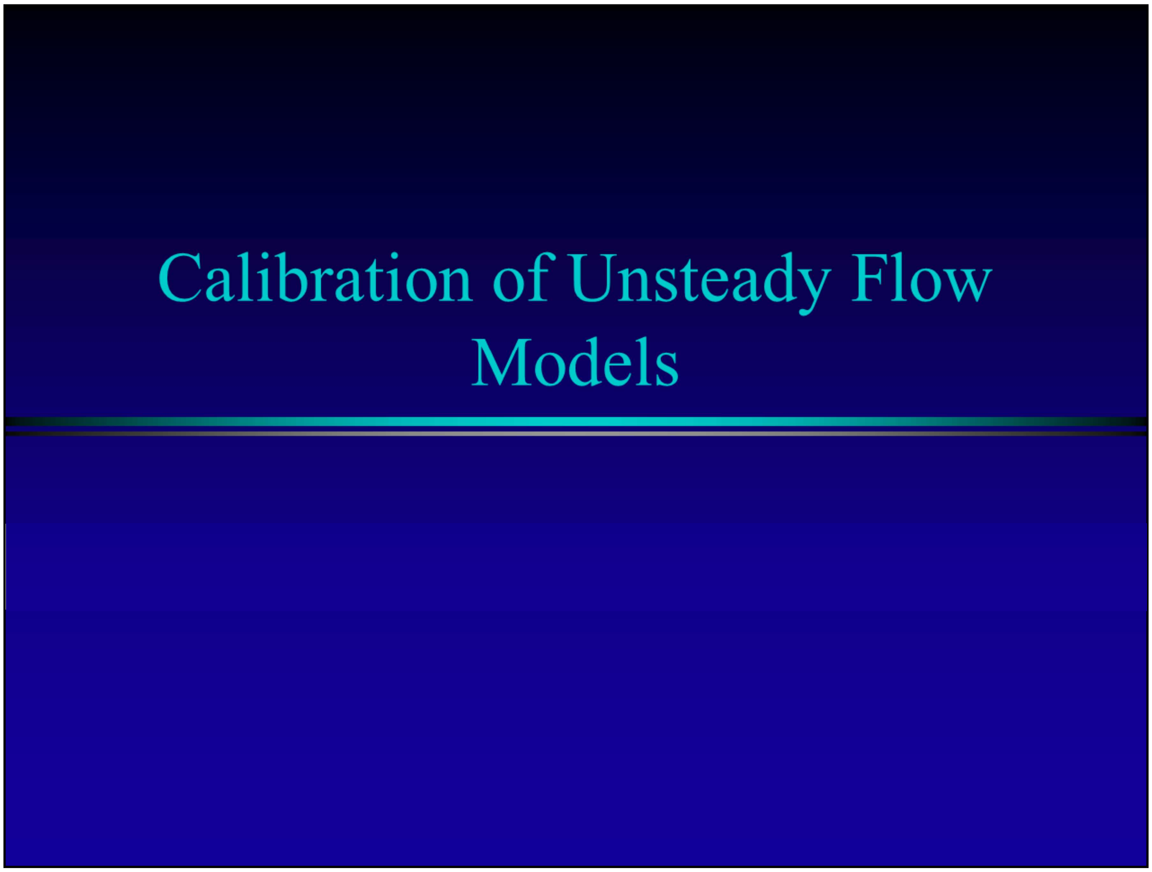
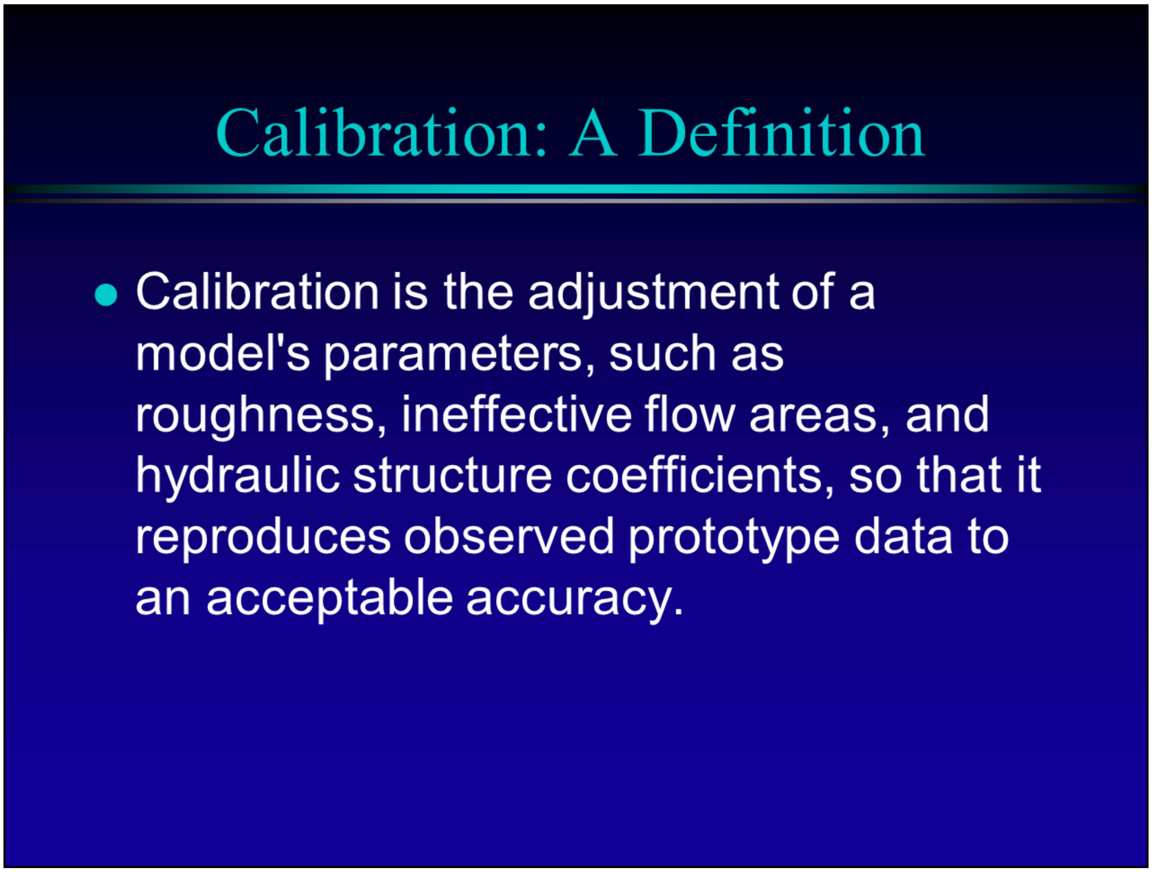


Calibration of Unsteady Flow Models

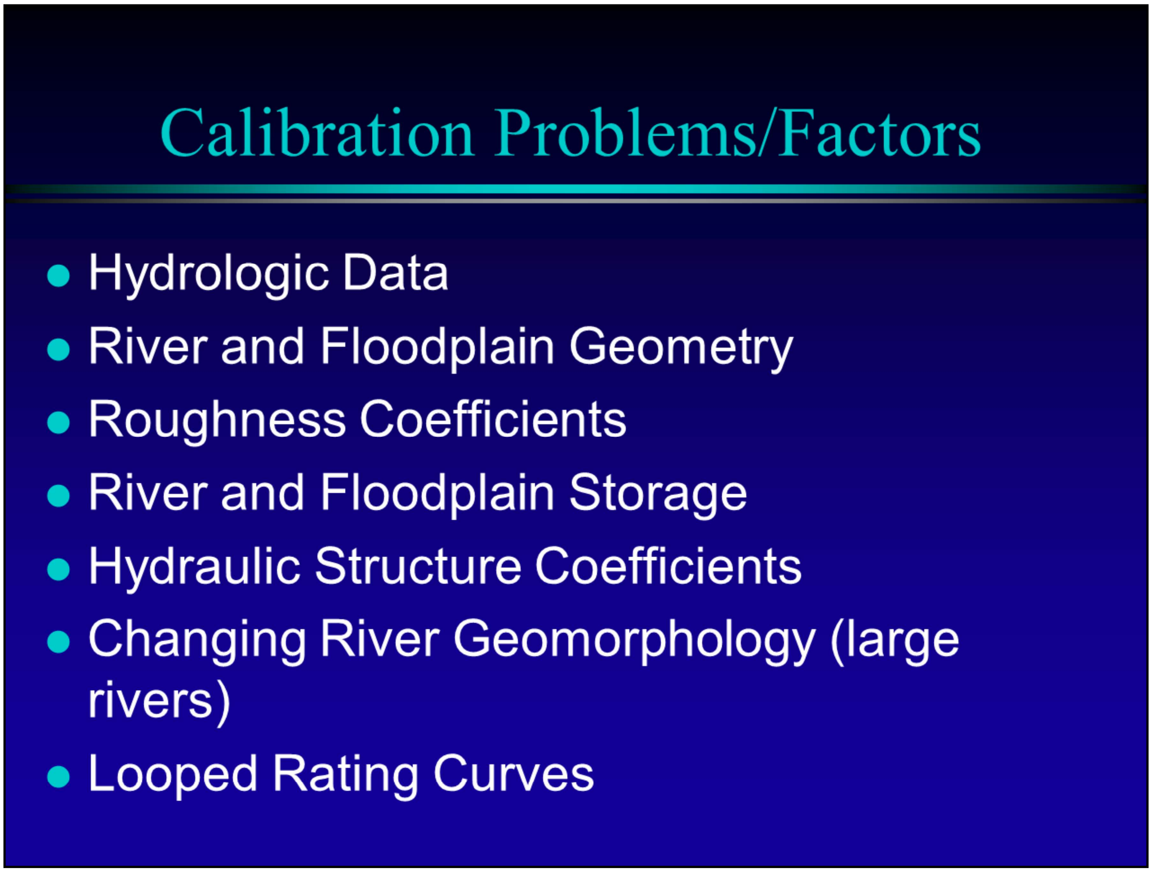
Objectives

- To provide students with the ability to undertake the calibration of an unsteady flow model to observed events.
- To identify data problems and gaps
- To learn to develop models that consistently reproduce observed stages, flows, and timing.



Calibration: A Definition

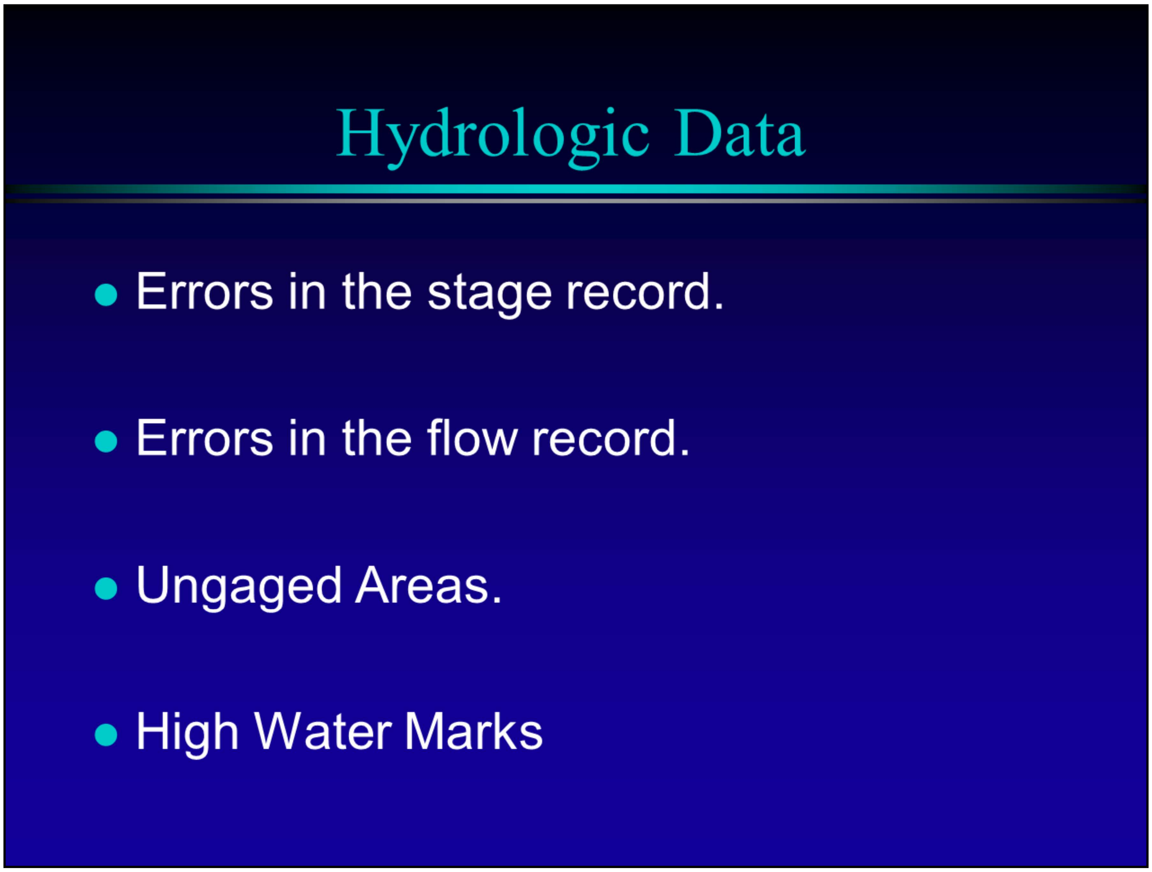
- Calibration is the adjustment of a model's parameters, such as roughness, ineffective flow areas, and hydraulic structure coefficients, so that it reproduces observed prototype data to an acceptable accuracy.



Calibration Problems/Factors

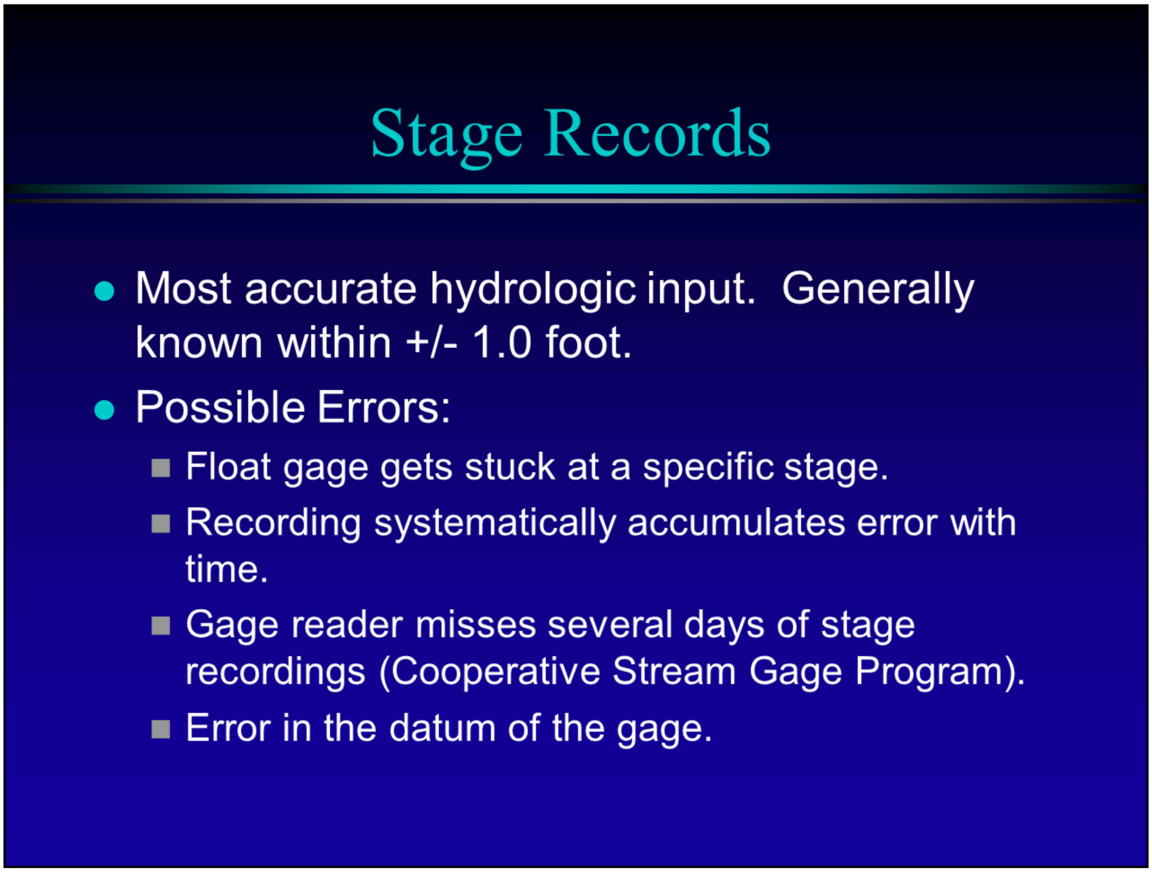
- Hydrologic Data
- River and Floodplain Geometry
- Roughness Coefficients
- River and Floodplain Storage
- Hydraulic Structure Coefficients
- Changing River Geomorphology (large rivers)
- Looped Rating Curves

Greatest problem is inconsistency: model will reproduce one event but not another. Modeler must become a detective who identifies errors and inconsistencies in the input data and identifies possible geomorphic changes in the system. Once the modeler understands the system, the modeler must develop procedures that compensate for any shortcomings. This could include adding storage cells to simulate flooded areas.



