Hydraulics 101 – Part I

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  - President/Co-founder of WEST Consultants, a nationally known 40 person water resources engineering firm
  - Taught Engineering and Computer programming at UC Davis and San Diego State University
  - National Director, Water Resources at PBS&J and HDR

DTW and Associates, LLC

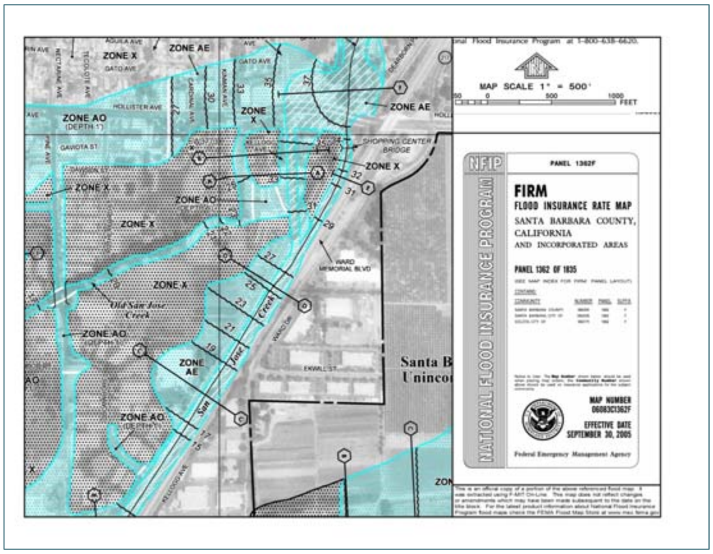
Course Outline, Part I

- What is Hydraulics?
- Things That We Look for in Hydraulics
- Characteristics of Flow
- Hydraulic Calculation Methods
- What is Important in Hydraulics?
- Channel and Floodplain Definitions
- Flow Terms
- Manning Equation
- Shear Stress and Applications
- Meanders

What is Hydraulics?

- The analysis of how water moves through a conveyance system – pipe networks, culverts, natural channels, etc.
- We’re looking at open channels only today.
- Flow information we can obtain from hydraulic analyses include:
  - o Depth
  - o Velocity
  - o Static and dynamic forces

For What is Hydraulics Used?
Generation of Flood Mapping



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For What is Hydraulics Used?
Facility Design

- Bridges
- Storm Drains
- Dams
- Detention Basins
- Channels
- Culverts
- Inlets
- Levees
- Weirs

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For What is Hydraulics Used?
Bridges

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For What is Hydraulics Used?
Storm Drains

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For What is Hydraulics Used?
Dams

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For What is Hydraulics Used?
Detention Basins

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For What is Hydraulics Used?
Design of Channels

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For What is Hydraulics Used?
Culverts – Outlets and Inlets

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For What is Hydraulics Used?
Levees

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For What is Hydraulics Used?
Weirs – AKA Low Head Dam

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For What is Hydraulics Used?
Environmental Issues – Discussed in Detail

- Creek Restoration
- Bank Protection
- Energy Dissipation
- Hydromodification

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For What is Hydraulics Used?
Stream/Creek Restoration

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For What is Hydraulics Used?
Bank Protection

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For What is Hydraulics Used?
Energy Dissipation

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For What is Hydraulics Used? Hydromodification

The alteration of the natural flow of water through a landscape. Often involves channel modification or channelization and usually undertaken out of a desire to improve our ability to use land or water resources, or to protect human health or safety.

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Things That We Look For in Hydraulics

- Flow rate (how much water per unit of time?)
- Volume (how much total water?)
- Velocity (how fast is it moving?)
- Force (how hard does it push, pull or drag – shear stress?)
- Loss in energy as the flow goes downstream
- Return Period (how likely is this flow condition to occur in any given year?)

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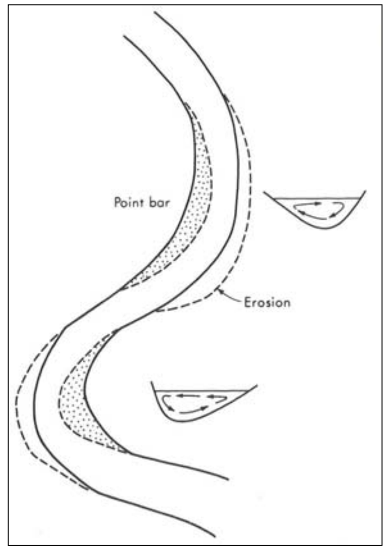
What to Look For (Natural Features)

- How big are the rocks in the channel?
- What kind of soil is in the banks?
- How steep are the banks?
- What kind of vegetation is on the banks and in the creek?
- Has there been rapid, recent channel scour?
- Is it on the outside of a bend?



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What to Look For (Man-made Features)

- Are there any structures close to the bank?
- What is the upstream development like?
- Is it recent?

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What is Important in Design or Analysis of a Stream?

