondary instruments are being checked here. In general, this method should not be applied to in-stream sensors, whose performance may be affected by the velocity or ruffled surface of the unaltered flow.

10.2.3.5 Make a plot of ΔH versus H as shown in figure 6. Include also the error bands estimated in section 10.2.2 (labeled A in figure 6). If the scatter of the ΔH points is small and apparently random, draw curve C through them as shown; but if obvious systematic differences appear between the points for the rising and falling stages separate curves should be drawn. Add another line, B, representing an acceptable ΔH beyond the limits of band A (section 8.4).

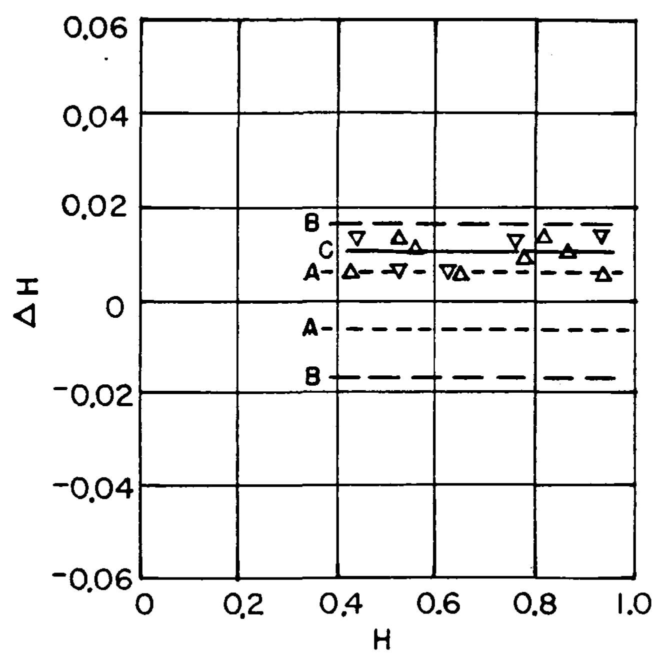

Figure 6. A method of evaluating depth-measuring instruments.

10.2.3.6 If curve C is inside of band B, and if further the scatter of the points around C is within prescribed limits, the instrument is operating acceptably; if not, see section 10.2.3.8.

10.2.3.7 Even if numerous ΔH points were obtained for figure 6, it should be realized that only a relatively short term effort was involved and no indication was obtained of errors due to long term drifts, temperature and humidity effects, general wear and other effects. Therefore:

- It is important to establish a program for routine and regular inspection and maintenance of the secondary instrument (section 11.1.2).
- This regular inspection must include check points on the depth measurement, using the reference depth gage left in place from the original performance check, to see that they still fall within the performance bands established in figure 6.

10.2.3.8 If curve C falls outside of zone B, the following should be noted:

- A constant displacement between B and C over the range of depths suggests the possibility of a zero-shift error in the secondary instrument. Should this be the case, reset the zero or otherwise adjust for the shift and repeat the procedure of this section (10.2.3).
- If C is a sloping straight line, there may be a need for gain or span adjustment in the secondary instrument. Repeat the procedure after adjustment.

10.2.3.9 Sections 10.2.3.5 and 10.2.3.8 provide one type of performance-test procedure that takes into account the uncertainty in the measurements that the commercial instrumentation is compared against. This is only a suggested procedure; other rationally based comparisons can be agreed upon.

10.2.4 Estimating the Error of a Discharge Obtained with a Depth Measuring Instrument..

10.2.4.1 Estimate the error in a single depth measurement by quadratically combining the reference-depth error and the scatter in the measured ΔH for a particular value of H. Continuing with the example of section 10.2.2, this gives with figure 6

$$[(0.006)^2 + (0.004)^2]^{1/2} \cong \pm 0.007 \text{ ft (2 mm)}$$

To this should be added quadratically any systematic residual error, which is 0.005 ft (1.5 mm) in the example of figure 6, giving an estimated depth error of

0.009 ft (2.7 mm). At H = 1.0 ft (0.30 m) this is a relative depth error of 0.9 percent. (Note: If one is working with a depth measurement that has been transmitted from the flume site, this additional receiving/recording error should be included; section 8.4.) The estimated error in discharge for a Parshall flume or Palmer-Bowlus flume with rectangular throat would be

$$[(3.0)^2 + (1.5 \times 0.9)^2]^{1/2} \cong 3.3 \text{ percent}$$

Here the 3.0 percent represents the estimated error in the flume coefficient (section 9.2.1.1 or 9.3.1.1) and the factor of 1.5 (approximate in the case of Parshall flumes) is the relative error in Q caused by a unit relative error in H. This factor will be larger for trapezoidal flumes, with a limiting value of 2.5 for triangular throats. The actual value can be determined for specific trapezoidal geometries from equation [5] and Table 2.

10.2.4.2 It is noted from the foregoing computation that, no matter how accurate the depth measurement, the accuracy of the flowrate determination is still limited by the 3 percent uncertainty in the flume coefficient. Therefore, any further reduction in the total estimated error will require an in-place calibration of the primary element. See section 10.3 for flume calibrations.

10.2.5 Checking a Flowrate Measurement/Recording Instrument.

10.2.5.1 Section 10.2.5 pertains to instruments that sense the depth but internally convert it to an indicated flowrate. Instruments that indicate only the depth were covered in section 10.2.3.

10.2.5.2 Check the manufacturer's literature to see that the instrument installation and operation are in accordance with recommended usage. Also check the instrument to see that a range has been selected to permit the largest available chart or indicator deflection at maximum flow.

10.2.5.3 Determine the reference error from the product of the reference-depth error (section 10.2.2) and the appropriate exponent of the head. For example, using again the error of 0.006 ft (1.9 mm) from section 10.2.2, for a 1-ft (0.305 m) Parshall flume operating at a depth of 1.2 ft (0.46 m) the reference error would be

$$100 \times 1.5 \times 0.006/1.2 = 0.75 \text{ percent}$$

The flume discharges 5.28 ft^3/s (0.150 m^3/s) at this depth so that the reference error is 0.04 ft^3/s (0.0011 m^3/s). This computation should be made for the anticipated flow range and the reference errors plotted as shown by curves A in figure 7. It is noted that the basic flume coefficient uncertainty of 3 percent was not included in this reference-error computation. The reason is that the intent of section 10.2.5 is to check the secondary instrument only, for initial calibration or for acceptance purposes. The response of the secondary instrument is not a function of uncertainty in the primary device (flume) and its performance evaluation need not involve that uncertainty.

