FLO-2D©

PRO VERSION

TWO-DIMENSIONAL

FLOOD ROUTING MODEL

CHANNEL GUIDELINES

NOVEMBER 2019 - BUILD NO. 19

FLO-2D Software, Inc.

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Chapter 1

This document supplements the FLO-2D Reference Manual, Data Input Manual and training materials such as the webinars and videos, lessons and short course PowerPoint presentations. It presents guidelines and information that are designed to assist the user in developing a model with a detailed 1-D channel. Here is a list of other available references for channel modeling:

C:\users\Public\Public Documents\FLO-2D PRO Documentation

- Data Input Manual
  - Chan.dat, chanbank.dat, xsec.dat
  - Profiles.exe processor program overview
  - Channel output files
- Workshop Lessons
  - Lesson 3 – Simple geometry and confluence
  - Lesson 4 – Simple cross section converter
  - Lesson 5 – Profiles.exe overview and example
  - Lesson 8 – Import from HEC-RAS
  - Lesson 14 – Advanced natural channel modeling
- QGIS Workshop Lessons
  - Lesson 2 – Import from HEC-RAS
- Example Projects w/Channels
  - Urban example
  - Lesson 15 – natural channel with levee
  - Alawai
  - Rio Grande
  - Goat
  - Aqueduct
  - Sediment transport

Sharefile.flo-2d.com – Webinar Series\Channel Series

- Videos
  - Basic channels
  - Advanced channel modeling
  - Channel optimization
  - Advanced natural channels

Channel Overview

The purpose of the FLO-2D 1-D channel component is to simulate channel conveyance and integrate channel and unconfined floodplain flow. Channel flow is simulated as one-dimensional depth averaged flow in the downstream direction. Average flow hydraulics of velocity and depth define the discharge between channel grid elements. Flow is represented by a single water surface within the channel cross section. There is no two-dimensional flow variation within the channel and there is no vertical velocity distribution, secondary currents, or superelevation in channel bends (Figure 1). Flow is only simulated in the downstream direction (x-direction = blue arrow in Figure 1).   The flow is routed between channel elements solving the full dynamic wave momentum equation and the continuity equation. The average flow path length between two channel elements is on the order of the length of the grid element and this precludes the simulation of hydraulic jumps over a short distance. The flow transition between subcritical and supercritical flow is based on the average conditions between two channel elements.

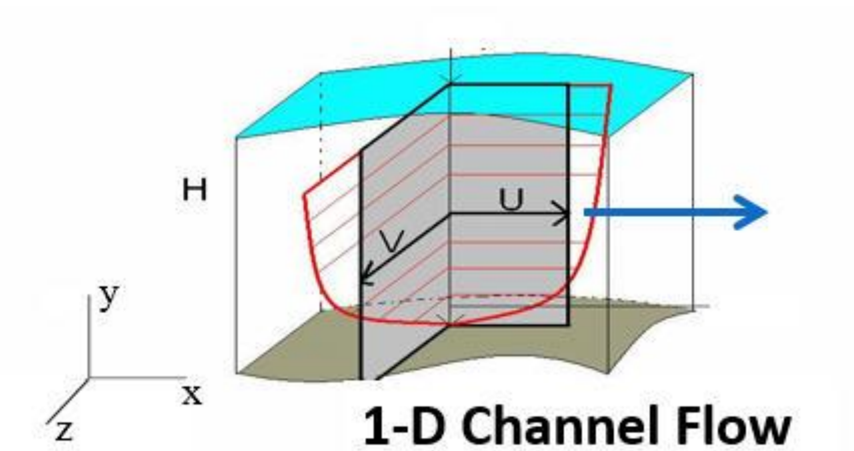


Figure 1. Channel Flow is One-Dimensional.

River flow is simulated with rectangular, trapezoidal or surveyed cross sections. The channels are setup in the CHAN.DAT file by: grid element number, cross section geometry that defines the relationship between the thalweg elevation and the bank elevations, average cross section roughness, and the length of channel within the grid element. Channel slope is computed as the difference between the channel element thalweg (lowest point in the cross section) elevation divided by the half the sum of the channel lengths within the channel elements. Channel elements must be contiguous to be able to share discharge. Tributary and split flow channel elements are contiguous to the left and or right bank of the main channel and need to be identified in the CHAN.DAT file.

Channel Geometry, Length and Roughness

There are four channel geometry options:

- R - Rectangular

- T - Trapezoidal
- N - Natural
- V - Regression Equation (not recommended except for unique cases)

The channel cross section options are rectangular, trapezoidal and natural. In FLO-2D, the floodwave movement in the channel is controlled by the rate of change in the discharge as a function of the rate of change in the flow area (∂Q/∂A). The cross section shape is not critical in the flood routing. It is important when reading the data to set up the relationship between flow area and depth. The rectangular and trapezoid channel bed elevations are computed by subtracting the channel depth from the lowest floodplain bank elevation unless the bank elevations are assigned in the CHAN.DAT file. For these cross sections, since the channel bed elevations are referenced to the floodplain elevation, it is important to review the PROFILES program bed slope before running the model. For the natural channel cross sections, the station data is given by the actual elevation, so the bed profile should reflect the field conditions. The user has several other options for setting up the channel data file including grouping the channel elements into segments, specifying initial flow depths, identifying contiguous channel elements that do not share discharge, and assigning limiting Froude numbers and depth variable n-value adjustments. For data file example refer to the FLO-2D Data Input Manual.

Rectangular

The rectangular channel geometry is defined by width, depth and length of channel inside the grid element (Figure 2).

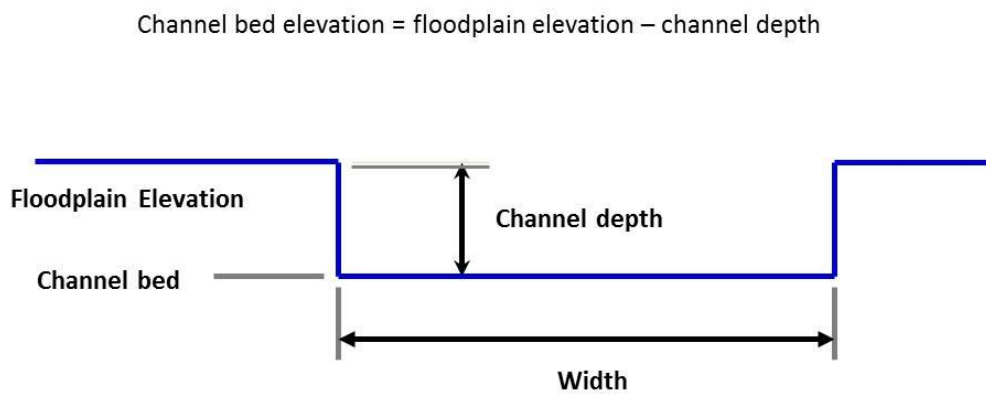


Figure 2. Rectangular Channel Geometry.

Note: The channel bank elevations can be entered directly in the CHAN.DAT file for both rectangular and trapezoidal channels.

Trapezoidal

Similarly, the trapezoidal channels are defined by bottom width, channel depth and side slopes (ratio of horizontal to vertical) (Figure 3). Again, the channel length is the length inside the grid element.

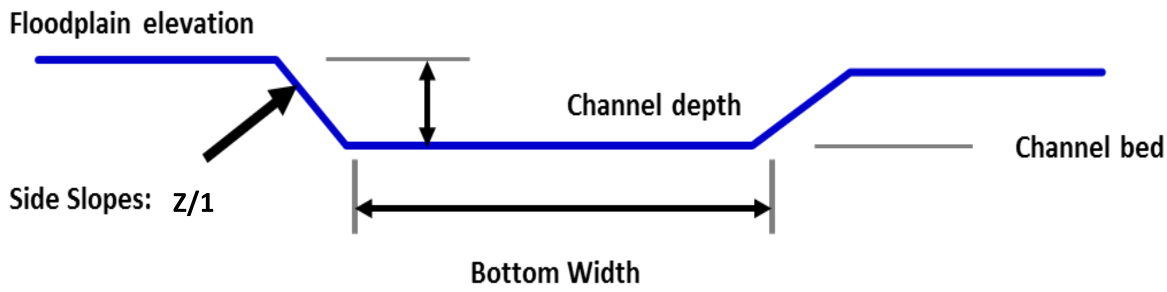


Figure 3. Trapezoidal Channel Geometry.

For small channels, urban channels, or channels with unknown detailed geometry or lack of survey data, a rectangular or trapezoidal cross section representation can be used by estimating the channel configuration. This is certainly the case for a channel with a conveyance capacity less than the 2-year flood event when the floods being simulated are 10-year event or larger. Most of the flood volume is on the floodplain in this situation.

The type of channel geometry can vary within a channel segment. A trapezoidal channel in one channel element can be followed by a rectangular or natural cross section in the next downstream element. Similar channel geometry is typically assigned by segment in CHAN.DAT. In urban areas, there may be a rectangular concrete channel that transitions to a natural cross section. Trapezoidal tributaries represented by one segment can join a mainstem channel segment that has natural cross section geometry.

Natural

Actual river natural cross sections can be modeled if the station and elevation data is available (Figure 4). Geo-referenced cross section station and elevation data can be obtained by survey (land or bathymetry) or by cutting cross sections from a digital terrain model data. This data can be entered directly into the model data files. To use natural cross section data, an XSEC.DAT file has to be created with all cross section station and elevation data. The cross sections are then assigned to a channel element in the CHAN.DAT. The relationship between the flow depth and channel geometry (flow area, wetted perimeter and topwidth) is based on an interpolation of depth between vertical slices as small trapezoids (Figure 5). The vertical slices stop at the lowest top of bank. For flow depths above this the cross section is extended vertically. This data constitutes a channel geometry rating table for each cross section. The cross section data in the XSEC.DAT file can be automatically assigned from a GEO-RAS geometry file using the GDS.

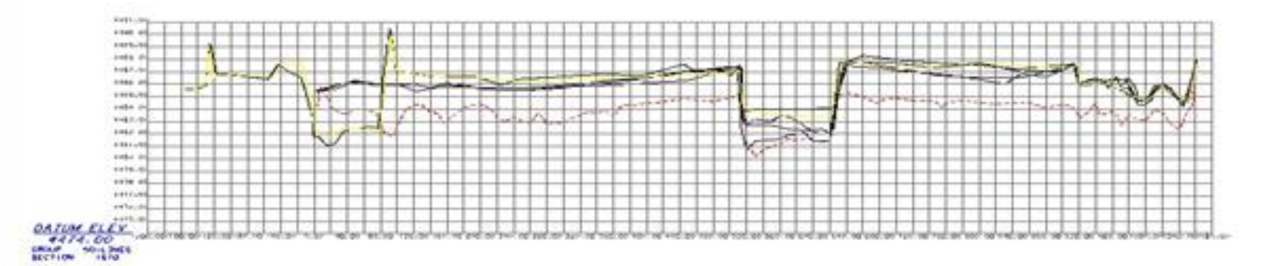


Figure 4. Natural Channel Cross Section Data.

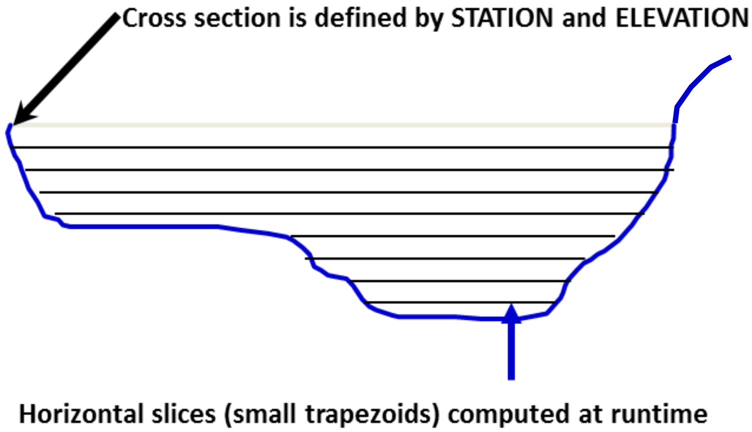


Figure 5. Natural Shape Cross Section Geometry.

Natural river cross sections should be spaced to represent a uniform river reach that may encompass any number of channel elements. Interpolations between cross sections facilitate transitions to changes in geometry. A surveyed or cut cross section might represent 5 to 10 elements but if the channel shape is uniform, cross sections can be spaced farther apart.

A channel cross-section can extend across multiple grid elements (Figure 6). If the channel width is greater than the grid element width, the right bank can extend into neighboring grid elements. For example, a channel may be 1,000 ft (300 m) wide and the grid element only 30 ft (10 m) square. The model also makes sure that there is sufficient floodplain surface area within the left and right bank grids after assigning the right bank. There must at least 5% of a bank grid element available for floodplain storage in order for the channel to interact with the bank floodplain elements to share discharge to the floodplain. Each bank element can have a unique elevation. If the two bank elevations are different in the CHAN.DAT file, the model automatically splits the channel into two elements even if the channel would fit into one grid element.

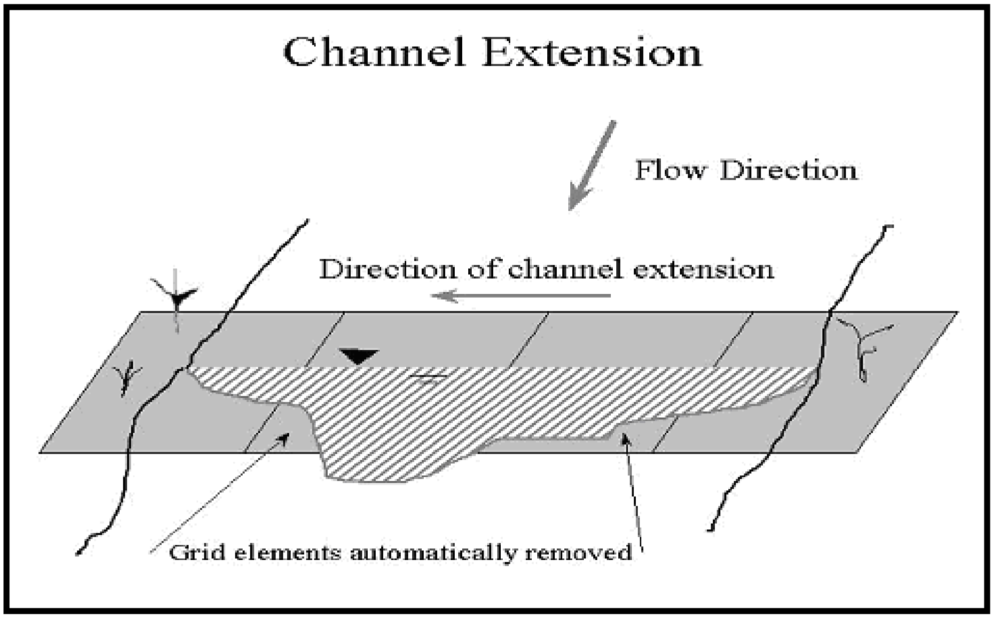


Figure 6. Channel Extension over Several Grid Elements.

There are three options for establishing the channel bank elevation to bed elevation relationship:

1. A prismatic channel element bed elevation (rectangular and trapezoidal channels) is determined by subtracting the assigned channel thalweg depth from the floodplain elevation. .
2. A bank elevation is assigned in the CHAN.DAT file and the channel bed elevation is computed by subtracting the channel depth from the lowest bank elevation. This is appropriated for rectangular and trapezoidal geometry.
3. Station/elevation cross section data is assigned in XSEC.DAT that represents the top of bank and bed elevations in the channel. When using actual cross section data for the channel geometry, option 3 should be applied.

Channel Development

There are several steps required when developing the 1-D channel component in the GDS. These include locating the channel position, interpolating the cross sections or entering geometry data, adjusting the slope, adjusting the length, and assigning the n-values. The step by step processes are outlined in several workshop lesson tutorials and videos. Specifically, Lessons 3, 4, 5, 8, and 14 are tutorials that deal with channel development. The Data Input Manual is another source of information for channel modeling. It lists and describes the data files and variables used to create channels. An overview of the overall process is briefly discussed below.

Locate the channel element with respect to the grid system

Using the GDS and an aerial photo, the channels can be assigned to a grid element. For channel flow to occur through a reach of river, the channel elements must be contiguous neighbors Using the background image, a polyline can be drawn along the left bank to select the left bank elements and then the individual cross sections can be identified with the appropriate channel bank element (Figure 7). This process is completely automated if a GEO-RAS geometry file can be imported with the cross section data.

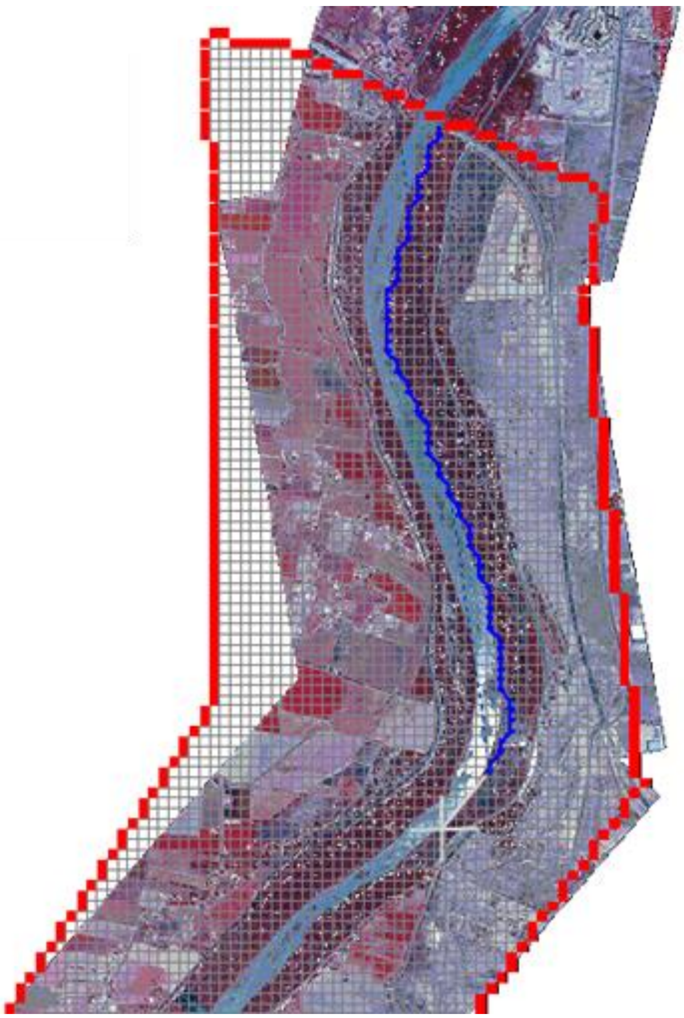


Figure 7. Channel Delineation.

Interpolate the Cross Section

Eventually, each left bank channel element is assigned a cross section in the CHAN.DAT file. Generally, there are only a few cross sections and numerous channel elements, so each cross section will be assigned to represent several channel elements. In the GDS, the surveyed or known cross sections are assigned to corresponding channel elements where they are located, the rest of the channel elements have a zero assigned as the cross section number (Figure 8). A shapefile of cross section locations can be used to help identify the cross section to channel element placement.

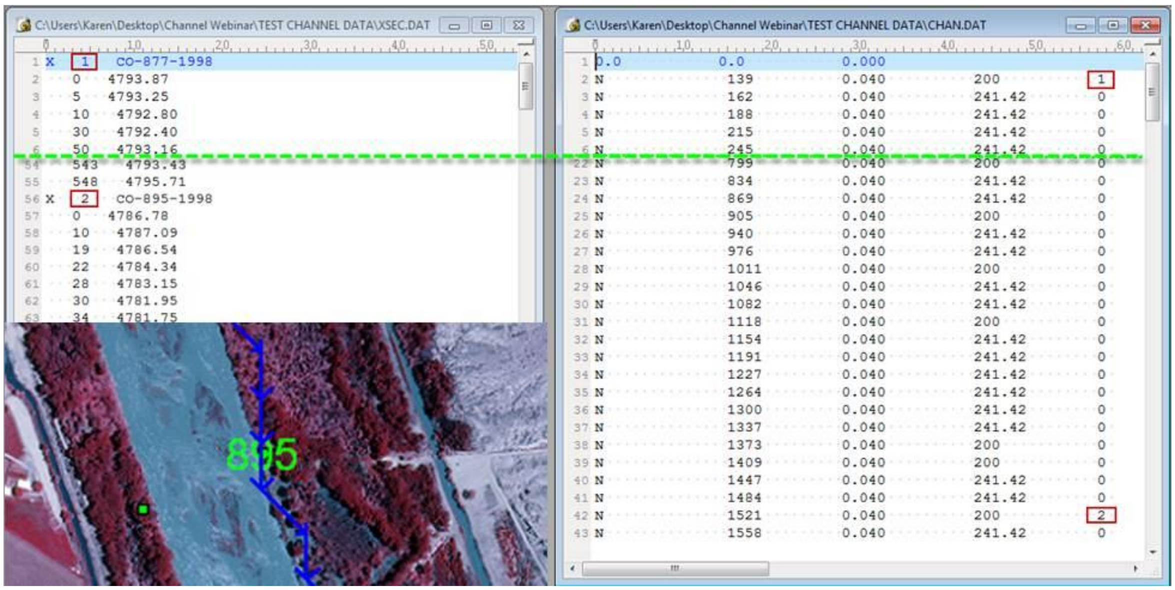


Figure 8. Cross Section Assignment.

When the cross sections have all been assigned the channel bed profile looks like a staircase (Figure 9 top) because the channel elements without a surveyed cross section not been interpolated. The intermediate grid elements without a surveyed cross section must be filled in using interpolation between known cross sections. The command can be performed in the GDS or in the PROFILES program. It adjusts and assigns a cross section data with a linear bed slope for each channel element (Figure 9). The cross section geometry interpolation has two loops. The first loop interpolates only the cross section shape and the second loop is a weighted flow area adjustment to achieve a more uniform rate of change in the flow area between interpolated cross sections. The original cross sections are not edited.

Figure 9. Channel Bed Profile Examples.

Adjust the Channel Bed Slope

Following the channel cross section interpolation, the bed slope is linear between two known or surveyed cross sections. There is no other data available to create a variable bed slope between cross sections. When reviewing the cross section slope, it is possible that there may be abrupt bed slope changes or adverse slope conditions that seem unreasonable. Adverse bed slope in the downstream direction can be accommodated by the model (Figure 9), but subsequent surveys or data collection, may justify adjustments to the bed slope. Re-interpolating the bed slope can be accomplished in the Profiles program for local cross section adjustments.

Assign the Right Bank Element

Once the channel geometry has been assigned and interpolated, the right bank elements can be assigned using a GDS menu command (Figure 10). After the assignment, the right or left banks can be realigned to the better represent the bank locations in the aerial image using mouse point and click commands.

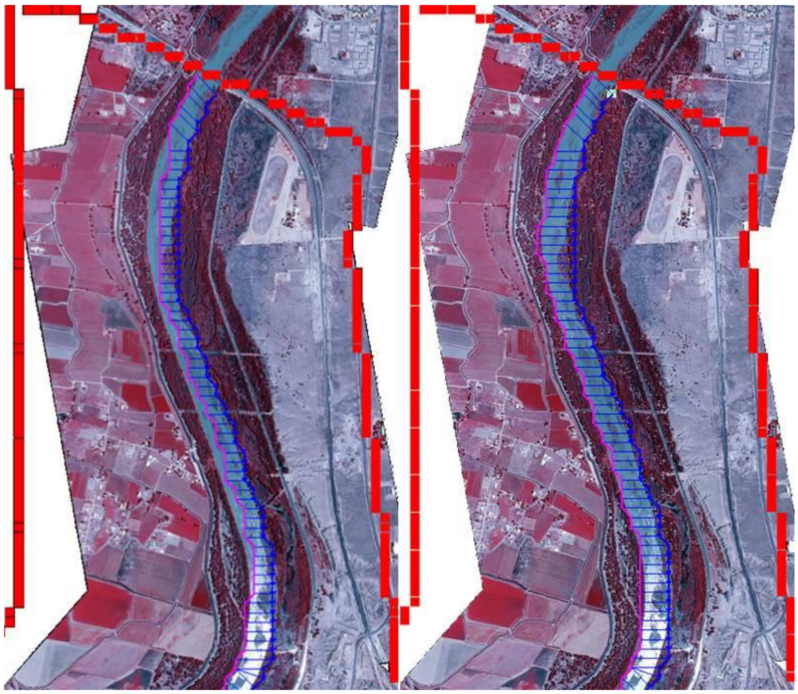


Figure 10. Right Bank Assignment and Realignment.

Channel Length Adjustment

The channel length within each grid element is initially estimated as a straight line for a half grid element and is reported in the GDS dialog box (Figure 11).