- Channel Stability (erosion or deposition potential)
- Overland Escape (What if the main channel plugs or fills in?)
- Maintainability
- Flow Capacity
- Environmental Sustainability

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Variables That Affect the Results: Discussed in Detail Later

- Roughness of the channel
- Losses – Waves, Turbulence, Expansions, Contractions
- Flow Area
- Wetted Perimeter
  (where the water is in contact with the stream)
- Hydraulic Radius
- Slope of the channel
- Effective slope

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Energy Loss: Surface Roughness

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Energy Losses: Waves/Turbulence/Surges

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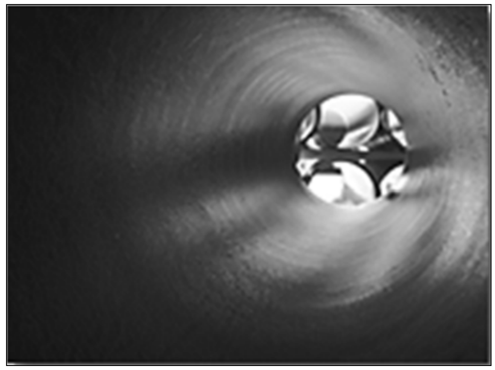
Hydraulic Equations

- Bernoulli Equation – basis for all hydraulic equations
- Natural Channels, Storm Water and Wastewater
  - Manning's Equation
- Potable Water (pipes)
  - Hazen-Williams Formula



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Characteristics of Flow

- Laminar flow
- Turbulent flow
- Normal depth
- Subcritical
- Supercritical

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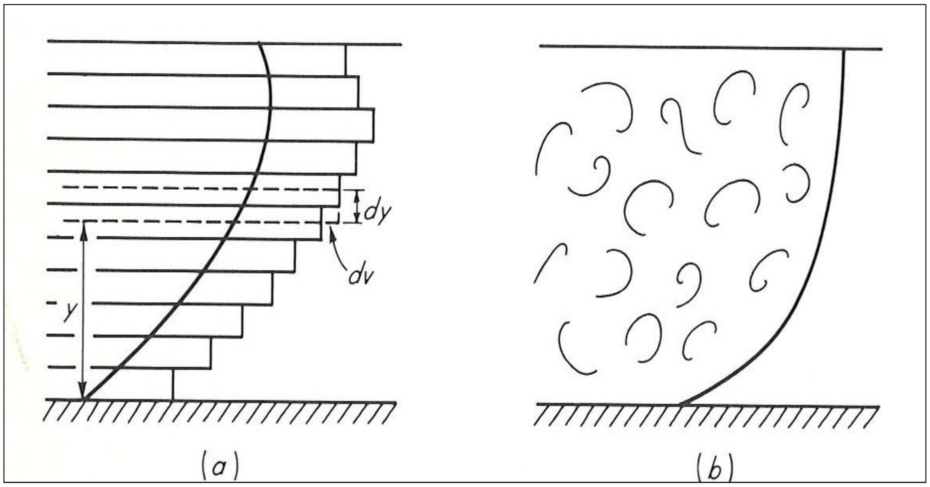
Laminar and Turbulent Flow

(Laminar rarely occurs in a natural stream)



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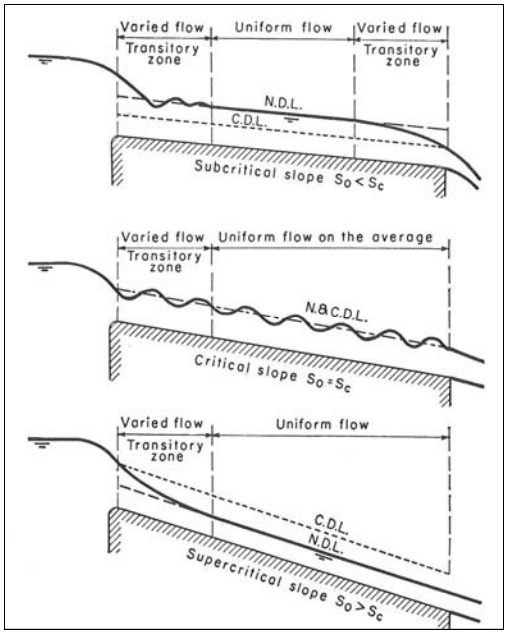
Normal Depth – "Happy stream"

Subcritical – downstream affects upstream

Critical Flow – transition between Sub and Supercritical flow

Supercritical – upstream affects downstream

Transition from Super to Subcritical flow going downstream is a hydraulic jump



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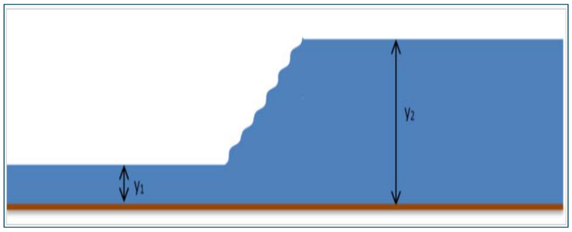
Hydraulic Jump



Hydraulic jumps have high turbulence and dissipate energy. They can severely erode a natural channel.

