Hydraulic Factors and Principals

Goals of this Session

• Review key basic principals
• Review available tools
• Review sources and techniques for estimating input parameters
Purposes of Hydraulic Analysis

• Water-surface elevations
  – Floodplain/flood boundary analysis
  – Channel capacity

• In-channel hydraulics
Hydraulic Analysis Techniques

- Normal depth
  - Manning/Chezy Equation
- Step-backwater
  - HEC-RAS
- Multi-dimensional analysis
  - FLO-2D
  - RMA-2
  - SRH-W
Uniform Flow

Velocity Head \( \left( \frac{V^2}{2g} \right) \)

Energy Line

Water Surface

Depth

Bed
mean depth = $\frac{\text{area}}{\text{top width}}$

hydraulic radius = $\frac{\text{area}}{\text{wetted perimeter}}$
Uniform Flow Formulas

Manning Equation: \[ V = \frac{1.486}{n} R^{2/3} S^{1/2} \]

Chezy Equation: \[ V = C R^{1/2} S^{1/2} \]

Darcy-Weisbach: \[ h_l = \frac{f L V^2}{D 2g} \]
Uniform Flow Formulas
Relationships Between Coefficients

Manning and Chezy:

\[ C = \frac{1.486}{n} R^{1/6} \]

...and Darcy:

\[ R = \frac{A}{P} = \frac{\pi D^2 / 4}{\pi D} = \frac{D}{4} \]
\[ \frac{h_l}{L} = S \]

\[ C = \sqrt{\frac{8g}{f}} = \frac{1.486}{n} R^{1/6} \]
Step Backwater Models

HEC-RAS
River Analysis System

User's Manual
Version 4.0
March 2008

US Army Corps of Engineers
Hydrologic Engineering Center


Legend
WS  100 year
WS  2 year
Ground
Left Levee
Right Levee

PajaritoNorth Main5

Tributary 2
North Branch
Cutoff Channel
Pajaro Arroyo Mainstem

Cutoff Channel

Tributary 2

North Branch
Pajaro Arroyo Mainstem

Cutoff Channel

Tributary 2

North Branch
Pajaro Arroyo Mainstem

Cutoff Channel

Tributary 2

North Branch
Pajaro Arroyo Mainstem
Gradually Varied Flow

Solve using standard-step method

Velocity Head \( \frac{V^2}{2g} \)

Energy Line

Water Surface

Depth

Bed
Modeling Assumptions

- Steady Flow
- Uniform or Gradually Varied Flow
- 1-Dimensional Approximation
- Flow Resistance
- Other Energy Losses
Modeling/Analysis
Data Needs and Issues

- Topography/bathymetry
- Roughness and loss coefficients
- Calibration Data
- Rigid boundary assumption
- Sub- versus supercritical flow
2-D Models

RECLAMATION
Managing Water in the West

Theory and User Manual for SRH-W Version 1.1
Sedimentation and River Hydraulic – Watershed model

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

November 2004
Channel Roughness

• Types of roughness
  – Grain
  – Form
    • Bedforms
    • Topography and channel irregularities

• Total Shear: \( t = g (R' + R'') S \)
  – \( R' \) = Hyd Radius due to grain resistance
  – \( R'' \) = Hyd Radius due to form resistance
CONCEPTUAL ILLUSTRATION
OF ROUGHNESS SCALES

SMALL SCALE ROUGHNESS

INTERMEDIATE SCALE ROUGHNESS

LARGE SCALE ROUGHNESS
Bedforms

1. Typical ripple pattern
2. Weak boil
3. Dunes with ripples superposed
4. Dunes
5. Plane bed
6. Antidune standing wave
7. Antidune breaking wave
8. Pool and chute

