

5.6 Flume Design Procedure

The intent of the design procedure is to determine the appropriate dimensions of a flow-measuring flume that will perform according to the criteria described in Section 5.2. That is, it will accurately measure discharge over the full range of flows to be measured. Design is often an iterative process and in many cases, there are a wide variety of flumes that will function adequately. This design procedure is aimed at providing a flume that is simple, easy to construct, and accurate.

The design process varies slightly with the channel conditions and with the source of rating tables and flume information (i.e., when design is being done with theory and equations, with rating tables for standard sizes, or with the computer program of Chapter 8, WinFlume). The basic steps in the process are given briefly below and discussed in more detail in subsequent sections. This is basically a trial and error process, although the methods for determining the amount of contraction required, described in Section 6.3.3, can speed up the process considerably.

5.6.1 Flume design steps (trial and error)

1. Obtain data on the channel and the flow condition within the channel, including the range of flows to be measured (Q_{min} and Q_{max}) and the associated tailwater levels (y_{2min} and y_{2max}). (Fill out the information in Figure 2.21. See, for example, Table 5.7).
2. Decide how much freeboard is required (F_1).
3. Decide on the allowable errors (X_{Qmin} and X_{Qmax}) in flow measurement at the minimum and maximum flow rates to be measured and determine the rating table errors (X_{Cmin} and X_{Cmax}).
4. Decide on the method of head detection, and its associated accuracy (δ_{h1}), and determine the head required to satisfy the accuracy criteria.
5. Decide on an initial shape for the control section and determine how that shape will be changed initially during the design process.
6. Select a trial contraction amount and initial flume longitudinal dimensions (if needed).
7. Determine the upstream head and the required head loss at Q_{min} and Q_{max} for this trial contraction (h_{1min} and h_{1max} , ΔH_{min} and ΔH_{max}).
8. Compare the results of this trial with the design criteria. If design criteria are not met, select a different contraction amount and repeat Steps 7 and 8 until design criteria and design aims are satisfied. (see Section 5.6.6 for recommendations).
9. Finalize flume or weir longitudinal dimensions according to criteria in Table 5.8, in Section 5.6.3.

When selecting from among standard flumes such as those in Table 5.2, the trial and error process is fast and straightforward. In fact, we recommend that the designer determine the full range of flume sizes that satisfy the design criterion. Then one can evaluate the tradeoffs between the various options. However, for general design, there may be too many options. An example is the selection of a rectangular flume

NAME OF SITE: Kodak, Colorado DATE: April 30
2001

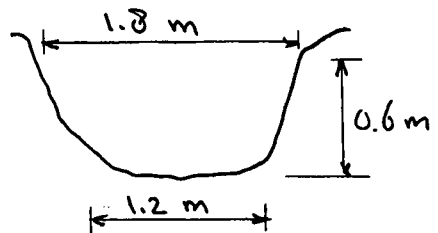
HYDRAULIC DEMANDS:

Range of flow to be measured, Q	Present water depth in channel, y_2	Minimum permitted error in measurement, X_0
$Q_{\min} = 0.085 \text{ m}^3/\text{s}$ $Q_{\max} = 0.340 \text{ m}^3/\text{s}$	$y_{2\min} = 0.25 \text{ m}$ $y_{2\max} = 0.46 \text{ m}$	$X_{Q\min} = 7.0\%$ $X_{Q\max} = 5.0\%$

HYDRAULIC DESCRIPTION:

Channel bottom with	$b_1 = \pm 1.2 \text{ m}$
Channel side slope	$z = - \text{ m}$
Channel depth	$d = - \text{ m}$
Maximum allowable water depth	$y_{1\max} = 0.60 \text{ m}$
Manning's n	$n = 0.050$
Hydraulic gradient	$S_f = 0.001$
Available drop in water surface at site	$\Delta h = 0.15 \text{ m}$
Drop in channel bottom at site	$\Delta p = 0.0 \text{ m}$

Sketch of channel cross section:



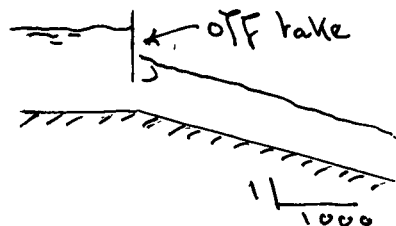
FUNCTION OF STRUCTURE

Measurement only	<input checked="" type="checkbox"/>
Regulation and measurement of flow rate	<input type="checkbox"/>

Concrete lined:

Earthen channel:

Profile along bottom of channel over length of $100b_1$



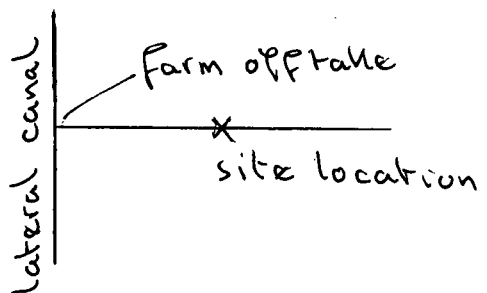
PERIOD OF STRUCTURE SERVICE

Day	<input type="checkbox"/>	Season	<input checked="" type="checkbox"/>
Month	<input type="checkbox"/>	Permanent	<input type="checkbox"/>

DESCRIPTION OF ENVIRONMENT

Irrigation System	Drainage System
Main <input type="checkbox"/>	From irrigated area <input type="checkbox"/>
Lateral <input type="checkbox"/>	Artificial drain <input type="checkbox"/>
Farm ditch <input checked="" type="checkbox"/>	Natural drain <input type="checkbox"/>
In field <input type="checkbox"/>	

Plan of site:



FURTHER DESCRIPTION
(attach photo)

Hypothetical site based on information obtained from Kodak Farms, Windsor, Colorado, USA

Table 5.7 Data for design example.

for an unlined canal where both width and sill height have a wide range of possible values. Generally, the choice between side and bottom contractions is made on the basis of flow measurement accuracy versus constructability of the device.