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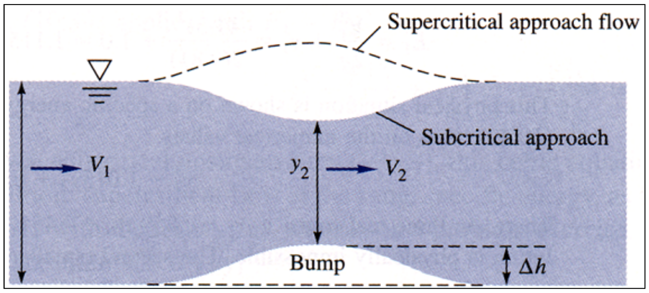
Comments on Super and Subcritical Flow

- For subcritical flow, flow depth will decrease going over a "bump" in a stream and increase for supercritical flow.
- For subcritical flow, flow depth will increase going over a "dip" in a stream and decrease for supercritical flow.



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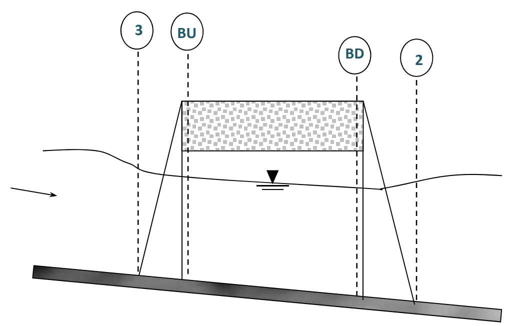
Comments on Sub- and Supercritical Flow

- For subcritical flow, the flow depth will decrease going through a contraction and increase for supercritical flow.
- For subcritical flow, the flow depth will increase going through an expansion and decrease for supercritical flow.

Subcritical flow through a bridge contraction



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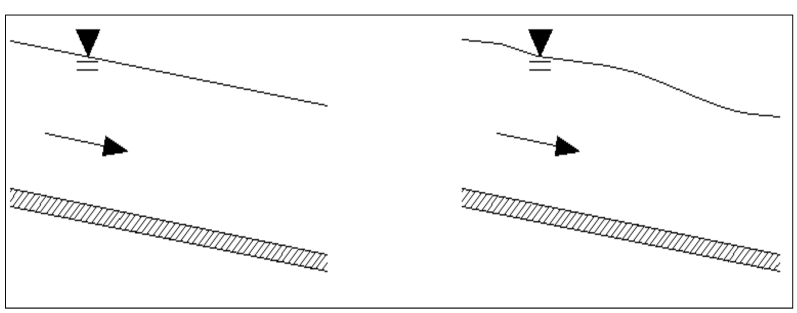
Flow Terms



(a) **Steady Flow**

Depth and velocity at a given location do not vary with time

(b) **Unsteady Flow**

Depth and velocity at a given location vary with time

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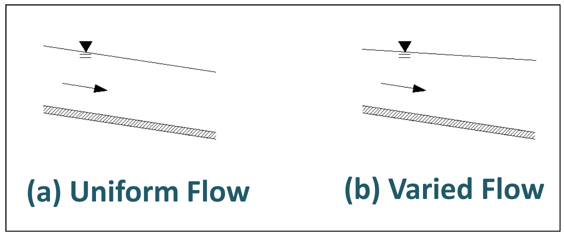
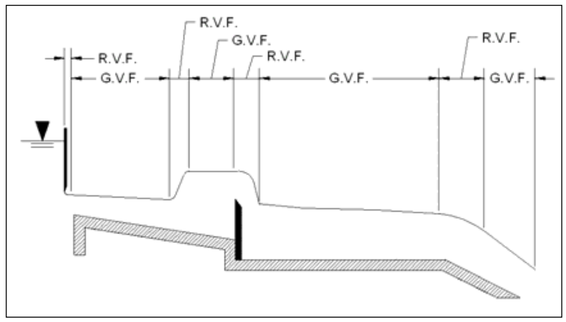
Flow Terms

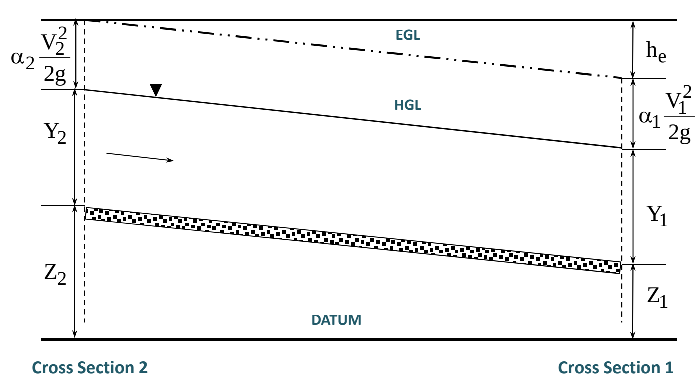
- Uniform flow – flow depth is constant in the downstream direction
- Gradually varied flow – flow depth slowly changes in the downstream direction
- Rapidly varied flow – flow depth changes rapidly in the downstream direction (bridges, culverts, weirs, sluice gates, change in flow regimes, etc.)





