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SIMPLIFIED DESIGN OF FLUMES AND WEIRS[†]

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ABSTRACT

Long-throated flumes and broad-crested weirs have become accepted standards for open-channel flow measurement during the past two decades. These structures offer the accuracy and reliability of critical-depth flow measurement, theoretically based calibrations, the lowest head loss requirement of any critical flow device, and extraordinary design and construction flexibility. Computer software developed in recent years has streamlined the design and calibration process. The software, WinFlume, has been described in several papers and a recent text. Although WinFlume is very easy to use, there is still a need for simplified design and calibration tools for situations where use of the computer model is not possible or desirable. This paper combines several previous efforts to provide such tools in both metric and English units for the most typical measurement applications encountered in irrigation and drainage systems. Pre-computed designs for trapezoidal broad-crested weirs, long-throated flumes with rectangular control sections, broad-crested weirs in circular pipes, V-shaped long-throated flumes, and portable RBC flumes are presented in easy-to-use tables that provide head and discharge ranges, construction dimensions, head loss requirements, and flume rating equation parameters. The use of the tables is demonstrated with examples, and construction methods are illustrated. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: flow measurement; flumes; weirs

RÉSUMÉ

Au cours des vingt dernières années, des canaux jaugeurs à col allongé et des déversoirs à crête épaisse sont devenus les normes acceptées pour les mesures de débit à surface libre. Ces structures possèdent l'exactitude et la fiabilité des mesures des débits de profondeur critique, des étalonnages théoriques, la caractéristique de perte de charge la plus basse de n'importe quel dispositif d'écoulement critique et une extraordinaire souplesse de conception et de fabrication. Un logiciel développé ces dernières années a simplifié les modalités de conception et d'étalonnage. Le logiciel, WinFlume, a été décrit dans plusieurs articles et dans un texte récent. Bien que WinFlume soit d'un emploi très facile, on a toujours besoin de conception et d'outils d'étalonnage simplifiés dans les cas où la modélisation par ordinateur n'est pas possible ou pas souhaitable. Cet article associe plusieurs efforts effectués auparavant pour fournir de tels outils utilisant des unités métriques et anglaises pour les programmes de mesures les plus courants rencontrés dans les systèmes de drainage et d'irrigation. Des conceptions précalculées pour des déversoirs à trapézoïdaux à crête épaisse, des canaux jaugeurs à col allongé à sections de contrôle rectangulaires, des déversoirs à crête épaisse dans des tuyaux circulaires, des canaux jaugeurs à col allongé en V et des canaux jaugeurs portables RBC sont présentés dans des tableaux faciles d'emploi qui indiquent les gammes de

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charge et de débit, les dimensions de la construction, les caractéristiques de perte de charge et les paramètres de l'équation de notation du canal jaugeur. L'utilisation des tableaux est démontrée à l'aide d'exemples et les méthodes de fabrication sont illustrées. Copyright © 2005 John Wiley & Sons, Ltd.

MOTS CLÉS: mesure du débit; canaux jaugeurs; déversoirs

INTRODUCTION

The terms "long-throated flume" and "broad-crested weir" encompass a large family of structures used to measure discharge in open channels. Other names commonly used to describe these structures are ramp flume or weir, and Replogle flume or weir. These structures all have a streamlined converging transition that leads to a raised sill and/or narrowed throat section within which critical-depth flow is produced. In addition, the length of the sill or throat in the direction of flow is sufficient that the streamlines passing through the critical-depth section are essentially parallel to one another. This characteristic allows established one-dimensional hydraulic theory to be used to determine the calibration relationship between the discharge and the sill-referenced head, h_1, measured in the approach channel upstream from the sill or throat (Clemmens *et al.*, 2001). Although the theory is straightforward, the required calculations are iterative and tedious, and thus a number of computer programs have been developed in recent years to assist in the design and calibration of these devices. The latest of these computer programs is WinFlume (Wahl *et al.*, 2000). The program operates on Microsoft Windows-based computers and is available free of charge to the public from a website maintained by the Bureau of Reclamation. Earlier programs were described by Clemmens *et al.* (1987, 1993) and Bos *et al.* (1984).

An important component of modern broad-crested weirs and long-throated flumes is the streamlined converging transition. Older broad-crested weirs had either no transition (just an abrupt raised sill) or a rounded leading edge that still allowed some flow separation and streamline curvature to occur in the throat. The characteristics of the transition influenced the flow at the critical section, and thus these devices still relied on empirical calibrations developed through laboratory or field testing (Ackers *et al.*, 1978). It became possible to develop theoretical calibrations when it was realized that a suitably gradual transition would simplify the flow condition at the critical section.

Long-throated flumes (this term will be used hereafter to generically indicate all of the structures described above) have the lowest head loss requirement of any critical-flow device, and are thus very adaptable to installation in existing canal systems. Rating tables with an uncertainty less than ± 2% can be determined using the computer program for any combination of prismatic approach channels and control sections, as long as the throat is constructed so that it is level in the flow direction. The computer program makes it easy to develop ratings for structures using as-built dimensions, permitting the accurate calibration of structures that have not been built exactly to specification (assuming the throat is level in the flow direction). In addition, these structures pass floating debris easily and can be designed to effectively pass sediment. Also, they are usually more economical to build than other critical-flow devices. All of these advantages have led long-throated flumes to become the structure of choice for many open-channel flow measurement applications.

Flume design and selection

Design is a two-step process. First, the control section shape is selected and its elevation set to allow the desired range of flows to be measured accurately without incurring excess submergence of the control section or causing an undue increase in water levels upstream from the site. Once the control section is selected, the lengths of the approach channel, converging transition, throat, and optional diverging transition are determined.

When WinFlume is used to design a flume, six design criteria are evaluated:

- The upstream head at maximum discharge must be sufficient to prevent submergence of the control section
- The upstream head at minimum discharge must be sufficient to prevent submergence of the control section

- The upstream flow depth at maximum discharge should not encroach upon the required freeboard in the upstream channel
- The Froude number in the approach channel should be less than 0.5 to ensure a stable water surface in the approach channel
- The combined flow measurement uncertainty considering both rating table and head measurement uncertainty must meet the designer's objective at maximum discharge
- The combined flow measurement uncertainty must meet the designer's objective at minimum discharge

The first four design criteria are affected by the size and vertical position of the control section. The uncertainty requirements are related to the size of the control section and the choice of head-measurement sensor and its uncertainty. Head measurement errors tend to be fixed regardless of the depth of flow, so a narrower control section that produces a larger upstream head for a given flow rate will have smaller percentage errors in head measurement and a smaller combined uncertainty.

Flume selection tables

To make the design of small flumes and weirs primarily a selection process, a number of tables of pre-computed flume and weir designs have been compiled and presented in several reference texts (Bos *et al.*, 1984; Bureau of Reclamation, 1997, 2001; Replogle *et al.*, 1999; Clemmens *et al.*, 2001). The selection tables have been specifically focused on small structures in common canal sizes. For larger structures, detailed analysis with the WinFlume program is recommended.

The selection tables presented in the previous texts have addressed five common types of structures:

- Trapezoidal broad-crested weirs—often called ramp flumes or Replogle weirs or flumes; usually installed in concrete-lined trapezoidal channels
- Flumes with rectangular control sections—a flexible design adaptable to a variety of situations
- Weirs installed in circular pipes—effective for measurement of flows in culverts, drainage pipes, etc.
- Long-throated flumes with V-shaped control sections—effective for measurement in natural channels and drainage ditches that experience a wide range of flow rates
- Portable RBC flumes—small, easily constructed, trapezoidal broad-crested weirs suitable for measuring flows of 0.026–50 $\mathrm{l\,s^{-1}}$ (0.48 to 777 $\mathrm{gal\,min^{-1}}$).

