FLOW MEASURING FLUMES FOR IRRIGATION FIELD SUPPLY CANALS IN THE YUMA MESA

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Flow measuring flumes for irrigation field supply canals in the Yuma Mesa

Executive summary: Existing irrigation management guidelines in the Yuma Mesa Irrigation Districts presume accurate measurement of irrigation field supply canal discharges. However, in these irrigation districts, often irrigation field supply canal discharges are not measured and in some farms, even when discharge is measured at the canal inlet, leakage losses in the canals are large enough to make the inlet flow rate to individual basins uncertain. Hence, uncertainty in canal discharges is often considered as one of the limitations to efficient management of irrigation systems in the area.

Long-throated flumes are widely used to measure discharges in irrigation canals. They are inexpensive and they can be used in a wide range of canal shapes and have minimal energy loss requirements to accurately measure canal flows compared to other critical flow measuring devices. Because of these advantages, long-throated flumes are already in use in parts of the Yuma Mesa Irrigation Districts. This study, therefore, aims at expanding the availability of flow measuring flumes in these irrigation districts by developing predesigned alternatives for typical canal geometry and hydraulic conditions. The design of alternative flumes presented in this report is based on standard long-throated flume design procedure and criteria.

Using standard design procedures and based on field evaluations in the Maricopa and Yuma Agricultural Centers of the University of Arizona (UA), three alternative flume designs (1.0ft sill height, 1.25ft sill height, and 1.5ft sill height) were developed. The canal geometry, for which these designs are developed, is of a standard shape and dimension widely used in the Yuma Mesa Irrigation Districts (trapezoidal cross-section with a bottom width of 2ft, a depth of 3ft, and a side slope of 1:1). The flow range used for the design is 7cfs to 25cfs, considered typical for the field supply canals of the Yuma Mesa Irrigation Districts. The flume designs were based on a canal tailwater characteristics derived using a field supply canal discharge commonly used in the area (*16cfs*) and the corresponding flow depth (*19in*), measured in the UA Yuma Mesa research farm. In addition, the sensitivity of the designs to changing canal hydraulic characteristics was evaluated and the designs were found to be robust.

Along with the predesigned flumes a package of field procedures for flume installation site selection, flume field evaluation and selection, and installation of flumes is compiled and presented in this report as well as in an accompanying flume field evaluation and installation guideline. The guideline is also accompanied with an Excel spreadsheet that presents the standard canal dimension for which the alternative designs are developed, the flume design specifications including design drawings, and help information (on field measurement procedures, on flume installation site selection criteria, and links to training materials and a web site to download and install WinFlume). The Excel worksheet is meant to serve as a quick reference tool to facilitate the flume field evaluation process. Hopefully, the field guideline document and the accompanying Excel spreadsheet provide trained irrigation technicians with a simple tool that can be used to select appropriate flume dimensions from a ready made design options and properly construct and install the selected flumes in the field supply canals. This way, the flume selection and installation process can be simplified, thereby facilitating a more expanded use of flow measuring flumes in irrigation field supply canals in the Yuma Mesa Irrigation Districts. To this end, field day was organized in Novemeber 2009 in the Yuma and Imperial Valley irrigation districts during which irrigaotrs were trained on flume field evaluation, selection of flumes from predesigned alternatives, and flume installation.

Although improvements in the accuracy of flow measurement is a prerequisite to raising irrigation performance at the field level, accurate discharge measurement need to be supplemented with accurate characterization of the field condition during irrigation and regular maintenance of irrigation field supply canals to minimize water losses through canal leakage between canal inlet and inlet into individual basins.

This report is presented in six chapters. Chapter 1 describes flow measurement problems and project objectives. A description of the long-throated flume, its components, and their functions is given in Chapter 2 of the report. A brief review of the hydraulic theory underlying flow measurement with critical flow measuring devices in general and long-throated flumes in particular is reviewed in Chapter 3. Chapter 4 presents a concise description of the design equations, design criteria, and design procedure. Chapter 5 describes the methodology used in the development and evaluation of predesigned flumes. References are presented in Chapter 6.

Chapter 1. Introduction

The Yuma Agricultural Center, a field station of the University of Arizona (UA), with funding from the United States Bureau of Reclamation, has developed irrigation management guidelines for the irrigation districts in the Yuma Mesa. The lack of accurate flow measuring devices in the field supply canals of many of the irrigated farms in the area is a constraint to the wider use of these technologies. The use of critical flow measuring devices that are accurate, inexpensive, and easy to construct will allow growers to have better control of their irrigation water supply and hence improve application efficiencies.

In principle, there are a wide variety of critical flow measuring devices that can be used in the Yuma Mesa, which include different types of flumes and weirs. Cost and accuracy are important factors in selecting an appropriate flow measuring structure for a given application. In this study, the objective is to retrofit existing field supply canals with flow measuring structures, hence adaptability of the structure in terms of satisfying the constraints related to geometry of, and available head loss in, existing canals are important considerations as well.

Long-throated flumes offer many advantages over other critical flow measuring devices (Bos, 1985; Bos, et al., 1986; Clemmens et al., 2001): (1) Provided critical flow occurs in the throat section, a rating table can be calculated with an error less than ±2% of the listed discharge for any combination of prismatic throat and arbitrarily shaped approach canal. (2) The throat section, perpendicular to the direction of flow, can be shaped in such a way that the entire range of discharge can be measured accurately. (3) The required head loss over the flume is minimal for modular flow. (4) The head loss requirement of long-throated flumes placed in any arbitrary canal can be calculated with sufficient accuracy based on hydraulic theory. (5) Because of their converging transition, these structures have little problems with floating debris. (6) Field observations and laboratory tests show that these structures can be designed to pass sediment under subcritical flow conditions, however, sedimentation in the approach canal can be a problem if flow carries excessive sediment load or if the approach canal velocity is significantly reduced. (7) Provided the throat section is horizontal rating tables can be computed based on post-construction dimensions. (8) Under a given hydraulic and other boundary conditions, long-throated flumes are the least expensive structures for measuring flows in open-channels accurately.

Due to the above listed advantages, long-throated flumes have been used as critical flow measuring device in some of the field supply canals in the irrigation districts of the Yuma Mesa. This study will, therefore, build on existing work, by Sanchez and Niblack (2005), to increase the availability of accurate and inexpensive flow measuring structures for small field supply canals in the Yuma Mesa. The objectives of this study are: (1) to develop designs of long-throated flumes for irrigation field supply canals, with geometries and hydraulic conditions, typical of the irrigation districts of the Yuma Mesa, (2) to compile simple guidelines for installation site selection, site survey, and installation of the flumes, and (3) to train local irrigation technicians on the use of these technologies, including post-construction (as-built) calibration of flumes. In this study, a computer program for the design, evaluation, and calibration of flumes (WinFlume) developed by Clemmens et al. (2001) is used.

Chapter 2. Description

A long-throated flume is a critical flow measuring device widely used in canals (Bos, 1989). It has a throat section with a level floor long enough to establish parallel flow (negligible streamline curvature) – a condition necessary to develop accurate discharge prediction equation based on simplified theory. Figures 1a and 1b show the sketch of a typical long-throated flume. A critical flow device (a description that encompasses different types of flumes and weirs) is a flow measuring structure that introduces sufficient contraction in the canal cross-section, so as to force the flow to accelerate and pass through the critical state over the structure. In long throated-flumes the contraction can be introduced in the form of a hump (raised canal invert) or a side contraction or both (Figures 1a and 1b). The aim is to separate (hydraulically speaking) the flow upstream of the control section (cross-section in the flume throat where critical flow occurs) from the flow downstream, hence conditions downstream of the structure will have no influence on the flow over the structure and flow in the approach canal. The flow through the control section, Q, can then be expressed as a unique function of depth,

h_1, measured at a suitably sited gaging station in the approach canal section upstream of the structure (Figure 1a).

$$Q = f(h_1) \qquad (1)$$

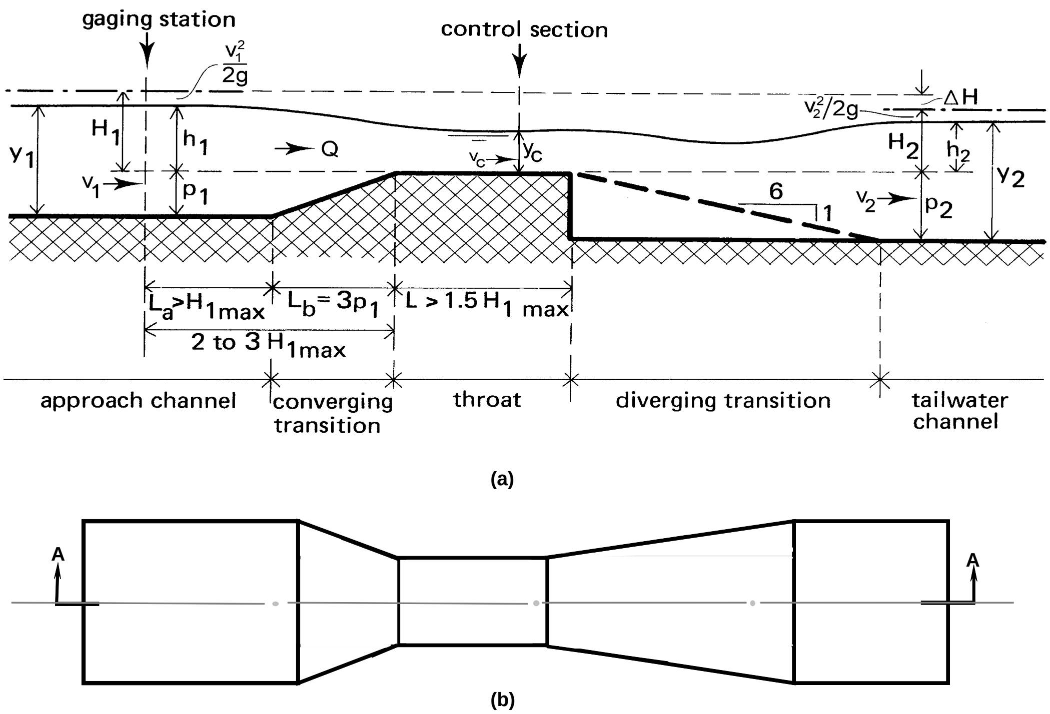


Figure 1 Sketch of a typical long-throated flume: (a) A longitudinal section along the center line of flume (Clemmens et al., 2001) and (b) Plan view of flume

Figures 1a and 1b show a typical long-throated flume with its five segments: (1) The approach canal segment is prismatic and is characterized by a stable subcritical flow, allowing accurate gaging of flow depth. (2) The converging transition is a region of accelerated flow in which the canal cross-section tappers over distance from the approach cross-section to the throat cross-section. In contrast to structures with abrupt upstream transition, such as broad crested weirs, this feature gives long-throated flumes the advantage of allowing the passage of sediment and suspended debris over the flume. (3) The throat section has a contracted section and is prismatic and has a level floor (sill).

It is sufficiently long to form parallel flow and small enough in cross-section to force critical flow at the control section over the entire range of flow rate to be measured. (4) There is an optional diverging transition in which the canal cross-section expands gradually from the throat section to the tailwater canal section. This is a zone of decelerated flow in which velocity head is converted into pressure head and is necessary if pressure head is to be recovered for maximum tolerance to downstream depth. (5) The tailwater canal section is part of the downstream canal segment and is affected by both downstream boundary conditions and upstream flow. The depth-discharge relationship in the tailwater section is an important flume design input. Another important issue here is the design of energy dissipating structures in the tailwater canal. However, the irrigation districts of the Yuma Mesa generally use lined canals, hence considerations relating to the design of energy dissipating structures in the tailwater canal are impertinent.

Based on laboratory studies and field observations recommendations were developed (Bos, 1989; Clemmens et al., 1990, Clemmens et al., 2001) regarding flow conditions and canal geometries constituting suitable sites for flume installation and for locating the gaging stations in the approach canal. These guidelines also include recommendations on the distance of the gaging station relative to the structure itself (Figure 1a). In addition, the recommendations propose ranges for the relative dimensions of the components of the flume often expressed as a function of the maximum total head to be measured by the structure. The accuracy of depth measurements and satisfaction of the assumptions made regarding the hydraulic conditions required for the proper functioning of the structure are the main considerations in setting these ranges. These ranges will be described in detail in subsequent sections.

Chapter 3. A review of the theory

Flow equations and assumptions:

Using the energy conservation equation for a steady one-dimensional ideal flow through a conduit, in this case an open channel, it can be shown that the following relation holds between the gaging station and the control section of a long-throated flume, Figure 2, (e.g., Bos, 1989; Clemmens et al., 2001):

$$h_1 + \frac{v_1^2}{2g} = h_c + \frac{v_c^2}{2g} \qquad (2)$$

h = sill referenced flow depth (with a length dimension, L), v = cross-sectional average velocity (with dimensions involving length and time, T), the subscripts *1* and *c* represent, respectively, variables at section 1 (gaging station) and the control section, and g = acceleration due to gravity (L/T^2).

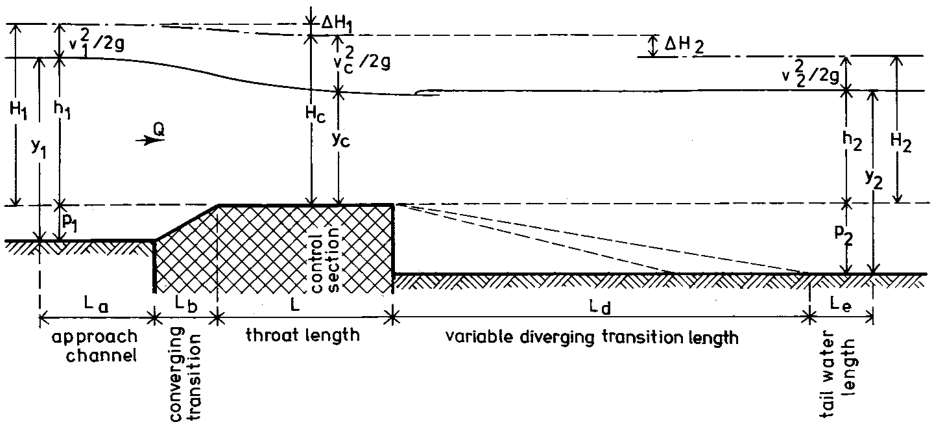


Figure 2 Description of the components of total head (energy per unit weight of water) and other pertinent terms (Clemmens et al., 2001)

The assumption of ideal flow implies: streamlines are parallel (hence at a cross-section pressure variation with depth is considered hydrostatic), fluid is ideal (that is frictionless – nonviscous), and that flow velocity is uniform over a cross-section. Flow rate can then be expressed as:

$$Q = A_c\sqrt{2g(H_1 - h_c)} \qquad (3)$$

where H_1 = the total head at the gaging station (L) and A_c = cross-sectional area of flow at the control section (L^2), Figure 2. Given a flow rate and canal cross-section, at the critical state of flow the specific energy, $E = h + v^2/2g$ (Eq. 2), is at a minimum. It can then be shown that Q can be expressed as a function of cross-sectional area, A_c, and top width, B_c, at the control section:

$$Q = \sqrt{g \frac{A_c^3}{B_c}} \qquad (4)$$

However, actual fluid flow involves energy losses due to boundary friction and the generation and dissipation of turbulent eddies. Streamlines can have more pronounced curvature toward the downstream end of the throat section (significant vertical acceleration), hence the pressure distribution at the control section may deviate from the assumed hydrostatic distribution unless the structure is properly dimensioned to minimize streamline curvature. In addition, because a real fluid (water) is viscous there is velocity gradient over a cross-section. In WinFlume, the software to be used in this study, friction head loss over a long throated flume is calculated with an equation given by Clemmens et al. (2001, p. 245). The friction coefficients for each section of the flume are calculated using a procedure developed by Replogle (1975) based on the boundary layer theory. The effect of velocity variation over a cross-section on the velocity head is taken into account by introducing a velocity distribution coefficient, α, in Eq. 2. Considering a long prismatic approach canal in which the flow is fully developed, WinFlume assumes a coefficient for the gaging station, α_1, equal to *1.04,* and the coefficient for the control section, α_c, is computed using an equation by Chow (1959) and refined by Replogle (1974) as a function of the friction coefficient at the throat section of the flume, the hydraulic radius, and the hydraulic depth. The energy equation can then be given as:

$$h_1 + \alpha_1 \frac{v_1^2}{2g} = h_c + \alpha_c \frac{v_c^2}{2g} + \Delta H_1 \qquad (5)$$

where ΔH_1 = the friction head loss between the gaging station and the control section (*L*). From Eq. 5, it can be shown that the discharge, considering friction head loss and the effects of nonuniform velocity distribution, is given as (Clemmens et al., 2001):

$$Q = \sqrt{\frac{g}{\alpha_c} \frac{A_c^3}{B_c}} \qquad (6)$$

A rigorous approach for taking into account the effect of nonhydrostatic pressure distribution requires the solution of a more complex form of the energy equation, which is generally not used in routine practical design and evaluation of hydraulic structures. Given the sill referenced upstream depth, h_1, the calculation of the corresponding Q or vice-versa using the ideal flow equation or using Eq. 6 requires iterative procedures (Bos et al., 1986; Clemmens et al., 2001).

Modular flow:

Eq. 6 is based on the assumption of free flow condition – critical flow occurs at the control section (Figure 2), hence Q can be expressed as a function of sill referenced flow depth, h, measured at a suitably sited gaging station upstream of the control section. However, to ensure that condition, there should be a minimum head loss over the flume: between the gaging station and the tailwater section (Bos, 1989; Clemmens, et al., 2001). The ratio, H_2/H_1 (H_1 and H_2 = sill referenced total head at the gaging station and tailwater section, respectively), is known as the submergence ratio and is used as an indicator of the effect of downstream flow conditions on flow upstream. As long as the submergence ratio is below a certain threshold, which varies depending on the structure, the flow upstream can be considered free flow (modular) and Eq. 6 is valid. When H_2/H_1 exceeds a threshold the flow becomes submerged (nonmodular) and flow rate is no longer a function of upstream depth only but it also becomes a function of tailwater depth. In general accuracy of Eq. 6 is adversely affected under submerged conditions. The ratio at which this transition occurs is known as the modular limit, *ML*, of the structure. The modular limit of a flow measuring structure is the submergence ratio that leads to a 1% reduction in the equivalent modular discharge (Replogle, 1977; Bos, 1989). Given the same set of conditions, long throated flumes are known to have a higher modular limit, hence less head loss requirements, relative to other critical depth flow measuring devices (Bos et al., 1986). This is an important advantage of long-throated flumes as regards flexibility.

The total head loss, ΔH, is the sum of the head losses between the gaging station and the control section, ΔH_1, (Eq. 5) and the head loss between the control section and the tailwater section, ΔH_2. ΔH_2 has two components, the friction loss over the diverging section of the flume and the tailwater channel and the energy conversion loss incurred as flow decelerates and kinetic energy is converted into potential energy. In WinFlume, the friction head loss component of ΔH_2 is calculated the same way as for the upstream segments of the flume (Clemmens, et al., 2001). The expansion head loss is calculated using a standard function that calculates the expansion loss in a conduit as a fraction (related to the expansion ratio) of a velocity head like expression dependent on velocities at the control and tailwater sections (Bos and Reinink, 1981; Bos, 1989; Clemmens, et al., 2001).

Head-discharge relationship, discharge coefficient (C_d), and flow measurement accuracy:

In general, it is convenient to measure sill-referenced upstream flow depth, h_1, and relate it with discharge. The discharge calculated with Eq. 4 (equation developed based on hydraulic theory) needs to be adjusted to take into account the effects of ideal flow assumptions, described above. The theoretical discharge computed with Eq. 4 is related to measured discharge or discharge calculated with Eq. 6 using an empirical constant (C_d), referred to as discharge coefficient. In general, the discharge coefficient is a constant in a function that relates measured discharge or discharge calculated with Eq. 6 with upstream head. In WinFlume, the calibration of long-throated flumes (i.e., the determination of the discharge coefficient of a head discharge relationship) is based on discharge calculated with Eq. 6 (Clemmens et al., 2001).

Based on extensive laboratory data, Bos (1985) showed that an empirical stage-discharge relationship for a long-throated flume can be calibrated accurately (with a maximum error of ±5%), provided the ratio between upstream total head, H_1, and throat section length, L (Figures 1a and 2), is within the range 0.1 and 1.0. As H_1/L exceeds 0.5 and approaches 1.0, the streamline curvature becomes more pronounced. Consequently, the error due to nonhydrostatic pressure distribution in the control section increases significantly. On the other hand, close to the lower ends of the range of H_1/L, friction becomes dominant. The theoretical approach for estimating friction losses in long-throated flumes can accurately account for friction head loss for H_1/L values that are as low as 0.05 (Clemmens et al., 2001). For H_1/L values lower than 0.05 friction becomes so significant that water surface is undular, with depths alternating between higher and lower stages, hence maintaining critical depth at the control section becomes difficult. In addition, for $H_1/L \leq 0.05$ measured discharges become increasingly sensitive to friction, hence errors in the specification of roughness characteristics of flume surfaces can have significant effect on measured discharge. If long-throated flumes are designed and operated such that $0.07 \leq H_1/L \leq 0.7$, mathematical models can accurately calculate rating curves with absolute errors less than 2% (Clemmens et al., 2001). This implies that L should be in the range $1.43H_1(Q_{max})$ and $14.3H_1(Q_{min})$, to minimize the sensitivity of measured discharge to friction and the deviation from hydrostatic pressure distribution at the control section. Equations for estimating calibration errors as a function of H_1/L for H_1/L values outside the range $[0.07 \leq H_1/L \leq 0.7]$ are given by Clemmens et al. (2001). These equations are formulated in such way that measurement errors increase rapidly when H_1/L increases above 0.7 or decreases below 0.07, hence making such design options less attractive.

In addition, the accuracy of flow measurement depends on a number of other factors (Clemmens et al., 2001):

(1) The method used to measure upstream depth and its setting can affect the magnitude of the systematic and random errors incurred in discharge measurement. Compared to its alternatives, the direct read-out staff gage mounted on canal side walls is relatively less accurate method for measuring sill-referenced upstream depth - with measurement errors exceeding 15mm (0.59in). However, it is simple to use, easy and inexpensive to construct and install, hence it is widely used in irrigation canals. Accurate zero-setting of the staff gage is necessary to minimize systematic errors in head or discharge readings.

(2) The range of flow depth to be measured determines the relative magnitudes of the random and systematic errors. Generally, flows with relatively larger depths can be measured more accurately than those with relatively shallower depths.

(3) The sensitivity of a structure affects its accuracy. Discharge measurement accuracy improves with a decrease in flume sensitivity – the rate of change of discharge with respect to sill referenced depth.

(4) Imprecision in flume construction and installation can be an important source of discharge measurement error. In general, flow rate estimates based on design rating curves are most sensitive to errors in constructed crest width, b_c, relative to design recommendations. Clemmens and Replogle (1980) indicated that about 1% error in

constructed crest width relative to design recommendations can results in a 1% error in discharge measurement. The head-discharge relationship is much less sensitive to construction imprecision related to flume sill height, *p*, and length, *L*, (Clemmens and Replogle, 1980; Replogle and Clemmens, 1981). In addition, nonlevel flume sill can be a source of systematic error in the measured discharge. In general, flume sill longitudinal slope of up to 2 degrees can lead to an error in the discharge coefficient, hence measured flow rate, of up to 5% (Bos, 1989). Hence, flume sill longitudinal slopes exceeding 2-3 degrees need to be avoided.

The design of long-throated flumes, using WinFlume, is based on a power-law stage-discharge, *Q(h)*, equation and other equations derived through simplifying assumptions, including ideal flow conditions (Bos, 1985; Bos, 1986; Clemmens et al., 1987; Clemmens and Bos, 1992; Clemmens et al., 2001). Flume design involves the selection of the shapes, dimensions, and construction materials of the flume components (Figures 1a and 1b) such that a set of design criteria and dimensional constraints are satisfied given a canal and its hydraulic characteristics. A brief description of design objectives, design criteria, and pertinent equations is presented subsequently.

Chapter 4. A review of flume design

Design objectives:

Given a canal segment with known boundary conditions, the range of flow rate to be measured, the tailwater characteristics, and the hydraulic resistance characteristics of the material used to construct the flume, the design objective of a long-throated flume can be stated as: Selecting a control section with sufficient contraction to maintain modular flow and acceptable levels of sensitivity and accuracy over the entire range of expected discharge variation, while at the same time maintaining a freeboard at the approach canal at maximum discharge at least equal to the minimum required freeboard, and a sufficiently stable water surface at the gaging station, at maximum discharge, for accurate gage reading.

Design criteria:

From the preceding description of the hydraulic design objective of a flume a set of design criteria emerges (Bos, 1986; Bos, 1989; Clemmens et al., 2001; Wahl et al., 2005):

(1) Water surface stability (tranquility) at the gaging station is measured in terms of Froude number (*Fr*). The lower the *Fr* relative to the critical state ($Fr = 1$), the more tranquil the flow is. However, too low an *Fr* means a condition favorable for sedimentation, hence if the flow carries appreciable amount of sediment very low *Fr* need to be avoided. In any case, *Fr* at maximum flow (Q_{max}) should not exceed 0.5 for accurate gage reading (Clemmens et al., 2001).

(2) The freeboard at Q_{max} should be grater than the minimum required freeboard, which can be specified as an absolute value or some fraction of the maximum sill referenced total head, $H_1(Q_{max})$. A freeboard of ($0.2H_{1max} \approx 0.2h_{1max}$) is recommended (Clemmens et al., 2001).

(3) For a given flow rate range, modular flow requirements ($H_2(Q)/H_1(Q) < ML$) need to be checked at both ends of the flow rate range (at Q_{max} and Q_{min}): $H_2(Q_{max})/H_1(Q_{max}) < ML$ and $H_2(Q_{min})/H_1(Q_{min}) < ML$. If flow is modular at both ends of the discharge range, it can be considered modular over the entier flow rate range (Bos, 1989; Clemmens et al., 2001).

(4) Accuracy requirements impose a restriction on the range of h_1 to be measured by a flume. Given the allowable errors at Q_{max} and Q_{min}, WinFlume calculates the minimum sill referenced upstream depths for $Q = Q_{max}$ and $Q = Q_{min}$ that can be measured with sufficient accuracy given a flow depth measurement method, sensitivity of the flume, and a rating table uncertainty (Clemmens, et al., 2001).

$$\left.\begin{aligned} h_1(Q_{\max}) &> \frac{u\delta_{h1}}{\sqrt{X_{Q\max}^2 - X_{C\max}^2}} \\ h_1(Q_{\min}) &> \frac{u\delta_{h1}}{\sqrt{X_{Q\min}^2 - X_{C\min}^2}} \end{aligned}\right\} \qquad (7)$$

where δ_{h1} = error associated with head measurement method, X_{Qmax} and X_{Qmin} = user specified maximum flow measurement errors at Q_{max} and Q_{min}, respectively, and X_{cmax} and X_{cmin} = rating curve errors at Q_{max} and Q_{min}, respectively. Under field conditions maximum discharge measurement errors (X_{Qmax} and X_{Qmin}) can be set taking into account the sill-referenced upstream head measurement method and whether it is measured inside a stilling well or in an open channel. To keep errors in computer generated rating curve, X_{cmax} and X_{cmin}, within ±2%, the length of the throat section needs to be between $1.43H_1(Q_{max})$ and $14.3H_1(Q_{min})$ (Clemmens et al., 2001). However, H_1/L can be outside these ranges if larger errors are acceptable.