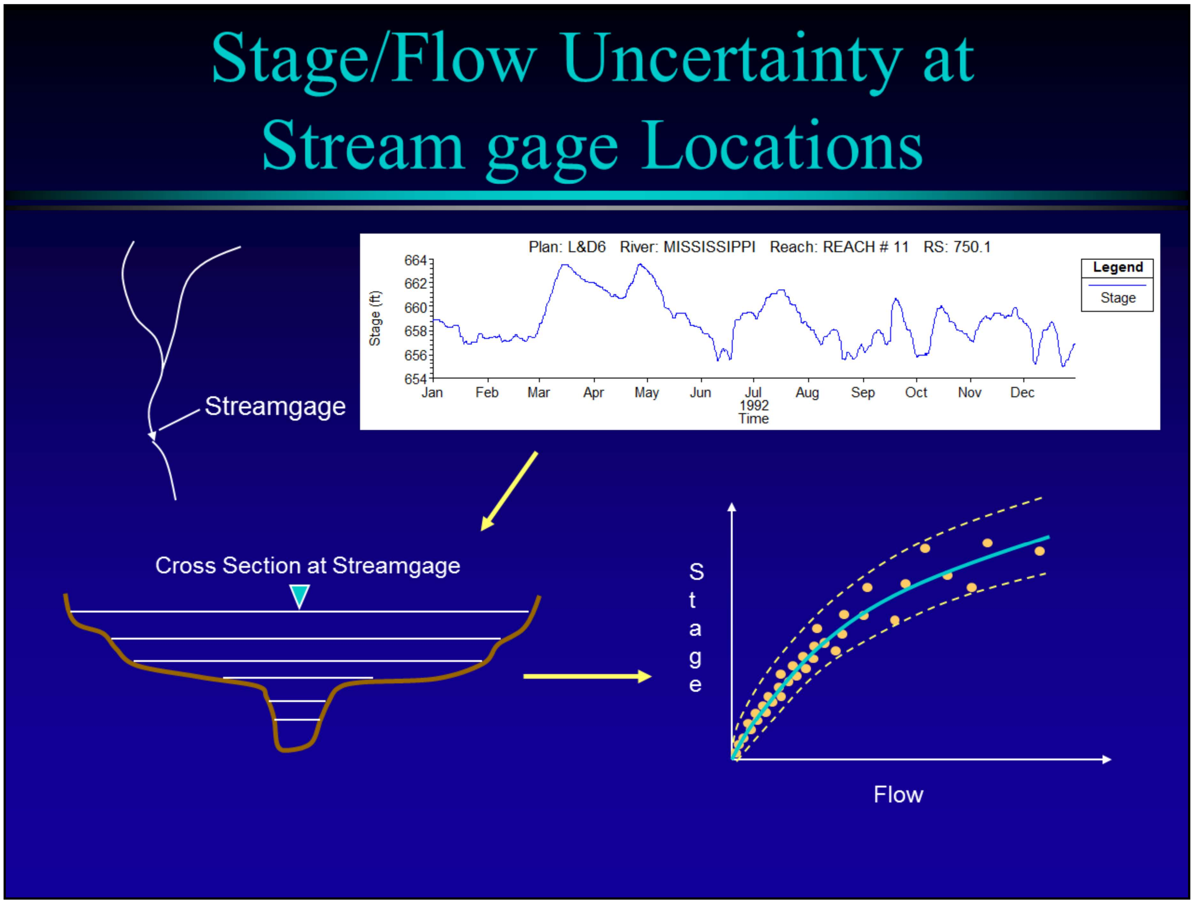
Hydrologic Data

- Errors in the stage record.
- Errors in the flow record.
- Ungaged Areas.
- High Water Marks

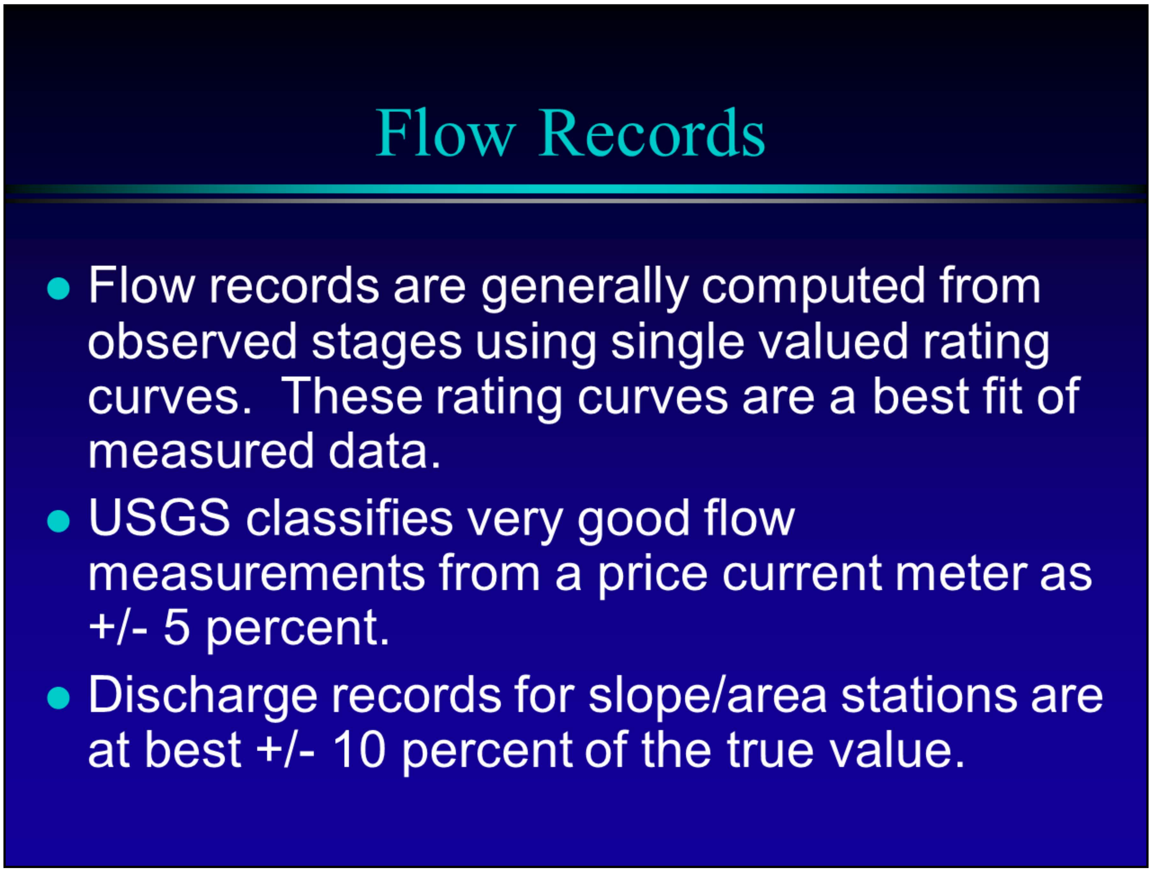


Stage Records

- Most accurate hydrologic input. Generally known within +/- 1.0 foot.
- Possible Errors:
  - Float gage gets stuck at a specific stage.
  - Recording systematically accumulates error with time.
  - Gage reader misses several days of stage recordings (Cooperative Stream Gage Program).
  - Error in the datum of the gage.



Stage/Flow Uncertainty at Stream gage Locations



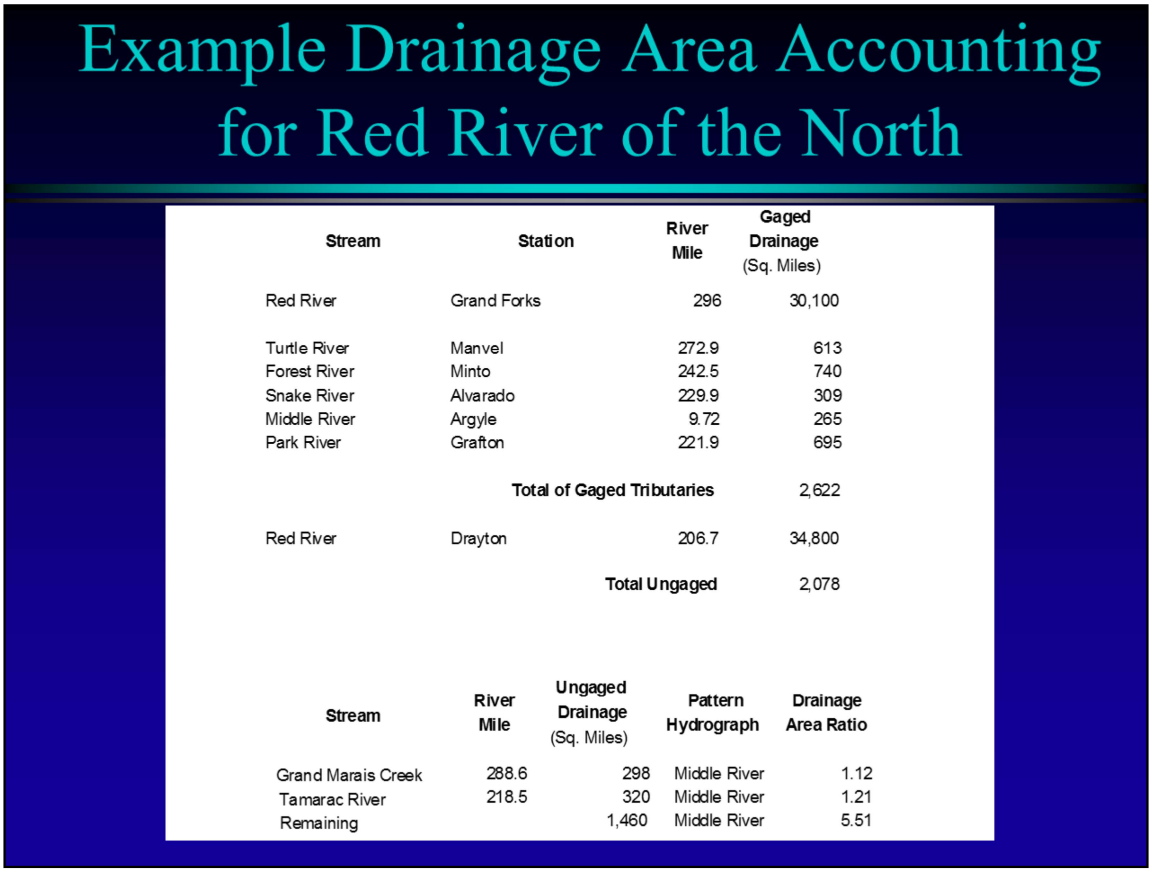
Flow Records

- Flow records are generally computed from observed stages using single valued rating curves. These rating curves are a best fit of measured data.
- USGS classifies very good flow measurements from a price current meter as +/- 5 percent.
- Discharge records for slope/area stations are at best +/- 10 percent of the true value.

USGS classifies good flow measurements from Price current meters to be within ±5% of the true value. Some believe that this assumed error is optimistic. In any case, ±5%, on many river systems, translates into a stage error of ±1 foot. Acoustic velocity meters provide a continuous record, but the current USGS technique calibrates these meters to reproduce measurements from Price current meters, so the AVM is as accurate as the current meter. Boat measurements are always suspect. Newer techniques using acoustic velocity meters with three beams mounted on boats are thought to be much better. Published discharge records should also be scrutinized. Continuous discharge is computed from discharge measurements, usually taken at bi-weekly or monthly intervals and the continuous stage record. The measurements are compiled into a rating curve and the departures of subsequent measurements from the rating curve are used to define shifts. The shifts are temporary changes in the rating curve due to unsteady flow effects (looped rating curve) and short term geomorphic changes. The quality of the record depends on the frequency of discharge measurements and the skill of the hydrologist. The only way to tell is to compare the discharge measurements to the flow record. Still, if the measurements are infrequent, one can only apply the flow record to the model and see how well the stage record is reproduced. Remember! Most published flow records are in mean daily flow. The modeler must somehow assign time values to these records.

Ungaged Drainage Areas

- For the model to be accurate, it must have flow input from all of the contributing area.
- In many studies a significant portion of the area is ungaged.
- Discharge from ungaged areas can be estimated from:
  - Hydrologic models
  - Flow from a gaged watershed with similar hydrologic characteristics, multiplied by a simple drainage area ratio.



Example Drainage Area Accounting for Red River of the North

Stream	Station	River Mile	Gaged Drainage (Sq. Miles)
Red River	Grand Forks	296	30,100
Turtle River	Manvel	272.9	613
Forest River	Minto	242.5	740
Snake River	Alvarado	229.9	309
Middle River	Argyle	9.72	265
Park River	Grafton	221.9	695
	Total of Gaged Tributaries		2,622
Red River	Drayton	206.7	34,800
	Total Ungaged		2,078

Stream	River Mile	Ungaged Drainage (Sq. Miles)	Pattern Hydrograph	Drainage Area Ratio
Grand Marais Creek	288.6	298	Middle River	1.12
Tamarac River	218.5	320	Middle River	1.21
Remaining		1,460	Middle River	5.51

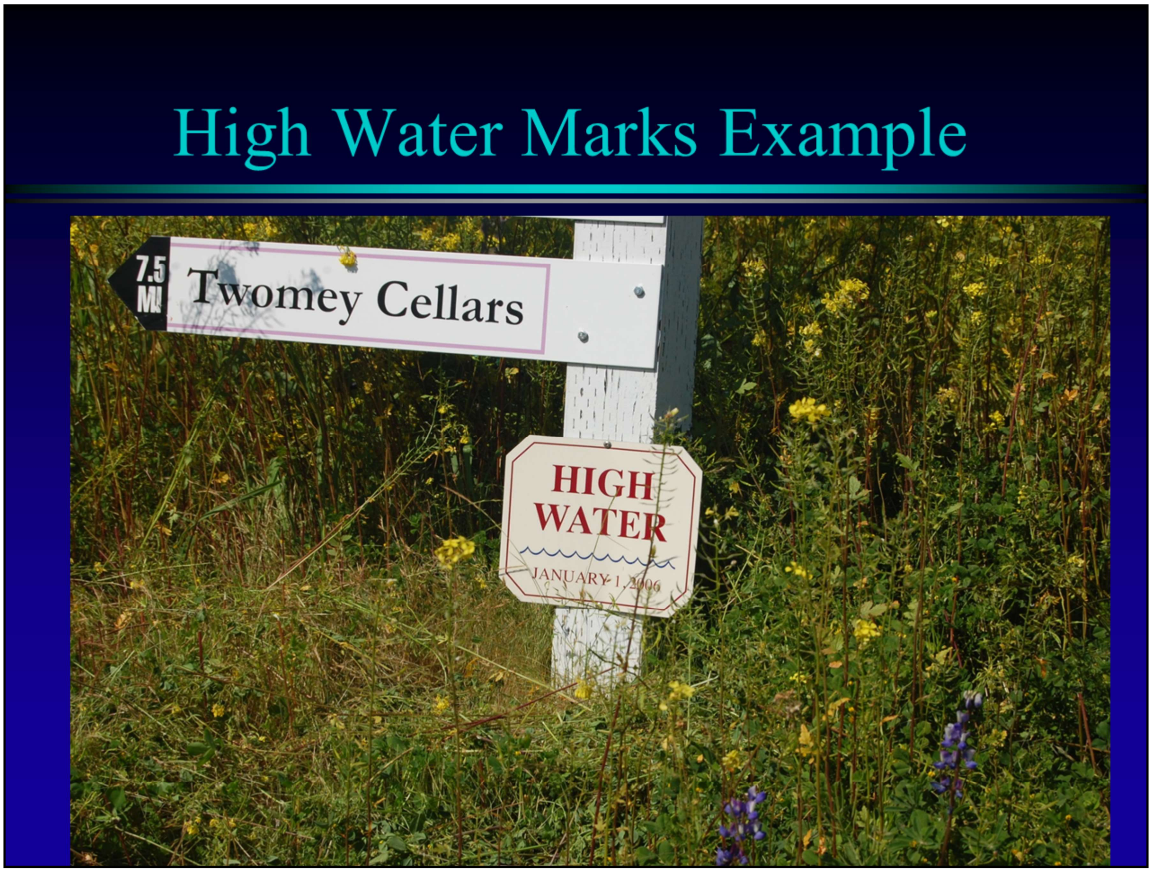
Drainage area accounting for the Red River of the North between Grand Forks and Drayton. Ungaged areas are accounted for by using a pattern hydrograph of a similar watershed (Middle River), then calculating a drainage area ratio of contributing areas (Ungaged area divided by pattern hydrograph area).

High Water Marks

- High water marks are estimated from the upper limit of stains and debris deposits found on buildings, bridges, trees, and other structures.
- Wind and wave actions can cause the debris lines to be higher than the actual water surface.
- Capillary action causes stains on buildings to migrate upward.
- High water marks in the overbank area are often higher than in the channel. Overbank water is moving slower and may be closer to energy gradline.
- High water marks on bridge piers are often equal to the energy gradeline, not the average water surface.

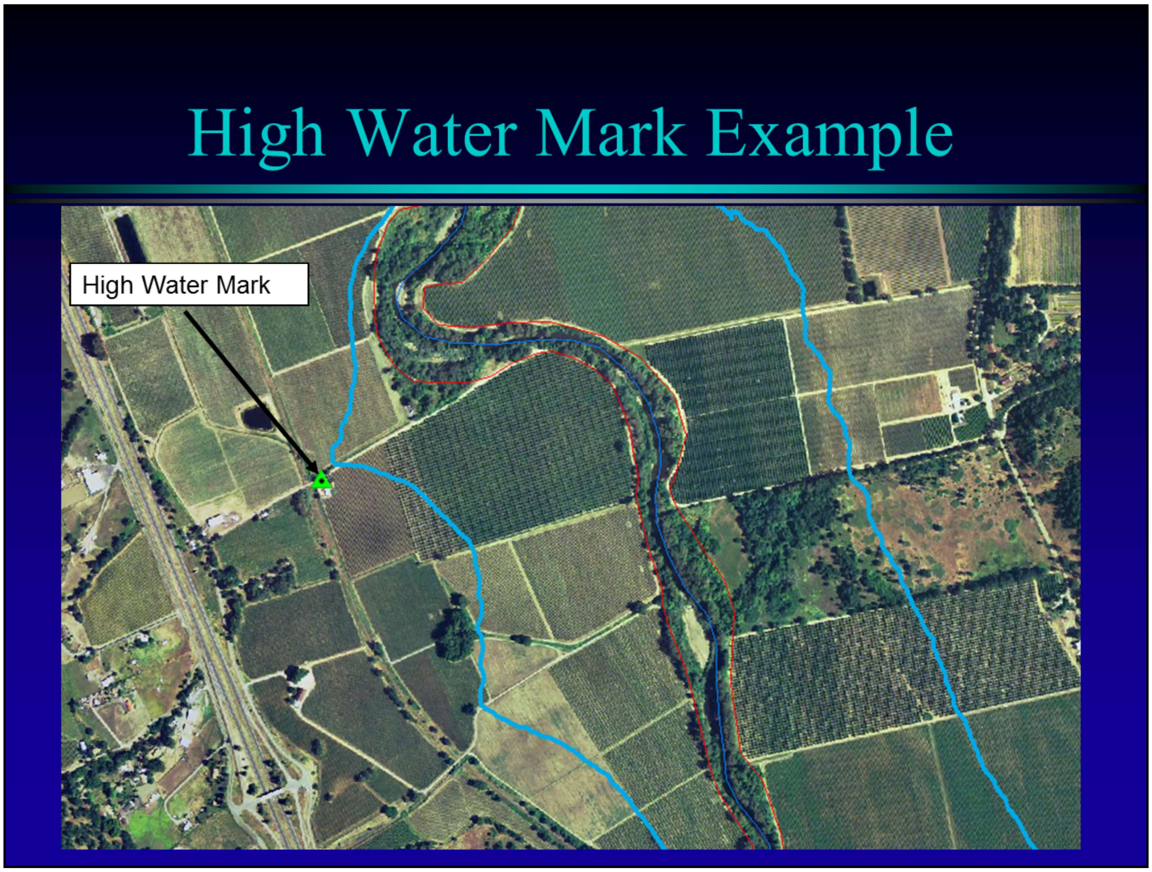
High Water Marks Example

These High water Marks were drawn on the side of a movie theater in the town of Rio California, along the Russian River, after each flood of significance. Some one also got very creative with the art work below each water line.



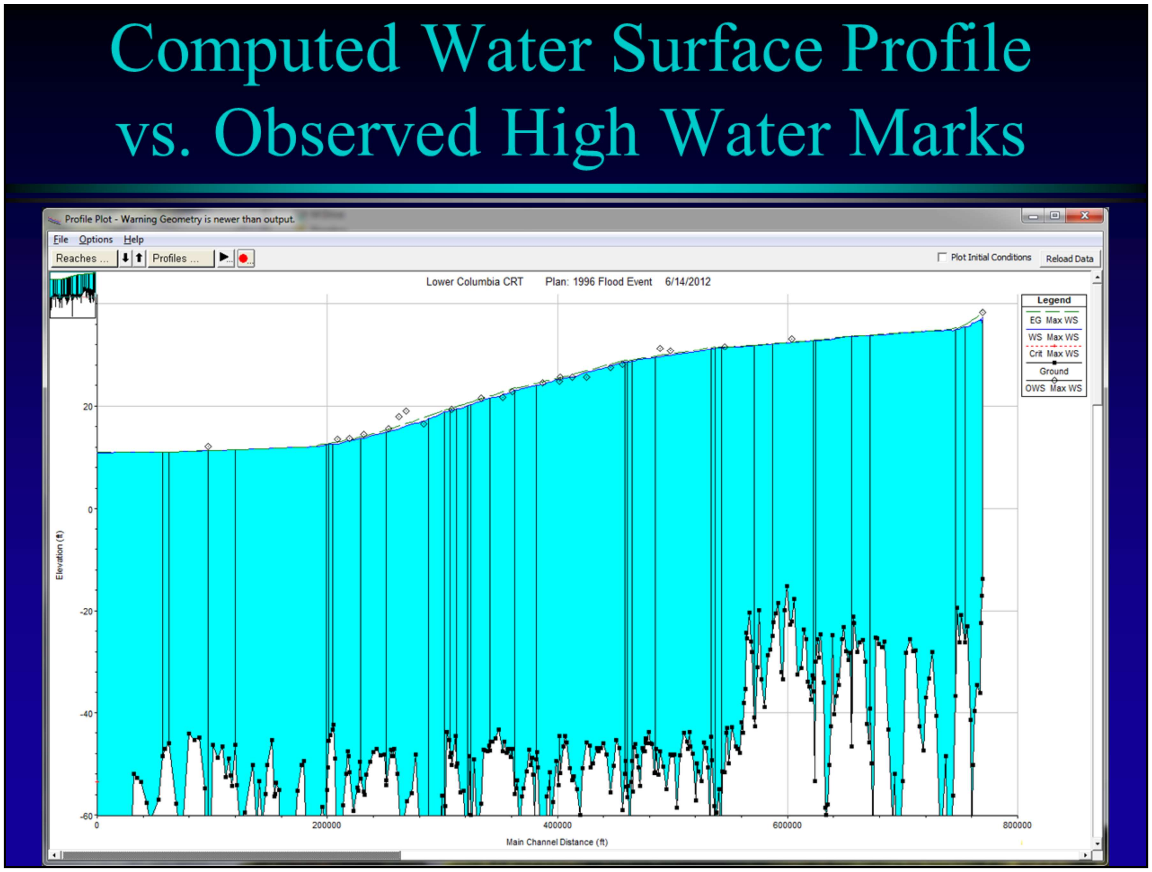
High Water Marks Example

This is another High water mark along the Russian River in California. This was at an intersection of two roads, that could easily be found on a map/Terrain model for verification of the computed floodplain boundary for that event.