Washed out dunes

Chutes and pools
Bedforms

Ripples

Dunes

Antidunes

Bars
Water Surface and Bed Configuration

(a) Tranquil Flow, Alluvial Channel
(b) Tranquil Flow, Rigid Boundary
(c) Rapid Flow, Alluvial Channel
(d) Rapid Flow, Rigid Boundary
FIG. 2.76.—Relation of Bed Form to Stream Power and Median Fall Diameter of Bed Sediment Proposed by Simons and Richardson (1966)
Relative Resistance in Sand-bed Channels

BED FORM

<table>
<thead>
<tr>
<th>Plain Bed</th>
<th>Ripples</th>
<th>Dunes</th>
<th>Transition</th>
<th>Plain Bed</th>
<th>Standing Waves and Antidunes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Surface</td>
<td>▼</td>
<td>▼</td>
<td>▼</td>
<td>▼</td>
<td>▼</td>
</tr>
<tr>
<td>Bed</td>
<td>▼</td>
<td>▼</td>
<td>▼</td>
<td>▼</td>
<td>▼</td>
</tr>
</tbody>
</table>

Resistance to flow (Manning's roughness coefficient)

STREAM POWER

Lower Regime | Transition | Upper Regime
Roughness Characteristics of Natural Channels
## Base Manning’s n Values

<table>
<thead>
<tr>
<th>Channel or Floodplain Type</th>
<th>Bed Material Median Size (mm)</th>
<th>Base n-value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sand Channels</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower regime flow</td>
<td>0.2 - 2.0</td>
<td>0.030</td>
<td>Chow (1959); Barnes (1967)</td>
</tr>
<tr>
<td>Upper regime flow</td>
<td>0.2</td>
<td>0.012</td>
<td>Benson and Dalrymple (1984)</td>
</tr>
<tr>
<td>Upper regime flow</td>
<td>0.3</td>
<td>0.017</td>
<td>Benson and Dalrymple (1984)</td>
</tr>
<tr>
<td>Upper regime flow</td>
<td>0.4</td>
<td>0.020</td>
<td>Benson and Dalrymple (1984)</td>
</tr>
<tr>
<td>Upper regime flow</td>
<td>0.5</td>
<td>0.022</td>
<td>Benson and Dalrymple (1984)</td>
</tr>
<tr>
<td>Upper regime flow</td>
<td>0.6</td>
<td>0.023</td>
<td>Benson and Dalrymple (1984)</td>
</tr>
<tr>
<td>Upper regime flow</td>
<td>0.8</td>
<td>0.025</td>
<td>Benson and Dalrymple (1984)</td>
</tr>
<tr>
<td>Upper regime flow</td>
<td>1.0</td>
<td>0.026</td>
<td>Benson and Dalrymple (1984)</td>
</tr>
</tbody>
</table>
Manning’s $n$ – Channels
Cowan (1956)

\[ n = \left( n_b + n_1 + n_2 + n_3 + n_4 \right) m \]

where \( n_b \) = the base value for a straight, uniform channel
\( n_1 \) = value for surface irregularities in the cross section
\( n_2 \) = value for variations in shape and size of the channel
\( n_3 \) = value for obstructions
\( n_4 \) = value for vegetation and flow conditions
\( m \) = correction factor for sinuosity of the channel
Manning’s n-value
Brownlie (1983)

LOWER REGIME

\[ n = [1.6940 \left( \frac{R}{D_{50}} \right)^{0.1374} S^{0.1112} G^{0.1605}] 0.034 D_{50}^{0.167} \]

UPPER REGIME

\[ n = [1.0213 \left( \frac{R}{D_{50}} \right)^{0.0662} S^{0.0395} G^{0.1282}] 0.034 D_{50}^{0.167} \]

R = hydraulic radius in feet
S = channel slope
G = gradation coefficient of the bed material
Manning’s n-value
Brownlie (1983)

\[ G = \frac{1}{2} \left( \frac{D_{84}}{D_{50}} + \frac{D_{50}}{D_{16}} \right) \]

\[ F_g = \frac{V}{\sqrt{S_g - 1)gD_{50}}} \quad F_g' = \frac{1.74}{S_g^{1/3}} \]