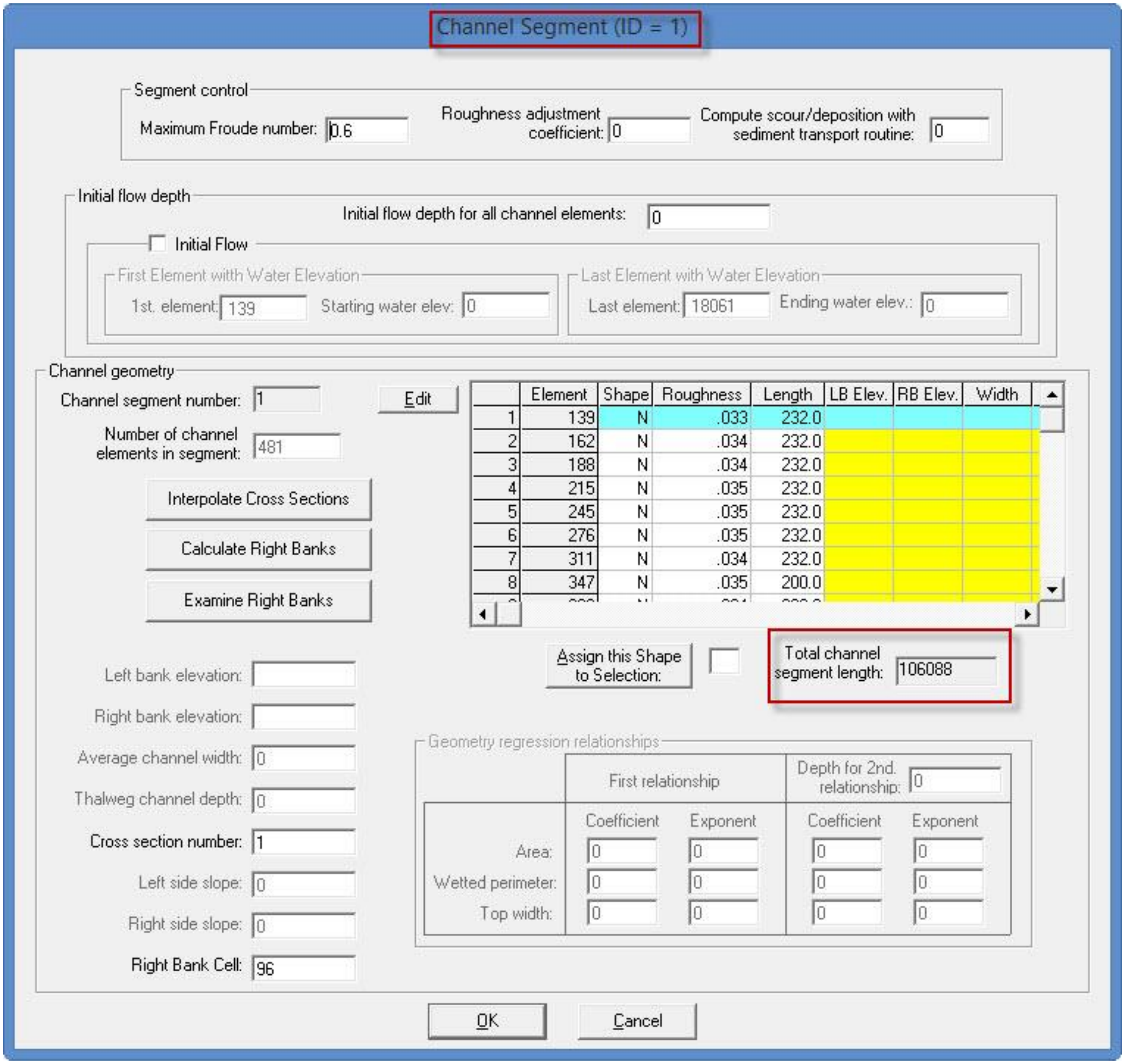


Figure 11. Channel Segment Length and Segment Number.

This value is based on the position of each grid element with respect to its contiguous upstream and downstream neighbors. The length is the sum half the length of the grid element from the center of the node to the edge or corner closest to the upstream or downstream node (Figure 12).

Figure 12. Channel Length for 3 Channel Elements.

The total channel length in the dialog box represents the sum of the individual grid element channel lengths. Using the GDS distance measurement tool in the Tools menu, a channel centerline length can be computed. (This can also be done in any GIS or CADD program). Knowing the channel center-line length, individual channel element lengths can be adjusted so that the total channel length shown in the dialog box matches the centerline length within an acceptable tolerance (e.g. one ft or meter). The total bankfull channel volume is the sum of all the channel element cross section areas times the channel lengths. Adjusting the channel element lengths to have an accurate total channel volume will improve the relationship between the flood volume in the channel and the flood volume on the floodplain. Figure 13 shows the total distance of the channel in the GDS and the isolated channel lengths in the CHAN.DAT file.

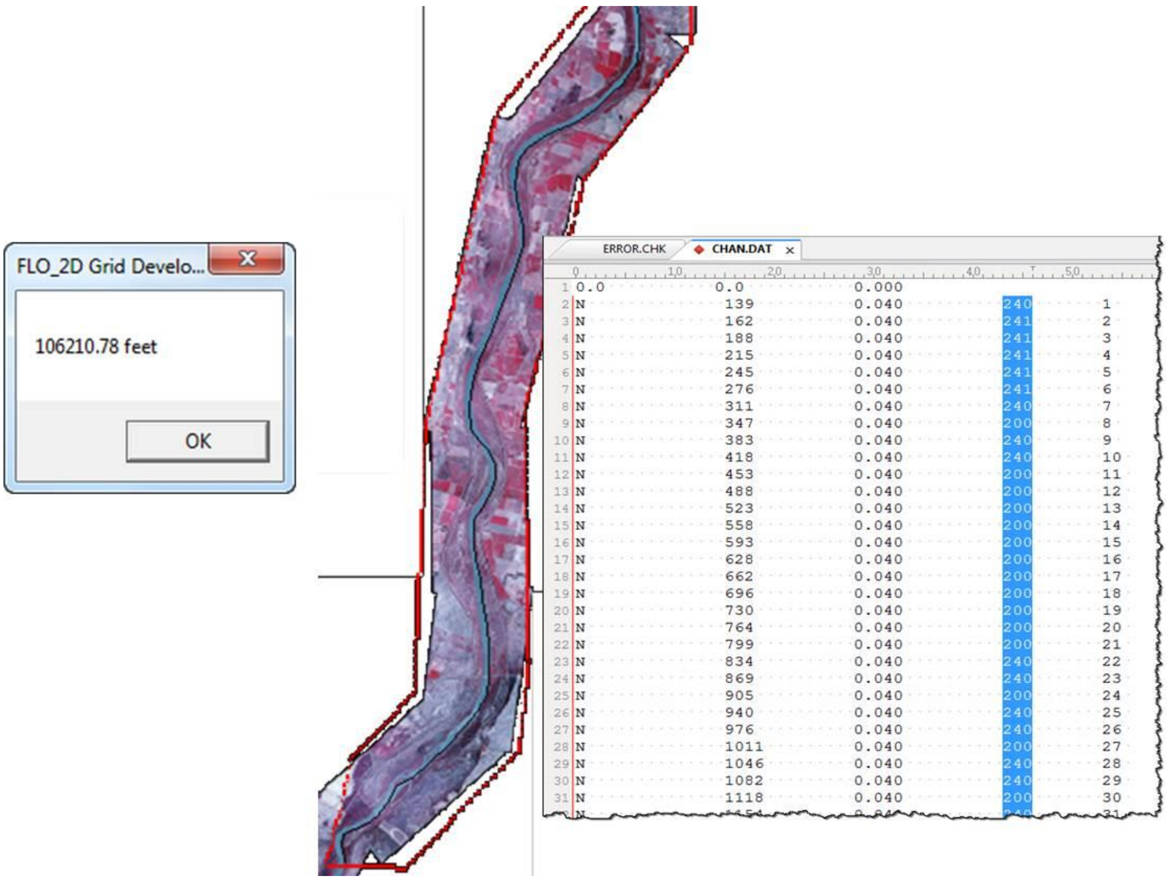


Figure 13. Channel Length.

Channel Roughness

Open channel uniform flow is characterized by a constant depth, velocity, flow area and discharge such that the bed slope, water surface slope and energy grade line are all parallel. Generally, uniform flow dictates that the flow is also steady. Unsteady, uniform flow typically does not occur naturally. For practical purposes, natural uniform flow assumes the turbulent boundary layer is fully developed and the vertical velocity distribution is logarithmic. There are a number of mean velocity equations for open channel uniform flow and Manning's equation is the best known of these:

$$V = 1.486/n\ R^{2/3}\ S^{1/2}$$

where V = velocity, R = hydraulic radius, S = friction slope, n = Manning's roughness coefficient.

The hydraulic radius exponent value (0.667) has been known to vary over a range from about 0.59 to 0.85 depending primarily on channel geometry and roughness (Chow, 1959). The roughness coefficient or Manning's n-value varies with a number of factors including but not limited to bed friction, bed form, expansion/contraction, vegetation, obstructions, and flow depth. As the flow departs from a steady, uniform condition, the n-value must increase if the hydraulic radius and slope exponents remain the same. Higher n-values must be applied to represent accelerating or decelerating flow.

It is important to note that Manning's equation is an empirical formula that was developed on the basis of laboratory and field measurements for steady, uniform, fully developed turbulent flow. Its application however has become universal to virtually all flow conditions. In a FLO-2D flood simulation the flow is rarely steady or uniform. Channel backwater and ponded flow conditions are two instances when Manning's equation may not be appropriate. The flow resistance should be represented by a composite n-value that includes consideration for bed irregularities, obstructions, vegetation, variation in channel geometry, channel expansion and contraction, potential rapidly varying flow and variable river bed forms. Poor selection of n-values or failure to provide spatial variation in roughness can result in numerical surging. Using n-values that represent prismatic channel flow for non-prismatic natural channels should be avoided.

Manning's n-value is also known to increase with decreasing flow depth (Chow, 1959). Manning's equation will overpredict the velocity for shallow flow if typical n-values have been assigned that represent bankfull flow (blue line in Figure 14). Bankfull flow is depicted by the Blue Line. The green Line represents the flow in the photo. Bankfull discharge n-value = 0.035. When the remnant ripples in the photo are covered by a flow of 0.1 ft, n-value = 0.060. When computing velocity for shallow flow depths on the order of 0.1 ft or smaller (tolerance TOL value), unique n-values should be used. In lieu of using different velocity equations, one for deeper flow and one for shallow flow, it is necessary to compensate for overpredicting the low flow velocity by assigning higher shallow n-values or by using depth variable n-value adjustment or both.

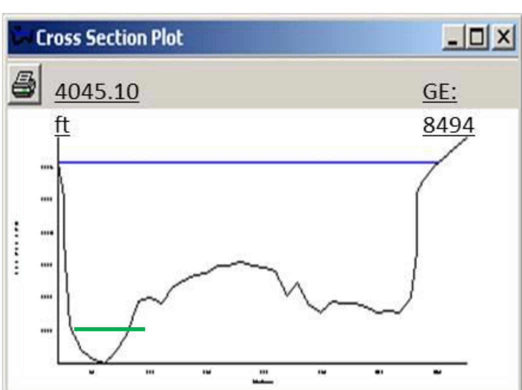


Figure 14. Low Flow vs. Bank Full Discharge.

A channel roughness adjustment can be assigned in the CHAN.DAT file to estimate the n-value at depths below bankfull discharge (Figure 15 – red box).

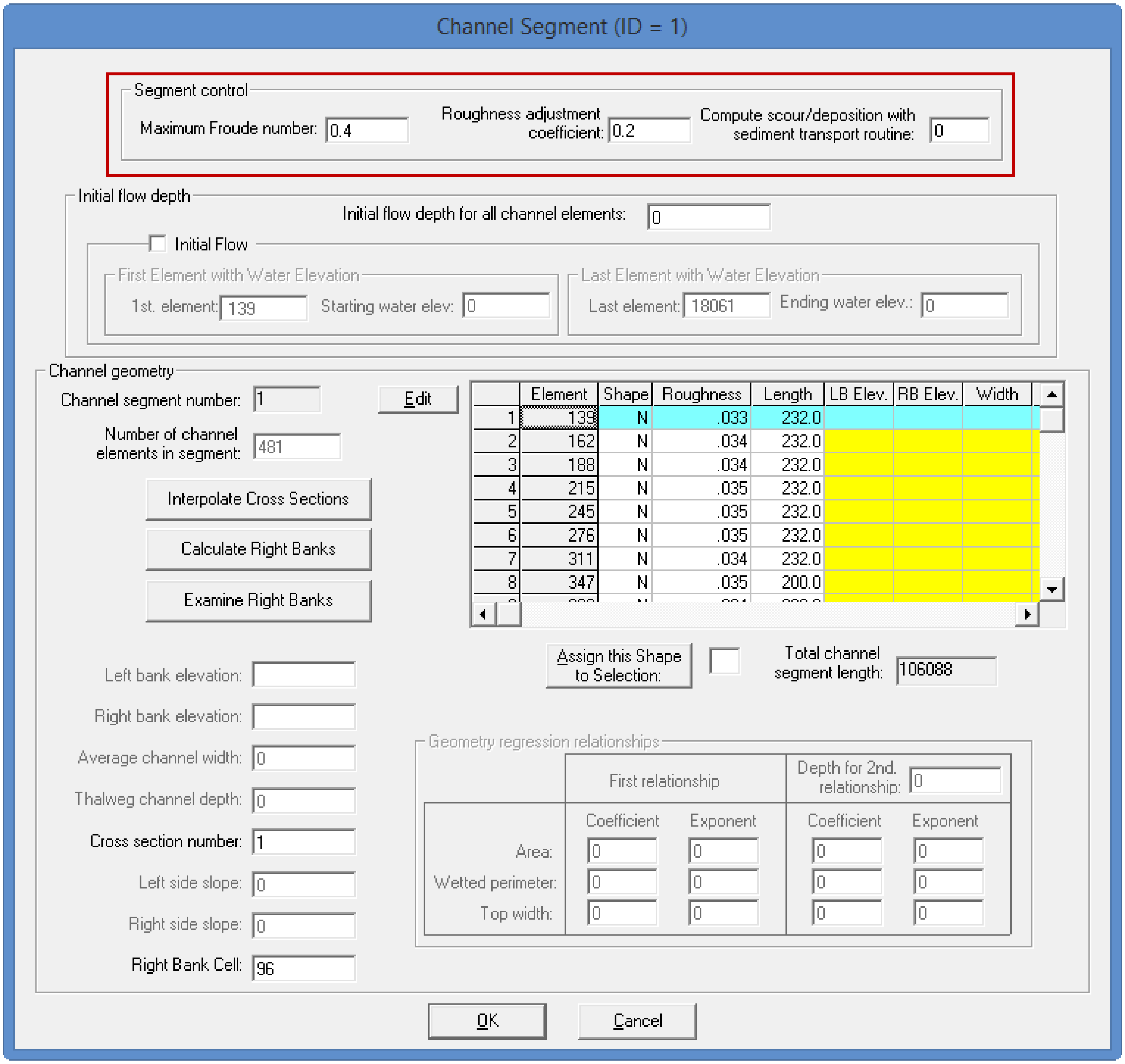


Figure 15. Channel Control Variables.

The n-value assigned in CHAN.DAT should represent the flow roughness near bankfull flow. The depth integrated n-value based on the ROUGHADJ coefficient (0.2 to 0.4) will result in an n-value of 1.5 to 1.8 times the assigned bankfull n-value at a depth of 0.5 ft (0.15 m). Figure 16 shows the relationship between the SHALLOWN (0.2) and the depth integrated n-value for a cross section with a bankfull n-value of 0.03 and ROUGHADJ = 0.4. With this temporal roughness adjustment during the FLO-2D simulation, the arrival of a floodwave can be accurately simulated. If only one n-value is assigned representing bankfull discharge, the Caballo dam release floodwave shown in Figure 17, would arrive at a gaging station in El Paso (107 miles downstream) 6 to 8 hours too soon. Similarly, matching the measured hydrographs at the Jensen, Utah gage from diurnal power plant releases at Flaming Gorge Dam would not be possible without the depth integrated n-value adjustment (Figure 18).

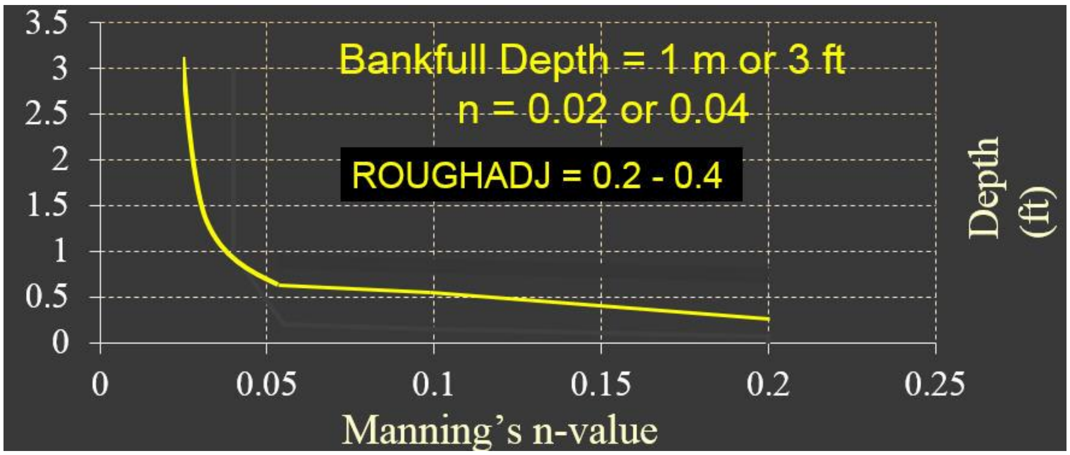


Figure 16. Depth Variable Roughness.

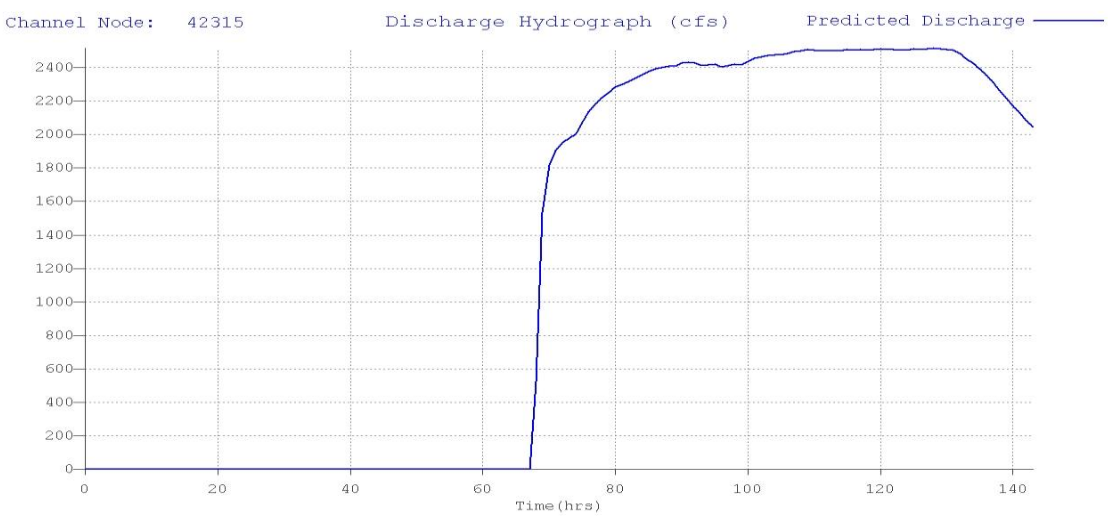


Figure 17. Dam Release Hydrograph El Paso, TX.

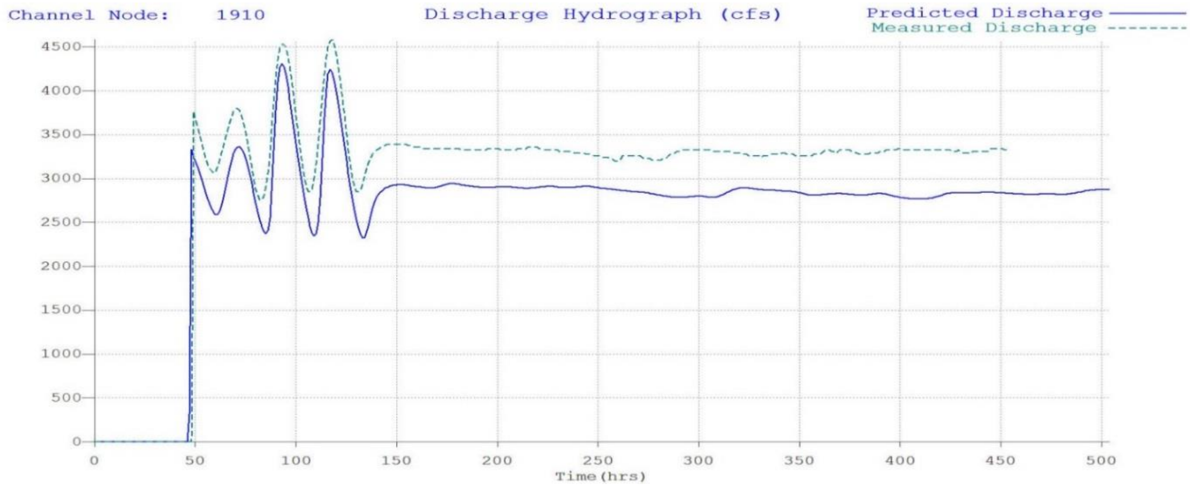


Figure 18. Dam Release Hydrograph Jenson, UT.[1]

The applicability of Manning's equation to a given flow condition depends on the relative submergence of the roughness elements (d/k_s) where d is the flow depth and k_s is the effective roughness height. In general, Manning's equation is appropriate for a relative submergence greater than 100 (Julien, 1995):

$$d/k_s > 100$$

The typical roughness height for grain size bed materials can range from 0.0015 ft for rough concrete to 0.01 ft for coarse sand or uniform earth channels. In this case Manning's equation for a coarse sand plane bed would be applicable to as low as 0.7 ft. In general, Manning's equation should apply (with limited variation n-value with the roughness height if the flow depth is roughly 25 times or more than the relative roughness (Simons and Senturk, 1976 and Chow, 1959). Using these criteria, a flow depth for coarse sand would be about 0.25 ft.

The depth integrated roughness is given by the equation:

$$n_d = n_b \, r_c \, e^{-(r2 \, depth/dmax)}$$

where:

depth = flow depth
d_{max} = bankfull depth
n_b = bankfull n-value
n_d = n-value at the flow depth
r2 = ROUGHADJ factor (0.2 – 0.4)
$r_c = 1./e^{-(r2)}$

[1] The difference in the predicted hydrograph and the measured hydrograph is around 200cfs. This is due to unmeasured tributary flow between the dam and the gage.

The bankfull n-value is defined as the n-value for a depth of 3 ft or 1 m for overland or floodplain and the ROUGHADJ default value is 0.4. The ROUGHADJ factor can be higher ranging up to 1.0 or more, but a typical range is from 0.2 to 0.4. The application of the depth variable roughness has the following advantages:

- Can be used to reduce or eliminate surging from low to high flow;
- Accounts for submerged roughness elements;
- Enhances the modeling upper regime sediment transport.

The basic guidelines for roughness assignment and temporal variation in a FLO-2D model are:

- SHALLOWN – for very shallow flows up to 0.2 ft
- SHALLOWN/2 for flows up to 0.5 ft
- Assign n-values for floodplain flow depths > 3 ft or 1 m (channel – bankfull)
- Use depth integrated n-values (default for floodplain)
- Calibrate n-values for reasonable Froude numbers – adjusted at runtime

Channel – Floodplain Flow Exchange

The channel-floodplain exchange is computed for each channel bank element and is based on the potential water surface elevation difference between the channel and the floodplain for both the left and right bank (Figure 19). The flow can overtop the left bank without overtopping the right bank, they are independent. The velocity of either the channel overbank or the return flow to the channel is computed using the diffusive wave momentum equation. It is assumed that the overbank flow velocity is relatively moderate or small compared to the channel and thus the acceleration terms are negligible. The channel-floodplain flow exchange is limited by the available exchange volume. For return flow to the channel, if the channel water surface is less than the bank elevation, the bank elevation is used to compute the slope for the return flow velocity. The slope is the given by path length (a function of the available floodplain surface area) and the difference between the floodplain water surface elevation and the top of bank elevation. Overbank discharge or return flow to the channel is computed using the floodplain assigned roughness. The overland flow can enter a previously dry channel.