The previous texts have taken different approaches to these configurations, with varying levels of generalization in the presentation of the design and calibration data. Some have provided complete rating tables, while others have provided rating equations of the form $Q = K_1(h_1 + K_2)^U$, where Q is the discharge, h_1 is the upstream sill-reference head, and K_1, K_2, and U are empirical coefficients. Some have provided information in only one units system (metric or English). Finally, some of the information given previously has been difficult to use because of typographic errors in the publications (Bureau of Reclamation, 1997; Replogle *et al.*, 1999). To make these tables of pre-computed flume and weir designs more useful to irrigators and water managers, this paper presents the selection tables in a compact, standardized form, with usage examples and illustrations of common construction techniques. More detailed design examples are provided in Clemmens *et al.* (2001).

The designs given in the selection tables were developed with the WinFlume program or its predecessors. Designs shown in the tables meet the Froude number requirement and reasonable measurement uncertainty criteria, assuming the use of a staff gage for upstream head measurement. The designs are not checked against the freeboard and submergence criteria, since these depend upon site-specific factors. Users of the tables must manually check the upstream flow depth versus the canal bank or lining height and must check the allowable tailwater levels (determined from flume head loss requirements given in the tables) against the known or expected tailwater conditions at the site. If there are problems with freeboard or submergence, the sill elevation must be changed or the control section size or shape adjusted. Once the control section parameters are established, the lengths of the flume components can be determined.

A note about H_1 versus h_1. In the selection tables that follow, lengths of flume components and required head losses are often referenced to the upstream total energy head, H_1, which includes the velocity head. However, rating equations are based on the observed upstream gaged head, h_1, which does not include the velocity head. For the purpose of determining length dimensions and estimating head losses, h_1 can be used as a rough estimate of H_1. If calculations show that the head loss requirement is close to the available head at the site, it may be necessary to make a more accurate head loss calculation using H_1.

TRAPEZOIDAL BROAD-CRESTED WEIRS

The trapezoidal broad-crested weir (Figure 1) is a very common measurement device. Construction is straightforward in existing concrete-lined canals, requiring only a horizontal sill and an upstream ramp. This configuration is commonly called a ramp flume or a Replogle flume or weir. Many construction methods are possible, utilizing cast-in-place concrete, pre-cast concrete, or prefabricated wood or steel panels. Tables I and II provide weir selections for canals dimensioned in metric units, and Tables III and IV address English units. For a given canal size and shape, a range of weirs of varying sill heights and crest widths are shown. For the range of discharges to be measured, the user can identify one or more weirs that will potentially work at the site. The rating equation parameters and head loss requirements of each weir are given in the table and can be used to verify that satisfactory freeboard and head loss are available at the site. The rating equation parameters were obtained by curve-fitting to rating tables developed with the WinFlume software.

Several of the weirs can be used for a range of canal bottom widths, at different sill heights. Ratings are accurate over these ranges of bottom widths because the change in flow area upstream from the structure is small enough that velocity head changes in the approach channel are negligible, causing a systematic error in measured discharge of less than 1%.

Example

Consider a trapezoidal concrete-lined canal whose base width is 1 m, with 1.5 : 1 (horizontal : vertical) side slopes and a maximum depth of 1.5 m. The range of flows to be measured is 0.4–4.5 $m^3 s^{-1}$. Tailwater levels downstream from the proposed weir site are given by the Manning equation (Strickler equation) with roughness coefficient $n = 0.014$ and bed slope of 0.0008. We wish to maintain a freeboard level of at least 20% of the upstream head on the weir.

For this range of flows, it appears in Table I that weirs P_m, Q_m, or R_m may be satisfactory. We will choose weir P_m initially, which has a sill height of 0.5 m. We must check to be sure that the selected weir will meet the freeboard requirement at maximum discharge and remain free-flowing over the full range of discharges. To do so, we will use the rating equation given in Table II, $Q = 6.814(h_1 + 0.0255)^{1.886}$. We rearrange this equation to allow us to compute the upstream head for a given discharge, $h_1 = (Q/6.814)^{(1/1.886)} - 0.0255$. At a discharge of 0.4 $m^3 s^{-1}$ the upstream head is 0.197 m, and at a discharge of 4.5 $m^3 s^{-1}$ the upstream head is 0.776 m. Solving the Manning equation yields tailwater flow depths of 0.358 m and 1.181 m at minimum and maximum flow, respectively.

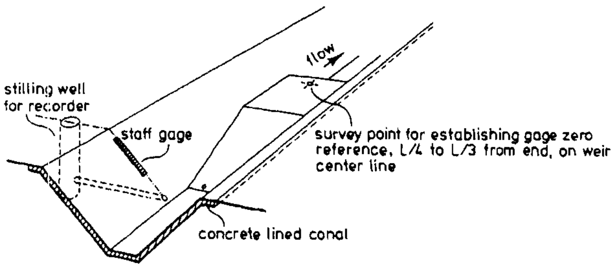


Figure 1. Broad-crested weir in a lined trapezoidal canal

Table I. Broad-crested weirs for lined trapezoidal canals dimensioned in metric units[a]

Canal shape		Maximum canal depth[b] d (m)	Range of canal capacities		Weir selections	Weir shape		
Side slopes z_1	Bottom width b_1 (m)		Lower[c] $Q_{\min}$ ($m^3 s^{-1}$)	Upper $Q_{\max}$ ($m^3 s^{-1}$)		Crest width b_c (m)	Sill height $p1$ (m)	Minimum head loss ΔH (m)
1.0	0.25	0.70	0.08	0.14[d]	A_m	0.50	0.125	0.015
			0.09	0.24[d]	B_m	0.60	0.175	0.018
			0.10	0.38[d]	C_m	0.70	0.225	0.022
			0.11	0.43[d]	D_{m1}	0.80	0.275	0.026
			0.12	0.37	E_{m1}	0.90	0.325	0.030
			0.13	0.32	F_{m1}	1.00	0.375	0.033
1.0	0.30	0.75	0.09	0.21[d]	B_m	0.60	0.150	0.017
			0.10	0.34[d]	C_m	0.70	0.200	0.021
			0.11	0.52	D_{m2}	0.80	0.250	0.025
			0.12	0.52	E_{m1}	0.90	0.300	0.029
			0.13	0.44	F_{m1}	1.00	0.350	0.033
			0.16	0.31	G_{m1}	1.20	0.450	0.039
1.0	0.50	0.8	0.11	0.33[d]	D_{m2}	0.80	0.150	0.019
			0.12	0.52[d]	E_{m1} or E_{m2}	0.90	0.200	0.024
			0.12	0.68[d]	F_{m1} or F_{m2}	1.00	0.250	0.029
			0.16	0.64	G_{m1}	1.20	0.350	0.037
			0.18	0.46	H_m	1.40	0.450	0.043
			0.20	0.29	I_m	1.60	0.550	0.048
1.0	0.60	0.9	0.12	0.39[d]	E_{m2}	0.90	0.150	0.021
			0.13	0.62[d]	F_{m2}	1.00	0.200	0.025
			0.16	1.09	G_{m1}	1.20	0.300	0.035
			0.18	0.86	H_m	1.40	0.400	0.043
			0.20	0.64	I_m	1.60	0.500	0.050
			0.22	0.43	J_m	1.80	0.600	0.049
1.0	0.75	1.0	0.16	0.91[d]	G_{m2}	1.20	0.225	0.030
			0.18	1.51	H_m	1.40	0.325	0.038
			0.20	1.22	I_m	1.60	0.425	0.047
			0.22	0.94	J_m	1.80	0.525	0.053
1.5	0.60	1.2	0.20	1.3[d]	K_m	1.50	0.300	0.031
			0.24	2.1[d]	L_m	1.75	0.383	0.038
			0.27	2.5	M_m	2.00	0.467	0.044
			0.29	2.2	N_m	2.25	0.550	0.050
			0.32	1.8	P_m	2.50	0.633	0.056
			0.35	1.4	Q_m	2.75	0.717	0.059
1.5	0.75	1.4	0.24	1.8[d]	L_m	1.75	0.333	0.036
			0.27	2.8[d]	M_m	2.00	0.417	0.042
			0.29	3.9[d]	N_m	2.25	0.500	0.049
			0.32	3.5	P_m	2.50	0.583	0.055
			0.35	3.1	Q_m	2.75	0.667	0.062
			0.38	2.6	R_m	3.00	0.750	0.066
1.5	1.00	1.6	0.29	3.4[d]	N_m	2.25	0.417	0.046
			0.32	4.7	P_m	2.50	0.500	0.052
			0.35	5.7	Q_m	2.75	0.583	0.059
			0.38	5.1	R_m	3.00	0.667	0.065
			0.43	3.9	S_m	3.50	0.833	0.081
1.5	1.25	1.7	0.32	4.1[d]	P_m	2.50	0.417	0.048
			0.35	5.6[d]	Q_m	2.75	0.500	0.055
			0.38	7.2	R_m	3.00	0.583	0.061
			0.43	5.9	S_m	3.50	0.750	0.074
			0.49	4.5	T_m	4.00	0.917	0.084
			0.55	3.3	U_m	4.50	1.083	0.089