5.6.2 Design equations

The design requirements can be put into equation form, as follows:

$$\text{Modular flow at } Q_{max} \quad H_{1max} > H_{2max} + \Delta H_{max} \quad 5.7$$

or approximately

$$h_{1max} > h_{2max} + \Delta h_{max}$$

$$\text{Modular flow at } Q_{min} \quad H_{1min} > H_{2min} + \Delta H_{min} \quad 5.8$$

or approximately

$$h_{1min} > h_{2min} + \Delta h_{min}$$

$$\text{Freeboard} \quad h_{1max} < d - p_1 - F_1 \quad 5.9$$

$$\text{Froude number} \quad Fr_1 = \frac{Q_{max}/A_{1max}}{\sqrt{gA_{1max}/B_{1max}}} < 0.5 \quad 5.10$$

or

$$\frac{A_{1max}^3}{B_{1max}} > \frac{4Q_{max}^2}{g}$$

$$\text{Accuracy at } Q_{max} \quad h_{1max} > \frac{u\delta_{h1}}{\sqrt{X_{Qmax}^2 - X_{Cmax}^2}} \quad 5.11$$

$$\text{Accuracy at } Q_{min} \quad h_{1min} > \frac{u\delta_{h1}}{\sqrt{X_{Qmin}^2 - X_{Cmin}^2}} \quad 5.12$$

Equations 5.7 through 5.12 are written so that the upstream head, h_1 , and/or variables that are known functions of h_1 , are on the left hand side. All of these inequalities prefer larger heads except the relationship for freeboard (Equation 5.9), which requires a smaller upstream head. The initial tradeoffs are between Equation 5.9 and Equations 5.7, 5.8 and 5.10.

Design starts with assuming an initial contraction amount. A good starting point is a contraction that is roughly one half of the approach section area (not counting the freeboard). The heads, h_{1min} and h_{1max} , for the design flows, Q_{min} and Q_{max} , can then be determined from rating tables, from the equations presented in either Section 6.4 or 6.5, or from the software in Chapter 8. This implies that initial values for the flume longitudinal dimensions have been chosen. Once these heads have been determined, Equations 5.7 through 5.12 can be evaluated. If the above design criteria are not satisfied, a higher or lower contraction amount can be tried.

In Equations 5.11 and 5.12, values for X_C depend on how the head-discharge relationship is determined. If the standard flumes and rating tables given in this book are used, the rating table errors are provided in the tables. They range from 2 to 3% (additional error is added if interpolation between columns is needed). If the head-discharge equations of Section 6.4 are used, then X_C can be found from Equation 6.28. If the head-discharge relationship is determined from the model of Section 6.5 or the program of Chapter 8, X_C can be found from Equation 6.44. Note that X_C from these equations depends upon H_1/L , and thus depends on flume dimensions. Initial values for X_C can be taken as 5% or 2% for Equation 6.28 and 6.44, respectively.

5.6.3 Requirements for flume longitudinal dimensions

The flumes and weirs presented in this book can provide accurate flow measurements only if constructed with appropriate dimensions so that they fit the

Table 5.8 Requirements for Flume Longitudinal Dimensions.

Dimension	Requirements
Approach section length, L_a	$L_a \approx H_{1max}$ $2 H_{1max} < L_a + L_b < 3 H_{1max}$
Converging transition length, L_b	Provide transition angle between 2.5:1 and 4.5:1, with 3:1 preferred. $L_b \approx 3 p_1$ for bottom contraction. $L_b \approx 3(B_1 - B^*)/2$ for symmetrical side contraction (see Section 6.3.3). Use the larger of these two for a combined contraction.
Throat length, L	$1.43 H_{1max} < L < 14.3 H_{1min}$ for model or computer rating. $1.0 H_{1max} < L < 10 H_{1min}$ for rating based on experiments.
Diverging transition length, L_d	$L_d < 10 p_2$, $L_a = 6p_2$ recommended.
Diverging transition slope, $m:1$	m equal to either 0 or 6 is recommended.
Tailwater channel length, L_e^*	$L_e = 10(p_2 + L/2) - L_d$

* The length L_e is often not a part of the actual structure; WinFlume uses this length for calculation of friction losses in the diverging transition. When constructing a full-length rectangular-throated weir like that shown in Figure 5.10, L_e is the length of the additional energy recovery section downstream from the diverging transition.

requirements for analysis as long-throated flumes. Primarily this involves the lengths of the various flume components in the direction of flow. These length requirements ensure that the desired flow conditions occur so that the hydraulic theory described in Chapter 6 can be applied. The length requirements are summarized in Table 5.8. The reasoning behind these requirements includes the following:

- The gaging station should be located far enough upstream from the crest and converging section to be out of the drawdown zone that is created as the flow accelerates toward critical velocity at the control section. However, the gaging station should not be so far upstream that unnecessary head loss occurs between the gaging station and the control section. The gaging station should be at least H_{1max} upstream from the start of the converging transition, and about 2 to 3 times H_{1max} upstream from the sill or throat.
- The converging transition should be gradual, without offsets or sudden changes in wall alignment that might cause flow separation as the flow contracts toward the control section. The converging transition should not be too long, or the structure will be unnecessarily expensive. Transition slopes of 2.5:1 to 4.5:1 are recommended.
- For best measurement accuracy, a throat length should be selected so that $0.07 \leq H_1/L \leq 0.7$ at all measured flow rates.
- If a diverging transition is used, the recommended slope is 6:1 (horizontal:vertical) for good energy recovery and economical construction. The slope should not be flatter than 10:1.

The WinFlume computer program described in Chapter 8 checks flume designs against these requirements. If a device does not meet the requirements, warning messages will be generated, and the program will suggest lengths needed to correct the problem. Resolving these warning messages is straightforward in most cases, although the length of the converging transition can be problematic in a few unusual cases. Details and some suggestions for resolving such problems are provided in Section 8.8.9.

5.6.4 Selection of standard broad-crested weirs for lined trapezoidal channels

For lined trapezoidal canals, broad-crested weirs are an attractive option since they can be easily retrofitted into the existing lined section. The selection procedure follows the flume design steps given in Section 5.6.1 as follows:

1. Determine the range of discharges to be measured, Q_{max} and Q_{min} . Then, estimate or determine by separate means, the canal flow depth (y_2 , Figure 5.2) without the weir in place for the maximum design discharge Q_{max} . This tailwater depth will be used to evaluate the weir design for submergence.