\( F_g \leq F_g' \) Lower Regime
\( F_g > F_g' \) Upper Regime
## Base Manning’s n Values

<table>
<thead>
<tr>
<th>Channel or Floodplain Type</th>
<th>Bed Material Median Size (mm)</th>
<th>Base n-value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable channels and floodplains</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tined concrete</td>
<td></td>
<td>0.018</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Shotcrete</td>
<td></td>
<td>0.025</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Reinforce concrete pipe</td>
<td></td>
<td>0.013</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Trowled concrete</td>
<td></td>
<td>0.013</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>No-joint cast in place concrete pipe</td>
<td></td>
<td>0.014</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Reinforced concrete box</td>
<td></td>
<td>0.015</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Reinforced concrete arch</td>
<td></td>
<td>0.015</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Streets</td>
<td></td>
<td>0.017</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Flush grouted riprap</td>
<td></td>
<td>0.020</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Corrugated metal pipe</td>
<td></td>
<td>0.025</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Grass-lined channels (sodded &amp; irrigated)</td>
<td></td>
<td>0.025</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Earth-lined channels (smooth)</td>
<td></td>
<td>0.030</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Wire-tied riprap</td>
<td></td>
<td>0.040</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Medium weight dumped riprap</td>
<td></td>
<td>0.045</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Grouted riprap (exposed rock)</td>
<td></td>
<td>0.045</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
<tr>
<td>Jetty type riprap (D_{50} &gt; 24&quot;)</td>
<td></td>
<td>0.050</td>
<td>DPM 22, Table 22.3 B-1</td>
</tr>
</tbody>
</table>
Concrete-lined Channel with Sediment
Composite Roughness

Equal Velocity
Horton (1935)

Conveyance Weighting
Lotter (1935)

\[ n_c = \left[ \frac{\sum_{i=1}^{N} P_i n_i^{1.5}}{P} \right]^{2/3} \]

\[ n_c = \frac{A_t R_t^{2/3}}{\sum \frac{A_i R_i^{2/3}}{n_i}} \]
<table>
<thead>
<tr>
<th>Conditions</th>
<th>$n$ -value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$n_1$ - Cross-section Irregularity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smooth</td>
<td>0</td>
<td>Smoothest channel</td>
</tr>
<tr>
<td>Minor</td>
<td>0.001-0.005</td>
<td>Slightly eroded sideslopes</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.006-0.010</td>
<td>Moderately rough bed and banks</td>
</tr>
<tr>
<td>Severe</td>
<td>0.011-0.020</td>
<td>Badly sloughed and scalloped banks</td>
</tr>
<tr>
<td><strong>$n_2$ - Variation in Cross-sectional Shape and Size</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gradual</td>
<td>0</td>
<td>Gradual changes</td>
</tr>
<tr>
<td>Alternating Occasionally</td>
<td>0.001-0.015</td>
<td>Occasional shifts from large to small section</td>
</tr>
<tr>
<td>Alternating Frequently</td>
<td>0.010-0.015</td>
<td>Frequent changes in cross-sectional shape</td>
</tr>
<tr>
<td><strong>$n_3$ - Obstructions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negligible</td>
<td>0-0.004</td>
<td>Obstructions &lt; 5% of cross-section area</td>
</tr>
<tr>
<td>Minor</td>
<td>0.005-0.015</td>
<td>Obstructions &lt; 15% of cross-section area</td>
</tr>
<tr>
<td>Appreciable</td>
<td>0.020-0.030</td>
<td>Obstructions 15-50% of cross-section area</td>
</tr>
<tr>
<td>Severe</td>
<td>0.040-0.060</td>
<td>Obstructions &gt; 50% of cross-section area</td>
</tr>
<tr>
<td><strong>$n_4$ - Vegetation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td>0.002-0.010</td>
<td>Flow depth &gt; 2x vegetation height</td>
</tr>
<tr>
<td>Medium</td>
<td>0.010-0.025</td>
<td>Flow depth &gt; vegetation height</td>
</tr>
<tr>
<td>Large</td>
<td>0.025-0.050</td>
<td>Flow depth &lt; vegetation height</td>
</tr>
<tr>
<td>Very Large</td>
<td>0.050-0.100</td>
<td>Flow depth &lt; 0.5 vegetation height</td>
</tr>
<tr>
<td><strong>M - Sinuosity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor</td>
<td>1.0</td>
<td>Sinuosity &lt; 1.2</td>
</tr>
<tr>
<td>Appreciable</td>
<td>1.15</td>
<td>1.2 Sinuosity &lt; 1.5</td>
</tr>
<tr>
<td>Severe</td>
<td>1.30</td>
<td>Sinuosity &gt; 1.5</td>
</tr>
</tbody>
</table>
Manning’s n - Floodplains