1-Dimensional Energy Equation

$$Z_2 + Y_2 + \alpha_2 \frac{V_2^2}{2g} = Z_1 + Y_1 + \alpha_1 \frac{V_1^2}{2g} + h_e$$



1-Dimensional Energy Equation: Terms

- Z = elevation of the bottom of the stream
- Y = flow depth
- V = flow velocity
- g = gravitational force
- $V^2/2g$ = Velocity head (energy due to moving water)
- α = energy distribution factor (helps combines sub-sectional velocity heads)
- h_e = energy loss
  = friction loss + expansion or contraction loss

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Manning's Equation

$$V = (1.49 / n)\ R^{2/3}\ S_f^{1/2} \quad \text{(in English Units)}$$

V = Water velocity, ft/sec

n = Manning's roughness coefficient

R = Hydraulic radius = area/wetted perimeter, ft

S_f = Energy slope (also called the friction slope)

Note: 1.49 = 1 if all terms are in metric units

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Continuity Equation

$$Q = V A$$

Q = discharge, cfs

V = velocity, ft/sec

A = flow area, ft^2

Combining equations: $Q = (1.49/n) A R^{2/3} S^{1/2}$

Note: 1.49 = 1 if all terms are in metric units

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R = Hydraulic Radius = Flow Area/Wetted Perimeter

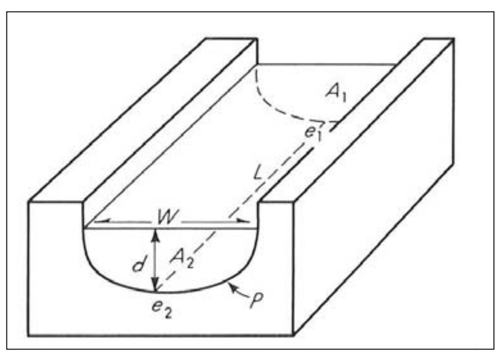
For a wide stream, the hydraulic radius is close to the flow depth.

Example 1 – for a rectangular channel that has a width (W) 2 times the depth (D), W = 2D

R = (D x 2D)/(2D + 2D) = 0.75D

Example 2 – for a rectangular channel that has a width (W) 10 times the depth, W = 10D

R = (D x 10D)/(2D + 10D) = 0.92D



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Selecting Manning ‘n’ Values

- Surface roughness of the material forming the channel wetted perimeter
- Vegetation
- Irregularity of wetted perimeter, cross section size, shape
- Channel alignment
- Erosion and deposition of sediment

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Selecting Manning ‘n’ Values

- Obstructions due to debris, bridge piers, or other structures
- Size and shape of channel
- Stage and discharge
- Seasonal change (water temperature and vegetation)
- Suspended sediment and bed load

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Selecting Manning ‘n’ Values

- For a flood control design, the high end of the range of potential Manning’s n values may be of greatest interest
- For a sediment transport or scour investigation the low end of the potential range of values may be of most importance
- Consider the sensitivity of analysis and design results over the range of potential Manning’s n values
- Compare site characteristics to available references for calibrated Manning’s n values at other similar locations
- References on the selection of Manning’s n exist (Arcement and Schneider, 1984; Barnes, 1967; Chow, 1959; Hicks and Mason, 1998)

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Selecting Manning ‘n’ Values

Type of Channel and Description	Minimum	Normal	Maximum
A. *Natural Streams*			
1. Main Channels			
a. Clean, straight, full, no rifts or deep pools	0.025	0.030	0.033
b. Same as above, but more stones and weeds	0.030	0.035	0.040
c. Clean, winding, some pools and shoals	0.033	0.040	0.045
d. Same as above, but some weeds and stones	0.035	0.045	0.050
e. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. Same as "d" but more stones	0.045	0.050	0.060
g. Sluggish reaches, weedy. deep pools	0.050	0.070	0.080
h. Very weedy reaches, deep pools, or floodways with heavy stands of timber and brush	0.070	0.100	0.150

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Type of Channel and Description	Minimum	Normal	Maximum
2. Flood Plains			
a. Pasture no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated areas			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees, in winter	0.035	0.050	0.060
3. Light brush and trees, in summer	0.040	0.060	0.080
4. Medium to dense brush, in winter	0.045	0.070	0.110
5. Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
2. Same as above, but heavy sprouts	0.050	0.060	0.080
3. Heavy stand of timber, few down trees, little undergrowth, flow below branches	0.080	0.100	0.120
4. Same as above, but with flow into branches	0.100	0.120	0.160
5. Dense willows, summer, straight	0.110	0.150	0.200