Continues

Table 1. Continued

Canal shape		Maximum canal depth[b] d (m)	Range of canal capacities		Weir selections	Weir shape		Minimum head loss ΔH (m)
Side slopes z_1	Bottom width b_1 (m)		Lower[c] $Q_{\min}$ ($m^3 s^{-1}$)	Upper $Q_{\max}$ ($m^3 s^{-1}$)		Crest width b_c (m)	Sill height $p1$ (m)	
1.5	1.50	1.8	0.35	4.8[d]	Q_m	2.75	0.417	0.051
			0.38	6.5	R_m	3.00	0.500	0.058
			0.43	8.1	S_m	3.50	0.667	0.071
			0.49	6.6	T_m	4.00	0.833	0.083
			0.55	5.1	U_m	4.50	1.000	0.092

[a] $L_a \geq H_{1\max}$; $L_b = 3\,p_1$; $L_a + L_b > 2$ to $3\,H_{1\max}$ $L > 1.5\,H_{1\max}$, but within range given in Table II $d > 1.2\,h_{1\max} + p_1$ $\Delta H > 0.1\,H_1$.

[b] Maximum recommended canal depth.

[c] Limited by sensitivity.

[d] Limited by Froude number; otherwise limited by canal depth.

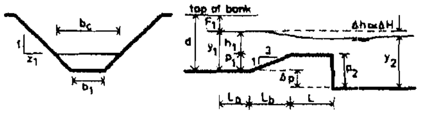


Table II. Rating equation parameters for broad-crested weirs in lined trapezoidal canals in metric units $Q = K_1(h_1 + K_2)^U$, where Q is discharge in $m^3 s^{-1}$ and h_1 is upstream head in meters

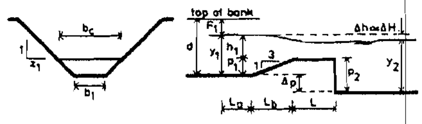
	Weir A_m	Weir B_m	Weir C_m	Weir D_{m1}	Weir D_{m2}	Weir E_{m1}	Weir E_{m2}	Weir F_{m1}
b_c (m)	0.50	0.60	0.70	0.80	0.80	0.90	0.90	1.00
L (m)	0.23–0.34	0.30–0.42	0.35–0.51	0.40–0.58	0.30–0.45	0.38–0.56	0.38–0.56	0.42–0.61
K_1	2.226	2.389	2.675	2.849	2.879	2.956	3.081	3.140
K_2	0.0083	0.0083	0.0122	0.0120	0.0089	0.0100	0.01023	0.0097
U	1.898	1.872	1.900	1.879	1.843	1.832	1.847	1.814
	Weir F_{m2}	Weir G_{m1}	Weir G_{m2}	Weir H_m	Weir I_m	Weir J_m	Weir K_m	Weir L_m
b_c (m)	1.00	1.20	1.20	1.40	1.60	1.80	1.50	1.75
L (m)	0.42–0.61	0.50–0.75	0.45–0.68	0.56–0.84	0.48–0.71	0.40–0.60	0.48–0.72	0.58–0.87
K_1	2.226	3.640	3.751	4.070	4.217	4.351	5.007	5.472
K_2	0.0083	0.0101	0.0126	0.0129	0.0088	0.0054	0.0193	0.0209
U	1.898	1.815	1.841	1.824	1.751	1.685	1.915	1.907
	Weir M_m	Weir N_m	Weir P_m	Weir Q_m	Weir R_m	Weir S_m	Weir T_m	Weir U_m
b_c (m)	2.00	2.25	2.50	2.75	3.00	3.50	4.00	4.50
L (m)	0.65–0.97	0.75–1.10	0.80–1.20	0.85–1.28	0.95–1.40	0.95–1.40	0.85–1.20	0.68–1.00
K_1	5.924	6.342	6.814	7.288	7.692	8.529	9.213	9.853
K_2	0.0194	0.0264	0.0255	0.0240	0.0239	0.0197	0.0131	0.0089
U	1.881	1.907	1.886	1.870	1.857	1.812	1.740	1.681

At maximum flow, the upstream depth is the sum of the sill height and upstream head, $0.5 + 0.776 = 1.276$ m. The required freeboard is 20% of 0.776 m, or 0.155 m. The actual freeboard is the canal depth minus the flow depth, or $1.5 - 1.276 = 0.224$ m. This exceeds the required freeboard, so the freeboard is adequate. Table I shows that the required head loss for this weir is at least 0.052 m. Thus, the allowable tailwater depth at maximum discharge is $1.276 - 0.052 = 1.224$ m. Since the actual tailwater depth is lower, the weir will flow free at maximum discharge. A similar check shows that the weir also flows free at minimum discharge.