**Manning’s Roughness Coefficients**

**United States Geological Survey Water-supply Paper 2339**

**Metric Version**

$n = n_b + n_1 + n_3 + n_4$

$n_b$ = base value of $n$ for a bare soil surface
<table>
<thead>
<tr>
<th>Flood-Plain Conditions</th>
<th>$n$ Value Adjustment</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>0.000</td>
<td>Compares to the smoothest, flattest flood-plain attainable in a given bed material.</td>
</tr>
<tr>
<td>Minor</td>
<td>0.001-0.005</td>
<td>Is a Flood Plain Slightly irregular in shape. A few rises and dips or sloughs may be more visible on the flood plain.</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.006-0.010</td>
<td>Has more rises and dips. Sloughs and hummocks may occur.</td>
</tr>
<tr>
<td>Severe</td>
<td>0.011-0.020</td>
<td>Flood Plain very irregular in shape. Many rises and dips or sloughs are visible. Irregular ground surfaces in pasture land and furrows perpendicular to the flow are also included.</td>
</tr>
</tbody>
</table>

**Variation of Flood-Plain cross section ($n_v$)**

| Gradual | 0.0 | Not applicable |

**Effect of obstruction ($n_o$)**

| Negligible | 0.000-0.004 | Few scattered obstructions, which include debris deposits, stumps, exposed roots, logs, piers, or isolated boulders, that occupy less than 5 percent of the cross-sectional area. |
| Minor      | 0.040-0.050 | Obstructions occupy less than 15 percent of the cross-sectional area. |
| Appreciable| 0.020-0.030 | Obstructions occupy from 15 percent to 50 percent of the cross-sectional area. |

**Amount of vegetation ($n_v$)**

| Small      | 0.001-0.010 | Dense growths of flexible turf grass, such as Bermuda, or weeds growing where the average depth of flow is at least two times the height of the vegetation; supple tree seedlings such as willow, cottonwood, arrow-weed, or saltcedar growing where the average depth of flow is at least three times the height of the vegetation. |
| Medium     | 0.010-0.025 | Turf grass growing where the average depth of flow is from one to two times the height of the vegetation; moderately dense stemy grass, weeds, or tree seedlings growing where the average depth of flow is from two to three times the height of the vegetation; brushy, moderately dense vegetation, similar to 1-to-2-year-old willow trees in the dormant season. |
| Large      | 0.025-0.050 | Turf grass growing where the average depth of flow is about equal to the height of the vegetation; 8-to-10-years-old willow or cottonwood trees, growing with some weeds and brush (none of the vegetation in foliage) where the hydraulic radius exceeds 0.607 m., or mature row crops such as small vegetables, or mature field crops where depth flow is at least twice the height of the vegetation. |
| Very Large | 0.050-0.100 | Turf grass growing where the average depth of flow is less than half the height of the vegetation; or moderate to dense brush, or heavy stand of timber with few down trees and little undergrowth where depth of flow is below branches, or mature field crops where depth of flow is less than the height of the vegetation. |
| Extreme    | 0.100-0.200 | Dense bushy willow, mesquite, and saltcedar (all vegetation in full foliage), or heavy stand of timber, few down trees, depth of reaching branches. |