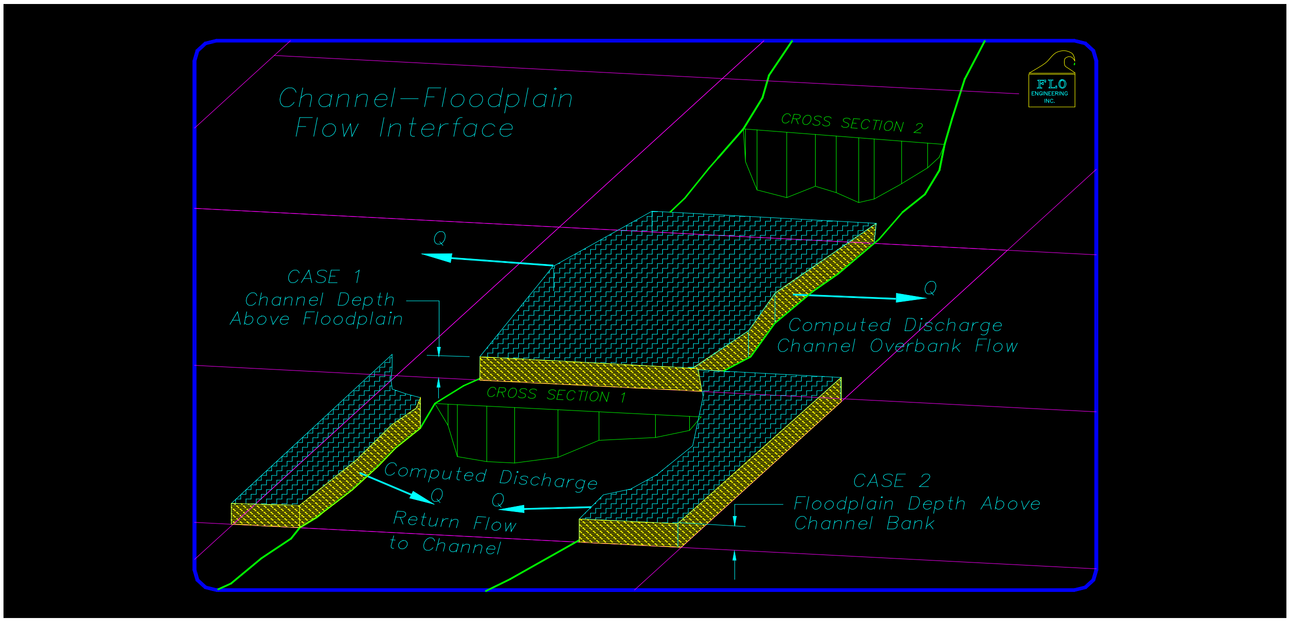


Figure 19. Channel Floodplain Flow Exchange.

Channel flow is exchanged with the floodplain grid elements in a separate routine after the channel and floodplain flow subroutines have been completed. The exchange flow is not subject to the numerical stability criteria associated with the channel or the floodplain. When the channel interface routine is called, the floodplain and the channel computation loops for the timestep have been completed. The interface routine is internal to the model and there are no data requirements for its application.

The channel top-of-bank elevation typically does not match the interpolated floodplain elevation containing the bank element. Often the floodplain elevation interpolation includes some DTM points that are within the dry channel (on the bed or banks of the channel). This lowers the floodplain elevation with for the bank element. When a model simulation begins, if the difference between the surveyed top-of-bank elevation and the floodplain elevation are different by 1 ft or more, the floodplain elevation is reset to the channel top-of-bank elevation. Alternatively, if the overbank slope (difference between the channel top-of-bank and floodplain elevations divided by the grid element side) is greater than 0.01 (1 percent), the floodplain elevation is reset to the channel top-of-bank. This reduces the opportunity for severe overbank or return flow discharge based on unrealistic floodplain conditions.

The floodplain elements with the channel banks n-values are also reset to a minimum 0.065 value to account for channel bank vegetation, floodplain surface irregularities and plunging overbank flow conditions. Often n-values assigned for parking areas, streets or other urban features with n-values are inadvertently assigned to the bank elements. When shapefiles are used to assign n-values, the bank elements can fall within the shapefile limits for a street or parking lot. A minimum n-value assignment of 0.065 will help to avoid overbank exchange discharge spikes that might affect the channel numerical stability.

The 1D natural channel conveyance capacity is based on the highest bank elevation with the lower bank extended vertically to match the higher bank elevation. This eliminates the potential of the natural channel being represented with an exceedingly low bank with essentially no cross sectional flow area. The channel routing is similar to the HEC-RAS assessment of channel cross sections. It does not significantly change the potential for overbank discharge exchange with the floodplain. It only slightly increases the flow area for channel hydraulic computations. The channel conveyance flow area for a natural channel is increased by the green space in Figure 20.

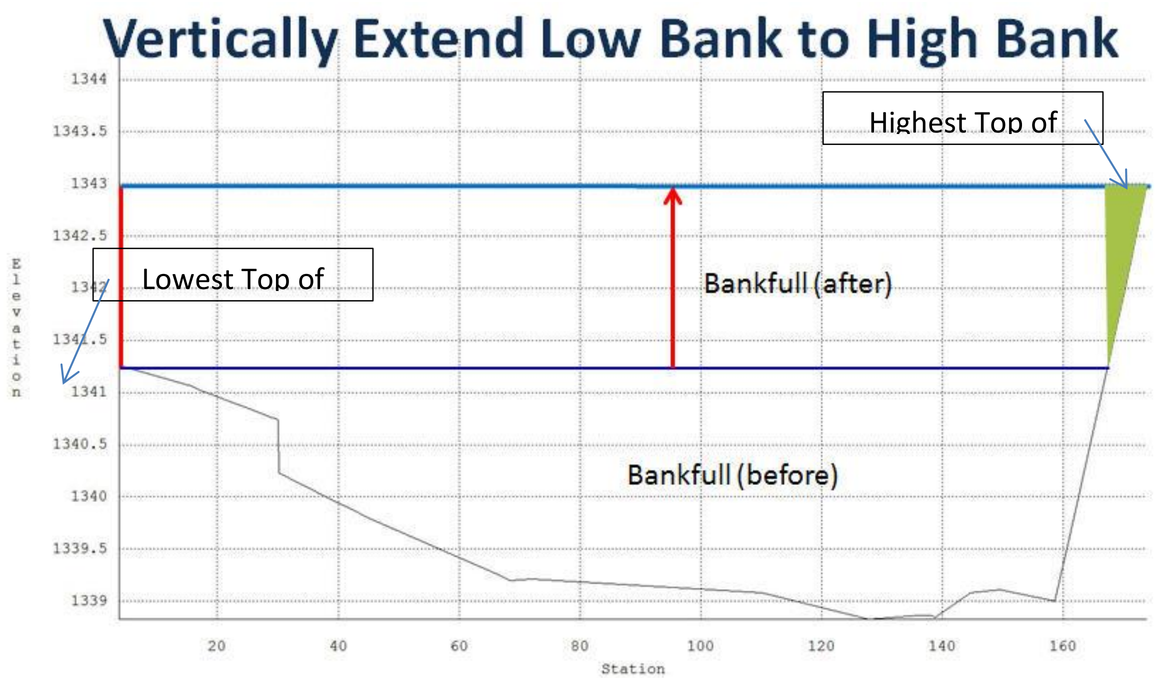


Figure 20. Vertical Extension of the Lowest Top of Bank to the Highest Top of Bank.

Channel Numerical Stability and Volume Conservation

Channel numerical stability requires the convergence of the routing algorithm solution to the full dynamic wave equation for velocity. For almost any channel configuration, a small timestep will eliminate the numerical surging. The key to efficient computational flood routing for a finite difference model with an explicit numerical scheme is appropriate numerical stability criteria that limits the timestep to avoid surging and yet allows timesteps that are large enough to complete the simulation in a reasonable time.

FLO-2D has a variable timestep that is a function of the numerical stability criteria. The numerical stability criteria are checked for the every channel element for every timestep. If the numerical stability criteria for any channel element are exceeded, the timestep is decreased and all the previous hydraulic computations for that timestep are discarded.

The Courant Number is used in the FLO-2D model as the stability criteria to control the timestep. The Courant Number relates the floodwave movement to the model discretization in time and space. The concept of the Courant Number is that a particle of fluid should not travel more than one spatial increment Δx (channel element length) in one timestep Δt. In the FLO-2D model the Courant number limits the timestep Δt by:

$$\Delta t = C \, \Delta x / (V + c)$$

where:

C = Courant Number ($C \leq 1.0$)
Δx = square grid element width
V = depth averaged velocity
c = floodwave celerity = $(gd)^{0.5}$ where g is gravitation acceleration and d is the flow depth

The Courant Number C can vary from 0.0 to 1.0 (recommended range 0.2 to 0.6), and a value of 1.0 in FLO-2D would enable the model to have the largest possible timestep. While the Courant condition is a necessary condition solution convergence, it is not always sufficient to guarantee numerical stability. When C is set to 1.0, artificial or numerical diffusivity is theoretically zero for a linear convective equation. In previous versions of FLO-2D, the Courant Number was hardwired in the model with a value of C = 1.0. Recent testing has shown that the model can run faster (more consistent higher timesteps) with greater stability if the Courant Number is set to values less than 1.0. A starting value of C = 0.6 is recommended. Some guidelines for applying the Courant number are:

1. Use the default stability criteria for the initial simulation:
    - Courant Number C = 0.6
    - DEPTOL = 0.0
    - WAVEMAX = 0.0.
2. If the model has no numerical surging or unreasonable maximum velocities, the model can run faster by increasing the Courant Number to 0.7 or 0.8.
3. If the model has some numerical instability, decrease the Courant Number by 0.1 to a minimum value of 0.3.
4. After a flood simulation is complete, review the TIME.OUT file to determine which of the stability criterion is slowing down the model.

It has been determined that the Courant Number is more effective in controlling numerical instability surging than the other FLO-2D stability parameters DEPTOL and WAVEMAX. It is recommended that both parameters be set to zero.

Channel instability arises because of a mismatch in the channel flow area, friction slope and n-value (Figure 21). Discharge is a function of the friction slope S_f in Manning's equations to the one-half power and is inversely proportional to the n-value, but the discharge is a function of the flow area A to approximately the 5/3 power.

$$Q = f(A, S, n)$$

where $A = a\, d^b$ and a = power regression coefficient and b = power regression exponent

Assigning a reasonable n-value that balances flow area and slope will make the model more stable.

To identify channel surging, first review the VELTIMEC.OUT file for any unreasonable maximum velocities (listed by grid element and time in descending order). The CHANMAX.OUT file lists the maximum discharge, maximum stage and time of occurrence, and can also be reviewed for numerical instability. The HYDROG program plotted hydrographs (Figure 21) can also reveal channel surging. Typically steep rising hydrographs and small channel storage cause the most frequent surging issues (Figure 22). The rate of change in the discharge flux ($\Delta Q/\Delta t$) is the culprit.

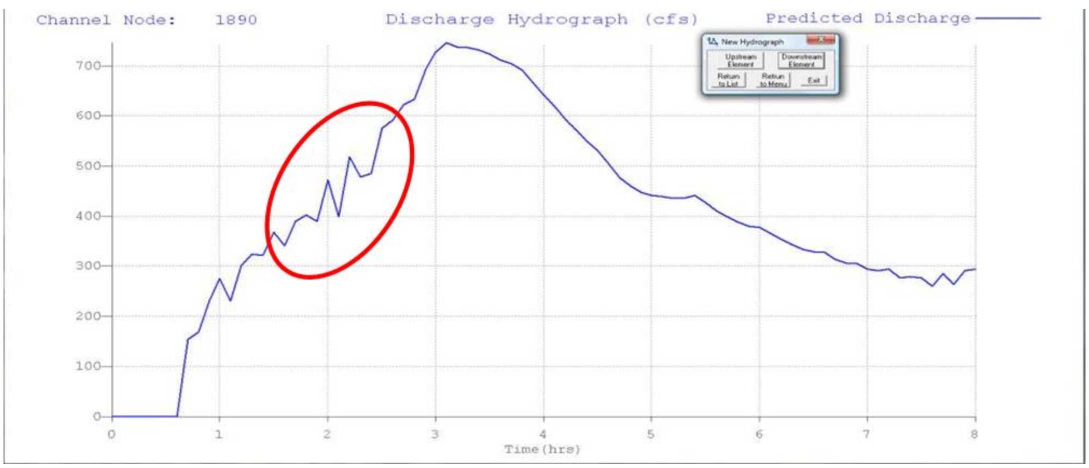


Figure 21. Surging Observed in a Channel Element Hydrograph.

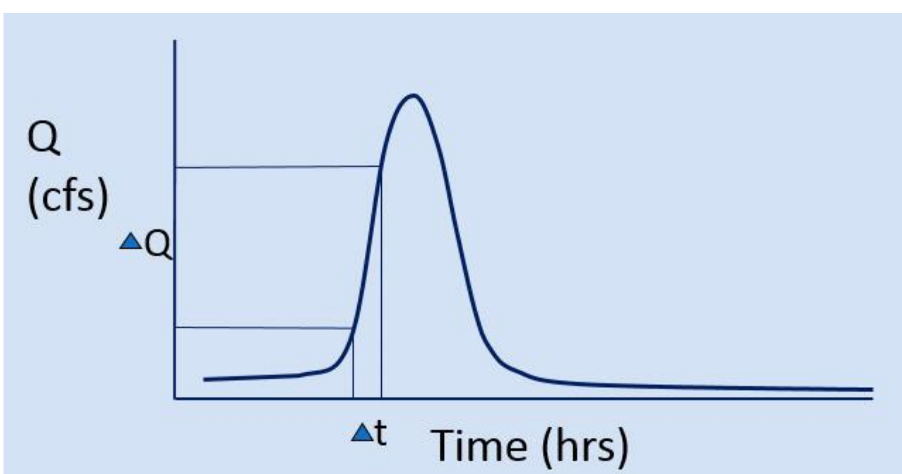


Figure 22. Steep Rising Hydrograph.

A steep rising hydrograph, intense rainfall, or severe overland flow to the channel may cause instability near the inflow node or at any location in the channel where the conveyance capacity may be highly variable. To eliminate channel surging, perform the following steps:

1. Check the bed profile for unreasonable spikes (PROFILES program – Figure 23);
2. Adjust the n-values (particularly in channel area transition reaches);
3. Adjust the flow area - smooth out the area transitions (re-interpolate the cross sections);
4. Apply the depth variable roughness;
5. Use limiting Froude number FROUDC.

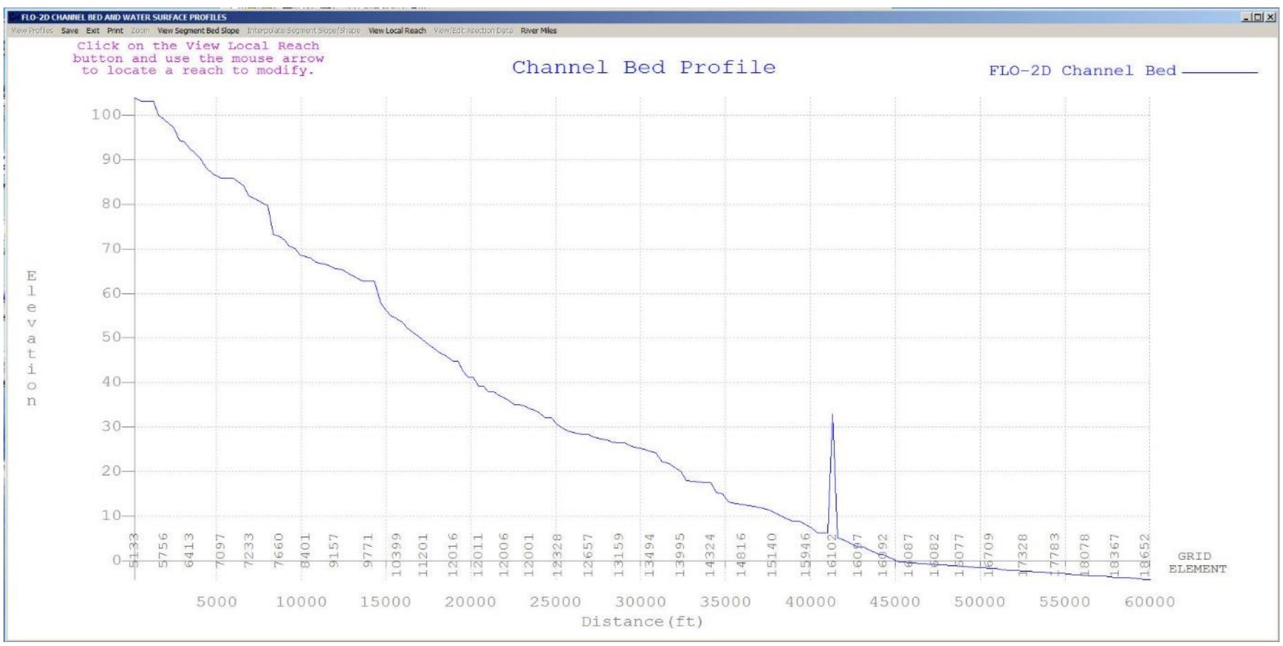


Figure 23. Check the Channel Bed Profile for Data Errors.

The Froude number is important for several reasons:

- It delineates subcritical and supercritical flow;
- It is the ratio of average flow velocity to shallow wave celerity;
- It relates the movement of a translational wave to the stream flow;
- It defines an appropriate relationship between velocity and depth.

Most models report the Froude number or provide warnings when the Froude number is high, but do not make any model adjustments at runtime to limit unreasonable Froude numbers from being encountered. The Froude number is directly related to model stability through the Courant number:

$$C = c(F + 1)/(\Delta x / \Delta t)$$

where:

C = selected value of Courant number
F = Froude number
c = wave celerity = $(gd)^{0.5}$; d = flow depth, g = gravitational acceleration
Δt = timestep
Δx = channel element length

Channel instability arises when the Froude number is high, the timestep is large, or the computation length is small (small channel conveyance capacity).

Jia (1990) suggested that the trend towards a minimum Froude number is a mechanism that controls the channel adjustment. The minimum Froude number concept states that an alluvial channel system tends to seek its lowest potential energy and attain higher stability as it evolves. This indicates that the greater the bed material movement, the lower the channel stability. It follows, therefore, that a channel with low bed material transport and high stability will also have minimum hydraulic values. As alluvial channels approach equilibrium conditions, the Froude number will seek a value that reflects minimum bed material motion and maximum channel stability. Since the Froude number identifies a hydraulic state, the most stable condition for sand-bed channel equilibrium is directly related to a minimum Froude number.

Establishing a limiting Froude number in a flood routing model can help maintain the numerical stability. In alluvial channels, the practical range of Froude numbers at bankfull discharge is 0.4 to 0.6. Typically supercritical flow on alluvial fans is suppressed by high rates of sediment transport. High velocities and shallow depths on alluvial surfaces will dissipate energy with sediment entrainment. Supercritical flow is more prevalent on hard surfaces such as concrete-lined channels. Jia (1990) provides a relationship to estimate a minimum Froude number (Fr_{min}) for stable alluvial channels at equilibrium:

$$Fr_{(min)} = 4.49\ d^{-0.186}\ (VS)^{0.377}$$

Where:

d = representative sediment size (typically D_{50})
V = velocity and S = bed slope.

Recommended limiting Froude numbers are:

- Major rivers: 0.3 – 0.6
- Floodplain: 0.5 – 0.8
- Alluvial fans: 0.9 – 1.1
- Street flow: 1.1 – 1.75

When a limiting Froude number (FROUDC in CHAN.DAT) is assigned, the model computes the channel Froude number for each timestep. If the limiting Froude number is exceeded, the Manning's n-value is increased according to the following criteria:

percent change from the original n-value	n-value increment increase
< 20	0.0002
20 < % < 50	0.0001
50 < % < 100	0.00002
100 < % < 200	0.000002

On the recessional limb, when the limiting Froude number is no longer exceeded, the n-value is decreased by 0.0001. This increase in flow resistance mimics increasing energy loss as the flow accelerates. When the limiting Froude is exceeded, the changes in the n-value are reported in the ROUGH.OUT file. When the simulation is completed the maximum n-values in the ROUGH.OUT file are written to CHAN.RGH. After reviewing the maximum n-value changes in ROUGH.OUT and making any necessary changes in the CHAN.RGH file, this file can be renamed to CHAN.DAT for the next simulation. In this manner, the channel n-value is spatially calibrated to a reasonable Froude number. Spatially variable limiting channel Froude numbers (FROUDC) can be assigned by segment (reach) in the first line of each segment (control line). For the final model product, the ROUGH.OUT should be almost empty and the limiting Froude numbers can be turned off.

Supercritical flow in alluvial mobile bed channels is limited because of the rapid energy dissipation associated with sediment entrainment and bed erosion. As slope increases, competent flow for sediment transport asymptotically approaches critical flow. In most instances, flow is forced to be less than critical by incipient motion thresholds. This will define a limiting Froude number as given by Grant (1997):

$$F_r = 3.85\ S^{0.33} \quad \text{gravel bed } (\tau^*_{cr} = 0.03)$$

$$F_r = 5.18\ S^{0.11} \quad \text{sand bed } (\tau^*_{cr} = 0.06)$$

For mobile bed channels a steep slope is required for flow to approach critical because the hydraulics oscillate with sediment entrainment. These relationships define the upper limit Froude number for sand and gravel for slopes < 0.10. There is a unique relationship that exists between slope, flow area and roughness. The Froude number (Fr) is related to the flow resistance K and the energy slope S as given by:

$$Fr = (KS)^{0.5}$$

If there is a mismatch between these physical variables in a flood routing model, then high velocities can occur that may result in flow surging. Assigning a limiting Froude number has several practical advantages. First, it helps to maintain the average flow velocity within a reasonable range. Secondly, a review of the increased n-values in ROUGH.OUT will identify any trouble spots where the velocity exceeds a reasonable value. In this case, the roughness value is increased to offset an inappropriate flow area and slope relationship. When the adjusted n-values in CHAN.RGH are used for the next simulation, the effect of the mismatched variables is reduced and numerical surging is dampened. In addition, the increased n-values can prevent oversteepening of the frontal wave. The final n-values used in a simulation should be carefully reviewed for reasonableness. The limiting Froude numbers can be set to "0" for the final simulation to avoid any additional adjustments in the n-values.

In summary, most channel surging occurs in channel transition reaches from wide to narrow or narrow to wide because of the mismatched change in n-value (or no n-value variation) with the changing flow area and bed slope. This will be discussed further in the troubleshooting section. Steady, uniform flow (Manning's eqn.) n-values are not equivalent to unsteady, non-uniform grid element n-values in a discretized flood routing model. FLO-2D numerical stability is inherently linked to the Courant number and a reasonable local Froude number.

A complex urban model can conserve volume and still have channel instability. Surging is often limited to a few channel elements over one time step or just a few time steps. Volume conservation errors are almost always data errors and typically grow with time. A volume conservation error that is greater than 0.001 percent can be improved. A successful simulation generally has a volume conservation error less than 0.000100 percent. The volume conservation accounting can be reviewed in the SUMMARY.OUT (Figure 24) as shown below for a project that had excellent volume conservation.

```
    335.001                  6.702               -0.000629         0.000001
    336.000                  6.702                0.000143         0.000000
===============================================================================
                    MASS BALANCE    INFLOW - OUTFLOW VOLUME
===============================================================================
                          *** INFLOW (ACRE-FEET) ***

                                                WATER

INFLOW HYDROGRAPH                             100199.37
                                              ---------

===============================================================================
                          *** OUTFLOW (ACRE-FT) ***

          OVERLAND FLOW                         WATER

WATER LOST TO INFILTRATION                      4393.02

WATER LOST TO EVAPORATION                        494.90

FLOODPLAIN STORAGE                              2342.14

FLOODPLAIN OUTFLOW HYDROGRAPH                    405.07
                                              ---------

FLOODPLAIN OUTFLOW, INFILTRATION & STORAGE      7635.12

          CHANNEL FLOW

CHANNEL INFILTRATION                             841.57

CHANNEL EVAPORATION                             1047.86

CHANNEL STORAGE                                11873.42

CHANNEL OUTFLOW                                78801.39
                                              ---------

CHANNEL OUTFLOW AND STORAGE                    92564.24

===============================================================================
                                *** TOTALS ***

TOTAL OUTFLOW FROM GRID SYSTEM                 79206.46

TOTAL VOLUME OF OUTFLOW AND STORAGE           100199.36

TOTAL EVAPORATION:                                 3.52 INCHES
```

Volume Conservation

Figure 24. SUMMARY.OUT Example.