Design constraints:

In addition to these primary design criteria, the relative dimensions of the converging transition, the diverging transition, and the location of the gaging station relative to the throat section and the converging transition need to meet certain requirements (Bos, 1986; Bos, 1989; Clemmens et al., 1990; Clemmens et al., 2001):

(1) The gaging station need to be located at a distance of at least $H_1(Q_{max})$ from the upstream end of the converging transition and it should also be sited between $2H_1(Q_{max})$ to $3H_1(Q_{max})$ from the upstream end of the throat section (Figure 1). If the gaging station is placed too close to the throat section, the depth reading may be affected by the drawdown at the control section.

(2) The converging transition should have a negative slope (horizontal:vertical) between 2.5 to 4.5. A more abrupt converging transition leads to flow separation and energy loss due to turbulence not taken into account by the procedure used to calculate head loss in the converging transition (see section on review of theory).

(3) The diverging transition should preferably have a positive slope (horizontal:vertical) of about 6. However, it should not exceed 10, as it would entail excessive energy loss and higher construction cost. This is an optional feature and is not needed if the available head loss over the flume is sufficient to maintain modular flow over the entire range of discharge to be measured.

(4) In order to ensure critical depth at the center of the flume, WinFlume requires that the minimum L should be twice the bottom width of the throat section.

(5) WinFlume sets the tailwater canal length at $10(p_2+L/2)-L_d$ for the purpose of friction head loss calculation in the diverging transition.

(6) It is important that the approach canal, where the gaging station is located, is straight for about $30H_{1max}$ (where H_{1max} = maximum total head at the gaging station) to provide a stable tranquil flow unaffected by upstream sources of turbulence, so that sill referenced flow depth is measured with sufficient accuracy.

Design equations and procedure:

From design perspective the throat section is perhaps the most important part of the structure and the determination of its dimension and shape is an important element of the design process. The dimensions of other sections can be selected based on the relative dimensions of the throat and the approach/tailwater canal section in such a way that the constraints listed above are satisfied. Note that here the canal forms both the approach and tailwater sections.

Maximum contraction is preferable from the point of view of satisfying modular flow requirements and the need to maintain tranquil flow in the approach canal section, however, it may not satisfy the freeboard requirements. On the other hand, minimum contraction may be favored from the point of view of satisfying the freeboard requirement, however, the structure can be susceptible to submergence (especially if tailwater characteristics is not accurately defined) and flow in the approach canal may not be tranquil enough. In addition, measurement errors can be more pronounced with structures that have minimum contraction, because of the relatively high sensitivity of Q to h in such structures. In general, there could be a range of contractions that meet the design criteria for a given canal geometry and hydraulic conditions. For a given set of conditions maximum contraction is one that produces a flow in the approach canal, at $Q = Q_{max}$, with a freeboard exactly equal to the minimum required to avoid overtopping. The minimum contraction is the smallest amount needed to maintain sufficiently tranquil flow at the approach section at Q_{max} and modular flow at Q_{max} and Q_{min} (Clemmens et al., 2001). If such a range cannot be defined then it simply means that there is no workable long-throated flume that can be used in that canal segment.

The design of long-throated flumes is generally based on a head-discharge relationship of the form (Clemmens et al., 1987):

$$Q = C_1 y_c^u \qquad (8)$$

and an assumption that cross-sectional area of flow can be expressed as power function of flow depth

$$A = C_2 y_c^{u_a} \qquad (9)$$

where C_1 = a coefficient dependent on geometry (shape and dimension of cross-section) and acceleration due to gravity, C_2 = a coefficient dependent on geometry, y_c = critical depth, u and u_a = exponents dependent on cross-section shape. It can be shown that u = 1.5 for rectangle, 2.5 for triangle, with trapezoidal and power-law cross-sections falling in between and $u_a = u\text{-}0.5$. For a trapezoidal section, Eq. 9 and hence Eq. 8 are approximate, although the error introduced by using these equations are generally negligible.

Key to the long-throated flume design procedure in WinFlume are two equations derived based on the expressions for Q and A (Eqs. 8 and 9), a simplification that assumes that the water surface elevation at the control section is the same as in the approach canal section, and that flow is frictionless (Clemmens et al., 1987; Clemmens and Bos, 1992; Clemmens et al., 2001). One of these equations relate flow conditions at the control section and approach canal:

$$Fr_1^{\,2} = \left(\frac{2u-1}{2u}\right)^{2u}\left(\frac{A^*}{A_1}\right)^3\left(\frac{B_1}{B^*}\right)C_v^2 \qquad (10)$$

where A^* and B^* = cross-sectional area and top-width of flow, respectively, at the control section assuming the water surface elevation there is the same as that in the approach section, A_1 and B_1 = cross-sectional area and top-width of flow, respectively, at the approach section, and C_v = velocity coefficient expressed as $\left(\frac{H_1}{h_1}\right)^u$. Note that Eq. 10 relates the contraction ratio (A^*/A_1) needed for a critical flow at the control section with the Fr in the gaging station. Another useful relationship derived based on ideal flow assumptions is one that relates the contraction ratio (A^*/A_1) to cross-sectional shape, and the velocity coefficient (Clemmens and Bos, 1992; Clemmens et al., 2001).

$$\left(\frac{A^*}{A_1}\right)^2 = (2u-1)\left(\frac{2u}{2u-1}\right)^{2u}\left(\frac{C_v^{(1/u)}-1}{C_v^2}\right) \qquad (11)$$

Given a discharge, canal geometry, upstream depth, shape of throat section, and top width ratio, Eqs. 10 and 11 can be solved iteratively for the contraction ratio and the velocity coefficient. This allows the development of a design approach that selects the size and shape of the throat cross-section in such a way that critical depth occurs at the control section while at the same time the flow condition at the approach canal is tranquil - as characterized by Fr_1. WinFlume uses these equations to compute maximum and minimum contractions that meet the submergence and freeboard requirements and to provide a range of design alternatives (Clemmens et al., 2001). Detailed flume design procedure and example calculations are presented by Clemmens et al. (2001). This procedure, a summary of which is presented subsequently, can be used to develop tailor made new designs, for canals of any shape and size, with WinFlume. The procedure can also be used to select appropriate flumes from predesigned alternatives presented by Clemmens et al. (2001).

Flume design begins with the specification of design inputs, which include: range of discharge to be measured, tailwater depth-discharge relationship, freeboard requirement (generally set at $0.2H_{1max} \approx 0.2h_{1max}$), allowable flow measurement and rating table errors, head measurement method and associated accuracy, initial control section shape, contraction amount, and longitudinal flume dimensions (Clemmens et al., 2001). In addition, the hydraulic resistance characteristics of the flume, which depends on the construction material, needs to be specified. In general, error in the specification of the roughness characteristics of the long-throated flumes is not critical in terms of its effect on the accuracy of discharge measurements (Replogle and Clemmens, 1981).

Design calculation begins by determining upstream head (h_1) and the required head loss (ΔH) at Q_{min} and Q_{max} for the initial contraction (Clemmens et al., 2001). The result is then compared with the design criteria described in the preceding section. If design criteria are not met, then the contraction amount needs to be changed and the corresponding h_{1min}, h_{1max}, ΔH_{min}, and ΔH_{max} be recalculated. This step is repeated until design criteria are met. Flume longitudinal dimensions for both the converging/diverging and throat sections are finalized in accord with the criteria outlined in the preceding section. WinFlume design outputs include the sill level from the canal invert, p, the flume crest width, b_c, length of the flume crest, L, slopes of the converging section of the flume and its length (L_b, Figure 2) as well as drawings of the longitudinal-section and cross-sections of the flume and the canal.

Given a canal and associated hydraulic characteristics, the above procedure can be used to develop a flume design. WinFlume, however, uses the procedure to develop a range of design options, between the maximum and minimum contractions, that satisfy the design criteria.

Flume designs based on the simplifications described above and equations (Eqs. 8-11) derived thereof introduce discharge prediction errors within a margin of 10% (Clemmens et al., 1987). While this approach results in acceptable designs, once the structure is designed its head-discharge relationship needs to be calibrated to account for friction head loss and nonhydrostatic pressure distribution at the control section and gaging station. WinFlume thus generates the rating table and parameters of the head-discharge relationship for the selected design(s). As described in the preceding section, WinFlume relates discharge calculated based on hydraulic theory with sill-referenced upstream head to produce the rating curve, over the range of flow rate to be measured, for the selected design with ±2% error. In addition, the wall gage module of WinFlume can be used to design a direct read-out staff gage graduated with depth units (sill-referenced upstream depth) or corresponding discharge.

Chapter 5. Methodology

As outlined in the objectives of the study, prototype long-throated flume designs will be developed for irrigation field supply canals typical of the irrigation districts in the Yuma Mesa. However, the development of the procedure for flume installation site selection, flume design, flume installation, and evaluation and possibly post-construction (as-built) calibration of the flume will be performed on a selected site in the Yuma Mesa

Irrigation Districts. The University of Arizona Yuma Mesa research farm has a well maintained irrigation research facility with lined field supply canal of standard geometry (widely used in the Yuma Mesa Irrigation Districts), hence it will be used to conduct this study. The flumes are to be constructed from structural grade plastic-lumber (a relatively cheap, lightweight, and structurally strong material) that can easily be constructed in an off-site workshop and transported and assembled on the installation site.

The following is a list of activities to be undertaken in the study: (1) description of the specifics of the type of flow measurement structure to be used, (2) selection of flume installation site in the UA farm and conduct site survey, including definition of the geometric and hydraulic characteristics of the field supply canal and the specification of design inputs, (3) flume design and calibration – consider five flumes with different contractions from predesigned alternatives (Clemmens et al., 2001), (4) flume construction, and (5) installation and field evaluation of selected structures. A standard field supply canal dimension of 2ft bottom width, 3ft depth, and 1:1 side slope is widely used in the Yuma Mesa Irrigation Districts, including in the field supply canal of the UA Yuma Mesa research farm. Therefore, the flume designs selected based on field tests in the UA farm will have wide application in the Yuma Mesa Irrigation Districts. The results of step 5, above, will serve as a template for demonstration and training of irrigators in growers' farms. Note that the irrigation field supply canals to which this study is applicable are lined prismatic canals in relatively good conditions with minimal soil settlement effects, and relatively low leakage losses.

5.1. Description of the type of flow measuring structure to be used and construction materials

Given the objective of this study, which is retrofitting of existing canals with critical flow measuring structures, the long-throated flume offers many technical advantages compared to other critical flow devices. Of particular interest here is the flexibility of such flumes in terms of satisfying the constraints related to the geometry of, and the available head loss in, existing canals. In addition, for the same set of geometric and hydraulic conditions these flumes cost less (Bos et al., 1986). Consequently, long-throated flumes have been used as flow measurement structure in some farms in the

Yuma Mesa irrigation districts. Hence, this study aims at building on existing work, by Sanchez and Niblack (2005), to expand the availability of such flumes for flow measurement in field supply canals in the Yuma Mesa irrigation districts.

The type of long-throated flume that is of interest here is a portable structure made of inexpensive and light-weight material (structural grade plastic-lumber) that is easy to cast into desired shapes and dimensions in an off-site workshop and transport and assemble on the installation site. Structural grade plastic-lumber is strong and is also durable for use under the conditions of infrequent intermittent wetting that the flumes are to be subjected to when used in irrigation field supply canals. Considering ease of construction and installation, the throat section of the flume has a raised sill only with no side contraction and diverging transition (Figures 3a and 3b). Hence, the flume considered here has two sections, an upstream ramp and a flume crest of appropriate dimensions. This assumes that the available head loss in a typical irrigation field supply canal in the Yuma Mesa is adequate to maintain modular flow over the range of flow rate to be measured without the need for a downstream diverging section. Noting that a typical field supply canal cross-section in the irrigation districts of the Yuma Mesa is trapezoidal, the throat section of the flume is trapezoidal as well. In general, irrigation field supply canal discharges in the Yuma Mesa vary between *7cfs* and *25cfs*, with a Q_{max} to Q_{min} ratio of about 4.0. This range of discharge can be measured accurately with a flume that has a trapezoidal throat section.

These canals have a uniform gentle slope, hence the sill of the flume also has the same longitudinal slope as the canal bottom and that the sill height is the same on both the upstream and downstream ends of the flume (i.e., $p_1 = p_2 = p$, Figures 3a and 3d). In principle, the longitudinal slope of the flume sill introduces systematic error in discharge estimates made on the basis of design rating curves. However, typically the bottom slope of the field supply canal is about 0.025%, which is very small, hence the discharge measurement error due to nonlevel sill is negligible, hence it is assumed that the drop in canal bed is negligible.

Noting that this study aims at retrofitting existing irrigation field supply canals with portable flumes, a convenient, inexpensive, and reasonably accurate alternative for gaging flow rate is to use a staff gage. In this study, a direct read-out staff gage graduated in discharge units (*cfs*) and placed on the side of the canal is to be used for the purpose. Details regarding the design and installation staff gages will be provided in a subsequent section.

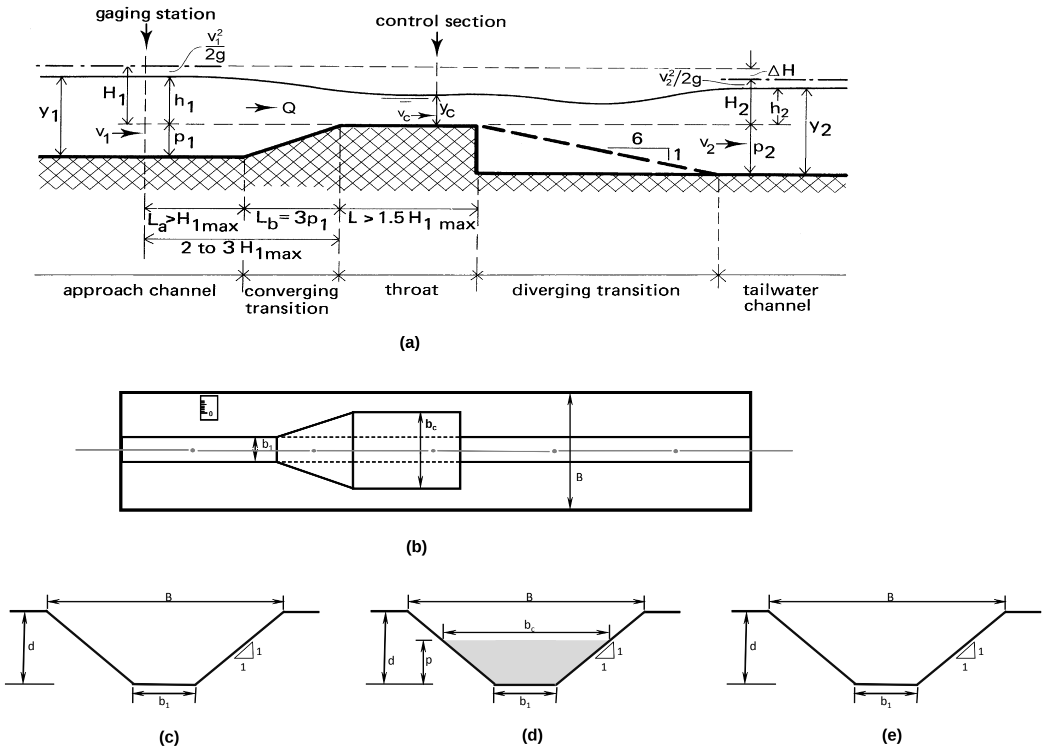


Figure 3 A sketch of long-throated flume for the Yuma-Mesa: (a) a longitudinal section along the centre line of flume (Clemmens et al., 2001), (b) Plan view of flume, (c) Approach canal cross-section, (d) Cross-section at control section, and (e) Tailwater canal cross-section (b_1 = canal bottom width, B = canal top width, b_c = flume crest width, and $p = p_1 = p_2$ is flume sill height)

5.2. Flume installation site selection and survey

Flume installation site selection: The following factors need to be considered in selecting flume installation site:

(i) Flow measuring structures should be sited such that the sill referenced depth at the gaging station can be measured with sufficient accuracy. This requires the formation of a stable subcritical flow ($Fr < 0.5$) in the approach canal. The approach canal needs to be straight, prismatic, and free of any source of

turbulence (e.g., sluice gates) for a distance of at least $30H_{1Max}$ from the gaging station (Clemmens et al., 2001). However, H_{1Max} may not be known at the preliminary site survey phase of the study, hence an alternative criterion is that the length of the approach canal section should be about ten times the average (the sum of the canal top width and bottom width divided by two) canal width (Bos et al., 1986).

(ii) The resultant backwater needs to be checked to prevent submerged conditions in an upstream structure, e.g., an irrigation off-take structure. Given a canal, alternative flume sill heights and discharges, a range of inundation scenarios can be studied using water surface profile calculations. For this study, however, we have assumed that the distance criteria given above are adequate to prevent submerged conditions in an upstream structure as well. In general, the flume should not be too close to the upstream off-take to cause water to backup to the point of reducing flow into the canal. However, this assumption needs to be verified through field evaluation.

(iii) If the canal depth is variable, the flume should be placed in a section where there could be adequate freeboard provided the site satisfies the other design requirements.

(iv) The flume needs to be installed in a canal reach with a stable bottom (Bos et al., 1986). Typically, canals in the irrigation districts of the Yuma Mesa are lined, hence this may not be a problem.

(v) Although availability of a drop (relative to freeboard and submergence requirements) is a consideration in selecting a site for a flow measuring structure, in the irrigation canals of the Yuma Mesa where field supply canals are typically laid on a relatively flat uniform slope there is no abrupt localized drop.

Flume installation site survey: The following need to be determined for the flume installation site: *(1)* canal shape and dimensions, *(2)* hydraulic characteristics (Manning's roughness coefficient, hydraulic gradient, hydraulic drops, boundary conditions), *(3)* the range of flow rate to be measured, and *(4)* the method for characterizing head-discharge relationships in the tailwater canal and the determination of pertinent *Q-h* data. A form for recording information on flume installation site survey is shown in Table 1 (Bos et al., 1986, Clemmens et al., 2001). As an example, Tables 1 and 2 summarize the flume design input data for the canal in the UA Yuma Mesa research farm. Although the field supply canals in the Yuma Mesa Irrigation Districts are predominantly of the standard size given in Table 1 and the flume designs presented here are for the standard canal dimension and associated hydraulic condition, the field measurement procedure outlined below can still be used to check if canal dimensions and hydraulic conditions for any given farm are consistent with the standard condition considered in the flume designs presented here:

(i) Flume installation site survey data is to be summarized in Table 1.

(ii) Measure canal dimensions (in the Yuma Mesa irrigation districts a typical canal has trapezoidal shape and is concrete lined):

- Canal bottom width (b_1) in *ft* or *in*
- Canal top width (B) in *ft* or *in*
- Canal depth (d) in *ft* or *in*
- Drop in canal bottom at site, Δp, in *ft* or i*n*, if there is one.

A guideline on field measurement of these quantities is presented in *Appendix 1*. In relatively new canals these may be obtained from design documents. In relatively older canals soil settlement and other factors may have changed the dimensions. Field measurements can be used to establish current dimensions.

(iii) Conduct profile survey of canal bottom over a distance of $100b_1$ *(see Appendix 1)*. For a typical irrigation field supply canal in the Yuma Mesa, canal bottom profile has a constant gradient of about 0.00025. Thus, if the bottom slope is to be checked elevation readings at two points along the central transect along with the distance between them are sufficient.

(iv) Determine maximum and minimum flow rates (Q_{max} and Q_{min}):

- If canal is relatively new, Q_{max} and Q_{min} can be obtained from design documents.
- In well maintained, but relatively older canals, where conditions assumed at design are no longer valid, the following steps can be used to verify the discharge range:

- Consult with growers/irrigators about gate (off-take from main canal) settings for maximum and minimum flows.
- Obtain irrigators'/growers' estimates of corresponding maximum and minimum discharges.
- Set gate for maximum and minimum flows (as described by irrigator) and measure discharges, Q_{max} and Q_{min}, using indirect flow measuring devices (see *Appendix 1* for further discussion).

(v) Tailwater depth-discharge relationship is difficult to characterize in many farms in the irrigation districts of the Yuma Mesa. During the canal filling phase, there is backwater in the canal, hence flow is a function of downstream no-flow boundary as well as conditions at the upstream end. Soon after the start of irrigation (a gate is opened), flow in the canal occurs without backwater. How to characterize tailwater using one of the five options available in WinFlume requires answering the question: during field supply canal operation, what is the most convenient time for accurate measurement of flow rate? In this study, it is assumed that discharge will be measured when a basin is irrigated (i.e., in the absence of backwater). Hence, the WinFlume option that extrapolates a single depth-discharge measurement over the range of discharge variation, using Manning's equation, will be used to characterize the tailwater depth-discharge relationship used in the flume design. Flow depth should therefore be measured some time after one of the sluice gates (basin inlet) are opened at a point close to the flume installation site.

The above assumes that flow measurement may not be performed when all gates (basin inlets) are closed and that a calibrated indirect flow measuring device is available for discharge measurement. To ensure that these devices are not out of calibration, they need to be checked regularly and if necessary be recalibrated. Note that regular checking and recalibration of these devices may require assistance from manufacturers and additional service fee. Follow manufacturer's recommendations in measuring flow rate with indirect flow measurement devices. Some additional points are outlined in *Appendix 7*.

(vi) Considering a well maintained rough concrete lined canal (i.e., not a new smooth concrete surface) as a typical field supply canal in the Yuma Mesa Irrigation Districts, a Manning *n* of 0.014 can be used. Given the geometry of the canal, the hydraulic gradient (friction slope), S_f , can then be calculated with the Manning equation (Table 1).

5.3. Design and calibration of flumes for typical irrigation field supply canals in the Yuma Mesa Irrigation Districts

Description of the general procedure: As described above, the design of a long-throated flume involves the selection of the shapes, dimensions, and construction materials of the different components of the structure (Figures 3a and 3b) such that a set of design criteria and dimensional constraints are satisfied, given a canal and the range of flow rate to be measured. Key to the flume design process is the selection of the geometry and the material of the throat section. The converging transition of the flume is to be dimensioned based on the geometry of the throat section relative to the approach canal section in such a way that a set of criteria listed in Chapter 4 are satisfied (see the section that reviews flume design approach). One of two approaches can be used for designing flumes:
(1) Select flumes from predesigned alternatives (Clemmens et al., 2001, Wahl et al., 2005). Tables 5.2 and 5.3 (Clemmens et al., 2001) present pre-computed flume selections as a function of canal dimensions (side slope, bottom width, and canal depth) and discharge ranges. These tables provide flume sill height, crest width, and minimum head loss for modular flow, and constraints on flume sill length, freeboard, length of the converging section, and location of the gaging station relative to the flume. Another set of tables provide rating equations and tables (Appendix 4, Clemmens et al., 2001). These flumes meet the Froude number and accuracy criteria (Wahl et al., 2005). However, since freeboard and modular flow related requirements are specific to the site, for the precomputed flumes these requirements need to be evaluated in the field or evaluated with WinFlume before construction. In addition, such an evaluation helps select actual dimensions of flume components, such that the design requirements and/or dimensional constraints under actual hydraulic conditions are met.

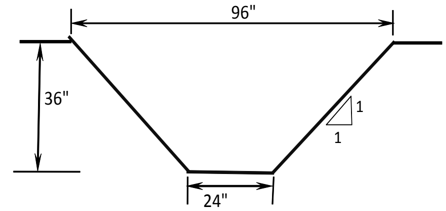
Table 1 Flume installation site survey data form (Bos et al., 1986, Clemmens et al., 2001)

Name of site: University of Arizona Yuma Mesa farm		Date: 03/27/09
HYDRAULIC DEMANDS		
Range of flow, Q, to be measured	Present water depth in canal, y_2	Maximum permissible error in flow measurement
$^*Q_{min}$ = *8.0*	y_{2min} = *1.33* *ft*	X_{Qmin} = *15.0* *%*
$^*Q_{max}$ = *26.0*	y_{2max} = *1.92* *ft*	X_{Qmax} = *8.0* *%*

HYDRAULIC DESCRIPTION

Canal bottom width	b_1	=	2.0	ft
Canal side slope	z	=	1.0	-
Canal depth	d	=	3.0	ft
Maximum allowable Water depth	y_{1max}	=	1.92	ft
Manning's n	n	=	0.014	-
Hydraulic gradient	S_f	=	0.00186	-
Available drop in Water depth at site	Δh	=	0.0	ft
Drop in channel bottom at site	Δp	=	0.0	ft

Sketch of canal cross-section:



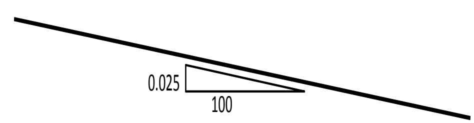
Concrete lined: × ☐

Earthen channel: ☐

FUNCTION OF STRUCTURE

Flow measurement only

Bottom profile of canal over a distance of $100b_1$



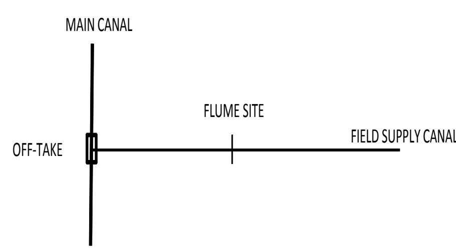
PERIOD OF STRUCTURE SRVICE

Day	☐	Season	☐
Month	☐	Permanent	× ☐

DESCRIPITION OF ENVIRONMENT

Irrigation system		Drainage system	
Main	☐	From irrigated area	☐
Lateral	☐	Artificial drain	☐
Farm ditch	× ☐	Natural drain	☐
In field	☐		

Plan of site:



FURTHER DESCRIPTION (attach photo)

**= these are field measured flow depth and discharge values, however, the discharge range used in design is 7-25cfs, S_f is calculated based on the depth and discharge pair: 19in-16cfs.*

(2) The second approach involves the use of the WinFlume program to develop tailor-made designs, given a specific set of hydraulic and geometric conditions.