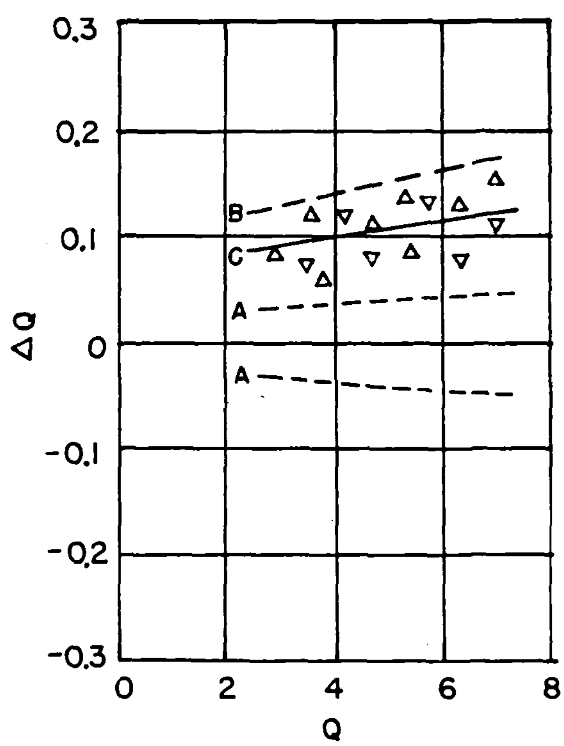

Figure 7. A method of evaluating flowrate measuring instruments.

10.2.5.4 Add to curve A (figure 7) flowrates corresponding to the allowable error in the secondary instrument (section 8.4), giving curve B.

10.2.5.5 At a convenient flowrate that is steady enough to permit readings, observe the reference depth manually (section 10.2.1) and read the indicated flowrate at the same time.

- Compute the discharge corresponding to the measured reference depth using the appropriate depth-discharge relation from section 4.3 or 6.2.
- Enter the difference between indicated and calculated flowrate, ΔQ, in figure 7.

10.2.5.6 Repeat step 10.2.5.5 at several flowrates covering the anticipated discharge range, in such a way that an indication of instrument repeatability is obtained.

- As an absolute minimum, three such points should be obtained -- one each at a low, medium and high flowrate; but it must be noted that this procedure gives no indication of instrument repeatability and is correspondingly less authoritative for instrument evaluation.
- If the flow is cyclic, points should be obtained for both the rising and falling stages so that errors due to float lag, gear backlash or similar effects will be visible.
- In order to accumulate numerous points in a reasonable time, it may be necessary to create depth changes artificially; for example, by manually backing up the flow or by changing stilling-well levels independently of the flume. In many cases such artifices are acceptable (always provided that reference-depth measurements and corresponding error estimates can be made), since only the secondary instruments are being checked here. In general, this method should not be applied to in-stream sensors, whose performance may be affected by the velocity or ruffled surface of the unaltered flow.

10.2.5.7 If the scatter of the ΔQ points is small and apparently random, draw curve C through them as in the example of figure 7; but if obvious systematic differences appear between the points for rising and falling stages, separate curves should be drawn.

10.2.5.8 If curve C is entirely inside of band B, and if further the scatter of the points around C is within prescribed limits, the instrument is performing acceptably; if not, see section 10.2.5.10.

10.2.5.9 Even if numerous ΔQ points were obtained for figure 7, it should be realized that only a relatively short term effort was involved and no indication was obtained of errors due to long term drifts, temperature and humidity effects, general wear and other effects. Therefore:

- It is important to establish a program for routine and

- regular inspection and maintenance of the secondary system (section 11.1.2).
- This regular inspection must include check points on ΔQ, using the reference-depth gage left in place from the original performance check, to see that they still fall within the performance bands established in figure 7.

10.2.5.10 If curve C falls outside of zone B, the following should be noted:
- ΔQ curves shaped like those in figure 8 suggest the possibility of a zero-shift error in the secondary. Should this be the case, reset the zero or otherwise adjust for the shift and repeat the procedure of this section (10.2.5).
- If curve C is a sloping straight line passing through zero, there may be a need for a span or gain adjustment in the secondary. Repeat the procedure after adjustment.

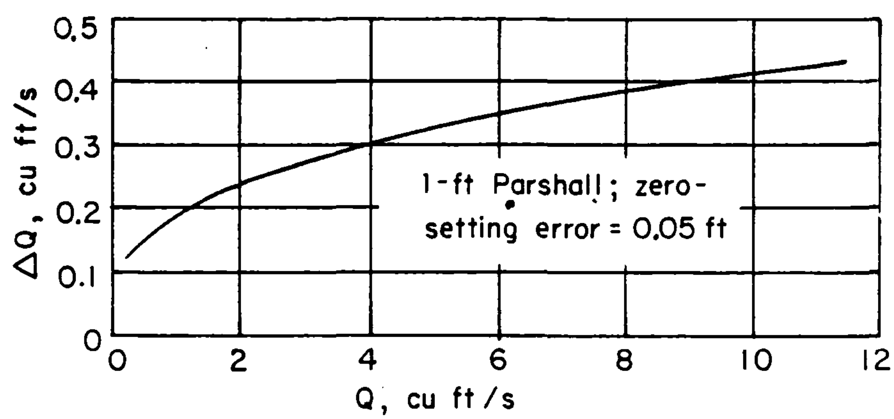

Figure 8. Example of zero-shift error.

10.2.5.11 Section 10.2.5 provides one type of performance-test procedure that takes into account the uncertainty in the measurements that the commercial instrumentation is being compared against. This is only a suggested procedure; other rationally based comparisons can be agreed upon.

10.2.6 Estimating the Error of a Single Discharge Measurement Obtained with a Flowrate-Measuring Instrument.

10.2.6.1 At a given flowrate, combine quadratically the percentage reference error (section 10.2.5.3), the percentage error represented by the scatter limits in figure 7, any remaining systematic error indicated in figure 7, and the basic 3 percent uncertainty in the flume coefficient. (Note: If one is working with a measurement that has been transmitted from the flume site, this additional recording/receiving error should be included; section 8.4.3.)

10.2.6.2 No matter how accurate the secondary instrument is, the accuracy of a flowrate measurement is clearly still limited by the potential 3 percent error in the flume coefficient. Therefore, any further reduction in the total estimated error will require an in-place calibration of the flume. See section 10.3 for flume calibrations.

10.3 Calibrating the Primary Device (Flume)

10.3.1 General.

10.3.1.1 Section 10.3 pertains to complete in-place calibration of flume systems that do not qualify for secondary-only calibration according to section 10.1.1.1.

10.3.1.2 The purpose of section 10.3 is to provide a general overview of methods for calibrating the flume coefficient so that, coupled with a separate calibration of the secondary instruments (section 10.2), a complete calibration of the measuring system is accomplished. In this way, those differences between the calibrated and recorded flowrates that are chargeable to the primary device can be assigned to it, and future monitoring can be restricted to the secondary instrumentation.

10.3.1.3 Whatever calibration method is used, it should satisfy the following requirements:

- The calibration tests should be performed for at least three flowrates -- low, medium and high. If possible, the process should be repeated several times at each flowrate.
- The reference staff gage or point gage (section 10.2.1) should be used to measure the flume depth during these calibrations.
- If the calibration flow measurements are made at a location away from the immediate vicinity of the flume, equivalence of the flowrate at the measurement location to that through the flume must be assured.