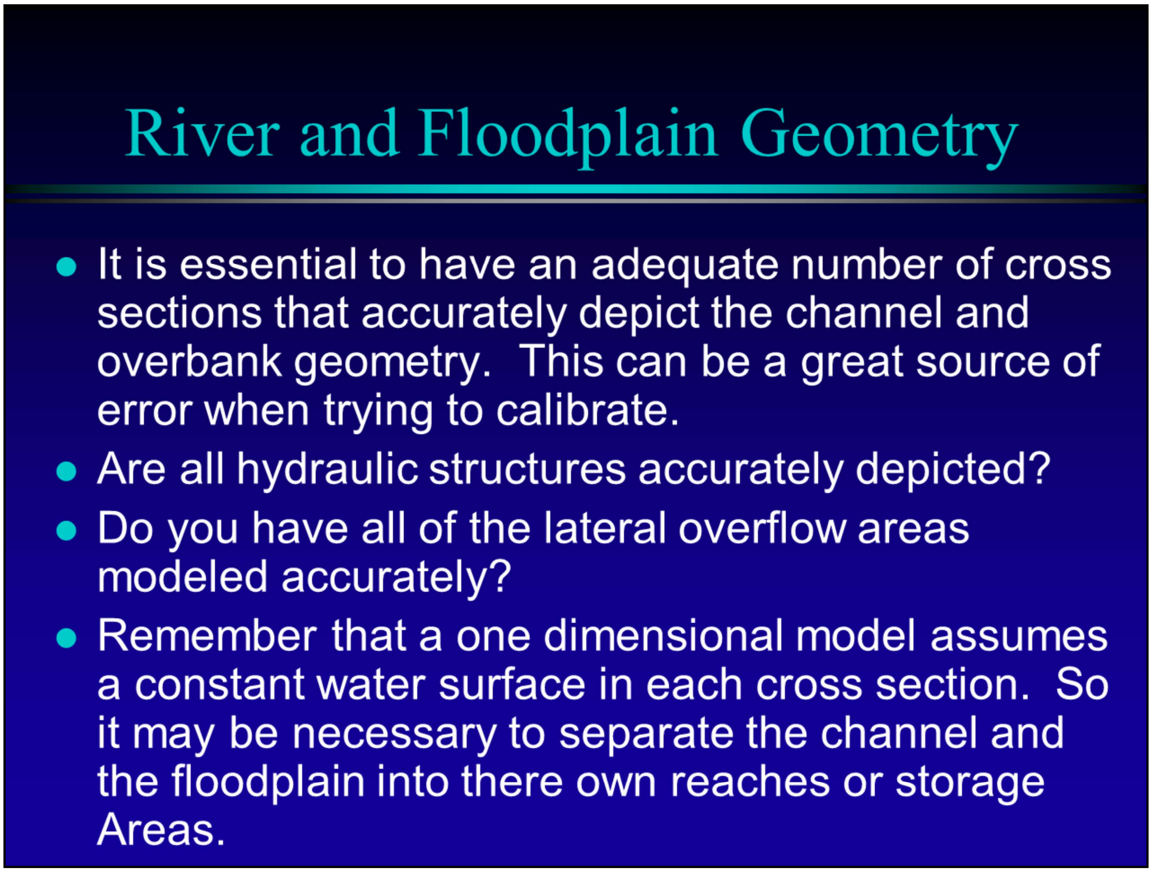
High Water Mark Example

The green triangle with the black dot is a high water mark location obtained while talking to the Farmer who owns this land. This is another good example of a floodplain boundary high water mark.



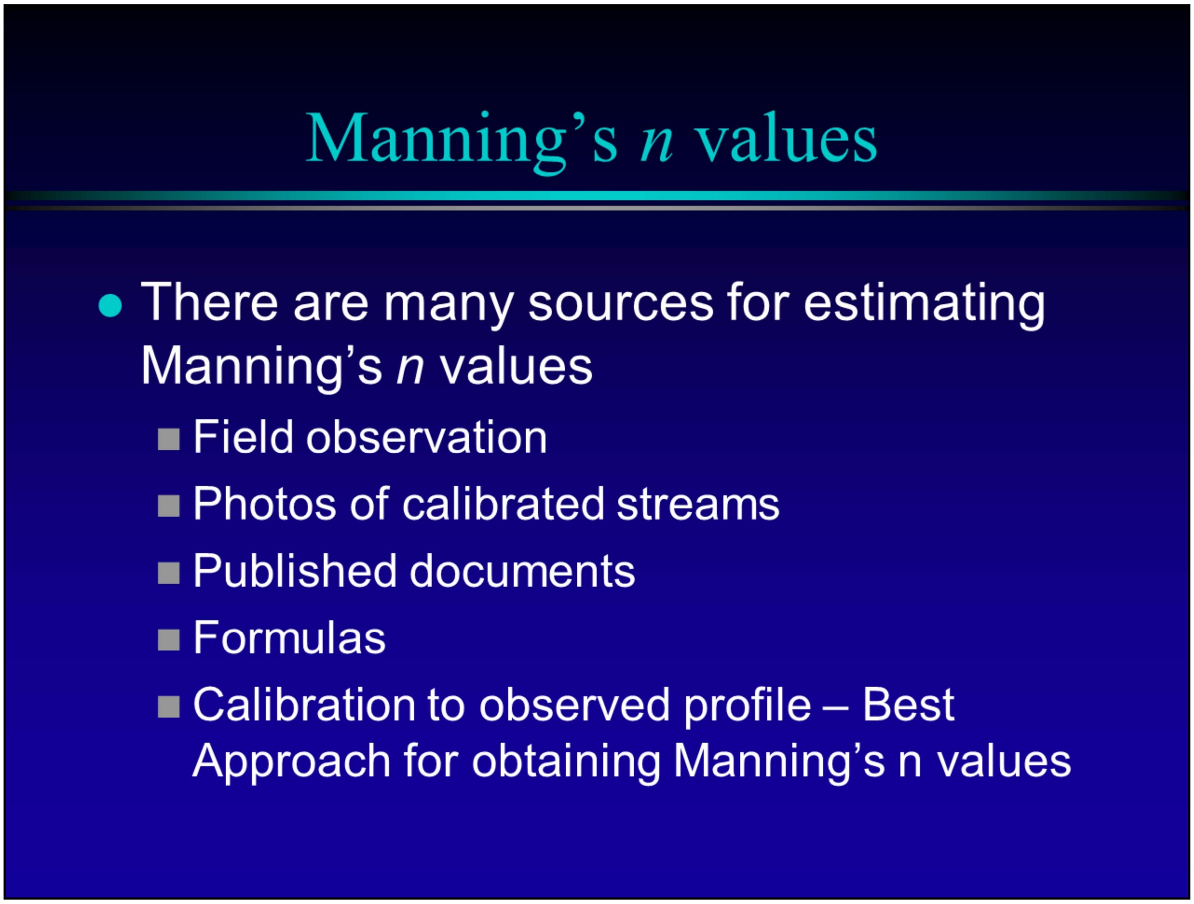
Computed Water Surface Profile vs. Observed High Water Marks

Shown in the Figure above is a comparison between high water marks and the computed maximum water surface profile. Note the scatter in the high water marks, particularly around river station 230. Which mark is accurate?



River and Floodplain Geometry

- It is essential to have an adequate number of cross sections that accurately depict the channel and overbank geometry. This can be a great source of error when trying to calibrate.
- Are all hydraulic structures accurately depicted?
- Do you have all of the lateral overflow areas modeled accurately?
- Remember that a one dimensional model assumes a constant water surface in each cross section. So it may be necessary to separate the channel and the floodplain into there own reaches or storage Areas.



Manning’s *n* values

- There are many sources for estimating Manning’s *n* values
  - Field observation
  - Photos of calibrated streams
  - Published documents
  - Formulas
  - Calibration to observed profile – Best Approach for obtaining Manning’s n values

There are many sources for estimating Manning’s *n* values.

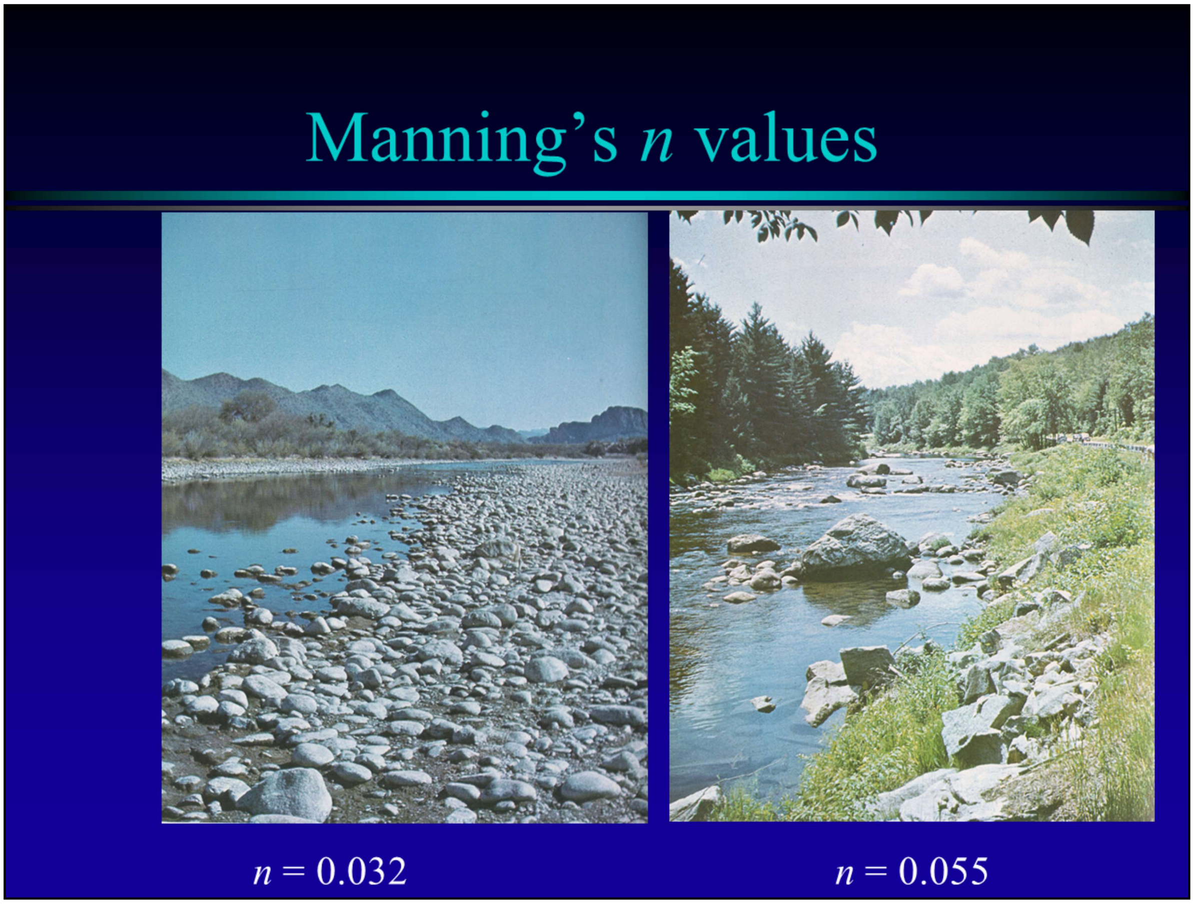
The best method is to have an experienced hydraulic engineer making observations in the field. But as the saying goes: “it takes experience to get experience”.

If an engineer is stuck in the office and has pictures, you can compare them to published documents. Or you can rely on formulas which create a composite *n* value based on the characteristics we talked about earlier. You can also use the hydraulic model itself and calibrate *n* values to observed profile data.

In the end, good engineers use all of the methods together to finalize *n* values.

References for estimating Manning’s n values:

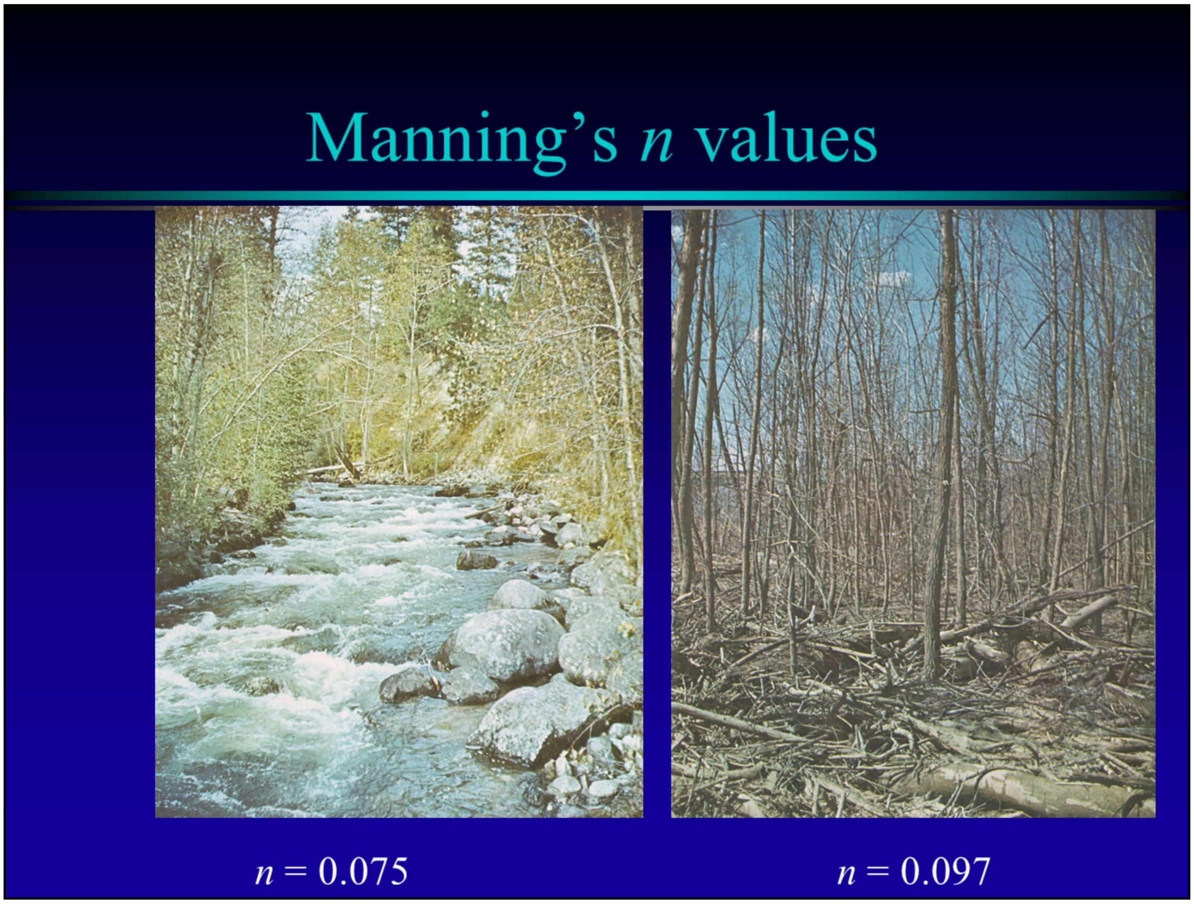
1. Chow, VT, 1959. Open-Channel Hydraulics, McGraw-Hill, Inc., USA.
2. Barnes, HH, 1967. Roughness Characteristics of Natural Channels, Geological Survey Water-Supply Paper 1849, USGS.
3. Phillips, JV and TL Ingersoll, 1998. Verification of Roughness Coefficients for Selected Natural and Constructed Stream Channels in Arizona, USGS Professional Paper 1584, USGS.
4. Hicks, DM and PD Mason, 1991. Roughness Characteristics of New Zealand Rivers, Water Resources Survey, New Zealand.