Table III. Broad-crested weirs for lined trapezoidal canals dimensioned in English units[a]

Canal shape		Maximum canal depth[b] d (ft)	Range of canal capacities		Weir selections	Weir shape		Minimum head loss ΔH (ft)
Side slopes z_1	Bottom width b_1 (ft)		Lower[c] $Q_{\min}$ ($ft^3 s^{-1}$)	Upper $Q_{\max}$ ($ft^3 s^{-1}$)		Crest width b_c (ft)	Sill height p_1 (ft)	
1.0	1.0	2.5	1.9	8[d]	A_e	2.0	0.50	0.06
			4.2	16[d]	B_e	2.5	0.75	0.08
			4.8	19	C_e	3.0	1.00	0.10
			5.6	15	D_e	3.5	1.25	0.12
			6.2	11	E_e	4.0	1.50	0.13
1.0	2.0	3.0	5.6	27[d]	D_e	3.5	0.75	0.10
			6.2	40	E_e	4.0	1.00	0.12
			6.8	33	F_e	4.5	1.25	0.14
			7.4	27	G_e	5.0	1.50	0.15
			8.2	22	H_e	5.5	1.75	0.16
1.25	1.0	3.0	5.0	19[d]	I_e	3	0.80	0.08
			6.4	35	J_e	4	1.20	0.11
			7.6	26	K_e	5	1.60	0.14
1.25	2.0	4.0	6.4	31[d]	J_e	4	0.80	0.10
			7.6	64[d]	K_e	5	1.20	0.13
			8.9	78	L_e	6	1.60	0.16
			10.1	62	M_e	7	2.00	0.18
			11.4	46	N_e	8	2.40	0.20
1.5	2.0	4.0	8	49[d]	P_e	5	1.00	0.11
			9	82[d]	Q_e	6	1.33	0.13
			11	86	R_e	7	1.67	0.16
			12	72	S_e	8	2.00	0.18
			13	60	T_e	9	2.33	0.20
1.5	3.0	5.0	9	66[d]	Q_e	6	1.00	0.12
			11	108[d]	R_e	7	1.33	0.14
			12	140[d]	S_e	8	1.67	0.17
			13	160	T_e	9	2.00	0.20
			14	140	U_e	10	2.33	0.22
			17	95	V_e	12	3.00	0.25
1.5	4.0	5.5	12	135[d]	S_e	8	1.33	0.15
			13	200[d]	T_e	9	1.67	0.18
			14	235	U_e	10	2.00	0.21
			17	175	V_e	12	2.67	0.26
			19	125	W_e	14	3.33	0.28
1.5	5.0	6.0	14	235[d]	U_e	10	1.67	0.20
			17	285	V_e	12	2.33	0.25
			19	220	W_e	14	3.00	0.29
			22	160	X_e	16	3.67	0.32

Notes: [a] $L_a \geq \Delta H_{1\max}; L_b = 3p_1; L_a + L_b > 2$ to $3H_{1\max}$
$L > 1.5H_{1\max}$, but within range given in Table III
$d > 1.2h_{1\max} + p_1$
$\Delta H > 0.1H_1$.
[b] Maximum recommended canal depth.
[c] Limited by sensitivity.
[d] Limited by Froude number; otherwise limited by canal depth.



The notes at the bottom of Table I are used to determine the lengths of the different parts of the structure. The approach distance from the staff gage to the start of the ramp should be at least equal to the maximum head, so a length of 1 m is appropriate. The ramp length should be three times the sill height, or 1.5 m. The throat length should at least 1.5 times the maximum head and within the range shown in Table II, so a length of 1.2 m is selected.

Table IV. Rating equation parameters for broad-crested weirs in lined trapezoidal canals in English units $Q = K_1(h_1 + K_2)^U$, where Q is discharge in $\mathrm{ft}^3\,\mathrm{s}^{-1}$ and h_1 is upstream head in feet

Parameters	Weir A_c	Weir B_c	Weir C_c	Weir D_c	Weir E_c	Weir F_c	Weir G_c	Weir H_c
b_c, ft	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
L, ft	0.9–1.3	1.2–1.8	1.3–1.9	1.6–2.1	1.7–2.1	1.5–2.2	1.5–2.2	1.1–1.6
K_1	9.309	10.40	11.88	13.62	14.32	16.04	17.74	19.38
K_2	0.029	0.045	0.038	0.039	0.057	0.043	0.030	0.019
U	1.879	1.905	1.844	1.843	1.872	1.801	1.737	1.683
Parameters	Weir I_c	Weir J_c	Weir K_c	Weir L_c	Weir M_c	Weir N_c	Weir P_c	Weir Q_c
b_c, ft	3.0	4.0	5.0	6.0	7.0	8.0	5.0	6.0
L, ft	1.2–1.8	1.8–2.2	2.0–2.9	2.0–3.0	1.7-2.5	1.4–2.0	1.6–2.4	2.2–3.3
K_1	12.68	14.91	16.96	19.89	23.53	26.79	18.78	20.38
K_2	0.041	0.063	0.078	0.067	0.045	0.034	0.053	0.076
U	1.898	1.912	1.919	1.861	1.772	1.724	1.891	1.914
Parameters	Weir R_c	Weir S_c	Weir T_c	Weir U_c	Weir V_c	Weir W_c	Weir X_c	
b_c, ft	7.0	8.0	9.0	10.0	12.0	14.0	16.0	
L, ft	2.6–3.9	2.6–3.9	2.8–4.2	3.0–4.4	3.1–4.6	2.6–3.8	2.0–2.9	
K_1	23.59	24.44	27.06	29.86	35.85	43.56	50.96	
K_2	0.064	0.097	0.091	0.086	0.071	0.045	0.024	
U	1.873	1.907	1.879	1.86	1.805	1.726	1.660	

FLUMES WITH RECTANGULAR CONTROL SECTIONS

When flow measurement is needed in unlined earthen channels it is often convenient to build a structure with a rectangular control section (Figure 2). This type of flume is easily constructed from brick or concrete block (Figure 3). Prefabricated fiberglass flumes with fixed rectangular throats are also available, as well as galvanized steel flumes with an adjustable sill elevation. Tables V and VI provide information needed to select the sill height and size the throat width of these structures. The tables are based on the unit discharge through the throat. Information is given for structures in different width ranges, since the relative influence of friction along the channel walls changes the calibration to some degree. For each width range, several sill height options are shown,

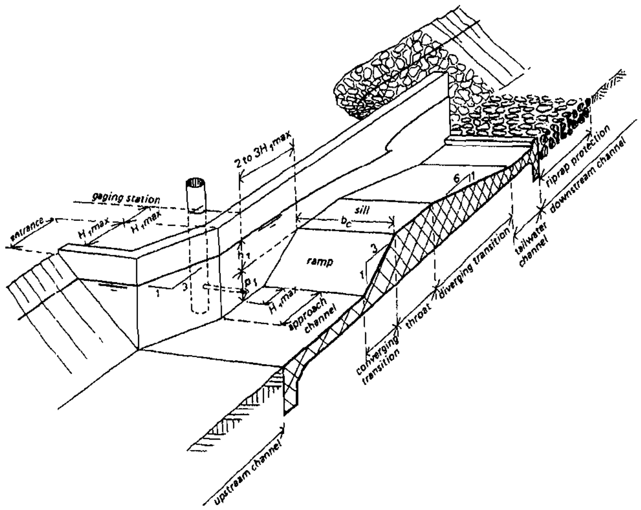


Figure 2. Rectangular-throated broad-crested weir installed in an earthen channel

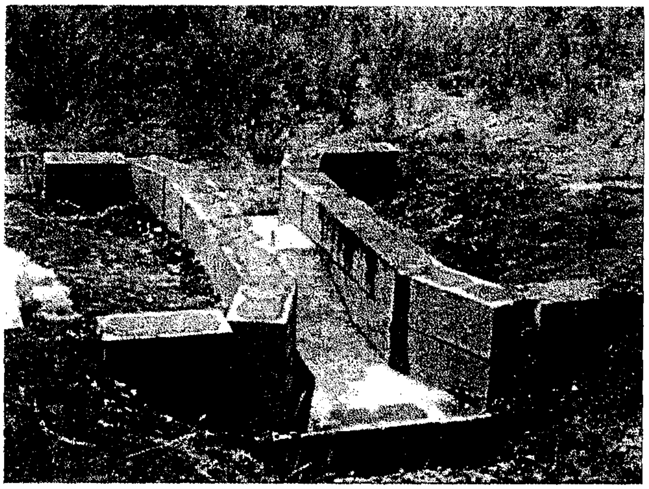


Figure 3. Long-throated flume with a rectangular throat section, constructed from concrete block

since the sill height affects the approach velocity and changes the rating of the structure. To use sill heights other than those shown, the user may interpolate, using the data for an infinite sill height as a boundary. For that case, the velocity of approach is negligible.

