**Lecture 2**
Flumes for Open-Channel Flow Measurement

> *"Superb accuracy in water measurement, Jessica thought."*
> *Dune*, F. Herbert (1965)

I. Procedure for Installing a Parshall Flume to Ensure Free Flow

- If possible, you will want to specify the installation of a Parshall flume such that it operates under free-flow conditions throughout the required flow range
- To do this, you need to specify the minimum elevation of the upstream floor of the flume
- Follow these simple steps to obtain a free-flow in a Parshall flume, up to a specified maximum discharge:

  1. Determine the maximum flow rate (discharge) to be measured
  2. Locate the high water line on the canal bank where the flume is to be installed, or otherwise determine the maximum depth of flow on the upstream side
  3. Select a standard flume size and calculate h_u from the free-flow equation corresponding to the maximum discharge capacity of the canal
  4. Place the floor of the flume at a depth not exceeding the transition submergence, S_t, multiplied by h_u below the high water line

- In general, the floor of the flume should be placed as high in the canal as grade and other conditions permit, but not so high that upstream free board is compromised.
- The downstream water surface elevation will be unaffected by the installation of the flume (at least for the same flow rate)
- As an example, a 0.61-m Parshall flume is shown in the figure below
- The transition submergence, S_t, for the 0.61-m flume is 66% (see table)
- The maximum discharge in the canal is given as 0.75 m³/s, which for free-flow conditions must have an upstream depth of (see Eq. 3): $h_u = (0.75/1.429)^{1/1.55} = 0.66$ m
- With the transition submergence of 0.66, this gives a depth to the flume floor of 0.66(0.660 m) = 0.436 m from the downstream water surface
- Therefore, the flume crest (elevation of h_u tap) should be set no lower than 0.436 m below the normal maximum water surface for this design flow rate, otherwise the regime will be submerged flow
- However, if the normal depth for this flow rate were less than 0.436 m, you would place the floor of the flume on the bottom of the channel and still have free flow conditions
- The approximate head loss across the structure at the maximum flow rate will be the difference between 0.660 and 0.436 m, or 0.224 m
- This same procedure can be applied to other types of open-channel measurement flumes
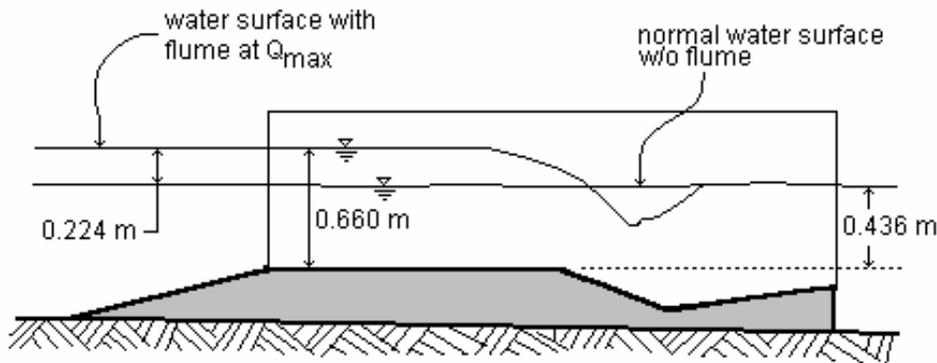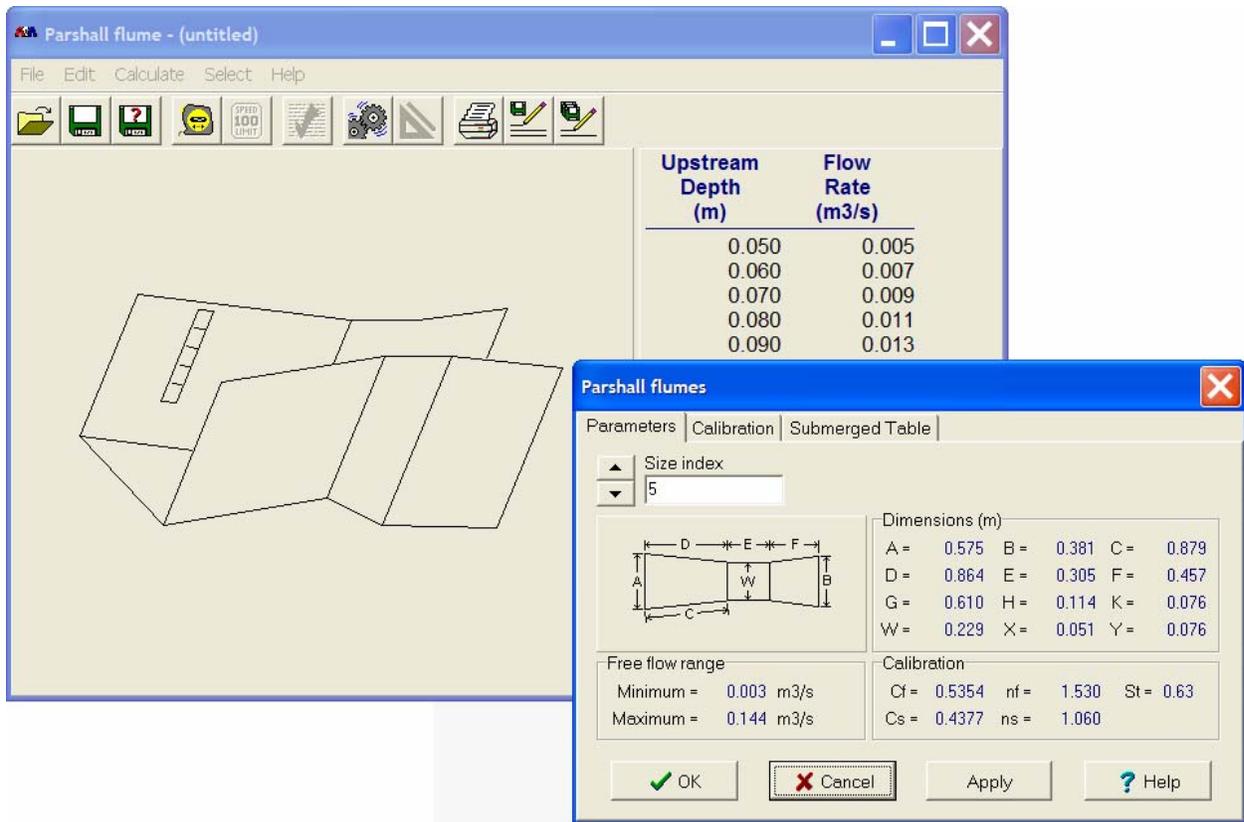
II. Non-Standard Parshall Flume Calibrations