The CHVOLUME.OUT file reports the channel volume conservation. Usually if there is a volume conservation error it is in the channel and both CHVOLUME.OUT and SUMMARY.OUT will report the same error. CHVOLUME.OUT (Figure 25) is listed below:

CHANNEL VOLUME CONSERVATION (ACRE FEET)

TIME (HRS)	INFLOW + RAIN	CHANNEL STORAGE	CHANNEL OUTFLOW	OVERBANK OUTFLOW	RETURN INFLOW	INFILTRATION	EVAPORATION	VOLUME CONSERVATION
0.10	0.07	0.07	0.00	0.00	0.00	0.00	0.00	0.000000
0.20	0.42	0.42	0.00	0.00	0.00	0.00	0.00	0.000000
0.30	1.17	1.17	0.00	0.00	0.00	0.00	0.00	0.000000
0.40	2.33	2.15	0.00	0.18	0.00	0.00	0.00	0.000000
0.50	3.91	3.60	0.00	0.31	0.01	0.00	0.00	0.000000
0.60	5.87	5.37	0.00	0.60	0.10	0.00	0.00	0.000000
0.70	8.19	7.29	0.00	1.07	0.16	0.00	0.00	0.000000
0.80	10.79	9.60	0.00	1.41	0.21	0.00	0.00	0.000000
0.90	13.78	12.33	0.00	1.66	0.22	0.00	0.00	0.000000
1.00	17.12	15.40	0.00	1.94	0.22	0.00	0.00	0.000000
1.10	20.79	18.55	0.08	2.37	0.22	0.00	0.00	0.000000
1.20	24.75	19.42	2.46	3.08	0.22	0.00	0.00	0.000000
1.30	29.08	19.94	5.27	4.10	0.24	0.00	0.00	0.000000
1.40	33.65	20.47	8.15	5.38	0.35	0.00	0.00	0.000000
...								
9.10	686.25	16.18	517.48	582.13	429.54	0.00	0.00	-0.000043
9.20	688.11	15.86	520.24	582.14	430.14	0.00	0.00	0.000051
9.30	689.91	15.55	522.92	582.15	430.71	0.00	0.00	0.000014
9.40	691.68	15.23	525.53	582.16	431.25	0.00	0.00	0.000016
9.50	693.35	14.93	528.01	582.16	431.75	0.00	0.00	0.000009
9.60	694.98	14.63	530.42	582.16	432.22	0.00	0.00	-0.000020
9.70	696.52	14.32	532.70	582.16	432.66	0.00	0.00	0.000000
9.80	698.02	14.01	534.93	582.16	433.08	0.00	0.00	-0.000003
9.90	699.44	13.71	537.05	582.16	433.48	0.00	0.00	0.000017
10.00	700.79	13.37	539.11	582.17	433.85	0.00	0.00	0.000000

No Volume Conservation Error

Figure 25. CHVOLUME.OUT Example.

Channel data issues that might lead to a volume conservation error include:

- Inappropriate Profile
- Wrong or missing channel elements (typos)
- No channel outflow element
- Missing bank stations in the cross section data
- Conflicts with hydraulic structures or other components
- Radical cross section shape or area changes between two contiguous elements

Every completed FLO-2D project should demonstrate that volume was accurately conserved. Troubleshooting channel volume conservation errors is discussed in Chapter 3.

Chapter 2

Guidelines and Getting Started - Channels in the Urban Environment

Overview

When getting started on a new FLO-2D project, initially create an overland flow model with an inflow and outflow node. If necessary, create fake inflow hydrograph(s) and let the water run all over the grid system (Figure 26). This will indicate the potential area of inundation. Following this preliminary simulation, the details can be added to create an urban model. Starting simple and gradually building a project will avoid many component conflicts. Constructing a complex project with many details before the preliminary simulation is highly discouraged. A suggested order of component development is:

- Finalize the inflow hydrology – perhaps add return period inflow hydrographs where appropriate.
- Add the rain and infiltration. This will complete the total source volume.

Turn off the rainfall and infiltration and test the remaining components using temporary inflow hydrographs as needed to test specific components.

- Add mainstem channels in segments.
- Add tributary channels as separate segments.
- Add channel hydraulic structures.
- Add other urban components in no specific order…streets, buildings – ARF values, levees, etc.
- Add the storm drain.
- Other details: Sediment transport, groundwater, mudflows, etc.

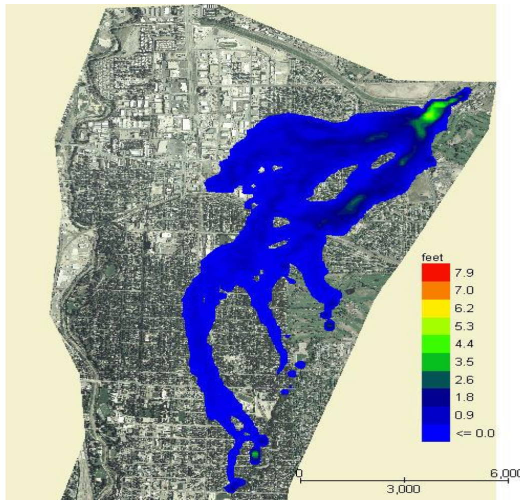


Figure 26. Start a Project with a Grid System and an Inflow Hydrograph Only.

Cutting channel cross sections from DTM data

Any GIS program can be used to cut cross section profiles from an elevation data set. One of the most functional software for this task is HECGeoRAS because it has an excellent cross section editor. HECGeoRAS works well for developing the entire channel system including cross sections, banks, and a channel thalweg line. HECGeoRAS channels can be imported directly into the GDS and the cross section conversion program works well. Civil 3D is also well suited for cross section development. Its visual functionality is probably the most robust of available GIS editing programs. Civil 3D also has an extensive self-help library with tutorials and videos.

Cutting cross sections requires several GIS source files including high resolution elevation data, polyline shapefiles of the banks, channel thalweg and cross sections. It may also be necessary to refine the elevation data using breaklines to help define the thalweg and banks. Elevation data should be in the form of a TIN or high-resolution raster to help facilitate editing the data. When cutting the profile of a cross section, the station elevation orientation should be from left to right looking down stream.

Cutting cross sections from elevation data can have problems that should be addressed before finalizing the cross section data base. Regardless of the level of accuracy, an elevation dataset will have some overlap in the channel beds and banks and the profile cutting tools from different software will give different results. Cutting cross sections from different elevation data files may give different results. Cutting the profile in slightly different places will also give different results. The elevation data is only valid as of the day it is flown. As the dataset ages, the actual channel geometry evolves with flow. Some of the issues are:

- What was the original channel morphology and how much has it changed?
- What is the channel base flow?

- How does the base flow change in the downstream direction?
- What will be the bed form at high flows?

These questions can usually be answered during a site visit. Look at the overall picture including the channel geometry, makeup of the bed material, any obstructions and how the channel evolves in the downstream direction. Take pictures and notes to help understand what the channel system is trying to do. Determine the slope of the channel and estimate a trapezoidal or rectangular area. Do a calculation to estimate a bank full discharge. If the cut cross sections cannot contain that discharge, they need to be reviewed. Go over photographs of the channel, review the aerials and review the elevation data. This process will probably reveal reasons for discrepancies in capacity.

Working with channel cross section data

Some of the issues associated with channel geometry data are discussed in this section. The best approach for working with cross section data is to review each channel element cross section plot and the corresponding flow area, top width and wetted perimeter in the PROFILES program to identify any radical variations in the geometry on a channel element basis.

Flow area variation

Cross sections can have a similar appearance but have a completely different geometry (Figure 27). In this figure, two cross sections are contiguous but only one controls the flow. One cross section has a bank full flow area of 33 ft^2 and the second one has 139 ft^2. It is necessary to review the data source for each cross section to ensure they represent the physical configuration.

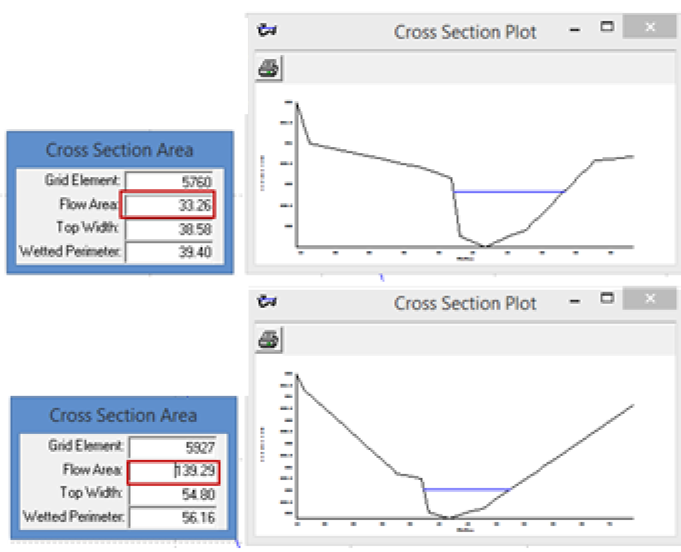


Figure 27. Cross Section Comparison.

Braided channels

Braided channels can be poorly represented by cut cross sections. The top of banks may be obscured with a cut cross section showing multiple high points that could be the active channel (Figure 28). The braided channel may also be reworked by recent flooding creating wide variation in flow areas. Typically, the braided channel will convey a 2-year to 5-year return period flood within its banks. The channel may increase its bankfull capacity during the flood event. If the cut cross section cannot be accurately delineated with aerial photos or field observations, the channel cross section shape may have to be estimated or small grid elements can replace the 1-D channel.

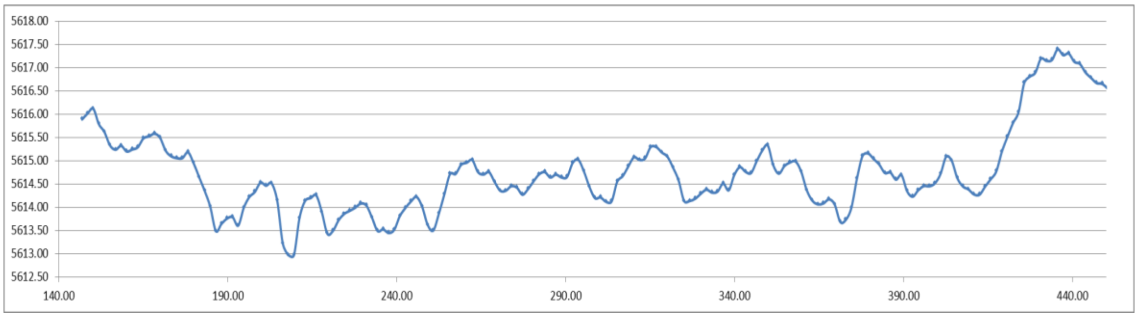


Figure 28. Braided Channel Cross Section.

Braided channels are difficult to model for split flow conditions and the channel can rework itself during flood events. Sediment deposition and slope variation can produce temporally variable channel geometry. Figure 29 and Figure 30 show the area where the cross section in Figure 28 was cut. The channel geometry and shape for these two dates varies significantly. Typically the braided channel will convey a 2-year to 5-year return period flood within its banks because it has a highly mobile bed. The channel will increase its bankfull capacity during the flood event. If the cut cross section cannot be accurately delineated with aerial photos or field observations, the channel cross section shape may have to be estimated.

Figure 29. Braided Channel 2012. (Source Google Earth)

Figure 30. Braided Channel 2014. (Source: Google Earth)

Undefined banks

Another common problem with cut cross sections is that the bank definition is not captured. This can occur if the channel width is too narrow or if the elevation data has insufficient resolution. Figure 31 right bank is not captured. This is probably because the cross section was not long enough or the elevation data didn't have enough resolution along the right bank. This is one of the most common errors of cut cross sections.

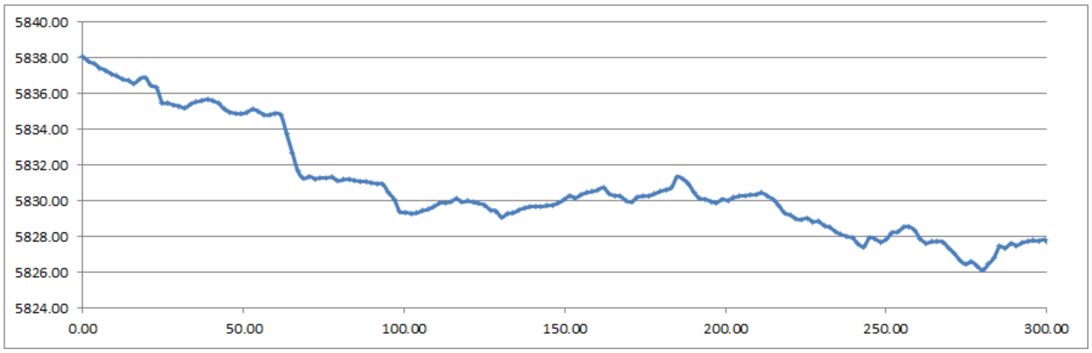


Figure 31. Cross Section Missing Right Bank.

Split flows and Islands

Islands are typically higher than one or both banks due to sediment deposition. Figure 32 shows that the secondary channel on the right has a lower right bank elevation than the top of the island and consequently, the top of the island is presumed to be the right bank for the entire cross section. For some islands, splitting the river into two channels with a confluence may be more expedient. The other approach is to lower the island below the right bank.

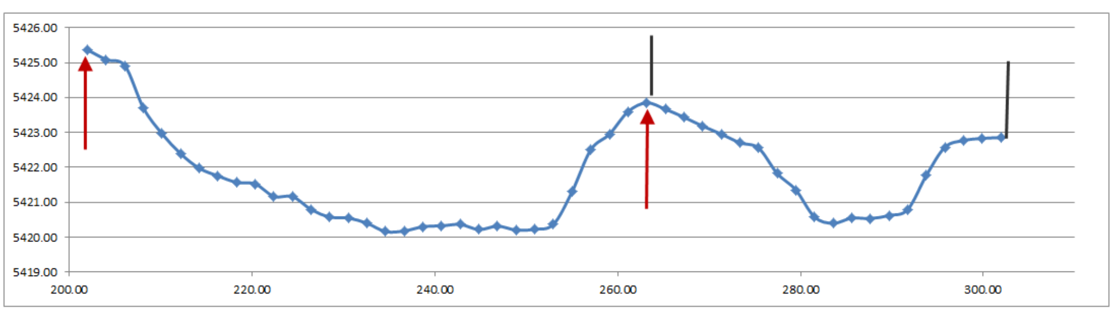


Figure 32. Split Flows.

Under water

LiDAR and IFSAR data does not penetrate water surfaces, the bottom of the channel is modeled as a line, lacking sufficient detail below water line (Figure 33). Bathometric data is needed to fully define the cross section geometry. It may be necessary to estimate the missing wet channel reach conveyance in the thalweg if a portion of the channel has a dry thalweg.

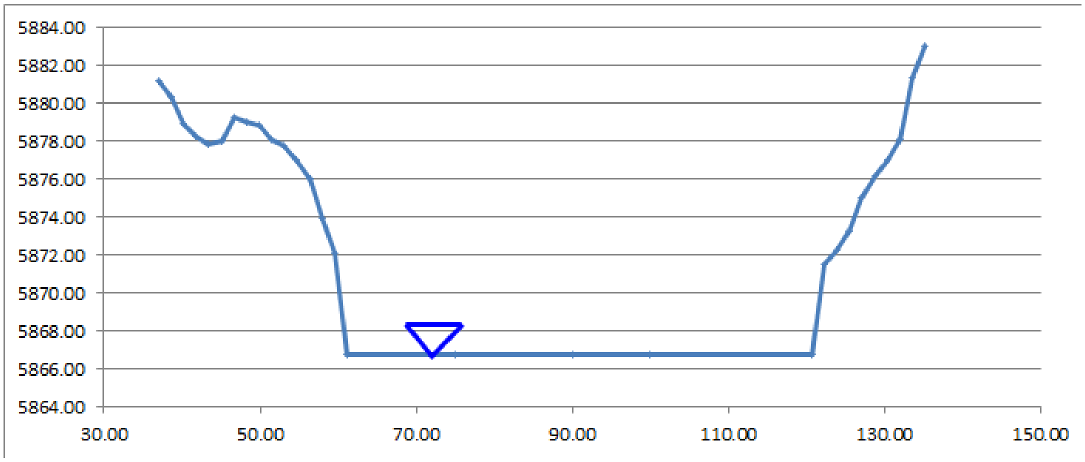


Figure 33. Water Surface.

Urban channels

Urban trapezoidal and rectangular concrete channels are often modelled as natural channels with station-elevation with only a minimum number of stations. In the red points represent the station and elevation pairs listed in the XSEC.DAT for this cross section. Four station points are insufficient to define the rating table for the natural cross section geometry. It is more appropriate to model urban design channels with the Rectangular or Trapezoidal method.

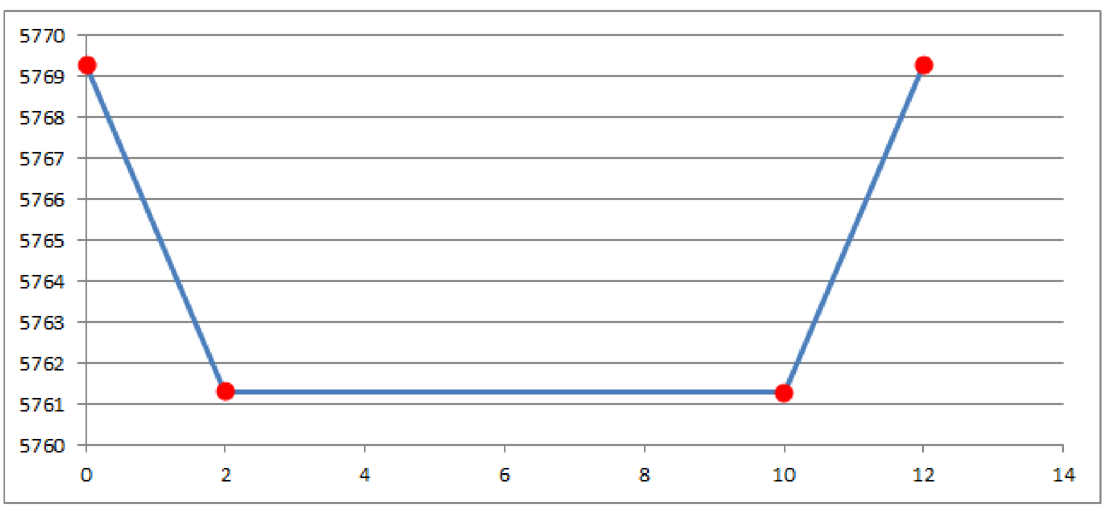


Figure 34. Urban Design Channel.

If modeling a rectangular or trapezoidal channel with station elevation data, it's best to fill in the points at regular intervals. Use 10 or more station/elevation points (Figure 35). This will ensure the model creates the proper flow area rating tables and that the Profiles program correctly interpolates the thalweg and channel shape.

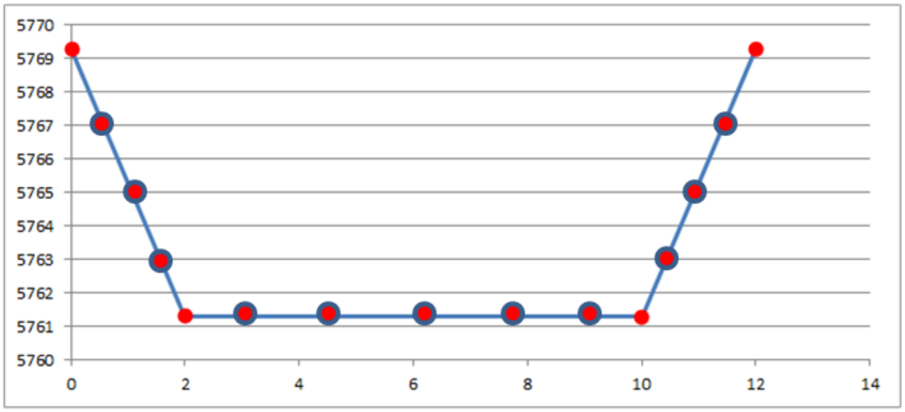


Figure 35. Urban Design Channel Corrected.

Confluences

Channel routing is established by assigning channel connections at model runtime. Each channel connection is identified when the CHAN.DAT file is read. Confluences or split flows, where a given channel element has three or more connections (i.e. upstream, downstream and split/confluence), must be assigned by adding a line C at the end of the CHAN.DAT file. The format is:

C 4507 4559

The tributary should be listed first (4507) and the main channel second (4559). Each tributary or split flow channel element will have a unique line C. If there is only one tributary confluence, there is only one line C. The channel confluence guidelines are as follows:

The tributary or split flow channel segment should not include the main channel confluence channel element. A channel element should only be listed once in the CHAN.DAT file. In Figure 36, the red arrows indicate the *incorrect* method.

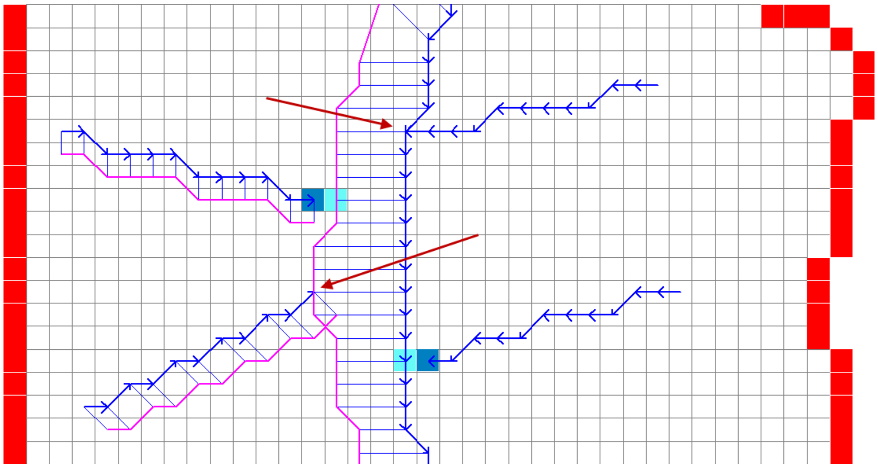


Figure 36. Tributary Element in a Main Channel Bank.

The last tributary channel element before the confluence should be the last channel element listed for that tributary channel segment (Figure 37 – green arrows indicate correct method). Dark blue element is the Tributary Confluence Node and the light cyan element is the Main Channel Node.

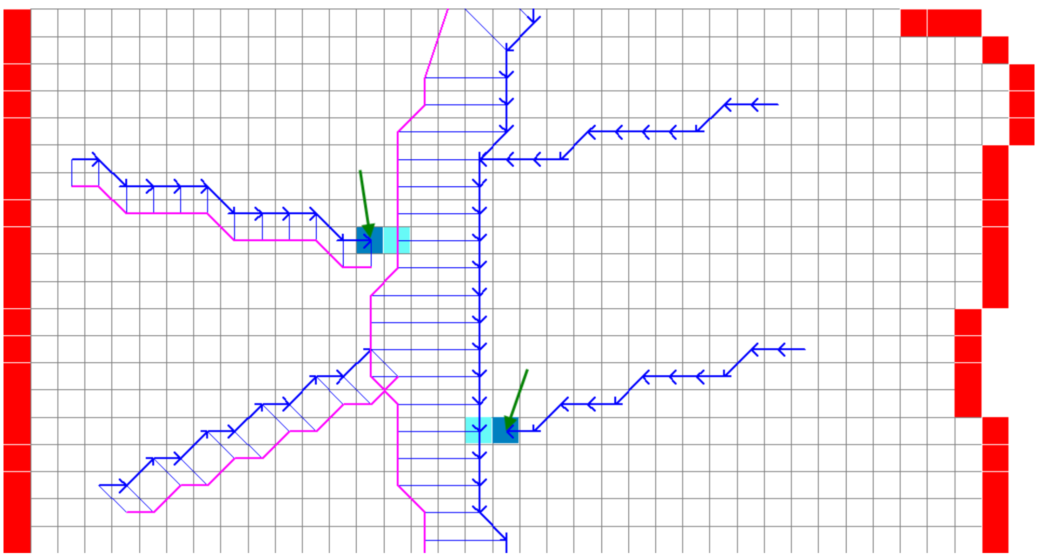


Figure 37. Tributary Channel Ends Adjacent to Main Channel Bank.

The first split channel element after the confluence should be the first channel element listed for that channel segment. In this case it was also necessary to "Add the Confluence Pair" (Figure 38).