In general the use of the precomputed flume selections (Celmmens et al., 2001) has the advantage of being convenient and can be used as a starting point in the selection of appropriate flume designs in the current study. Precomputed alternatives, that match the standard field supply canal size (which is *2ft* bed width, *3ft* depth, and *1:1* side slope) and discharge ranges (*7cfs*-*25cfs*) for the Yuma Mesa Irrigation Districts, are available. However, these selections need to be evaluated, under the specific hydraulic conditions in the Yuma Mesa, with respect to all the design criteria and dimensional constraints described in the preceding section. In this study, a procedure that combines the two flume design approaches will be used: (1) first precomputed alternatives will be selected from Tables 5.3 and R.2, *Appendix 4,* (Clemmens et al., 2001) based on irrigation field supply canal dimensions and ranges of flow rates in the Yuma Mesa irrigation districts, (2) given the tailwater characteristics of the canal, the selected flumes will be checked for meeting the flume design criteria and dimensional constraints with WinFlume and will be modified as needed, and (3) Those that meet all the design criteria and dimensional requirements will be further evaluated in the field.

Data description and flume selection: Tables 1 and 2 summarize the data used in flume design for the Yuma Mesa Irrigation Districts. The standard field supply canal size widely used in the Yuma Mesa irrigation districts has trapezoidal cross-section with bed width of 2.0ft, a side slope of 1:1, and a canal depth of 3.0ft (Table 1). The flow rate supplied to individual irrigation farms is generally constant, but varies from farm to farm approximately in the range *7.0cfs* to *25.0cfs*. A simple approach used in WinFlume for characterizing the tailwater depth-discharge relationship is to use an expression derived based on Manning equation to extrapolate depth-discharge relationships over the entire discharge range using a pair of flow depth and discharge measurement under flow conditions where there is no backwater. This approach is used here. Three pair of flow depths and discharges were measured in the University of Arizona Yuma Mesa research farm: *26cfs* and *23in*, *16cfs* and *19in,* and *8cfs* and *16in*. Since, *16cfs* represents the middle of the discharge range supplied to irrigation field supply canal in the Yuma Mesa Irrigation Districts, it is chosen along with the corresponding depth (*19in*) for use in the evaluation of the precomputed flumes. It is hypothesized here that the use of depth-discharge values in the middle of the range minimizes the extrapolation error in tailwater characterization. Eventually, the selected flumes will also be checked against a tailwater characteristics based on the maximum tailwater depth (*23in*) and the corresponding discharge (*26cfs*).

The minimum freeboard is taken as $0.2h_{1max}$, where h_{1max} is the sill-referenced upstream depth at $Q = Q_{max}$. The head measurement method is a staff gage placed on canal sidewalls, hence head reading error is about 15*mm (≈0.0492ft*). Although this head measurement method is simple and convenient to install and operate and is inexpensive, it, however, increases the uncertainty in the discharge measurement as will be shown subsequently. In addition, the hydraulic resistance characteristics of the flume, which depends on the construction material, need to be specified. In this study, the absolute roughness of plastic-lumber is approximated by a material with very low hydraulic roughness charcteristics programmed into WinFlume (concrete-smooth custom, roughness height of 0.000492ft). In general, error in the specification of the roughness characteristics of the long-throated flumes is not critical in terms of its effect on the accuracy of discharge measurements (Replogle and Clemmens, 1981). Maximum flow measurement error, which is the sum of head reading and calibration errors, are set at 15% at Q_{min} and 8% at Q_{max} (Table 2).

Selection from precomputed flumes: Based on the canal dimensions and discharge ranges typical of the Yuma Mesa Irrigation Districts (Table 2), five alternative flume designs (Flume types D_e, E_e, F_e, G_e, and H_e) are selected from the precomputed flumes presented in Table 5.3 (Clemmens et al. 2001). The flume sill height, crest width, minimum head loss are summarized in Table 3. As noted above these flumes need to be evaluated first with WinFlume and then through field evaluation under the hydraulic conditions typical of the irrigation field supply canals in the Yuma Mesa to identify their limitations and advantages under actual flow conditions in the Yuma Mesa Irrigation Districts.

Check design with WinFlume: The five precomputed flumes summarized in Tables 3 are evaluated with the design functionality of the WinFlume program for the hydraulic conditions typical of the Yuma Mesa Irrigation Districts and the design requirements summarized in Table 2. Detailed description of the WinFlume program, availability, theoretical basis, and usage of program in design, calibration, evaluation of long-throated flumes (broad crested weirs) is provided by Clemmens et al. (2001). A brief introduction of the WinFlume program is presented in *Appendix 2*.

Table 2 Design input for the UA research farm

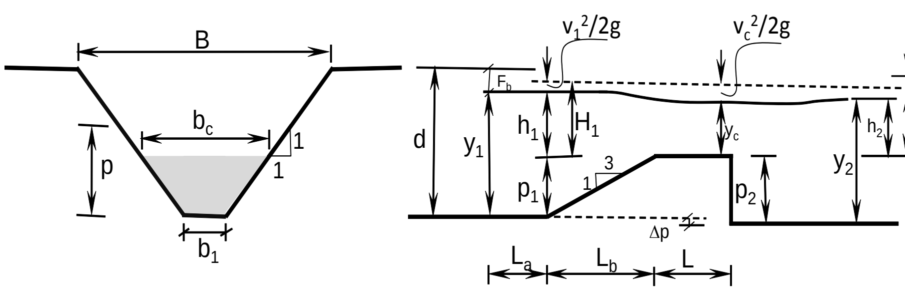
Design input	Unit	Value
Canal bed width, b_1,	*ft*	2.0
Side slope, z,	-	1.0
Canal depth,d,	*ft*	3.0
Depth for tailwater characterization, Y[1]*,*	*ft*	1.58
Canal discharge for tailwater characterization, Q[1]*,*	*cfs*	16.0
Q_{min}	*cfs*	7.0
Q_{max}	*cfs*	25.0
Maximum Froude number at Q_{max}[2]	-	0.5
Discharge measurement error at Q_{max}	%	8.0
Discharge measurement error at Q_{min}	%	15.0
Minimum freeboard requirement[2]	-	$0.2h_{1max}$
Roughness height for plastic-lumber	*ft*	In WinFlume, the hydraulic roughness characteristics of plastic-lumber is approximated by concrete-smooth, custom
Head measurement error (considering head measurement method -- staff gage without a stilling well with Fr < 0.5[2])	*ft*	0.0492

[1]The tailwater specification option used is single flow depth-discharge data based on Manning equation. All flumes considered here have a raised sill, with no side contractions, thus noting that the field supply canals are trapezoidal, the throat sections of the flumes considered here are also trapezoidal. [2]Corresponding values are based on recommendations by Clemmens et al. (2001).

Table 3 Selected precomputed flumes from Clemmens et al. (2001) for irrigation field supply canals in the Yuma Mesa Irrigation Districts[a]

Canal dimensions			Range of canal capacities		Flume selections (See Table 4)	Flume shape		Minimum head loss ΔH (ft)
Side slope, *Z* *(-)*	Bottom width, b_1 (ft)	Maximum canal depth[b], *d* (ft)	Lower[c] Q_{min} (ft^3/s)	Upper Q_{max} (ft^3/s)		Crest width b_c (ft)	Sill height p_1 (ft)	
1	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

Notes: [a] $L_a \geq \Delta H_{1max}$; $L_b = 3p_1$; $L_a + L_b > 2$ to $3H_{1max}$
$L > 1{:}5H_{1max}$, but within range given in Table 4
$d > 1{:}2\ h_{1max} + p_1$
$\Delta H > 0{:}1H_1$
[b] Maximum recommended canal depth
[c] Limited by sensitivity
[d] Limited by Froude number; otherwise limited by canal depth



B = Canal top width, b_1 = canal bottom width, *d* = canal depth, b_c = flume crest width, p_1 = flume sill height upstream end, p_2 = flume sill height downstream end, *p* = for the portable flumes considered in this study - $p_1 = p_2 = p$ = flume sill height, y_1 = flow depth in approach canal, y_2 = flow depth in tailwater canal, F_b = freeboard in approach canal (gaging station), ΔH = headloss over the flume, Δp = hydraulic drop, L_a = length of approach channel, L_b = length of converging transition, and *L* = length of the flume throat.

As described in a preceding section, design calculation begins by determining upstream head (h_1) and the required head loss (ΔH) at Q_{min} and Q_{max} for the initial control section size and shape. The result is then compared with the design criteria described in the preceding section. If design criteria are not met, then the contraction amount needs to be changed and the corresponding h_{1min}, h_{1max}, ΔH_{min}, and ΔH_{max} be recalculated. This step is repeated until design criteria are met. Flume longitudinal dimensions for both the converging and throat sections are finalized in accord with the criteria outlined in the preceding section. WinFlume design outputs include the sill level from the canal invert, *p*, the flume crest width, b_c, length of the flume crest, *L*, slopes of the converging section of the flume and its length (L_b, Figure 2) as well as drawings of the longitudinal-section and cross-sections of the flume and the canal. In addition, WinFlume produces a range of designs between the maximum and minimum control section sizes that meet the design criteria on Froude number, freeboard, and modular flow requirements. However, for some of the alternative designs the dimension of the converging section may need adjustment to meet pertinent dimensional constraints and in some cases the accuracy requirements may not be met.

Evaluation of the precomputed flume designs with WinFlume, based on canal geometric and hydraulic data summarized in Table 2, showed that the flume with a sill height of 0.75ft (option D_e) is highly susceptible to submergence, hence is not considered further. In addition, flume type H_e (sill height 1.75ft) will cause a high enough backwater in the approach canal to reduce freeboard below the minimum required to prevent overtopping. Therefore, this flume option, as well, is not considered in subsequent analyses. The remaining designs: flume type E_e (sill height of 1.0ft), F_e (sill height of 1.25ft), and G_e (sill height of 1.5ft) were evaluated with WinFlume and the exact lengths of the control section and converging transition are selected in such a way as to ensure that they meet all the design and dimensional requirements. The following is an example of the procedure used in evaluating the precomputed flume selections for the Yuma conditions with WinFlume.

Considering flume type E_e (Tables 3), the flume sill height is 1.0ft, the crest width is 4.0ft, and the crest length is in the range of 1.7ft to 2.1ft (Table R.2, Clemmens et al., 2001). The corresponding rating equation is shown in Table 4. In addition, the length of the converging section is set at 3.0ft resulting in a slope (horizontal:vertical) of 3:1 and the gaging station is set at 3ft from the upstream end of the converging transition. Evaluation of flume type E_e with respect to the six design criteria *[$F_{r1}(Q_{max}) < 0.5$, $0.2h_1(Q_{max}) <$ Freeboard, tailwater depth at Q_{max} < maximum allowed to prevent submergence at Q_{max}, tailwater depth at Q_{min} < maximum allowed to prevent submergence at Q_{min}, h_{1min} required for accuracy at $Q_{max} < h_1(Q_{max})$, and h_{1min} required for accuracy at $Q_{min} < h_1(Q_{min})$]* show that acceptable design can be obtained with flume crest length that is at least 1.7ft, however, design improves as crest length is increased to 2.1ft, the upper limit of the crest length in the range indicated in Table R.2. Hence, the length of the flume crest is set at 2.1ft.

The flume data report, which summarizes the input data and results of evaluation of the predesigned flume with a sill height of 1.0ft is presented in *Appendix 3*. The results show that the precomputed flume - with a flume crest length of 2.1ft and converging section length of 3ft - satisfies all the six design criteria. It also satisfies the constraints as related to the dimensions of the flume and location of the gaging station relative to the flume. As described above, WinFlume also provides alternative designs with varying contractions, spanning the minimum (p = 0.747ft and b_c = 3.494ft) and the maximum (p = *1.6*ft and b_c = 5.2ft) control section sizes that satisfy the design requirements. This result is presented in Table 3.3, *Appendix 3*. As described earlier a flume sill height lower than 0.75ft generally do not meet the submergence criteria. For flume sill height of 1.25ft and above (Table 3.3), the length of the upstream converging transition is too short (should at least be 3.13ft) and can lead to flow separation and the formation of turbulent eddies and energy loss not taken into account in the friction head loss calculation. Thus, the length of the upstream ramp needs to be increased to meet pertinent dimensional constraint. The rest of the alternative designs in Table 3.3 with sill heights ranging from 0.8ft to 1.2ft meet both the design criteria as well as the dimensional constraints, hence will be considered further.

In principle, any of the designs within this range can be selected. However, as described in the preceding sections, flume options with minimum contractions are susceptible to submergence (especially when tailwater characteristics is not well defined) and the Froude number requirement for providing stable water surface at the approach canal may not be met. With options that provide maximum contraction, the backwater at the approach canal can be too high leading to overtopping and/or reducing the flow at the inlet into the field supply canal. This suggests that designs that are in the middle of the range are the ones that provide the best compromise between these conflicting requirements. As can bee seen from Table 3.3, the modified design (p = 1.0ft, L_a = 3.0ft, L_b = 3.0ft, and L = 2.1ft) meets all the design criteria, flume dimensional restrictions, as well as practical considerations as related to uncertainties in canal hydraulic characteristics. In addition, it can be noted from Table 3.3 that minor changes in the actual flume sill height due to imprecision in construction and installation still result in a flume with acceptable performance, although recalibration using as-built dimensions may be needed. Hence, flume type E_e with a crest length of 2.1ft and an upstream ramp with a slope of 3:1 (horizontal:vertical) results in an acceptable design considering the canal geometric and hydraulic characteristics in the UA Yuma Mesa research farm and is selected as one of the alternative flume designs to be field tested. Figure 3.1 (*Appendix 3*) depicts the longitudinal section of the flume and cross-sections at the approach canal, the control section, and the tailwater section for flume sill height of 1.0ft. Figure 3.2, in *Appendix 3*, shows the dimensions of the canal cross-section where the flume is to be installed and dimensions of the components of the flume.

Rating table with WinFlume: WinFlume generates the rating table and parameters of the head-discharge relationship for the selected design. Table 3.4 in *Appendix 3* present the rating table and rating curve for flume sill height of 1.0ft, respectively. As described in the preceding section, WinFlume relates discharge calculated based on hydraulic theory with sill-referenced upstream head to produce the rating curve, over the range of flow rate to be measured, for the selected design with ±2% error.

Using the procedure described above two additional alternative flume designs: flume sill heights of 1.25ft and 1.5ft are selected. The output obtained from WinFlume evaluation of these flume options is summarized in *Appendices* 4 and 5. A summary of the flume dimensions, discharge, and rating tables are presented in Tables 4 and 5. Although the rating tables (Tables 3.4, 4.4, and 5.4) in *Appendices 3-5* show larger ranges of discharge measurement capability, considering practical lower limits on canal discharges and sensitivity and accuracy, the ranges shown in Table 5 are practically useful. In addition, WinFlume outputs the corresponding gage paper taking into account the canal side slope. The wall gage module of WinFlume can be used for this purpose. This is discussed in more detail in *Appendix 2*.

Sensitivity of flume designs to tailwater characteristics: The sensitivity of the selected flume designs was evaluated with WinFlume based on a canal tailwater characteristics derived using the maximum field measured depth of *23in* and the corresponding discharge (*26cfs)*. For the 1.0ft sill height flume, the design developed based on a tailwater characteristics (derived with a flow depth-discharge data of 23in and 26cfs), in fact, showed marginal improvement relative to the design developed on the basis of a tailwater that is *19in* deep at *16cfs*. The submergence protection at Q_{max} increased from *0.179ft* to *0.278ft* and at Q_{min} it increased from *0.497ft* to *0.553ft*. The other design criteria remained unchanged at the same level as those obtained when the tailwater characteristics was derived based on a discharge of *16cfs* and a flow depth of *19in*. There was no change in the rating table and equation for the *1.0ft* sill height flume. For the *1.25ft* and *1.5ft* sill heights there was no change in the design as well as the rating equations and table when the depth-discharge data representing the upper limit of the range, instead of the average value, was used to represent canal tailwater characteristics.

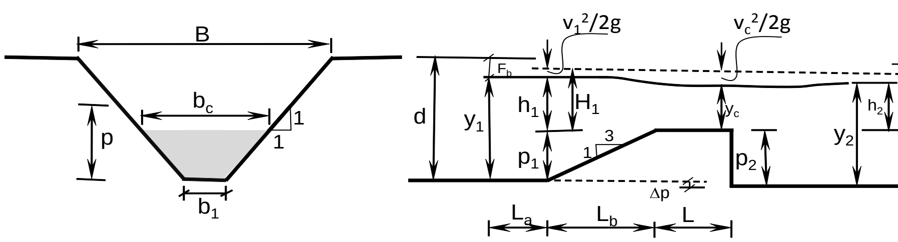
Table 4 Broad-crested weirs for lined trapezoidal irrigation field supply canals in the Yuma Mesa Irrigation Districts, selected designs[a]

Canal dimensions			Range of canal capacities		Flume selections (See Table 4)[d]	Flume shape		Minimum head loss
Side slope, Z	Bottom width, b_1 (ft)	Maximum canal depth[b], (ft)	Lower[c] Q_{min} (ft^3/s)	Upper Q_{max} (ft^3/s)		Crest width b_c (ft)	Sill height p (ft)	ΔH (ft)
1	2.0	3.0	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

Notes: [a] $L_a \geq \Delta H_{1max}$; $L_b = 3p_1$; $L_a + L_b > 2$ to $3H_{1max}$, $L > 1{:}5H_{1max}$, but within range given in Table 4, $d > 1{:}2\ h_{1max} + p_1$, $\Delta H > 0.1H_1$.

[b] Maximum recommended canal depth, [c] Limited by sensitivity.

[d] Although the rating curve shows a larger range of discharge measurement capability (Tables 3.4, 4.4, and 5.4), based on practical and accuracy considerations the range here is kept the same as the range used for the precomputed flumes (Table R.2, Clemmens et al., 2001)



B = Canal top width, b_1 = canal bottom width, d = canal depth, b_c = flume crest width, p_1 = flume sill height upstream end, p_2 = flume sill height downstream end, p = for the portable flumes considered in this study $p_1 = p_2 = p$ = flume sill height, y_1 = flow depth in approach canal, y_2 = flow depth in tailwater canal, F_b = freeboard in approach canal (gaging station), ΔH = head loss over the flume, Δp = hydraulic drop, L_a = length of approach channel, L_b = length of converging transition, and L_c = length of the flume throat section.

Table 5 Rating equations for the selected predesigned alternative flumes (see Table 3)

Flume type, dimensions and location of gaging station					*Range of Q*[a] *(ft)*	Calibration equation, $Q = K_1(h_1 + K_2)^u$		
Flume type	b_c *(ft)*	L_a *(ft)*	L_b *(ft)*	L_c *(ft)*		K_1 ($ft^{(3-u)}/s$)	K_2 *(ft)*	u *(-)*
E_e	4.0	3.0	3.00	2.1	$6.2 \leq Q \leq 40$	14.67	0.04524	1.830
F_e	4.5	3.0	3.75	2.0	$6.8 \leq Q \leq 33$	16.22	0.03628	1.779
G_e	5.0	3.0	4.50	2.0	$7.4 \leq Q \leq 27$	17.75	0.02944	1.740

[a]Discharge ranges are those indicated in Table 3. Upper limits of the discharge ranges pertinent to the Yuma Mesa Irrigation Districts are given in the rating tables (Tables 3.4-5.4, Appendices 3-5)

Comparison of the three selected flumes for three different discharge ranges: The three flumes (1.0ft, 1.25ft, and 1.5ft sill heights) selected above are compared under three discharge ranges spanning the typical field supply canal discharge variation in the Yuma Mesa (7.0*cfs*-25*cfs*): lower range (7.0*cfs*-12.0*cfs*), middle range (12.0*cfs*-18*cfs*), and higher range (18.0*cfs*-25*cfs*). The canal tailwater characteristic was based on a discharge of 16cfs and a flow depth of 19in. The results, obtained using simulations with WinFlume are summarized in Table 6. The objective is to provided a set of results that can be used as preliminary guide in the field evaluation and selection of flumes from the three predesigned alternatives.

For a given discharge range the design improves, with respect to Froude number and submergence criteria, as sill height is increased (Table 6). On the other hand, given a discharge range, an increase in sill height results in a design with a reduced margin, between the actual freeboard and the minimum required, and a decrease in measurement accuracy. The results summarized in Table 6 show that the flume with the smallest sill height (1.0ft) is more susceptible to submergence in the higher discharge range of 18-25*cfs*. Hence, susceptibility to submergence is an issue that need to be carefully monitored during field evaluation of the 1.0ft flume under the discharge range 18-25cfs. In addition, if the flume with the largest sill height (1.5ft) is used in a canal with a discharge in the range 18-25*cfs*, the available margin between the actual and the minimum required freeboard could be very small (0.078ft) and could result in canal overtopping. Thus, this result suggests that during field evaluation of the 1.5ft sill flume under the highest discharge range (18-25cfs), freeboard and canal overtopping is an issue to be carefully monitored. Discharge measurement errors at Q_{max}, in the range 7-12cfs for all the three flume sill heights and in the range 12-18cfs for sill heights of 1.25ft and 1.5ft, marginally exceeded the expected measurement uncertainty (8.0%), Table 6. It is important to note that these measurement errors can be attributed to the validity of using the same error tolerance level of 8.0% at Q_{max} for the lower discharge subintervals (7-12cfs and 12-18cfs). Note that it is appropriate to use larger error tolerance criteria at Q_{max} for these discharge ranges.

Considering freeboard and submergence, the midsized flume (flume sill height of 1.25ft) provides acceptable performance over the three discharge ranges, hence it can be considered as the flume that can be applied to the entire field supply canal discharge range in the Yuma Mesa Irrigation Districts. As tailwater characteristics may vary from canal to canal, these results are to be used as a rough guide to assist in actual field evaluation of the flumes.

Table 6 Comparison of the three selected flume designs for three different discharge ranges

Flume sill height 1.0ft				
Design criteria	Unit	*Ranges of Q*		
		7- 12 cfs	*12-18cfs*	*18-25cfs*
Fr (Q_{max})	-	0.264	0.319	0.366
Freeboard (Q_{max})*/minimum*	*ft*	1.144/0.171	0.923/0.215	0.707/0.259
Submergence protection at Q_{max}	*ft*	0.373	0.269	0.176
Submergence protection at Q_{min}	*ft*	0.495	0.373	0.269
Sill referenced upstream depth at Q_{max}*/ minimum for accuracy/error*	*ft/ft/%*	0.856/1.035/9.59*	1.077/1.055/7.85	1.293/1.074/6.73
Sill referenced upstream depth at Q_{min}*/ minimum for accuracy/error*	*ft/ft/%*	0.625/0.529/12.74	0.856/0.541/9.59	1.077/0.551/7.85
Flume sill height 1.25ft				
Design criteria	*Unit*	*Ranges of Q*		
		7- 12 cfs	*12-18cfs*	*18-25cfs*
Fr (Q_{max})	-	*0.216*	*0.267*	*0.312*
Freeboard (Q_{max})*/minimum*	*ft*	*0.939/0.162*	*0.723/0.205*	*0.514/0.247*
Submergence protection at Q_{max}	*ft*	*0.571*	*0.459*	*0.359*
Submergence protection at Q_{min}	*ft*	*0.704*	*0.571*	*0.458*
Sill referenced upstream depth at Q_{max}*/ minimum for accuracy/error*	*ft/ft/%*	*0.812/ 1.022/ 9.97**	*1.027/1.040/8.09**	*1.236/1.057/6.91*
Sill referenced upstream depth at Q_{min}*/ minimum for accuracy/error*	*ft/ft/%*	0.589/ 0.524/ 13.37	0.812/0.534/9.97	1.026/0.543/8.1
Flume sill height 1.5ft				
Design criteria	Unit	*Ranges of Q*		
		7- 12 cfs	*12-18cfs*	*18-25cfs*
Fr (Q_{max})	-	*0.179*	*0.226*	*0.268*
Freeboard (Q_{max})*/minimum*	*ft*	0.729/0.154	0.520/0.196	0.315/0.237
Submergence protection at Q_{max}	*ft*	0.772	0.651	0.545
Submergence protection at Q_{min}	*ft*	0.916	0.772	0.651
Sill referenced upstream depth at Q_{max}*/ minimum for accuracy/error*	*ft/ft/%*	0.771/1.012/10.37*	0.980/1.028/8.37*	1.185/1.043/7.10
Sill referenced upstream depth at Q_{min}*/ minimum for accuracy/error*	*ft/ft/%*	0.556/0.520/14.03	0.771/0.529/10.37	0.980/0.537/8.37

$*$ = error exceeds the expected discharge measurement uncertainty at Q_{max}, which is 8.0%

5.4. Construction of the flume(s)

Considering standard dimensions of available construction material (structural grade plastic-lumber) and portability of flumes, the design dimensions of the flumes were revised for construction purposes. The resulting flumes (using construction dimensions) were evaluated with WinFlume. A summary of the input data sets (construction dimensions) and results of evaluation of the flumes are presented in Tables 7.1 and 7.2 for flume sill height 1.0ft; in Tables 8.1 and 8.2 for flume sill height 1.25ft and in Tables 9.1 and 9.2 for flume sill height 1.5ft *(Appendices 7-9)*. The construction dimensions and the corresponding rating equations are presented in Table 7. In general, the designs are acceptable although improvements are possible by increasing the length of the upstream ramp for sill heights of 1.25ft and 1.5ft. However, as mentioned above practical considerations limit flume ramp sizes to those shown in Figures 7.1, 7.2, 8.1, 8.2, 9.1 and 9.2, *Appendices* 7-9. The rating tables (given in Tables 7.3, 8.3, and 9.3, for sill heights of 1.0ft, 1.25ft, and 1.5ft, respectively) are slightly different from those calculated based on design dimensions, given in *Appendices 3-5*. Field evaluation will be used to further evaluate these flumes.

It is assumed here that the canal reach in which the flume is to be installed makes up both the approach and tailwater canal sections. The flume will have only vertical contraction, p, where b_c is the corresponding crest width (Figures 3a, 3b, and 3d). The flume sill height and converging transitions are to be constructed in accord with construction specifications given in Figures 7.2 and 7.3 for flume sill height of 1.0ft; Figures 8.2 and 8.3 for flume sill height of 1.25ft; and Figures 9.2 and 9.3 for the 1.5ft sill height.

As can be seen from Figures 7.2, 7.3, 8.2, 8.3, 9.2 and 9.3, the crest section needs to have a 1:1 slope along its edges that fit into the canal side walls. The converging section of the flume needs to be beveled at a 1:3 slope along its edge at the joint with the flume sill. Along the edges that fits into the canal wall the converging section needs to have a 1.05:1 slope. This is based on the assumption that the upstream ramp has 3:1 (horizontal:vertical) slope, hence steeper/flatter slopes may require slight changes. However, in practice the error in using this value is negligible.

Construction tolerance for long-throated flumes and associated discharge measurement errors were discussed in *Chapter 3*. In general, measured discharge is most sensitive to errors in constructed flume crest width (Clemmens and Replogle, 1980; Replogle and Clemmens, 1981). Construction imprecision in flume sill height, p, and length, L, are generally less critical. However, in a trapezoidal canal with a flume that has vertical contraction only, b_c is a function of p as well, hence significant error in constructed flume sill height can have a significant effect on discharge measurement accuracy.