- Some Parshall flumes were incorrectly constructed or were intentionally built with a non-standard size
- Others have settled over time such that the flume is out of level either cross-wise or longitudinally (in the direction of flow), or both
- Some flumes have the taps for measuring h_u and h_d at the wrong locations (too high or too low, or too far upstream or downstream)
- Some flumes have moss, weeds, sediment or other debris that cause the calibration to shift from that given for standard conditions
- Several researchers have worked independently to develop calibration adjustments for many of the unfortunate anomalies that have befallen many Parshall flumes in the field, but a general calibration for non-standard flumes requires 3-D modeling
- There are calibration corrections for out-of-level installations and for low-flow conditions

III. Hysteresis Effects in Parshall Flumes

- There have been reports by some researchers that hysteresis effects have been observed in the laboratory under submerged-flow conditions in Parshall flumes
- The effect is to have two different flow rates for the same submergence, S, value, depending on whether the downstream depth is rising or falling
- There is no evidence of this hysteresis effect in Cutthroat flumes, which are discussed below

IV. Software

- You can use the **ACA** program to develop calibration tables for Parshall, Cutthroat, and trapezoidal flumes
- Download **ACA** from:
  http://www.engineering.usu.edu/bie/faculty/merkley/Software.htm
- You can also download the **WinFlume** program from:
  http://www.usbr.gov/pmts/hydraulics_lab/winflume/index.html

Upstream Depth (m)	Flow Rate (m3/s)
0.050	0.005
0.060	0.007
0.070	0.009
0.080	0.011
0.090	0.013

Parshall flumes

Parameters | Calibration | Submerged Table

Size index
5

Dimensions (m)

A =	0.575	B =	0.381	C =	0.879
D =	0.864	E =	0.305	F =	0.457
G =	0.610	H =	0.114	K =	0.076
W =	0.229	X =	0.051	Y =	0.076

Free flow range

Minimum = 0.003 m3/s
Maximum = 0.144 m3/s

Calibration

Cf = 0.5354   nf = 1.530   St = 0.63
Cs = 0.4377   ns = 1.060

✓ OK   ✗ Cancel   Apply   ? Help

V. Submerged-Flow, Constant Flow Rate

- Suppose you have a constant flow rate through a Parshall flume
- How will h_u change for different h_d values under submerged-flow conditions?
- This situation could occur in a laboratory flume, or in the field where a downstream gate is incrementally closed, raising the depth downstream of the Parshall flume, but with a constant upstream inflow
- The graph below is for steady-state flow conditions with a 0.914-m Parshall flume
- Note that h_u is always greater than h_d (otherwise the flow would move upstream, or there would be no flow)

Parshall Flume (W = 0.914 m)