The portable and temporary weirs described in Section 3.3.3 are useful for determining the flow properties of the canal. For small canals, it is often possible to

select a weir size either by observing the suitability of the temporary structure or through trial and error using several temporary structures. If y_2 cannot be measured at Q_{max} , the normal depth in the canal downstream from the weir at Q_{max} can be determined using the procedures given in Section 5.3.2. For lined channels where the flow depth is determined by channel friction (i.e., channels flowing at normal depth as opposed to flow depth resulting from the backwater effect of a downstream structure), weir design based on Q_{max} is sufficient. However, if other factors affect the flow depth so that the tailwater level drops more slowly with discharge than the flow depth upstream from the weir, submergence must also be checked at the minimum flow rate Q_{min} , and thus, y_2 at Q_{min} will need to be determined.

2. Determine the required freeboard, F_1 . We recommend freeboard in the amount of 20% of the upstream sill-referenced head, $F_1 = 0.20 h_{1max}$.
3. Select the desired flow measurement accuracy and determine the rating table uncertainty, X_C . For these weirs, we recommend $X_{Q_{min}} = 8\%$ and $X_{Q_{max}} = 5\%$, with $X_C = 2\%$. ($X_C = 3\%$ for rating Tables R.1 and R.2, but 2% when the rating is computed with WinFlume).
4. Choose a head measurement method and determine its measurement error, δ_{h_1} . For example, select $\delta_{h_1} = 10$ mm for head reading with a staff gage with an approach section Froude number, Fr_1 , of roughly 0.3 (roughly interpolated from Table 4.1). These data will be used to compute the needed upstream heads to satisfy the accuracy requirements using Equations 5.11 and 5.12. For these weirs, u is approximately 1.8.
5. Consult Table 5.2 (metric) or Table 5.3 (English) and locate the canal shape that fits the canal in question.
6. Select a weir for that canal shape so that the maximum design discharge, Q_{max} falls within the range of canal capacities (Columns 4 and 5).

If the canal shape does not appear in Table 5.2 or 5.3, one may still be able to obtain a flume design. If the canal bottom width is between two specified values, use the wider bottom and recalculate the sill heights based on the side slope with b_c for each weir and b_1 for that canal. If the side slopes differ from those given such that the area of the control section A^* varies by more than 1 or 2%, these rating tables cannot be used. (For further explanation, see Section 6.3.3 and Figure 6.11.) If the discharge falls below the ranges given, this style of weir is not applicable to your situation. The rectangular weirs of Section 5.5.2 may be more appropriate. These weirs form a list of trial structures; one or more may meet the design requirements. Evaluate them in Step 7 through 9, starting with the weir with the lowest sill. The lowest sill is recommended because it is the least expensive to construct, it has the least effect on upstream flow conditions, it has the lowest potential for sediment deposition, and it can be raised far easier than a higher sill can be lowered.

7. Determine the sill-referenced heads h_1 from the rating table for the weir selected in Step 6 (Tables R.1 or R.2, Appendix 4), and determine the required head loss ΔH for maintaining modular flow. Use either the value given for the weir selected in Table 5.2 or 5.3, or use $0.1H_1$, whichever is larger. Since h_1 is usually close to H_1 , a value of $0.1h_1$ may be used as a first approximation.

8. Start by checking the submergence at Q_{max} . If that is not satisfied, choose the weir with the next highest sill height and repeat Step 7. If the submergence check is satisfied, check the freeboard. If the freeboard criterion is not satisfied, choose the next lowest sill height and repeat Step 7. If that sill height has already proven unsuccessful, then these standard flume sizes will not work for this site or one or more restrictions will have to be relaxed. If the submergence criteria at Q_{max} and the freeboard criteria are met, continue on and check the design criteria for Froude number, submergence at Q_{min} , and accuracy at Q_{min} and Q_{max} .
9. If design criteria are not met, select a higher or lower sill height and repeat Steps 7 and 8 (see Section 5.6.6 for recommendations).
10. Determine the appropriate weir dimensions from Table 5.7. We recommend a 3:1 ramp, except where the sill is relatively high compared to the flow depth. We recommend $L > 1.5 H_{lmax}$, but not less than the values given in the heading of either Table R.1 or R.2.

Example selection of standard broad-crested weirs for lined trapezoidal channels

Given: the data from the example in Section 5.3.2, where the bottom width $b = 0.3$ m, side slopes are 1:1, canal depth $d = 0.55$ m, bottom slope $S_b = 0.00050$ m/m, Manning roughness coefficient $n = 0.015$, and the range of discharges is from $Q_{min} = 0.05$ m³/s to $Q_{max} = 0.15$ m³/s;

Task: Follow the design procedure given above to select a suitable structure.

1. Note from the example in Section 5.3.2 that the tailwater levels at Q_{min} and Q_{max} are 0.240 m and 0.412 m, respectively.
2. Choose the recommended freeboard equal to 20% of h_1 at Q_{max} .
3. Choose accuracy requirements of $X_{Q_{min}} = 8\%$ and $X_{Q_{max}} = 5\%$. Use $X_C = 2\%$.
4. Assume head to be measured with a wall-mounted staff gage, roughly $\delta_{h_1} = 7$ mm. (Assume $u = 1.8$ for Equations 5.11 and 5.12).
5. Find canal shape in Table 5.2. Note maximum canal depth is much greater than depth of this canal (0.75 versus 0.55 m).
6. Note that all the weirs listed, B_m through G_{m1} , have sufficient capacity, but the desired lower limit of flow rate is lower than all the lower limits listed. This implies that the method of head detection and desired accuracy need to be further examined.
7. For each weir, B_m through G_{m1} , determine the head at minimum and maximum discharge from Table R.1 and estimate the head-loss values from Table 5.2. The required freeboard F_1 is computed as 20% of h_{1max} .