The flume will be pre-cast to construction specifications from plastic-lumber in an off-site workshop in two parts – the upstream ramp and the throat section. The sections are transported to the installation site and assembled. The structure needs to be sufficiently sturdy so as to minimize deformation during installation or subsequent operation, hence both flume crest and upstream ramp are reinforced by 2”×4” and 2”×6” beam (Figures 7.2 and 7.3, 8.2 and 8.3, and 9.2 and 9.3). The joint between the upstream ramp and the crest of the flume sill needs to be smooth and perhaps beveled to prevent flow separation. The ramp may need to have a hole near the canal bottom to allow water to drain freely once the tailwater canal section is drained, so as to prevent water stagnation upstream of the flume. In addition, since plastic-lumber is light-weight material, clips riveted or screwed to the canal wall are to be used to hold it in place, especially during the canal filling phases in which the backwater may lift the flume sill and ramp.

A gage placed on the canal wall is used here to measure head. The staff gage will be graduated in *cfs*. The staff gage can be made from different materials: steel, aluminum, baked enamel. The design and setting of the staff gage is discussed in *section 5.6* and *Appendix 2*.

Table 7 Rating equations based on construction dimensions of the selected designs (see Table 3)

Flume type, dimensions and location of gaging station					Range of Q^a (ft)	Calibration equation, $Q = K_1(h_1 + K_2)^u$		
Flume type	b_c (ft)	L_a (ft)	L_b (ft)	L (ft)		K_1 ($ft^{(3-u)}/s$)	K_2 (ft)	u (-)
E_e	4.0	3.0	3.00	2.666	$6.2 \leq Q \leq 40$	14.65	0.0435	1.830
F_e	4.5	3.0	3.54	2.33	$6.8 \leq Q \leq 33$	16.19	0.0362	1.781
G_e	5.0	3.0	3.71	2.0	$7.4 \leq Q \leq 27$	17.74	0.0300	1.741

[a]Discharge ranges are those indicated in Table 3. Upper limits of the discharge ranges pertinent to the Yuma Mesa Irrigation Districts are given in the rating tables (Tables 7.3-9.3, Appendices 7-9)

5.5. Field evaluation and as-built calibration of flume

Maricopa evaluation: With the objective of evaluating the limitations of the field procedure described above, before its actual application in the relatively larger irrigation field supply canals of the Yuma Mesa; portable flumes of three different flume sill heights were designed and constructed in the USDA-ARS-ALARC, Maricopa, and were evaluated in an irrigation field supply canal in the Maricopa Agricultural Center (MAC) of the University of Arizona. Compared to the canals in the Yuma Mesa, these canals are smaller in size (1ft bottom width, 2.5ft depth, and 1:1 side slope). The flumes used in this test are made of plywood (flume crest and upstream ramp) and used a 2”×4” beam to reinforce the plywood crest. These flumes were placed at a suitable site in an irrigation field supply canal in a MAC farm, while water is running in the canal. Each of the three flumes were field tested at the same location in the canal. Once the ramp and the flume crest are placed inside the canal, sill referenced upstream depth was measured using a portable point gage (Clemmens et al., 2001). The point gage can measure sill referenced upstream depth with a maximum error of ±0.1mm, a description of the apparatus including components and its setup and usage is reproduced in *Appendix 6* from Clemmens et al. (2001).

The apparatus used has a depth sensing pipe to be placed in the water near the depth gaging location, a cup that acts as a stilling well, a tube connecting the sensing pipe and cup, a point gage, and support beam to span the canal. During measurement the rigid support beam is placed across the canal and both the point gage and the cup were attached to it. The sensing pipe was placed in the stream with its rounded nose pointing directly into the direction of the flow. Readings were taken with the point gage resting on the flume throat at the control section. The point gage is then raised sufficiently high so that the cup can be placed below the point gage. The cup was then lowered below the flowing water level to purge air in the transparent hose connecting the cup and sensing pipe. Cup was raised above the flowing water level and water level in the cup is allowed to stabilize. Then the point gage was lowered to touch the water level in the cup and readings were taken. Repeated readings were taken as a check. The difference between the two readings represent the sill referenced upstream depth, which is then used to determine the corresponding discharge from the rating table.

The experience gained in this exercise showed that in the relatively larger canals of the Yuma Mesa, perhaps installing flumes while water is running in the canal may be highly inconvenient and can lead to incorrect installations – such as a nonlevel flume crest. Hence, flumes need to be installed in dry canals. In addition, accurate field test of the structure may require allowing a longer time for water level in the cup to stabilize and monitoring flow conditions upstream of the turnout during the time of the field test. In general, a comparison of discharge measured with the three flumes showed that flumes are inexpensive, easy to construct, and accurate flow measuring devices for irrigation canals.

Yuma Evaluation: The three flumes (1.0ft, 1.25ft, and 1.5ft sill height, *Table 7* and *Appendices 7-9*) were constructed from structural grade plastic-lumber in accord with the construction specifications (Figures 7.2 and 7.3 for 1.0ft sill height, Figures 8.2 and 8.3 for 1.25ft sill height, and Figures 9.2 and 9.3 for 1.5ft sill height). The flumes were installed in a dry canal at three selected sites along the field supply canal of the University of Arizona Yuma Mesa research farm approximately 300ft apart. They were arranged in such order: the 1.5ft sill flume is placed at about 600ft from the inlet end of the canal, the 1.0ft sill height flume is at the downstream most measurement section and the 1.25ft sill height flume was placed mid-way between these two flumes. The dimensions of the canal are summarized in Table 2. The canal is closed at the downstream end and during discharge measurement a basin is irrigated (a sluice gate is opened). For each of the test flumes upstream head was measured using a point gage apparatus (*Appendix 6*). In all the three flumes modular flow conditions were established and actual free board was sufficiently large.

A discharge of *16cfs* and *22cfs* (measured with an existing built-in flume located at the off-stake form the main canal) is delivered to the inlet of the field supply canal. 16cfs is about the most commonly used discharge in the irrigated farms in the area, whereas 22cfs represents a value close to the maximum field supply canal discharge used in the Yuma Mesa irrigation districts. The discharges measured with the 1.5ft sill height flume, at a section about 600ft from the canal off-take, are *15.2cfs* and *20.5cfs* compared, respectively, to the *16cfs* and *22cf* measured at the canal inlet with the built-in flume. These represent absolute relative differences (with respect to measurements with the built-in flume) of 5.0% and 7.3%. In addition, corresponding to a discharge reading of *15cfs* at the built-in flume (off-take from the main canal), the measured discharge with the 1.25ft and 1.0ft sill height flumes are *14.9cfs* and *13.8cfs*, respectively. These are equivalent to relative differences of 0.67% for the 1.25ft sill height flume and 8.0% for the 1.0ft sill height flume. The observed relative difference between the measurements at the head end of the canal and the test flumes is at most 8.0%. In all cases, measured discharges are larger for the built-in flume relative to the three test flumes. This suggests the existence of systematic error. Moreover, the smallest discharge reading (*13.8cfs*) was obtained with the 1.0ft sill height flume, which was placed at the most downstream flow measurement section. The corresponding discharge measured with the 1.25ft sill flume (located at a distance of about 300ft upstream from the most downstream flow measurement point) is *14.9cfs*. The decreasing trend in discharge measurement along the canal in the direction of flow may suggest that small leakage losses (through closed gates to individual basins), may partially account for some of the differences in measurements. In general various sources may account for the observed differences: (1) since readings in the built-in and test flumes were not simultaneous, flow delivered to the head end of the field supply canal may fluctuate in response to various factors upstream of the off-take from the main canal, (2) Given that the flume is more than a decade old, there may be systematic errors in the built-in flume that have to do with some minor maintenance needs, (3) relatively small (perhaps minor) leakage through the sluice gates may have contributed to the observed differences in discharge measurements. Considering these factors, the observed differences between the discharges measured by the built-in flume and the test flumes are deemed acceptable.

Due to imprecision in the construction and installation of flumes, actual flume dimensions and settings may differ from design recommendations, hence post-construction evaluation and often calibration is necessary. To conduct recalibration of the structure with WinFlume, as-built dimensions, cross-section shapes, and other pertinent properties of the flume and the canal as well as the range of head/discharge need to be specified. WinFlume will then generate the rating table for the structure in as-built condition. However, in the flume evaluations in the Yuma Mesa UA farm, the flumes were constructed to design specifications and appropriately placed in the field supply canal, hence new calibrations were not needed. The procedure for as-built calibration of flumes is described in chapter six of an accompanying document: "A guideline for the selection and installation of irrigation field supply canal flow measuring flumes in the Yuma Mesa Irrigation Districts"

5.6. Design and installation of gages

The flumes presented in this report are used along with a direct read-out gage mounted on the sides of the canal and labeled directly with discharge (in place of the sill referenced upstream depth) to measure canal discharges. WinFlume can be used to design the wall gage taking into account the side slope of the canal on which the gage is to be placed. For details see discussion on *Appendix 2*.

Accurate zero-setting of the staff gage is necessary to minimize systematic error. The following procedure for installing the gaging station is reproduced from Clemmens et al. (2001) with slight modification:

1. Determine the location of the gaging station in accord with specifications in Figure 3a.
2. Using surveyor's level take a back sight on a selected benchmark. The benchmark can be any relatively permanent feature around the site of installation of the

structure and its elevation can be assumed or measured. By adding the back sight to the elevation of the benchmark, the elevation of the line of sight is calculated.

3. Take a foresight at the sill crest to determine the elevation of the sill crest.
4. Determine the most common discharge, Q, to be measured by the flume and read the corresponding h_1 value from the appropriate rating table.
5. Subtract h_1 from the foresight reading taken at the sill crest to find the reading on the leveling rod if it were to be placed on the mark for h_1, or corresponding Q, value on the scale.
6. Place the gage on the sidewall at the correct location (Figure 3a).
7. Place the leveling staff on the side wall next to the gage and slide it slowly up and down the wall until the reading in the leveling staff equals the difference between the foresight taken at the sill crest and h_1.
8. Slide the gage such that the mark for the most common discharge is aligned with the leveling staff.
9. Mark the gage holes or slots and the gage top and bottom on the side wall. Drill the holes, secure the anchors, and tentatively attach the gage to the canal wall. Check the rod reading on the gage and if necessary adjust the gage to correct location and fasten securely.

Chapter 6. Summary

In this study, the long-throated flume (widely used to measure flow in irrigation canals) is selected for use in the Yuma Mesa irrigation districts. These flumes are inexpensive and accurate, but also simple to construct and use. Given their flexibility in terms of meeting geometric and head loss requirements under a wide range of conditions, they are ideal for use in situations where existing irrigation canals are to be retrofitted with flow measuring structures. Because of these advantages these structures are used in parts of the Yuma Mesa irrigation districts and this study is aimed at expanding their availability by providing predesigned alternatives for a canal geometry and hydraulic characteristics typical of the Yuma Mesa irrigation districts.

The construction material selected for use is structural grade plastic-lumber. Structural grade plastic lumber is inexpensive (material cost per structure in the Yuma

Mesa field supply canals is only about $50.0) and strong enough to stand the weight of the water, given appropriate reinforcements. Since the structure in field supply canals are to be used only intermittently (once a week for a few hours during the spring-summer months and once in two to three weeks during the fall-winter months) deterioration of the material through inundation is not expected to be significant. In addition, given the light weight of plastic lumber, the flumes made from plastic-lumber are highly portable.

The design of the alternative flumes presented in these report is based on the design procedure and criteria on which the WinFlume program (Clemmens et al., 2001) is based. The starting point is the precomputed flumes provided in Clemmens et al. (2001). Clemmens et al. (2001) presented precomputed flume selections for a range of standard canal dimensions and discharge ranges. In the precomputed designs of Clemmens et al. (2001) (Table 5.3), there are five flumes (flume sill heights of 0.75ft, 1.0ft, 1.25ft, 1.5ft, and 1.75ft) that match the canal geometry and discharge range of a typical irrigation field supply canal in the Yuma Mesa irrigation districts. In general, the precomputed flumes meet some of the design requirements, hence need to be evaluated either in field or using a model (or through a combination of both approaches) to ensure that all flume design and dimensional requirements are met under the specific set of hydraulic conditions in which the flumes are to be operated. In this study, an evaluation procedure that combines modeling and field evaluation was used. The results of the evaluations showed that, out of the five precomputed alternatives; three flumes with sill heights of 1.0ft, 1.25ft, and 1.5ft meet the requirements of modular flow, Froude number, minimum freeboard, and accuracy over the range of canal discharge typical of the Yuma Mesa Irrigations Districts.

Procedures for flume installation site selection, site survey, installation, and field evaluation and as-built calibration have been compiled in this report. In addition, an accompanying document presents a brief and simple description of the hydraulic theory of flow measurement with flumes, and a compilation of pertinent field procedures. This document is designed to be used as a guideline for irrigation technicians for flume installation site selection, evaluation, and as-built calibration of the flumes. An Excel worksheet is developed as a quick reference tool to facilitate the flume field evaluation, selection, and installation process. The excel worksheet can be used along with the field guideline document or as a stand alone tool. Field day was organized in November of 2009 in which irrigators in the Yuma and Imperial Valley were trained on the use of the flume selection, installation, and evaluation tools compiled as part of this project.

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Appendix 1. Field measurement guidelines

(i) Profile survey

- Equipment needed: (surveyor's level, measuring tape, and chalk)
- Determine the points, along the center line of canal, at which elevation readings are to be taken and mark the points with a chalk or a marker, etc.
- Setup surveyor's level in working order, if possible at a point where all readings can be taken from the same point.
- Take a back sight reading from a bench mark and calculate elevation of line of sight as the sum of the elevation of bench mark and back sight reading. Bench mark can be any relatively permanent feature near the potential flume installation site with an assumed or measured elevation.
- At each of the points along the center line of the canal take a foresight reading and determine the elevation of the point by subtracting the foresight reading from the elevation of the line of sight.
- If at some point during the survey it becomes necessary to move the instrument to continue the survey, the following steps are to be followed to determine the new height of instrument:
    - Setup the instrument in a suitable location.
    - Take a back sight reading in one of the points whose elevation has already been determined and use that reading to determine the new elevation of the line of sight.
    - Complete the remaining survey by taking foresight readings at each of the remaining points and subtracting them from the elevation of the line of sight.

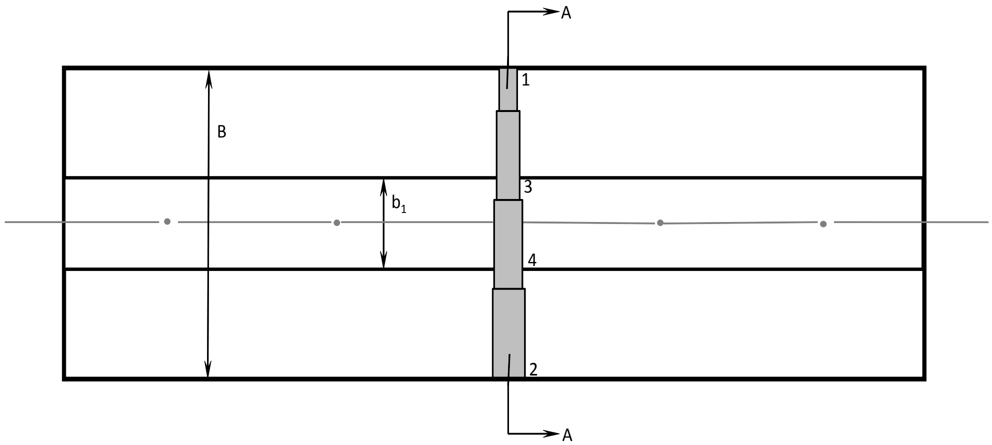
(ii) Measurement of canal dimensions

- Materials and equipment required (surveyor's level, leveling staff/rod, plum-bob, measuring tape, chalk/marker, spirit level, a relatively wide telescopic rod).
- Use a suitable equipment to establish the cross-section at which measurements of canal dimensions are to be made. Make sure that measurements are made on a section that is perpendicular to the center line of the canal. A simple field approach is outlined here:

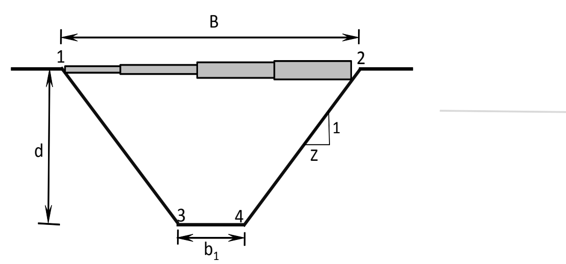
- Hold a telescopic rod (which can be a leveling rod, if available) across the width of the canal (Figures 1.1a and 1.1b). Assuming the rod is sufficiently wide it fits into the canal only if it is placed perpendicular to the center line of the canal.
- Use a spirit level to ensure that the telescopic rod is level and mark the end points on the edge of the canal (points 1 and 2, Figures 1.1a and 1.1b).
- Drop a plum-bob to locate two points (points 3 and 4, Figures 1.1a and 1.1b) on the cross-section and at the canal bottom and mark the two points.
- Measure canal top width (horizontal distance between points 1 and 2) and canal bottom width (distance between points 3 and 4) with a measuring tape (Figures 1.1a and 1.1b).

- Depth measurements can be made using surveyors level:
  - Set the surveyor's level in proper operational order.
  - Take a back sight on a bench mark.
  - Elevation of the line of sight is calculated as the sum of the back sight and elevation of bench mark from datum.
  - Move the leveling staff to one of the points (point 1 or 2, Figures 1.1a and 1.1b) on the edge of the canal at the selected canal cross-section and make sure that it is vertical.
  - Take a foresight reading and subtract it from the elevation of the line of sight to obtain the elevation of the point on the edge of the canal.
  - Move the leveling staff and set it in the canal bottom at the selected cross-section (on either point 3 or 4, Figures 1.1a and 1.1b) and take another foresight reading. Calculate the elevation of the canal bottom at the selected cross-section by subtracting the foresight reading from the elevation of the line of sight.
  - Canal depth is the difference between the elevation of the canal edge and the elevation of the canal bottom at the selected cross-section.

Note that it is assumed here that there is no differential settlement between the two sides of the canal and hence corresponding points on the two side walls of the canal are at the same elevation.



(a)



(b)

Figure 1.1 A sketch of field method for determining the canal cross-section at which canal dimensions are to be measured with a telescopic rod: (a) Plan view and (b) Cross-section along A-A

(iii) Determine side slope as the ratio of half the difference between canal top width and bottom width to canal depth.

(iv) Indirect flow measuring devices generally use what is known as the velocity area method: measure velocity and multiply it by the flow cross-sectional area to determine corresponding discharge.

- Flow velocities vary over a cross-section. Hence, to determine an average velocity for a cross-section, measurements of velocity need to be made at a number of points in the cross-section and averaged over the cross-sectional area.

- There are also calibration errors, which may generally be smaller at high flows and larger at low flows. To minimize calibration errors, it is advisable to make a couple of average velocity measurements over a cross-section.
- Hence, the average velocity in a cross-section is the average of the average cross-sectional velocities determined in a couple of measurements.

Appendix 2. A brief introduction to the WinFlume program

WinFlume is public domain computer program developed, through years of collaborative efforts, by the United States Department of Agriculture Water Conservation Laboratory, Phoenix; the United States Bureau of Reclamation, Denver; and the International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. Detailed description of the program, availability, theoretical basis, and usage of program in design, calibration, and evaluation of long-throated flumes (broad crested weirs) is provided by Clemmens et al. (2001).

WinFlume has a well developed Graphical User Interface. When starting the WinFlume program the menu bar contains three commands: *File*, *Options*, and *Help*. The *Help* command provides the access to help info on WinFlume capabilities, definition and description of technical terms, etc. With the *Options* menu item the user can specify the units for variables, user name, and select default options for display of water surface profiles and program settings. In general, design of flumes with WinFlume begins by making selections, using the *File* command, whether a new flume is to be designed, or a flume definition file from a previous WinFlume session is to be loaded for refinement/ modification, or a file created with earlier version of WinFlume (Flume 3.0) is to be opened for modification. The selection of any one of these three options from the pull-down menu under the *File* command leads (skipping a few steps) to the main design window with three smaller widows, displaying:

(1) The upper half of the window shows the bottom profile along the center line of the canal, between the approach and the tailwater sections. This window can be used to edit the dimensions of the various sections of the flume: the length of the approach section (L_a), the length of the converging transition (L_b), and length of the flume crest (L), length of downstream diverging transition, flume sill height, and canal depth.

(2) The window in the lower left-hand quarter displays cross-sections at the gaging station, control section, and tailwater section. This window can be used to edit the cross-sectional dimensions at the gaging station, control section, and tailwater section.

(3) The window on the lower right hand corner provides the elevation view of the control section from the upstream and downstream ends of the flume and a brief design report based on the six design criteria.

In this window, the menu bar provides three more menu commands in addition to the three described above: *Flume&Canal*, *Design*, and *Reports/Graphs*. With the pull-down menu under the menu option *Flume&Canal*, the user can access the option *Flume Properties&Canal Data*. Selection of this menu item opens a tabbed dialog box that allows the specification of flume crest type, construction material, and related hydraulic roughness properties. In addition, this dialog box allows the user to select the range of discharge to be measured by the flume, the option for characterizing tailwater from the five alternatives available in WinFlume, and to specify the pertinent input data on flow depth and discharge.

Selection of the menu command *Design* opens a pull-down menu with a couple of menu items, including:

Site Selection Tips, which provides brief descriptions of criteria to be considered in the selection of an appropriate site for flume installation;

Flume Wizard, this option provides access to a dialog box that guides the user through a step-by-step input of the data on canal and flume properties data and design requirements;

Flume Properties, Canal Data, &Design Requirements: The option provides access through a tabbed dialog box to four windows in which the user can specify: (1) flume crest type, construction material, and related hydraulic roughness properties, (2) the range of discharge to be measured by the flume, the option for characterizing tailwater from the five alternatives available in WinFlume, and the pertinent input data on flow depth and discharge, (3) the sill-referenced upstream head measurement method, related uncertainty, and allowable flow measurement uncertainty, and (4) freeboard requirements.

Review of Current Design: This option allows review of current design for the specific flume definition. The report contains a comparison of design requirements and actual conditions for the six design criteria described in the preceding sections. It also contains a summary of the input data.

Evaluate Alternative Designs: This option provides access to a dialog box in which an evaluation report on a range of control section sizes and corresponding flow conditions using the design criteria described in preceding sections.

Selection of the third menu command, *Reports/Graphs*, in the menu bar leads to a pull-down menu with the options: *Rating Tables & Graphs*, *Rating Equations*, *Wall Gage*, *Flume Data Report*, *Flume Drawing Printout*, and *Copy Flume Drawing to Clipboard*. Clicking on the option *Rating Tables & Graphs* leads to a tabbed dialog box that can be used to view rating tables. Selection of the option *Rating Equations* opens another tabbed dialog box that provides access to rating equation, rating table, and rating curve.

The menu option *Wall Gage* provides access to wall gage data report which is a rating table that takes into account the canal side slope on which the gage is installed. It also provides access to wall gage design capability of WinFlume to generate a full-scale wall gage paper, labeled with depth or discharge, for use in the construction of the gage. The following procedure is to be used to design a full-scale wall gage paper that can be used to construct the actual wall gage from steel, or aluminum, or baked enamel:

1. Selecting the menu option *Wall Gage* opens a tabbed dialog box with three tabs: *Options*, *Wall Gage Data*, and *Wall Gage Plots*
2. In the *Options* tab, the depth and discharge range expected to be measured can be specified, selection can be made whether gage is referenced from flume sill or upstream channel bottom, and the side slope of the canal can be set.
3. The *Wall Gage Data* tab provides the rating table with vertical gage and with a gage laid on the canal wall (taking into account the side slope).
4. The *Wall Gage Plots* tab provides access to the WinFlume functionality for designing a full-scale wall gage paper with head or discharge labels. In this study, the wall gage paper is to be labeled directly with discharge. There are options to specify the size of thick marks on the gage, the font size, label spacing, decimal places to show on the gage. In addition, the specific printer that is to be used to printout the wall gage paper need to be calibrated. To do so, click on the option *Calibrate Printer* and print a trial page. The test line on the print out should be 24cm long, if not specify the actual measurement in centimeters and WinFlume calculates a *Scale Ratio* to be used to calibrate the printer. Figure 2.1 shows wall gage paper printed in three segments, which can be used to construct the actual wall gage from an appropriate material.

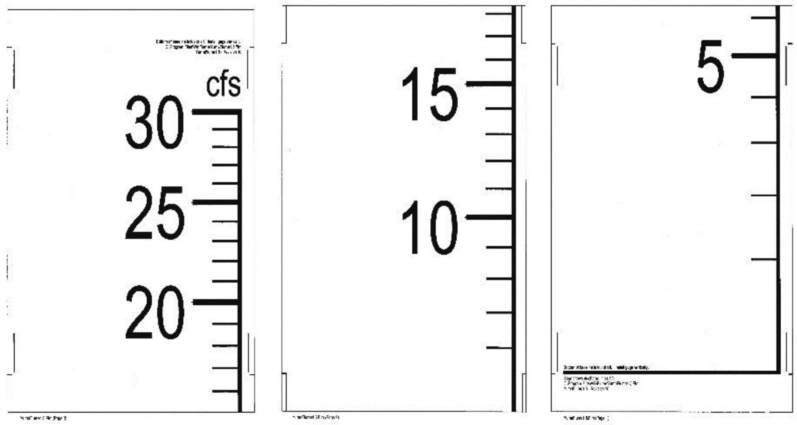


Figure 2.1. Example wall gage paper printed in three segments

Selection of the menu option *Flume Data Report* from the *Reports/Graphs* menu opens a tabbed dialog box that provides access to the WinFlume design report for the specific flume definition. The report contains a comparison of design requirements and actual conditions for the six design criteria described in the preceding sections. It also contains a summary of the input data. The menu options *Flume Drawing Printout* and *Copy Flume Drawing to Clipboard* allows printing flume drawings to disk or to printer or to copy to clipboard so that it can be copied to a design report (for instance an MS WORD document).

Appendix 3. Flume design summary (WinFlume) - Flume type E_e (sill height 1.0ft, Table 3)

Table 3.1 FLUME DATA REPORT

GENERAL DATA ON FLUME
Type of structure: Stationary Crest
Type of lining: Concrete - smooth [custom]
Roughness height of flume: 0.000492 ft

BOTTOM PROFILE DATA
Length per section: Approach section, La = 3.000 ft
Converging transition, Lb = 3.000 ft
Control section, L = 2.100 ft
Diverging transition, Ld = 0.000 ft

Vertical dimensions: Upstream channel depth = 3.000 ft
Height of sill, p1 = 1.000 ft
Bed drop = 0.000 ft
Diverging transition = Abrupt Expansion

-- APPROACH SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

-- CONTROL SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 4.000 ft
Side slopes = 1.00:1

-- TAILWATER SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

Table 3.2 SUMMARY EVALUATION OF FLUME DESIGN

Design is acceptable.