Submerged flow conditions.
Constant flow rate: $Q_s = 1.00$ m³/s.
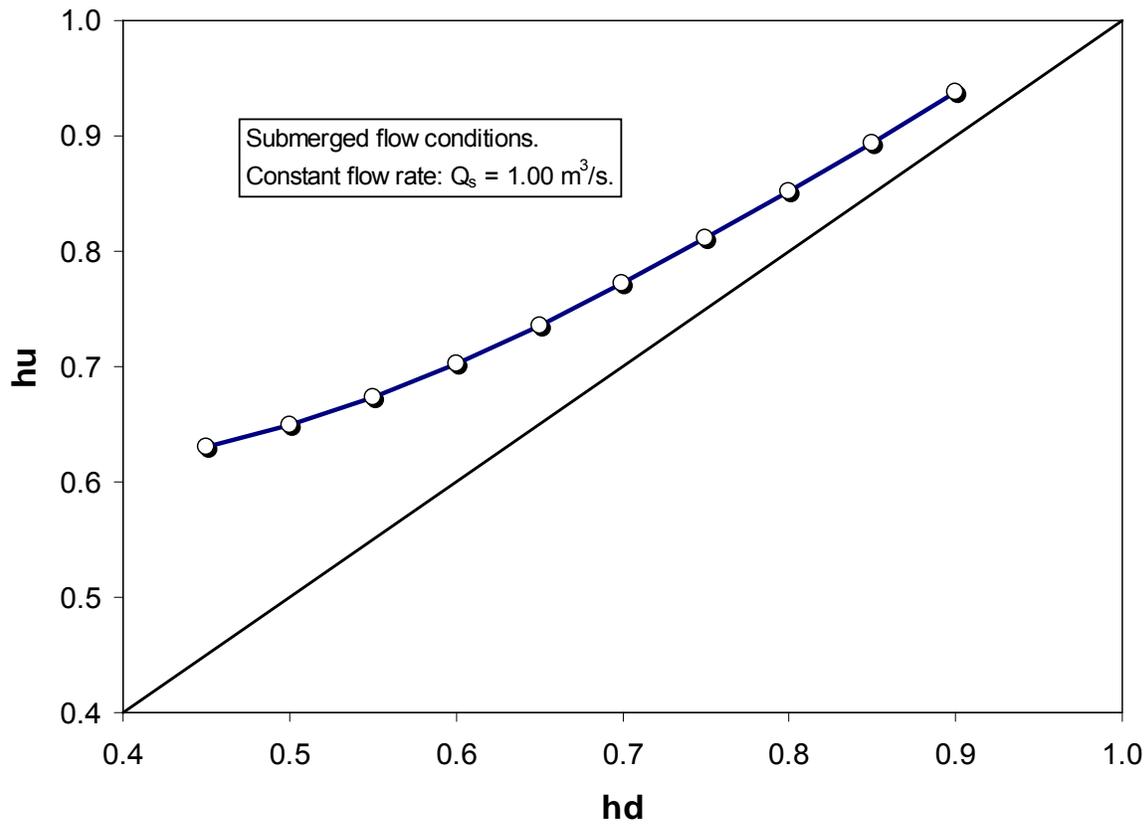
hd	hu	Q	S	Regime
(m)	(m)	(m3/s)		
0.15	0.714	0.999	0.210	free
0.20	0.664	0.999	0.301	free
0.25	0.634	0.999	0.394	free
0.30	0.619	1.000	0.485	free
0.35	0.615	1.002	0.569	free
0.40	0.619	1.000	0.646	free
0.45	0.631	1.000	0.713	submerged
0.50	0.650	1.001	0.769	submerged
0.55	0.674	1.000	0.816	submerged
0.60	0.703	1.000	0.853	submerged
0.65	0.736	1.000	0.883	submerged
0.70	0.772	0.999	0.907	submerged
0.75	0.811	1.001	0.925	submerged
0.80	0.852	1.004	0.939	submerged
0.85	0.894	1.000	0.951	submerged
0.90	0.938	1.002	0.959	submerged

VI. Cutthroat Flumes

- The Cutthroat flume was developed at USU from 1966-1990
- A Cutthroat flume is a rectangular open-channel constriction with a flat bottom and zero length in the throat section (earlier versions did have a throat section)
- Because the flume has a throat section of zero length, the flume was given the name "Cutthroat" by the developers (Skogerboe, et al. 1967)

A Cutthroat flume

- The floor of the flume is level (as opposed to a Parshall flume), which has the following advantages:

    1. ease of construction – the flume can be readily placed inside a concrete-lined channel
    2. the flume can be placed on the channel bed

- The Cutthroat flume was developed to operate satisfactorily under both free-flow and submerged-flow conditions
- Unlike Parshall flumes, all Cutthroat flumes have the same dimensional ratios
- It has been shown by experiment that downstream flow depths measured in the diverging outlet section give more accurate submerged-flow calibration curves than those measured in the throat section of a Parshall flume
- The centers of the taps for the US and DS head measurements are both located ½-inch above the floor of the flume, and the tap diameters should be ¼-inch