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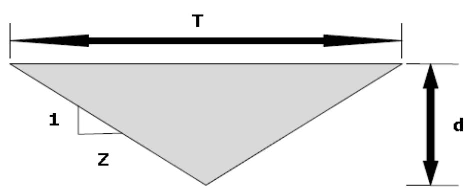
Dimensions of Channels

V-Shaped Channel



Cross Sectional Area (A) = Zd^2

Top Width (T) = 2dZ

Hydraulic Radius (R) = $\frac{Zd}{2\sqrt{Z^2+1}}$

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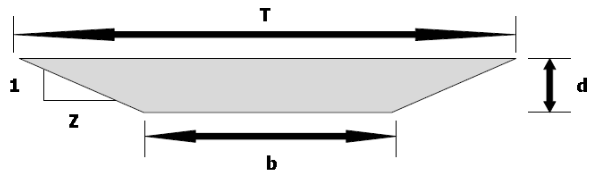
Dimensions of Channels

Trapezoidal Channel



Cross Sectional Area (A) = bd +Zd^2

Top Width (T) = b + 2dZ

Hydraulic Radius (R) = $\frac{bd + Zd^2}{b + 2d\sqrt{Z^2 + 1}}$

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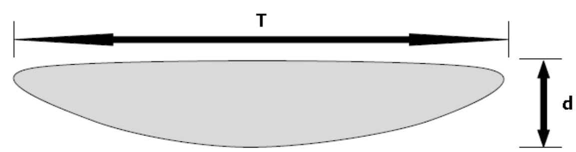
Dimensions of Channels

Parabolic Channel



Cross Sectional Area (A) = 2/3Td

Top Width (T) = 1.5A/d

Hydraulic Radius (R) = $\frac{T^2 d}{1.5T^2 + 4d^2}$

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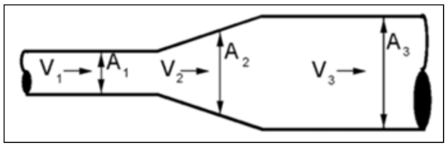
Interpreting and Checking The Results

- Continuity : Q (volume/time)

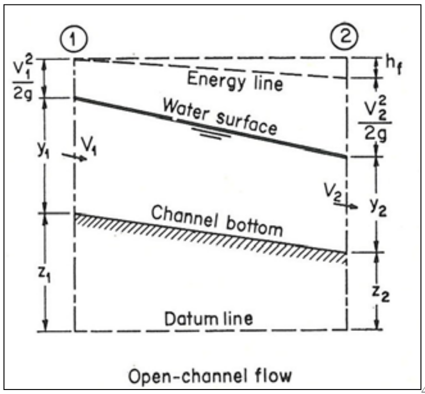
  = V (length/time) x A (area)



- Energy Grade Line - energy of water decreases in the downhill direction.

- Conservation of Energy – Account for all energy gains and losses

- Hydraulic Grade Line – The elevation of the water. If confined, the elevation of the water if it was not confined



Shear Stress: Hydrodynamic Forces Acting on Channel Boundary

$$\tau_o = \gamma_w R S_f$$

τ_o = Bed shear stress (sometimes called applied shear stress)

γ_w = Unit weight of water

R = Hydraulic radius = flow area/wetted perimeter

(maximum flow depth is normally used for design)

S_f = Energy slope (usually taken as the water surface slope or the slope of the streambed for design)

Application of Hydraulic Shear Stress

- τ_c is critical shear stress of a material (e.g., natural material, riprap, articulated blocks, ECBs,TRMs, etc.) on a streambed or banks that results in the material movement on the surface
- If $\tau_o > \tau_c$
  - o Erosion of bed/bank or movement of material occurs
- If $\tau_o < \tau_c$
  - o Bed/bank or material does not move and is stable

Application of Hydraulic Shear Stress

Material	n	Clear Water (diversion structures) V (ft/sec)	Clear Water (diversion structures) τ_o (lb/ft^2)	Water Transporting Colloidal Silts (on site and down slope) V (ft/sec)	Water Transporting Colloidal Silts (on site and down slope) τ_o (lb/ft^2)
Fine sand, colloidal	0.020	1.50	0.027	2.50	0.075
Sandy loam, noncolloidal	0.020	1.75	0.037	2.50	0.075
Silt loam, noncolloidal	0.020	2.00	0.048	3.00	0.11
Alluvial silts, noncolloidal	0.020	2.00	0.048	3.50	0.15
Ordinary firm loam	0.020	2.50	0.075	3.50	0.15
Volcanic ash	0.020	2.50	0.075	3.50	0.15
Stiff clay, very colloidal	0.025	3.75	0.26	5.00	0.46
Alluvial silts, colloidal	0.025	3.75	0.26	5.00	0.46
Shales and hardpans	0.025	6.00	0.67	6.00	0.67
Fine gravel	0.020	2.50	0.075	5.00	0.32
Graded loam to cobbles when noncolloidal	0.030	3.75	0.38	5.00	0.66
Graded silts to cobbles when noncolloidal	0.030	4.00	0.43	5.50	0.80
Coarse gravel, noncolloidal	0.025	4.00	0.30	6.00	0.67
Cobbles and shingles	0.035	5.00	0.91	5.50	1.10

Example Problem 1

A trapezoidal diversion channel is to be constructed on natural silt loam soil to carry a Q_{10} of 270 cfs. It is on a slope of 0.02 (2%), 3H:1V side slopes (Z = 3), bottom width of 4 feet. What is the shear stress and will it cause erosion of the channel?