10.3.1.4 There is no single calibration method that is applicable to all situations. The choice may depend not only on technical factors described in the following sections but also on such factors as the availability of manpower, funds, and in-plant laboratory capability. These sections point out some advantages and disadvantages of several common calibration methods and conditions for their use. The major methods applicable here are:

- Volumetric
- Comparison with reference meter
- Dilution
- Salt velocity
- Velocity-area traverse

10.3.2 Volumetric Calibration.

10.3.2.1 The feasibility of volumetric calibration depends upon the availability of tank space and connecting conduits. The potential accuracy is high, provided that:

- The tank is regular in configuration so that its lateral dimensions can be measured within acceptable limits of accuracy.
- The tank is large enough to permit a test run of sufficient length for the effect of timing errors at the start and finish to be kept within acceptable limits.
- The change in liquid level during the run is large enough so that the starting and finishing depths (probably obtained by the "on-the-run" method) can be measured within acceptable relative error limits.
- The flowrate remains relatively constant during the run.

10.3.2.2 Estimate the uncertainty of the resulting Q as a combination of the estimated errors of the measurements of the lateral area, the depth change, and the elapsed time. This uncertainty combined with the estimated error of the simultaneously measured flume depth gives an estimated of the error in the flume coefficient.

10.3.3 Comparison with a Reference Meter.

10.3.3.1 In this context a reference meter is a flowrate measuring device whose performance can be referenced to published standards or to recommended practices that are acceptable to the involved parties. Examples include:

- Standard venturi tubes and venturi nozzles (references 12.3, 12.4, 12.5)
- Orifice plates (references 12.3, 12.4)
- Thin plate weirs (reference 12.6)

10.3.3.2 Meters to be used as reference devices must meet all requirements of the accepted standards in fabrication, installation and use, so that their coefficients and uncertainties can be used in the flume calibrations. (It is noted in this regard that the stringent upstream approach conditions required by published standards are unlikely to be satisfied under most treatment-plant conditions.)

10.3.3.3 When a differential-pressure type of meter is used as the reference device, measure the differential pressure with a U-tube manometer. If a commercial secondary device is to be used in place of a manometer, it must have had a recent calibration and complete information on its performance must be available. Further, its error must be included in the uncertainty of the derived flume coefficient.

10.3.3.4 When a standard weir is used as the reference instrument, measure its head with a point gage or equivalent device and use the same care as described for reference-depth measurements in section 10.2.1.

10.3.3.5 It may be acceptable to use as a reference meter an instrument for which there are no published standards provided that:

- The device has been recently calibrated and its current accuracy and repeatability can be satisfactorily documented.
- The device is used under effectively the same conditions for which it was calibrated.

Examples of such devices are:

- Propeller meters
- Segmental orifices
- Electromagnetic flowmeters
- Acoustic flowmeters

10.3.4 Dilution Method.

10.3.4.1 In the dilution method the flowrate is deduced from the dilution of measurable properties (e.g., color, conductivity, or fluorescence) of tracer chemicals added to a turbulent flow in known amounts. The calibration can be done by either the constant-rate injection method, or the slug injection method. The constant-rate method is recommended here because it appears more practical for in-plant use and because documentation on it is available in the form of published standards, e.g., (references 12.7,12.8).

10.3.4.2 In the constant rate injection method, a tracer solution of accurately known concentration is injected upstream at a rate which is constant and accurately measurable. At a downstream distance long enough for complete mixing, the flow is sampled and the concentration determined after a steady state or concentration "plateau" is attained. The flowrate, Q, is then determined from

$$Q = q(c_1 - c_2)/(c_2 - c_o) \qquad [9]$$

where q is the rate at which the sample of concentration c_1 is injected; c_2 is the measured "plateau" concentration downstream; and c_o (which may be close to zero) is the background concentration of the tracer chemical existing in the flow.

10.3.4.3 This method requires accurate measurement of q and of all concentrations; skilled personnel and specialized equipment are needed. However, under optimum conditions the potential accuracy is high. See references 12.7 and 12.8 for methods of estimating errors.

10.3.4.4 The tracer property must be conservative, since losses by absorption to solids in the flow will result in an apparent reduction in c_2. The fluorescent dye Rhodamine WT has been used successfully in sewage without losses.

10.3.5 Salt-Velocity Method.

10.3.5.1 In the salt-velocity method, brine is injected suddenly at an upstream station in such a way that it becomes well distributed across the section very rapidly. The time of passage of the salt pulse between two downstream stations is measured by means of electrodes which detect the increased conductivity associated with the passage of the brine. The flowrate then can be determined provided the volume of the conduit between the electrodes is accurately known. This method has a potential for 1 percent accuracy under optimum conditions. The accuracy actually obtained depends upon the tranverse mixing and coherence of the injected brine slug, upon the accuracy of determination of the centers of gravity of the tracer-conductivity records and the time separating them, as well as upon the accuracy of the aforementioned volume determination.

10.3.5.2 Published standards for the salt-velocity method are written for circular pipes flowing full (referemces 12.4, 12.9), and these or similar references must be consulted for details of the method. A sufficient length of (preferably straight) pipe upstream of the first electrode is necessary to insure complete lateral mixing of the salt slug when it reaches the electrode. This length can be as short as four diameters when the injection is done internally in the standard manner (references 12.4, 12.9). The distance between the two sets of electrodes must be at least four diameters.

10.3.5.3 The liquid being measured must have a significantly smaller electrical conductivity than the brine.

10.3.5.4 The brine injection must be sudden, with an injection interval of the order of 1 second and no leakage thereafter.

10.3.5.5 The electrodes and the brine-injection devices are intrusive, so that the method might not be suitable for raw sewage.

10.3.5.6 In principle, this method can be adapted to other shapes of conduits or channels provided that the approach length and the electrode spacing and configuration are modified to compensate for the shape change in a manner that is hydrodynamically sound and agreeable to the involved parties.

10.3.6 Velocity-Area Method.

10.3.6.1 The velocity-area method is applied to a flow cross section by measuring a number of velocities, each representative of the average velocity within an incremental area, and summing the resulting velocity-area products over the cross section.

10.3.6.2 The velocities can be measured by point-velocity measuring instruments such as rotating-element current meters, electromagnetic current meters, Pitot tubes, etc., or by acoustic velocity meters, which measure an average velocity component along a line path. The point-velocity instruments often tend to clog and cannot always be used effectively in raw sewage. However, rotating and electromagnetic current meters often can be conveniently used in open channels that discharge treated effluent (see also section 10.3.6.4). Pitot tubes are generally restricted to closed (full) conduit flows where velocities are more likely to be high enough for their use.