Manning's *n* values

$n = 0.032$

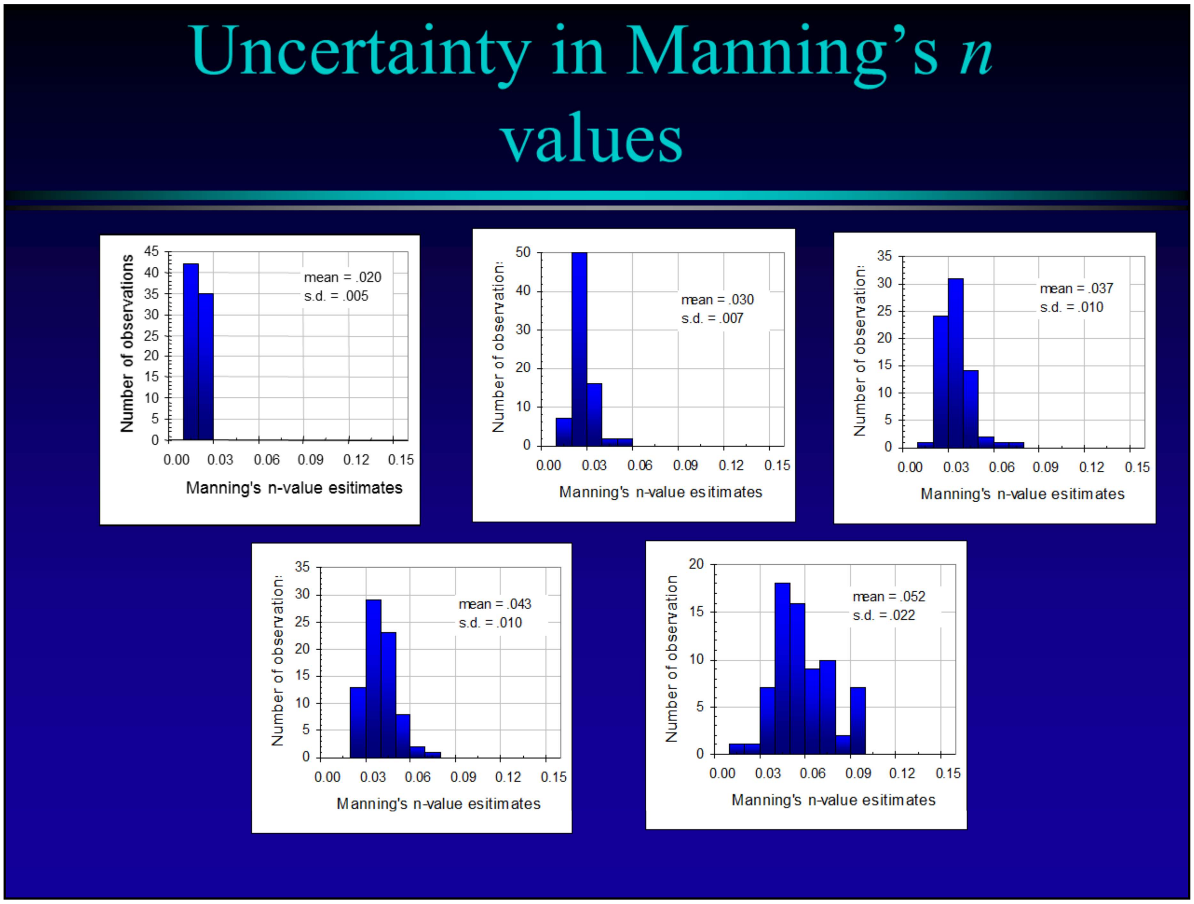
$n = 0.055$



Manning's *n* values

$n = 0.075$

$n = 0.097$



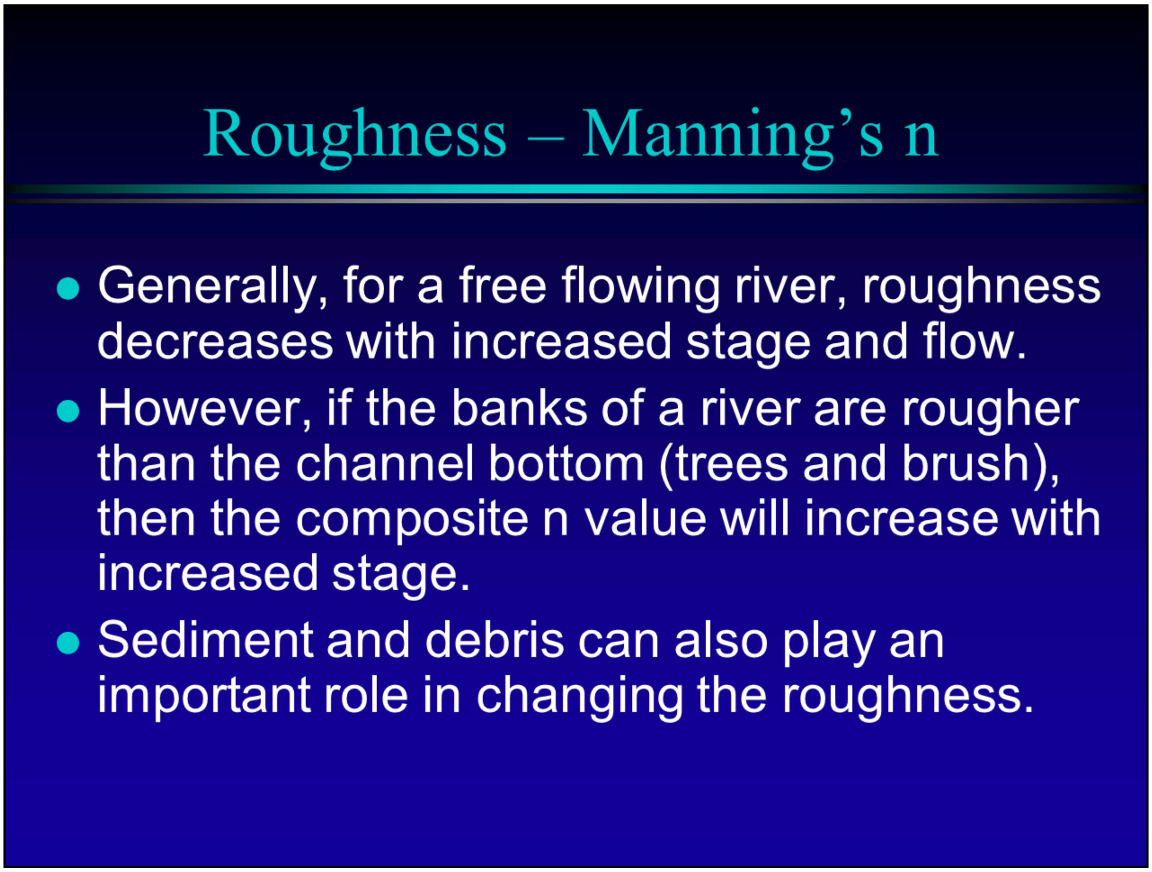
Uncertainty in Manning's *n* values

These charts are adopted from an HEC research document (RD-26).

Statistics are derived from surveyed engineers. Engineers were shown various river channel cross sections (all are from different streams) and asked to estimate the Manning's *n* value for each of them. Note that the Standard Deviation for the the estimates decreases as the *n* value decrease. What does this tell us about estimating roughness coefficients?

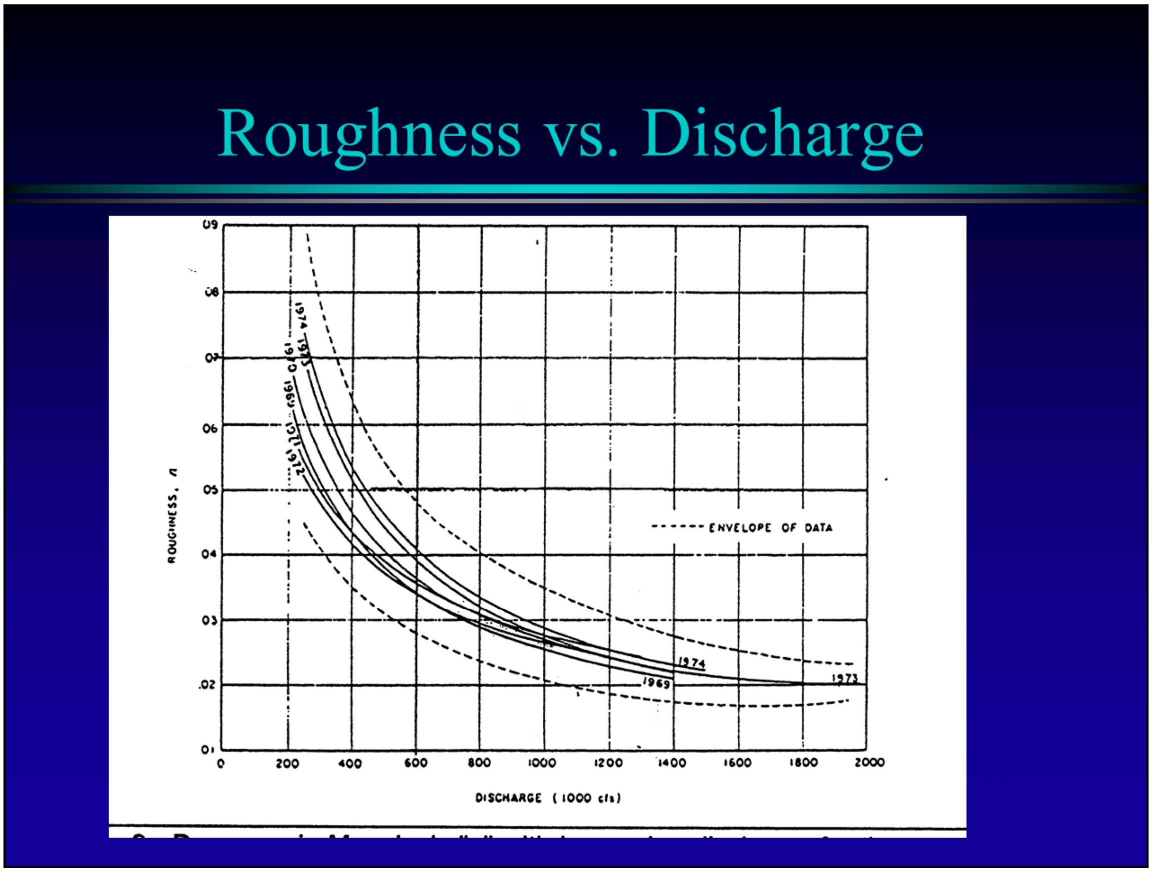
To start with, it is not easy and for any cross section you can get quite a bit of variability in estimates from experienced people. This is due to the tremendous cross-sectional variability.

Second, there is more knowledge and calibrated studies on low *n* value channels. A typical main channel *n* value is 0.035, but if you were to show engineers a concrete lined channel all *n* values would fall between 0.012 and 0.016 (there would be very, very little variability in responses).



Roughness – Manning’s n

- Generally, for a free flowing river, roughness decreases with increased stage and flow.
- However, if the banks of a river are rougher than the channel bottom (trees and brush), then the composite n value will increase with increased stage.
- Sediment and debris can also play an important role in changing the roughness.



Roughness vs. Discharge

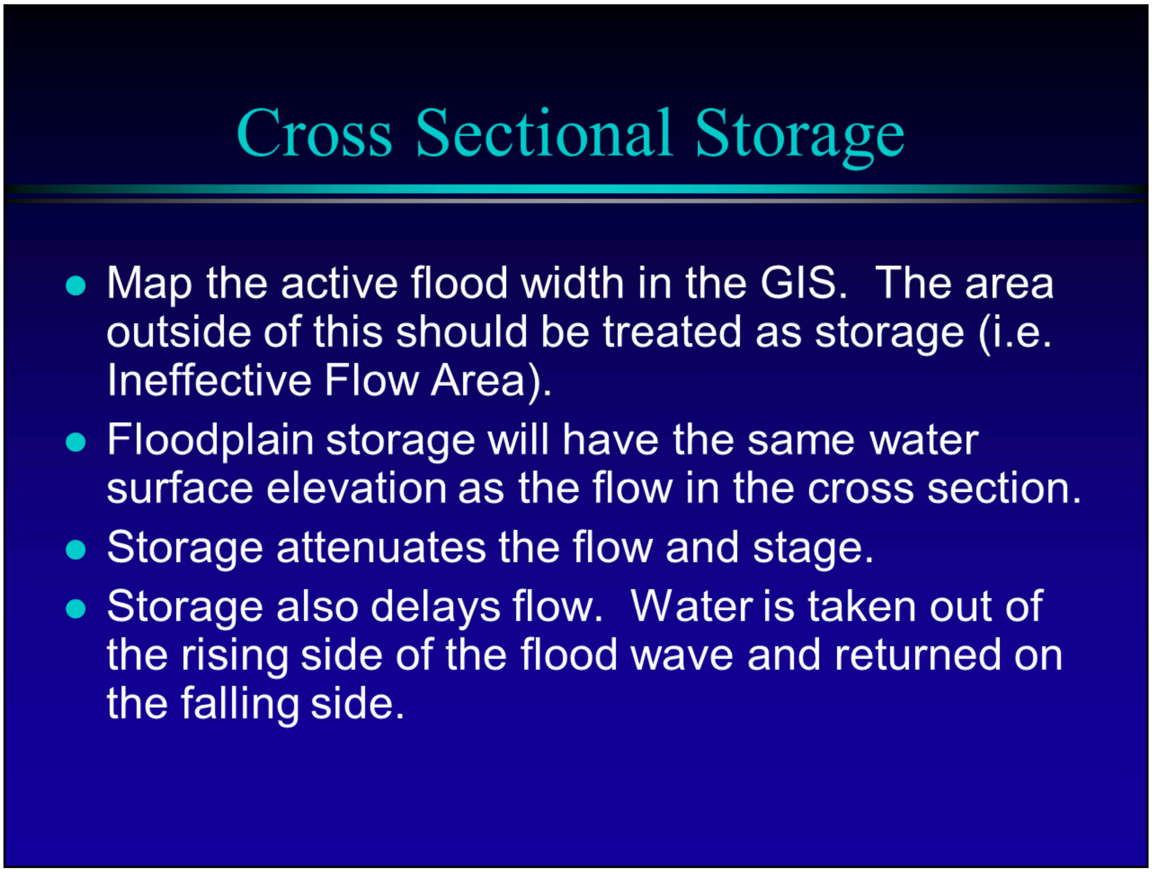
The Figure above shows decreasing Manning's n with increased discharge for the Mississippi River at Arkansas City.

Additional Uncertainty

- Accuracy of the Terrain Data
- Downstream Boundary Conditions
- Obstructions:
  - Buildings – in overbank areas
  - Debris
    - Mud and Debris flows
    - Debris blockages at bridges and culverts
  - Ice
    - location, ice thickness, roughness
- Erosion/deposition, bed forms, changing n

There are many additional factors that add uncertainty to a hydraulic model. More complicated a hydraulic models require greater attention to detail. Hydraulic structures need scrutiny to decide upon coefficients – will the bridge be submerged or not during any event? It is also difficult to predict obstructions to flow developing. Will a debris or ice jam occur during a given flow? Where will it occur? And what will it look like? All are questions that need to be addressed.

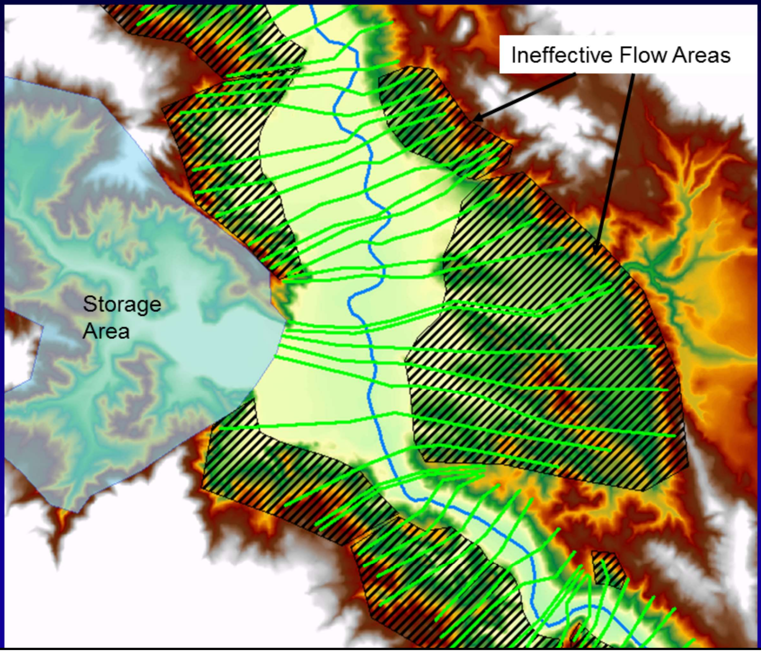
We also don’t model the bed moving. In reality the river bed may be eroding or aggregating. How will this affect my results? The river may pick up large amounts of the bed, thereby increasing the volume moving downstream.

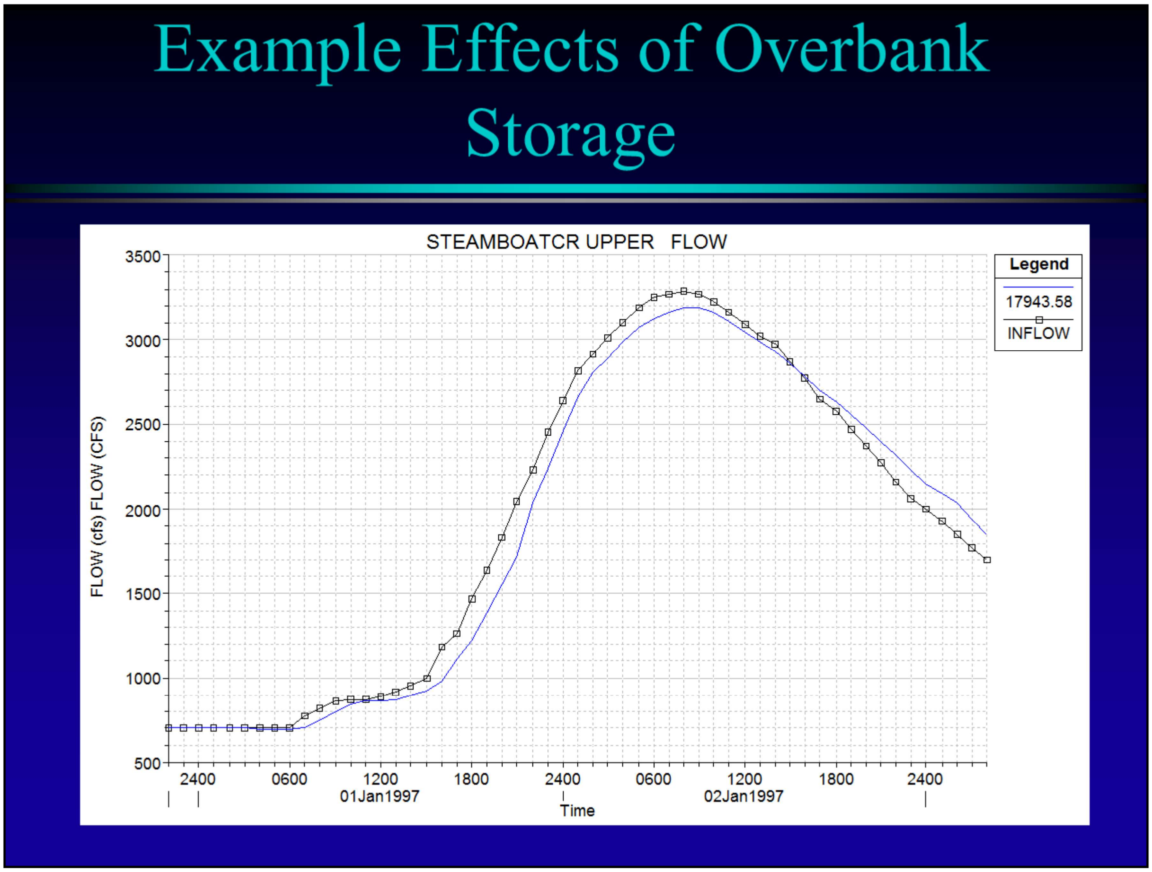


Cross Sectional Storage

- Map the active flood width in the GIS. The area outside of this should be treated as storage (i.e. Ineffective Flow Area).
- Floodplain storage will have the same water surface elevation as the flow in the cross section.
- Storage attenuates the flow and stage.
- Storage also delays flow. Water is taken out of the rising side of the flood wave and returned on the falling side.