The rating equation parameters in Tables V and VI apply only when the gaging station is located in a rectangular approach channel exactly the same width as the throat (e.g. Figure 2). If the head is measured upstream, in the wider earthen section, the approach velocity will be significantly lower and the rating must be adjusted. A procedure for doing so is described in Clemmens *et al.* (2001), but it is generally simpler in such a case to use the WinFlume computer program to model the structure.

Example

Suppose we wish to measure flows ranging from 0.1 to 1.3 $m^3 s^{-1}$ in an earth-lined canal that is 1 m deep and approximately trapezoidal with a base width of 1.5 m and side slopes of 2 : 1. The tailwater depth at a discharge of 0.1 $m^3 s^{-1}$ is 0.15 m, and the tailwater depth at maximum discharge is 0.6 m. We must maintain freeboard of at least 10% of the upstream flow depth. This sets a maximum upstream flow depth of about 0.91 m.

We can use Table V to select a design. First, we must determine which range of throat widths to use. If the throat is only 1 m wide, the range of unit discharges (discharge per unit of throat width) would be 0.1–1.3 $m^3 s^{-1} m^{-1}$. None of the options in the section for throat widths of 0.5–1.0 m cover this range of discharges, so we will have to make the throat wider. If we make the throat 1.5 m wide, the range of unit discharges is 0.067 to 0.867 $m^3 s^{-1} m^{-1}$, which appears to be a workable range.

Next, we must determine the sill height. For a sill height of 0.2 m, the rating equation is $Q = b_c K_1 (h_1 + K_2)^U$, or $Q = 1.5(2.095)(h_1 + 0.004)^{1.627}$. Solving algebraically for h_1, we obtain $h_1 = 0.116$ m at $Q = 0.1$ $m^3 s^{-1}$ and $h_1 = 0.577$ m at $Q = 1.3$ $m^3 s^{-1}$. The upstream flow depths are thus 0.316 and 0.777 m at minimum and maximum flow, respectively. The freeboard at maximum discharge is $1.0 - 0.777 = 0.223$ m, which is more than 10% of the flow depth, so there is adequate freeboard. The required head loss is the greater of 0.046 m or $0.4H_1$ if we allow the flow to discharge directly into the downstream trapezoidal section with an abrupt expansion. Thus, the maximum allowable tailwater level at maximum flow is the upstream depth minus $0.4H_1$, or $0.777 - 0.4(0.577) = 0.546$ m. The actual tailwater level is 0.6 m, so the flume will be submerged. We could raise the sill, or another alternative is to extend the side walls of the throat section downstream (e.g. Figure 2), thus reducing the head loss requirement to the larger of 0.046 m or $0.1H_1$. This changes the allowable tailwater level at maximum flow to $0.777 - 0.1(0.577) = 0.719$ m. At minimum flow, the allowable tailwater level is $0.316 - 0.1(0.116) = 0.304$ m. The actual tailwater levels are lower than these limits, so the design is acceptable.

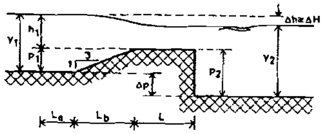
Table V. Rectangular-throated weirs and flumes for earthen channels, metric units

$q = K_1(h_1 + K_2)^U$ where q is the unit discharge in $m^3 s^{-1}$ per meter of throat width, and h_1 is the sill referenced head in meters
$Q = qb_c$ where Q is the total discharge in $m^3 s^{-1}$ and b_c is the throat width in meters

	$0.1 \le b_c \le 0.2\,m, L = 0.2\,m$			$0.2 \le b_c \le 0.3\,m, L = 0.35\,m$			$0.3 \le b_c \le 0.5\,m, L = 0.5\,m$		
Parameters	$p_1 = 0.05\,m$	$p_1 = 0.1\,m$	$p_1 = \infty$	$p_1 = 0.1\,m$	$p_1 = 0.2\,m$	$p_1 = \infty$	$p_1 = 0.1\,ft$	$p_1 = 0.2\,ft$	$p_1 = \infty$
K_1	2.449	2.194	1.817	2.271	2.012	1.744	2.276	2.017	1.731
K_2	0.0003	0	0	0.0014	0	0	0.0013	0.0007	0
U	1.608	1.581	1.530	1.612	1.562	1.517	1.615	1.574	1.517
h_1, range	0.014–0.130	0.014–0.146	0.026–0.130	0.025–0.235	0.025–0.235	0.025–0.330	0.035–0.330	0.035–0.330	0.035–0.330
q, range	0.003–0.092	0.003–0.091	0.003–0.079	0.006–0.221	0.006–0.200	0.006–0.192	0.011–0.381	0.011–0.353	0.011–0.353
ΔH, m	0.012	0.018	$0.4H_1$	0.025	0.030	$0.4H_1$	0.027	0.044	$0.4H_1$

	$0.5 \le b_c \le 1.0\,m, L = 0.75\,m$				$1.0 \le b_c \le 2.0\,m, L = 1.0\,m$			
Parameters	$p_1 = 0.1\,m$	$p_1 = 0.2\,m$	$p_1 = 0.3\,m$	$p_1 = \infty$	$p_1 = 0.2\,m$	$p_1 = 0.3\,m$	$p_1 = 0.4\,m$	$p_1 = \infty$
K_1	2.316	2.081	1.973	1.709	2.095	1.976	1.887	1.702
K_2	0.003	0.003	0.003	0	0.004	0.0027	0	0
U	1.641	1.611	1.594	1.516	1.627	1.598	1.560	1.519
h_1, range	0.050–0.360	0.050–0.500	0.050–0.500	0.050–0.500	0.070–0.670	0.070–0.670	0.070–0.670	0.070–0.670
q, range	0.019–0.438	0.018–0.689	0.018–0.660	0.018–0.595	0.030–1.110	0.030–1.059	0.030–1.028	0.030–0.925
ΔH, m	0.028	0.048	0.063	$0.4H_1$	0.046	0.066	0.086	$0.4H_1$

	$b_c \ge 2.0\,m, L = 1.5\,m$			
Parameters	$p_1 = 0.2\,m$	$p_1 = 0.4\,m$	$p_1 = 0.6\,m$	$p_1 = \infty$
K_1	2.108	1.933	1.854	1.677
K_2	0.005	0.007	0.006	0
U	1.641	1.618	1.596	1.540
h_1, range	0.12–0.70	0.12–0.95	0.12–0.97	0.1–1.0
q, range	0.067–1.20	0.067–1.80	0.067–1.80	0.051–1.689
ΔH, m	0.053	0.092	0.122	$0.4H_1$



$L_a = h_{1\,max}$ and $L_b = 2$ to 3 times p_1 and $L_a + L_b = 2$ to 3 times $h_{1\,max}$.
$\Delta H = 0.1H_1$, or value listed, whichever is greater, for flumes discharging into a rectangular tailwater channel of the same width as the crest, b_c.
$\Delta H = 0.4H_1$, or value listed, whichever is greater, for flumes with an abrupt expansion into a tailwater channel wider than the crest width, b_c.