10.3.6.3 The accuracy of this method depends upon whether the sampling grid is dense enough to yield the average velocity in the section, whether each velocity is sampled long enough to give a time-average value, and upon the accuracy of the velocity-measuring instrument itself (reference 12.10). These sampling requirements tend to make this a lengthy measurement, so it can be used only where sufficiently long periods of essentially steady flow are available.

10.3.6.4 In cases where a point-velocity instrument is used in an open channel, the following conditions must be observed.

- The average velocity in the section preferably should exceed 1 ft per second (0.30 m/s).
- Use only velocity-measuring instruments that have been recently calibrated and whose present accuracy and uncertainty can be estimated to the satisfaction of involved parties.
- Consult reference (9) for distribution of velocity sampling points in the cross section, and reference (10) for error estimates.

11. OPERATION AND MAINTENANCE

11.1 Short Term

11.1.1 Follow manufacturers' instructions for short-term servicing of commercial secondary instruments, in addition to the specific recommendations in the following.

11.1.2 After the initial tests described in section 10.2 have been completed, check at least one ΔH or ΔQ point (section 10.2.3 or 10.2.5) daily. If a point falls beyond the previously established band, it may be necessary to obtain more points in order to determine whether a zero or span adjustment or other repair is necessary. Once a performance history has been established, this check can be made less frequently if warranted, but always at least once a week.

11.1.3 Stilling Wells.

11.1.3.1 Check the stilling-well purge flow daily.

11.1.3.2 Check the stilling well for solids accumulation and clean as necessary. It is recommended that this check be made daily until a sediment-accumulation history has been established, at which time the interval can be lengthened. As part of this procedure, also check to see that the orifice or pipe connecting the flume and stilling well is completely unobstructed.

11.1.4 Float Gages and Other Secondary Devices.

11.1.4.1 Floats in stilling wells should be checked for grease or slime accumulation and wiped clean as necessary. Make this check daily until a coating history is established.

11.1.4.2 Scow floats used in raw sewage should be checked hourly for fouling by debris. Regardless of where they are used, they should be checked for grease, slime or other accumulation as in section 11.1.4.1.

11.1.4.3 Bubbler tubes should be blown down at least weekly.

11.1.4.4 Immersed electrical sensors should be wiped clean daily, unless it can be shown that less frequent attention is adequate.

11.1.5 Flumes.

11.1.5.1 Flume surfaces should be wiped down weekly to free them of slimes or other coatings. The flow need not be interrupted for this type of cleaning.

11.1.5.2 Check daily for upstream bottom deposits until a deposit history is established. Remove deposits as necessary.

11.2 Long Term

11.2.1 Follow manufacturers' instructions for long-term maintenance of commercial secondary instruments, in addition to the following specific recommendations.

11.2.2 Six months after the initial tests, check the longitudinal and transverse levels of the flume for any changes due to settlement.

11.2.3 Check the zero of the reference-depth gage every three months and adjust as necessary.

11.2.4 Check for deterioration of flume surfaces every six months, particularly in the case of concrete flumes. Severely deteriorated surfaces may have to be relined to restore them to their original roughness.

12. REFERENCES

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12.3 International Standards Organization, "Measurement of Fluid Flow by Means of Orifice Plates, Nozzles and Venturi Tubes Inserted in Circular Cross-Section Conduits Running Full," ISO/DIS 5167, 1976, draft revision of R781.

12.4 American Society of Mechanical Engineers, "Fluid Meters -- Their Theory and Application," 6th ed., 1971.

12.5 American Society for Testing and Materials, "Standard Method of Flow Measurement of Water by the Venturi Meter Tube," ASTM D2458-69.

12.6 British Standards Institution, Standard No. 2680-4A, "Methods of Measurement of Liquid Flow in Open Channels: Part 4A, Thin Plate Weirs and Venturi Flumes," 1965.

12.7 International Standards Organization, "Measurement of Water Flow in Closed Conduits--Tracer Methods, Part I; General," ISO No. 2975/1, 1974.

12.8 International Standards Organization, "Measurement of Water Flow in Closed Conduits--Tracer Methods, Part II; Constant Rate Injection Method Using Non-radioactive Tracers," ISO DIS 2975/II.

12.9 International Electrotechnical Commission, "International Code for the Field Acceptance Tests of Hydraulic Turbines," Publication 41, 1963.

12.10 International Standards Organization, "Liquid Flow Measurement Open Channels -- Velocity-Area Methods," ISO 748, 1973.

TABLE A.1. PARSHALL FLUME DISCHARGE

Discharge in cu ft per sec, for various throat widths

H_a ft	1 in	2 in	3 in	6 in	9 in	1 ft	1.5 ft	2 ft	3 ft	4 ft	5 ft	6 ft	7 ft	8 ft
0.05	.0033	.0065												
0.06	.0043	.0086												
0.07	.0055	.0110												
0.08	.0068	.0135												
0.09	.0081	.0162												
0.10	.0095	.0191	.0280	.054	.091									
0.11	.0110	.0221	.032	.063	.105									
0.12	.0126	.0253	.037	.072	.120									
0.13	.0143	.0286	.042	.082	.135									
0.14	.0160	.0321	.047	.092	.152									
0.15	.0179	.0357	.052	.103	.168									
0.16	.0197	.039	.058	.114	.186									
0.17	.0217	.043	.064	.125	.204									
0.18	.0237	.047	.070	.137	.223									
0.19	.0258	.052	.076	.149	.242									
0.20	.0279	.056	.082	.162	.262	.35	.50	.66	.97	1.26				
0.22	.032	.065	.095	.188	.30	.40	.58	.77	1.12	1.47				
0.24	.037	.074	.109	.216	.35	.46	.67	.88	1.28	1.69				
0.26	.042	.084	.123	.245	.39	.51	.76	.99	1.46	1.91	2.36	2.80		
0.28	.047	.094	.138	.276	.44	.58	.85	1.11	1.64	2.15	2.65	3.15		
0.30	.052	.105	.153	.307	.49	.64	.94	1.24	1.82	2.39	2.96	3.52	4.08	4.62
0.32	.058	.116	.170	.34	.54	.71	1.04	1.37	2.02	2.65	3.28	3.90	4.52	5.13
0.34	.063	.127	.187	.38	.59	.77	1.14	1.50	2.22	2.92	3.61	4.30	4.98	5.66
0.36	.069	.139	.205	.41	.64	.84	1.25	1.64	2.42	3.20	3.95	4.71	5.46	6.20
0.38	.075	.151	.222	.45	.70	.92	1.35	1.79	2.64	3.48	4.31	5.13	5.95	6.74
0.40	.082	.163	.240	.48	.76	.99	1.47	1.93	2.86	3.77	4.67	5.57	6.46	7.34

(continued)

TABLE A.1 (continued)