Cutthroat Flume Sizes

- The dimensions of a Cutthroat flume are identified by the flume width and length (W x L, e.g. 4" x 3.0')
- The flume lengths of 1.5, 3.0, 4.5, 6.0, 7.5, 9.0 ft are sufficient for most applications
- The most common ratios of W/L are 1/9, 2/9, 3/9, and 4/9
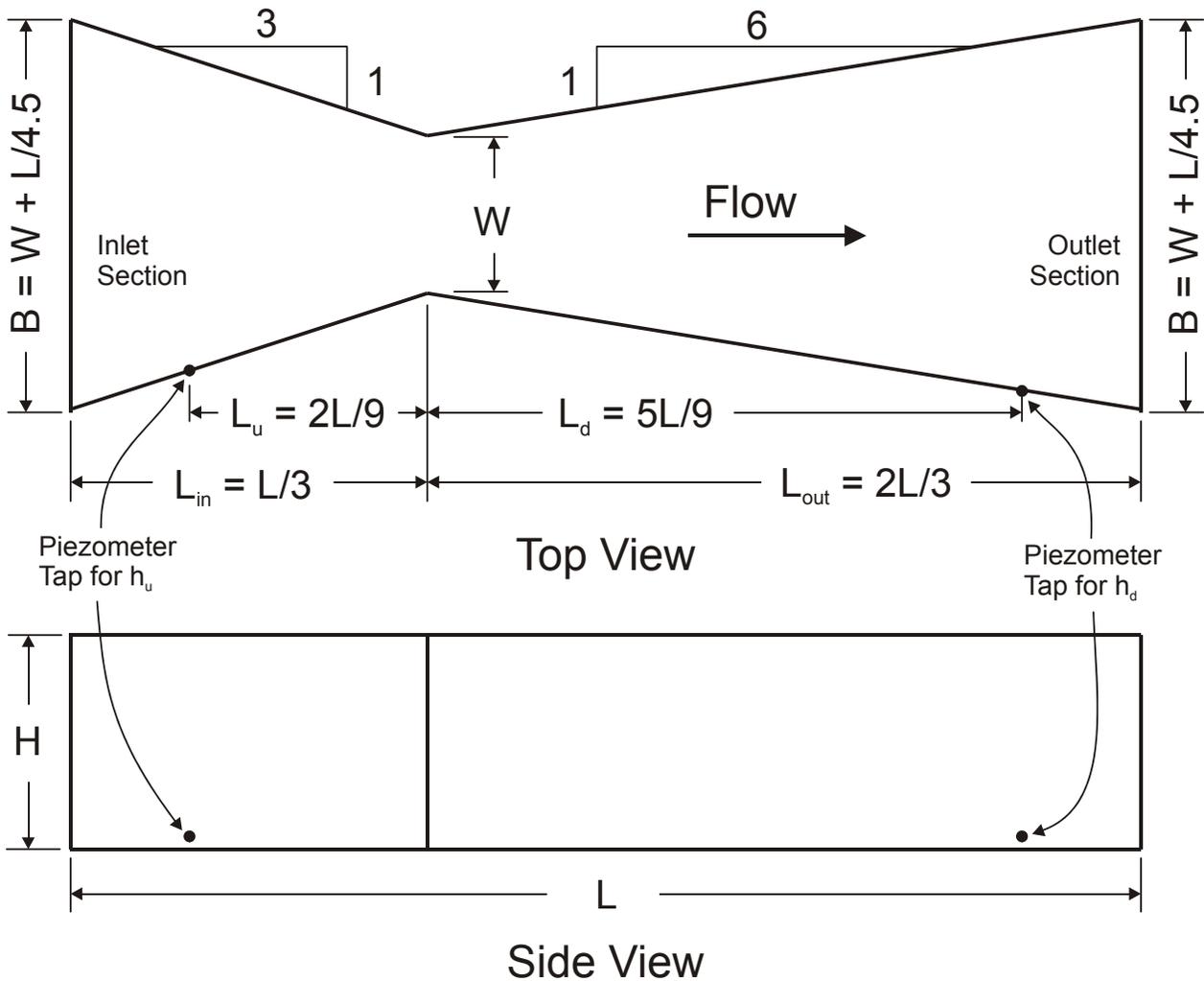- The recommended ratio of h_u/L is equal to or less than 0.33

Free-flow equation

- For Cutthroat flumes the free-flow equation takes the same general form as for Parshall flumes, and other channel "constrictions":

$$Q_f = C_f W \left(h_u\right)^{n_f} \tag{1}$$

where Q_f is the free-flow discharge; W is the throat width; C_f is the free-flow coefficient; and n_f is the free-flow exponent

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- That is, *almost any* non-orifice constriction in an open channel can be calibrated using Eq. 1, given free-flow conditions
- The depth, h_u, is measured from the upstream tap location (½-inch above the flume floor)

Top View

$B = W + L/4.5$

3 / 1

6 / 1

W

Flow

Inlet Section

Outlet Section

$L_u = 2L/9$

$L_d = 5L/9$

$B = W + L/4.5$

$L_{in} = L/3$

$L_{out} = 2L/3$

Piezometer Tap for h_u

Piezometer Tap for h_d

Side View

H

L

- For any given flume size, the flume wall height, H, is equal to h_u for Q_{max}, according to the above equation, although a slightly larger H-value can be used to prevent the occurrence of overflow
- So, solve the above free-flow equation for h_u, and apply the appropriate Q_{max} value from the table below; the minimum H-value is equal to the calculated h_u

Submerged-flow equation

- For Cutthroat flumes the submerged-flow equation also takes the same general form as for Parshall flumes, and other channel constrictions:

$$Q_s = \frac{C_s W (h_u - h_d)^{n_f}}{[-(\log_{10} S)]^{n_s}} \qquad (2)$$

where C_s = submerged-flow coefficient; W is the throat width; and $S = h_d/h_u$

- Equation 2 differs from the submerged-flow equation given previously for Parshall flumes in that the C_2 term is omitted
- The coefficients C_f and C_s are functions of flume length, L, and throat width, W
- The generalized free-flow and submerged-flow coefficients and exponents for standard-sized Cutthroat flumes can be taken from the following table (metric units: for Q in m^3/s and head (depth) in m, and using a *base 10 logarithm* in Eq. 2)
- *Almost any* non-orifice constriction in an open channel can be calibrated using Eq. 2, given submerged-flow conditions