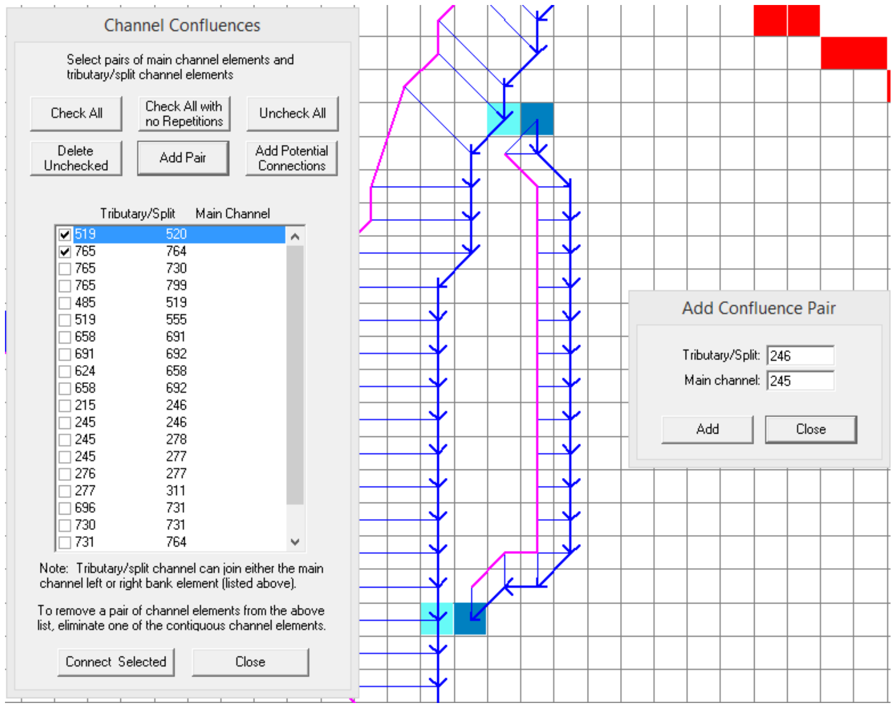


Figure 38. Split Flow Condition.

The tributary or split flow element must be contiguous the main channel. It cannot be separated by one or more floodplain elements from the main channel. The red circle in Figure 39 shows this incorrect configuration.

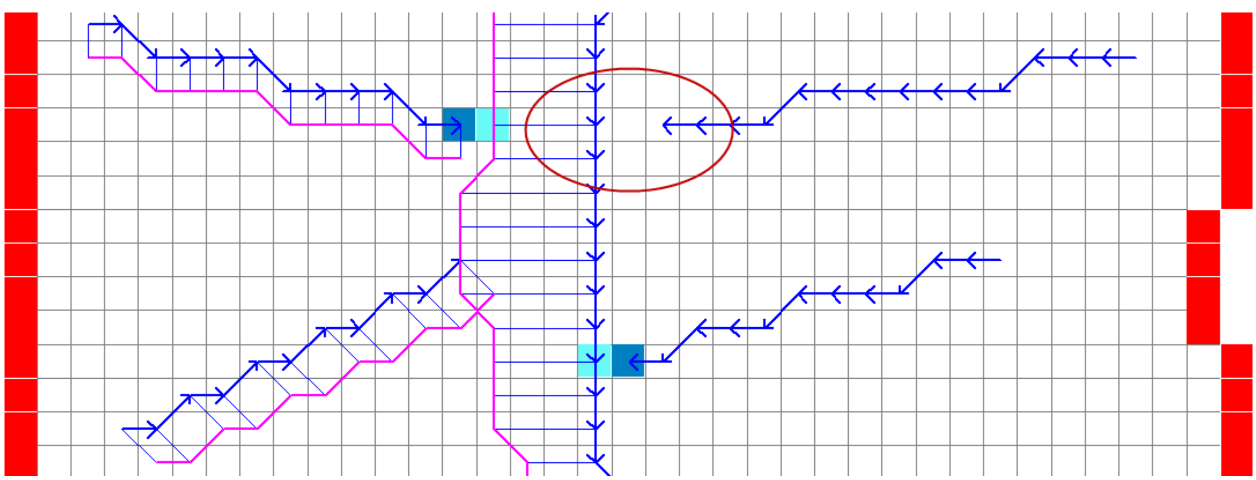


Figure 39. Tributary Channel Element not Contiguous to Main Channel.

The tributary element can be contiguous to either a left or right bank main channel element. If the tributary joins the main channel right bank element, Line C in CHAN.DAT should list the tributary/split channel element and the main channel right bank element (respectively). The FLO-2D model will find the left bank channel element at model runtime (Figure 37).

The user assigns the channel confluence in a dialog box that lists tributary/split channel element in a data entry field column and the main channel element in a second data entry field column. The dialog box is activated by a channel confluence command under the 'Tools' pull down menu shown in Figure 40. The data entry will list all the potential channel confluences and split flow locations. The channel confluences/split flows elements can be added, edited or deleted. When the User clicks on any pair in the Dialog box, the corresponding elements will be highlighted momentarily on the GDS screen. This helps the user identify which element pairs to select.

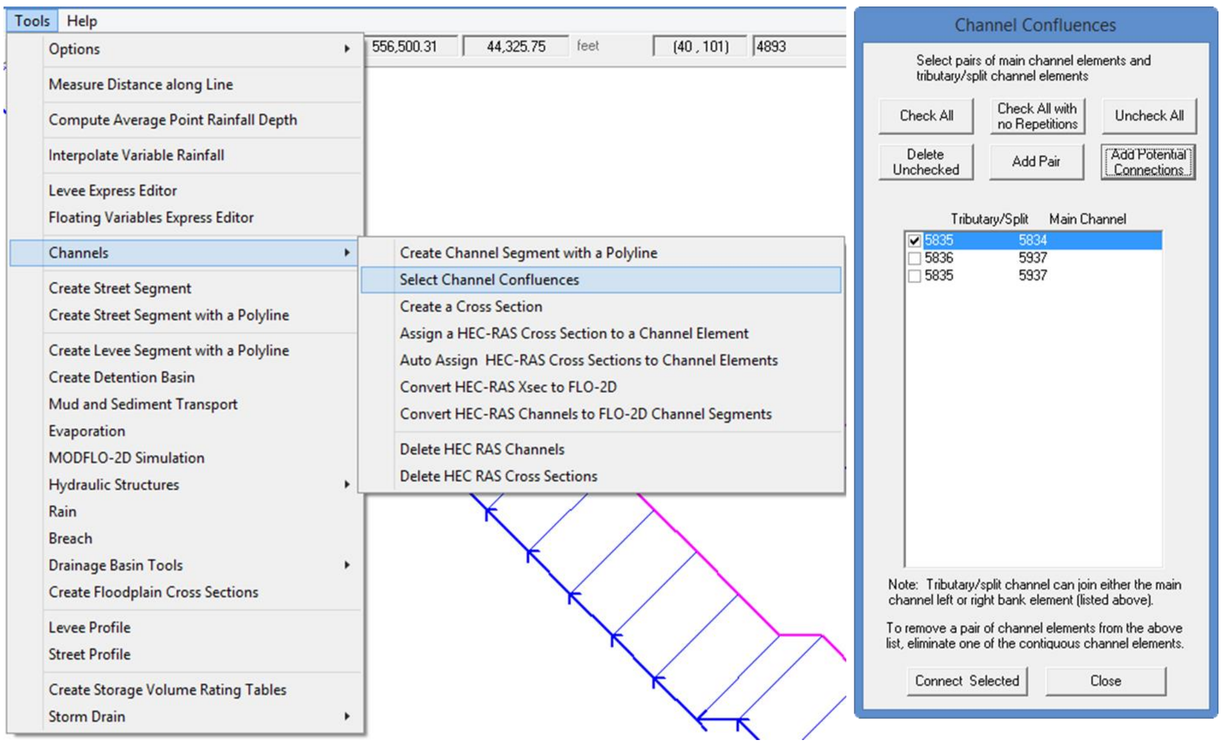


Figure 40. Confluence dialog boxes.

The following are guidelines to avoid having numerical stability issues at the confluence. Use the PROFILE program when reviewing the confluence channel element geometry.

- The channel bed elevations for the tributary and main channel upstream of the confluence should have the same approximate slope.
- The tributary flow area for the last channel element or two upstream of the confluence can be increased to reduce observed numerical instability.
- The roughness values for the tributary and main channel upstream and downstream of the confluence should be increased to reflect the highly turbulent flow constriction.

Channel Infiltration

Although channel bed and bank seepage is usually only a minor portion of the total infiltration losses in the system, it can affect the floodwave progression in a long ephemeral channel. The surface area of a natural channel is used to approximate the wetted perimeter to compute the infiltration volume. The hydraulic conductivity in the Green-Ampt equation is the only parameter required for channel infiltration, which can be simulated on a segment or reach basis. A temporal variation in the channel seepage loss can be computed with a decay function using the initial and final hydraulic conductivity and the infiltration storage soil depth. Channel infiltration loss is a detail that is usually ignored for short duration flood events less than 100 hrs in an urban environment.   It generally has limited impact on the floodwave in a short channel for a short duration. Highly porous, semi-arid channels may have high infiltration that may require calibration in order to match stream gage records. Infiltration will not be a cause of volume conservation error or instability in the channel.

Levees and Channels

Levees can be assigned along channels without issues (Figure 41). In urban areas, levees may also represent fences, berms, or flood walls that are assigned with shapefiles. When constructing the levee component it is only necessary to avoid drawing the levees into the interior channel. There is an automated error message at runtime to alert the user to this condition.

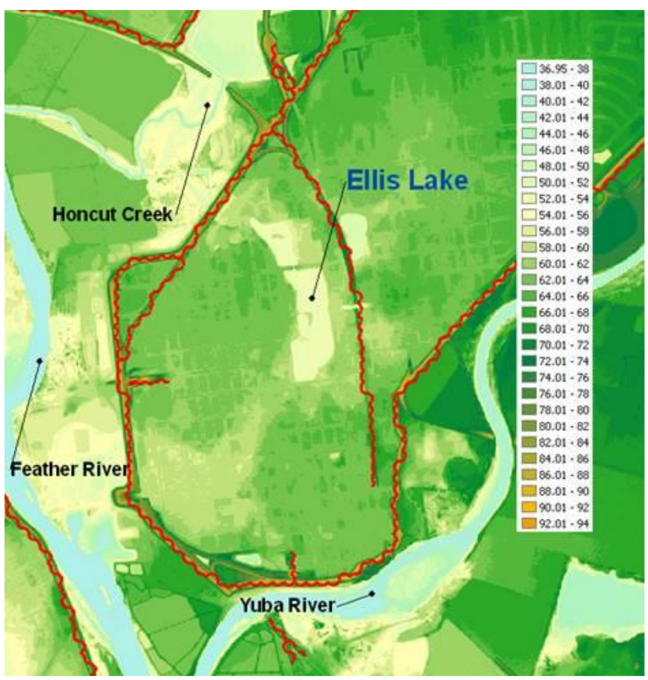


Figure 41. Levees and River Channel Configuration.

Channel routing instability or volume conservation errors may occur when levees fail or are over-topped. These modeling issues are channel flood routing problems, not levee and channel conflicts. Water stored behind levees can created ponding flow conditions (Figure 42). Ponded water is not an open channel flow condition and must be assigned a reasonable n-value for deep, still water (see Ponded Water Guidelines document).

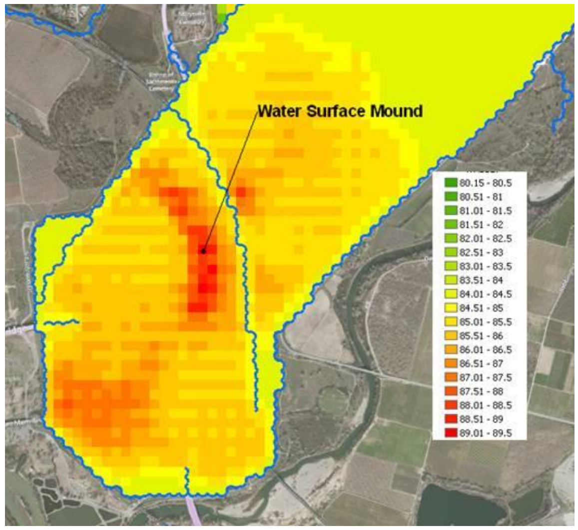


Figure 42. Ponded Area Behind Rivers Levees from a Levee Breach Upstream.

Hydraulic Structures

Channels and hydraulic structures can be used to simulate a variety of features. Hydraulic structures can interact with the channel in three ways:

- *channel to channel*
- *floodplain to channel*
- *channel to floodplain*

Figure 43 shows examples of the three configurations. Flow in the figure is north to south. Red circles show the three configurations from top to bottom. The hydraulic structure can represent any feature that controls the water surface and discharge such as bridges, culverts, weirs or pumps. Discharge through the hydraulic structure can be based on rating curves or rating tables or if the structure represents a culvert, generalized culvert equations for inlet and outlet control can be applied. Refer to the Data Input Manual or Hydraulic Structure Guidelines for more details.

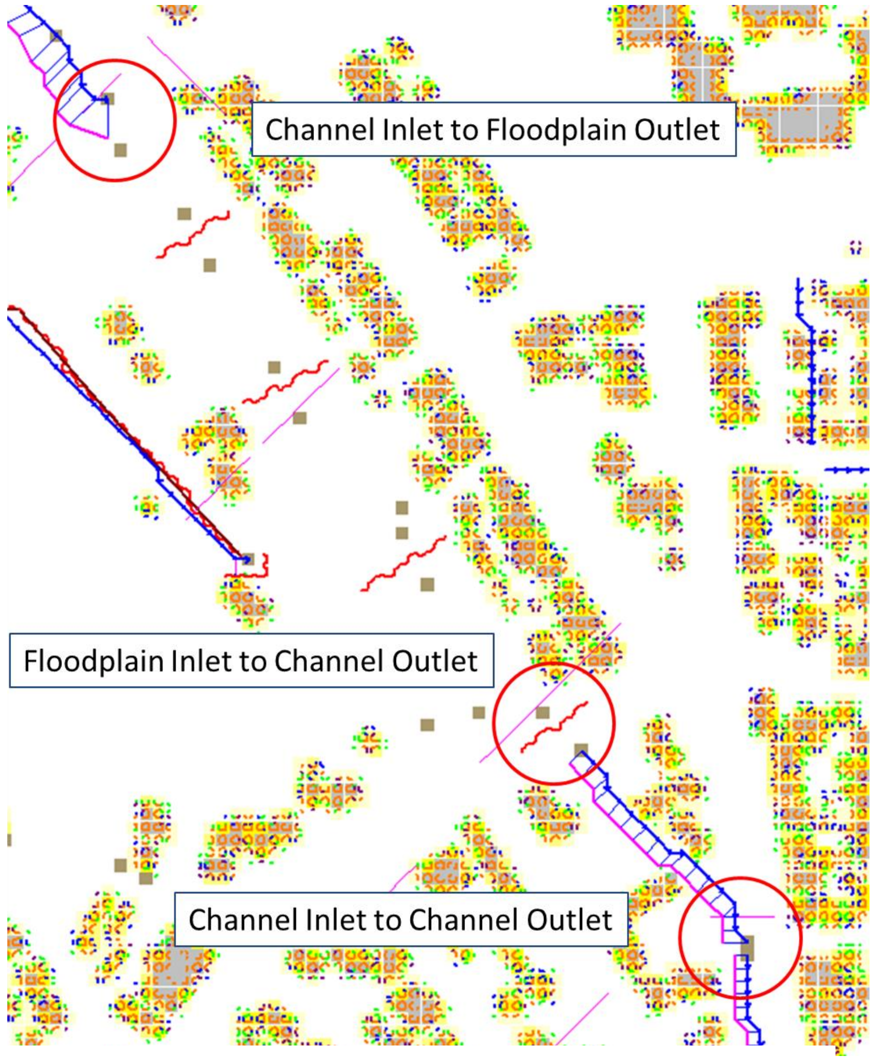


Figure 43. Hydraulic Structure / Channel Examples.

Hydraulic Structure Rating Curves and Tables

The hydraulic structure stage-discharge relationship can be assigned as either a rating curve or rating table that is based on the headwater depth above the channel thalweg (assumed to be the hydraulic structure invert elevation) unless a headwater reference elevation is specified. A discharge rating curve uses headwater depth to calculate discharge:

$Q = a \text{ depth}^{b}$ where a = coefficient, b = exponent

A broadcrested weir (Figure 44) discharge curve is an example of a rating curve:

$Q = C\,L\,h_d^{\,1.5}$ where C = 2.65 - 3.40 in English Units

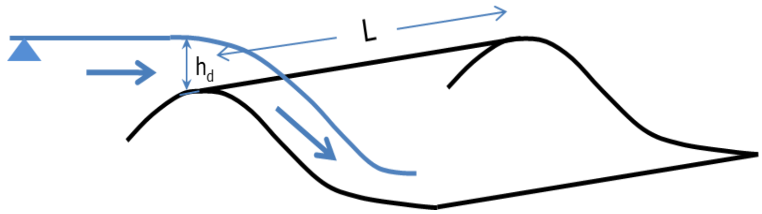


Figure 44. Broadcrested Weir Definition.

More than one rating curve relationship can be used to simulate blockage, or changes in inlet or outlet control. The primary hydraulic structure interaction with the channels is backwater effects when the rating curve or table predicts less discharge than the upstream normal flow depth condition. Several important features of hydraulic structures are:

- If rating curve or table computes an outflow discharge that is less than inflow to the inlet element, backwater will occur whether the flow is inlet or outlet controlled.
- The rating table is more reliable and accurate than a curve.
- Flow through a long culvert can be simulated with a rating curve or table using the culvert length. Culvert routing (Muskingum volume routing method) is appropriate for culverts 500 ft or longer.
- Flow upstream thru the hydraulic structure is OK.
- If levees are used with hydraulic structures in contiguous inflow and outflow nodes, the hydraulic structure discharge is terminated with levee failure.
- Optional multiple inlets to a single hydraulic structure outlet can mimic storm drain collection.
- Hydraulic structure inlet and outlet channel elements need not be contiguous (Figure 45)

Figure 45. Hydraulic Structure (Culvert) Connecting Two Channel Elements.

If a structure spans more than one channel element in a channel segment:

- Split the channel into two segments
- Set culvert inlet node at the end of the 1st segment
- Set outlet node at the start of the 2nd segment

The hydraulic structure rating table or curve can be created from:

- HEC-RAS, HY-8 or other suitable program. Always check with the regulating agency to determine what software will be accepted.
- Two cross sections upstream and two downstream of a bridge can be used to generate a rating table with HEC-RAS.
- Culvert tables or programs
- Weir and spillway equations

Hydraulic structures can be used to discharge into lateral retention basins, or to simulate pump discharge into or out of the river or conveyance system. The relationship between the structure headwater and tailwater can be accounted for by using the INOUTCONT parameter in the HYSTRUC.DAT file (Figure 46). The INOUTCONT parameter does not apply to the generalized culvert equations.

- If INOUTCONT = 0, discharge Q only goes **downstream.** Q is evaluated by the headwater depth H_w.
- Set INOUTCONT = 1 the discharge Q = Q * SUBFACTOR; where SUBFACTOR is computed by the model based on HY8 submergence criteria as defined by (initially SUBFACTOR = 1.0):

    IF DELTA > 0.975, SUBFACTOR = SUBFACTOR – 0.01
    IF DELTA < 0.975, SUBFACTOR = SUBFACTOR + 0.015
    IF DELTA > 1, SUBFACTOR = SUBFACTOR - 0.01* DELTA

  where DELTA = ratio of the headwater to the tailwater depth (T_w/H_w) shown in Figure 46.
- If INOUTCONT = 2, discharge can go **upstream**

Headwater depth H_w and tailwater T_w can switch with submergence to allow flow to go upstream. For upstream discharge through the culvert, the outflow node must have upstream flow into it from the downstream channel.

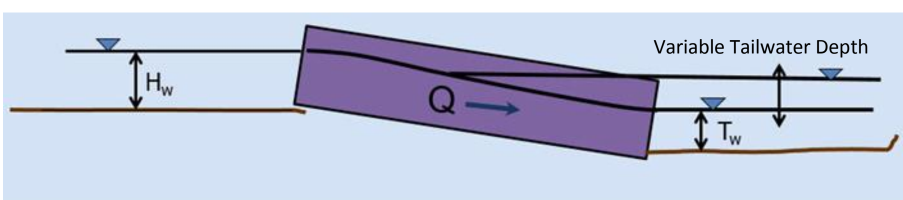


Figure 46. Variable Culvert Tailwater Condition.

Generalized Culvert Equations

Culvert flow can be simulated using generalized culvert equations to predict culvert discharge for circular or rectangular box culvert under inlet or outlet control. These equations are based on the U.S. Dept. of Transportation Highway Manual (2005) and the culvert data is entered with the hydraulic structure data in HYSTRUC.DAT (Figure 47).

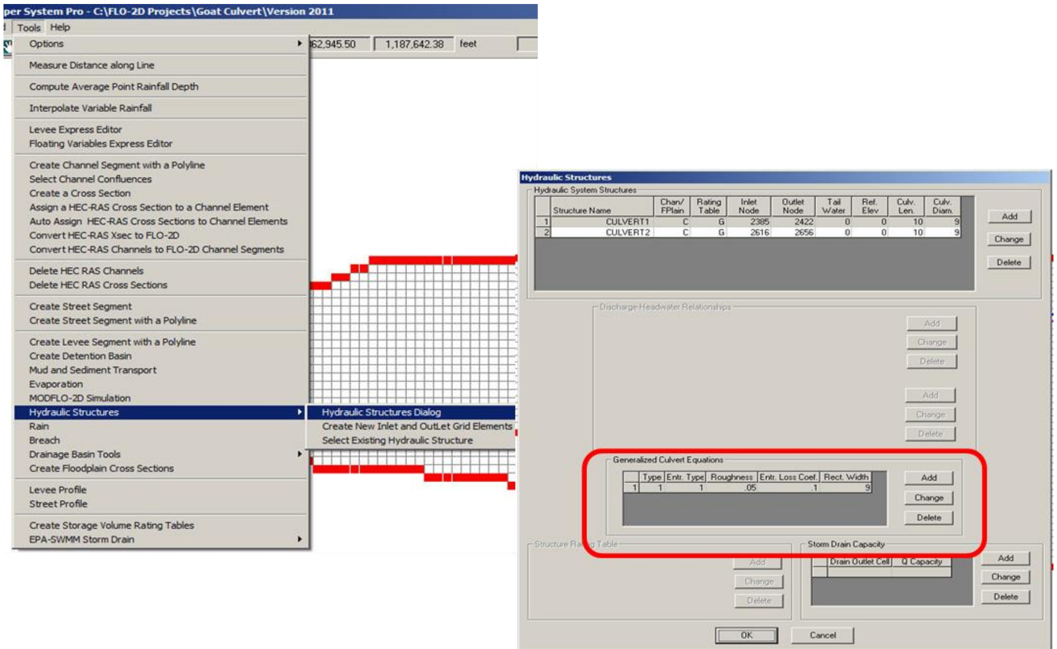


Figure 47. Select the Hydraulic Structures Dialog Box.

The data requirements for the generalized culvert equations include:

- Length
- Diameter
- Rectangular Width
- Type – Box or Pipe
- Entrance Type (3)
- Entrance Loss Coefficient
- Roughness

All the possible flow scenarios involving inlet and outlet control are analyzed internally by the generalized culvert equations, based on tailwater elevation, friction losses, slope, and entrance control and headwater elevation.

Channel Hydraulic Structure Troubleshooting

Hydraulic structures can be a primary source of numerical instability in the channel when the rating curve or table does not match the upstream flow very well. This is common for low flow conditions. While FLO-2D can accurately replicate backwater effects, accelerating flow through a hydraulic structure will typically only occur with a concrete apron structure. A rating curve or table that accelerates the flow through the bridge or culvert will pull down the water surface elevation in the inlet node. This will cause surging as the headwater drops until the discharge is low enough to replenish the volume in the inlet node starting the surge cycle again.

The hydraulic structures that have the following flood routing issues will result in Warning Messages written to the ERROR.CHK file:

- Adverse slope between the inflow and outflow nodes;
- Inflow or outflow cells that also contain levee, streets or ARF's;
- Rating table data where the first pair of stage-discharge values are non-zero (must be 0.0.);
- The rate of increase in the rating table values is unreasonably high.

Error Messages are written to the ERROR.CHK file for the following channel conditions:

- Reference elevation is lower than the inlet or outlet grid elevations.
- Inflow or outflow nodes are also assigned as channel elements.
- Assignment of a channel element to more than one hydraulic structure inlet node.
- Rating table must have increasing stage and Q.

