CHAPTER 5

OPEN CHANNEL HYDROLOGY

5.9 Gradually Varied Flow

5.9.1 Background

The most common occurrence of gradually varied flow in storm drainage is the backwater created by culverts, storm sewer inlets, or channel constrictions. For these conditions, the flow depth will be greater than normal depth in the channel and the water surface profile should be computed using backwater techniques.

Many computer programs are available for computation of backwater curves. The most general and widely used programs are, HEC-2, developed by the U.S. Army Corps of Engineers (1982) and Bridge Waterways Analysis Model (WSPRO) developed for the Federal Highway Administration. These programs can be used to compute water surface profiles for both natural and artificial channels.

For prismatic channels, the backwater calculation can be computed manually using the direct step method. For an irregular nonuniform channel, the standard step method is recommended, although it is a more tedious and iterative process. The use of HEC-2 is recommended for standard step calculations.

Cross sections for water surface profile calculations should be normal to the direction of flood flow. The number of sections required will depend on the irregularity of the stream and flood plain. In general, a cross section should be obtained at each location where there are significant changes in stream width, shape, or vegetal patterns. Section should usually be no more than 4 to 5 channel widths apart or 100 ft apart for ditches or streams and 500 ft apart for flood plains, unless the channel is very regular.

5.9.2 Direct Step Method

The direct step method is limited to prismatic channels. A form for recording the calculations described below is presented in Table 5.9.2-1

Table 5.9.2-1
Water Surface Profile Computation Form For The Direct Step Method

Location _____

Q = _____ n = _____ S_O = _____ α = _____ y_c = _____ y_n = _____

y (1)	A (2)	R (3)	v (4)	$\alpha v^2/2g$ (5)	E (6)	ΔE (7)	S_f (8)	$\bar{S}_f$ (9)	$S_O - \bar{S}_f$ (10)	Δx (11)	x (12)
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22.											

Notes: _____

(8) $S_f = \frac{n^2 v^2}{2.22 R^{4/3}}$ (11) $\Delta x = \frac{\Delta E}{S_O - \bar{S}_f}$

5.9.2.1 Record the following parameters across the top of Table 5.9.2-1:

Q = design flow (cfs)
n = manning's n value
S_O = channel bottom slope (ft/ft)
α = energy coefficient
y_c = critical depth (ft)

y_n = normal depth (ft)

5.9.2.2 Using the desired range of flow depths, y, recorded in column 1, compute the cross-sectional area, A, the hydraulic radius, R, and average velocity, v, and record results in columns 2, 3, and 4, respectively.

5.9.2.3 Compute the velocity head, $v^2/2g$, in ft, and record the result in column 5.

5.9.2.4 Compute specific energy, delta E, in ft, by summing the velocity head in column 5 and the depth of flow in column 1. Record the result in column 6.

5.9.2.5 Compute the change in specific energy, delta E, between the current and previous flow depths and record the result in column 7 (not applicable for row 1).

5.9.2.6 Compute the friction slope using the

$$S_f = (n^2 v^2)/(2.22\, R^{4/3})$$ **(Eq. 5.9.2.6-1)**

Where: S_f = friction slope (ft/ft)
n = manning's n value
v = average velocity (ft/s)
R = hydraulic radius (ft)

Record the result in column 8.

5.9.2.7 Determine the average of the friction slope between this depth and the previous depth (not applicable for row 1). Record the result in the column 9.

5.9.2.8 Determine the difference between the bottom slope, S_O, and the average friction slope, S_f, from column 9 (not applicable for row 1). Record the result in column 10.

5.9.2.9 Compute the length of channel between consecutive rows or depths of flow using the equation:

$$delta\ x = delta\ E/(S_O - S_f) = Col.7/Col.10$$ **(Eq. 5.9.2.9-1)**

Where:

delta x = length of channel between consecutive depths of flow (ft)
delta E = change in specific energy (ft)
S_O = bottom slope (ft/ft)

S_f = friction slope (ft/ft)
Record the result in column 11.