Type of Channel and Description	Minimum	Normal	Maximum
A. *Natural Streams*			
1. **Main Channels**			
a. Clean, straight, full, no rifts or deep pools	0.025	0.030	0.033
b. Same as above, but more stones and weeds	0.030	0.035	0.040
c. Clean, winding, some pools and shoals	0.033	0.040	0.045
d. Same as above, but some weeds and stones	0.035	0.045	0.050
e. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. Same as "d" but more stones	0.045	0.050	0.060
g. Sluggish reaches, weedy. deep pools	0.050	0.070	0.080
h. Very weedy reaches, deep pools, or floodways with heavy stands of timber and brush	0.070	0.100	0.150

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Example Problem 1

For a Manning's n = 0.03 (can vary as low as 0.025), the parameters given, and an on-line calculator – note there are numerous ones you can use (http://www.eng.auburn.edu/~xzf0001/Handbook/Channels.html), the following information was determined.

- Flow depth y = 2.55 ft. (use instead of hydraulic radius, R)
- Flow velocity = 9.1 fps
- Wetted perimeter = 20.2 ft.
- Flow area = 29.8 ft^2
- Assume slope of channel is the energy slope

Shear stress = $\tau_o = \gamma_w R S_f$ = 62.4 x 2.55 x 0.02 = 3.18 lb/ft^2

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Example Problem 1

The shear stress of 3.18 lb/ft^2 and velocity of 9.1 ft/s exceeds the allowable shear stress of 0.048 lb/ft^2 and velocity 0f 2.0 ft/s for silt loam - so the channel will erode.

Material	n	Clear Water (diversion structures) V (ft/sec)	Clear Water (diversion structures) τ_o (lb/ft^2)	Water Transporting Colloidal Silts (on site and down slope) V (ft/sec)	Water Transporting Colloidal Silts (on site and down slope) τ_o (lb/ft^2)
Fine sand, colloidal	0.020	1.50	0.027	2.50	0.075
Sandy loam, noncolloidal	0.020	1.75	0.037	2.50	0.075
Silt loam, noncolloidal	0.020	2.00	0.048	3.00	0.11
Alluvial silts, noncolloidal	0.020	2.00	0.048	3.50	0.15
Ordinary firm loam	0.020	2.50	0.075	3.50	0.15
Volcanic ash	0.020	2.50	0.075	3.50	0.15
Stiff clay, very colloidal	0.025	3.75	0.26	5.00	0.46
Alluvial silts, colloidal	0.025	3.75	0.26	5.00	0.46
Shales and hardpans	0.025	6.00	0.67	6.00	0.67
Fine gravel	0.020	2.50	0.075	5.00	0.32
Graded loam to cobbles when noncolloidal	0.030	3.75	0.38	5.00	0.66
Graded silts to cobbles when noncolloidal	0.030	4.00	0.43	5.50	0.80
Coarse gravel, noncolloidal	0.025	4.00	0.30	6.00	0.67
Cobbles and shingles	0.035	5.00	0.91	5.50	1.10

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Application of Hydraulic Shear Stress

Rolled Erosion Control Products (RECP)

Blanket	v_{max} (ft/s)	t_{all} (lbs/ft^2)
Straw, no nets	3.0	1.00
Straw, 1 net	3.5	1.25
Straw, 2 nets	4.5	1.50
70% Straw, 30% Coir	8.0	2.00
Excelsior, 2 nets	8.5	2.30
Polypropylene, 2 nets	9.0	3.20
Coir Netting, 900 g	15.0	4.60

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Application of Hydraulic Shear Stress

Turf Reinforced Mats (TRM)		
TRM	v_{max} (ft/s)	t_{all} (lbs/ft^2)
NAG, SC250; bare soil	9.5	2.50
NAG, C350; bare soil	10.5	3.00
NAG, P550; bare soil	12.5	3.25
Pro/Enka II; bare soil	13.0	10.0
Pro/Enka, 7220, BFM, vegetated	14.0	8.0
NAG, C350; vegetated	20.0	10.0
NAG, P550; vegetated	25.0	12.5

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Application of Hydraulic Shear Stress

Lining	n	v_{max} (ft/s)	t_{all} (lbs/ft^2)
Rock, Class A	variable	7.5	1.0
Rock, Class B	variable	10.0	2.0
Rock, Class 1	variable	12.5	3.0
Rock, Class 2	variable	14.0	4.0
Reno Mattress	0.025	13 – 18	8.35
Gabions	0.027	22	8.35
Concrete	0.017		100.0