H_a ft	1 in	2 in	3 in	6 in	9 in	1 ft	1.5 ft	2 ft	3 ft	4 ft	5 ft	6 ft	7 ft	8 ft
	Discharge in cu ft per sec, for various throat widths													
0.42	.088	.176	.259	.52	.81	1.07	1.58	2.09	3.08	4.07	5.05	6.02	6.98	7.94
0.44	.095	.189	.278	.56	.87	1.15	1.70	2.24	3.32	4.38	5.43	6.48	7.52	8.55
0.46	.101	.203	.298	.60	.94	1.23	1.82	2.40	3.56	4.70	5.83	6.96	8.08	9.19
0.48	.108	.217	.318	.65	1.00	1.31	1.94	2.56	3.80	5.03	6.24	7.45	8.65	9.84
0.50	.115	.231	.339	.69	1.06	1.39	2.07	2.73	4.05	5.36	6.66	7.94	9.23	10.51
0.52	.123	.245	.360	.73	1.13	1.48	2.19	2.90	4.31	5.70	7.09	8.46	9.83	11.19
0.54	.130	.260	.382	.78	1.20	1.57	2.33	3.08	4.57	6.05	7.52	8.98	10.45	11.89
0.56	.138	.275	.404	.82	1.26	1.66	2.46	3.26	4.84	6.41	7.97	9.52	11.07	12.60
0.58	.145	.291	.426	.87	1.33	1.75	2.60	3.44	5.11	6.77	8.43	10.07	11.71	13.33
0.60	.153	.306	.449	.92	1.41	1.84	2.73	3.62	5.39	7.15	8.89	10.63	12.36	14.08
0.62	.161	.322	.473	.97	1.48	1.93	2.88	3.81	5.68	7.53	9.37	11.20	13.02	14.84
0.64	.169	.338	.497	1.02	1.55	2.03	3.02	4.01	5.97	7.91	9.85	11.78	13.70	15.62
0.66	.178	.355	.521	1.07	1.63	2.13	3.17	4.20	6.26	8.31	10.34	12.38	14.40	16.41
0.68	.186	.372	.546	1.12	1.70	2.23	3.32	4.40	6.56	8.71	10.85	12.98	15.10	17.22
0.70		.389	.571	1.17	1.78	2.33	3.47	4.60	6.86	9.11	11.36	13.59	15.82	18.04
0.72		.406	.60	1.23	1.86	2.43	3.62	4.81	7.17	9.53	11.88	14.22	16.55	18.87
0.74		.424	.62	1.28	1.94	2.53	3.78	5.02	7.49	9.95	12.40	14.85	17.29	19.71
0.76		.442	.65	1.34	2.02	2.63	3.93	5.23	7.81	10.38	12.94	15.49	18.04	20.57
0.78		.460	.67	1.39	2.10	2.74	4.09	5.44	8.13	10.81	13.48	16.15	18.81	21.46
0.80			.70	1.45	2.18	2.85	4.26	5.66	8.46	11.25	14.04	16.81	19.59	22.36
0.82			.73	1.50	2.27	2.96	4.42	5.88	8.79	11.70	14.60	17.49	20.39	23.26
0.84			.76	1.56	2.35	3.07	4.59	6.11	9.13	12.15	15.17	18.17	21.18	24.18
0.86			.79	1.62	2.44	3.18	4.76	6.33	9.48	12.61	15.75	18.87	21.99	25.11
0.88			.81	1.68	2.52	3.29	4.93	6.56	9.82	13.07	16.33	19.57	22.82	26.06
0.90			.84	1.74	2.61	3.41	5.10	6.79	10.17	13.55	16.92	20.29	23.66	27.02

(continued)

TABLE A.1 (continued)

H_a ft	1 in	2 in	3 in	6 in	9 in	1 ft	1.5 ft	2 ft	3 ft	4 ft	5 ft	6 ft	7 ft	8 ft
	Discharge in cu ft per sec, for various throat widths													
0.92			.87	1.81	2.70	3.52	5.28	7.03	10.53	14.03	17.52	21.01	24.50	27.99
0.94			.90	1.87	2.79	3.64	5.46	7.27	10.89	14.51	18.13	21.75	25.36	28.97
0.96			.93	1.93	2.88	3.76	5.63	7.51	11.26	15.00	18.75	22.49	26.22	29.97
0.98			.96	2.00	2.98	3.88	5.82	7.75	11.63	15.50	19.37	23.24	27.10	30.98
1.00			.99	2.06	3.07	4.00	6.00	8.00	12.00	16.00	20.00	24.00	28.00	32.00
1.05			1.07	2.23	3.31	4.31	6.47	8.63	12.96	17.28	21.61	25.94	30.28	34.61
1.10				2.39	3.55	4.62	6.95	9.27	13.93	18.60	23.26	27.94	32.62	37.30
1.15				2.57	3.80	4.95	7.44	9.94	14.94	19.94	24.96	30.00	35.02	40.06
1.20				2.75	4.06	5.28	7.94	10.61	15.96	21.33	26.71	32.10	37.50	42.89
1.25				2.93	4.32	5.62	8.46	11.31	17.02	22.75	28.50	34.26	40.02	45.80
1.30				3.12	4.59	5.96	8.98	12.01	18.10	24.21	30.33	36.47	42.62	48.78
1.35				3.31	4.86	6.32	9.52	12.74	19.20	25.69	32.20	38.74	45.26	51.84
1.40				3.51	5.14	6.68	10.07	13.48	20.32	27.21	34.11	41.05	47.99	54.95
1.45				3.71	5.42	7.04	10.63	14.23	21.47	28.76	36.06	43.42	50.76	58.14
1.50				3.91	5.71	7.41	11.19	15.00	22.64	30.34	38.06	45.82	53.59	61.38
1.55					6.00	7.79	11.77	15.78	23.84	31.95	40.09	48.28	56.48	64.71
1.60					6.30	8.18	12.36	16.58	25.05	33.59	42.17	50.79	59.42	68.10
1.65					6.61	8.57	12.96	17.38	26.29	35.26	44.28	53.34	62.42	71.56
1.70					6.91	8.97	13.57	18.21	27.55	36.96	46.43	55.95	65.48	75.07
1.75					7.23	9.38	14.19	19.04	28.82	38.69	48.61	58.60	68.59	78.66
1.80					7.55	9.79	14.82	19.90	30.13	40.45	50.83	61.29	71.75	82.29
1.85					7.87	10.20	15.45	20.76	31.45	42.24	53.09	64.01	74.98	86.00
1.90					8.20	10.62	16.10	21.63	32.79	44.05	55.39	66.81	78.24	89.76
1.95					8.53	11.06	16.76	22.53	34.14	45.90	57.72	69.63	81.57	93.59
2.00					8.87	11.49	17.42	23.43	35.53	47.77	60.08	72.50	84.94	97.48

(continued)

TABLE A.1 (continued)