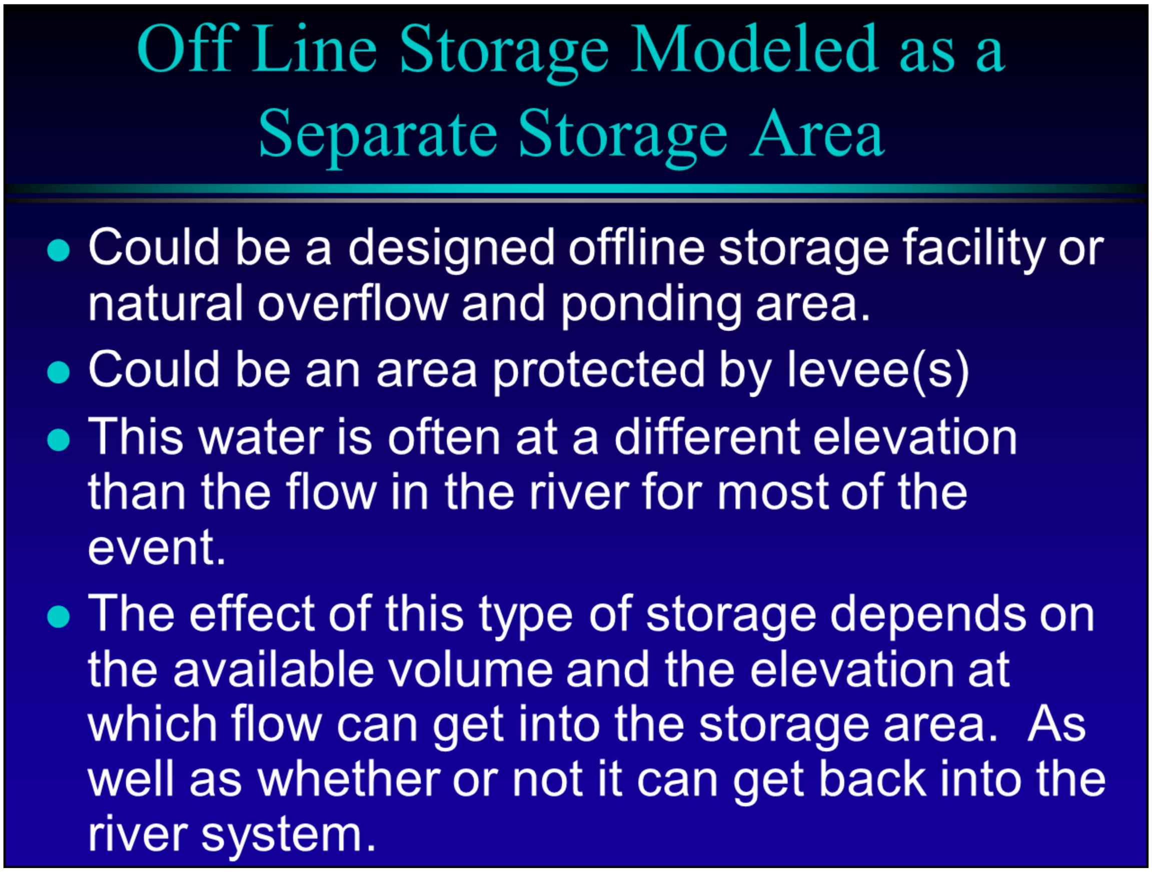
Example Ineffective Flow Areas





Example Effects of Overbank Storage

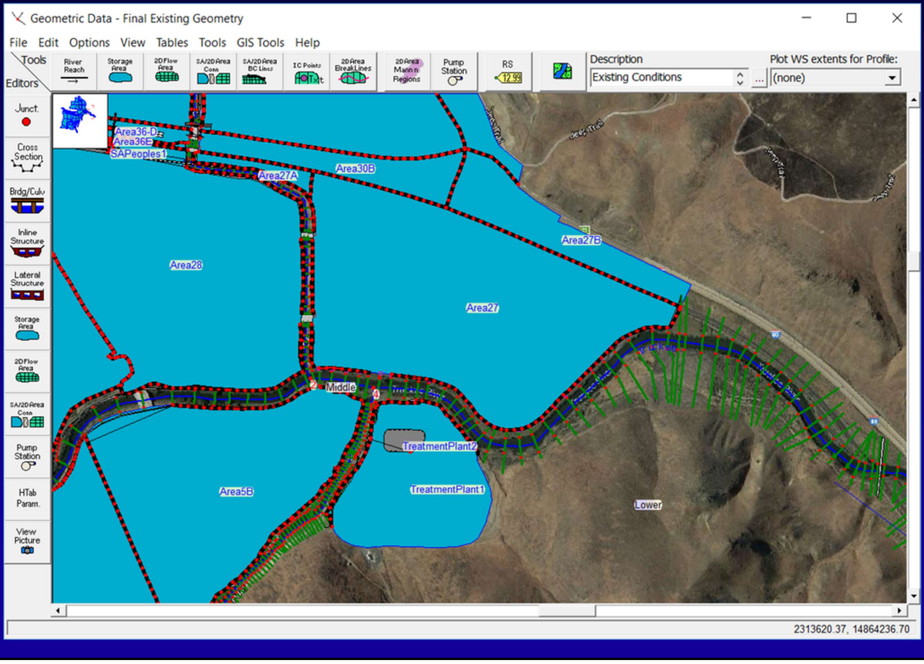
Example of the effects of overbank storage. In this example, the water goes out into storage during the rising side of the flood wave, as well as during the peak flow. After the peak flow passes, the water begins to come out of the storage in the overbank and increases the flow on the following side of the floodwave.



Off Line Storage Modeled as a Separate Storage Area

- Could be a designed offline storage facility or natural overflow and ponding area.
- Could be an area protected by levee(s)
- This water is often at a different elevation than the flow in the river for most of the event.
- The effect of this type of storage depends on the available volume and the elevation at which flow can get into the storage area. As well as whether or not it can get back into the river system.

Example Storage Areas behind Levees

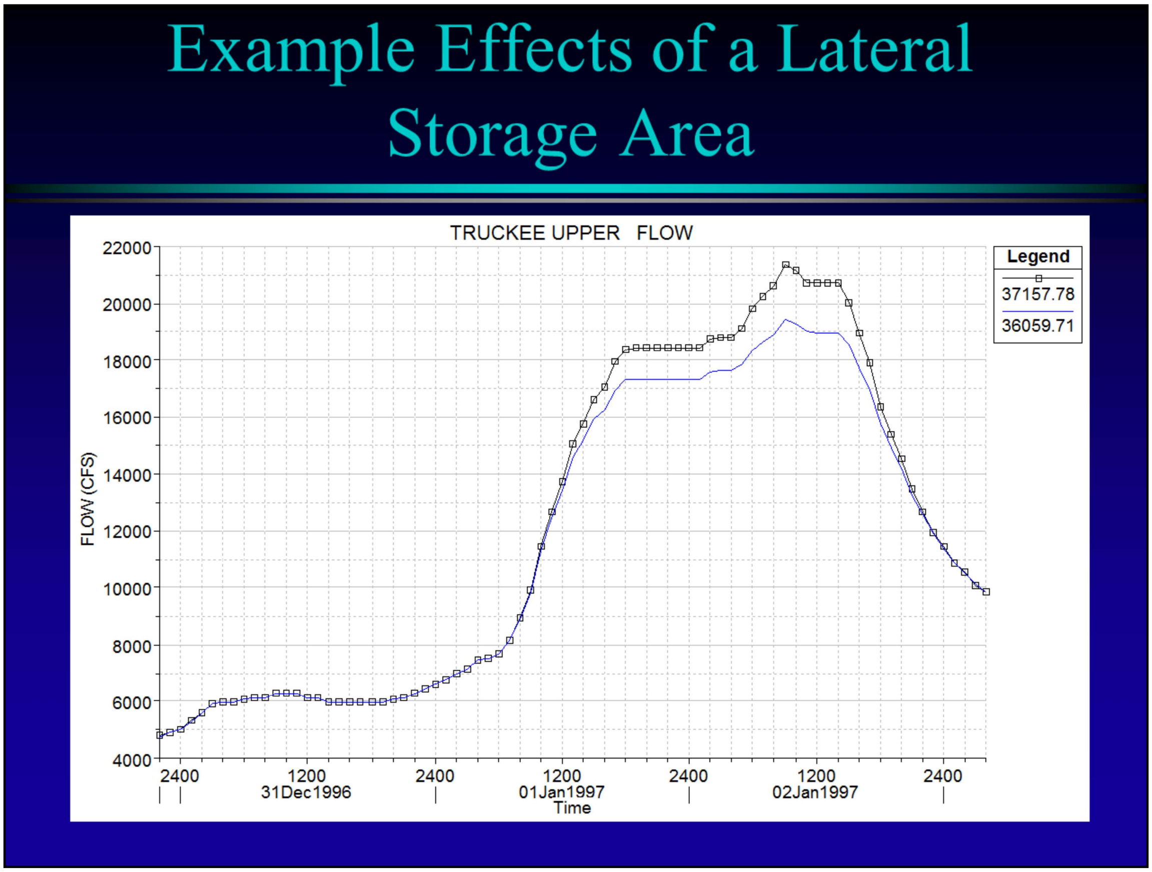


Geometric Data - Final Existing Geometry

Description: Existing Conditions

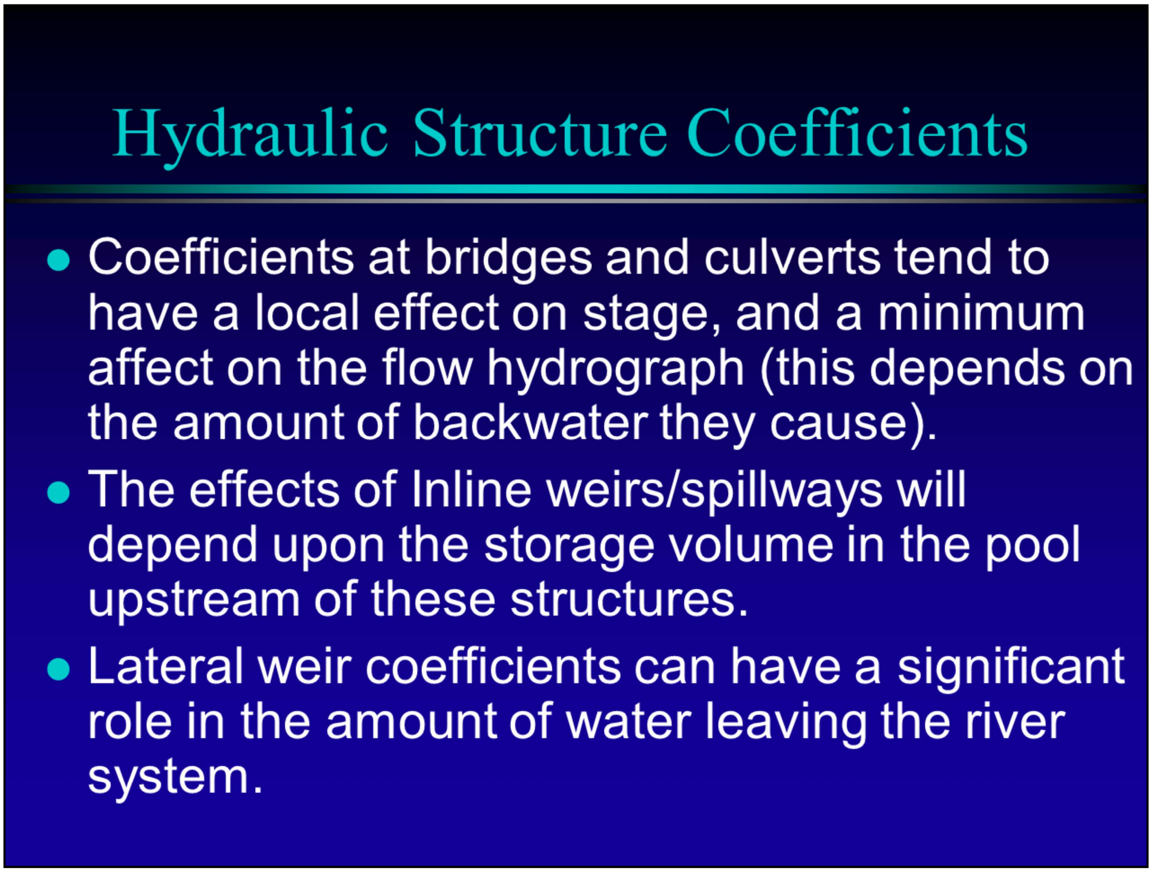
Plot WS extents for Profile: (none)

2313620.37, 14864236.70



Example Effects of a Lateral Storage Area

This is an example of an off-line storage area that is connected to the river through a lateral spillway. The flow upstream and downstream of the offline storage area remains the same until the water surface elevation gets higher than the lateral weir. Water goes out into the lateral storage facility the whole time it is above the weir (I.e. the storage area elevation is always lower than the river elevation in this example). This continues until later in the event, when the river elevation is below the lateral weir and flow can no longer leave the river. In this example, the flow in the storage area does not get back into the river system until much later in the event, and it is at a very slow rate (possible drained by culverts to a downstream location).



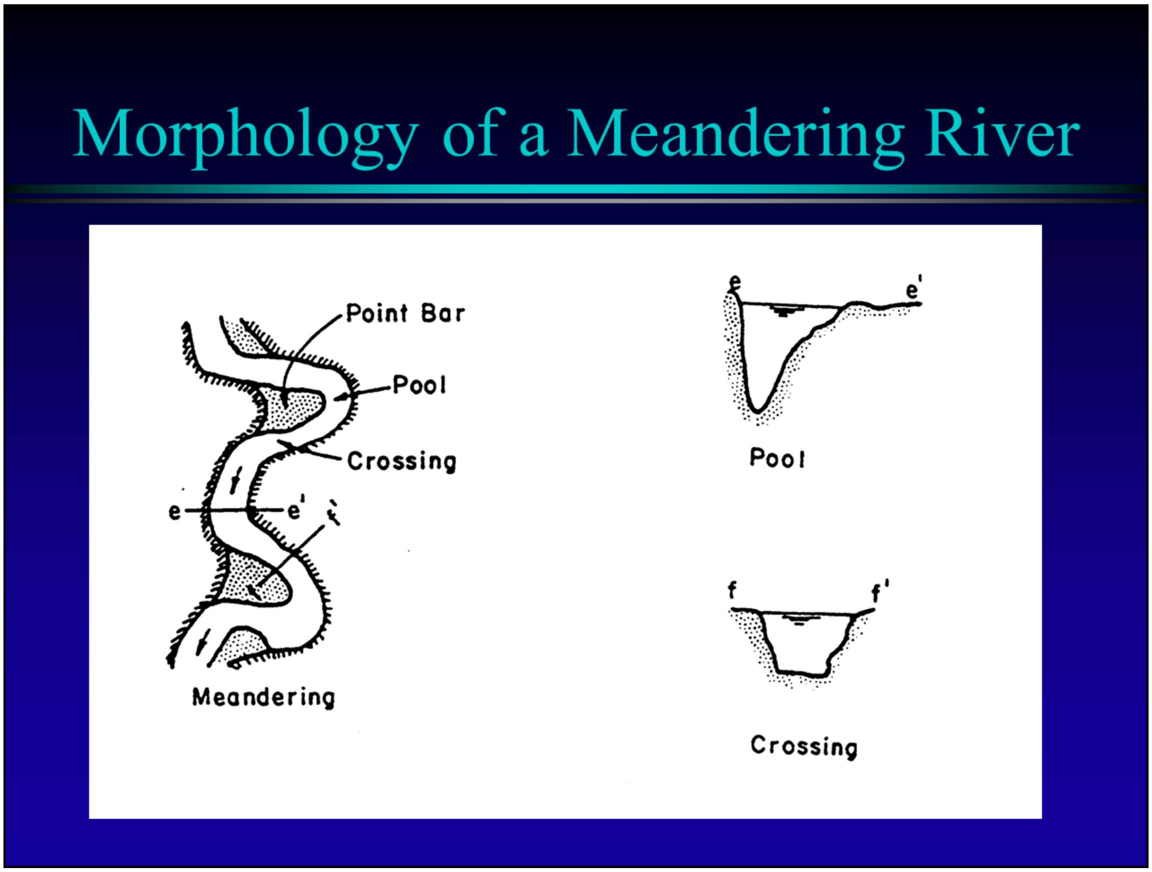
Hydraulic Structure Coefficients

- Coefficients at bridges and culverts tend to have a local effect on stage, and a minimum affect on the flow hydrograph (this depends on the amount of backwater they cause).
- The effects of Inline weirs/spillways will depend upon the storage volume in the pool upstream of these structures.
- Lateral weir coefficients can have a significant role in the amount of water leaving the river system.

Modeling Alluvial Streams

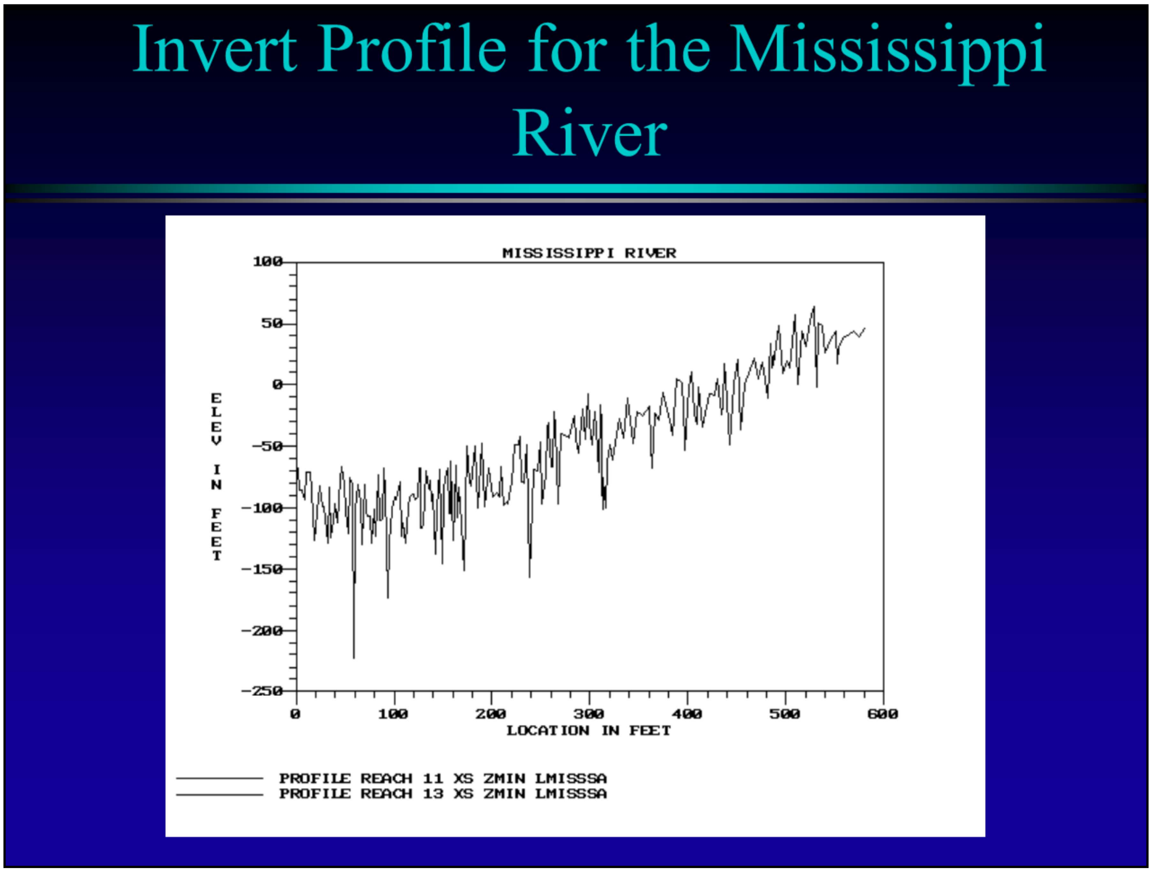
- In an alluvial stream the channel boundary, as well as the meandering pattern of the stream, are continuously being re-worked by the flow of water.
- The re-working is greatest during high flow, when the velocity, depth of water, and sediment transport capacity are the greatest.
- These changes can cause changes in roughness, or even more dynamic changes, such as cutting off the meandering loop

Alluvium is unconsolidated granular material which is deposited by flowing water. An alluvial river is incised into these alluvial deposits. The flow characteristics of the stream are defined by the geometry and roughness of the cross-section below the water surface. The cross-section of the river is continuously being re-worked by the flowing water. The reworking is greatest during high flow, when the velocity, depth of water, and sediment transport capacity are the greatest. For some streams, which approach an equilibrium condition, the change in morphology (landforms) is small. For other streams, the change in morphology is much larger. The change can be manifest as changes in roughness or a more dynamic change such as the cut-off of a meander loop which shortens the stream and starts a process which completely redefines the bed.