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Example Problem 2

- For the channel in example problem 1, determine a channel lining that would prevent the channel from eroding.
- We anticipate using a TRM without vegetation (it must be stable when initially placed) so the n value is assumed to be 0.025 (check with manufacturer's specifications).
- For the channel information given and using n = 0.025, the flow depth = 2.35 ft, and flow velocity = 10.4 ft/s

Shear stress = $\tau_o = \gamma_w R S_f$ = 62.4 x 2.35 x 0.02 = 2.93 lb/ft^2

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Example Problem 2

For shear stress = 2.93 lb/ft^2 and velocity = 10.4 ft/s, **NAG C350, bare soil**, will work for both shear stress and velocity (dashed red). However, since the TRM allowable values are so close to the actual conditions, suggest using **NAG P550, bare soil** (solid red).

Turf Reinforced Mats (TRM)

TRM	v_{max} (ft/s)	t_{all} (lbs/ft^2)
NAG, SC250; bare soil	9.5	2.50
NAG, C350; bare soil	10.5	3.00
NAG, P550; bare soil	12.5	3.25
Pro/Enka II; bare soil	13.0	10.0
Pro/Enka, 7220, BFM, vegetated	14.0	8.0
NAG, C350; vegetated	20.0	10.0
NAG, P550; vegetated	25.0	12.5

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Commonly Used Hydraulic Computer Programs to Get Hydraulic Parameters

- **Single Cross-Section Analyzers**
  - WinXSPRO (U.S.D.A., Forest Service)
  - QUICK-2 (Federal Emergency Management Agency)
  - FlowMaster (Haestad Methods, Inc.)
- **1-D Steady Flow Programs**
  - HEC-RAS (U.S. Army Corps of Engineers)
  - HEC-2 (U.S. Army Corps of Engineers)
  - WSPRO (U.S.G.S. and FHWA)
  - WSP-2 (U.S.D.A., NRCS)
  - SWMM (U.S. Environmental Protection Agency)

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Floodplain and Stream Features

(also see next slide)

- **Geomorphic Floodplain** is the alluvial surface adjacent to the channel that is frequently inundated.
- **Terraces** are abandoned floodplains formed when the river flowed at a higher level. They are produced by the incision of the previous floodplain.
- **Berms** are formed when the channel is attempting to establish stability.
- **Bankfull depth** is the depth of the water in the main channel where the water starts to significantly overflow into the overbanks .

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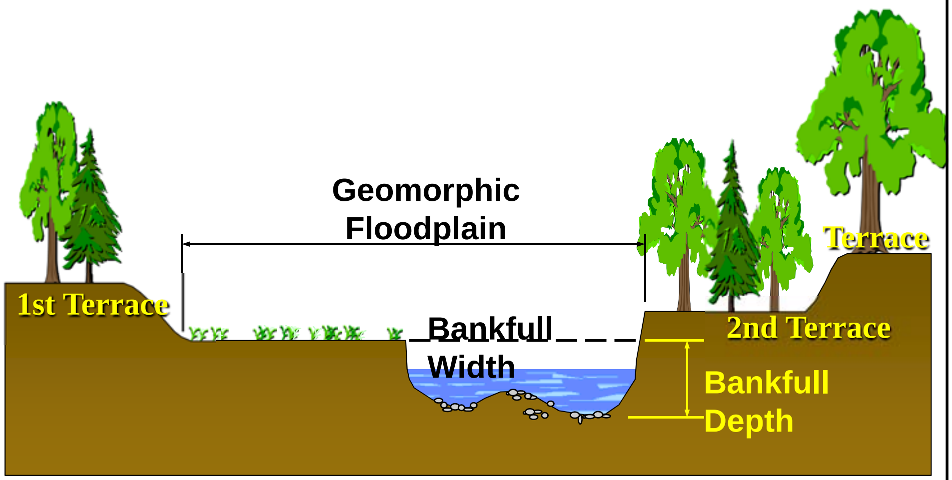
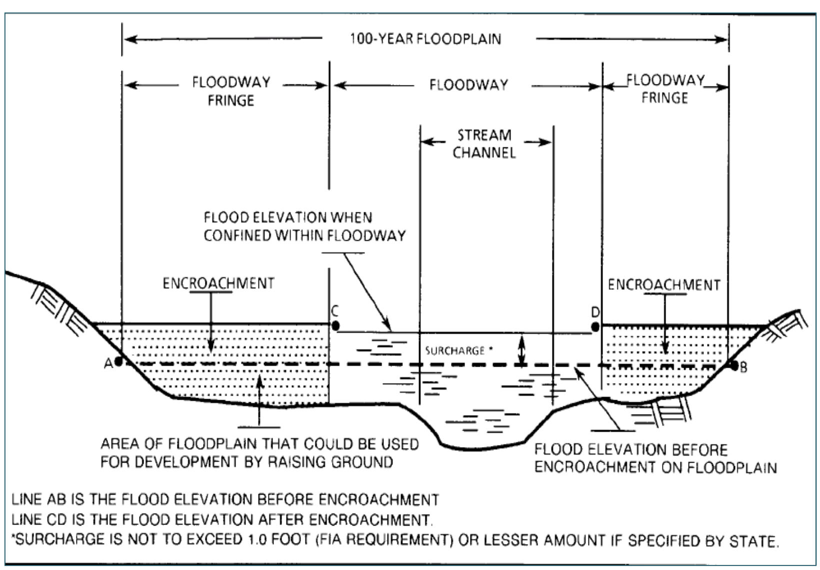
Floodplain and Stream Features