Cutthroat Flume Calibration Parameters for <u>metric</u> units (depth and W in m and flow rate in m^3/s)

W (m)	L (m)	C_f	n_f	S_t	C_s	n_s	Discharge (m^3/s) min	max
0.051	0.457	5.673	1.98	0.553	3.894	1.45	0.0001	0.007
0.102	0.457	5.675	1.97	0.651	3.191	1.58	0.0002	0.014
0.152	0.457	5.639	1.95	0.734	2.634	1.67	0.0004	0.022
0.203	0.457	5.579	1.94	0.798	2.241	1.73	0.0005	0.030
0.102	0.914	3.483	1.84	0.580	2.337	1.38	0.0002	0.040
0.203	0.914	3.486	1.83	0.674	1.952	1.49	0.0005	0.081
0.305	0.914	3.459	1.81	0.754	1.636	1.57	0.0008	0.123
0.406	0.914	3.427	1.80	0.815	1.411	1.64	0.0011	0.165
0.152	1.372	2.702	1.72	0.614	1.752	1.34	0.0005	0.107
0.305	1.372	2.704	1.71	0.708	1.469	1.49	0.0010	0.217
0.457	1.372	2.684	1.69	0.788	1.238	1.50	0.0015	0.326
0.610	1.372	2.658	1.68	0.849	1.070	1.54	0.0021	0.436
0.203	1.829	2.351	1.66	0.629	1.506	1.30	0.0007	0.210
0.406	1.829	2.353	1.64	0.723	1.269	1.39	0.0014	0.424
0.610	1.829	2.335	1.63	0.801	1.077	1.45	0.0023	0.636
0.813	1.829	2.315	1.61	0.862	0.934	1.50	0.0031	0.846
0.254	2.286	2.147	1.61	0.641	1.363	1.28	0.0009	0.352
0.508	2.286	2.148	1.60	0.735	1.152	1.37	0.0019	0.707
0.762	2.286	2.131	1.58	0.811	0.982	1.42	0.0031	1.056
1.016	2.286	2.111	1.57	0.873	0.850	1.47	0.0043	1.400
0.305	2.743	2.030	1.58	0.651	1.279	1.27	0.0012	0.537
0.610	2.743	2.031	1.57	0.743	1.085	1.35	0.0025	1.076
0.914	2.743	2.024	1.55	0.820	0.929	1.40	0.0039	1.611
1.219	2.743	2.000	1.54	0.882	0.804	1.44	0.0055	2.124

- Note that n_f approaches 1.5 for larger W values, but never gets down to 1.5
- As for the Parshall flume data given previously, the submerged-flow calibration is for base 10 logarithms
- Note that the coefficient conversion to English units is as follows:

$$C_{f\,(English)} = \frac{(0.3048)^{1+n_f}}{(0.3048)^3} C_{f\,(metric)} \tag{3}$$

- The next table shows the calibration parameters for English units

**Cutthroat Flume Calibration Parameters for <u>English</u> units
(depth and W in ft and flow rate in cfs)**

W (ft)	L (ft)	C_f	n_f	S_t	C_s	n_s	Discharge (cfs)	
							min	max
0.167	1.50	5.796	1.98	0.553	3.978	1.45	0.004	0.24
0.333	1.50	5.895	1.97	0.651	3.315	1.58	0.008	0.50
0.500	1.50	5.956	1.95	0.734	2.782	1.67	0.013	0.77
0.667	1.50	5.999	1.94	0.798	2.409	1.73	0.018	1.04
0.333	3.00	4.212	1.84	0.580	2.826	1.38	0.009	1.40
0.667	3.00	4.287	1.83	0.674	2.400	1.49	0.018	2.86
1.000	3.00	4.330	1.81	0.754	2.048	1.57	0.029	4.33
1.333	3.00	4.361	1.80	0.815	1.796	1.64	0.040	5.82
0.500	4.50	3.764	1.72	0.614	2.440	1.34	0.016	3.78
1.000	4.50	3.830	1.71	0.708	2.081	1.49	0.034	7.65
1.500	4.50	3.869	1.69	0.788	1.785	1.50	0.053	11.5
2.000	4.50	3.897	1.68	0.849	1.569	1.54	0.074	15.4
0.667	6.00	3.534	1.66	0.629	2.264	1.30	0.024	7.43
1.333	6.00	3.596	1.64	0.723	1.940	1.39	0.050	15.0
2.000	6.00	3.633	1.63	0.801	1.676	1.45	0.080	22.5
2.667	6.00	3.662	1.61	0.862	1.478	1.50	0.111	29.9
0.833	7.50	3.400	1.61	0.641	2.159	1.28	0.032	12.4
1.667	7.50	3.459	1.60	0.735	1.855	1.37	0.068	25.0
2.500	7.50	3.494	1.58	0.811	1.610	1.42	0.108	37.3
3.333	7.50	3.519	1.57	0.873	1.417	1.47	0.151	49.4
1.000	9.00	3.340	1.58	0.651	2.104	1.27	0.042	19.0
2.000	9.00	3.398	1.57	0.743	1.815	1.35	0.088	38.0
3.000	9.00	3.442	1.55	0.820	1.580	1.40	0.139	56.9
4.000	9.00	3.458	1.54	0.882	1.390	1.44	0.194	75.0