Table VI. Rectangular-throated weirs and flumes for earthen channels, English units

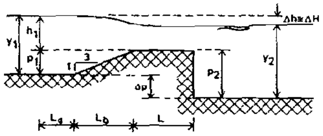
$q = K_1(h_1 + K_2)^U$ where q is the unit discharge in $\text{ft}^3\,\text{s}^{-1}$ per foot of throat width, and h_1 is the sill referenced head in feet

$Q = qb_c$ where Q is the total discharge in $\text{ft}^3\,\text{s}^{-1}$ and b_c is the throat width in feet

	$0.35 \le b_c \le 0.65\,\text{ft}, L = 0.75\,\text{ft}$			$0.65 \le b_c \le 1.0\,\text{ft}, L = 1.0\,\text{ft}$			$1.0 \le b_c \le 1.5\,\text{ft}, L = 1.5\,\text{ft}$		
Parameters	$p_1 = 0.125\,\text{ft}$	$p_1 = 0.25\,\text{ft}$	$p_1 = \infty$	$p_1 = 0.25\,\text{ft}$	$p_1 = 0.5\,\text{ft}$	$p_1 = \infty$	$p_1 = 0.25\,\text{ft}$	$p_1 = 0.5\,\text{ft}$	$p_1 = \infty$
K_1	3.996	3.610	3.126	3.696	3.385	3.089	3.686	3.400	3.059
K_2	0	0	0	0.004	0	0	0	0	0
U	1.612	1.581	1.526	1.617	1.562	1.518	1.598	1.569	1.515
h_1, range	0.06–0.46	0.06–0.48	0.05–0.5	0.08–0.7	0.08–0.7	0.08–0.8	0.1–0.9	0.1–1.0	0.1–1.0
q, range	0.04–1.15	0.04–1.14	0.03–1.08	0.07–2.1	0.07–1.95	0.07–1.8	0.09–3.1	0.09–3.4	0.09–3.1
ΔH, ft	0.04	0.06	$0.4H_1$	0.06	0.10	$0.4H_1$	0.07	0.11	$0.4H_1$

	$1.5 \le b_c \le 3.0\,\text{ft}, L = 2.25\,\text{ft}$				$3.0 \le b_c \le 6.0\,\text{ft}, L = 3.0\,\text{ft}$			
Parameters	$p_1 = 0.25\,\text{ft}$	$p_1 = 0.5\,\text{ft}$	$p_1 = 1.0\,\text{ft}$	$p_1 = \infty$	$p_1 = 0.5\,\text{ft}$	$p_1 = 1.0\,\text{ft}$	$p_1 = 1.5\,\text{ft}$	$p_1 = \infty$
K_1	3.662	3.375	3.19	3.036	3.362	3.169	3.167	3.027
K_2	0.008	0.011	0.009	0	0.013	0.013	0	0
U	1.643	1.625	1.587	1.514	1.636	1.605	1.557	1.519
h_1, range	0.15–1.0	0.15–1.5	0.15–1.5	0.15–1.5	0.21–1.84	0.22–1.93	0.21–1.98	0.2–2.04
q, range	0.18–3.2	0.17–6.6	0.17–6.1	0.17–5.6	0.29–9.24	0.29–9.28	0.29–9.26	0.26–9.24
ΔH, ft	0.07	0.13	0.2	$0.4H_1$	0.13	0.22	0.29	$0.4H_1$

	$b_c \ge 6.0\,\text{ft}, L = 4.0\,\text{ft}$			
Parameters	$p_1 = 1.0\,\text{ft}$	$p_1 = 1.5\,\text{ft}$	$p_1 = 2.0\,\text{ft}$	$p_1 = \infty$
K_1	3.125	3.150	3.105	2.999
K_2	0.017	0.016	0	0
U	1.621	1.575	1.563	1.521
h_1, range	0.3–3.0	0.3–2.6	0.3–2.64	0.3–3.0
q, range	0.48–19	0.48–14.2	0.48–14.2	0.48–16
ΔH, ft	0.25	0.33	0.40	$0.4H_1$



$L_a = h_{1\,\max}$ and $L_b = 2$ to 3 times p_1 and $L_a + L_b = 2$ to 3 times $h_{1\,\max}$.

$\Delta H = 0.1H_1$, or value listed, whichever is greater, for flumes discharging into a rectangular tailwater channel of the same width as the crest, b_c.

$\Delta H = 0.4H_1$, or value listed, whichever is greater, for flumes with an abrupt expansion into a tailwater channel wider than the crest width, b_c.

The notes at the bottom of Table V help us determine the lengths of the flume components. The distance from the gage to the start of the converging ramp is chosen to be 0.75 m (recognizing that H_1 will be somewhat greater than h_1), the ramp length is 0.6 m, and the control section length is 1 m. Downstream from this structure, rip-rap protection of the channel should be provided for a distance of about 2.5 m (four times the maximum downstream flow depth). Clemmens *et al.* (2001) provide more details about energy dissipation and erosion protection downstream from weirs and flumes.

WEIRS FOR CIRCULAR PIPES

Broad-crested weirs constructed in circular conduits make convenient portable and permanent measurement structures. A bottom ramp leads to a flat crest whose height is generally 20–50% of the pipe diameter. The sill height is chosen to limit the upstream flow depth to less than 90% of the pipe diameter. Figure 4 shows how to lay out the shape for the bottom ramp, which is a portion of an ellipse. These weirs are especially convenient for measurements in culverts, where they can be constructed in place, or pre-cast in the culvert before it is installed in the channel. Small, portable weirs can be created by installing a ramp and sill in a section of circular pipe small enough to be moved from site to site. Adding leveling bubbles on top of the device facilitates an effective installation.

Table VII provides weir selection and calibration data for different ratios of sill height to pipe diameter. The data are scaled in reference to the pipe diameter, with discharge ranges and rating equation coefficients appropriate for metric or English units. The data in Table VII were developed by using WinFlume to analyze weirs of varying sill height in 1 ft and 1 m diameter pipes, assuming smooth concrete roughness for the ramp and sill. The user scales the dimensions and discharge characteristics using relationships based on the concepts of Froude-scale modeling. Small differences from the computed calibrations will occur when the results are scaled to other pipe sizes because

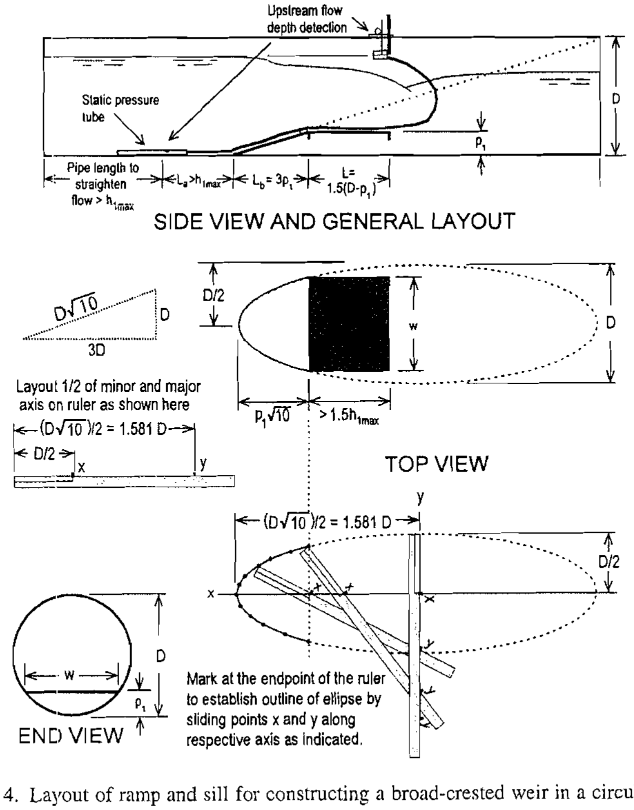


Figure 4. Layout of ramp and sill for constructing a broad-crested weir in a circular pipe