H_a ft	1 in	2 in	3 in	6 in	9 in	1 ft	1.5 ft	2 ft	3 ft	4 ft	5 ft	6 ft	7 ft	8 ft
						Discharge in cu ft per sec, for various throat widths								
2.05						11.93	18.10	24.34	36.94	49.67	62.48	75.42	88.37	101.4
2.10						12.37	18.78	25.27	38.35	51.59	64.92	78.37	91.84	105.4
2.15						12.82	19.47	26.20	39.79	53.54	67.39	81.36	95.37	109.5
2.20						13.28	20.17	27.15	41.25	55.52	69.90	84.41	98.94	113.6
2.25						13.74	20.88	28.12	42.73	57.52	72.43	87.49	102.6	117.8
2.30						14.21	21.60	29.09	44.22	59.56	75.01	90.61	106.2	122.0
2.35						14.68	22.33	30.08	45.74	61.61	77.61	93.77	110.0	126.3
2.40						15.16	23.06	31.08	47.27	63.69	80.25	96.97	113.7	130.7
2.45						15.64	23.81	32.08	48.82	65.80	82.92	100.2	117.5	135.1
2.50						16.13	24.56	33.11	50.39	67.93	85.62	103.5	121.4	139.5

TABLE A.2. METRIC COEFFICIENTS FOR PARSHALL FLUMES (use H in meters in eq.[1] and obtain Q in m^3/s)

Throat Width		C	n
1 in	2.5 cm	0.060	1.55
2 in	5.1 cm	0.121	1.55
3 in	7.6 cm	0.177	1.55
6 in	0.152 m	0.381	1.58
9 in	0.229 m	0.535	1.53
1 ft	0.305 m	0.691	1.522
1 1/2 ft	0.457 m	1.056	1.538
2 ft	0.610 m	1.429	1.550
3 ft	0.914 m	2.184	1.566
4 ft	1.219 m	2.954	1.578
5 ft	1.524 m	3.732	1.587
6 ft	1.829 m	4.518	1.595
7 ft	2.134 m	5.313	1.601
8 ft	2.438 m	6.115	1.607

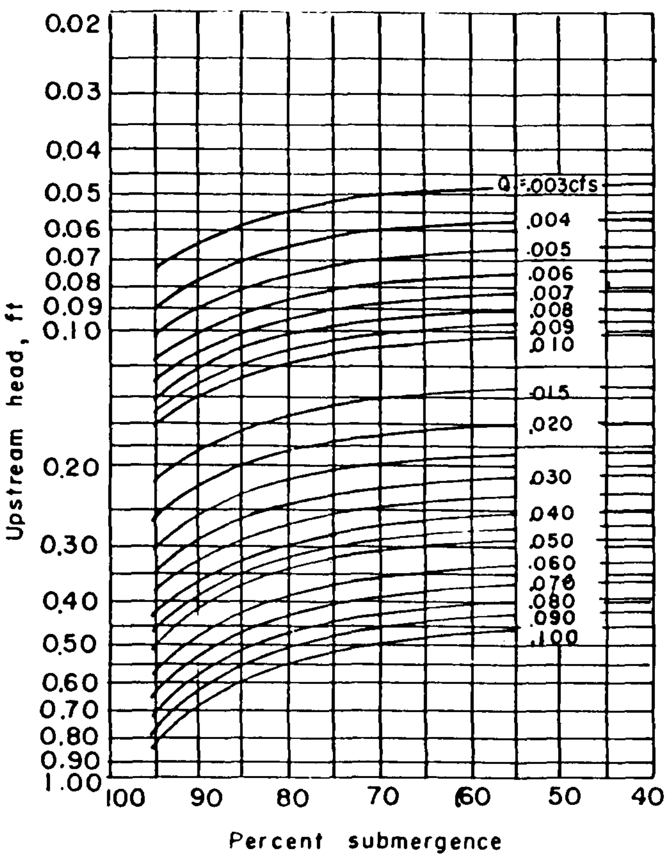

Figure A.1. Rate of submerged flow through a 1-inch Parshall flume (Ref. 12.1).

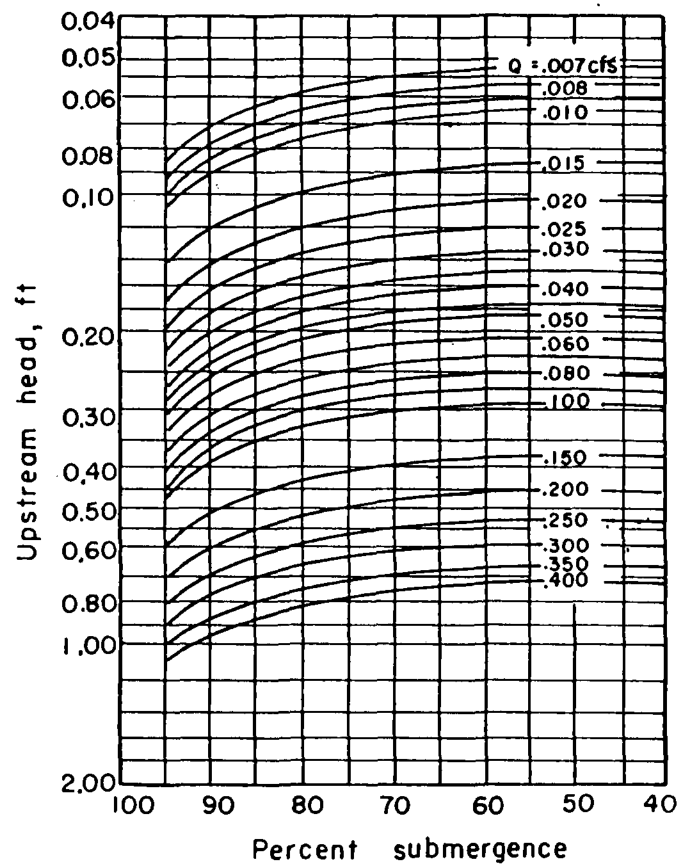

Figure A.2. Rate of submerged flow through a 2-inch Parshall flume (Ref.12.1).