<u>Unified Discharge Calibrations</u>

- Skogerboe also developed "unified discharge" calibrations for Cutthroat flumes, such that it is *not necessary to select from the above standard flume sizes*
- A regression analysis on the graphical results from Skogerboe yields these five calibration parameter equations:

$$C_f = 6.5851L^{-0.3310}W^{1.025} \tag{4}$$

$$n_f = 2.0936L^{-0.1225} - 0.128(W/L) \tag{5}$$

$$n_s = 2.003(W/L)^{0.1318}L^{-0.07044(W/L)-0.07131} \tag{6}$$

$$S_t = 0.9653(W/L)^{0.2760}L^{0.04322(W/L)^{-0.3555}} \tag{7}$$

$$C_s = \frac{C_f\left(-\log_{10} S_t\right)^{n_s}}{\left(1-S_t\right)^{n_f}} \tag{8}$$

- Note that Eqs. 4-8 are for English units (L and W in ft; Q in cfs)
- The maximum percent difference in the Cutthroat flume calibration parameters is less than 2%, comparing the results of Eqs. 4-8 with the calibration parameters for the 24 standard Cutthroat flume sizes

VII. Trapezoidal Flumes

- Trapezoidal flumes are often used for small flows, such as for individual furrows in surface irrigation evaluations
- The typical standard calibrated flume is composed of five sections: approach, converging, throat, diverging, and exit
- However, the approach and exit sections are not necessary part of the flume itself
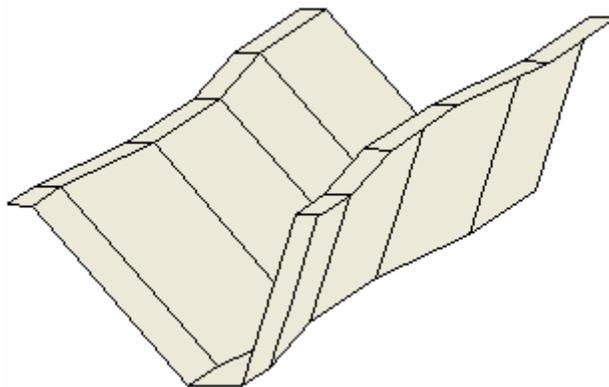
- Ideally, trapezoidal flumes can measure discharge with an accuracy of ±5% under free-flow conditions
- But the attainment of this level of accuracy depends on proper installation, accurate stage measurement, and adherence to specified tolerances in the construction of the throat section
- Discharge measurement errors are approximately 1.5 to 2.5 times the error in the stage reading for correctly installed flumes with variations in throat geometry from rectangular to triangular sections