Weir	h_{1max} (m)	h_{1min} (m)	p_1 (m)	ΔH (m)	y_{1max} (m)	h_{2max} (m)	h_{2min} (m)	F_1 (m)
B_m	0.219	0.118	0.15	0.017	0.369	0.262	0.09	0.044
C_m	0.208	0.110	0.20	0.021	0.408	0.212	0.04	0.042
D_{m1}	0.197	0.103	0.25	0.025	0.447	0.162	-0.01	0.039
E_{m1}	0.187	0.097	0.30	0.029	0.487	0.112	-0.06	0.037
F_{m1}	0.178	0.091	0.35	0.033	0.528	0.062	-0.11	0.036
G_{m1}	0.163	0.083	0.40	0.039	0.563	0.012	-0.16	0.033

8. Examine the design criteria for each weir. The WinFlume program actually determines the range of sill heights that will satisfy the submergence and freeboard requirements. For this example, the range of sill heights is 0.24 m to 0.33 m. Thus, of the standard weirs, only the 0.25-m and 0.3-m high sill are acceptable, and the 0.25-m high sill only barely satisfies the submergence criteria at maximum flow.

	Modular flow at Q_{max} , Equation 5.7 $H_{1max} > H_{2max} + \Delta H_{max}$ or approximately $h_{1max} > h_{2max} + \Delta h_{max}$	Modular flow at Q_{min} , Equation 5.8 $H_{1min} > H_{2min} + \Delta H_{min}$ or approximately $h_{1min} > h_{2min} + \Delta h_{min}$	Freeboard Equation 5.9 $h_{1max} < d - p_1 - F_1$
Weir			
B_m	0.219 ∇ 0.262 + 0.017	0.118 > 0.09 + 0.017	0.219 < 0.55 - 0.15 - 0.044
C_m	0.208 ∇ 0.212 + 0.021	0.110 > 0.04 + 0.021	0.208 < 0.55 - 0.20 - 0.042
D_{m1}	0.197 > 0.162 + 0.025	0.103 > -0.01 + 0.025	0.197 < 0.55 - 0.25 - 0.039
E_{m1}	0.187 > 0.112 + 0.029	0.097 > -0.06 + 0.029	0.187 < 0.55 - 0.30 - 0.037
F_{m1}	0.178 > 0.062 + 0.033	0.091 > -0.11 + 0.033	0.178 \nless 0.55 - 0.35 - 0.036
G_{m1}	0.163 > 0.012 + 0.039	0.083 > -0.16 + 0.039	0.163 \nless 0.55 - 0.40 - 0.033

	Froude Number Equation 5.10 $Fr_1 = \frac{Q_{max}/A_{1max}}{\sqrt{gA_{1max}/B_{1max}}} < 0.5$	Accuracy at Q_{max} Equation 5.11 $h_{1max} > \frac{u\delta_{h1}}{\sqrt{X_{Q_{max}}^2 - X_{C_{max}}^2}}$	Accuracy at Q_{min} Equation 5.12 $h_{1min} > \frac{u\delta_{h1}}{\sqrt{X_{Q_{min}}^2 - X_{C_{min}}^2}}$
Weir			
B_m	0.399 < 0.5	0.219 ∇ 0.275	0.118 ∇ 0.163
C_m	0.327 < 0.5	0.208 ∇ 0.275	0.110 ∇ 0.163
D_{m1}	0.272 < 0.5	0.197 ∇ 0.275	0.103 ∇ 0.163
E_{m1}	0.228 < 0.5	0.187 ∇ 0.275	0.097 ∇ 0.163
F_{m1}	0.193 < 0.5	0.178 ∇ 0.275	0.091 ∇ 0.163
G_{m1}	0.165 < 0.5	0.163 ∇ 0.275	0.083 ∇ 0.163

9. Select weir E_{m1} , since it satisfies both modular flow and freeboard requirements, and provides a slight safety margin in case of higher tailwater levels in the future (e.g., due to weed growth or concrete deterioration). Note that none of these weirs meet the accuracy criteria. Actually, for the lower sills the accuracy is worse since the head detection error value we used was based on the assumption of the approach channel Froude number being less than 0.2; the actual Froude number reaches nearly 0.4. Reasonable accuracy at maximum flow can be obtained by reading the water level in a stilling well ($\delta_{h1} = 5$ mm with $h_{1max} = 0.187$ m gives 5.2% accuracy). This still does not quite satisfy our accuracy requirement at minimum flow (9.5% rather than 8% accuracy), but is close enough that we will accept this result. If the rating tables are used directly ($X_c=3\%$), then the accuracies reduce to 5.7% and 9.8% for Q_{max} and Q_{min} , respectively. If greater accuracy is required, then either a narrower flume is needed or the water depth must be measured with a more accurate gage (e.g., point gage).
10. Determine the longitudinal dimensions of the structure from Table 5.7: $L_a = 0.2$ m, $L_b = 0.9$ m, $L = 0.35$ m, $L_d = 0$ m, and the downstream slope expansion factor is $m = 0$ since there is adequate head drop available and we do not need a downstream ramp.

5.6.5 Selection of rectangular broad-crested weirs for earthen channels

Because of the wide variety of shapes that can be encountered in earthen channels and the range of discharges to be measured, it is rather complicated to determine the interrelated values of h_{1max} , p_1 and b_c for a structure. Rectangular weirs have proven to be an effective option for these unlined canals since a rectangular section can be constructed fairly easily out of block, stone, or masonry. (For channels deeper than about 1.5 m (5 ft), custom designed structures are recommended, often trapezoidal or triangular rather than rectangular.) Although this situation makes the design process somewhat more complicated, it allows the designer greater flexibility and expands the applicability of the weirs. In particular, because earthen channels are often very inefficient sections, flow velocities tend to be low, requiring considerable contraction. Often a side contraction is required to produce sufficient upstream head to achieve reasonable accuracy. Criteria for accuracy are useful for reducing the range of structures to be considered.