**Degree of Meander ($m$)**

| 1.0 | Not Applicable |
Superelevation in Bends

L  meander wavelength
M_L  meander arc length
w  average width at bankfull discharge
M_A  meander amplitude
r_c  radius of curvature
θ  arc angle
Superelevation in Bends

$$\Delta Z = C \frac{V^2 W}{gR_c}$$
## Superelevation Formula Coefficients

<table>
<thead>
<tr>
<th>Flow Type</th>
<th>Channel Cross Section</th>
<th>Type of Curve</th>
<th>Value of C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tranquil</td>
<td>Rectangular</td>
<td>Simple circular</td>
<td>0.5</td>
</tr>
<tr>
<td>Tranquil</td>
<td>Trapezoidal</td>
<td>Simple circular</td>
<td>0.5</td>
</tr>
<tr>
<td>Rapid</td>
<td>Rectangular</td>
<td>Simple circular</td>
<td>1.0</td>
</tr>
<tr>
<td>Rapid</td>
<td>Trapezoidal</td>
<td>Simple circular</td>
<td>1.0</td>
</tr>
<tr>
<td>Rapid</td>
<td>Rectangular</td>
<td>Spiral transitions</td>
<td>0.5</td>
</tr>
<tr>
<td>Rapid</td>
<td>Trapezoidal</td>
<td>Spiral transitions</td>
<td>1.0</td>
</tr>
<tr>
<td>Rapid</td>
<td>Rectangular</td>
<td>Spiral banked</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Supercritical Flow in Natural Channels

Velocity Head \( \frac{V^2}{2g} \)

Energy Line

Water Surface

Depth

Bed
Supercritical Flow in Natural Channels

\[ CWSEL_{seq} = CWSEL + 0.5\left(\frac{A}{W}\right)\left(\sqrt{1+8F_r^2} - 3\right) \]

\[ F_r = \frac{V}{\sqrt{gY}} = \frac{Q}{A\sqrt{Ag}/W} \]
Hydraulic Analysis Workshop
Example Problems
Hydraulics

Given an arroyo with the following characteristics:

- Relatively flat bottom with minor cross section irregularity, gradual variation in cross section shape,
- Negligible obstructions (small vegetation),
- Vertical bank - 3 feet high,
- Sparse vegetation within the active channel,
- Minor sinuosity,
- 100-year peak discharge = 1,045 cfs,
- Channel width (W) = 39 feet,
- Bed slope (S0) = 4%,
- Bed material size $D_{50} = 1.9$ mm, $D_{84} = 4.2$ mm, $D_{16} = 0.48$ mm, and
- Channel thalweg (minimum bed) elevation = 6,000 ft MSL.
1. Compute normal depth, velocity and Froude Number for the peak of the 100-year storm.

Use Manning's equation assuming wide rectangular channel (i.e., $R \approx y$) to compute normal depth (Equation 3.3):

$$q = V_y = \frac{1.49}{n} y^{5/3} \sqrt{S_f}$$

From continuity, $q = Q/W_d = 1045/39 = 26.8 \text{ cfs/ft}$

Estimate Manning's $n$ using Brownlie's equation for the base $n$-value ($n_b$) and Equation 3.11 to adjust $n_b$ for channel irregularities, etc. Due to the steepness of the arroyo, upper regime flow is expected; therefore, use Equation 3.13 for $n_b$:

$$n_b = [1.0213 (R/D_{50})^{0.0662} S_0^{0.0395} G^{0.1282}] 0.034 D_{50}^{0.167}$$
Hydraulics

Example Problem #1

1. Compute normal depth, velocity and Froude Number for the peak of the 100-year storm.

Use Brownlie to estimate $n_b$

$$n_b = [1.0213 \ (R/D_{50})^{0.0662} \ S_0^{0.0395} \ G^{0.1282}] \ 0.034 \ D_{50}^{0.167}$$

$$G = \frac{1}{2} \left( \frac{D_{54}}{D_{50}} + \frac{D_{50}}{D_{16}} \right) = \frac{1}{2} \left( \frac{4.2}{1.9} + \frac{1.9}{.48} \right) = 3.1$$