EVALUATION OF FLUME DESIGN FOR EACH DESIGN REQUIREMENT

Ok. Froude number at Qmax = 0.367 Maximum allowed = 0.500

Ok. Freeboard at Qmax = 0.710 ft Minimum allowed = 0.258 ft

Ok. Tailwater at Qmax = 1.981 ft Maximum allowed = 2.160 ft
Submergence Protection at Qmax = 0.179 ft

Ok. Tailwater at Qmin = 1.019 ft Maximum allowed = 1.516 ft
Submergence Protection at Qmin = 0.497 ft

Ok. Head at Qmax = 1.290 ft Minimum for accuracy = 0.843 ft
Expected discharge measurement uncertainty at Qmax = ±3.57 %

Ok. Head at Qmin = 0.623 ft Minimum for accuracy = 0.473 ft
Expected discharge measurement uncertainty at Qmin = ±6.20 %

CONTROL SECTION DATA

Section shape = SIMPLE TRAPEZOID
Bottom width = 4.000 ft
Side slopes = 1.00:1
Sill Height, p1 = 1.000 ft

DESIGN CRITERIA

Structure Type: Stationary Crest
Freeboard design criterion: Freeboard >= 20% of upstream sill-referenced head
Allowable discharge measurement errors for a single measurement:
  At minimum discharge: ±8%
  At maximum discharge: ±5%
Head detection method: Staff gage in stilling well, Fr=0.5
  Expected measurement uncertainty = ±0.022966 ft
Design discharges and associated tailwater levels:
  Minimum discharge = 7.000 cu. ft/s Minimum tailwater depth = 1.019 ft
  Maximum discharge = 25.000 cu. ft/s Maximum tailwater depth = 1.981 ft
Tailwater calculation method: Manning's equation using one Q-y2 measurement
  Q = 16.000 cu. ft/s ---> y2 = 1.580 ft

ESTIMATED UNCERTAINTY OF TOTALIZED OR AVERAGED FLOW

With measurements made every 1 second, for a duration of 1 second,
the estimated uncertainty of totalized or averaged flow is ±4.1%

NOTE: The uncertainty given above is ONLY an estimate. It is most useful for making a comparative evaluation of competing design alternatives. The estimate assumes that there is a relatively uniform distribution of flows between Qmin and Qmax during the averaging period. If the distribution of flows is not relatively uniform, the uncertainty associated with one or a few large flows will dominate, negating most of the uncertainty improvement normally obtained through averaging and totalizing.

Table 3.3 Evaluation of alternative designs (WinFlume)

Flume dimensions		*Design criteria*						Head loss comment	Actual headloss	Actual Froude number at Q_{max}	Extra freeboard at Q_{max}	Submergence protection	Estimated random error at Q_{min} and Q_{max}
Sill height *(ft)*	Throat width *(ft)*	Froude number	Freeboard at Q_{max}	Tailwater		Accuracy							
				at Q_{max}	at Q_{min}	at Q_{max}	at Q_{min}		*(ft)*	*(-)*	*(ft)*	*(ft)*	*(%)*
0.747	3.494	OK	OK	OK	OK	OK	OK	Minimum	0.11	0.44	0.64	0.00	±6.60-12.20%
0.75	3.5	OK	OK	OK	OK	OK	OK	-	0.12	0.44	0.63	0.00	±6.60-12.21%
0.8	3.6	OK	OK	OK	OK	OK	OK	-	0.15	0.42	0.60	0.04	±6.63-12.32%
0.85	3.7	OK	OK	OK	OK	OK	OK	-	0.19	0.41	0.56	0.07	±6.66-12.43%
0.9	3.8	OK	OK	OK	OK	OK	OK	-	0.23	0.39	0.52	0.11	±6.68-12.54%
0.95	3.9	OK	OK	OK	OK	OK	OK	-	0.27	0.38	0.49	0.14	±6.71-12.66%
1.0	4.0	OK	OK	OK	OK	OK	OK	-	0.31	0.37	0.45	0.18	±6.74-12.78%
1.05	4.1	OK	OK	OK	OK	OK	OK	-	0.35	0.36	0.41	0.21	±6.77-12.90%
1.1	4.2	OK	OK	OK	OK	OK	OK	-	0.39	0.34	0.38	0.25	±6.81-13.02%
1.15	4.3	OK	OK	OK	OK	OK	OK	-	0.43	0.33	0.34	0.29	±6.84-13.14%
1.186	4.372	OK	OK	OK	OK	OK	OK	Intermediate	0.45	0.33	0.31	0.31	±6.87-13.23%
1.2	4.4	OK	OK	OK	OK	OK	OK	-	0.47	0.32	0.30	0.32	±6.88-13.27%
1.25	4.5	OK	OK	OK	OK	OK	OK	-	0.51	0.31	0.27	0.36	±6.91-13.39%
1.3	4.6	OK	OK	OK	OK	OK	OK	-	0.54	0.30	0.23	0.40	±6.95-13.52%
1.35	4.7	OK	OK	OK	OK	OK	OK	-	0.58	0.29	0.19	0.43	±6.98-13.64%
1.4	4.8	OK	OK	OK	OK	OK	OK	-	0.62	0.28	0.15	0.47	±7.02-13.77%
1.45	4.9	OK	OK	OK	OK	OK	OK	-	0.66	0.28	0.12	0.51	±7.06-13.90%
1.5	5.0	OK	OK	OK	OK	OK	OK	-	0.70	0.27	0.08	0.54	±7.10-14.02%
1.55	5.1	OK	OK	OK	OK	OK	OK	-	0.74	0.26	0.04	0.58	±7.14-14.15%
1.6	5.2	OK	OK	OK	OK	OK	OK	Maximum	0.78	0.25	0.0	0.62	±7.18-14.28%

Method of Contraction Change = Raise or Lower Sill Height, Evaluation Increment = 0.05, for sill height of 0.75ft and below the flume crest length need to be at least 2.12ft, and for flume sill height of 1.25ft and above converging section should at least be 3.13ft

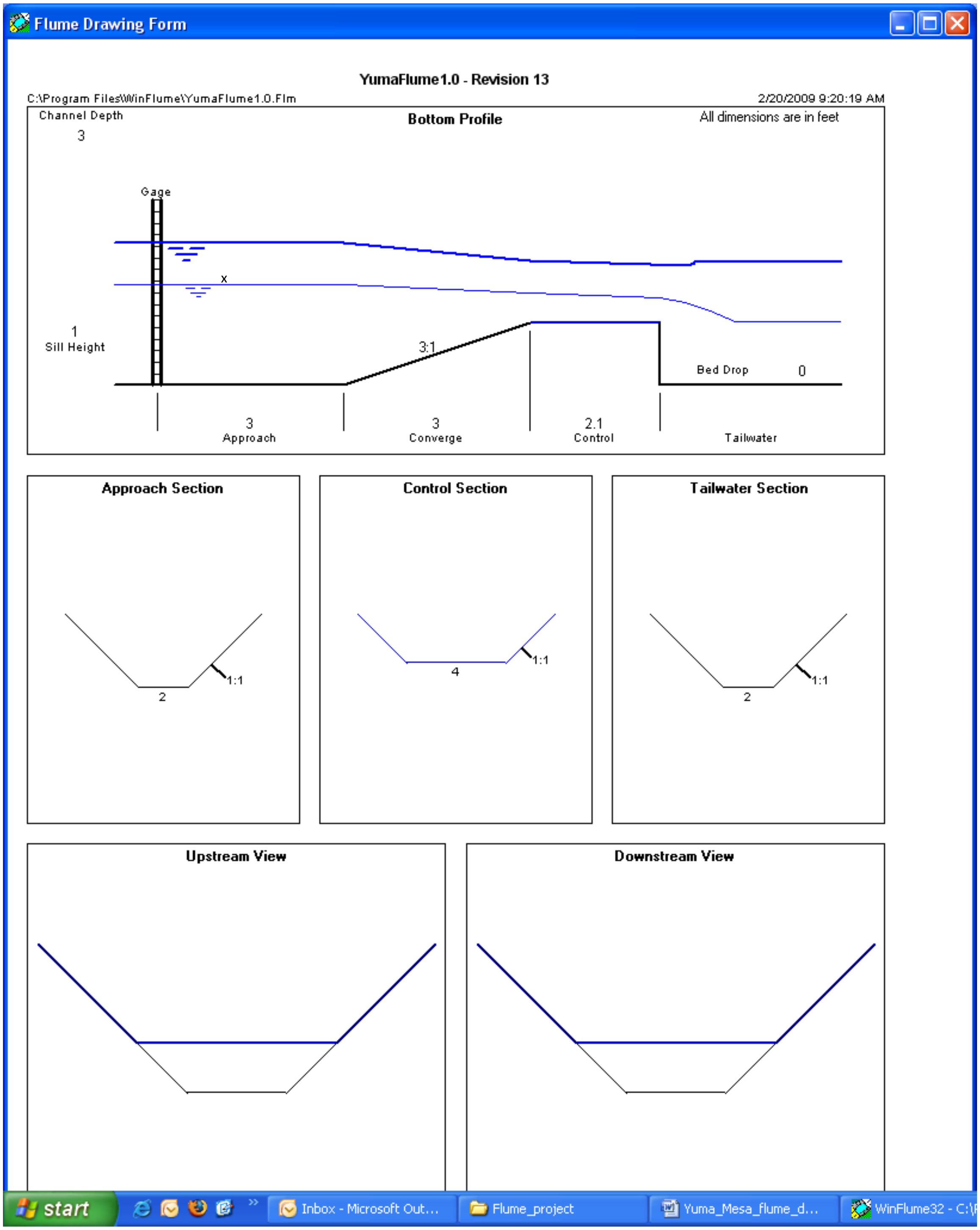


Figure 3.1 Flume bottom profile and cross-section dimensions for 1.0ft sill height - design

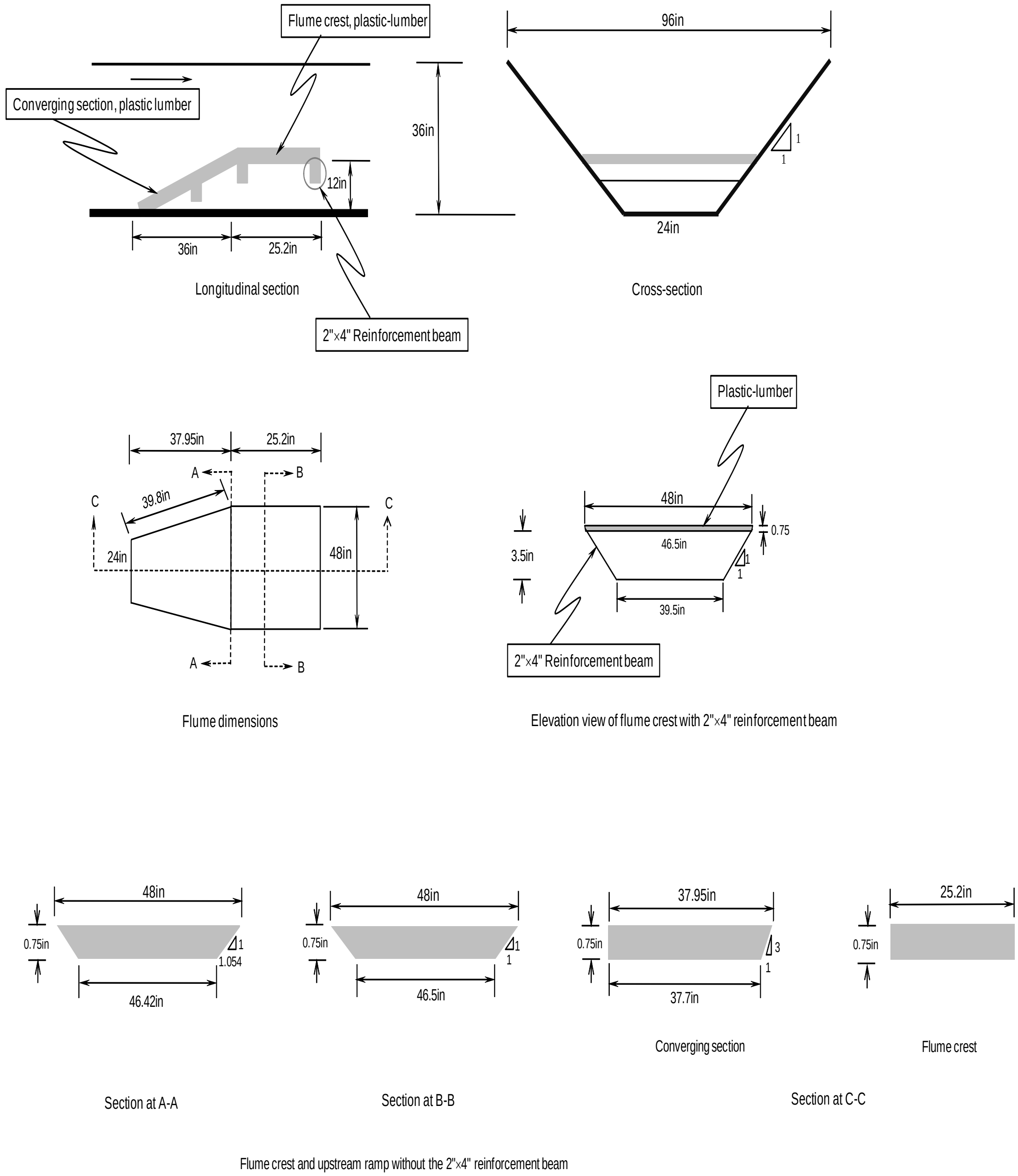


Figure 3.2 Flume design dimensions for 1.0ft sill height

Table 3.4 Rating table and equation for 1.0ft sill height – design dimensions

h1 Sill Referenced Head at Gage feet	Q Theoretical Discharge cu. ft/s	Q_fit Curve Fit Equation Discharge cu. ft/s	D=Q_fit-Q Difference cu. ft/s	(D/Q)*100% Difference %	Warnings
0.187	1.00	1.01	+0.010	+1.04	-
0.289	2.00	1.98	-0.023	-1.13	-
0.372	3.00	2.97	-0.033	-1.09	-
0.444	4.00	3.97	-0.030	-0.75	-
0.509	5.00	4.98	-0.020	-0.40	-
0.568	6.00	5.99	-0.006	-0.10	-
0.623	7.00	7.01	+0.009	+0.13	-
0.674	8.00	8.02	+0.024	+0.30	-
0.722	9.00	9.04	+0.038	+0.43	-
0.768	10.00	10.05	+0.051	+0.51	-
0.812	11.00	11.06	+0.062	+0.56	-
0.854	12.00	12.07	+0.070	+0.58	-
0.894	13.00	13.08	+0.075	+0.58	-
0.933	14.00	14.08	+0.080	+0.57	-
0.970	15.00	15.08	+0.080	+0.53	-
1.006	16.00	16.08	+0.077	+0.48	-
1.041	17.00	17.07	+0.070	+0.41	-
1.075	18.00	18.06	+0.061	+0.34	-
1.108	19.00	19.05	+0.049	+0.26	-
1.141	20.00	20.03	+0.033	+0.16	-
1.172	21.00	21.01	+0.014	+0.07	-
1.203	22.00	21.99	-0.008	-0.03	-
1.233	23.00	22.97	-0.032	-0.14	-
1.262	24.00	23.94	-0.060	-0.25	-
1.290	25.00	24.91	-0.091	-0.37	-
1.319	26.00	25.87	-0.125	-0.48	-
1.346	27.00	26.84	-0.162	-0.60	-
1.373	28.00	27.80	-0.202	-0.72	6
1.400	29.00	28.76	-0.245	-0.84	6

Equation: Q_fit = K1 * (h1 + K2) ^ u
Parameters: K1 = 14.67, K2 = 0.04524, u = 1.830, Coefficient of determination: 0.99995471

Theoretical discharge (Q) is determined by the WinFlume model, using hydraulic theory and empirical relationships determined from laboratory testing. It is the most accurate estimate of discharge. Curve fit discharge (Q_fit) is computed with the equation above, which was fitted to the theoretical discharge values. The 'difference' columns show the difference between the flow rates computed from the simplified equation and those obtained from the theoretical WinFlume model.

Summary of Warning Messages

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6 - Upstream energy head / control section length exceeds 0.7.

Appendix 4 Flume design summary (WinFlume) - Flume type F_e (sill height 1.25ft, Table 3)

Table 4.1 FLUME DATA REPORT

GENERAL DATA ON FLUME
Type of structure: Stationary Crest
Type of lining: Concrete - smooth [custom]
Roughness height of flume: 0.000492 ft

BOTTOM PROFILE DATA
Length per section: Approach section, La = 3.000 ft
Converging transition, Lb = 3.750 ft
Control section, L = 2.000 ft
Diverging transition, Ld = 0.000 ft

Vertical dimensions: Upstream channel depth = 3.000 ft
Height of sill, p1 = 1.250 ft
Bed drop = 0.000 ft
Diverging transition = Abrupt Expansion

-- APPROACH SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

-- CONTROL SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 4.500 ft
Side slopes = 1.00:1

-- TAILWATER SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

Table 4.2 SUMMARY EVALUATION OF FLUME DESIGN

Design is acceptable.

EVALUATION OF FLUME DESIGN FOR EACH DESIGN REQUIREMENT

Ok. Froude number at Qmax = 0.312 Maximum allowed = 0.500

Ok. Freeboard at Qmax = 0.514 ft Minimum allowed = 0.247 ft

Ok. Tailwater at Qmax = 1.981 ft Maximum allowed = 2.340 ft
Submergence Protection at Qmax = 0.359 ft

Ok. Tailwater at Qmin = 1.019 ft Maximum allowed = 1.723 ft
Submergence Protection at Qmin = 0.704 ft

Ok. Head at Qmax = 1.236 ft Minimum for accuracy = 0.829 ft
Expected discharge measurement uncertainty at Qmax = ±3.64 %

Ok. Head at Qmin = 0.588 ft Minimum for accuracy = 0.468 ft
Expected discharge measurement uncertainty at Qmin = ±6.47 %

CONTROL SECTION DATA

Section shape = SIMPLE TRAPEZOID
Bottom width = 4.500 ft
Side slopes = 1.00:1
Sill Height, p1 = 1.250 ft

DESIGN CRITERIA

Structure Type: Stationary Crest
Freeboard design criterion: Freeboard >= 20% of upstream sill-referenced head
Allowable discharge measurement errors for a single measurement:
At minimum discharge: ±8%
At maximum discharge: ±5%
Head detection method: Staff gage in stilling well, Fr=0.5
Expected measurement uncertainty = ±0.022966 ft
Design discharges and associated tailwater levels:
Minimum discharge = 7.000 cu. ft/s Minimum tailwater depth = 1.019 ft
Maximum discharge = 25.000 cu. ft/s Maximum tailwater depth = 1.981 ft
Tailwater calculation method: Manning's equation using one Q-y2 measurement
Q = 16.000 cu. ft/s ---> y2 = 1.580 ft

ESTIMATED UNCERTAINTY OF TOTALIZED OR AVERAGED FLOW

With measurements made every 1 second, for a duration of 1 second,
the estimated uncertainty of totalized or averaged flow is ±4.3%

NOTE: The uncertainty given above is ONLY an estimate. It is most useful for making a comparative evaluation of competing design alternatives. The estimate assumes that there is a relatively uniform distribution of flows between Qmin and Qmax during the averaging period. If the distribution of flows is not relatively uniform, the uncertainty associated with one or a few large flows will dominate, negating most of the uncertainty improvement normally obtained through averaging and totalizing.

Table 4.3 Evaluation of alternative designs (WinFlume)

Flume dimensions		*Design criteria*						Head loss comment	Actual headloss	Actual Froude number at Q_{max}	Extra freeboard at Q_{max}	Submergence protection	Estimated random error at Q_{min} and Q_{max}
Sill height *(ft)*	Throat width *(ft)*	Froude number	Freeboard at Q_{max}	Tailwater at Q_{max}	Tailwater at Q_{min}	Accuracy at Q_{max}	Accuracy at Q_{min}		*(ft)*	*(-)*	*(ft)*	*(ft)*	*(%)*
0.747	3.494	OK	OK	OK	OK	OK	OK	Minimum	0.11	0.44	0.64	0.00	±6.60-12.21%
0.75	3.5	OK	OK	OK	OK	OK	OK	-	0.12	0.44	0.63	0.00	±6.60-12.21%
0.8	3.6	OK	OK	OK	OK	OK	OK	-	0.15	0.42	0.60	0.04	±6.63-12.32%
0.85	3.7	OK	OK	OK	OK	OK	OK	-	0.19	0.41	0.56	0.07	±6.66-12.43%
0.9	3.8	OK	OK	OK	OK	OK	OK	-	0.23	0.39	0.52	0.11	±6.68-12.55%
0.95	3.9	OK	OK	OK	OK	OK	OK	-	0.27	0.38	0.49	0.14	±6.71-12.66%
1.0	4.0	OK	OK	OK	OK	OK	OK	-	0.31	0.37	0.45	0.18	±6.74-12.78%
1.05	4.1	OK	OK	OK	OK	OK	OK	-	0.35	0.36	0.41	0.21	±6.77-12.90%
1.1	4.2	OK	OK	OK	OK	OK	OK	-	0.39	0.34	0.38	0.25	±6.81-13.02%
1.15	4.3	OK	OK	OK	OK	OK	OK	-	0.43	0.33	0.34	0.29	±6.84-13.14%
1.186	4.372	OK	OK	OK	OK	OK	OK	Intermediate	0.45	0.33	0.31	0.31	±6.87-13.23%
1.2	4.4	OK	OK	OK	OK	OK	OK	-	0.47	0.32	0.30	0.32	±6.88-13.27%
1.25	4.5	OK	OK	OK	OK	OK	OK	-	0.51	0.31	0.27	0.36	±6.91-13.39%
1.3	4.6	OK	OK	OK	OK	OK	OK	-	0.54	0.30	0.23	0.40	±6.95-13.52%
1.35	4.7	OK	OK	OK	OK	OK	OK	-	0.58	0.29	0.19	0.43	±6.98-13.64%
1.4	4.8	OK	OK	OK	OK	OK	OK	-	0.62	0.28	0.15	0.47	±7.02-13.77%
1.45	4.9	OK	OK	OK	OK	OK	OK	-	0.66	0.28	0.12	0.51	±7.06-13.90%
1.5	5.0	OK	OK	OK	OK	OK	OK	-	0.70	0.27	0.08	0.54	±7.10-14.03%
1.55	5.1	OK	OK	OK	OK	OK	OK	-	0.74	0.26	0.04	0.58	±7.14-14.15%
1.6	5.2	OK	OK	OK	OK	OK	OK	Maximum	0.78	0.25	0.0	0.62	±7.18-14.28%

Method of Contraction Change = Raise or Lower Sill Height, Evaluation Increment = 0.05, for sill height of 0.95ft and below flume crest length should be at least 2.02ft, for sill height of 1.55ft and above converging ramp length should be increased to at least 3.88ft

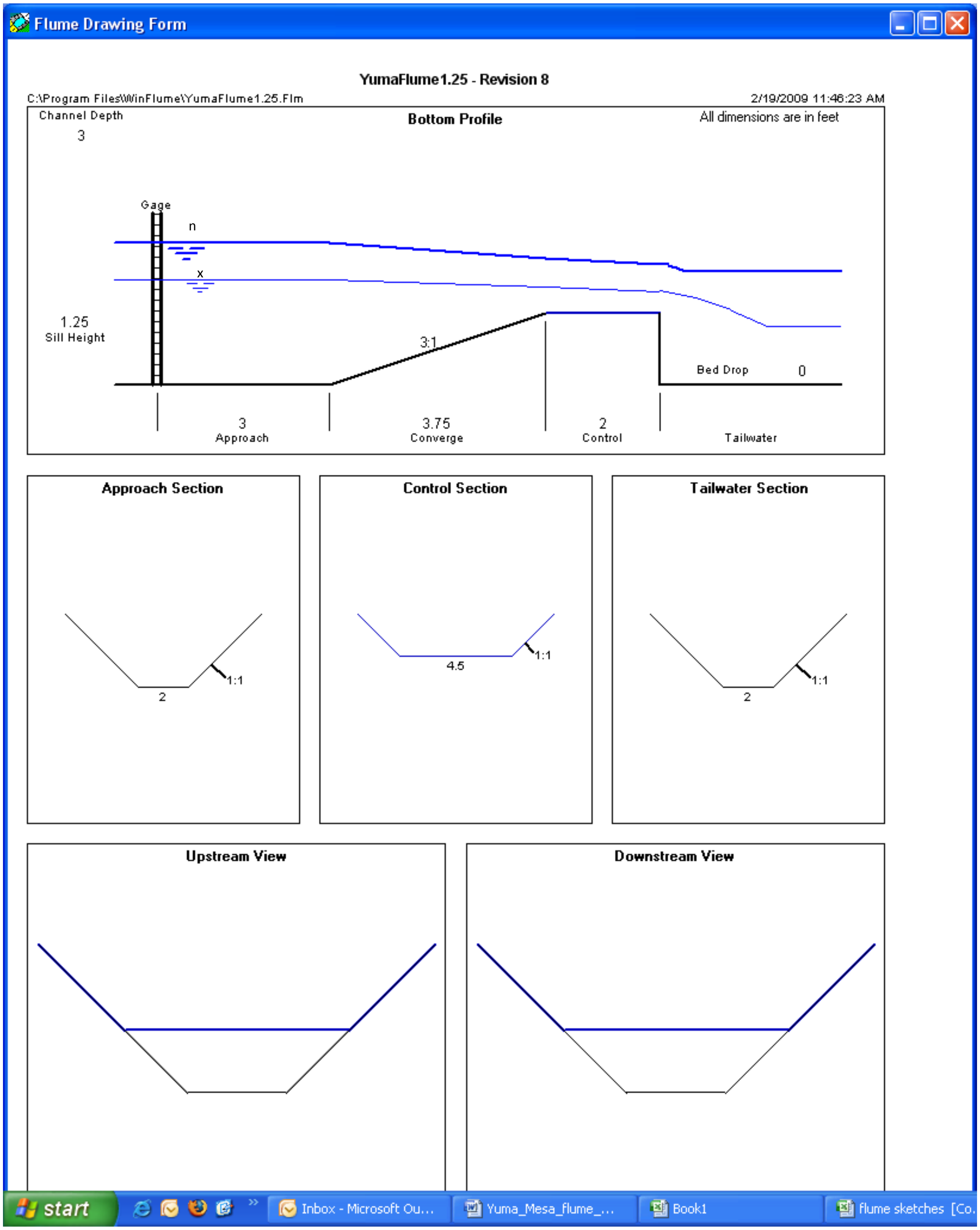

Figure 4.1 Flume bottom profile and cross-section dimensions for 1.25ft sill height -- design