The design steps for a rectangular weir in an earthen channel are similar to those given above for a lined trapezoidal channel:

1. Determine the range of discharges to be measured, Q_{max} and Q_{min} . Then, estimate or determine by separate means, the canal flow depth (y_2) without the weir in place for the maximum design discharge, Q_{max} , and the minimum design discharge, Q_{min} . These tailwater levels will be used to evaluate the weir for submergence at Q_{min} and Q_{max} . The portable and adjustable flumes of Section 3.3.3 or temporary weirs described in Section 3.2.3. are useful for determining the flow properties of the canal. For earthen canals, submergence should be checked at the minimum flow rate Q_{min} . This is because the upstream head created by a rectangular contraction often drops faster with declining discharge than do the levels in a downstream trapezoidal or rough earthen tailwater channel. As a result, submergence is often a greater issue at Q_{min} for rectangular-throated structures, so a higher sill may be needed to avoid submergence at minimum flow. This may make it more difficult to meet freeboard requirements at high flows.
2. Select the required freeboard. For earthen channels, we recommend freeboard as a percentage, at least 10%, of the channel depth, $F_1 = 0.10(d)$. This effectively gives a maximum water level, $y_{1max} = 0.9(d)$.
3. Select the desired flow measurement accuracy. For these weirs, we recommend $X_{Q_{min}} = 8\%$ and $X_{Q_{max}} = 5\%$, with $X_C = 2\%$.
4. Select $\delta_{h_1} = 10$ mm for a head reading with a staff gage in a channel with Fr_1 roughly equal to 0.3 (see Table 4.1 for adjustment if necessary). This will be used to compute the needed upstream heads, h_{1min} and h_{1max} , to satisfy the accuracy requirements with Equation 5.11 and 5.12. For these weirs, u is approximately 1.5.
5. Consider a rectangular cross section for the entire flume (including approach and tailwater channels) that is narrower than the earthen channel top width but wider than the bottom width. For very low velocity canals, consideration should be given to placing the bottom of the approach channel above the bottom of the earthen canal.

Table 5.9 Options for satisfying design requirements.

<i>Design Requirement</i>	<i>Options to Consider if Requirement is not Satisfied</i>
Modular Flow at Q_{max} (submergence)	<ul style="list-style-type: none"> • Raise the crest • Narrow the control section at Q_{max} • Add a downstream ramp (6:1 slope recommended) • Choose a location where more drop is available
Modular Flow at Q_{min} (submergence)	<ul style="list-style-type: none"> • Raise the crest • Narrow the control section at Q_{min} • Add a downstream ramp (6:1 slope recommended) • Choose a location where more drop is available
Freeboard at Q_{max}	<ul style="list-style-type: none"> • Lower the crest • Widen the control section at Q_{max}, or • Raise the maximum allowable water level (decrease required freeboard or increase height of canal banks)
Froude Number at Q_{max}	<ul style="list-style-type: none"> • Increase approach channel depth at Q_{max} (by increasing contraction) • Deepen the approach channel • Increase approach channel top width
Accuracy at Q_{max}	<ul style="list-style-type: none"> • Narrow the control section at Q_{max} • Use a more accurate head-detection method • Increase the allowable measurement error at Q_{max}
Accuracy at Q_{min}	<ul style="list-style-type: none"> • Narrow the control section at Q_{min} • Use a more accurate head-detection method • Increase the allowable measurement error at Q_{min}

6. Enter Tables R.3 or R.4 (Appendix 4) with values of h_{1min} and h_{1max} from Step 4. Find a table containing both h_1 values. Read over to one of the columns and select a unit discharge q . Calculate the required widths from $b_c = Q/q$. Use the smaller b_c computed from Q_{min}/q_{min} and Q_{max}/q_{max} . If the b_c from q_{min} is smaller, recompute $q_{max} = Q_{max}/b_c$ and be sure that it is still in the column from which the q values were chosen. If not, go to the table for the next widest set of weirs. If the weir is wider than the average channel width, use a narrower weir, if possible. Also, check to be sure that the width chosen is within the width range for that set of ratings. If the width is too narrow, go to the next widest grouping and repeat. If the width is too wide, go to the next narrowest grouping. If the head range for this grouping is too small, you will have to use a wider weir and allow more error in the measurement, or use the methods of Chapter 6 or 8 to develop a new rating. Start by selecting the lowest sill height in the table or the sill height for the lowest sill for which the range of heads is included.
7. Determine the sill-referenced heads h_1 from the rating table for the weir selected in Step 6 (Tables R.3 or R.4). And determine the required head loss ΔH for maintaining modular flow. Use the value given for the weir selected in Table R.3 or R.4 or $0.1H_1$, whichever is larger. Since h_1 is usually close to H_1 , $0.1h_1$ may be used as a first approximation. For a structure discharging into a wide channel, use $0.4H_1$ or compute the actual head loss (see Section 6.6).
8. Evaluate the design criteria, starting with the submergence at Q_{max} . If that is not

satisfied, choose the next highest sill height and repeat Step 7. If that is satisfied, check the freeboard. If the freeboard criteria is not satisfied, choose the next lowest sill height and repeat Step 7. If that sill height has already proven unsuccessful, then either these standard sill heights will not work in that canal, the structure width will have to be changed, or one or more design requirements will have to be relaxed. Continue on and check the design criteria for Froude number, submergence at Q_{min} , and accuracy at Q_{min} and Q_{max} .

9. Alter the structure width or sill height according to the criteria that are not met, or relax the design criteria. (see Section 5.6.6 for recommendations).
10. Determine the appropriate longitudinal dimensions from Table 5.7. We recommend a 3:1 ramp, except where the sill is relatively high compared to the flow depth. We recommend $L > 1.5 H_{1max}$, but not less than the values given in the heading of either Table R.3 or R.4.