Throat End View

End View

Plan View

Side View
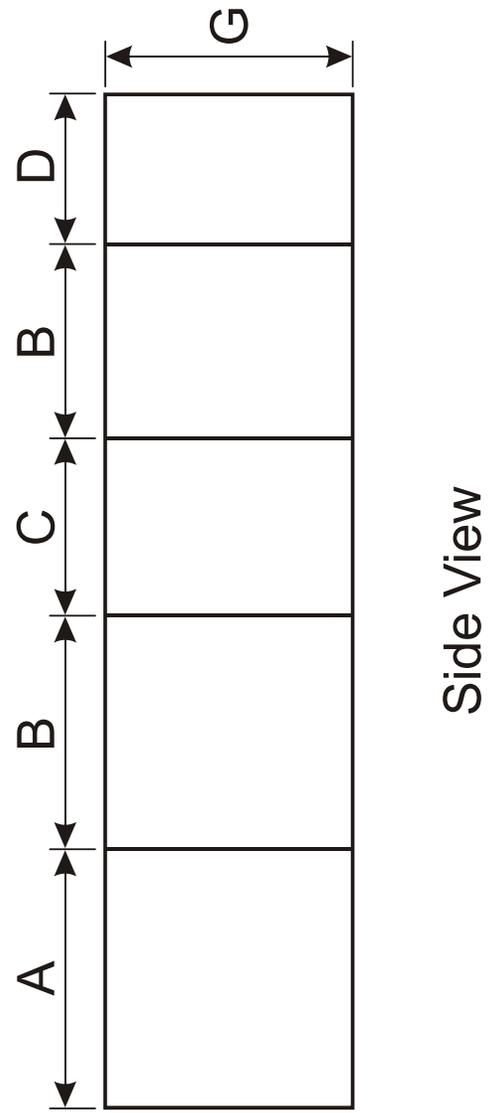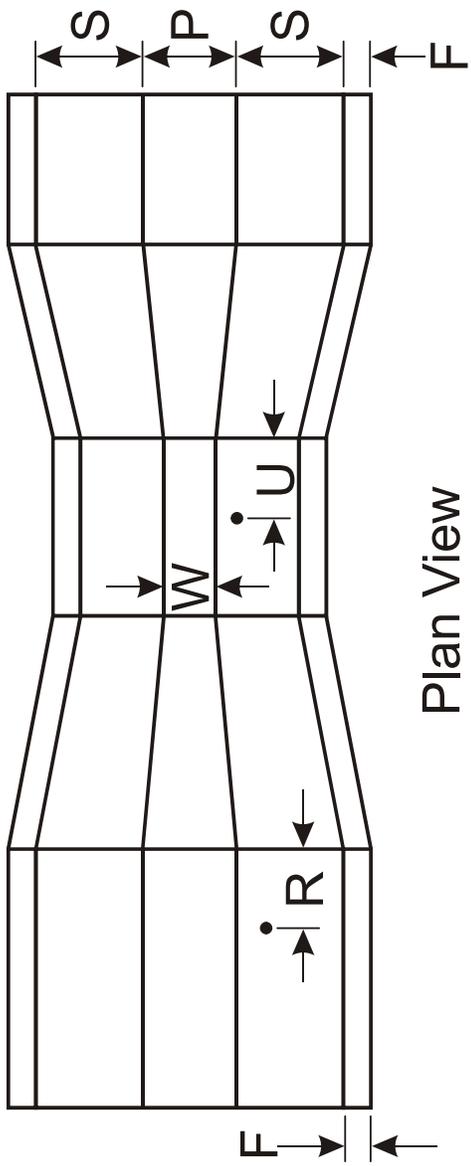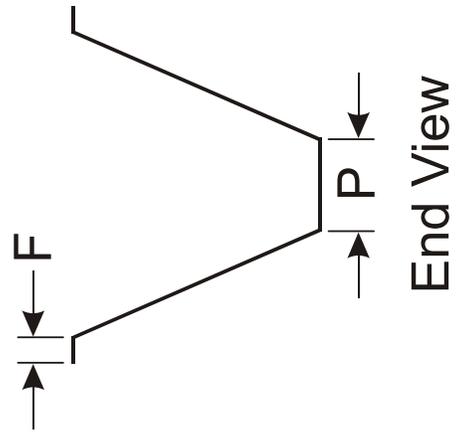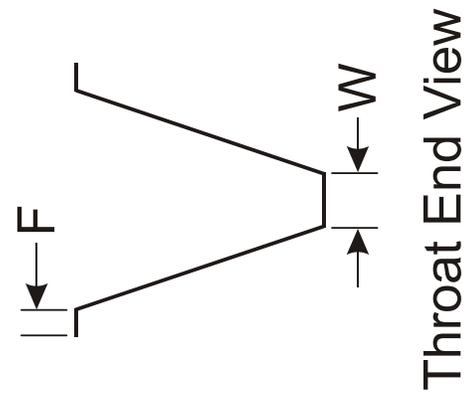
- In the following table with seven trapezoidal flume sizes, the first two flumes are V-notch (zero base width in the throat, and the last five have trapezoidal throat cross sections

Flume Number	Description	Dimensions (inches)											
		A	B	C	D	E	F	G	P	R	S	U	W
1	Large 60°-V	7.00	6.90	7.00	3.00	7.00	1.00	6.75	2.00	1.50	4.00	3.50	0.00
2	Small 60°-V	5.00	6.05	5.00	2.00	4.25	1.00	4.00	2.00	1.00	2.38	2.50	0.00
3	2"-60° WSC	8.00	6.41	8.50	3.00	8.50	1.00	13.50	4.90	1.50	6.00	4.30	2.00
4	2"-45° WSC	8.00	8.38	8.50	3.00	8.50	1.00	10.60	4.90	1.50	10.60	4.30	2.00
5	2"-30° WSC	8.00	8.38	8.50	3.00	8.50	1.00	10.00	4.90	1.50	17.30	4.30	2.00
6	4"-60° WSC	9.00	9.81	10.00	3.00	10.00	1.00	13.90	8.00	1.50	8.00	5.00	4.00
7	2"-30° CSU	10.00	10.00	10.00	3.00	10.80	1.00	9.70	10.00	1.50	16.80	5.00	2.00

Note: All dimensions are in inches. WSC are Washington State Univ Calibrations, while CSU are Colorado State Univ Calibrations (adapted from Robinson & Chamberlain 1960)

- Trapezoidal flume calibrations are for free-flow regimes only (although it would be possible to generate submerged-flow calibrations from laboratory data)
- The following equation is used for free-flow calibration

$$Q_f = C_{ft} \left(h_u \right)^{n_{ft}} \tag{9}$$

where the calibration parameters for the above seven flume sizes are given in the table below:

Flume Number	C_{ft}	n_{ft}	Q_{max} (cfs)
1	1.55	2.58	0.35
2	1.55	2.58	0.09
3	1.99	2.04	2.53
4	3.32	2.18	2.53
5	5.92	2.28	3.91
6	2.63	1.83	3.44
7	4.80	2.26	2.97