The most frequent problem with application of the hydraulic structure routine is a mismatched flow condition. This occurs when the discharge through the structure defined by the rating curve or table is greater than the upstream inflow to the structure. This condition distorts the upstream water surface primarily by accelerating flow through the structure and pulling down the inlet headwater. If the hydraulic structure debouches water into the channel from a tributary or floodplain node, surging flow could occur with a high rate of change in the discharge. Review the HYDROSTRUCT.OUT and HYCHAN.OUT files for surging. If surging is noted in the hydraulic structure hydrograph or the channel hydrographs near the inlet, the rating table or curve will need adjustment. The following conditions should be reviewed:

- Shallow flows less than 1 ft in depth with velocity > 5 fps. Warning message
- Downstream WSEL > upstream WSEL with INOUTCONT < 2 (potential upstream flow thru the structure). Warning message.
- Rating table adjusted with SUBFACTOR. Warning message and revised table values are written to **REVISED_RATING_TABLE.OUT** file.

Storm Drains

This section is intended to document appropriate methods for integrating storm drain with a 1D channel. Refer to the Storm Drain Manual for complete guidelines for applying the storm drain component. Integrating a storm drain network into an urban model requires an understanding of how the storm drains will interact with the surface flow. In the FLO-2D model, the most complex interaction occurs between the storm drain features and the 1-D channel component. The storm drain system interfaces with channels through inlets and outfalls. An early identification of storm drain database deficiencies can save time and resources on a project.

Storm Drain Inlet – Channel Considerations

After initial set up of the urban project, the following issues related to the storm drain inlet to channel system should be addressed:

- Inlet locations:
  - ✓ Inlets must be inside the FLO-2D computational domain;
  - ✓ Inlets cannot be assigned to the interior channel elements;
  - ✓ Inlets should not be assigned to the channel bank elements.
- Inlet elevations:
  - ✓ Channels discharging to a storm drain inlet should have a thalweg that matches the inlet invert elevation;
  - ✓ In most instances, the inlet should be set up as a vertical inlet in the SWMMFLO.DAT file.

Storm drain inlets should not be assigned to an interior channel element. If a channel discharges directly to a storm drain pipe inlet, similar to a culvert inlet, assign the inlet to the channel left bank element. For this configuration a vertical Type 4 inlet can be applied (refer to the Storm Drain Manual for details). Figure 48 and Figure 49 provide some additional details about setting up the inlet/channel interface. This system shows that the bed elevation of the channel is equal to the invert elevation of the inlet.

- Channel Bed Elevation = Bank Elevation – Depth = (299.8 – 3.5) = 296.3 ft
- Inlet Elevation = 296.3 ft

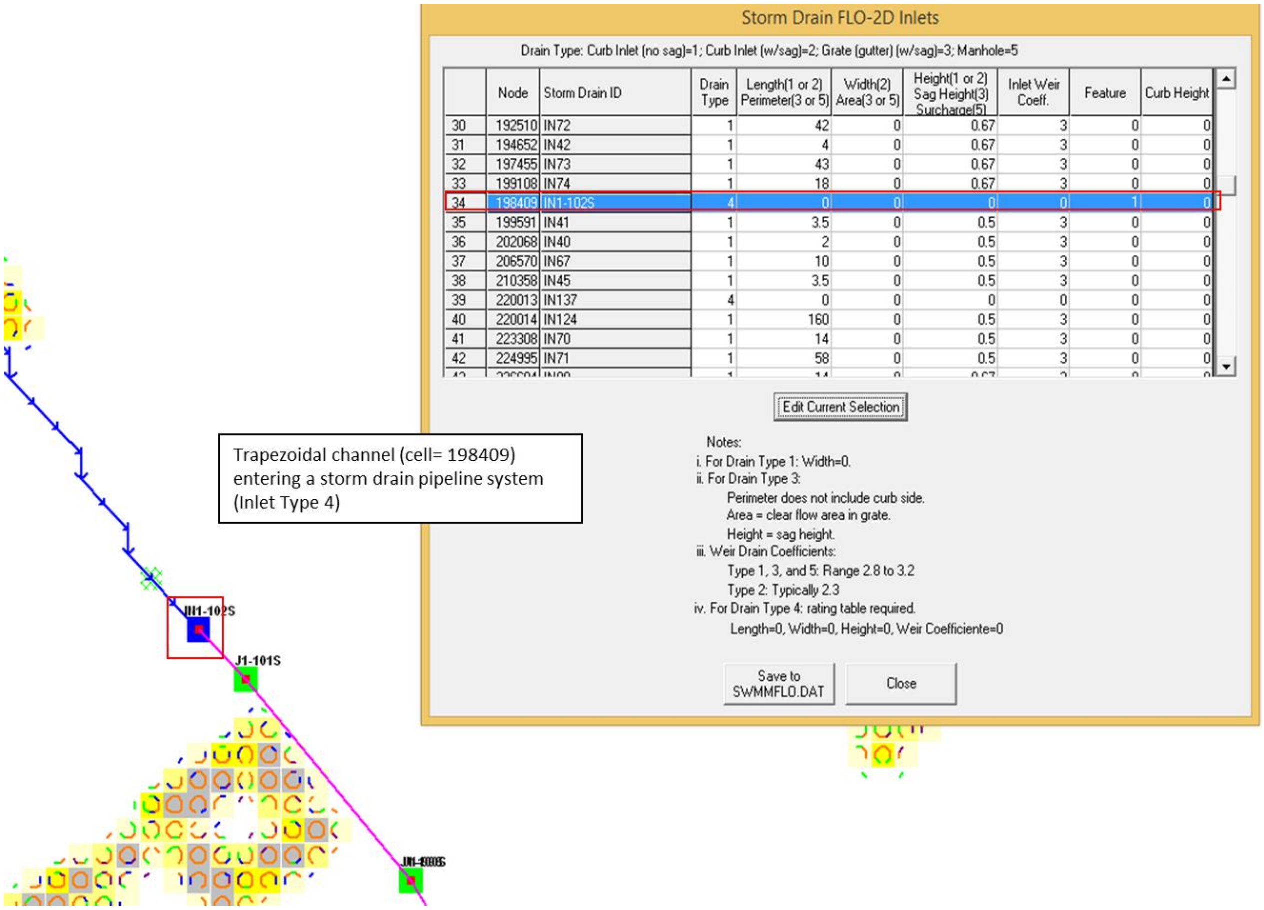


Figure 48. Trapezoidal 1-D Channel Discharging to a Storm Drain Inlet.

CHAN.DAT FILE

```
T   191815  304.22  304.22 0.021    5.00    3.50    30.40  1.50  1.50
T   192637  303.67  303.67 0.022    5.00    3.50    30.40  1.50  1.50
T   193459  303.12  303.12 0.020    5.00    3.50    30.40  1.50  1.50
T   194283  302.56  302.56 0.023    5.00    3.50    30.40  1.50  1.50
T   195107  302.01  302.01 0.020    5.00    3.50    30.40  1.50  1.50
T   195931  301.46  301.46 0.020    5.00    3.50    30.40  1.50  1.50
T   196756  300.91  300.91 0.020    5.00    3.50    30.40  1.50  1.50
T   197582  300.35  300.35 0.020    5.00    3.50    30.40  1.50  1.50
T   198409  299.80  299.80 0.020    5.00    3.50    30.40  1.50  1.50
```

Thalweg Channel Depth= 3.50 ft

Grid Elevation (198409)= 299.80 ft

SWMM.INP FILE

```
[JUNCTIONS]
;;               Invert     Max.       Init.      Surcharge  Ponded
;;Name           Elev.      Depth      Depth      Depth      Area
;;-------------- ---------- ---------- ---------- ---------- ----------
IN1              287.82     11.60      0          0.5        0
J10              275.92     7.49       0          0.5        0
IN100            307.04     6.13       0          0          0
IN101            306.8      6.27       0          0          0
IN10-1S          188.81     2.63       0          0          0
J102             306.49     6.19       0          0          0
IN103            274.06     4.46       0          0          0
J104             279.23     4.58       0          0          0
J105             295.68     6.59       0          0          0
J106             270.83     4.25       0          0          0
J107             238.96     8.72       0          0          0
J108             237.12     9.49       0          0          0
IN11             273.22     6.62       0          0          0
J110             272.93     4.56       0          0          0
J1-100S          285.46     9.28       0          0.5        0
J1-101S          291.78     11.92      0          0          0
IN1-102S         296.3      0          0          0          0
J111             263.47     4.87       0          0          0
```

Figure 49. Elevation of a Trapezoidal 1-D Channel Discharging to a Storm Drain Inlet.

Figure 50 shows another example of a storm drain system interfacing with a channel system. The surface water and the storm drain exchange flow based on the water surface elevation in the channel and the pressure head in the storm drain. The water surface elevation and the pressure head are a function of the following:

- Channel thalweg elevation = inlet invert elevation
- Channel bank elevation = inlet rim elevation

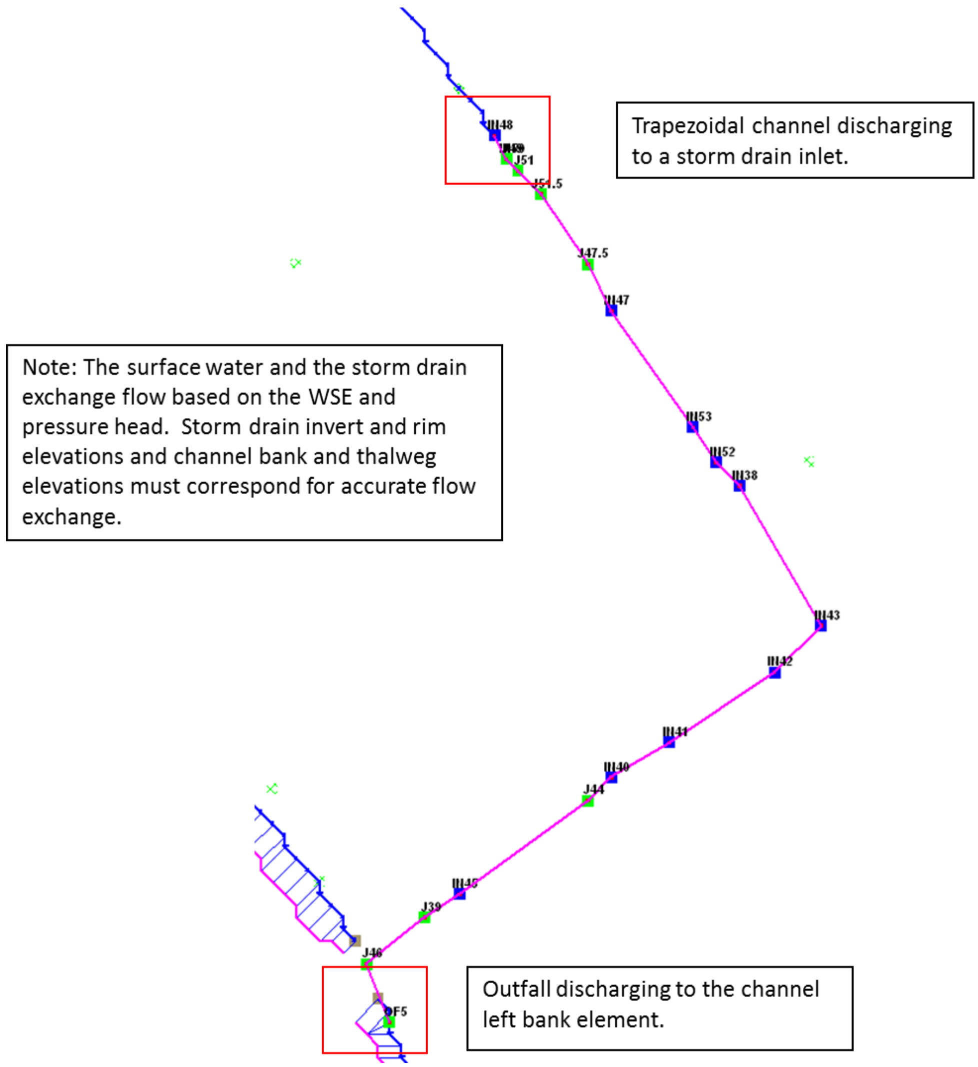


Figure 50. Complex Interaction between a Storm Drain Pipe and 1-D Channel.

Storm Drain Outfall – Channel Considerations

To connect a storm drain outfall to a channel element the following issues should be addressed:

- Outfall locations:
  - ✓ Are all outfalls inside the FLO-2D computational domain?
  - ✓ Are there outfalls assigned to the interior channel elements? This is not allowed.
  - ✓ Are outfalls assigned to the appropriate channel bank elements? They should be assigned to the left bank only.
- Outfall type:
  - ✓ Are outfalls set up as a FREE condition outfall type in the SWMM.inp file? This is required.
  - ✓ Is the switch to discharge flow back to the surface 'ON' in the SWMMOUTF.DAT file?

Figure 51 shows a complex storm drain – channel system where a channel feeds the storm drain as an inlet and flow returns to surface further downstream and back into the channel network.

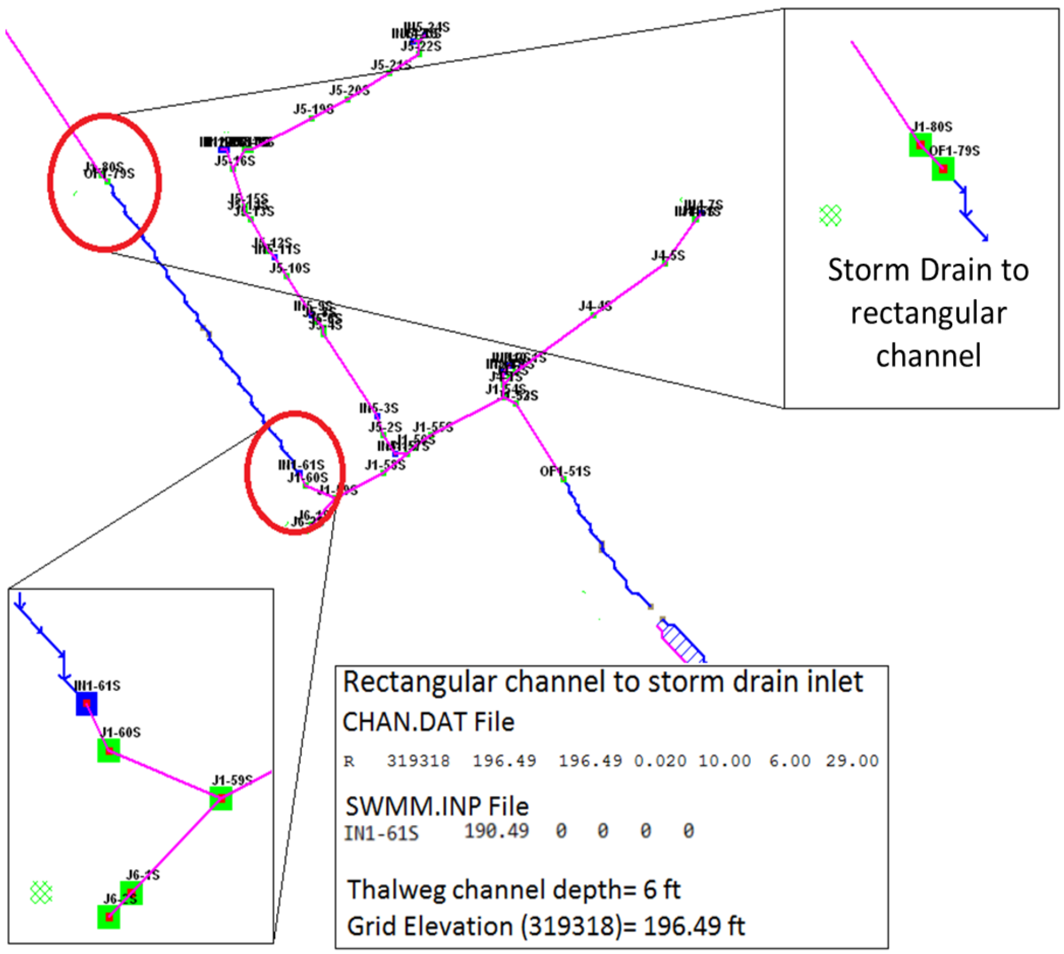


Figure 51. Complex Flow Exchange between a Storm Drain System and 1-D Channel.

Storm drain outfalls should be assigned to the channel left bank element. For most cases, the outfall invert elevation would be assigned to the channel element thalweg elevation. If the coordinates in the SWMM.inp file are the left bank element channel coordinates then the GDS will automatically assign the outfall node to the left bank element. The user can review that the outfall is correctly paired to the left bank element in the SWMMOUTF.DAT file. Refer to Figure 52 for an example of a storm drain that physically outfalls to the right bank but is extended to the left bank grid for modeling purposes. The user should verify that the final pipe length and invert elevation are correctly assigned to match reality even though the modeling connection does not.

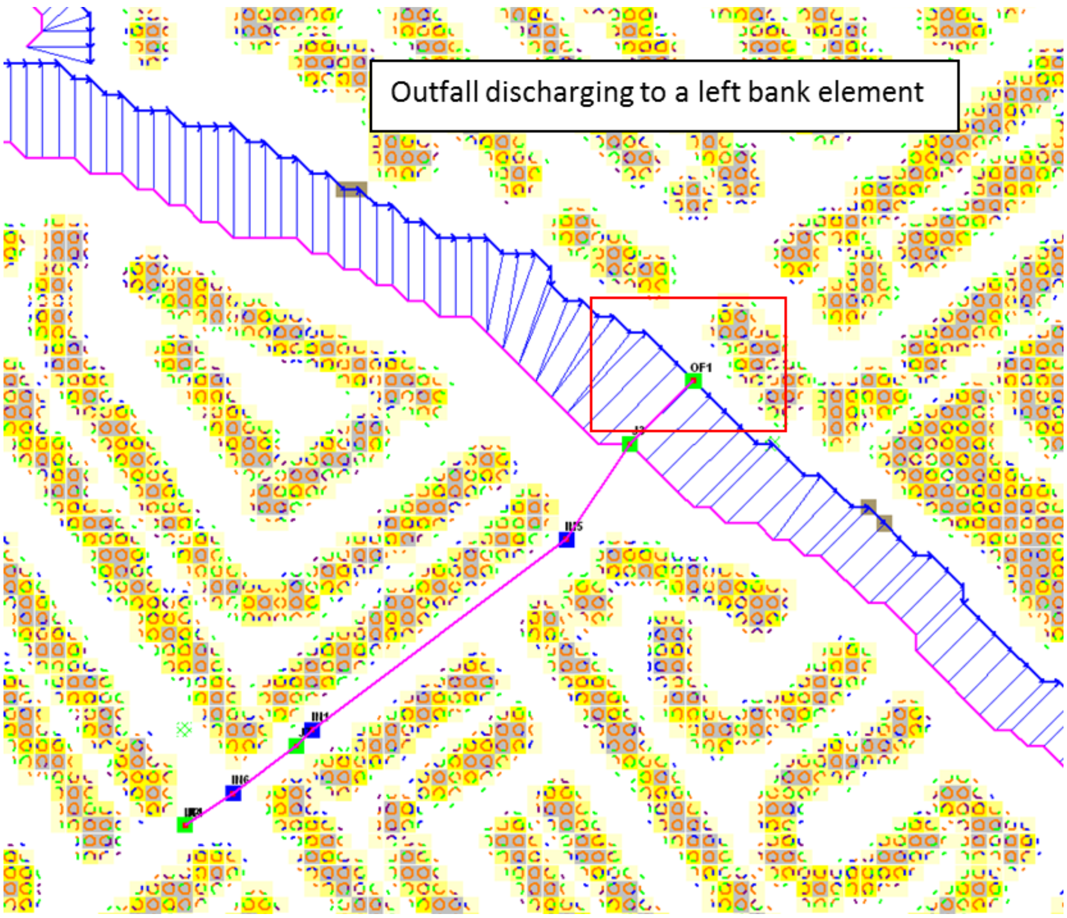


Figure 52. Typical Configuration of a Storm Drain Outfall Discharging to a Natural Channel.

The GDS uses coordinates of the different storm drain components from the SWMM.inp file to pair them with the grid elements in the surface layer. It is usually not necessary for the outfall coordinates in the SWMM.inp match the left bank channel element coordinate. The position is within the channel, the outfall will be correlated in the SWMMOUTF.DAT updating the grid element number to the closest left bank element number (Figure 53). The user should check every outfall to be sure it is correctly assigned to the appropriate left bank grid. In this case, the outfall coordinates in the SWMM.inp file do not have to be replaced since the storm drain discharge calculations will not be affected.

The bank elements in FLO-2D act as both floodplain and channel elements in order to facilitate the channel to floodplain exchange. It is not allowed to assign the outfall to the left bank floodplain element. If the outfall physically discharges to the floodplain elevation instead of the channel bed elevation, assign the outfall position to a contiguous element that is not a channel bank element. Assignment of the outfall to a right bank element, or a channel interior element will generate an error message because that configuration is not allowed.

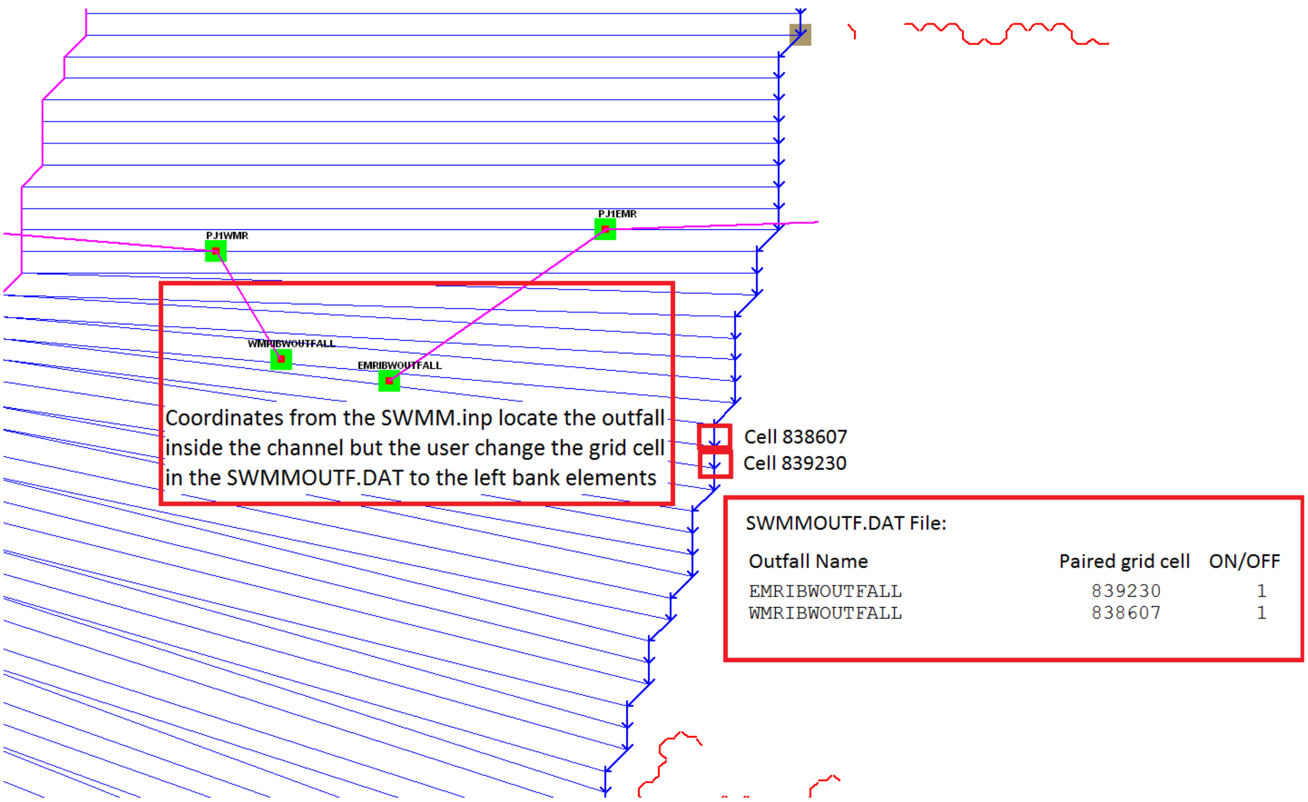


Figure 53. Outfall Nodes Paired to Interior Channel Elements by GDS.

The outfall invert elevation can be less than the channel thalweg elevations. If the outfall invert elevation is lower than the thalweg elevation (underground), then the storm drain would be assumed to be underwater with an initial tailwater depth. The pipe conduit should have a positive slope to the outfall. This configuration may represent the case for a ponded surface water condition that is assigned as a ground elevation because the ponded water will not contribute to downstream flooding. An outfall invert underground (or underwater) is imposed for this condition and an artificial head equal to the ground elevation is assigned to the outfall node for the entire simulation. This artificial head extends a level pool up the pipe, but the volume that goes into the pipe is not considered in the FLO-2D volume conservation accounting because the grid element is initially dry. The artificial volume is accounted for in the storm drain model as backwater. When the model runs, inflow may be added to either the outfall grid element or the upstream storm drain pipe network and the flow can go either in or out of the outfall pipe based on the pressure head (Figure 54). To account for volume conservation, the storm drain outflow that represents inflow volume to a FLO-2D channel is reported in the CHVOLUME.OUT file.