(Courtesy of George Athanasakes, Stantec)

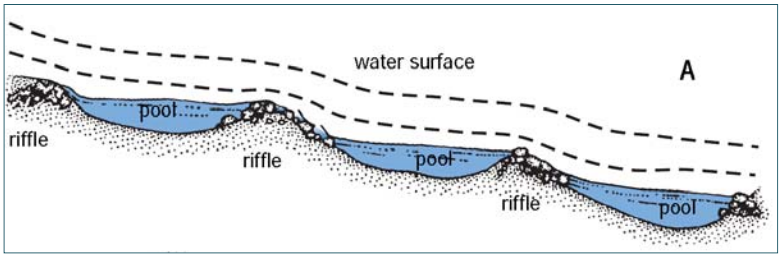


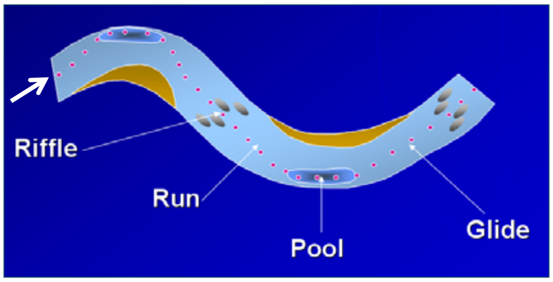
FEMA Floodplain Definitions and Delineations



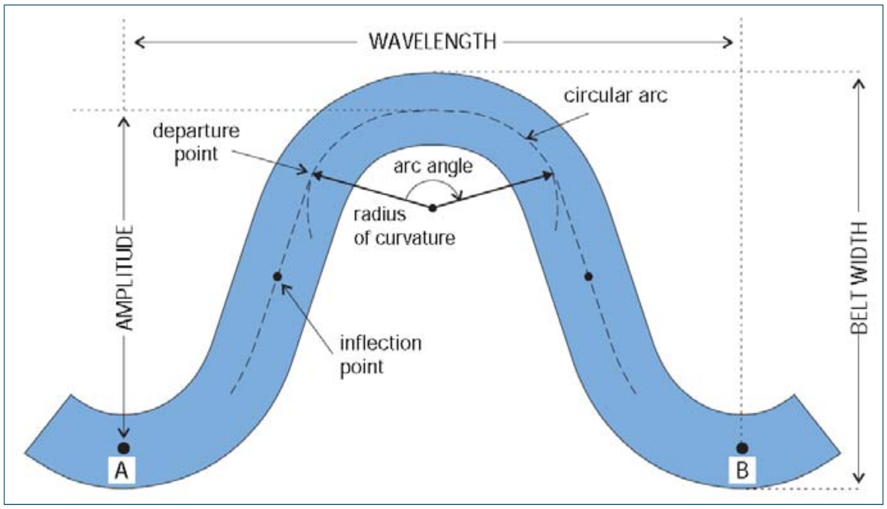
Terminology for Meandering Streams

(courtesy of George Athanasakes, Stantec)





Terminology for Meandering Streams

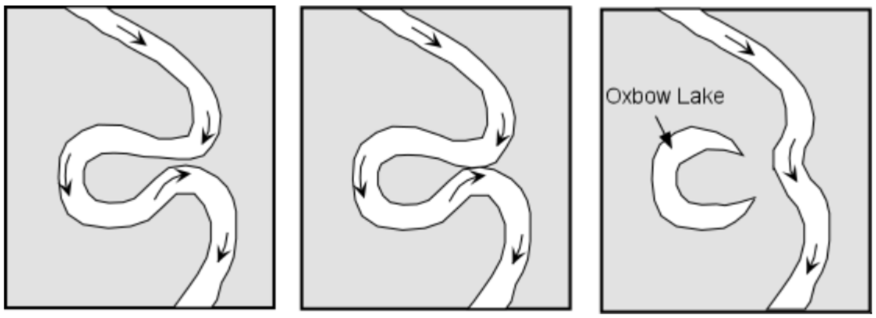


Formation of Oxbows in Meandering Streams

1. Meander sinuosity increases, causing the bend to move downstream

2. Bends merge together

3. Meander is abandoned as stream favors path of least resistance



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Please see Part II info…

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