Example selection of rectangular broad-crested weirs for earthen channels

1. The data for this example are shown in Table 5.8. Initially, the full-length structure of Figure 5.10 will be assumed.
2. Choose a freeboard of 10% of the channel depth. In this case, the maximum allowable water depth is 0.6 m. For Equation 5.9, we assume the channel depth is 0.6 m and the freeboard amount is zero.
3. Choose accuracy requirements of $X_{Qmin} = 7\%$ and $X_{Qmax} = 5\%$. Use $X_C = 2\%$.
4. Assume head to be measured with a wall-mounted staff gage, roughly $\delta_{h1} = 7$ mm for a Froude number of 0.2. (Assume $u = 1.5$ for Equations 5.11 and 5.12). Compute the minimum heads required to provide these accuracies at Q_{min} and Q_{max} from Equations 5.11 and 5.12.

$$h_{max} > \frac{u\delta_{h1}}{\sqrt{X_{Qmax}^2 - X_{Cmax}^2}} = \frac{1.5 * 0.007 \text{ m}}{\sqrt{0.05^2 - 0.02^2}} = 0.229 \text{ m}$$

$$h_{min} > \frac{u\delta_{h1}}{\sqrt{X_{Qmin}^2 - X_{Cmin}^2}} = \frac{1.5 * 0.007 \text{ m}}{\sqrt{0.07^2 - 0.02^2}} = 0.157 \text{ m}$$

5. Choose a rectangular cross section for the entire structure.
6. Enter Table R.3 with the above head values, roughly 0.16 and 0.23 m. Starting with the narrowest width range, choose the first table that contains both head values. This is the table for widths of 0.2 m to 0.3 m. The largest width is 0.3 m, which would produce a maximum unit discharge of 0.34 m³/s divided by 0.3 m, or 1.13 m³/s per meter width. The rating in this table does not go that high, so a larger width range is tried. At 0.5 m width, the maximum discharge would be 0.34/0.5 or 0.68 m³/s per meter width. Again, this table does not go that high. The next table has a 1 m width, giving 0.34 m³/s per meter width, which occurs in this table. So we start with widths in the range 0.5 to 1.0 m. For all these tables at the head of 0.23 m, the discharge is on the order of 0.2 m³/s per meter of width. Since the maximum flow rate is 0.34 m³/s, the width must be less than

0.34/0.2 or 1.7 m. Since the channel is effectively 1.2 m wide, the accuracy at maximum flow is not a limiting constraint. At a head of 0.16 m, flow rates in Table R.3 are on the order of 0.11 m³/s per meter width. Since the minimum flow is 0.085 m³/s, the width must be narrower than 0.085/0.11 or 0.77 m. The first trial will assume a 0.75 m width and it will be adjusted from there depending on other design limitations.

7. For a weir width of 0.75 m, the maximum unit discharge is 0.34 m³/s divided by 0.75 m, or 0.453 m³/s per meter width, while the minimum unit discharge is 0.113 m³/s per meter width. From Table R.3, only the higher two sill heights are acceptable, with the lower sill height causing the Froude number to be too high in the approach.

p_1 (m)	h_{1max} (m)	h_{1min} (m)	ΔH (m)	y_{1max} (m)	h_{2max} (m)	h_{2min} (m)
0.20	0.386	0.162	0.048	0.586	0.26	0.05
0.30	0.395	0.167	0.063	0.695	0.16	-0.05

8. The design criteria for these two designs are examined.

Sill Height	Modular flow at Q_{max} , Equation 5.7 $H_{1max} > H_{2max} + \Delta H_{max}$	Modular flow at Q_{min} , Equation 5.8 $H_{1min} > H_{2min} + \Delta H_{min}$	Freeboard Equation 5.9 $h_{1max} < d - p_1 - F_1$
p_1 (m)	or approximately $h_{1max} > h_{2max} + \Delta h_{max}$	or approximately $h_{1min} > h_{2min} + \Delta h_{min}$	
0.2	$0.386 > 0.26 + 0.048$	$0.162 > 0.05 + 0.048$	$0.368 < 0.6 - 0.20 - 0.0$
0.3	$0.395 > 0.16 + 0.063$	$0.167 > -0.05 + 0.063$	$0.395 < 0.6 - 0.30 - 0.0$

Sill Height	Froude Number Equation 5.10 $Fr_1 = \frac{Q_{max}/A_{1max}}{\sqrt{gA_{1max}/B_{1max}}} < 0.5$	Accuracy at Q_{max} Equation 5.11 $h_{1max} > \frac{u\delta_{h1}}{\sqrt{X_{Qmax}^2 - X_{Cmax}^2}}$	Accuracy at Q_{min} Equation 5.12 $h_{1min} > \frac{u\delta_{h1}}{\sqrt{X_{Qmin}^2 - X_{Cmin}^2}}$
p_1 (m)			
0.2	$0.323 < 0.5$	$0.386 > 0.229$	$0.162 > 0.157$
0.3	$0.250 < 0.5$	$0.395 > 0.229$	$0.167 > 0.157$

9. Choose the sill height of 0.2 m, since the higher sill causes the upstream water level to become too high. This design will satisfy the accuracy requirement. However, if rating table R.3 is used directly, X_C increases to 3% and the accuracy at Q_{max} and Q_{min} are 4.4% and 8.3%, respectively.
10. Dimensions are determined from Table 5.8: $L_a = 0.4$ m, $L_b = 0.6$ m, $L = 0.6$ m, $L_d = 0$ m, $m = 0$, $L_e = 5$ m. The requirement for the tailwater section makes this structure extremely long, while there is considerable extra head loss available. Without making detailed calculations for the specific channel, the head loss for a truncated structure (i.e., with $L_d = 0$ m and $L_e = 0$ m) is $0.4 H_{1max}$, or 0.154 m. Since only 0.126 m are available, the tailwater channel cannot be eliminated without a more detailed evaluation.

Methods for making the head loss calculations are given in Section 6.6, or the calculations can be made with the WinFlume software of Chapter 8 for the tailwater channel defined by the cross section of the earthen channel. In this case, the calculations would show that only 0.079 m of head loss is required for a truncated structure; thus there is plenty of head available.

5.6.6 What to do when design criteria are not met

For each of the design requirements, if the criteria are not met, the options for changes to satisfy the criteria are straightforward. These options are presented in Table 5.9. If more than one of the criteria are not met, the options may be conflicting, sometimes suggesting that a design is not possible for those criteria, or one or more criteria need to be relaxed, if feasible. However, sometimes the options only *appear* to conflict and a feasible design is possible. Take, for example, the requirements for modular flow and freeboard at Q_{max} . One suggests raising the crest; the other suggests lowering the crest. One suggests narrowing the control section; the other suggests widening the control section. Individually, these seem in direct conflict. However, it may be possible to both raise the crest and widen the control section and satisfy both requirements, because a wider control will require less head at Q_{max} , and thus less head loss (since ΔH is generally proportional to H_1). The reduced head loss may make it possible to satisfy both criteria. Until all the options are explored it is difficult to conclude that a design is not possible.