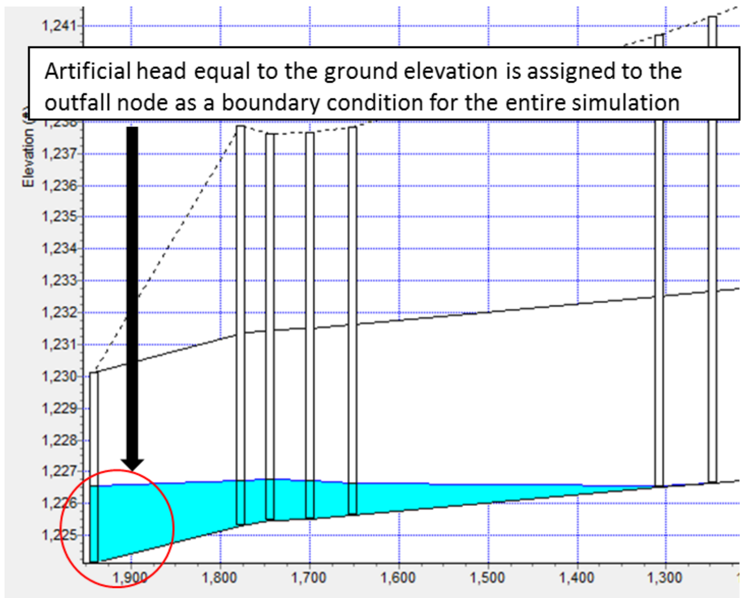


Figure 54. Underground Outfall Condition.

Water will flow in or out of the outfall pipe based on the relationship between the water surface elevation and pipe pressure head. Water can enter the storm drain when the external water surface elevation at the outfall is greater than the invert, but it could also evacuate from the storm drain if the hydraulic grade line in the storm drain at the 1st upstream junction is greater than the external water surface elevation at the outfall. This behavior can introduce oscillations in the system that can be explained as a respond to the interaction between external surface water and storm drain pressure (Figure 55).

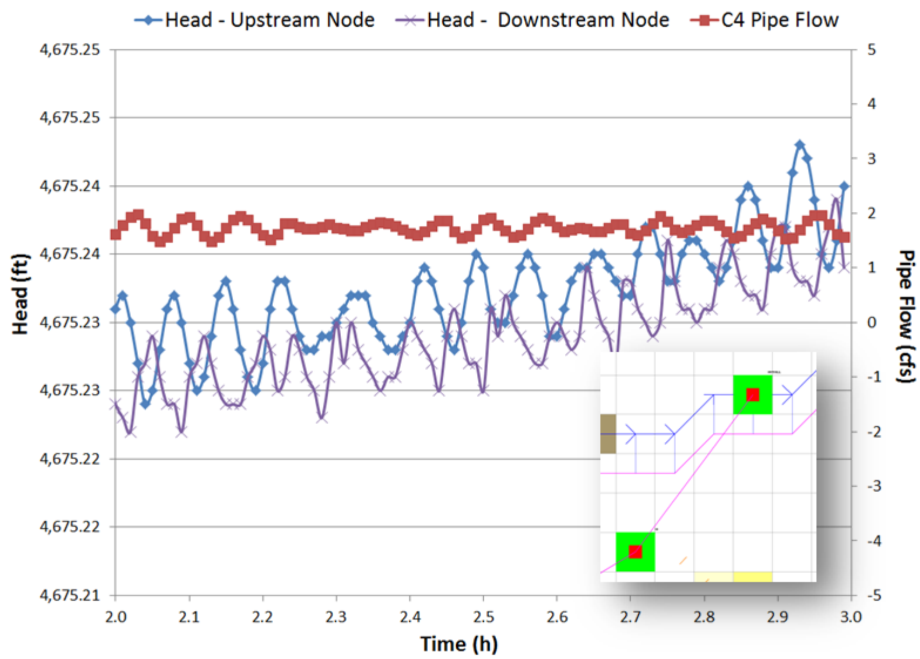


Figure 55. Head Variations Cause Pipe Discharge Oscillations.

Storm Drain Reference Manual

The FLO-2D storm drain manual is a comprehensive set of guidelines for modeling the overall surface to subsurface flow network. The manual includes instructions on getting started, modeling methodology, verification testing and trouble shooting. It contains a thorough list of error messages that are reported when data input parameters are not entered correctly or create a conflict between the two layers of the system.

Channel Termination

There are three ways to terminate a channel:

Outflow Node

The first method is to have a channel end with a channel outflow node and the flow is discharged off the grid system as essentially normal depth flow. This configuration is shown in Figure 56. This can occur regardless of the position of the channel outflow node on the grid system. This is the conventional method to end the channel flow whether the channel continues downstream after the outflow node or discharges into lake, bay or estuary.

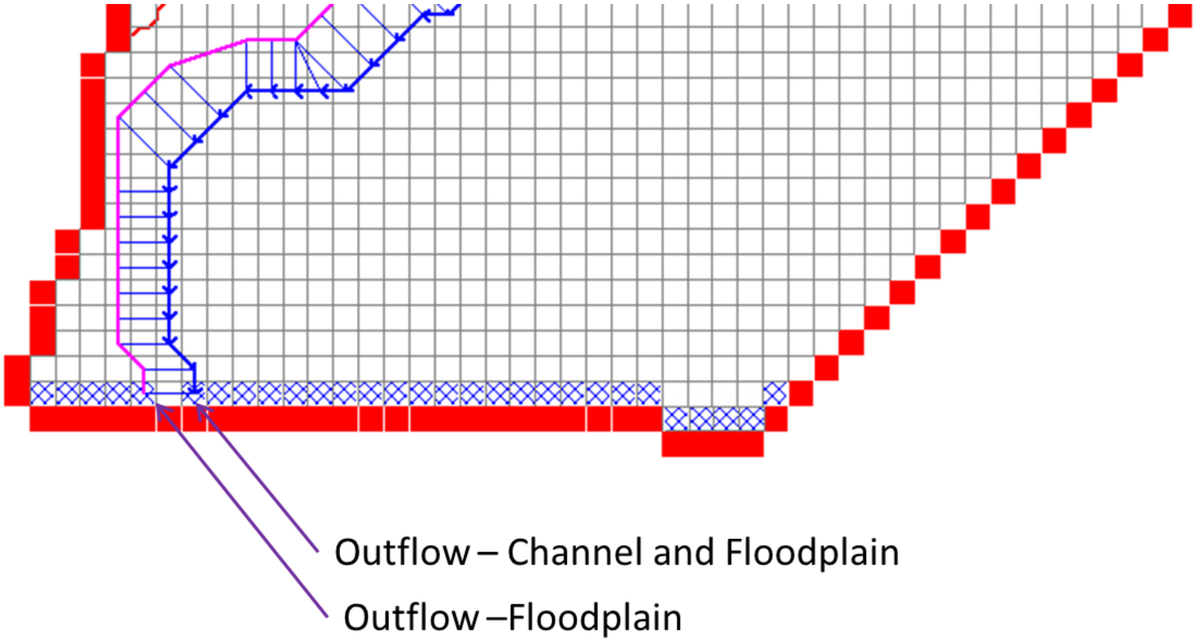


Figure 56. Channel Outflow Configuration.

Hydraulic Structure

The second method is to use a hydraulic structure to discharge the flow from a channel element to a floodplain element (Figure 57). This method might result in some flood routing instabilities or errors because the channel area could be much larger than the grid element area. If the peak discharge to grid element area ratio (Q_p/A) exceeds 10 cfs/ft^2 (30 cms/m^2), it might be better to use the third method.

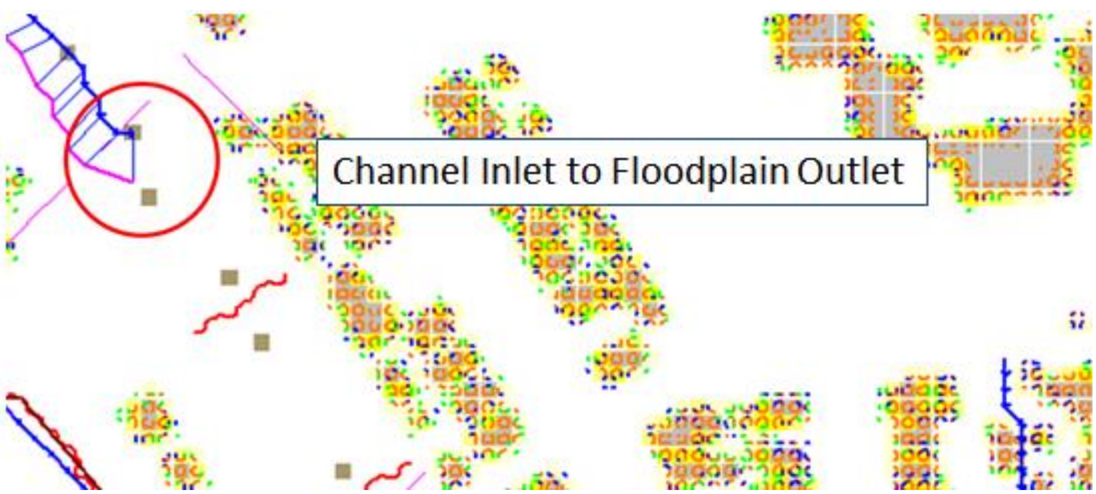


Figure 57. Channel to Floodplain - Hydraulic Structure.

Channel Termination on Floodplain

The third method of channel termination is to end the channel on the floodplain without a channel outflow node. The FLO-2D model can exchange flow between the floodplain and either end of the channel either as upstream inflow or downstream channel terminus outflow. The flow exchange occurs between the floodplain elements and the channel internal elements. Both ends of the channel can exchange flow with the floodplain at the same time in either direction as inflow or outflow depending on water surface elevation. To facilitate the channel/floodplain exchange the floodplain elevations should reflect the channel thalweg elevation. At the downstream end, expanding the channel while lowering the banks helps to simulate sediment deposition and loss of channel conveyance capacity.

This represents the case where a channel may terminate into a detention basin or gradually transitions to unconfined flow on an alluvial fan. For these cases, the recommended approach is to gradually widen the channel (Figure 58) and reduce the channel depth over a several channel elements with a slight decrease in the flow area to the channel end.

To allow channel discharge exchange from the interior channel elements at the end of the channel to the floodplain, it is only necessary to stop the channel without an outflow element. The interior channel elements discharge directly to the downstream floodplain elements at the end of the channel.

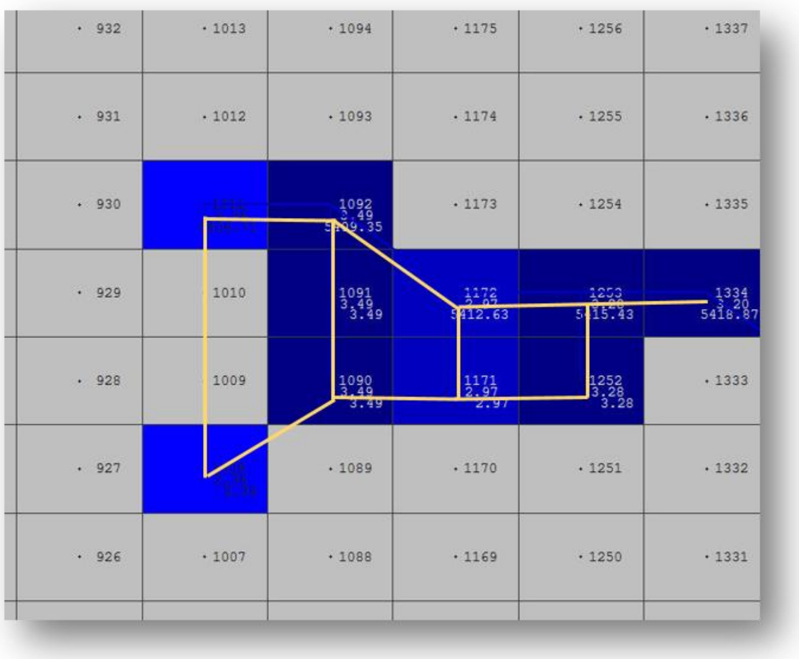


Figure 58. Channel termination (channel elements are marked by a yellow line).

In **Figure 3**, the channel right bank element is <u>1011</u> and the left bank element is <u>1008</u> at the downstream end of the channel. Grid elements <u>1009</u> and <u>1010</u> are interior channel elements at the end of the channel. At runtime, the floodplain elevations for the interior channel elements are reset to the channel thalweg elevation. The channel flow is exchanged with the floodplain surface in these two interior channel elements based on water surface elevation and then the floodplain flow is shared with the downstream elements (grid elements <u>927</u> through <u>930</u>) that are contiguous to the <u>1009</u> and <u>1010</u>. Flow can also be exchanged between the channel and floodplain through the lower bank elements as the channel widens. **Figure 4** and **5** show the flow moving across the floodplain downstream away from the channel.

Typically when a channel terminates on an alluvial fan, it becomes shallower and wider as the sediment deposition ensues with decreasing flow velocity. This may occur over a channel distance of several hundred or several thousand feet. To enable a realistic representation of the end of the channel, it is recommended to *slightly* decrease channel flow area in the downstream direction over the last 4 to 10 channel elements. In the example project depicted in the Figures, the channel decreases from a <u>6 ft. thalweg depth</u> to a <u>2 ft. thalweg depth</u> while increasing from a <u>240 ft. width</u> to <u>820 ft.</u> over the last five channel elements. The channel roughness may also increase with decreasing thalweg depth.

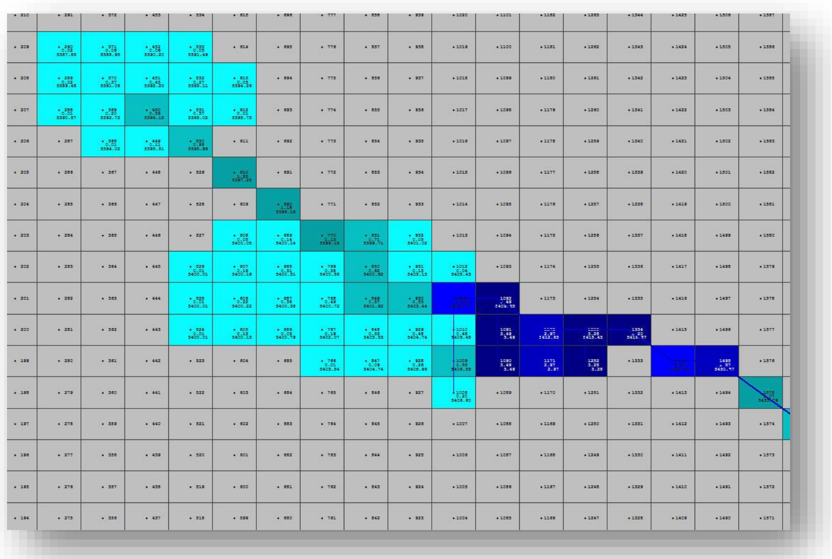


Figure 59. Combined maximum floodplain and channel flow depths.

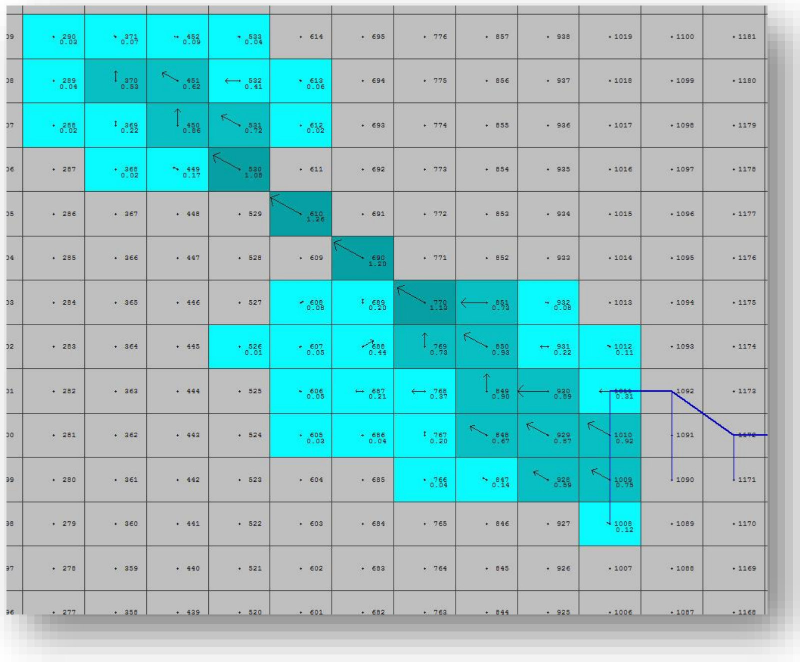
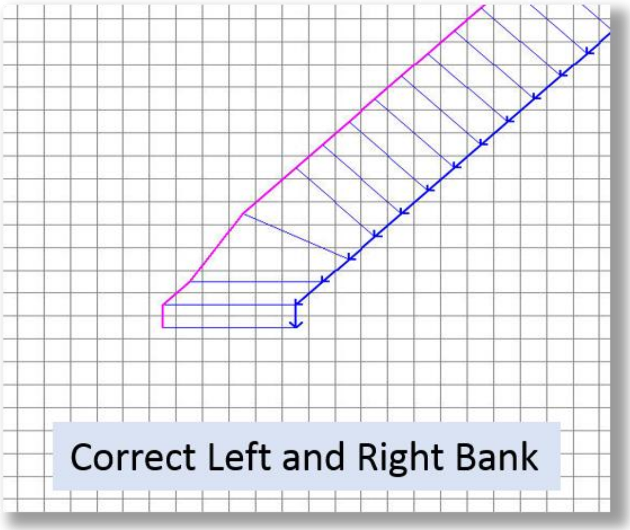


Figure 60. Maximum floodplain velocities showing the flow downstream of the channel.

The guidelines for setting up a **channel termination** to the floodplain are:

- Select a distance over which the channel will widen and become shallow (4 to 10 channel elements). The final channel cross section should have a thalweg less than 2.0 ft.
- Maintain essentially the same channel cross section flow area (with maybe a slight reduction) over the last few channel elements.
- Increase the n-values in the downstream direction.
- The floodplain elevations of the channel interior elements are set to the channel thalweg elevation of the last channel element and are identical.
- The downstream floodplain grid element elevations contiguous to the channel end elements should be lower than the channel end thalweg elevation to allow the flow to drain out of the channel.
- The channel can only terminate in one of the four compass directions. The end of the channel cannot extend from bank to bank across of the diagonal directions. At least three channel bank extensions should be oriented in one of the four compass directions as shown in Figure 61. The incorrect set-up will not yield correct discharge results from the channel to the floodplain.



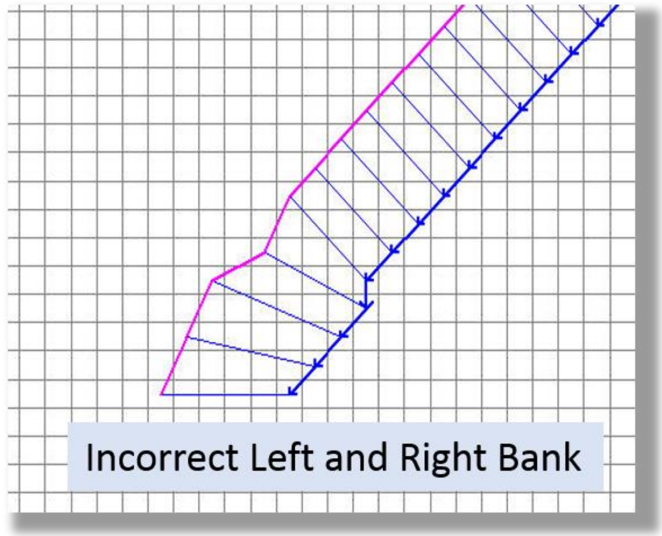


Figure 61. Channel Termination Bank Position.

Although it is not recommended, a uniform cross section can be used to the end of the channel as in the case of a rectangular concrete channel that just debouches onto the floodplain surface. If this was the project condition, it is suggested that the **1-D channel component** be continued some distance downstream of the concrete section to allow the alluvial channel flow area to gradually decrease and become wider and shallower as would occur in the natural setting.

Floodplain overland flow into the channel

The floodplain elements contiguous to the channel interior should match the channel thalweg elevation. All the floodplain elements sharing discharge to the channel can be set to the same bed elevation near the channel thalweg. As the floodplain transitions to channel flow the n-values can decrease to match the channel roughness. Figure 62 displays the floodplain relationship for inflow to the channel. The blue elements represent floodplain flow depth that enters the channel shown by blue line (left bank elements) and magenta line (right bank elements). The levee elements with red lines are not required but are used to facilitate this test model. Figure 63 shows the complete floodplain and channel scenario with channel termination about half way through the grid system.

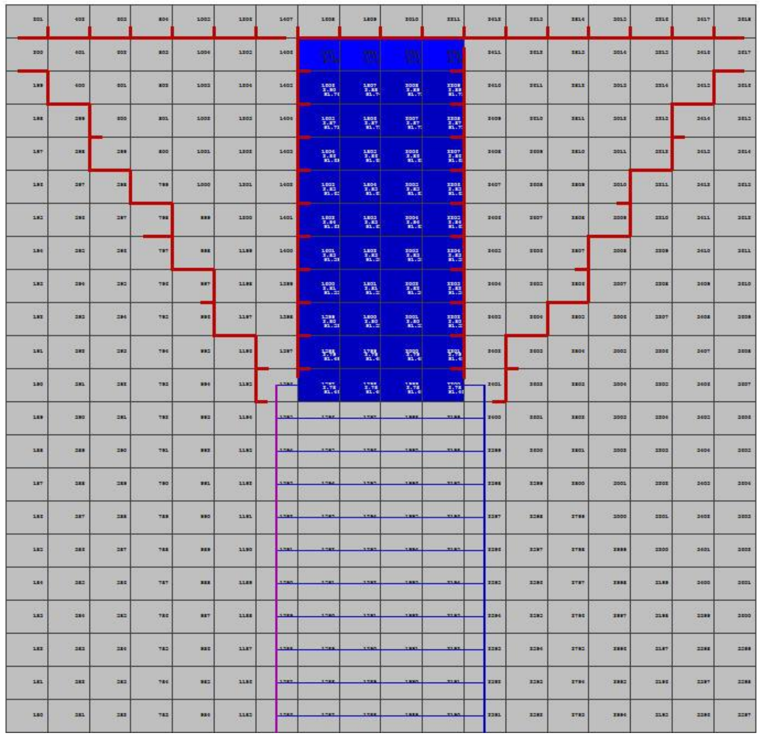


Figure 62. Floodplain flow entering the channel (from top of the image). Levees are shown in red.

The conventional method of assigning an inflow hydrograph to the upstream channel element in this case would not generate the same results with the flow only going down the channel. The inflow would leave the channel inflow element and flow upstream onto the floodplain. It is recommended that any inflow hydrographs be assigned to the upstream end of the floodplain grid system in this case.

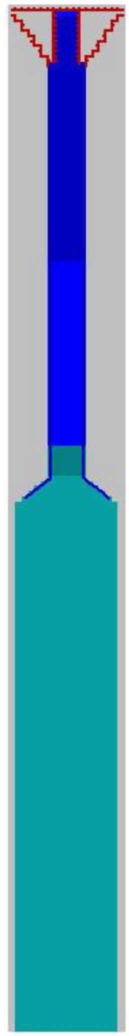


Figure 63. The channel widens and the flow exits the channel back to the floodplain.

Channel Troubleshooting

When a FLO-2D model simulation is complete, the first check for accuracy should be the volume conservation reported in SUMMARY.OUT and CHVOLUME.OUT. If the model did not conserve channel volume, then the error needs to be isolated to a short reach of channel to determine the issues. Initially, the other components that interact with the channel can be turned off such as rainfall, infiltration, and hydraulic structures. This can be done one component at time or all together at once. If the volume conservation error persists, then it may be necessary to turn off the channel segments or tributaries one at a time to isolate the problem. First make copies of the affected data files and then remove any inflow and outflow nodes to the segment. The removal of any channel elements (segments or tributaries) from the CHAN.DAT file would require that the XSEC.DAT and CHANBANK.DAT files also be modified by eliminating the corresponding cross sections and right banks. Another method for isolating a portion of the channel is to establish a new temporary inflow and outflow node in a short reach of channel (Figure 64).