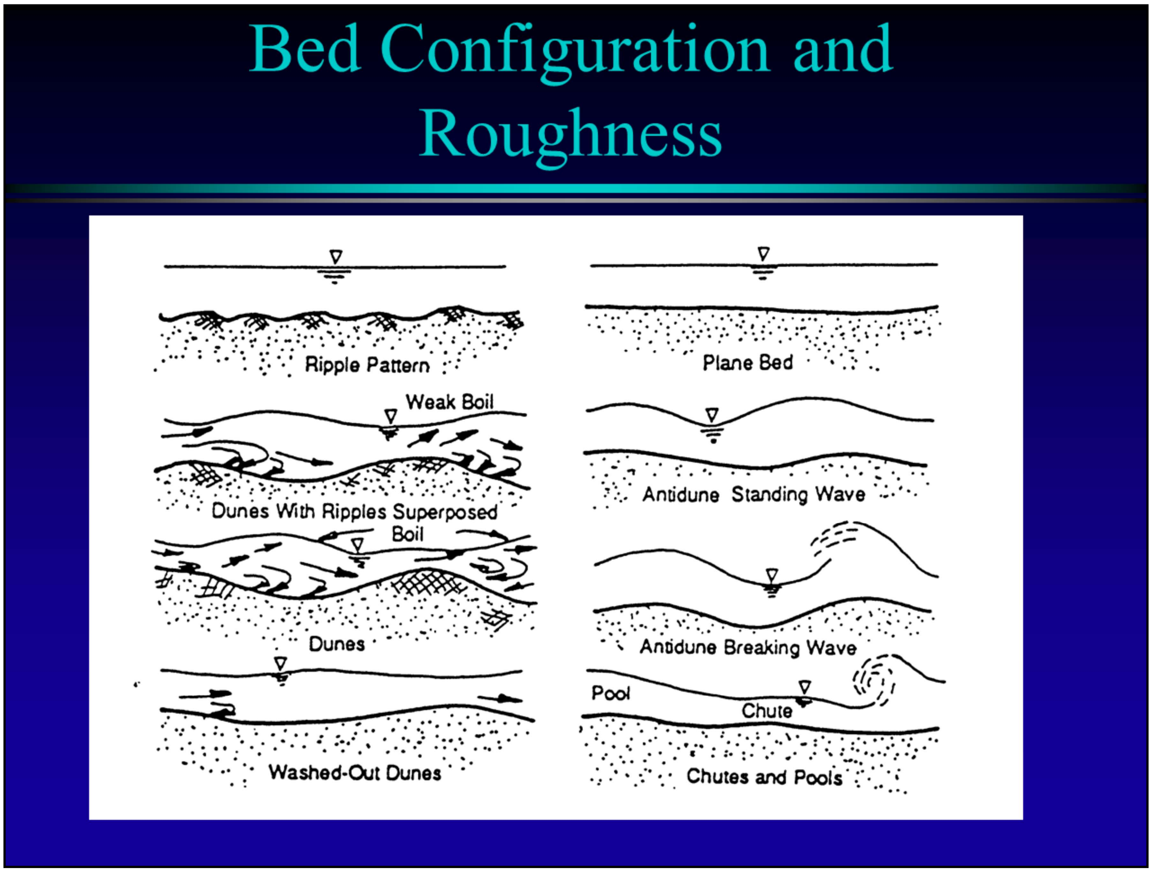
Morphology of a Meandering River

A typical meandering river is shown in the Figure above. Pools are at the outside of bends, and a typical pool cross-section is very deep. On the inside of the bend is a point bar. Crossings are between the meander bends. A typical crossing cross-section is much shallower and more rectangular than a pool cross-section.



Invert Profile for the Mississippi River

An invert profile for the Mississippi River is shown in the Figure above. Note the pools and crossings. The water surface profile is controlled by the crossing cross-sections, particularly at low flow. The conveyance property of pool cross-section is only remotely related to the water surface. This poses a significant problem when calibrating a large river.

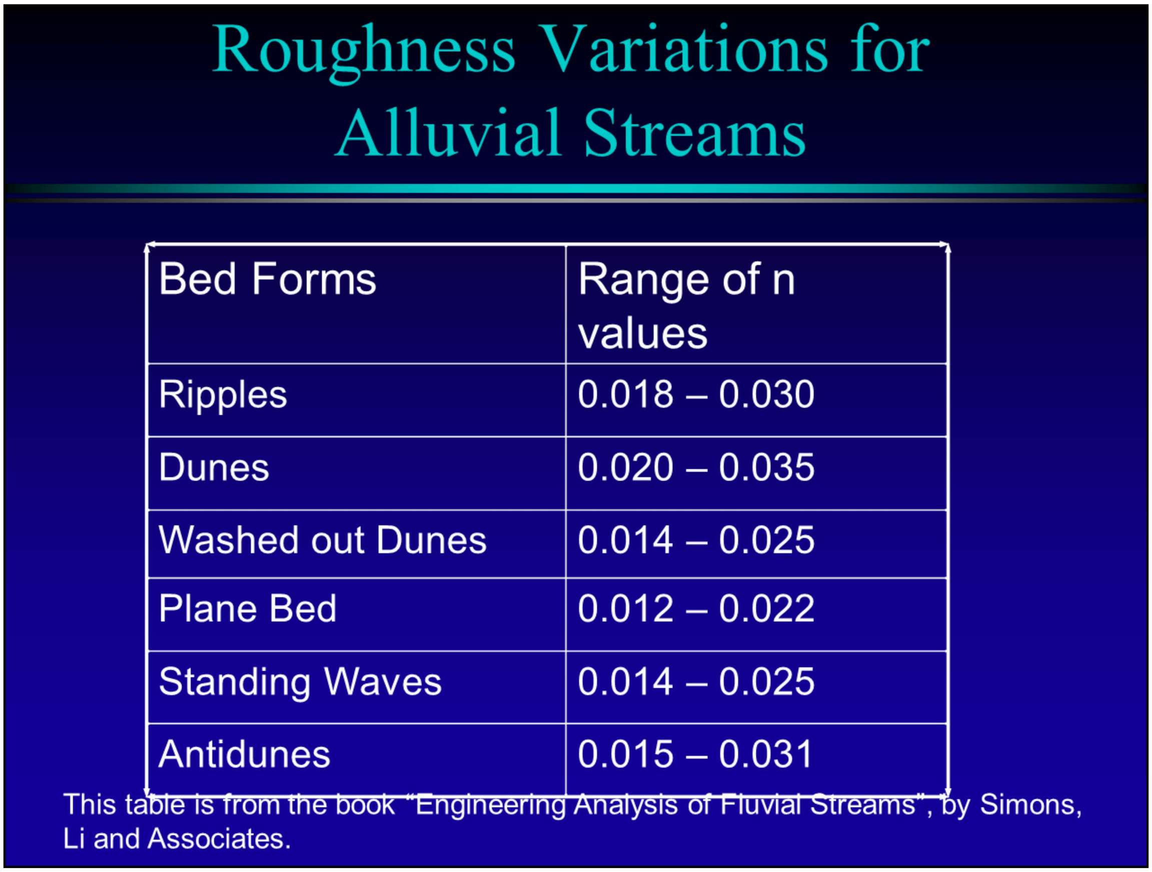


Bed Configuration and Roughness

As stage and flow increase you have an increase in stream power (stream power is a function of hydraulic radius, slope, and velocity). The bed forms in an alluvial stream tend to go through the following transitions:

a) Plane bed without sediment movement.
b) Ripples.
c) Dunes.
d) Plane bed with sediment movement.
e) Anti-dunes.
e) Chutes and pools.

Anti-dunes and chutes and pools are associated with high velocity streams approaching supercritical flow.

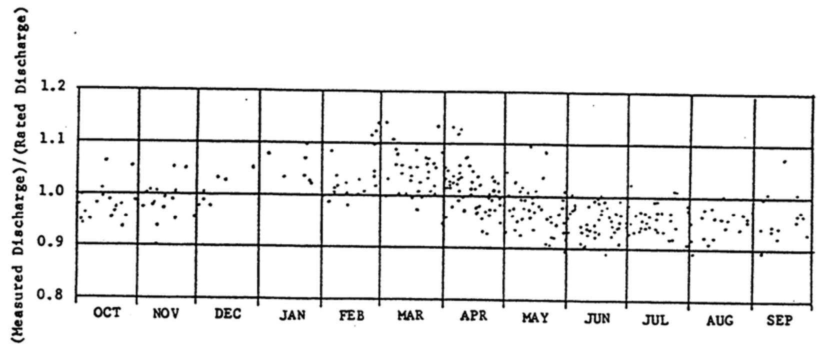


Roughness Variations for Alluvial Streams

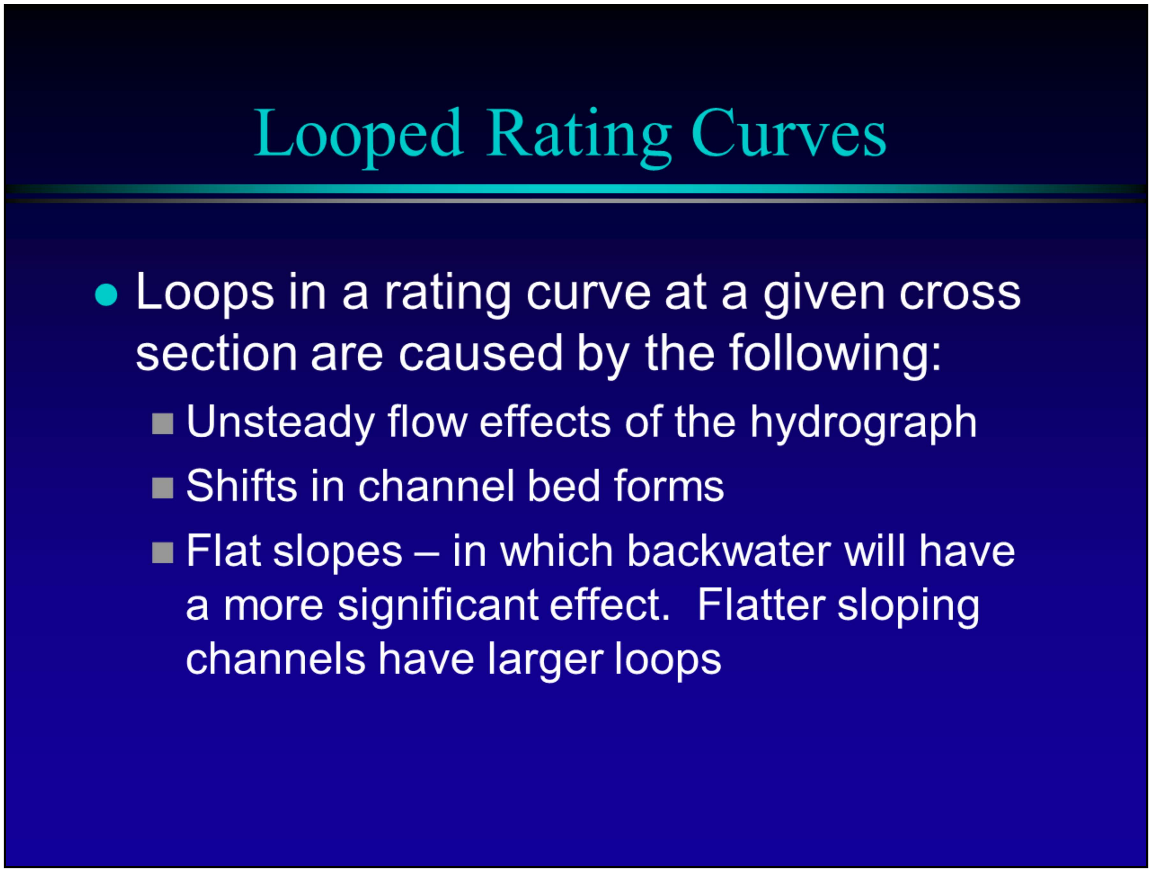
Bed Forms	Range of n values
Ripples	0.018 – 0.030
Dunes	0.020 – 0.035
Washed out Dunes	0.014 – 0.025
Plane Bed	0.012 – 0.022
Standing Waves	0.014 – 0.025
Antidunes	0.015 – 0.031

This table is from the book “Engineering Analysis of Fluvial Streams”, by Simons, Li and Associates.

Changes in Roughness due to Temperature

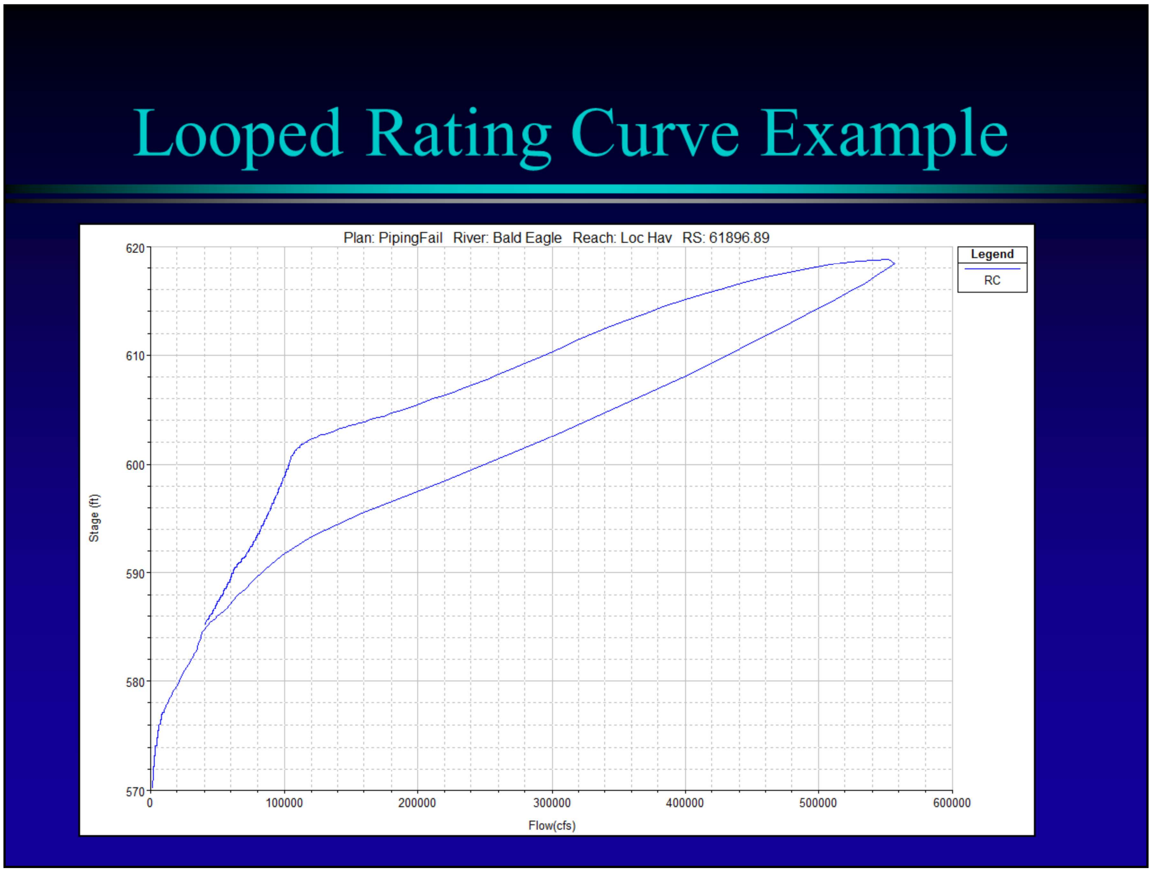


Bed forms change with water temperature. Because water is more viscous at lower temperatures, the water is more erosive, reducing the height and the length of the dunes. At higher temperatures, when the water is less viscous, the dunes are higher and of greater length. Since the larger dunes are more resistant to flow, the same flow will pass at a higher stage in the summer than in the winter. Larger streams such as the Mississippi River and the Missouri River show these trends. The Figure above shows the seasonal shift for the Mississippi River at St. Louis.



Looped Rating Curves

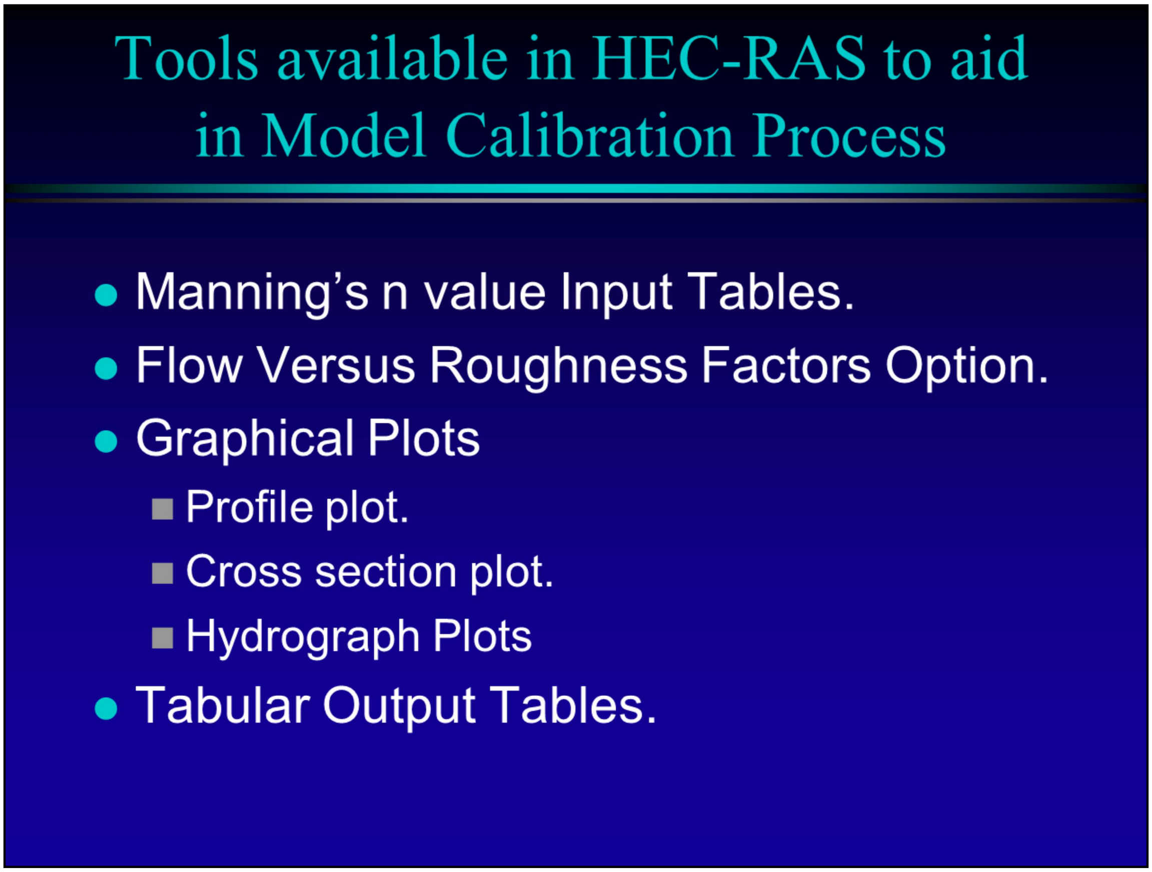
- Loops in a rating curve at a given cross section are caused by the following:
  - Unsteady flow effects of the hydrograph
  - Shifts in channel bed forms
  - Flat slopes – in which backwater will have a more significant effect. Flatter sloping channels have larger loops



Looped Rating Curve Example

Plan: PipingFail River: Bald Eagle Reach: Loc Hav RS: 61896.89

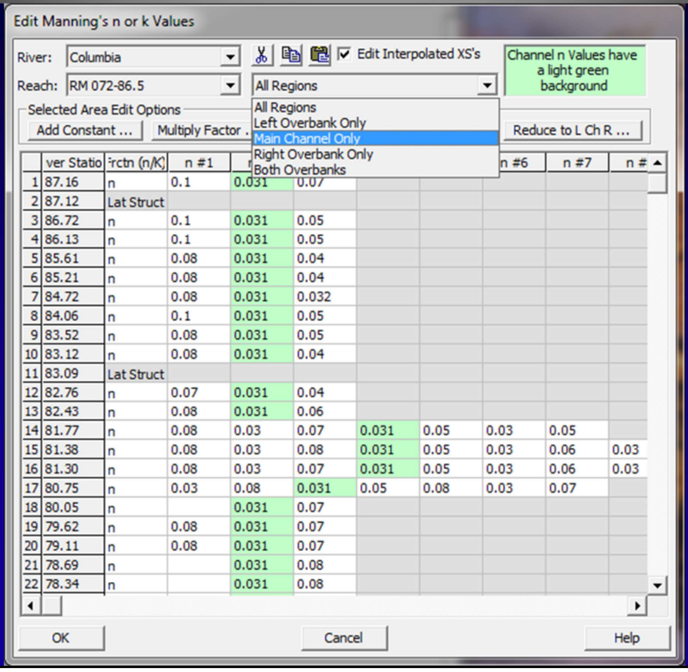
Excluding cataclysmic events such meander cutoffs or a new channel, the river will pass any given flow within a range of stages. The shift in stage is a result of shifts in bedforms, unsteady flow effects of the hydrograph, and backwater from downstream. Generally, the lower stages are associated with the rising side of a flood wave, and the higher stages are associated with the falling side of the flood wave.