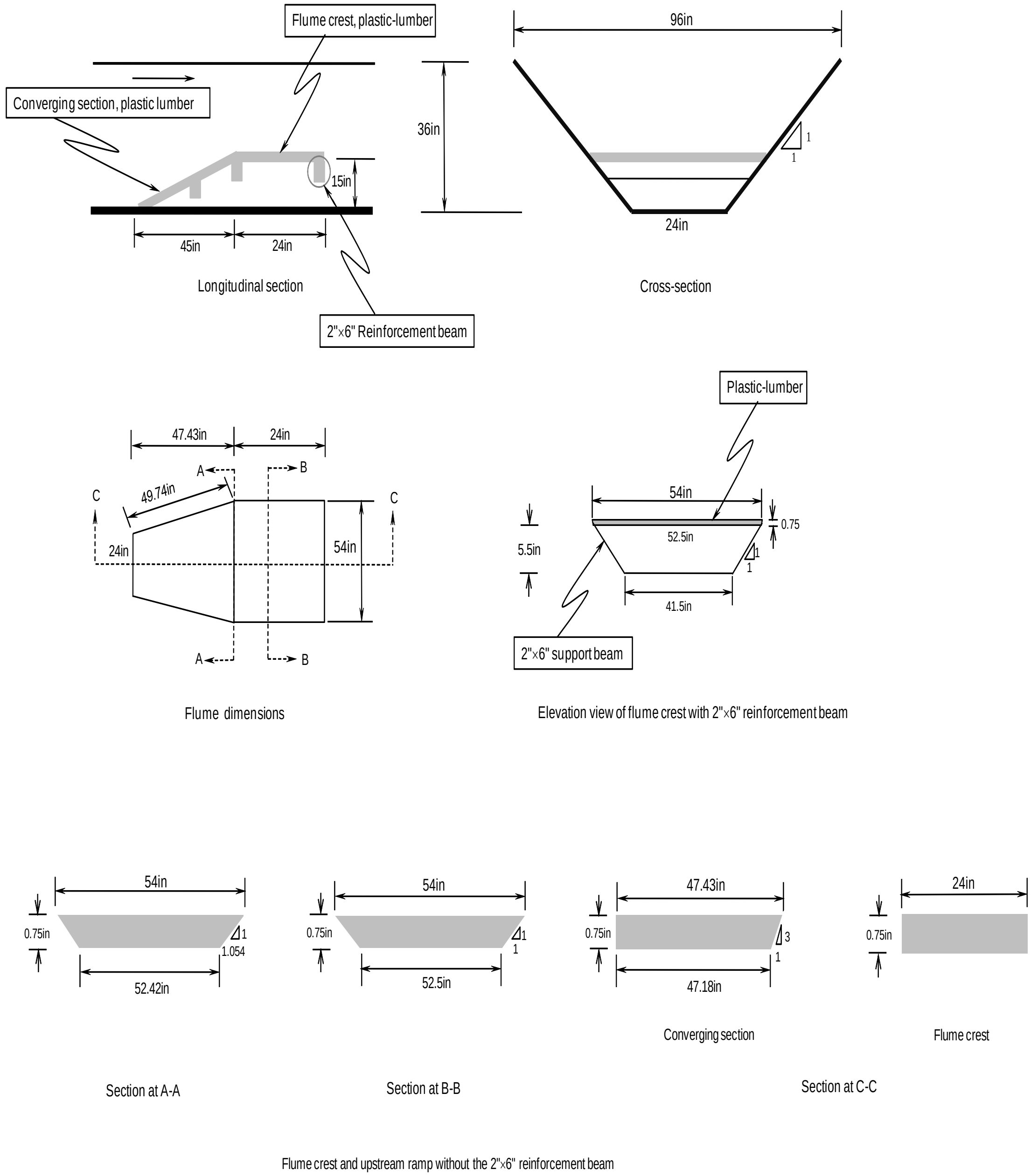

Figure 4.2 Flume design dimensions for 15in (1.25ft) sill height

Table 4.4 Rating table and equation for 1.25ft sill height - design dimensions

h_1 Sill Referenced Head at Gage feet	Q Curve Fit Theoretical Discharge cu. ft/s	Q_fit Equation Discharge cu. ft/s	D=Q_fit-Q Difference cu. ft/s	(D/Q)*100% Difference %	Warnings
0.174	1.00	1.01	+0.010	+1.04	-
0.270	2.00	1.98	-0.024	-1.18	-
0.349	3.00	2.97	-0.033	-1.10	-
0.417	4.00	3.97	-0.030	-0.75	-
0.479	5.00	4.98	-0.020	-0.40	-
0.535	6.00	5.99	-0.006	-0.10	-
0.588	7.00	7.01	+0.010	+0.14	-
0.637	8.00	8.03	+0.025	+0.32	-
0.684	9.00	9.04	+0.040	+0.44	-
0.728	10.00	10.05	+0.053	+0.53	-
0.770	11.00	11.06	+0.063	+0.58	-
0.811	12.00	12.07	+0.072	+0.60	-
0.850	13.00	13.08	+0.078	+0.60	-
0.887	14.00	14.08	+0.082	+0.59	-
0.924	15.00	15.08	+0.082	+0.55	-
0.959	16.00	16.08	+0.079	+0.49	-
0.993	17.00	17.07	+0.072	+0.42	-
1.026	18.00	18.06	+0.063	+0.35	-
1.058	19.00	19.05	+0.050	+0.26	-
1.090	20.00	20.03	+0.034	+0.17	-
1.121	21.00	21.01	+0.014	+0.07	-
1.150	22.00	21.99	-0.008	-0.04	-
1.180	23.00	22.97	-0.034	-0.15	-
1.208	24.00	23.94	-0.063	-0.26	-
1.236	25.00	24.91	-0.095	-0.38	-
1.264	26.00	25.87	-0.130	-0.50	-
1.291	27.00	26.83	-0.168	-0.62	-
1.317	28.00	27.79	-0.209	-0.75	6
1.343	29.00	28.75	-0.253	-0.87	6

Equation: Q_fit = K1 * (h1 + K2) ^ u
Parameters: K1 = 16.22, K2 = 0.03628, u = 1.779; Coefficient of determination: 0.99995257

Theoretical discharge (Q) is determined by the WinFlume model, using hydraulic theory and empirical relationships determined from laboratory testing. It is the most accurate estimate of discharge. Curve fit discharge (Q_fit) is computed with the equation above, which was fitted to the theoretical discharge values. The 'difference' columns show the difference between the flow rates computed from the simplified equation and those obtained from the theoretical WinFlume model.

Summary of Warning Messages

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6 - Upstream energy head / control section length exceeds 0.7.

Appendix 5 Flume design summary (WinFlume) - Flume type G_e (sill height 1.5ft, Table 3)

Table 5.1 FLUME DATA REPORT

GENERAL DATA ON FLUME
Type of structure: Stationary Crest
Type of lining: Concrete - smooth [custom]
Roughness height of flume: 0.000492 ft

BOTTOM PROFILE DATA
Length per section: Approach section, La = 3.000 ft
Converging transition, Lb = 4.500 ft
Control section, L = 2.000 ft
Diverging transition, Ld = 0.000 ft

Vertical dimensions: Upstream channel depth = 3.000 ft
Height of sill, p1 = 1.500 ft
Bed drop = 0.000 ft
Diverging transition = Abrupt Expansion

-- APPROACH SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

-- CONTROL SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 5.000 ft
Side slopes = 1.00:1

-- TAILWATER SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

Table 5.2 SUMMARY EVALUATION OF FLUME DESIGN –design dimensions

---

Design is acceptable.

EVALUATION OF FLUME DESIGN FOR EACH DESIGN REQUIREMENT

Ok. Froude number at Qmax = 0.268 Maximum allowed = 0.500

Ok. Freeboard at Qmax = 0.314 ft Minimum allowed = 0.237 ft

Ok. Tailwater at Qmax = 1.981 ft Maximum allowed = 2.526 ft
Submergence Protection at Qmax = 0.545 ft

Ok. Tailwater at Qmin = 1.019 ft Maximum allowed = 1.936 ft
Submergence Protection at Qmin = 0.916 ft

Ok. Head at Qmax = 1.186 ft Minimum for accuracy = 0.818 ft
Expected discharge measurement uncertainty at Qmax = ±3.71 %

Ok. Head at Qmin = 0.557 ft Minimum for accuracy = 0.464 ft
Expected discharge measurement uncertainty at Qmin = ±6.76 %

CONTROL SECTION DATA

Section shape = SIMPLE TRAPEZOID
Bottom width = 5.000 ft
Side slopes = 1.00:1
Sill Height, p1 = 1.500 ft

DESIGN CRITERIA

Structure Type: Stationary Crest
Freeboard design criterion: Freeboard >= 20% of upstream sill-referenced head
Allowable discharge measurement errors for a single measurement:
At minimum discharge: ±8%
At maximum discharge: ±5%
Head detection method: Staff gage in stilling well, Fr=0.5
Expected measurement uncertainty = ±0.022966 ft
Design discharges and associated tailwater levels:
Minimum discharge = 7.000 cu. ft/s Minimum tailwater depth = 1.019 ft
Maximum discharge = 25.000 cu. ft/s Maximum tailwater depth = 1.981 ft
Tailwater calculation method: Manning's equation using one Q-y2 measurement
Q = 16.000 cu. ft/s ---> y2 = 1.580 ft

ESTIMATED UNCERTAINTY OF TOTALIZED OR AVERAGED FLOW

With measurements made every 1 second, for a duration of 1 second,
the estimated uncertainty of totalized or averaged flow is ±4.4%

NOTE: The uncertainty given above is ONLY an estimate. It is most useful for making a comparative evaluation of competing design alternatives. The estimate assumes that there is a relatively uniform distribution of flows between Qmin and Qmax during the averaging period. If the distribution of flows is not relatively uniform, the uncertainty associated with one or a few large flows will dominate, negating most of the uncertainty improvement normally obtained through averaging and totalizing.

Table 5.3 Evaluation of alternative designs (WinFlume)

Flume dimensions		*Design criteria*						Head loss comment	Actual headloss *(ft)*	Actual Froude number at Q_{max} *(-)*	Extra freeboard at Q_{max} *(ft)*	Submergence protection *(ft)*	Estimated random error at Q_{min} and Q_{max} *(%)*
				Tailwater		Accuracy							
Sill height *(ft)*	Throat width *(ft)*	Froude number	Freeboard at Q_{max}	at Q_{max}	at Q_{min}	at Q_{max}	at Q_{min}						
0.747	3.494	OK	OK	OK	OK	OK	OK	Minimum	0.11	0.44	0.64	0.00	±6.60-12.20%
0.75	3.5	OK	OK	OK	OK	OK	OK	-	0.12	0.44	0.63	0.00	±6.60-12.21%
0.8	3.6	OK	OK	OK	OK	OK	OK	-	0.15	0.42	0.60	0.04	±6.63-12.31%
0.85	3.7	OK	OK	OK	OK	OK	OK	-	0.19	0.41	0.56	0.07	±6.65-12.43%
0.9	3.8	OK	OK	OK	OK	OK	OK	-	0.23	0.39	0.52	0.11	±6.68-12.43%
0.95	3.9	OK	OK	OK	OK	OK	OK	-	0.27	0.38	0.49	0.14	±6.71-12.66%
1.0	4.0	OK	OK	OK	OK	OK	OK	-	0.31	0.37	0.45	0.18	±6.74-12.77%
1.05	4.1	OK	OK	OK	OK	OK	OK	-	0.35	0.35	0.41	0.21	±6.77-12.89%
1.1	4.2	OK	OK	OK	OK	OK	OK	-	0.39	0.34	0.38	0.25	±6.81-13.02%
1.15	4.3	OK	OK	OK	OK	OK	OK	-	0.43	0.33	0.34	0.29	±6.84-13.14%
1.186	4.372	OK	OK	OK	OK	OK	OK	Intermediate	0.46	0.33	0.31	0.31	±6.86-13.23%
1.2	4.4	OK	OK	OK	OK	OK	OK	-	0.47	0.32	0.30	0.32	±6.87-13.26%
1.25	4.5	OK	OK	OK	OK	OK	OK	-	0.51	0.31	0.27	0.36	±6.91-13.39%
1.3	4.6	OK	OK	OK	OK	OK	OK	-	0.55	0.30	0.23	0.40	±6.95-13.51%
1.35	4.7	OK	OK	OK	OK	OK	OK	-	0.58	0.29	0.19	0.43	±6.98-13.64%
1.4	4.8	OK	OK	OK	OK	OK	OK	-	0.62	0.28	0.15	0.47	±7.02-13.76%
1.45	4.9	OK	OK	OK	OK	OK	OK	-	0.66	0.28	0.12	0.51	±7.06-13.89%
1.5	5.0	OK	OK	OK	OK	OK	OK	-	0.70	0.27	0.08	0.54	±7.10-14.02%
1.55	5.1	OK	OK	OK	OK	OK	OK	-	0.74	0.26	0.04	0.58	±7.14-14.15%
1.6	5.2	OK	OK	OK	OK	OK	OK	Maximum	0.78	0.25	0.0	0.62	±7.18-14.28%

Method of Contraction Change = Raise or Lower Sill Height, Evaluation Increment = 0.05, for sill height of 0.95ft and below, the flume crest length should at least be 2.02ft and converging section should not be longer than 4.28ft

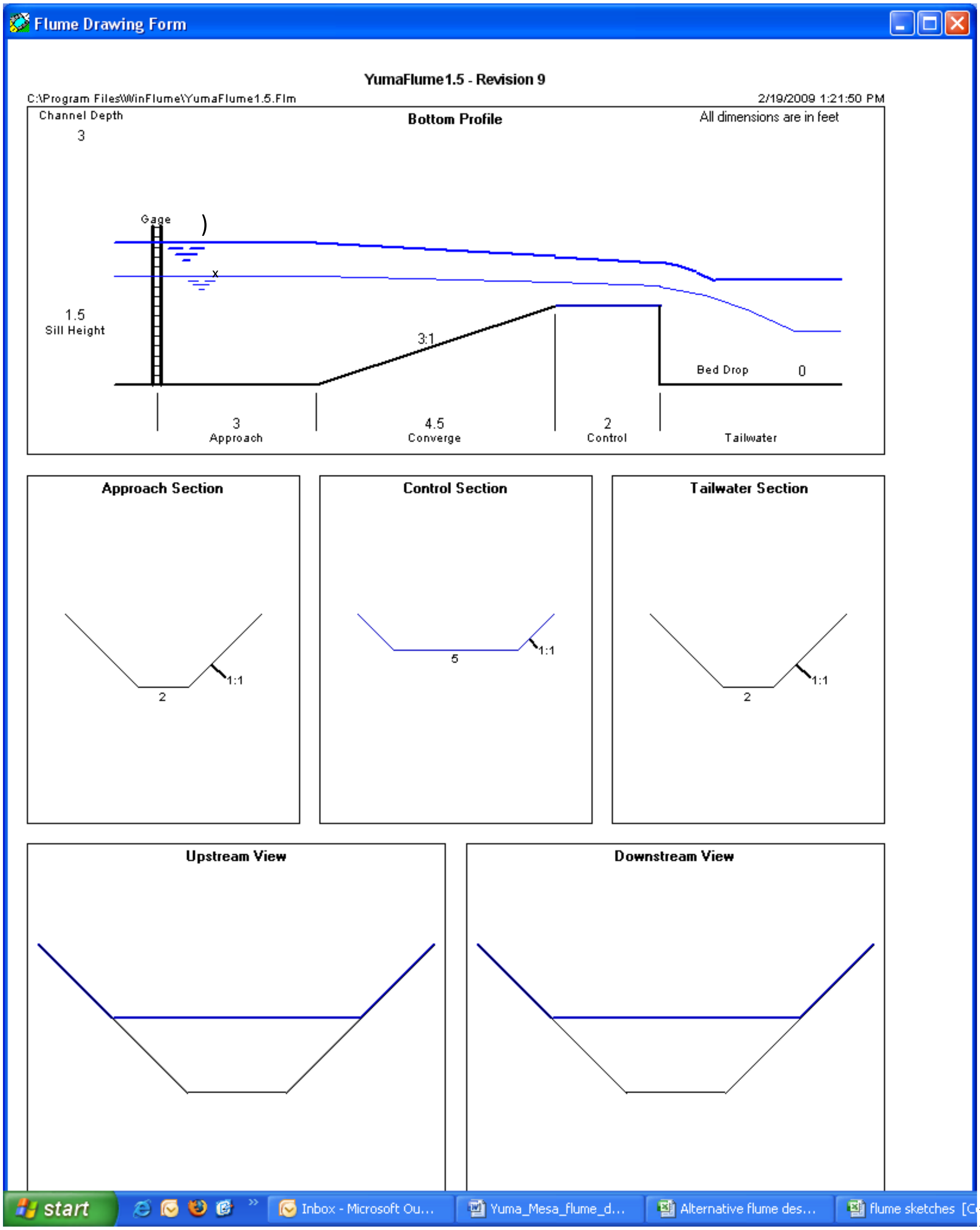

Figure 5.1 Flume bottom profile and cross-section dimensions for 1.5ft sill height – -- design

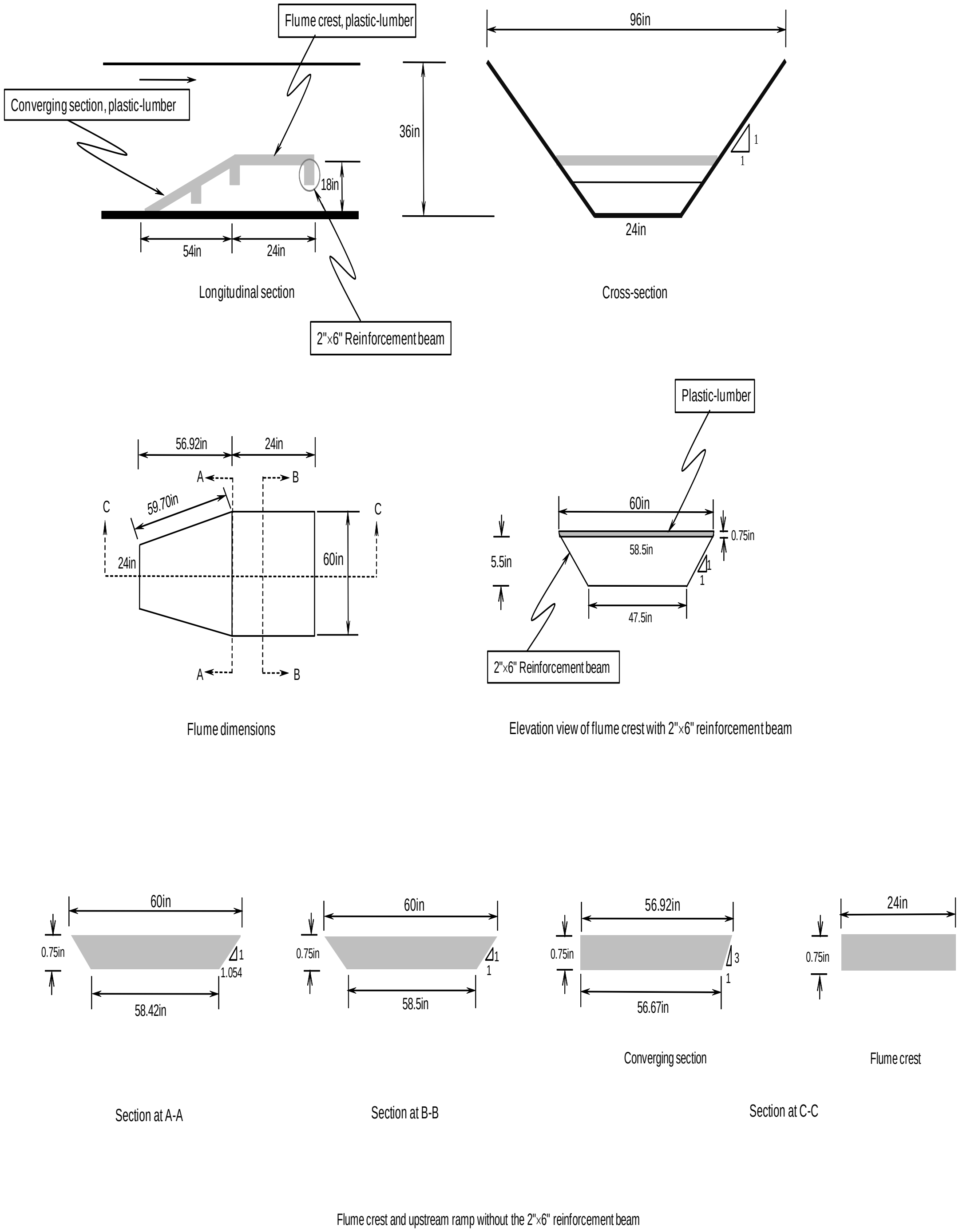

Figure 5.2 Flume design dimensions for 1.5ft sill height

Table 5.4 Rating table and equation (1.5ft sill height) – design dimensions

h_1 Sill Referenced Head at Gage feet	*Q* Theoretical Discharge cu. ft/s	*Q_fit* Curve Fit Equation Discharge cu. ft/s	*D=Q_fit-Q* Difference cu. ft/s	*(D/Q)*100%* Difference %	Warnings
0.163	1.00	1.01	+0.011	+1.08	-
0.254	2.00	1.98	-0.023	-1.14	-
0.328	3.00	2.97	-0.032	-1.07	-
0.393	4.00	3.97	-0.030	-0.74	-
0.452	5.00	4.98	-0.020	-0.41	-
0.506	6.00	5.99	-0.008	-0.13	-
0.557	7.00	7.01	+0.007	+0.10	-
0.604	8.00	8.02	+0.023	+0.29	-
0.649	9.00	9.04	+0.037	+0.41	-
0.692	10.00	10.05	+0.049	+0.49	-
0.732	11.00	11.06	+0.060	+0.55	-
0.772	12.00	12.07	+0.069	+0.57	-
0.809	13.00	13.07	+0.075	+0.57	-
0.846	14.00	14.08	+0.078	+0.56	-
0.881	15.00	15.08	+0.080	+0.53	-
0.915	16.00	16.08	+0.077	+0.48	-
0.948	17.00	17.07	+0.071	+0.42	-
0.981	18.00	18.06	+0.062	+0.35	-
1.012	19.00	19.05	+0.050	+0.26	-
1.043	20.00	20.03	+0.035	+0.17	-
1.072	21.00	21.02	+0.016	+0.08	-
1.102	22.00	21.99	-0.005	-0.02	-
1.130	23.00	22.97	-0.030	-0.13	-
1.158	24.00	23.94	-0.058	-0.24	-
1.186	25.00	24.91	-0.089	-0.36	-
1.212	26.00	25.88	-0.123	-0.47	-
1.239	27.00	26.84	-0.161	-0.59	-
1.265	28.00	27.80	-0.201	-0.72	-
1.290	29.00	28.76	-0.244	-0.84	-

Equation: Q_fit = K1 * (h1 + K2) ^ u
Parameters: K1 = 17.75, K2 = 0.02944, u = 1.740; Coefficient of determination: 0.99995502

Theoretical discharge (Q) is determined by the WinFlume model, using hydraulic theory and empirical relationships determined from laboratory testing. It is the most accurate estimate of discharge. Curve fit discharge (Q_fit) is computed with the equation above, which was fitted to the theoretical discharge values. The 'difference' columns show the difference between the flow rates computed from the simplified equation and those obtained from the theoretical WinFlume model.

Appendix 6. Procedure for measuring sill-referenced upstream head during field evaluation of flumes

A portable point gage apparatus can be used as a quick reliable method to field test portable structures in irrigation field supply canals. The apparatus required is shown in Figure 6.1. It includes: (1) a depth sensing pipe with perforations, the upstream end of which is plugged with a rubber stopper and rough-ground to a rounded point, (2) a cup used as a stilling well, (3) a point gage, and (4) a support beam to span the canal. The sensing pipe and hose can be any practical size. The point gage is commercially available through laboratory supply houses.

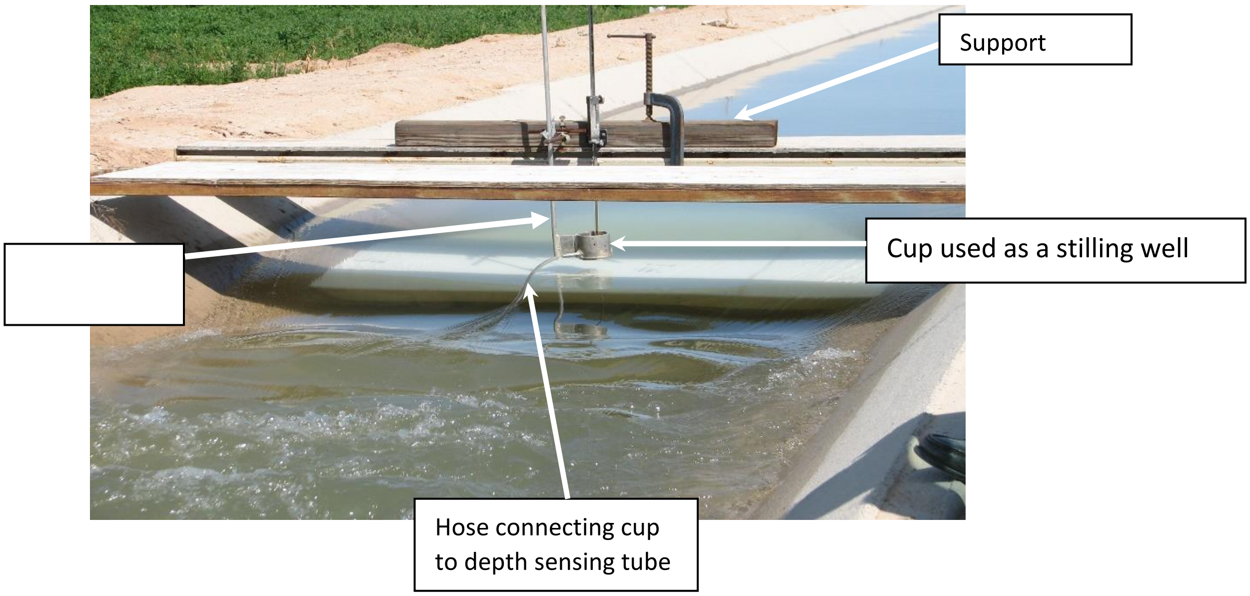

Figure 6.1. Point-gage apparatus for measuring sill-reference upstream head - during field evaluation of a flume in the UA Yuma Mesa farm

The following is a procedure, for using the point gage apparatus for measuring sill-referenced upstream head during field testing of portable flumes, reproduced from Clemmens et al. (2001):

1. Attach the point gage and the cup to a rigid support that can span the flow of water. Attach a transparent hose to the perforated sensing pipe (Figure 6.1). The perforation are about 0.3m from the closed nose of the sensing pipe.
2. Place the support of with the point gage across canal. Place the sensing pipe in the flowing stream, point the rounded nose directly into the direction of flow and locate the pipe sidewall sensing holes at the gaging station.