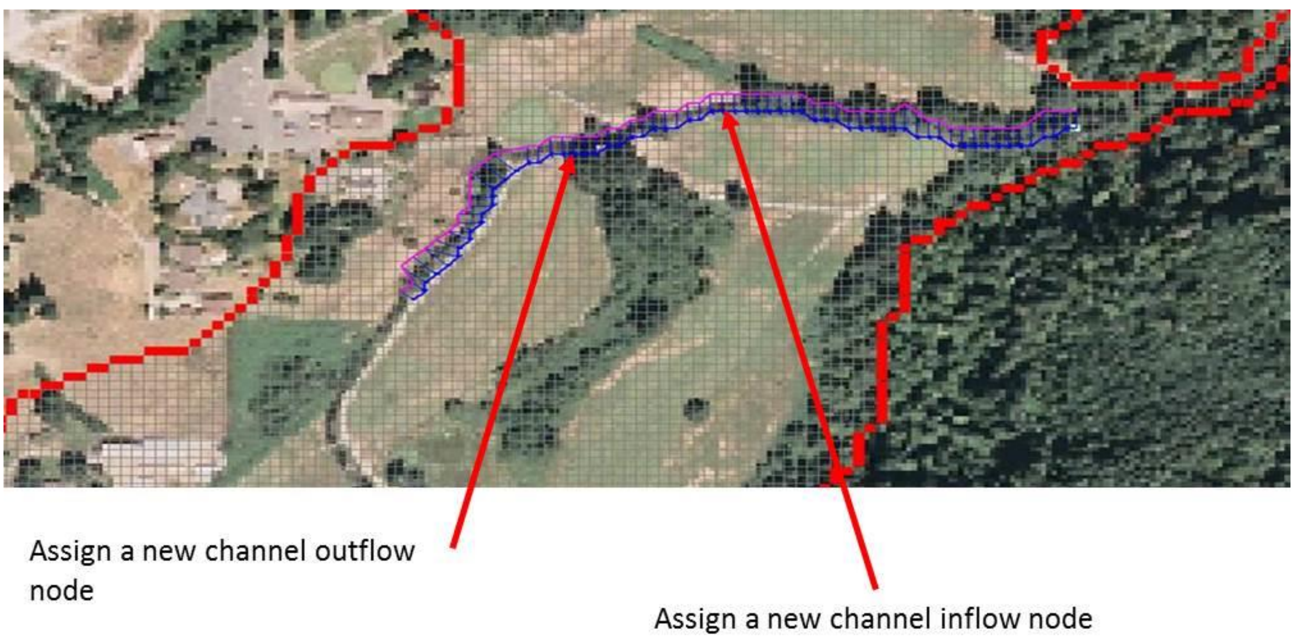


Figure 64. Isolate a Short Portion of the Channel.

Fixing a volume conservation error could entail adjusting the channel cross sections, reviewing the bank elevations, adjusting the hydraulic structures rating tables or eliminating other component conflicts. In general, volume conservation errors are the result of data errors and are usually identified in the ERROR.CHK file. They can also result from improper geometry resulting rapid variations in cross sectional area and/or slope and roughness coefficients.

For FLO-2D models using the 1-D channel component, most of the timestep decrements reported in the TIME.OUT file are attributed to the channel elements. The top few channel elements listed in the TIME.OUT file may also have surging associated with them which can be discerned by plotting the maximum discharge in PROFILES (Figure 65), reviewing CHANMAX.OUT or VELTIMEC.OUT. The most sensitive model scenario is a wide channel with small grid elements where the channel left and right banks are separate by ten or more grid elements. In this situation, the channel element conveyance capacity is relatively small because the channel length is short compared to the channel width.

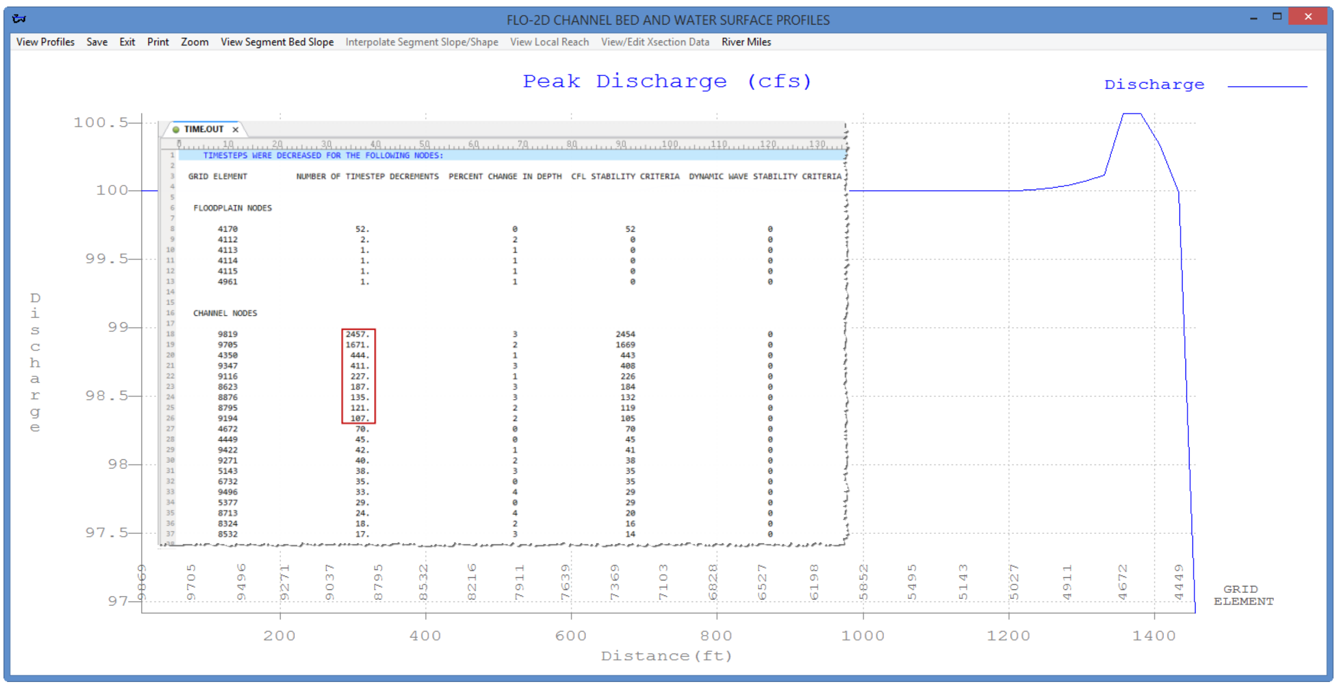


Figure 65. TIME.OUT and Profiles - Peak Discharge.

For example, a channel on the order of 800 ft wide was simulated on a grid system of 20 ft elements in Phoenix. Between the left and right bank elements, there were 40 or more elements (Figure 66). Each channel element was 20 ft to 28 ft long. For discharges over 10,000 cfs, this resulted in a large discharge flux with relatively small volume storage. Very small timesteps, less than 0.5 seconds were required to maintain numerical stability. To avoid small timesteps with such a large channel, it is necessary to select larger grid elements when generating the grid system. The choice of the grid element size has to be based on the project priority; either accurate channel flood routing or predicting the floodplain inundation in detail.

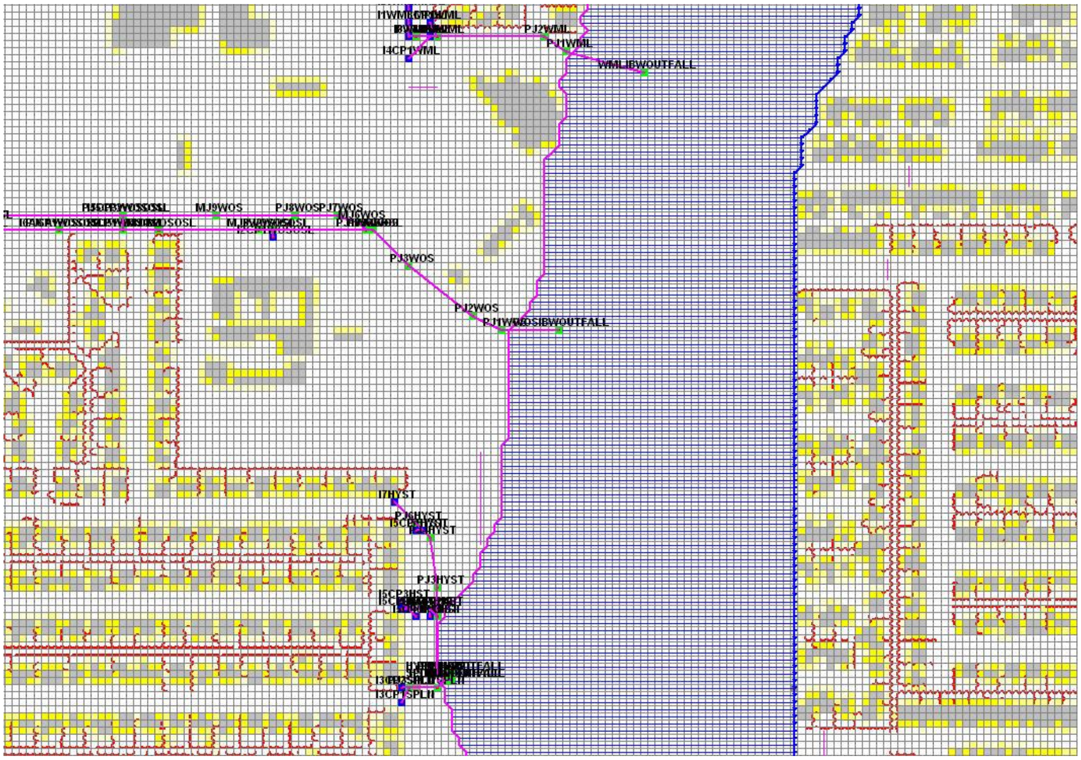


Figure 66. Wide Large Channel Assigned to a Small Grid System.

To compute smoother hydraulics between two channel grid elements the options are to adjust the bed slope, the cross section flow area or the roughness values. Abrupt changes in cross sections geometry from one channel element to another should be avoided. The channel flow area should make a gradual transition from a wide, shallow cross section to a narrow deep cross section occur over several channel grid elements. Adjust the channel geometry so that the maximum change in flow area between channel elements is less than 25%.

To improve the channel component performance, the following steps should be taken:

Review PROFILES peak discharge plots or the output files CHANMAX.OUT or VELTIMEC.OUT. Look for any channel elements with numerical surging (note spike – Figure 67).

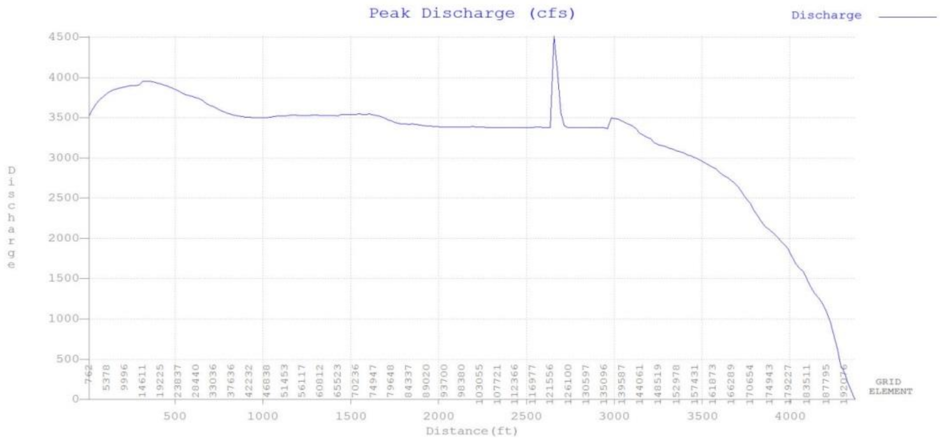


Figure 67. Channel Numerical Instability – Peak Discharge vs Channel Distance.

Review and adjust the bed slope with the PROFILES program. Adverse bed slopes are acceptable, but flat beds, spikes and other inconsistences should be reviewed (Figure 68 – red ovals). In a highly modified or constructed urban environment, this channel profile may be appropriate, but it should be edited if necessary to achieve a stable more realistic model.

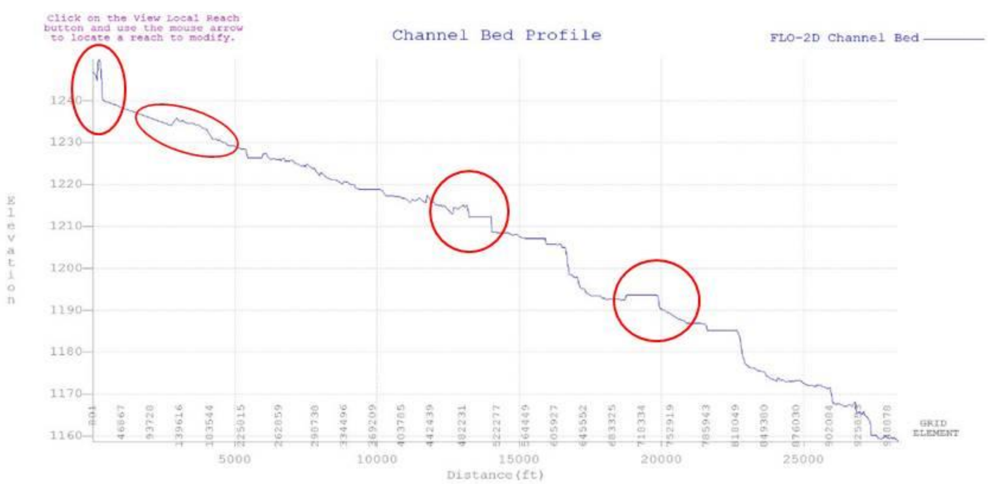
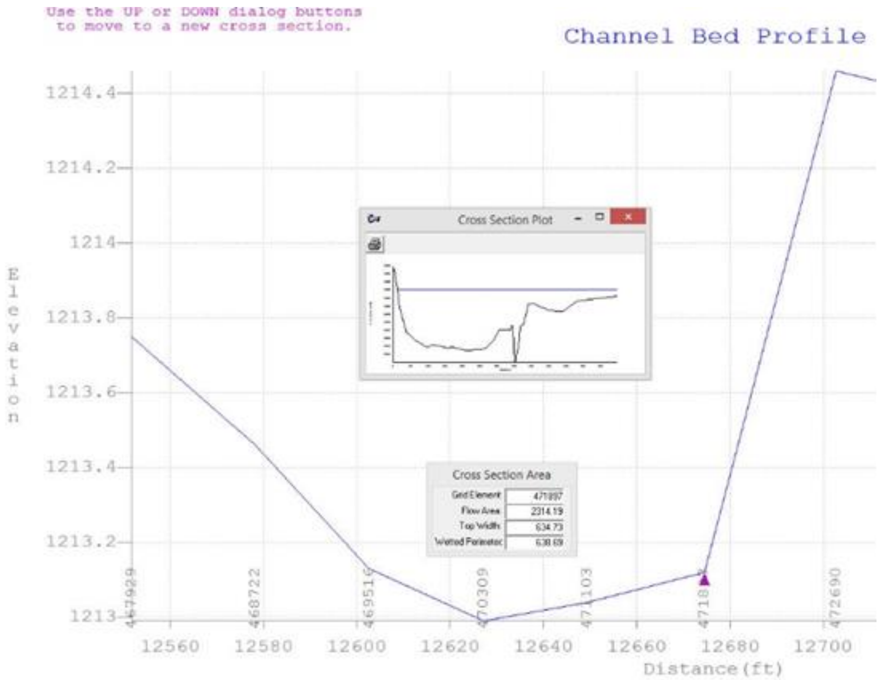


Figure 68. Review the Channel Bed Slope for Irregularities.

Reduce the variability between channel element cross section flow areas. Avoid abrupt cross section transitions between channel elements. Adjust the channel cross section geometry in the PROFILES program. Figure 69 A and B shows the change in channel shape between two contiguous channel elements with the same approximate bankfull flow area.



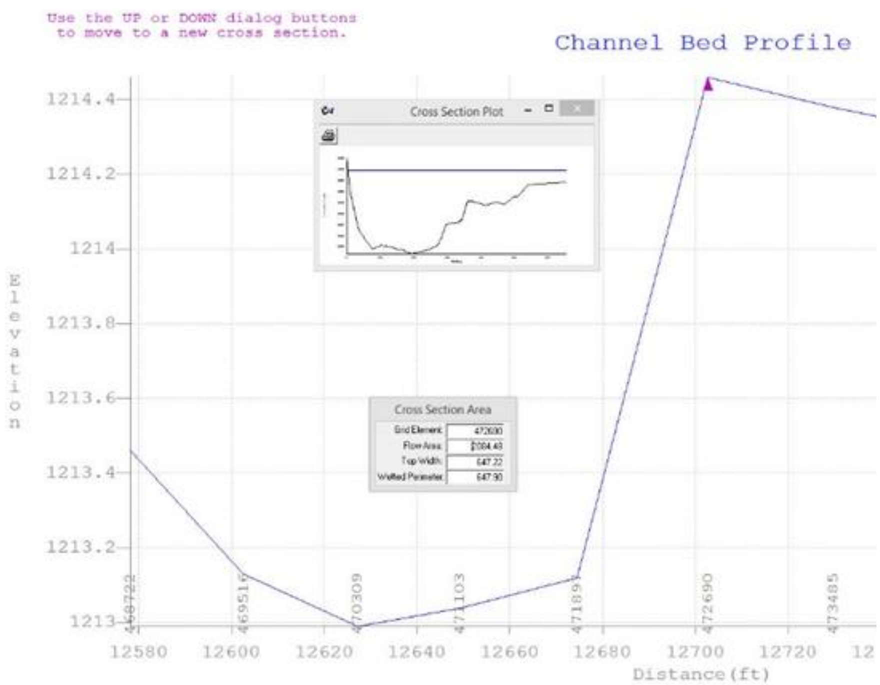


Figure 69 A and B. Change in Channel Geometry between Two Contiguous Channel Elements.

Figure 70 A - D show four consecutive channel elements with a bankfull flow area that varies from 4,600 ft^2 to 3,300 ft^2 to 3,250 ft^2 back to 4,100 ft^2. This is about a 33% change in bankfull conveyance capacity.

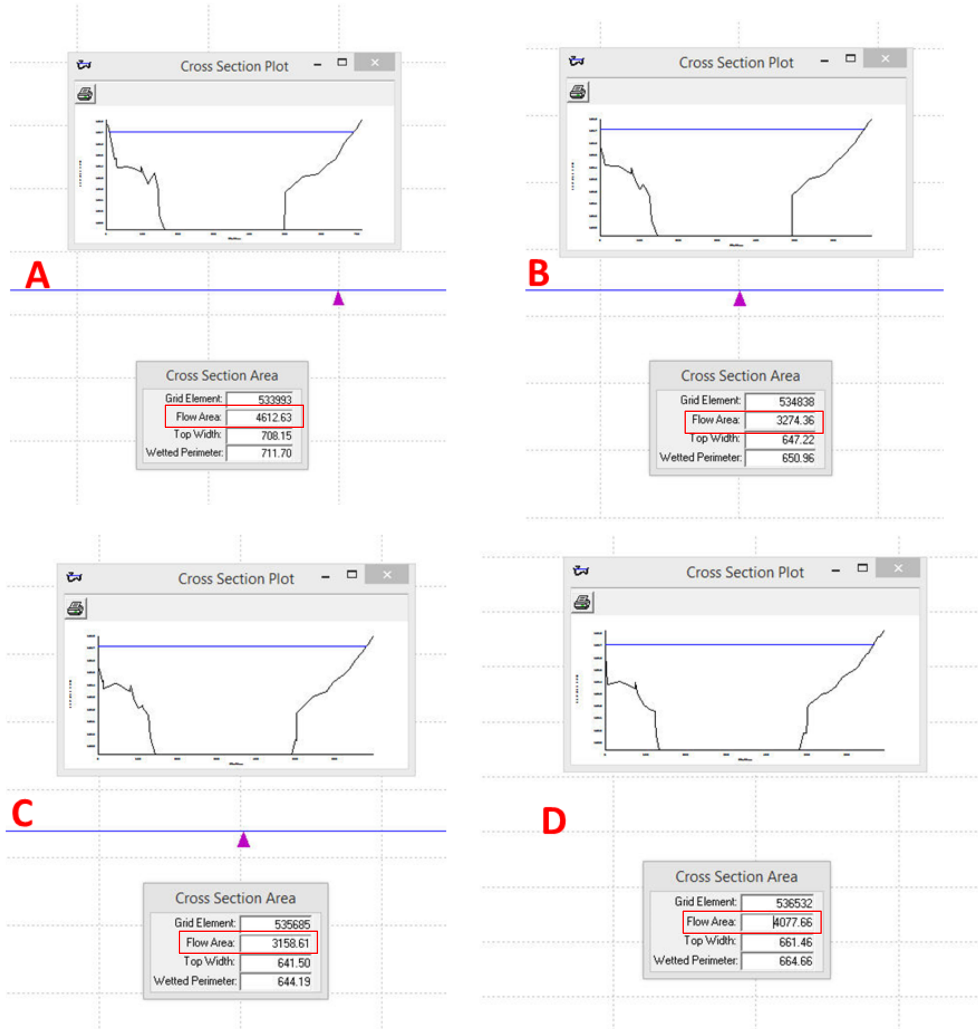


Figure 70. A-D Change in Bankfull Flow Area between Four Consecutive Channel Elements.

For the entire channel segment, the flow area varies from 223 ft^2 to 7,817 ft^2 with an average cross section flow area of 3,507 ft^2 as displayed in the PROFILES program n-value interpolation dialog box (**Error! Reference source not found.**). For a channel that should have approximately the same conveyance capacity, this is too much variation in the flow area. This indicates that each cross section in the model needs to be reviewed.

To improve numerical stability, increase the roughness in wide, shallow cross sections and decrease the roughness in narrow deep channel grid elements. Review the channel element roughness variation upstream and downstream of channel elements with spikes in discharge (Figure 71).

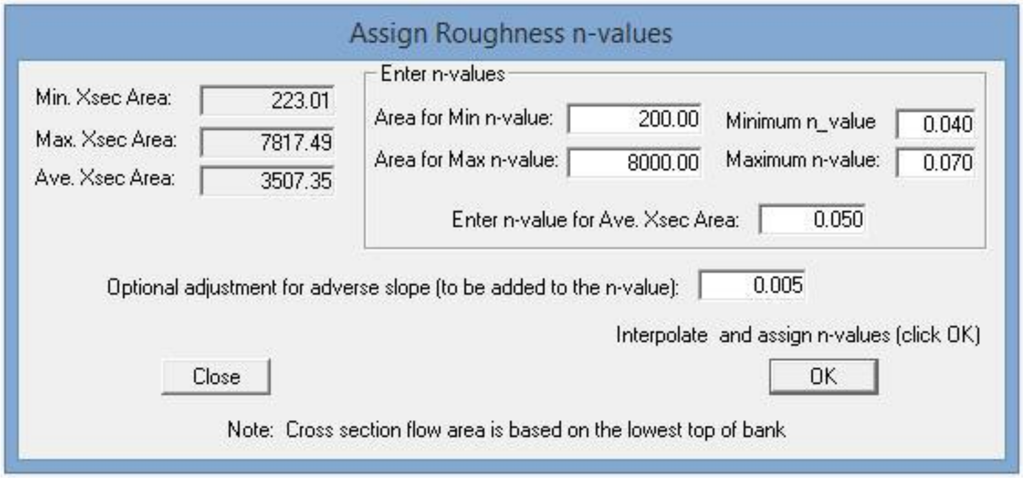


Figure 71. Variable n-value System Profiles.

Select a longer channel length within the channel grid element to allow more storage (Increase the lengths in the red outline in Table 1. The maximum length should be less than 1.5 times the grid element side.

Table 1. CHAN.DAT File with Channel Lengths Highlighted

N	801	0.04	20.23	1
N	1723	0.04	20.33	2
N	2646	0.04	20	3
N	3569	0.04	20	4
N	4492	0.04	20.04	5
N	5416	0.04	20.05	6
N	6340	0.04	20.53	7
N	7264	0.04	20	8
N	8188	0.04	20	9
N	9111	0.04	20	10
N	10034	0.04	20	11
N	10957	0.06	20.59	12

Small timesteps are the result of exceeding the numerical stability criteria (Courant criteria). The change in channel flow depth for a timestep may be too large. The primary reason for a slow flood simulation is that the discharge flux is too high for the selected grid element size (channel element conveyance capacity). Selecting a grid element size in proportion to the channel flow area and anticipated peak discharge is the most appropriate way to avoid a very slow model.

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