In many cases, design will be an iterative process, with many trials before a final design is selected. This procedure appears to be fairly complex; however, once the designer becomes familiar with the important features, the design becomes quick and easy. The difficult (but important) part is accurately estimating the flow conditions prior to placement of the structure. These, more than anything else, determine the constraints on the design. The following example should be helpful. It makes use of the WinFlume computer program described in Chapter 8.

Examples

Consider the design example given in Section 5.6.4. This is a concrete-lined trapezoidal channel with bottom width $b = 0.3$ m, side slopes of 1:1, canal depth $d = 0.55$ m, bottom slope $S_b = 0.00050$ m/m, and Manning roughness coefficient $n = 0.015$. The range of discharges is from $Q_{min} = 0.05$ m³/s to $Q_{max} = 0.15$ m³/s. We wanted to achieve measurement accuracy of $\pm 8\%$ at minimum flow and $\pm 5\%$ at maximum flow and maintain freeboard of at least 20% of h_1 . We determined the tailwater levels for this site in the example given in Section 5.3.2.

Recall that a weir was chosen with a crest height of 0.30 m, which for this channel shape produces a crest width of 0.90 m and a maximum sill-referenced head of 0.187 m. This original weir (Weir-0 in the table below) was constructed by using only a bottom contraction. While this weir satisfied the Froude number, freeboard, and submergence criteria, it did not satisfy the accuracy criteria. We determined that

use of a stilling well rather than a wall gage would provide sufficient accuracy, but suppose the designer wanted better accuracy with a wall gage. The flow cross section over this weir is very wide and shallow (0.187 m deep by 0.9 to 1.27 m wide, at maximum flow), making it difficult to accurately measure the small sill-referenced head. A combined side and bottom contraction may be possible that will increase the head at maximum flow and satisfy all the criteria.

A) First, we will try simply raising the trapezoidal section (0.30 m wide with 1:1 side slopes) vertically. WinFlume has an option for raising the entire shape. WinFlume also has a search procedure that determines how far the sill must be raised to yield an acceptable design. This analysis shows that acceptable flume designs can be found over a range of sill heights of 0.152 m to 0.189 m. Over this range of sill heights, because of the side contraction, the accuracy criteria are also met at both minimum and maximum flow. The middle of this range is a sill height of 0.17 m. This flume is listed as Flume-1 in the table below. A variety of other combinations of side and bottom contraction may also produce a satisfactory design. Because the accuracy criteria are barely met by the Flume-1 design, other acceptable designs would probably need a lower sill and narrower throat section.

Trial	Design Requirements					
	Froude No.	Freeboard	Submergence	Submergence	Accuracy	Accuracy
	Fr_1	F_1	y_{1max}	y_{2min}	h_{1max}	h_{1min}
	Actual < 0.5	Actual > Req.	Actual < Max.	Actual < Max.	Actual > Min.	Actual > Min.
Weir-0	0.228 < 0.5	0.064 > 0.037	0.412 < 0.458	0.240 < 0.375	0.186 > 0.247	0.097 > 0.141
Flume-1	0.245 < 0.5	0.080 > 0.060	0.412 < 0.429	0.240 < 0.307	0.300 > 0.292	0.169 > 0.161
Flume-2	0.267 < 0.5	0.049 > 0.060	0.412 > 0.412	0.240 < 0.290	0.298 > 0.292	0.168 > 0.161
Flume-3	0.281 < 0.5	0.061 > 0.059	0.412 > 0.403	0.240 < 0.281	0.297 > 0.292	0.168 > 0.161
Weir-4	0.272 < 0.5	0.054 > 0.039	0.412 < 0.420	0.240 < 0.332	0.197 > 0.250	0.103 > 0.143
Flume-5	0.281 < 0.5	0.061 > 0.059	0.412 < 0.417	0.240 < 0.293	0.297 > 0.292	0.168 > 0.161

B) Now we will assume that the canal depth is 0.50 m instead of 0.55 m. In this case, neither the original Weir-0 nor our new Flume-1 design will satisfy the freeboard criteria (i.e., actual freeboard would decrease by 0.05 m). We then move the entire throat cross section down to satisfy the freeboard requirement. At $p_1 = 0.152$ m and below, the submergence requirement is no longer satisfied, as shown by Flume-2 (Figure 5.13). This flume is right on the edge of submergence (i.e., less than 1 mm difference between actual and maximum allowed y_{2max}). If we continue to reduce the sill height, we eventually satisfy the freeboard requirement at $p_1 = 0.142$ m (Flume-3). In between these two sill heights, neither submergence nor freeboard is satisfied. This overlapping range of unsatisfied design criteria shows that no design is possible by raising or lowering the entire section and suggests the need to alter the shape. A shallower and wider flow through the throat would reduce the head, require less head loss (because ΔH is proportional to H_1), increase the available freeboard, and reduce the freeboard requirement (which is related to the head). To test this, we arbitrarily raise the sill to 0.25 m, then have WinFlume vary the amount of side

contraction to search for an acceptable design. Both freeboard and submergence are satisfied over a narrow range of throat widths; 0.724 to 0.800 m. The throat width of 0.8 m is a broad-crested weir design (Weir-4). Unfortunately, although the freeboard and submergence criteria are met, the accuracy requirements are not met. In fact, meeting the accuracy criteria would require a throat bottom width of 0.35 m or less. Between widths of 0.724 m and 0.35 m, neither freeboard nor accuracy is met. Since the unsatisfied criteria overlap, we have run out of options for improving the design in this manner. (Note that the overlapping range of widths will change with different sill heights. A few more sill heights would eventually verify that no design is possible, as they overlap with the overlapping ranges of unsatisfied design criteria for Flume-2 and Flume-3).