Note: for h_u in ft and Q in cfs

V-Notch Flumes

- When the throat base width of a trapezoidal flume is zero (W = 0, usually for the smaller sizes), these are called "V-notch flumes"
- Similar to the V-notch weir, it is most commonly used for measuring water with a small head due to a more rapid change of head with change in discharge
- Flume numbers 1 and 2 above are V-notch flumes because they have W = 0

VIII. Flume Calibration Procedure

- Sometimes it is necessary to develop site-specific calibrations in the field or in the laboratory
- For example, you might need to develop a custom calibration for a "hybrid" flume, or a flume that was constructed to nonstandard dimensions
- To calibrate based on field data for flow measurement, it is desired to find flow rating conditions for both free-flow and submerged-flow
- To analyze and solve for the value of the unknown parameters in the flow rating equation the following procedure applies:

    1. Transform the exponential equation into a linear equation using logarithms
    2. The slope and intersection of this line can be obtained by fitting the transformed data using linear regression, or graphically with log-log paper
    3. Finally, back-calculate to solve for the required unknown values

The linear equation is:

$$Y = a + bX \tag{10}$$

The transformed flume equations are:

Free-flow:

$$\log(Q_f) = \log(C_f W) + n_f \log(h_u) \tag{11}$$

So, applying Eq. 10 with measured pairs of Q_f and h_u, "a" is log C_f and "b" is n_f

Submerged-flow:

$$\log\left[\frac{Q_s}{(h_u - h_d)^{n_f}}\right] = \log(C_s W) - n_s \log\left[-(\log S)\right] \tag{12}$$

Again, applying Eq. 10 with measured pairs of Q_s and h_u and h_d, "a" is log C_s and "b" is n_s

- Straight lines can be plotted to show the relationship between log h_u and log Q_f for a free-flow rating, and between log (h_u-h_d) and log Q_S with several degrees of submergence for a submerged-flow rating
- If this is done using field or laboratory data, any base logarithm can be used, but the base must be specified
- Multiple linear regression can also be used to determine C_s, n_f, and n_s for submerged flow data only – this is discussed further in a later lecture

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IX. Sample Flume Calibrations

Free Flow

- Laboratory data for free-flow conditions in a flume are shown in the following table
- Free-flow conditions were determined for these data because a hydraulic jump was seen downstream of the throat section, indicating supercritical flow in the vicinity of the throat

Q (cfs)	hu (ft)
4.746	1.087
3.978	0.985
3.978	0.985
2.737	0.799
2.737	0.798
2.211	0.707
1.434	0.533
1.019	0.436
1.019	0.436
1.019	0.436
1.019	0.436
0.678	0.337

- Take the logarithm of Q and of h_u, then perform a linear regression (see Eqs. 10 and 11)
- The linear regression gives an R^2 value of 0.999 for the following calibration equation:

$$Q_f = 4.04 h_u^{1.66} \qquad (13)$$

where Q_f is in cfs; and h_u is in ft

- We could modify Eq. 13 to fit the form of Eq. 6, but for a custom flume calibration it is convenient to just include the throat width, W, in the coefficient, as shown in Eq. 13
- Note that the coefficient and exponent values in Eq. 13 have been rounded to three significant digits each – never show more precision than you can justify

Submerged Flow

- Data were then collected under submerged-flow conditions in the same flume
- The existence of submerged flow in the flume was verified by noting that there is not downstream hydraulic jump, and that any slight change in downstream depth produces a change in the upstream depth, for a constant flow rate
- Note that a constant flow rate for varying depths can usually only be obtained in a hydraulics laboratory, or in the field where there is an upstream pump, with an unsubmerged outlet, delivering water to the channel

- Groups of (essentially) constant flow rate data were taken, varying a downstream gate to change the submergence values, as shown in the table below

Q (cfs)	hu (ft)	hd (ft)
3.978	0.988	0.639
3.978	1.003	0.753
3.978	1.012	0.785
3.978	1.017	0.825
3.978	1.024	0.852
3.978	1.035	0.872
3.978	1.043	0.898
3.978	1.055	0.933
3.978	1.066	0.952
3.978	1.080	0.975
3.978	1.100	1.002
3.978	1.124	1.045
2.737	0.800	0.560
2.736	0.801	0.581
2.734	0.805	0.623
2.734	0.812	0.659
2.733	0.803	0.609
2.733	0.808	0.642
2.733	0.818	0.683
2.733	0.827	0.714
2.733	0.840	0.743
2.733	0.858	0.785
2.733	0.880	0.823
2.733	0.916	0.876
2.733	0.972	0.943
1.019	0.437	0.388
1.019	0.441	0.403
1.010	0.445	0.418
1.008	0.461	0.434
1.006	0.483	0.462
1.006	0.520	0.506

- In this case, we will use n_f in the submerged-flow equation (see Eq. 12), where n_f = 1.66, as determined above
- Perform a linear regression for $\ln[Q/(h_u - h_d)^{1.66}]$ and $\ln[-\log_{10}S]$, as shown in Eq. 12, giving an R^2 of 0.998 for

$$Q_s = \frac{1.93(h_u - h_d)^{1.66}}{(-\log_{10} S)^{1.45}} \tag{14}$$

where Q_s is in cfs; and h_u and h_d are in ft

- You should verify the above results in a spreadsheet application

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