Tools available in HEC-RAS to aid in Model Calibration Process

- Manning’s n value Input Tables.
- Flow Versus Roughness Factors Option.
- Graphical Plots
    - Profile plot.
    - Cross section plot.
    - Hydrograph Plots
- Tabular Output Tables.

Manning’s n Value Table



River: Columbia

Reach: RM 072-86.5

☑ Edit Interpolated XS's

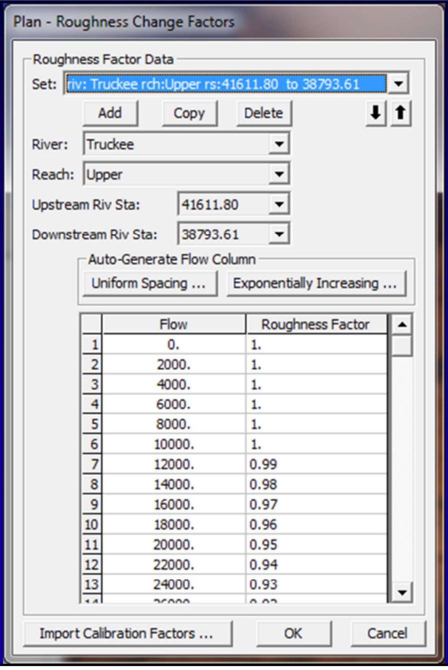
All Regions

Channel n Values have a light green background

	ver Statio	=rctn (n/K)	n #1					n #6	n #7	n #
1	87.16	n	0.1	0.031	0.07					
2	87.12	Lat Struct								
3	86.72	n	0.1	0.031	0.05					
4	86.13	n	0.1	0.031	0.05					
5	85.61	n	0.08	0.031	0.04					
6	85.21	n	0.08	0.031	0.04					
7	84.72	n	0.08	0.031	0.032					
8	84.06	n	0.1	0.031	0.05					
9	83.52	n	0.08	0.031	0.05					
10	83.12	n	0.08	0.031	0.04					
11	83.09	Lat Struct								
12	82.76	n	0.07	0.031	0.04					
13	82.43	n	0.08	0.031	0.06					
14	81.77	n	0.08	0.03	0.07	0.031	0.05	0.03	0.05	
15	81.38	n	0.08	0.03	0.08	0.031	0.05	0.03	0.06	0.03
16	81.30	n	0.08	0.03	0.07	0.031	0.05	0.03	0.06	0.03
17	80.75	n	0.03	0.08	0.031	0.05	0.08	0.03	0.07	
18	80.05	n		0.031	0.07					
19	79.62	n	0.08	0.031	0.07					
20	79.11	n	0.08	0.031	0.07					
21	78.69	n		0.031	0.08					
22	78.34	n		0.031	0.08					

The Manning’s n Table is available from the “Tables” menu on the Geometric Data editor in HEC-RAS. The table allows you to highlight portions of the table and then adjust all the highlighted values in a variety of ways, such as: add a constant, multiply by a factor, or change to a particular value. The table also allows you to display either all of the Manning’s n vales across the cross section; just the left overbank values; just the main channel values (highlighted with a green background); just the right overbank values; or just the left and right overbank values. This table does not allow you to change the stationing of the Manning’s n values (i.e. their location within the cross section).

Flow vs. Roughness Factors



Set: riv: Truckee rch:Upper rs:41611.80 to 38793.61

River: Truckee

Reach: Upper

Upstream Riv Sta: 41611.80

Downstream Riv Sta: 38793.61

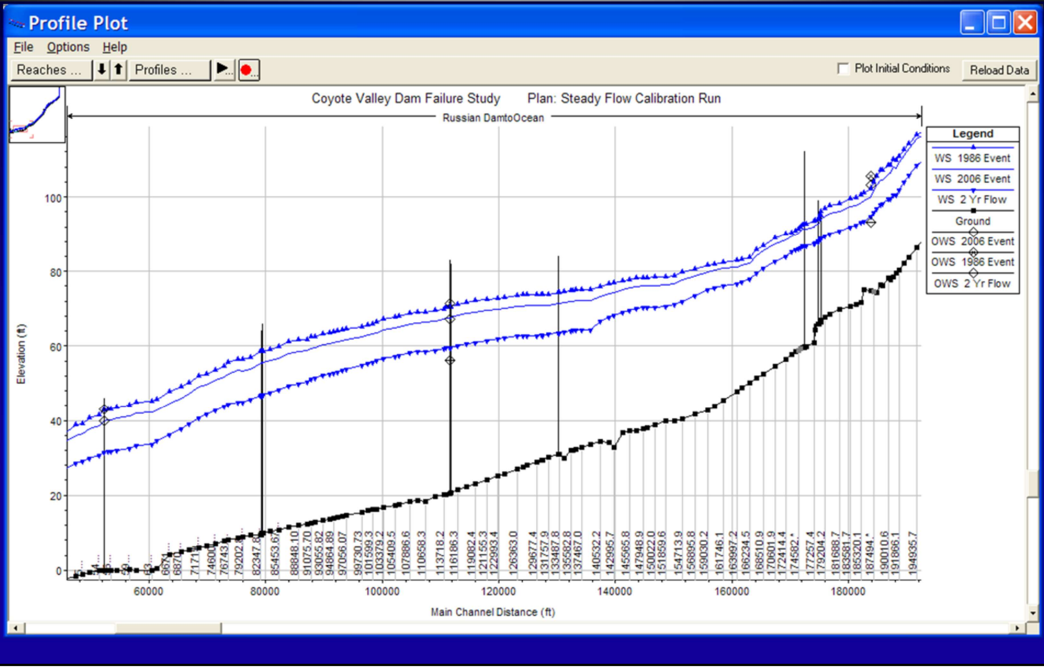
	Flow	Roughness Factor
1	0.	1.
2	2000.	1.
3	4000.	1.
4	6000.	1.
5	8000.	1.
6	10000.	1.
7	12000.	0.99
8	14000.	0.98
9	16000.	0.97
10	18000.	0.96
11	20000.	0.95
12	22000.	0.94
13	24000.	0.93

This option allows the user to adjust roughness coefficients with changes in flow. This feature is very useful for calibrating a steady or an unsteady flow model for flows that range from low to high. Roughness generally decreases with increasing flow and depth. This is especially true on larger river systems. This feature allows the user to adjust the roughness coefficients up or down in order to get a better match of observed data. To use this option, select Flow Roughness Factors from the Tools menu of the Geometric Data editor.

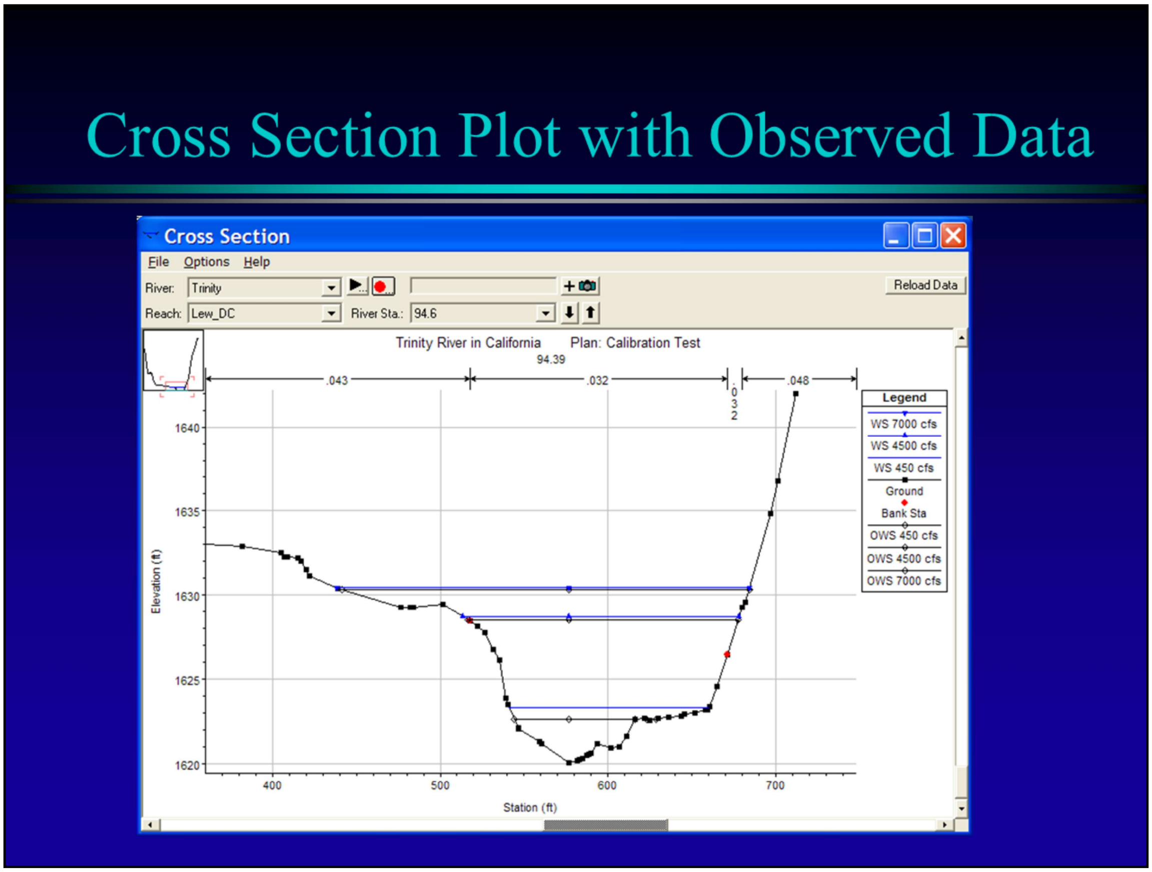
As shown in the Figure above, the user first selects a river, reach, and a range of cross sections to apply the factors to. Next, the user can either enter flow and roughness factors into the table directly, or they can use on of the two “Auto Generate Flow Column” buttons. Two options are available for auto generation of the flow column: one is based on equal increments of changing flow; the other is based on an exponentially increasing flow change rate.

`

Profile Plot with Observed Data



If the user enters Observed Data in the Steady Flow Data editor, when that profile is displayed, the observed values will be plotted on the profile plot.



Cross Section Plot with Observed Data

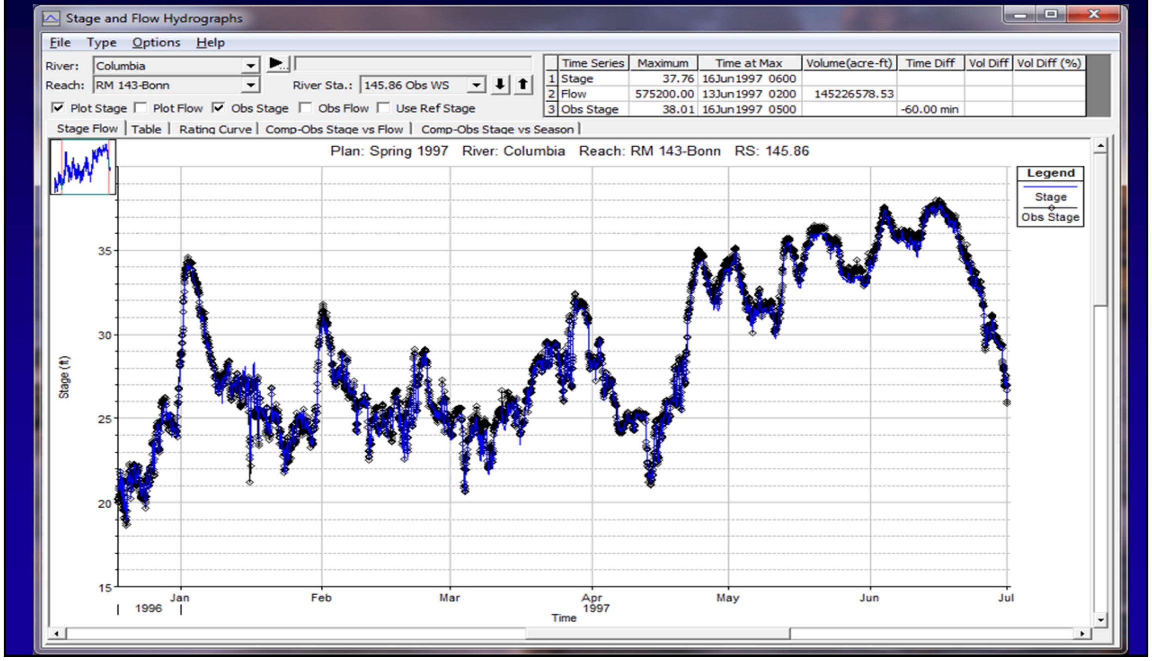
River: Trinity

Reach: Lew_DC

River Sta.: 94.6

If the user enters Observed Data in the Steady Flow Data editor, when that cross section location and profile is displayed, the observed values will be plotted on the cross section plot.

Hydrograph Plots



River: Columbia

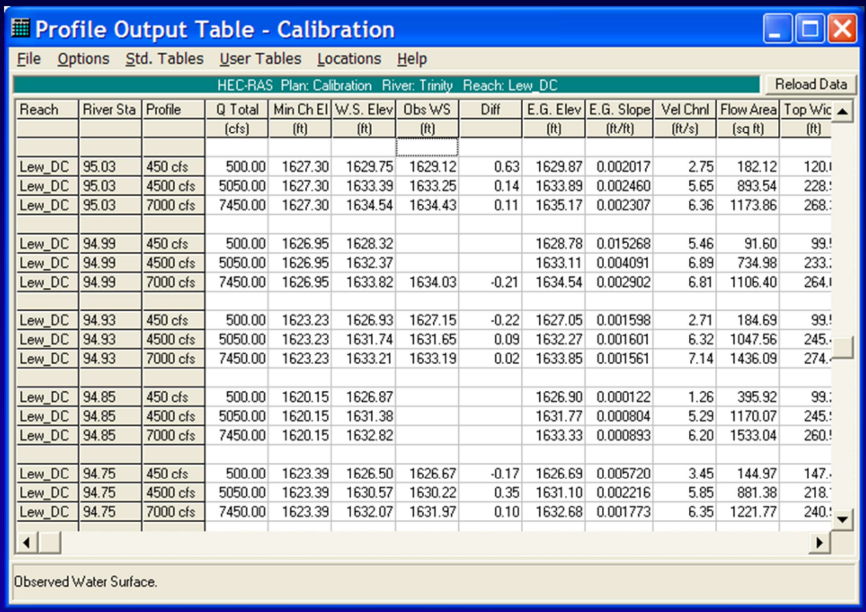
Reach: RM 143-Bonn

River Sta.: 145.86 Obs WS

☑ Plot Stage ☐ Plot Flow ☑ Obs Stage ☐ Obs Flow ☐ Use Ref Stage

	Time Series	Maximum	Time at Max	Volume(acre-ft)	Time Diff	Vol Diff	Vol Diff (%)
1	Stage	37.76	16Jun1997 0600				
2	Flow	575200.00	13Jun1997 0200	145226578.53			
3	Obs Stage	38.01	16Jun1997 0500		-60.00 min		

Tabular Output with Computed and Observed Water Surfaces



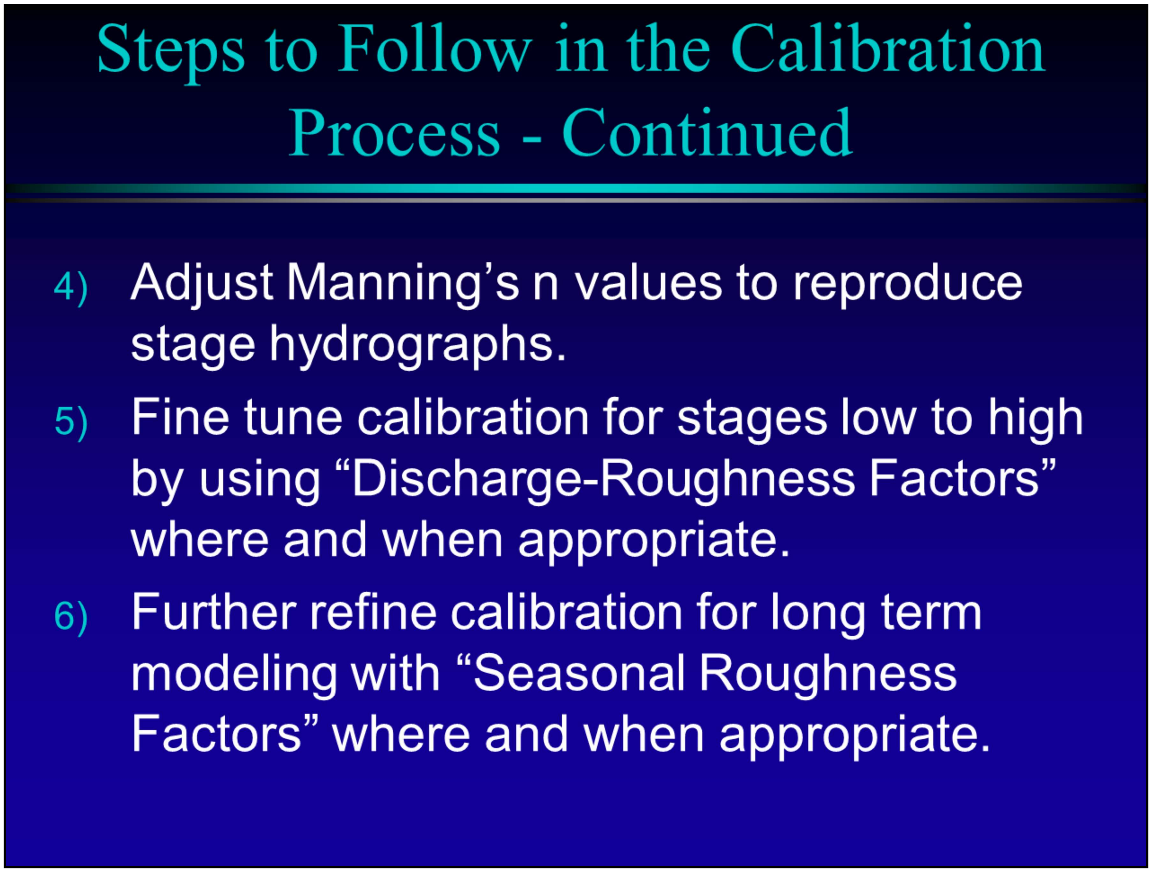
Reach	River Sta	Profile	Q Total (cfs)	Min Ch El (ft)	W.S. Elev (ft)	Obs WS (ft)	Diff	E.G. Elev (ft)	E.G. Slope (ft/ft)	Vel Chnl (ft/s)	Flow Area (sq ft)	Top Wic (ft)
Lew_DC	95.03	450 cfs	500.00	1627.30	1629.75	1629.12	0.63	1629.87	0.002017	2.75	182.12	120.
Lew_DC	95.03	4500 cfs	5050.00	1627.30	1633.39	1633.25	0.14	1633.89	0.002460	5.65	893.54	228.
Lew_DC	95.03	7000 cfs	7450.00	1627.30	1634.54	1634.43	0.11	1635.17	0.002307	6.36	1173.86	268.
Lew_DC	94.99	450 cfs	500.00	1626.95	1628.32			1628.78	0.015268	5.46	91.60	99.
Lew_DC	94.99	4500 cfs	5050.00	1626.95	1632.37			1633.11	0.004091	6.89	734.98	233.
Lew_DC	94.99	7000 cfs	7450.00	1626.95	1633.82	1634.03	-0.21	1634.54	0.002902	6.81	1106.40	264.
Lew_DC	94.93	450 cfs	500.00	1623.23	1626.93	1627.15	-0.22	1627.05	0.001598	2.71	184.69	99.
Lew_DC	94.93	4500 cfs	5050.00	1623.23	1631.74	1631.65	0.09	1632.27	0.001601	6.32	1047.56	245.
Lew_DC	94.93	7000 cfs	7450.00	1623.23	1633.21	1633.19	0.02	1633.85	0.001561	7.14	1436.09	274.
Lew_DC	94.85	450 cfs	500.00	1620.15	1626.87			1626.90	0.000122	1.26	395.92	99.
Lew_DC	94.85	4500 cfs	5050.00	1620.15	1631.38			1631.77	0.000804	5.29	1170.07	245.
Lew_DC	94.85	7000 cfs	7450.00	1620.15	1632.82			1633.33	0.000893	6.20	1533.04	260.
Lew_DC	94.75	450 cfs	500.00	1623.39	1626.50	1626.67	-0.17	1626.69	0.005720	3.45	144.97	147.
Lew_DC	94.75	4500 cfs	5050.00	1623.39	1630.57	1630.22	0.35	1631.10	0.002216	5.85	881.38	218.
Lew_DC	94.75	7000 cfs	7450.00	1623.39	1632.07	1631.97	0.10	1632.68	0.001773	6.35	1221.77	240.