- C) Another option for resolving the problem we faced in (B) is to add a diverging transition to the Flume-3 structure. This would reduce the head loss, which might allow us to reduce the sill height enough to meet the freeboard requirement. Since the flume was already narrow enough to satisfy the accuracy requirement, we would then have a design that meets all of the objectives. To test this in WinFlume, we add a 6:1 downstream ramp to Flume-3, since all criteria other than submergence are met. Adding the downstream ramp is sufficient to provide a satisfactory design (Flume-5). Analysis would show that sill heights of 0.137 m to 0.142 m will satisfy all criteria. When this flume is constructed, in the diverging transition we would provide both a 6:1 floor ramp and a 6:1 transition from the sidewalls of the throat section back to the sidewalls of the downstream channel.

To summarize, Figure 5.13 shows the cross sections for the various flumes and weirs. For the 0.55-m canal depth, the broad-crested weir was too high, causing the flow to be too wide and shallow to meet accuracy objectives. The Flume-1 design was narrower with deeper flow, which improved the accuracy of the flow measurement, meeting the design requirement. For the lower canal depth (0.50 m), a narrowed-throat design (Flume-2) that met accuracy requirements was so narrow that freeboard and submergence criteria could not be simultaneously satisfied. A broad-crested weir design (Weir-3) was found that could satisfy freeboard/submergence criteria, but did not meet the accuracy requirements. Finally, by adding a diverging transition to the Flume-2 design, we were able to develop a design (Flume-4) that satisfies all of the design criteria.

These examples demonstrate most of the essential tradeoffs to be considered in flume design. The Froude number in the approach channel and the submergence at minimum flow rate were the only criteria that did not come into play in the examples, as they were easily satisfied by all of the alternatives we considered. The design for the reduced canal depth was tightly constrained, as are many designs that must be retrofitted to existing canal system. Sometimes, a number of different options must be considered before an acceptable design is found. Designs for new canals are usually more straightforward because the head loss needed by the flume can be easily incorporated into the design of the canal system.

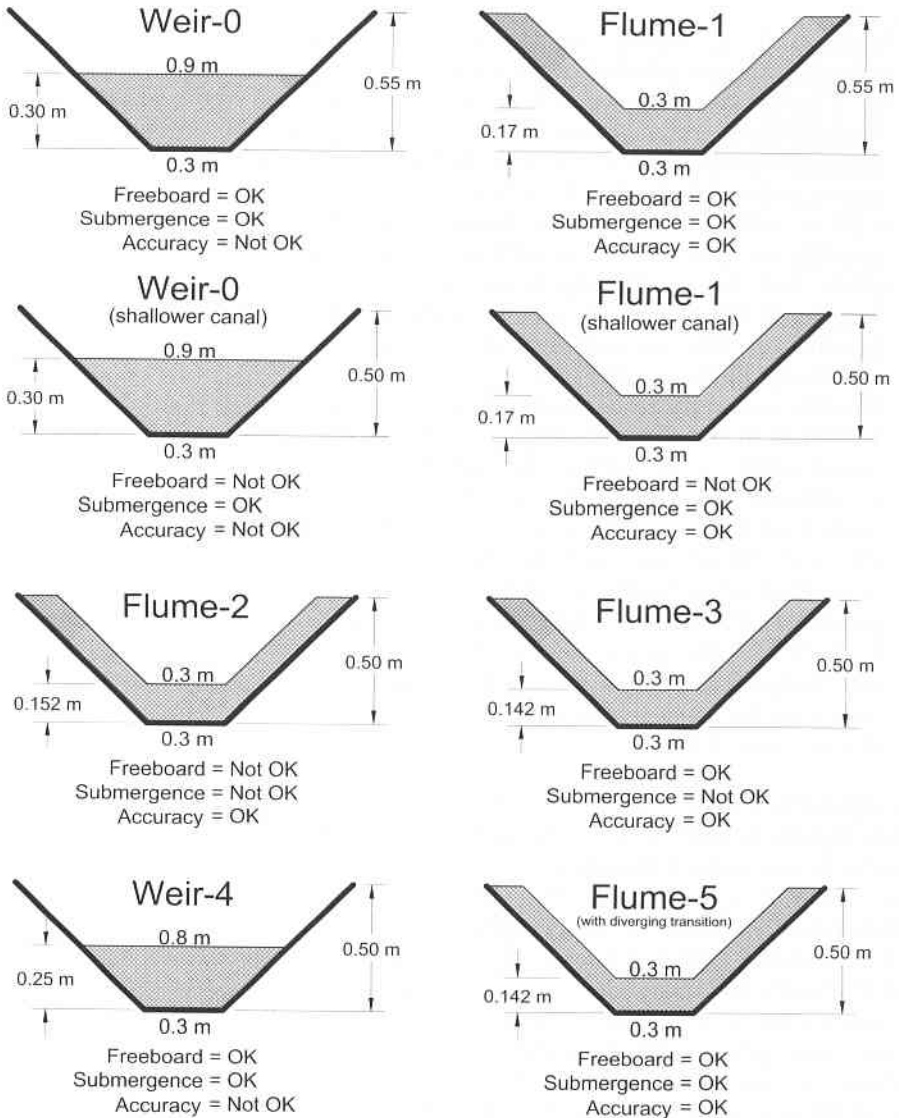


Figure 5.13. Comparison of various structures for design example.

5.7 Using WinFlume to Develop Custom Flume Designs

The procedures described in this chapter can be used to design a wide variety of flumes and weirs, using pre-computed designs for smaller structures in standardized canals. For design of larger structures, more detailed analysis is warranted, both to ensure that the structure satisfies the design requirements and to obtain the most accurate possible head-discharge rating. This analysis capability is provided by the WinFlume computer program (Chapter 8), which was used for the examples in

Section 5.6.6. The program evaluates a range of flume designs based on an initial throat section shape and a method of contraction change specified by the user. A report summarizing the acceptable designs is produced, and the user can then consider the tradeoffs among these designs before choosing a preferred structure. For tightly constrained problems, the user may need to examine several different methods of contraction change before arriving at a suitable design. Once a design has been selected, rating tables for the structure can be computed. Chapter 8 provides detailed information on the use of the program.