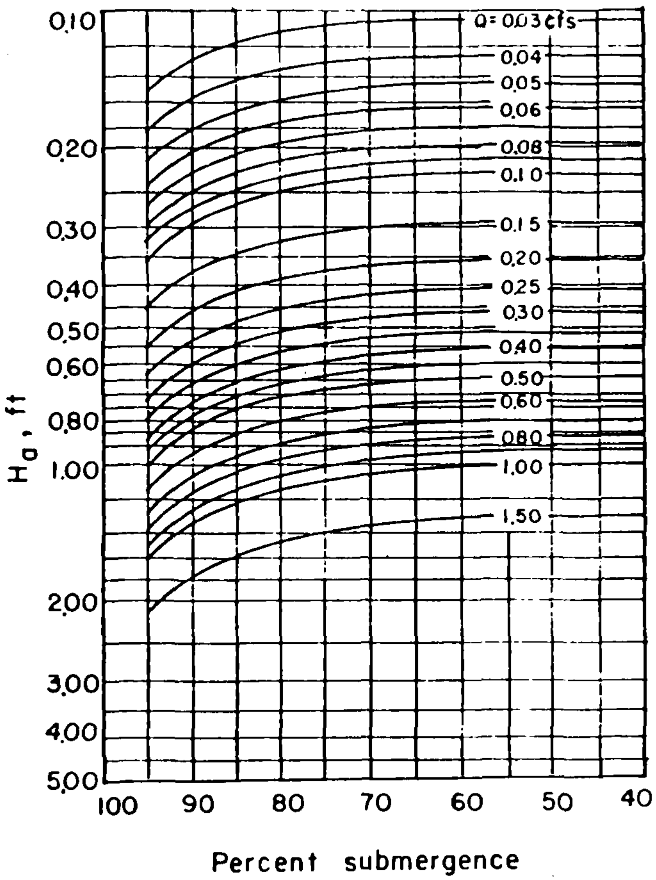

Figure A.3. Rate of submerged flow through a 3-inch Parshall flume (Ref. 12.1).

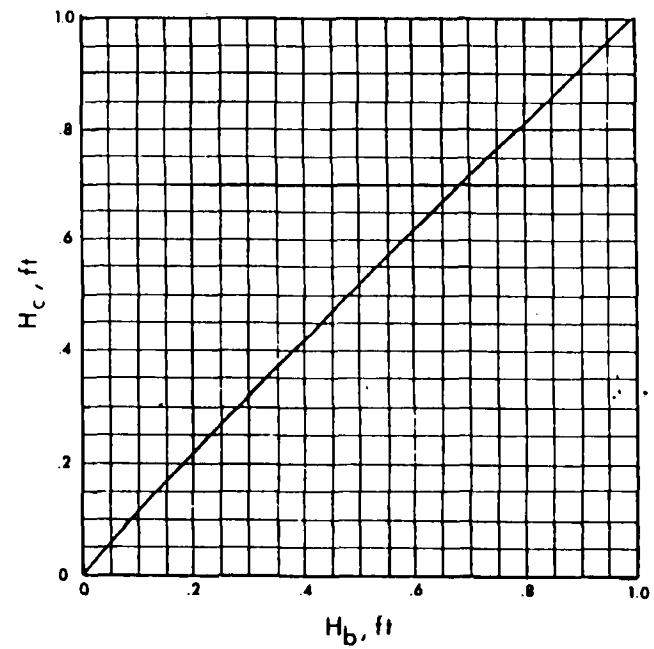

Figure A.4. Relationship of H_c and H_b gages for 1-, 2-, and 3-inch Parshall flumes for submergences greater than 50 percent (Ref. 12.1).

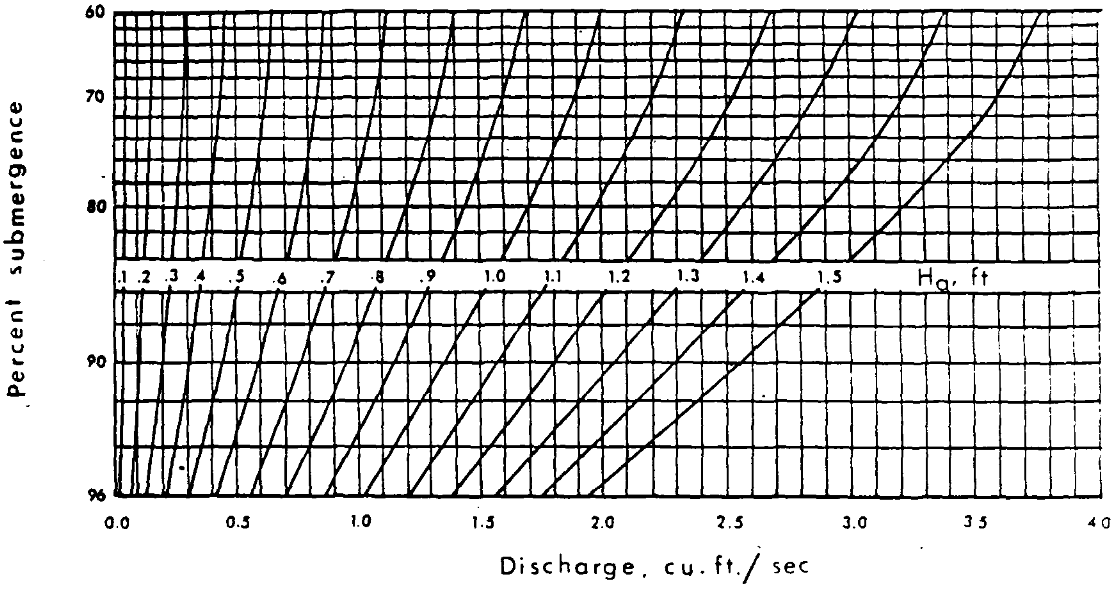

Figure A.5. Diagram for determining rate of submerged flow for a 6-inch Parshall flume (Ref. 12.1).

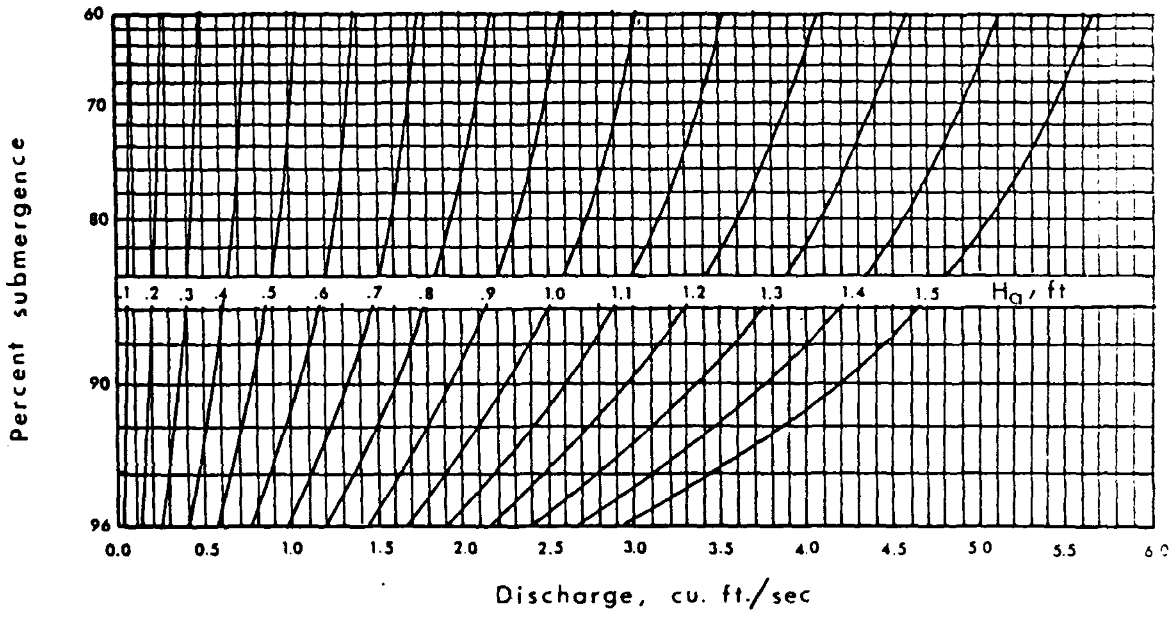

Figure A.6. Diagram for determining rate of submerged flow for a 9-inch Parshall flume (Ref. 12.1).