Observed Water Surface.

User's can create their own tables using the Summary Table Output capability. In this example, "Standard Table 1" was selected, then it was modified by adding two new variables: "Obs WS" which is the observed water surface elevation, and "Diff" which is just the difference in the two previous fields (which in this case shows the difference between the computed and observed water surface elevations).

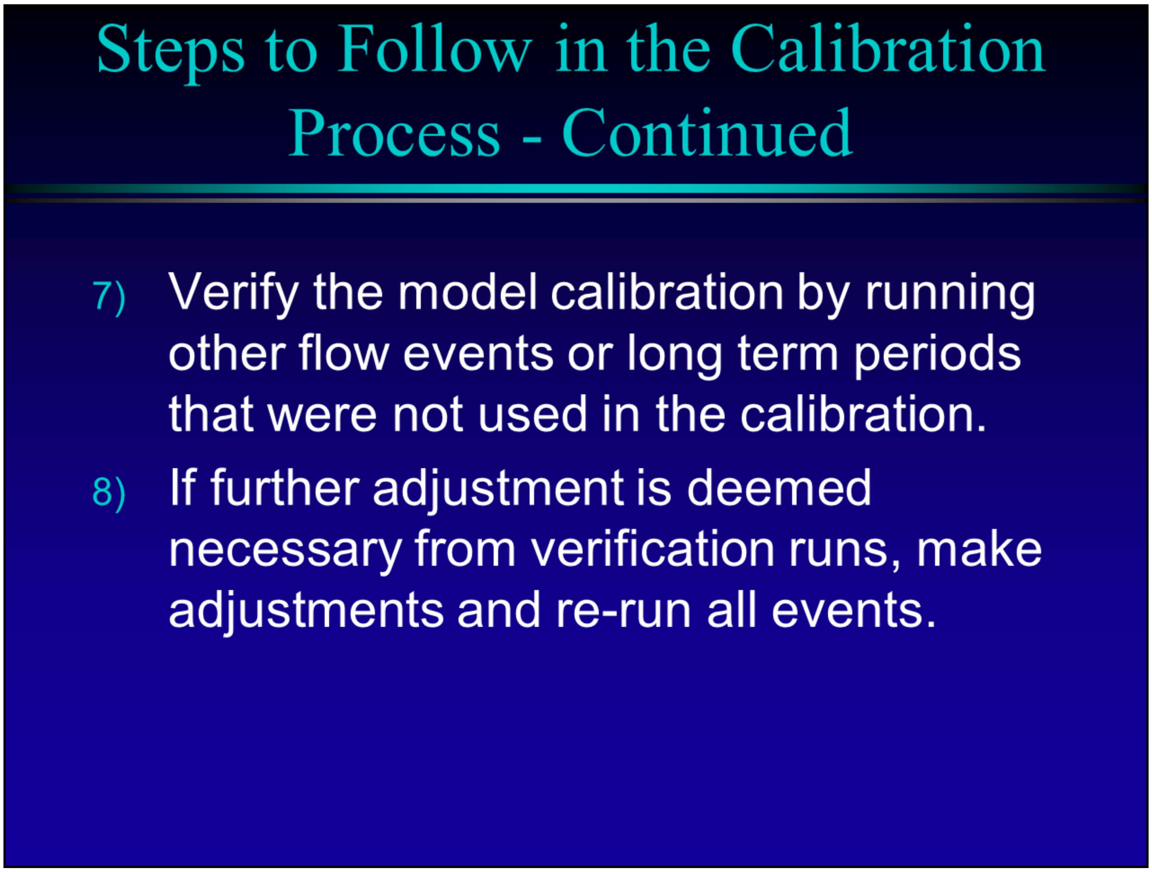
Steps to Follow in the Calibration Process

1) Run a range of discharges in the Steady-Flow mode, and calibrate n values too established rating curves at gages and known high water marks
2) Select specific events to run in unsteady flow mode. Ensure each event goes from low flow to high flow, and back to low flow.
3) Adjust storage (Ineffective areas) and lateral weir coefficients to get good reproduction of flow hydrographs (Concentrate on timing, peak, volume, and shape)



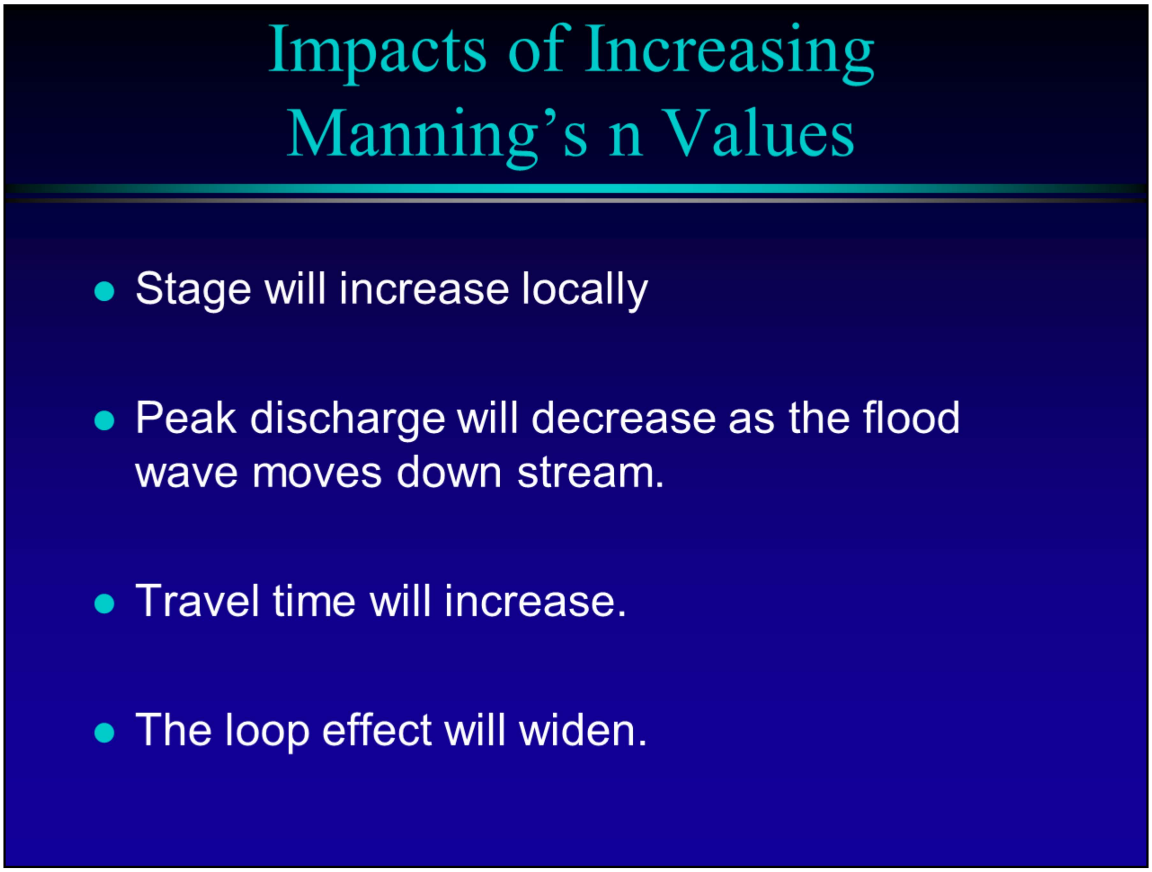
Steps to Follow in the Calibration Process - Continued

4) Adjust Manning's n values to reproduce stage hydrographs.
5) Fine tune calibration for stages low to high by using "Discharge-Roughness Factors" where and when appropriate.
6) Further refine calibration for long term modeling with "Seasonal Roughness Factors" where and when appropriate.



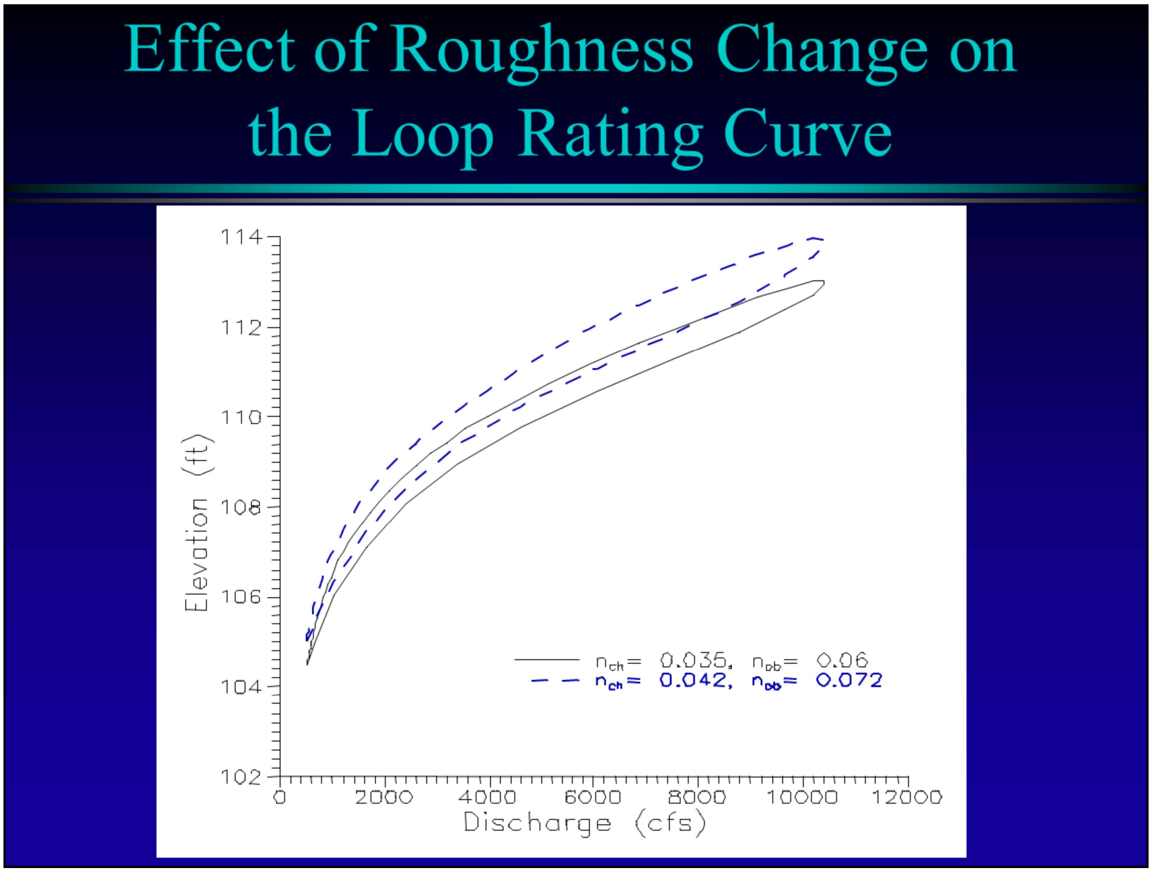
Steps to Follow in the Calibration Process - Continued

7) Verify the model calibration by running other flow events or long term periods that were not used in the calibration.
8) If further adjustment is deemed necessary from verification runs, make adjustments and re-run all events.

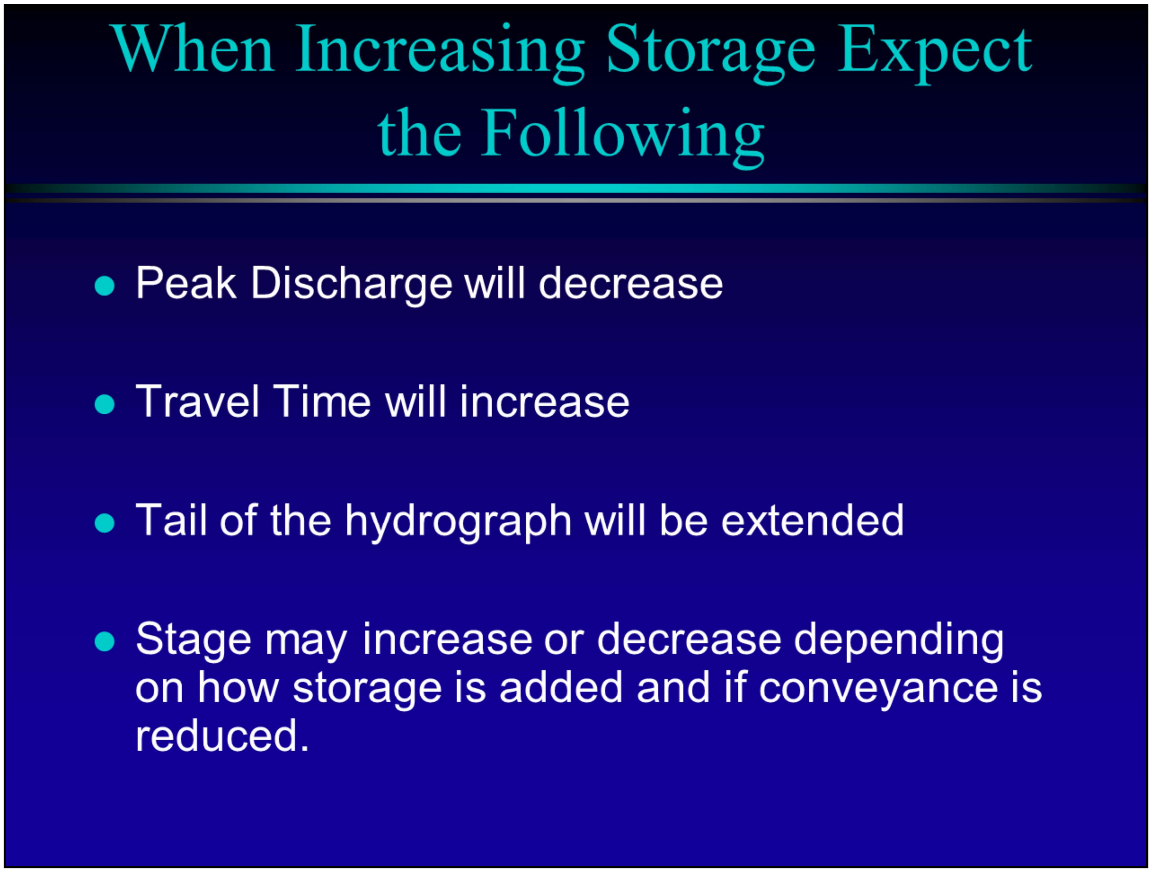


Impacts of Increasing Manning's n Values

- Stage will increase locally
- Peak discharge will decrease as the flood wave moves down stream.
- Travel time will increase.
- The loop effect will widen.

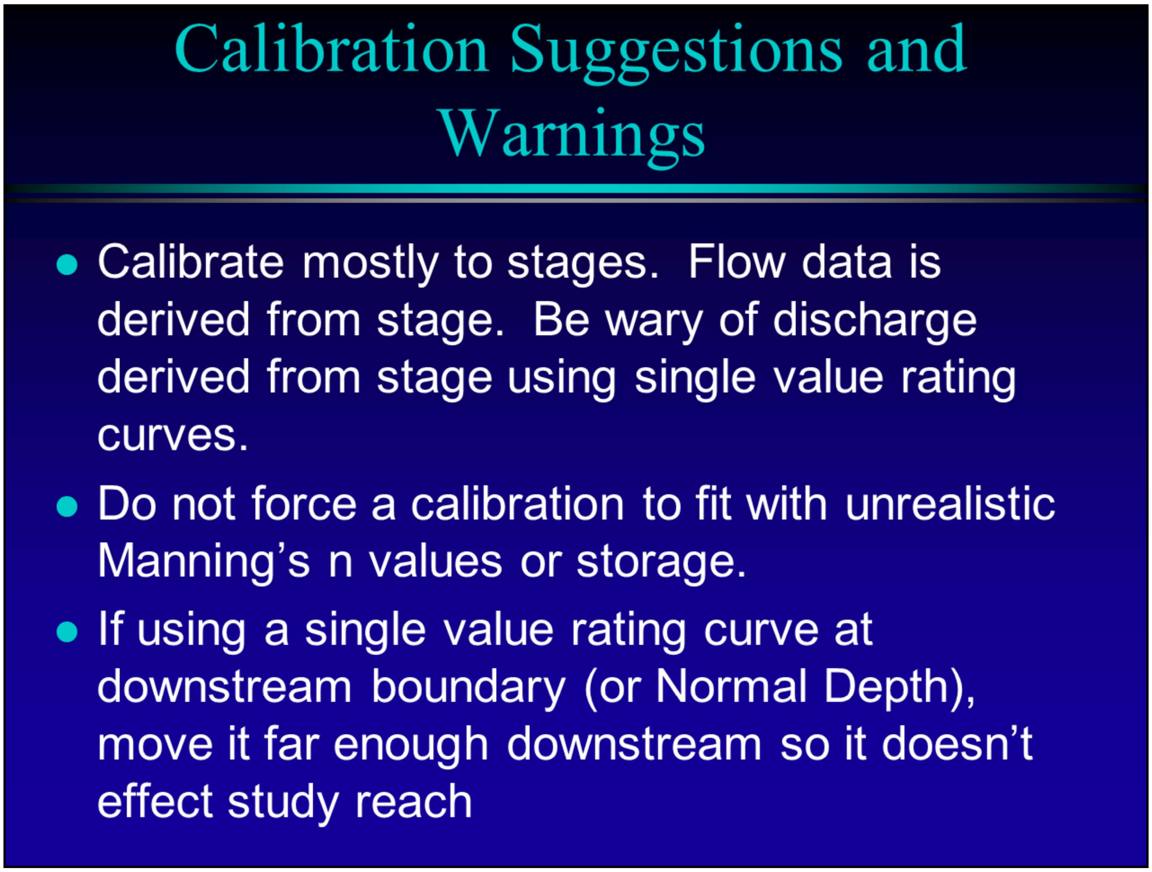


Effect of Roughness Change on the Loop Rating Curve



When Increasing Storage Expect the Following

- Peak Discharge will decrease
- Travel Time will increase
- Tail of the hydrograph will be extended
- Stage may increase or decrease depending on how storage is added and if conveyance is reduced.



Calibration Suggestions and Warnings

- Calibrate mostly to stages. Flow data is derived from stage. Be wary of discharge derived from stage using single value rating curves.
- Do not force a calibration to fit with unrealistic Manning’s n values or storage.
- If using a single value rating curve at downstream boundary (or Normal Depth), move it far enough downstream so it doesn’t effect study reach

Calibration Suggestions and Warnings - Continued

- Discrepancies may arise from a lack of quality cross section data
- The volume of off-channel storage areas is often underestimated, which results in a floodwave that travels to fast
- Be careful with old HEC-2 and RAS studies done for steady flow only. The cross sections may not depict the storage areas.

Calibration Suggestions and Warnings - Continued

- Calibration should be based on floods that encompass a wide range of flows
- For tidal rivers and flows into reservoirs, the inertial terms in the momentum equation are very important. Adjusting Manning's n values may not help. Check cross sectional shape and storage. Also try to set Theta as close to 0.6 as possible.
- You must be aware of any unique events that occurred during the flood. Such as levee breaches and overtopping.