3. With the point gage, take a reading with the point resting on the weir sill or flume throat bottom on the control section (sill-reference point). Read to ±1mm (0.003ft) or more precisely. Do not lean on the support for the point gage. Deflection will change the point gage readings.
4. Raise the point gage sufficiently high so that the funnel or cup can be placed below the point gage. (Do not move the point-gage setup between these readings)
5. Lower cup below water level to purge air from transparent hose and then attach the cup so that the water level is several centimeters deep in the bottom of the cup and the cup is above the flowing water level.
6. Lower the point gage and read the water level in the cup. Repeat this step as a check. It may take a minute or so for the water level in the cup to stabilize. Compute the sill-referenced upstream head as the difference between the two point-gage readings, which is then used in the rating table to determine discharge.

Appendix 7 Flume revised design (WinFlume) – Flume type E_e, (sill height 1.0ft, Table 3), constructed dimensions

Table 7.1 FLUME DATA REPORT

GENERAL DATA ON FLUME

Type of structure: Stationary Crest
Type of lining: Concrete - smooth [custom]
Roughness height of flume: 0.000492 ft

BOTTOM PROFILE DATA

Length per section: Approach section, La = 3.000 ft
Converging transition, Lb = 3.000 ft
Control section, L = 2.666 ft
Diverging transition, Ld = 0.000 ft

Vertical dimensions: Upstream channel depth = 3.000 ft
Height of sill, p1 = 1.000 ft
Bed drop = 0.000 ft
Diverging transition = Abrupt Expansion

-- APPROACH SECTION DATA --

Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

-- CONTROL SECTION DATA --

Section shape = SIMPLE TRAPEZOID
Bottom width = 4.000 ft
Side slopes = 1.00:1

-- TAILWATER SECTION DATA --

Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

Table 7.2 SUMMARY EVALUATION OF FLUME DESIGN –construction dimensions
----
Design is acceptable.

EVALUATION OF FLUME DESIGN FOR EACH DESIGN REQUIREMENT

Ok. Froude number at Qmax = 0.366 Maximum allowed = 0.500

Ok. Freeboard at Qmax = 0.707 ft Minimum allowed = 0.259 ft

Ok. Tailwater at Qmax = 1.981 ft Maximum allowed = 2.160 ft
Submergence Protection at Qmax = 0.179 ft

Ok. Tailwater at Qmin = 1.019 ft Maximum allowed = 1.517 ft
Submergence Protection at Qmin = 0.497 ft

Ok. Head at Qmax = 1.293 ft Minimum for accuracy = 1.074 ft
Expected discharge measurement uncertainty at Qmax = ±6.73 %

Ok. Head at Qmin = 0.625 ft Minimum for accuracy = 0.529 ft
Expected discharge measurement uncertainty at Qmin = ±12.74 %

CONTROL SECTION DATA

Section shape = SIMPLE TRAPEZOID
Bottom width = 4.000 ft
Side slopes = 1.00:1
Sill Height, p1 = 1.000 ft

DESIGN CRITERIA

Structure Type: Stationary Crest
Freeboard design criterion: Freeboard >= 20% of upstream sill-referenced head
Allowable discharge measurement errors for a single measurement:
At minimum discharge: ±15%
At maximum discharge: ±8%
Head detection method: Staff gage without stilling well, Fr=0.5
Expected measurement uncertainty = ±0.049213 ft
Design discharges and associated tailwater levels:
Minimum discharge = 7.000 cu. ft/s Minimum tailwater depth = 1.019 ft
Maximum discharge = 25.000 cu. ft/s Maximum tailwater depth = 1.981 ft
Tailwater calculation method: Manning's equation using one Q-y2 measurement
Q = 16.000 cu. ft/s ---> y2 = 1.580 ft

ESTIMATED UNCERTAINTY OF TOTALIZED OR AVERAGED FLOW

With measurements made every 1 second, for a duration of 1 second,
the estimated uncertainty of totalized or averaged flow is ±8.0%

NOTE: The uncertainty given above is ONLY an estimate. It is most useful for making a comparative evaluation of competing design alternatives. The estimate assumes that there is a relatively uniform distribution of flows between Qmin and Qmax during the averaging period. If the distribution of flows is not relatively uniform, the uncertainty associated with one or a few large flows will dominate, negating most of the uncertainty improvement normally obtained through averaging and totalizing.

Table 7.3 Rating table and Equation for 1.0ft sill height - construction dimensions

h1 Sill Referenced Head at Gage feet	Q Theoretical Discharge cu. ft/s	Q_fit Curve Fit Equation Discharge cu. ft/s	D=Q_fit-Q Difference cu. ft/s	(D/Q)*100% Difference %	Warnings
0.188	1.00	1.01	+0.011	+1.08	
0.291	2.00	1.98	-0.023	-1.13	
0.374	3.00	2.97	-0.033	-1.09	
0.446	4.00	3.97	-0.030	-0.75	
0.511	5.00	4.98	-0.020	-0.41	
0.570	6.00	5.99	-0.007	-0.11	
0.625	7.00	7.01	+0.008	+0.12	
0.676	8.00	8.02	+0.023	+0.29	
0.724	9.00	9.04	+0.038	+0.43	
0.770	10.00	10.05	+0.051	+0.51	
0.814	11.00	11.06	+0.061	+0.56	
0.856	12.00	12.07	+0.069	+0.58	
0.896	13.00	13.07	+0.075	+0.58	
0.935	14.00	14.08	+0.078	+0.55	
0.972	15.00	15.08	+0.077	+0.52	
1.008	16.00	16.07	+0.074	+0.46	
1.043	17.00	17.07	+0.068	+0.40	
1.077	18.00	18.06	+0.058	+0.32	
1.111	19.00	19.05	+0.048	+0.25	
1.143	20.00	20.03	+0.032	+0.16	
1.174	21.00	21.01	+0.014	+0.06	
1.205	22.00	21.99	-0.008	-0.04	
1.235	23.00	22.97	-0.033	-0.15	
1.264	24.00	23.94	-0.056	-0.23	
1.293	25.00	24.91	-0.086	-0.35	
1.321	26.00	25.88	-0.120	-0.46	
1.349	27.00	26.84	-0.156	-0.58	
1.376	28.00	27.80	-0.196	-0.70	
1.402	29.00	28.76	-0.238	-0.82	

Equation: Q_fit = K1 * (h1 + K2) ^ u

Parameters: K1 = 14.65, K2 = 0.04359, and u = 1.830, Coefficient of determination: 0.99995540

Theoretical discharge (Q) is determined by the WinFlume model, using hydraulic theory and empirical relationships determined from laboratory testing. It is the most accurate estimate of discharge. Curve fit discharge (Q_fit) is computed with the equation above, which was fitted to the theoretical discharge values. The 'difference' columns show the difference between the flow rates computed from the simplified equation and those obtained from the theoretical WinFlume model.

Summary of Warning Messages

No warnings.

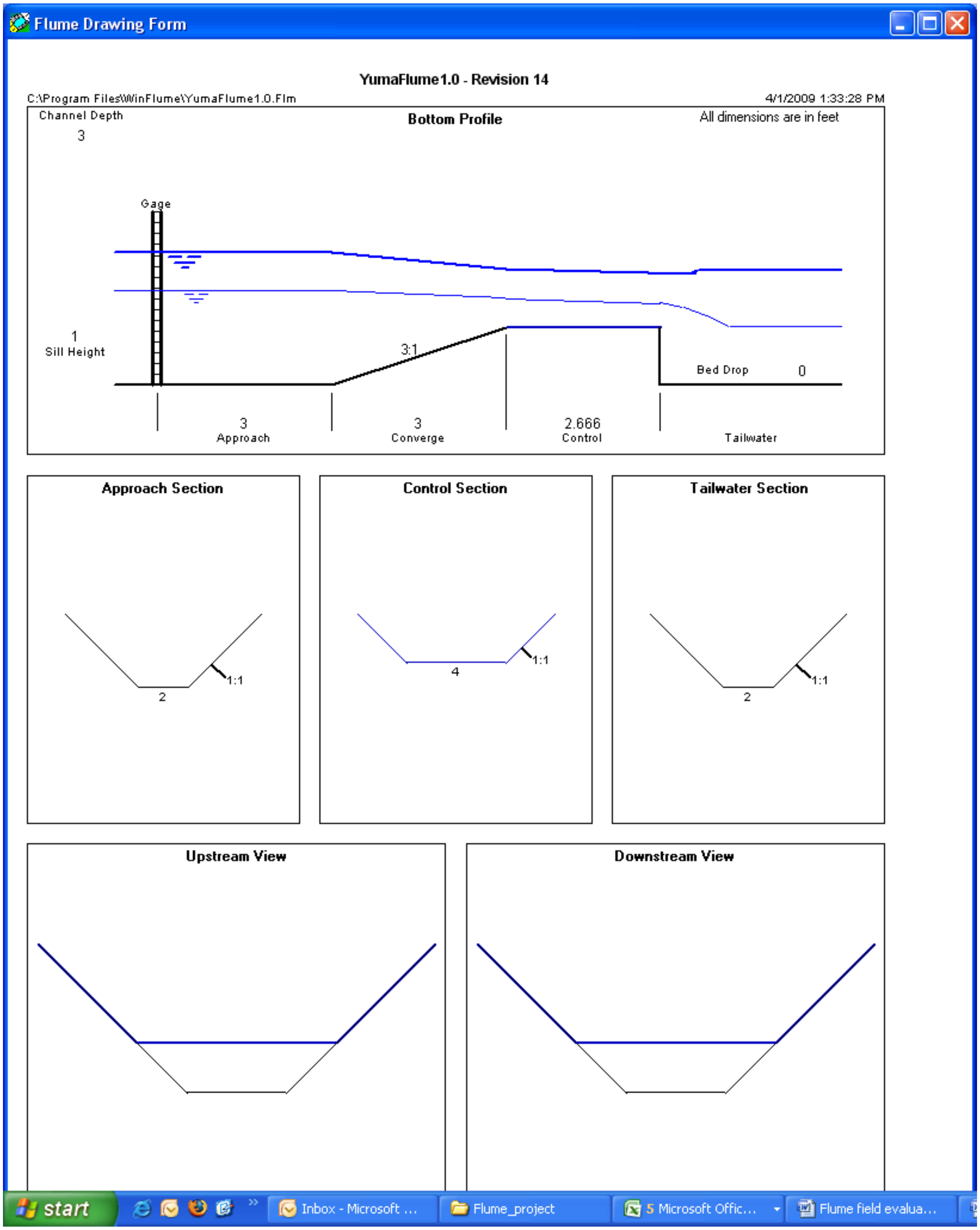

Figure 7.1 Flume bottom profile and cross-section dimensions for 1.0ft (12") sill height -- construction dimensions

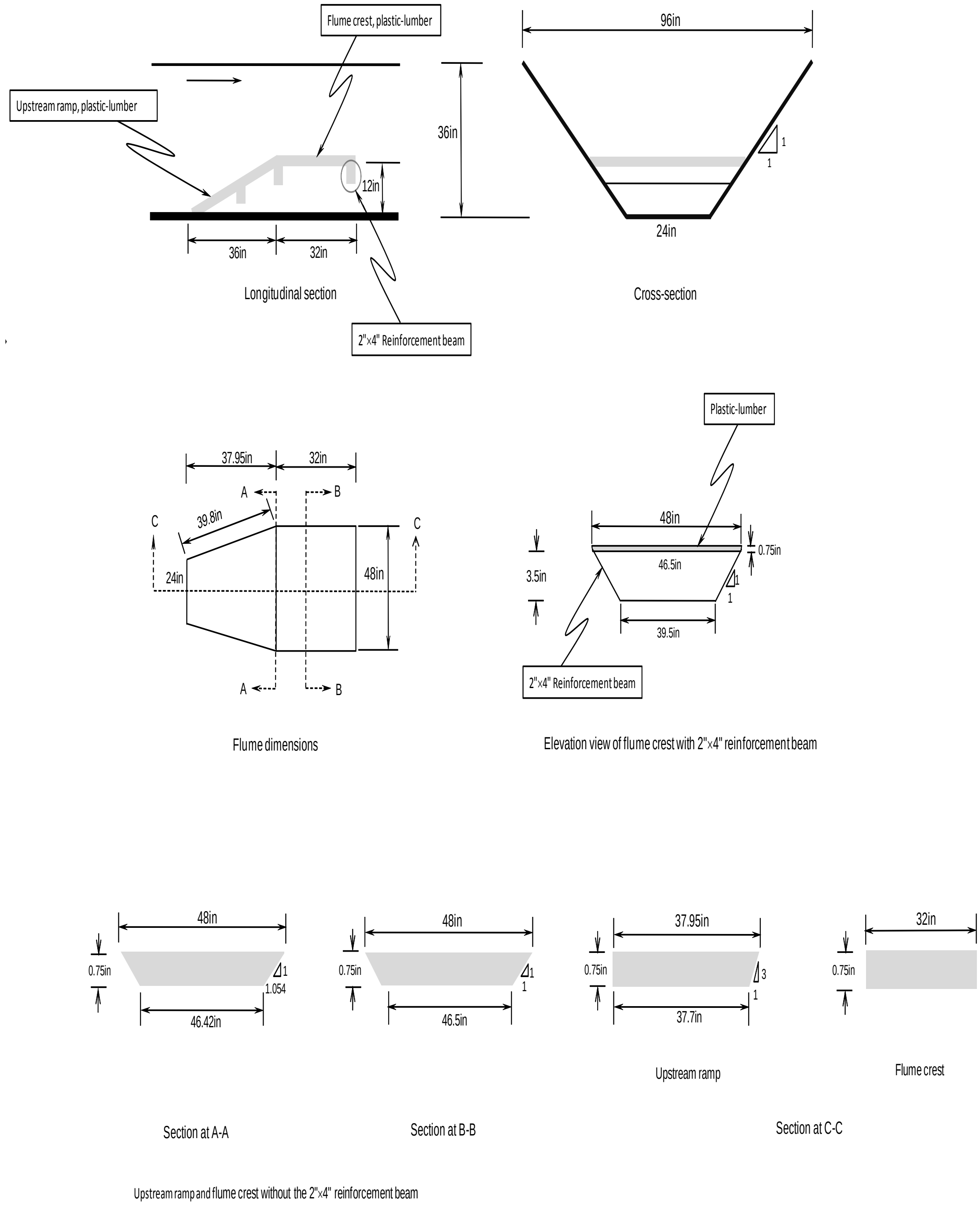

Figure 7.2 Flume construction dimensions for 1.0ft (12in) sill height

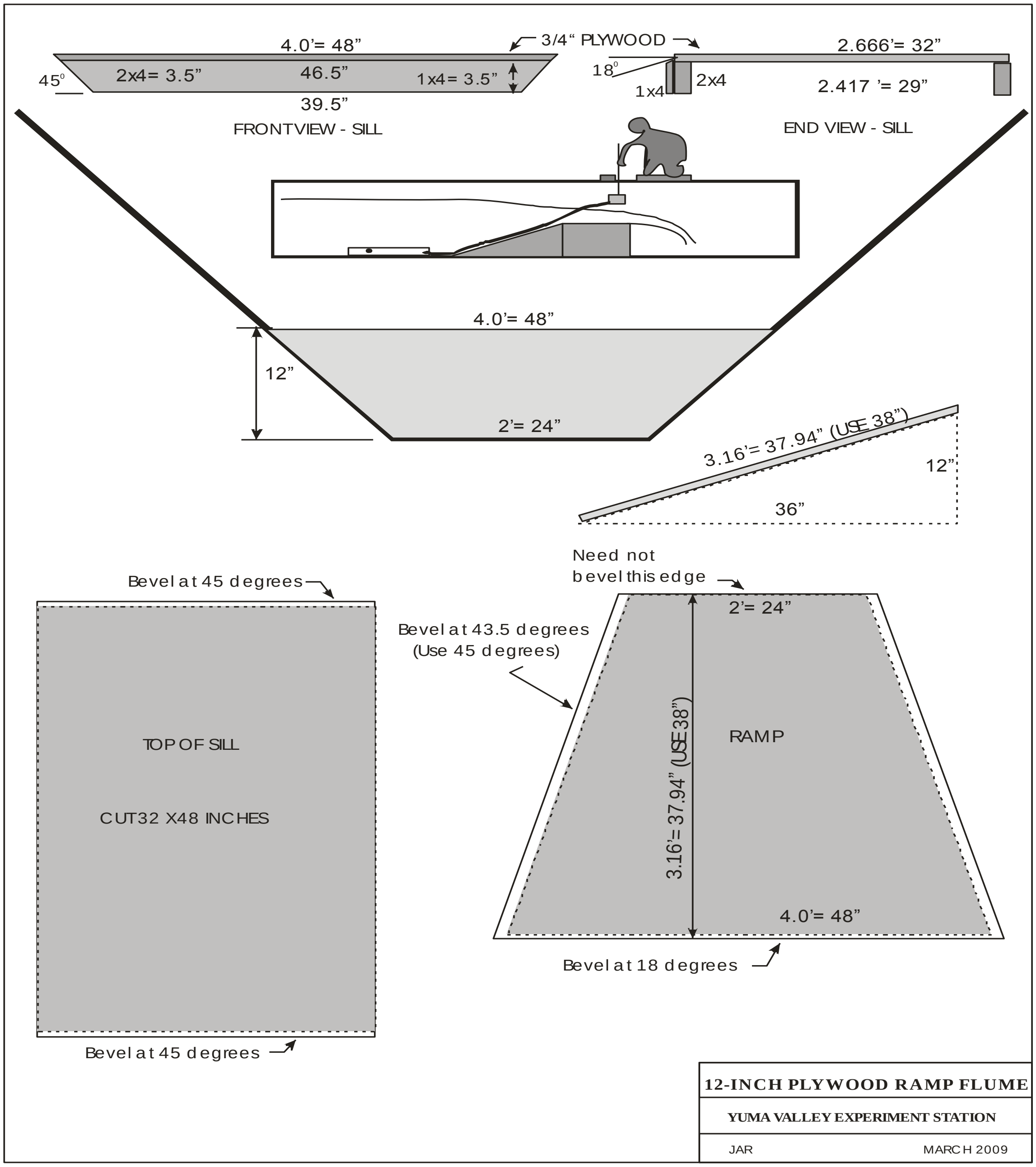

Figure 7.3 Flume construction drawings – 1.0ft (12in) sill height

Appendix 8 Flume revised design (WinFlume) – Flume type F_e, (sill height 1.25ft, Table 3), construction dimensions

Table 8.1 FLUME DATA REPORT

GENERAL DATA ON FLUME
Type of structure: Stationary Crest
Type of lining: Concrete - smooth [custom]
Roughness height of flume: 0.000492 ft

BOTTOM PROFILE DATA
Length per section: Approach section, La = 3.000 ft
Converging transition, Lb = 3.536 ft
Control section, L = 2.330 ft
Diverging transition, Ld = 0.000 ft

Vertical dimensions: Upstream channel depth = 3.000 ft
Height of sill, p1 = 1.250 ft
Bed drop = 0.000 ft
Diverging transition = Abrupt Expansion

-- APPROACH SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

-- CONTROL SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 4.500 ft
Side slopes = 1.00:1

-- TAILWATER SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

Table 8.2 SUMMARY EVALUATION OF FLUME DESIGN – construction dimensions

----

Design is acceptable.

EVALUATION OF FLUME DESIGN FOR EACH DESIGN REQUIREMENT

Ok. Froude number at Qmax = 0.312 Maximum allowed = 0.500

Ok. Freeboard at Qmax = 0.512 ft Minimum allowed = 0.248 ft

Ok. Tailwater at Qmax = 1.981 ft Maximum allowed = 2.341 ft
Submergence Protection at Qmax = 0.359 ft

Ok. Tailwater at Qmin = 1.019 ft Maximum allowed = 1.723 ft
Submergence Protection at Qmin = 0.704 ft

Ok. Head at Qmax = 1.238 ft Minimum for accuracy = 1.057 ft
Expected discharge measurement uncertainty at Qmax = ±6.91 %

Ok. Head at Qmin = 0.589 ft Minimum for accuracy = 0.524 ft
Expected discharge measurement uncertainty at Qmin = ±13.37 %

CONTROL SECTION DATA

Section shape = SIMPLE TRAPEZOID
Bottom width = 4.500 ft
Side slopes = 1.00:1
Sill Height, p1 = 1.250 ft

DESIGN CRITERIA

Structure Type: Stationary Crest
Freeboard design criterion: Freeboard >= 20% of upstream sill-referenced head
Allowable discharge measurement errors for a single measurement:
At minimum discharge: ±15%
At maximum discharge: ±8%
Head detection method: Staff gage without stilling well, Fr=0.5
Expected measurement uncertainty = ±0.049213 ft
Design discharges and associated tailwater levels:
Minimum discharge = 7.000 cu. ft/s Minimum tailwater depth = 1.019 ft
Maximum discharge = 25.000 cu. ft/s Maximum tailwater depth = 1.981 ft
Tailwater calculation method: Manning's equation using one Q-y2 measurement
Q = 16.000 cu. ft/s ---> y2 = 1.580 ft

ESTIMATED UNCERTAINTY OF TOTALIZED OR AVERAGED FLOW

With measurements made every 1 second, for a duration of 1 second,
the estimated uncertainty of totalized or averaged flow is ±8.3%

NOTE: The uncertainty given above is ONLY an estimate. It is most useful for making a comparative evaluation of competing design alternatives. The estimate assumes that there is a relatively uniform distribution of flows between Qmin and Qmax during the averaging period. If the distribution of flows is not relatively uniform, the uncertainty associated with one or a few large flows will dominate, negating most of the uncertainty improvement normally obtained through averaging and totalizing.

Table 8.3 Rating table and equation for a sill height of 1.25ft – construction dimensions

h1 Sill Referenced Head at Gage feet	Q Theoretical Discharge cu. ft/s	Q_fit Curve Fit Equation Discharge cu. ft/s	D=Q_fit-Q Difference cu. ft/s	(D/Q)*100% Difference %	Warnings
0.174	1.00	1.01	+0.010	+0.99	
0.271	2.00	1.98	-0.022	-1.08	
0.350	3.00	2.97	-0.032	-1.06	
0.418	4.00	3.97	-0.029	-0.74	
0.480	5.00	4.98	-0.020	-0.40	
0.536	6.00	5.99	-0.007	-0.11	
0.589	7.00	7.01	+0.008	+0.11	
0.638	8.00	8.02	+0.024	+0.30	
0.685	9.00	9.04	+0.038	+0.43	
0.729	10.00	10.05	+0.051	+0.51	
0.771	11.00	11.06	+0.062	+0.56	
0.812	12.00	12.07	+0.070	+0.58	
0.851	13.00	13.08	+0.076	+0.58	
0.888	14.00	14.08	+0.079	+0.56	
0.925	15.00	15.08	+0.079	+0.53	
0.960	16.00	16.08	+0.076	+0.47	
0.994	17.00	17.07	+0.072	+0.42	
1.027	18.00	18.06	+0.062	+0.35	
1.060	19.00	19.05	+0.050	+0.26	
1.091	20.00	20.03	+0.034	+0.17	
1.122	21.00	21.02	+0.015	+0.07	
1.152	22.00	21.99	-0.007	-0.03	
1.181	23.00	22.97	-0.032	-0.14	
1.210	24.00	23.94	-0.060	-0.25	
1.238	25.00	24.91	-0.092	-0.37	
1.265	26.00	25.87	-0.126	-0.48	
1.292	27.00	26.84	-0.164	-0.61	
1.318	28.00	27.80	-0.204	-0.73	
1.344	29.00	28.75	-0.248	-0.85	

Equation: Q_fit = K1 * (h1 + K2) ^ u
Parameters: K1 = 16.19, K2 = 0.03624, and u = 1.781, Coefficient of determination: 0.99995601

Theoretical discharge (Q) is determined by the WinFlume model, using hydraulic theory and empirical relationships determined from laboratory testing. It is the most accurate estimate of discharge. Curve fit discharge (Q_fit) is computed with the equation above, which was fitted to the theoretical discharge values. The 'difference' columns show the difference between the flow rates computed from the simplified equation and those obtained from the theoretical WinFlume model.

Summary of Warning Messages

No warnings.