Table VII. Weirs for circular pipes

Metric units

Length, diameter and sill height in meters, discharge in $m^3 s^{-1}$. Applicable to pipe diameters of 20 cm to 5 m

p_1/D	b_c/D	L_a/D	L_b/D	L/D	Range of h_1/D	Range of $Q/D^{5/2}$	K_1	K_2	U
0.20	0.800	0.50	0.60	0.700	0.080–0.43	0.032–0.539	2.297	0.008	1.757
0.25	0.866	0.60	0.75	1.125	0.080–0.57	0.033–0.845	2.176	0.005	1.695
0.30	0.917	0.55	0.90	1.050	0.075–0.53	0.031–0.740	2.090	0.003	1.649
0.35	0.954	0.50	1.05	0.975	0.070–0.50	0.029–0.660	1.988	0	1.591
0.40	0.980	0.45	1.20	0.900	0.065–0.46	0.027–0.565	1.905	0	1.563
0.45	0.995	0.40	1.35	0.825	0.060–0.42	0.024–0.478	1.831	0	1.543
0.50	1.000	0.35	1.50	0.750	0.060–0.38	0.024–0.398	1.750	0	1.524

English units

Length, diameter and sill height in feet, discharge in $ft^3 s^{-1}$. Applicable to pipe diameters of 2.5 inches to 5 ft.

p_1/D	b_c/D	L_a/D	L_b/D	L/D	Range of h_1/D	Range of $Q/D^{5/2}$	K_1	K_2	U
0.20	0.800	0.50	0.60	0.700	0.080–0.43	0.056–0.980	4.176	0.007	1.750
0.25	0.866	0.60	0.75	1.125	0.070–0.60	0.048–1.689	3.970	0.004	1.689
0.30	0.917	0.55	0.90	1.050	0.070–0.55	0.050–1.434	3.780	0	1.625
0.35	0.954	0.50	1.05	0.975	0.065–0.50	0.046–1.202	3.641	0	1.597
0.40	0.980	0.45	1.20	0.900	0.060–0.45	0.042–0.991	3.507	0	1.573
0.45	0.995	0.40	1.35	0.825	0.055–0.40	0.037–0.807	3.378	0	1.554
0.50	1.000	0.35	1.50	0.750	0.050–0.35	0.032–0.640	3.251	0	1.540

Pregage distance, $L_{pg} \geq h_{max}$

Approach, $L_a \geq h_{max}$

Converging, $L_b = 3p_1$

Control, $L_c \geq 1.5D - p_1$

Sill height $= p_1$

Dimensionless sill height $= p_1/D$

$h_{min} = 0.07D$

$h_{max} = [0.85D - p_1]$

$$Q = D^{2.5} K_1 \left(\frac{h_1}{D} + K_2\right)^U$$

$\Delta H = 0.1H_1$ for weirs with a 6:1 downstream transition ramp

$\Delta H = 0.2H_1$ for weirs with a vertical drop downstream from the crest

$\Delta H = 0.4H_1$ for weirs at the end of a pipe discharging into a wider downstream channel

Note: The length values shown are minimum lengths in direction of flow, and may be increased 30% with only a slight change in calibration.

the roughness of the construction materials is not scaled. The practical limit on the scaling ratio is a factor of about 5, allowing the data in Table VII to be used for pipe diameters ranging from 20 cm to 5 m and about 2.5 inches to 5 ft while retaining a rating table uncertainty of about ± 3%. For smaller of larger structures, one should develop a calibration using WinFlume.

The discharge equation for a given pipe size is

$$Q = D^{2.5} K_1 (h_1/D + K_2)^U$$

where Q = discharge, $m^3 s^{-1}$ or $ft^3 s^{-1}$, D = diameter of pipe, m or ft, K_1 = constant from Table VII, K_2 = constant from Table VII, h_1 = head measured from top of sill, m or ft and U = exponent.

Example

We wish to construct a portable measuring device, like that shown in Figure 5, using a short length of 0.3-m diameter, circular steel pipe. We need to measure flows ranging from 2 to 40 $l s^{-1}$ (0.002 to 0.04 $m^3 s^{-1}$). To use Table VII, we compute the range of $Q/D^{2.5}$, which is 0.041–0.811. Table VII shows that only a sill that is 25% of the pipe diameter will measure this range of flows. For that design, the rating equation is

$$Q = (0.3)^{2.5}(2.176)(h_1/0.3 + 0.005)^{1.695}$$

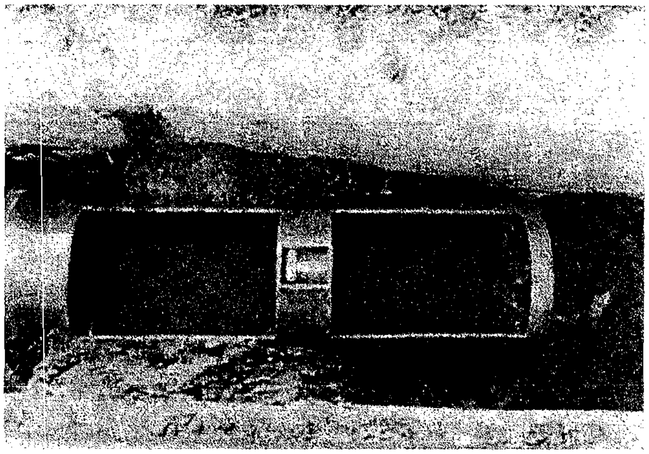


Figure 5. Example of a portable weir constructed in a circular pipe

V-SHAPED FLUMES

When measuring flows in natural channels or drainage canals, a structure that can measure a wide range of discharges is often needed. Flumes with a V-shaped throat (Figure 6) are well suited to this task, since the effective throat width varies with the flow, providing good sensitivity over a wide discharge range. Flumes with V-shaped throats can typically measure flows varying by a ratio of about 335 : 1. These flumes are typically constructed with side slope angles that are mild enough to allow the use of flat-slab construction techniques.

Table VIII provides rating equations for V-shaped flumes with side slopes of 1 : 1, 2 : 1, and 3 : 1. The base width of the approach channel is assumed to be 0.6 m (2 ft), and the throat is elevated 0.15 m (0.5 ft) above the approach channel. This basic design should be suitable for a wide range of applications, in channels up to 1 m deep. For larger channels and flow rates, WinFlume can be used to develop a custom design.