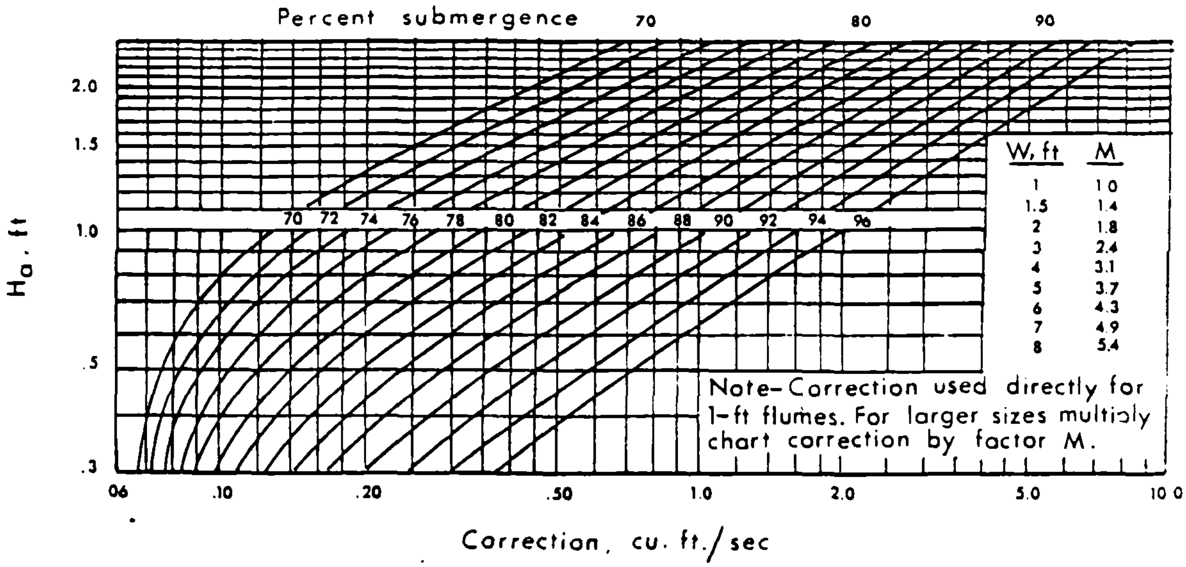

Figure A.7. Diagram for determining correction to be subtracted from free-discharge flow to obtain rate of submerged flow through Parshall flumes 1 to 8 feet wide (Ref. 12.1).

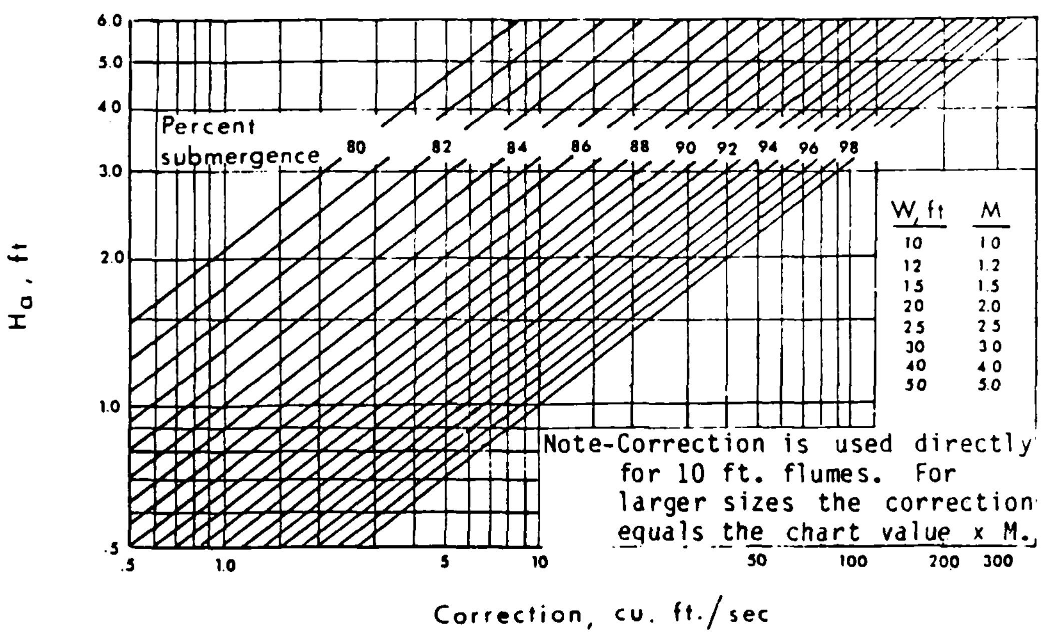

Figure A.8. Diagram for determining correction to be subtracted from free-discharge flow to obtain rate of submerged flow through Parshall flumes 10 to 50 feet wide (Ref. 12.1).

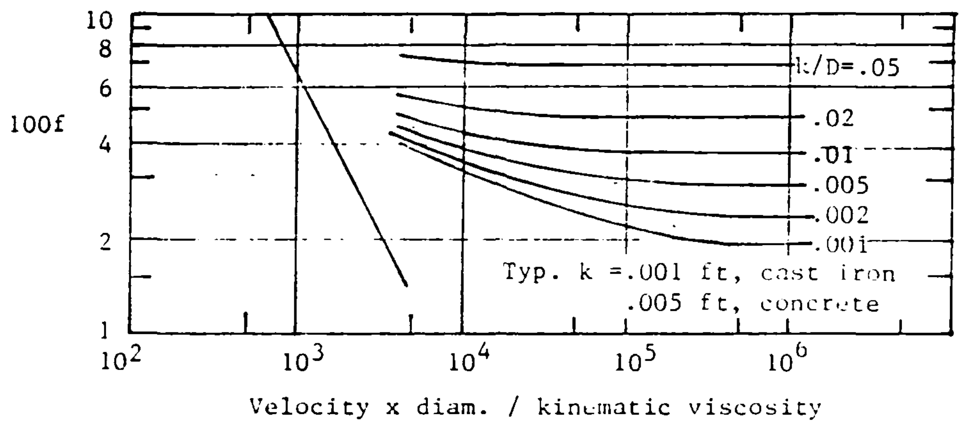

Figure A. 9. Friction-factor curves for stilling-well connector.