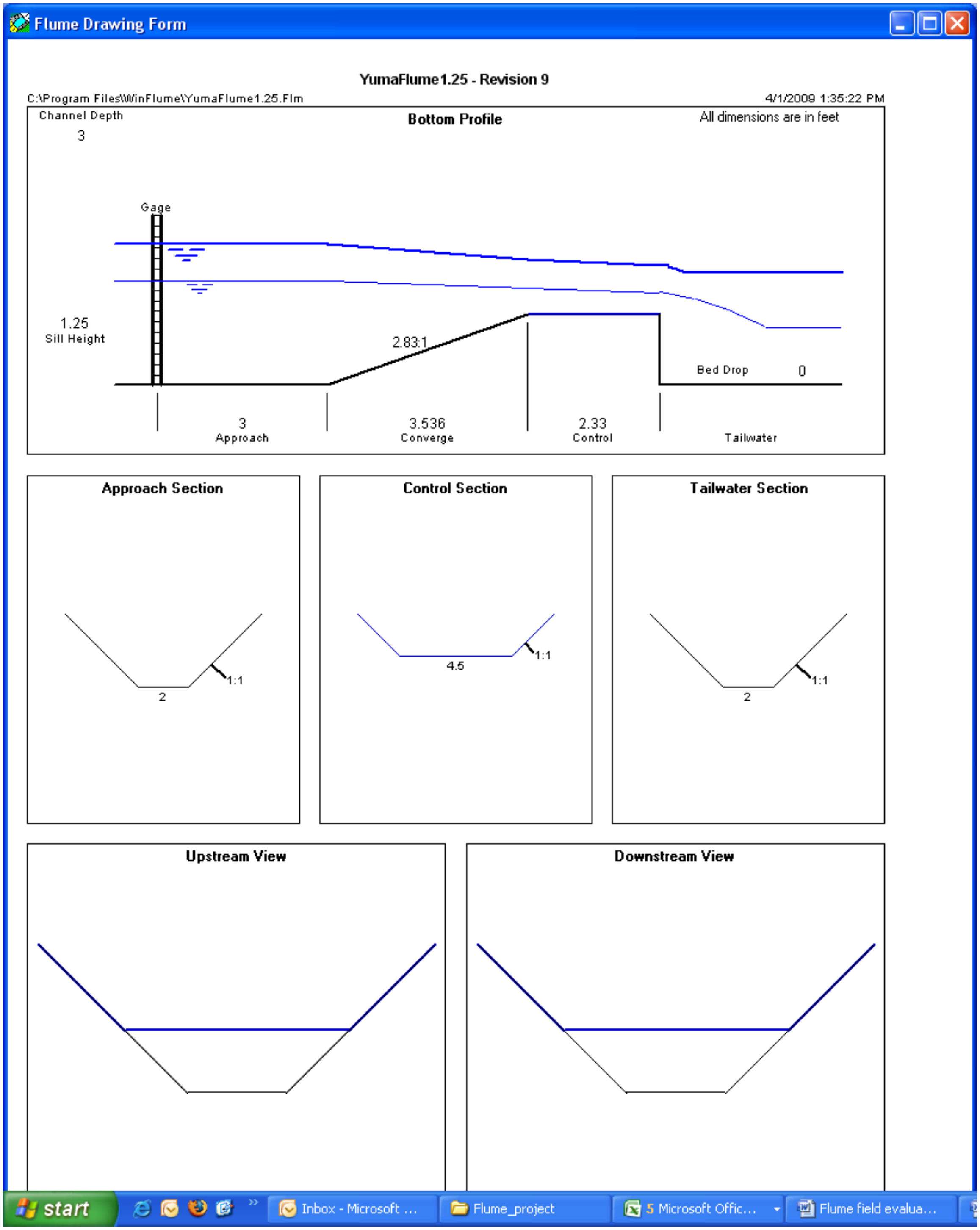

Figure 8.1 Flume bottom profile and cross-section dimensions for 1.25ft (15") sill height -- construction dimensions

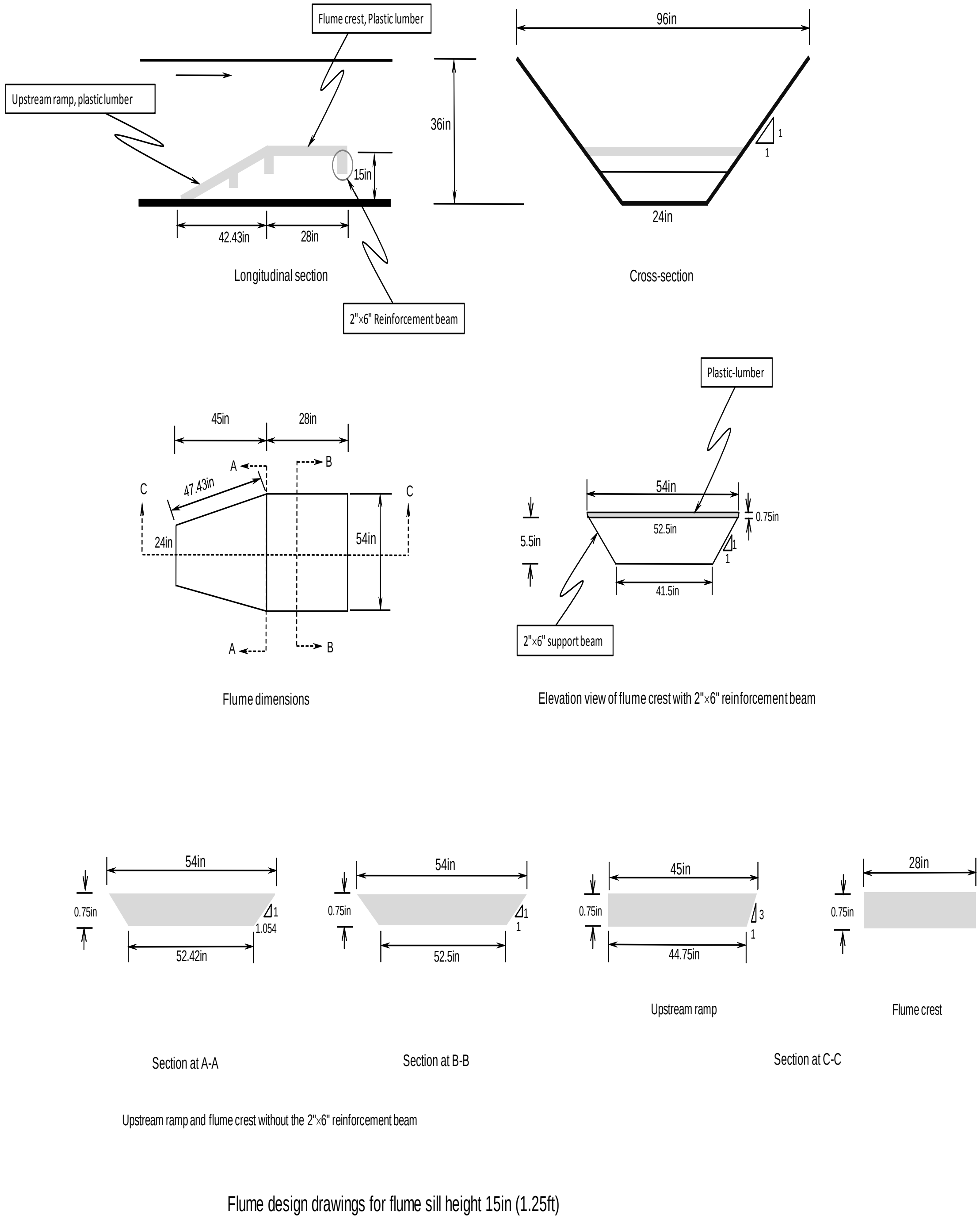

Figure 8.2 Flume construction dimensions for 1.25ft (15in) sill height

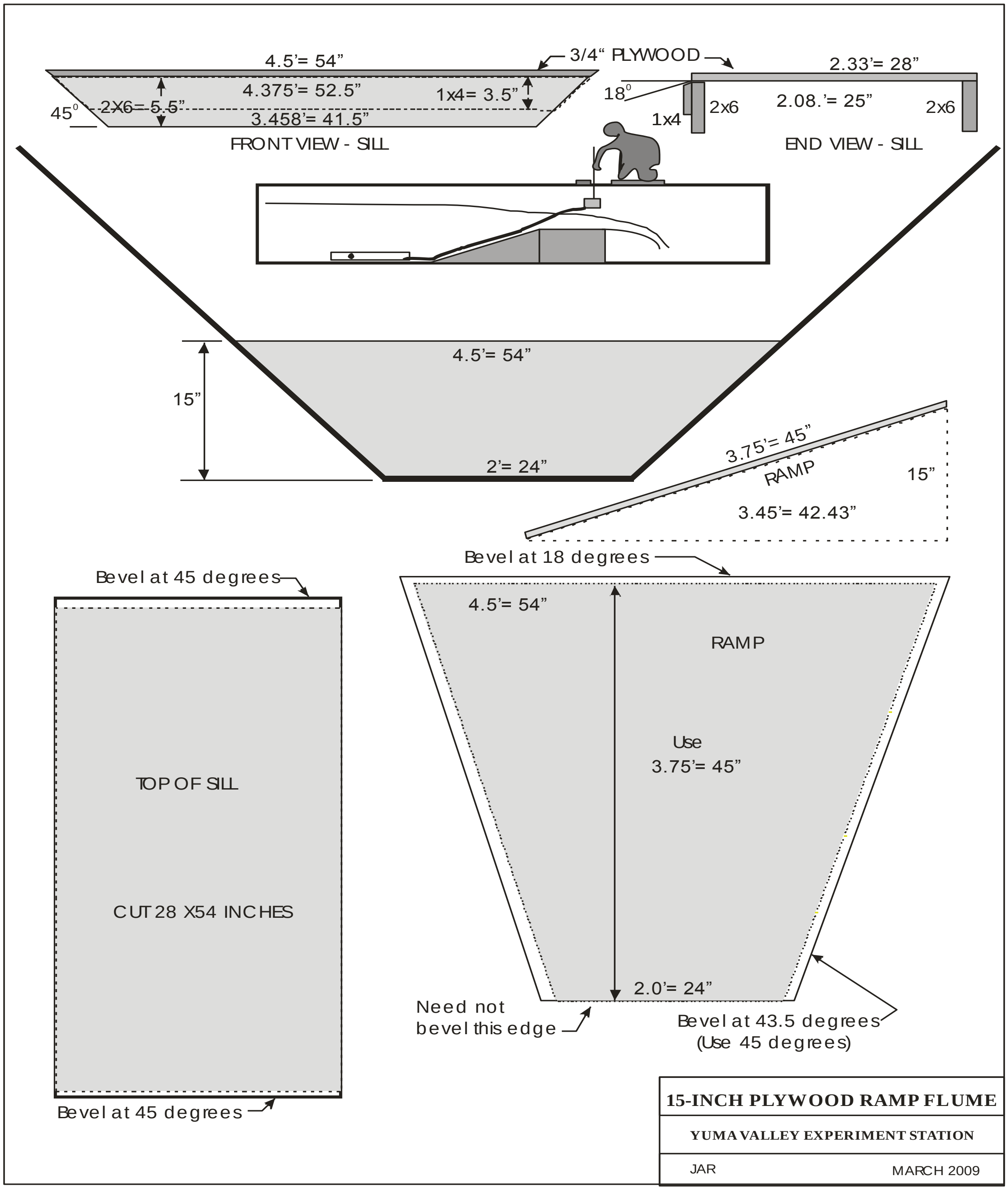

Figure 8.3 Flume construction drawings – 1.25ft (15in) sill height

Appendix 9 Flume revised design (WinFlume) – Flume type G_e, (sill height 1.5ft, Table 3), construction dimensions

Table 9.1 FLUME DATA REPORT

GENERAL DATA ON FLUME
Type of structure: Stationary Crest
Type of lining: Concrete - smooth [custom]
Roughness height of flume: 0.000492 ft

BOTTOM PROFILE DATA
Length per section: Approach section, La = 3.000 ft
Converging transition, Lb = 3.710 ft
Control section, L = 2.000 ft
Diverging transition, Ld = 0.000 ft

Vertical dimensions: Upstream channel depth = 3.000 ft
Height of sill, p1 = 1.500 ft
Bed drop = 0.000 ft
Diverging transition = Abrupt Expansion

-- APPROACH SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

-- CONTROL SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 5.000 ft
Side slopes = 1.00:1

-- TAILWATER SECTION DATA --
Section shape = SIMPLE TRAPEZOID
Bottom width = 2.000 ft
Side slopes = 1.00:1

Table 9.2 SUMMARY EVALUATION OF FLUME DESIGN – construction dimensions

----

Design is acceptable, but improvements are also possible.
Two errors or warnings.

EVALUATION OF FLUME DESIGN FOR EACH DESIGN REQUIREMENT

Ok. Froude number at Qmax = 0.268 Maximum allowed = 0.500

Ok. Freeboard at Qmax = 0.315 ft Minimum allowed = 0.237 ft

Ok. Tailwater at Qmax = 1.981 ft Maximum allowed = 2.526 ft
Submergence Protection at Qmax = 0.545 ft

Ok. Tailwater at Qmin = 1.019 ft Maximum allowed = 1.936 ft
Submergence Protection at Qmin = 0.916 ft

Ok. Head at Qmax = 1.185 ft Minimum for accuracy = 1.043 ft
Expected discharge measurement uncertainty at Qmax = ±7.10 %

Ok. Head at Qmin = 0.556 ft Minimum for accuracy = 0.520 ft
Expected discharge measurement uncertainty at Qmin = ±14.03 %

WARNING MESSAGES AND DESIGN SUGGESTIONS

WARNING MESSAGES AT MINIMUM DISCHARGE:
- Converging section is too short (ramp is too steep).
  Converging ramp length should be >= 3.75 ft

WARNING MESSAGES AT MAXIMUM DISCHARGE:
- Converging section is too short (ramp is too steep).
  Converging ramp length should be >= 3.75 ft

CONTROL SECTION DATA

Section shape = SIMPLE TRAPEZOID
Bottom width = 5.000 ft
Side slopes = 1.00:1
Sill Height, p1 = 1.500 ft

DESIGN CRITERIA

Structure Type: Stationary Crest

Freeboard design criterion: Freeboard >= 20% of upstream sill-referenced head
Allowable discharge measurement errors for a single measurement:
    At minimum discharge: ±15%
    At maximum discharge: ±8%
Head detection method: Staff gage without stilling well, Fr=0.5
    Expected measurement uncertainty = ±0.049213 ft
Design discharges and associated tailwater levels:
    Minimum discharge = 7.000 cu. ft/s   Minimum tailwater depth = 1.019 ft
    Maximum discharge = 25.000 cu. ft/s   Maximum tailwater depth = 1.981 ft
Tailwater calculation method: Manning's equation using one Q-y2 measurement
    Q = 16.000 cu. ft/s ---> y2 = 1.580 ft

ESTIMATED UNCERTAINTY OF TOTALIZED OR AVERAGED FLOW

With measurements made every 1 second, for a duration of 1 second,
the estimated uncertainty of totalized or averaged flow is ±8.6%

NOTE: The uncertainty given above is ONLY an estimate. It is most useful for making a comparative evaluation of competing design alternatives. The estimate assumes that there is a relatively uniform distribution of flows between Qmin and Qmax during the averaging period. If the distribution of flows is not relatively uniform, the uncertainty associated with one or a few large flows will dominate, negating most of the uncertainty improvement normally obtained through averaging and totalizing.

Table 9.3 Rating table and equation for 1.5ft flume sill height – construction dimensions

h1 Sill Referenced Head at Gage feet	Q Theoretical Discharge cu. ft/s	Q_fit Curve Fit Equation Discharge cu. ft/s	D=Q_fit-Q Difference cu. ft/s	(D/Q)*100% Difference %	Warnings
0.163	1.00	1.01	+0.011	+1.15	10
0.254	2.00	1.98	-0.023	-1.13	10
0.328	3.00	2.97	-0.032	-1.08	10
0.393	4.00	3.97	-0.030	-0.76	10
0.452	5.00	4.98	-0.022	-0.43	10
0.506	6.00	5.99	-0.009	-0.15	10
0.556	7.00	7.01	+0.006	+0.09	10
0.604	8.00	8.02	+0.021	+0.26	10
0.649	9.00	9.04	+0.035	+0.39	10
0.691	10.00	10.05	+0.048	+0.48	10
0.732	11.00	11.06	+0.059	+0.53	10
0.771	12.00	12.07	+0.067	+0.56	10
0.809	13.00	13.07	+0.073	+0.56	10
0.846	14.00	14.08	+0.077	+0.55	10
0.881	15.00	15.08	+0.079	+0.53	10
0.915	16.00	16.08	+0.076	+0.48	10
0.948	17.00	17.07	+0.071	+0.42	10
0.980	18.00	18.06	+0.062	+0.35	10
1.012	19.00	19.05	+0.051	+0.27	10
1.042	20.00	20.04	+0.036	+0.18	10
1.072	21.00	21.02	+0.018	+0.08	10
1.101	22.00	22.00	-0.003	-0.02	10
1.130	23.00	22.97	-0.028	-0.12	10
1.158	24.00	23.94	-0.055	-0.23	10
1.185	25.00	24.91	-0.086	-0.34	10
1.212	26.00	25.88	-0.119	-0.46	10
1.238	27.00	26.84	-0.156	-0.58	10
1.264	28.00	27.80	-0.196	-0.70	10
1.290	29.00	28.76	-0.238	-0.82	10

Equation: Q_fit = K1 * (h1 + K2) ^ u;
Parameters: K1 = 17.74, K2 = 0.03003, and u = 1.741, Coefficient of determination: 0.99995497

Theoretical discharge (Q) is determined by the WinFlume model, using hydraulic theory and empirical relationships determined from laboratory testing. It is the most accurate estimate of discharge. Curve fit discharge (Q_fit) is computed with the equation above, which was fitted to the theoretical discharge values. The 'difference' columns show the difference between the flow rates computed from the simplified equation and those obtained from the theoretical WinFlume model.

Summary of Warning Messages

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10 - Converging section is too short (ramp is too steep). Considering standard dimensions of available construction material, flume ramp length is set to 48in, this results in a ramp slope of about 2.47:1. Field evaluation showed that discharge measurement error because of the steeper ramp is negligible.

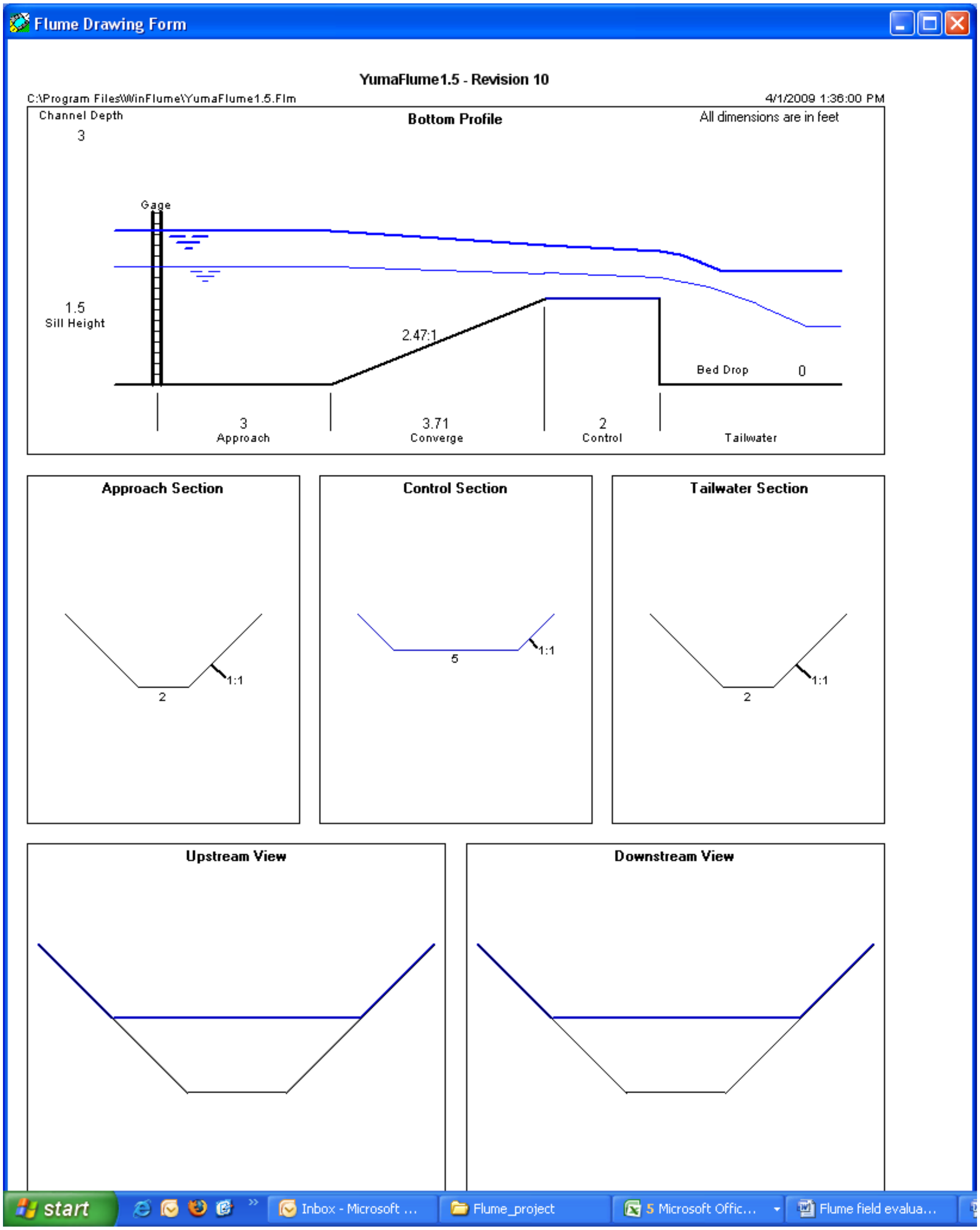

Figure 9.1 Flume bottom profile and cross-section dimensions for sill height 1.5ft (18”) -- construction dimensions

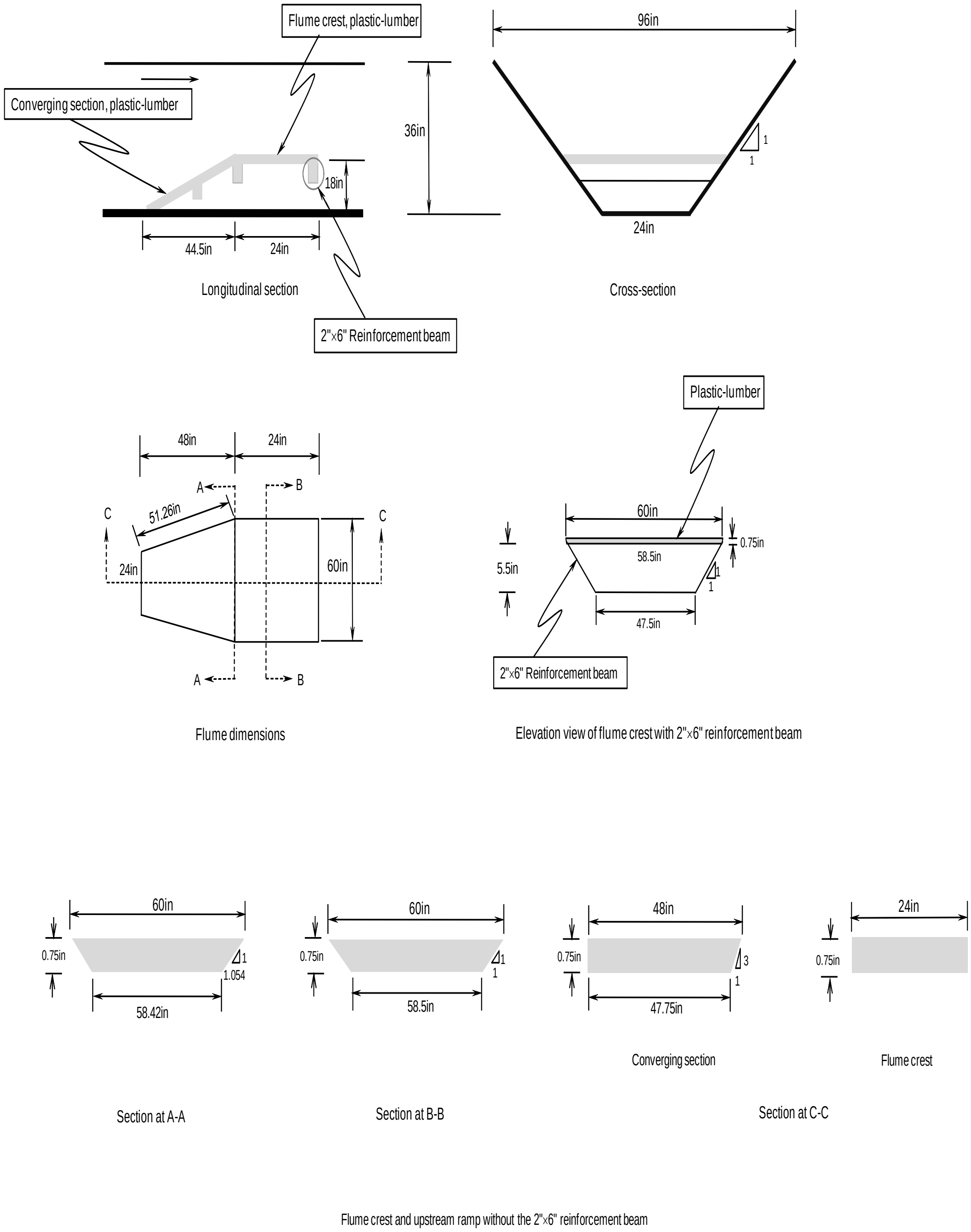

Figure 9.2 Flume construction dimensions for 1.5ft (18in) sill height

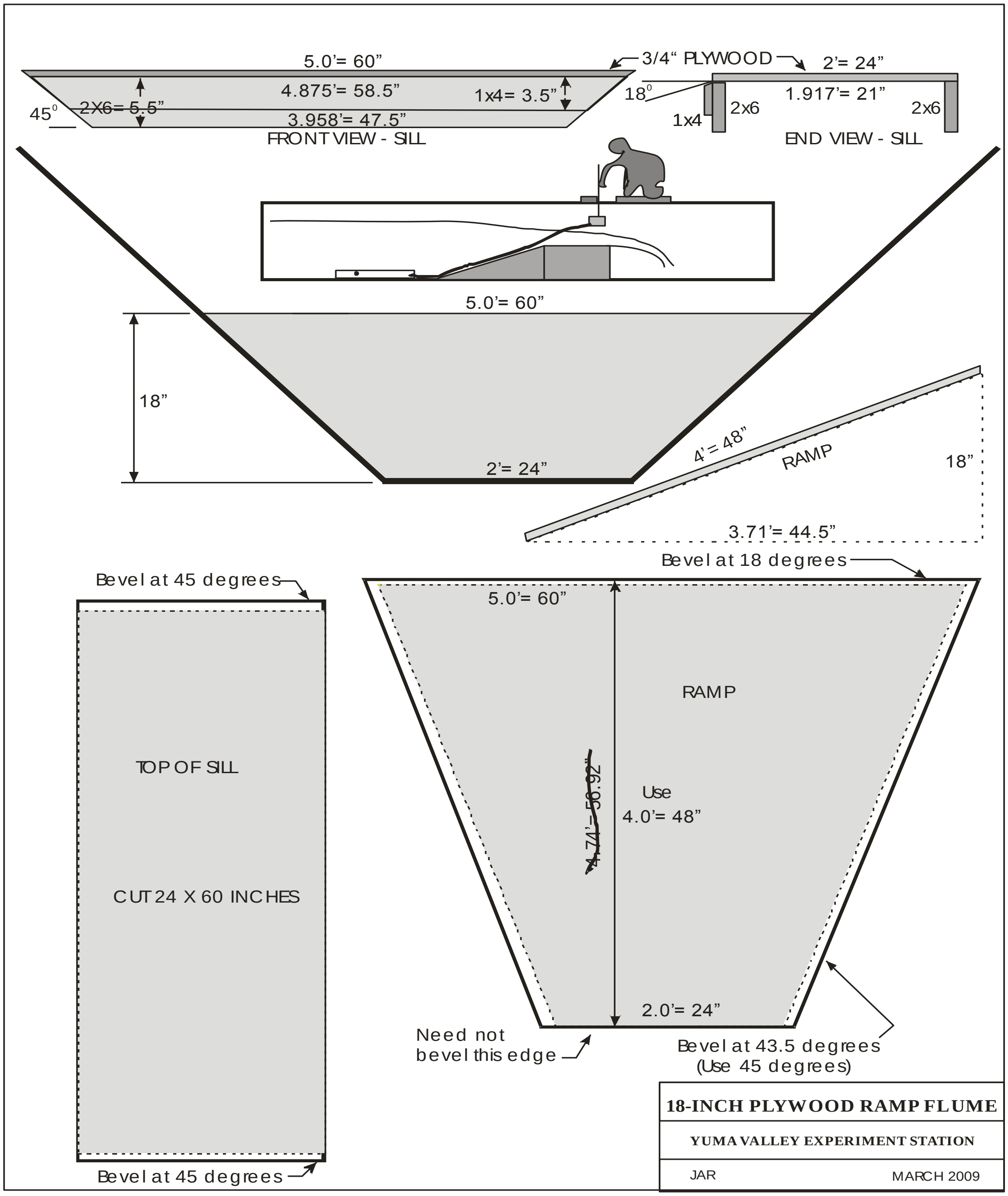

Figure 9.3 Flume construction drawings – 1.5ft (18in) sill height