5.9.2.10 Sum the distances from the starting point to give cumulative distances, x, for each depth in column 1 and record the result in column 12.

5.9.3 Standard Step Method

The standard step method is a trial and error procedure applicable to both natural and prismatic channels. The step computations are arranged in tabular form, as shown in Table 5.9.3-1 and described below:

5.9.3.1 Record the following parameters across the top of Table 5.9.3-1:
Q = design flow (cfs)
n = Manning's n value
α = energy coefficient
k_e = eddy head loss coefficient (ft)
y_c = critical depth (ft)
y_n = normal depth (ft)

5.9.3.2 Record the location of measured channel cross sections and the trial water surface elevation, z, for each section in columns 1 and 2. The trial elevation will be verified or rejected based on computations of the step method.

5.9.3.3 Determine the depth of flow, y, based on trial elevation and channel section data. Record the result in column 3.

5.9.3.4 Using the depth from Step 3 and section data, compute the cross-sectional area, A, in ft, and hydraulic radius, r, in ft. Record the results in columns 4 and 5.

5.9.3.5 Divide the design discharge by the cross-sectional area from Step 4 to compute the average velocity, v, in ft/s. Record the result in column 6.

5.9.3.6 Compute the velocity head, $v^2/2g$, in ft, and record the result in column 7.

5.9.3.7 Compute the total head, H, in ft, by summing the water surface elevation, z, in column 2 and the velocity head in column 7. Record the result in column 8.

5.9.3.8 Compute the friction slope, S_f, using equation 5.9.2.6-1 and record the result in column 9.

5.9.3.9 Determine the average friction slope, S_f, between the sections in each step (not applicable for row 1). Record the result in column 10.

5.9.3.10 Determine the distance between sections, delta x, and record the result in column 11.

5.9.3.11 Multiply the average friction slope, S_f (column 10), by the reach length, delta x (column 11), to give the friction loss in the reach, h_f. Record the result in column 12.

5.9.3.12 Compute the eddy loss using the equation:

$$h_e = (k_e v^2) / 2g \qquad \textbf{(Eq. 5.9.3.12-1)}$$

Where: h_e = eddy head loss (ft)
k_e = eddy head loss coefficient (ft) (for prismatic and regular channels,
k_e = 0; for gradually converging and diverging channels,
k_e = 0 to 0.1 or 0.2; for abrupt expansions and contractions, k_e = 0.5)

Table 5.9.3-1
Water surface Profile Computation Form For The Standard Step Method

Location _____

Q = _____ n = _____ S_o = _____ α = _____ k_e = _____ y_c = _____ y_n = _____

Station (1)	z (2)	y (3)	A (4)	R (5)	v (6)	$\alpha v^2/2g$ (7)	H (8)	S_f (9)	$\bar{S}_f$ (10)	Δx (11)	h_f (12)	h_e (13)	H (14)
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Notes: _____

(9) $S_f = \dfrac{n^2 v^2}{2.22R^{4/3}}$ (12) $h_f = \Delta x\, \bar{S}_f$ (13) $h_e = k_e \dfrac{v^2}{2g}$

K_e = O; for gradually converging and diverging channels, k_e = o to 0.1 or 0.2; for abrupt expansions and contractions, k_e = 0.5)
v = average velocity (ft/s) (column 6)
g = acceleration due to gravity (32.2 ft/s^2)

5.9.3.13 Compute the elevation of the total head, H, by adding the values of h_f and h_e (columns 12 and 13) to the elevation at the lower end of the reach, which is found in column 14 of the previous reach or row. Record the result in column 14.

5.9.3.14 If the value of H computed above does not agree closely with that entered in column 8, a new trial value of the water surface elevation is used in column 2 and calculations are repeated until agreement is obtained. The computation may then proceed to the next step or section reported in column 1.

END OF SECTION 5.9