PORTABLE RBC FLUMES

A family of five small, portable flumes called RBC flumes were designed for use in furrows and small earthen channels (Clemmens *et al.*, 1984). These flumes are scale models of one another with trapezoidal throats whose base width varies from 50 to 200 mm. Construction drawings showing all dimensions as multiples of the base width with step-by-step assembly instructions and other details are given by Clemmens *et al.* (1984, 2001). These flumes

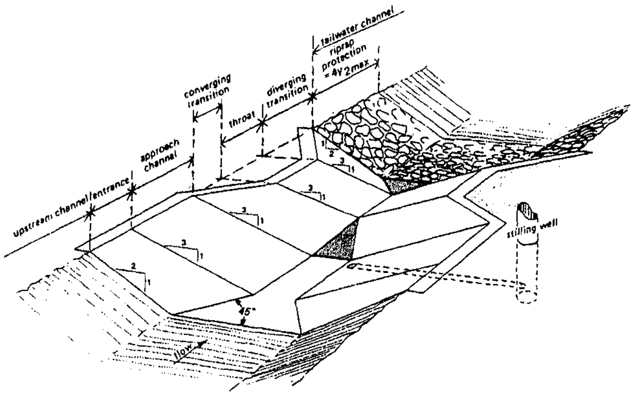


Figure 6. Flume with V-shaped control section

Table VIII. Flumes with V-shaped control sections

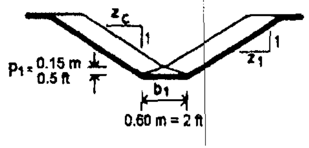
Metric units

z_c	Range of h_1 (m)	Range of Q ($m^3 s^{-1}$)	K_1	K_2	U	Head loss,[a] ΔH(m)
1	0.08–0.82	0.0020–0.794	1.319	0	2.564	0.09
2	0.08–0.82	0.0042–1.638	2.714	0	2.568	0.07 or $0.1H_1$
3	0.08–0.82	0.0063–2.495	4.123	0	2.571	0.06 or $0.1H_1$

English units

z_c	Range of h_1 (ft)	Range of Q ($ft^3 s^{-1}$)	K_1	K_2	U	Head loss,[a] ΔH(ft)
1	0.25–2.70	0.063–28.3	2.214	0	2.563	0.30
2	0.25–2.70	0.130–58.3	4.530	0	2.566	0.22 or $0.1H_1$
3	0.25–2.70	0.196–88.8	6.857	0	2.571	0.19 or $0.1H_1$

Subscripts:
1 denotes upstream channel.
2 denotes downstream channel.
c denotes control section.



$b_1 = b_2 = 0.60\,m \approx 2\,ft$
$p_1 = p_2 = 0.15\,m \approx 0.5\,ft$
$z_1 = z_c = z_2$
$b_c = 0$

Approach length, $L_a = 0.90\,m \approx 3\,ft$
Converging transition length, $L_b = 1.0\,m \approx 3.25\,ft$
Throat length, $L = 1.2\,m \approx 4\,ft$

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[a] Head loss values shown assume gradual downstream expansion. For an abrupt expansion into a stagnant pool, $\Delta H = 0.24H_1$.

are commonly constructed from 1-mm thick galvanized sheet metal. Fiberglass versions are also commercially available at this time.

The upstream sill-referenced head h_1 is measured in a translocated stilling well, a desirable feature of any portable flume or weir. The stilling well is mounted near the control section to minimize changes in the sill reference of the well caused by a slightly non-level installation. Even with this feature, a level installation is desirable so that tilt does not significantly affect the discharge coefficient. Cross-slope leveling of the flume is achieved by keeping the upstream edge of the cutoff parallel to the water surface; experienced users can judge adequate leveling by eye. The flume can be leveled in the flow direction using a carpenter's level. If the flume is installed for semi-permanent flow measurement, the stilling well is best located to the side of the flume (Figure 7) to avoid collecting floating debris. This location is also recommended on the two smallest RBC flumes ($b_c = 50$ or 75 mm) because it allows the use of a larger-diameter stilling-well tube. If the side mounted stilling well is used, the well should be located at a distance of 1.5 b_c from the downstream end of the flume (0.5 b_c upstream from the downstream end of the throat).

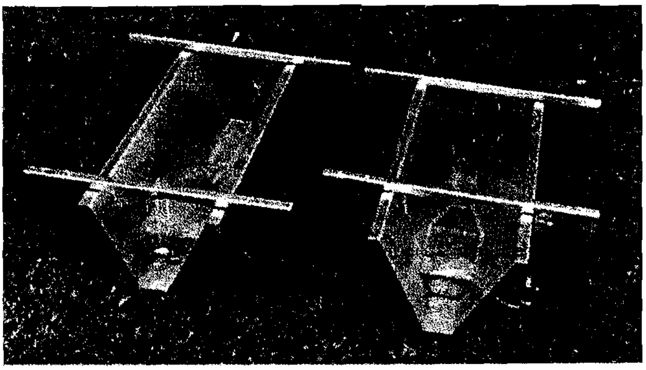


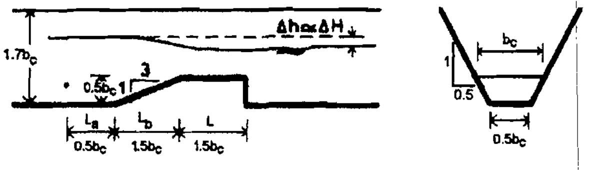
Figure 7. RBC flumes with center-mounted and side-mounted translocated stilling wells

Table IX. RBC flumes

Throat width b_c	Throat length L	Head range h_{min} to h_{max}	Discharge range Q_{min} to Q_{max}	Head loss ΔH	K_1	K_2	U
Metric units							
mm	mm	mm	$l\,s^{-1}$	mm	Coefficients apply with Q in $l\,s^{-1}$ and h_1 in mm		
50	75	5–50	0.03–1.5	10	0.001035	0.75	1.853
75	112.5	7–75	0.07–4.3	15	0.001347	1.313	1.853
100	150	10–100	0.16–8.7	20	0.001514	2.214	1.867
150	225	14–150	0.40–24.0	30	0.001929	3.603	1.870
200	300	20–200	0.94–49.0	40	0.002189	5.457	1.879
English units							
ft	ft	ft	gpm	ft	Coefficients apply with Q in gpm and h_1 in ft		
0.164	0.246	0.018–0.16	0.48–23.8	0.033	657.9	0.0025	1.853
0.246	0.369	0.026–0.25	1.11–68.2	0.049	854.7	0.0043	1.853
0.328	0.492	0.035–0.32	2.54–138	0.066	1040	0.0073	1.867
0.492	0.738	0.05–0.50	6.34–380	0.098	1348	0.0118	1.870
0.656	0.984	0.07–0.66	14.9–777	0.131	1615	0.0179	1.879

Subscripts:
1 denotes upstream channel.
2 denotes downstream channel.
c denotes control section.

$b_1 = b_2 = 0.5b_c$
Sill height, $p_1 = 0.5b_c$
$z_1 = z_c = z_2 = 0.5$
Approach length, $L_a = 0.5b_c$.
Converging transition length, $L_b = 1.5b_c$.
Throat length, $L = 1.5b_c$



Conversions: 448.8 gals min^{-1} (gpm) = 1 ft^3 s^{-1}; 1000 l s^{-1} = 1 m^3 s^{-1}.

Table IX provides ranges of discharge and head for RBC flumes, along with rating equation parameters needed to compute flow rates in metric or English units.

SUMMARY AND CONCLUSIONS

Long-throated flumes and broad-crested weirs are the most efficient, accurate, and adaptable critical-flow devices available for measuring discharge in open channels. A primary advantage is the fact that they can be calibrated by computer analysis, making the accurate rating of as-built structures possible and enabling the design of structures that meet unique site and operating requirements. For even more simplified application, precalibrated flume and weir designs have been presented here with tables that assist in their selection. In some cases (e.g. portable RBC flumes) devices can be selected directly from the tables with no additional calculations necessary. For permanent installations, the designer must verify that a selected structure will meet freeboard and allowable submergence criteria, and examples of these calculations have been given. Some of the many possible flume and weir construction techniques have also been illustrated.

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