Assume $R = 2$ feet

$$n_b = \left[ 1.0213 \left( \frac{2}{(1.9/304.8)} \right)^{0.0662} \ (0.04)^{0.0395} \ (3.1)^{0.1282} \right] \ 0.034 \left( \frac{1.9}{304.8} \right)^{0.167}$$

$$n_b = 0.022$$
Hydraulics
Example Problem #1

From Equation 3.11 and Table 3.2:

\[ n = (n_b + n_1 + n_2 + n_3 + n_4) m \]

\[ n = (0.022 + .004 + 0 + .002 + .007) 1.0 = 0.035 \]

Rearrange Equation 3.3:

\[
y = \left[ \frac{qn}{1.486 \sqrt{S_0}} \right]^3 = \left[ \frac{(268)(0.035)}{1.486 \sqrt{0.04}} \right]^3 = 2.0 \text{ft}
\]
Hydraulics
Example Problem #1

By continuity:

\[ v = \frac{q}{y} = \frac{26.8}{2.0} = 13.4 \text{ fps} \]

\[ A = \frac{Q}{v} = \frac{1045}{13.4} = 78.0 \text{ ft}^2 \]
Hydraulics
Example Problem #2

2. Compute normal depth water-surface elevation.

\[ WSEL_n = Z + Y_n = 6000 + 2.0 = 6002.0 \text{ ft MSL} \]

\[ WSEL_n = 6000 + 2.0 = 6002.0 \text{ ft MSL} \]
3. Compute energy gradeline elevation.

\[ EGL = Z + Y_n + \frac{V^2}{2g} = 6000 + 2.0 + \frac{13.4^2}{2g} = 6004.8 \text{ ft MSL} \]

\[ EGL = 6000 + 2.0 + \frac{13.4^2}{2g} = 6004.8 \text{ ft MSL} \]
Hydraulics
Example Problem #4

4. Compute critical depth \( y_c \) and critical water surface elevation \( (CWSEL_{\text{crit}}) \).

By continuity and Equation 3.23:

\[
y_c = 3 \sqrt{\frac{q^2}{g}}
\]

\[
y_c = 3 \sqrt{\frac{26.8^2}{g}} = 2.8 \text{ ft}
\]

\[
CWSEL_{\text{crit}} = Z + Y_c = 6002.8
\]
5. Compute conjugate (or sequent) depth and water surface elevation. (This is the expected high-water condition for natural channels. Bank protection and protection of structures will require appropriate freeboard.)

\[
CWSEL_{seq} = CWSEL + 0.5 \left( \frac{A}{W} \right) \left( \sqrt{1 + 8 F_r^2} - 3 \right)
\]

\[
CWSEL_{seq} = 6002 + 0.5 \left( \frac{78}{39} \right) \left( \sqrt{1 + 8(1.67)^2} \right) = 6002 + 1.83
\]

\[
= 6003.83 \text{ ft MSL}
\]
Superelevation on a Curve
Example Problem #1

At one location, the arroyo in the previous problem makes a bend. From available mapping, the radius of curvature of the bend \((r_c)\) is estimated to be 195 feet.

1. Compute the superelevation on the outside of the curve for normal depth, at the peak of the 100-year storm.

\[
\Delta Z = C \frac{v^2 W}{gr_c}
\]
Superelevation on a Curve
Example Problem #1

From Table 3.3, with rapid flow, rectangular channel, and circular curve, $C = 1.0$.

$$
\Delta Z = 1.0 \frac{(13.4)^2 (39)}{g(195)} = 1.1 \text{ feet}
$$
Superelevation on a Curve
Example Problem #2

2. Compute the expected water surface elevation on the outside of the bend.

\[
CWL_{Bend} = Z + y_n + \Delta Z
\]

= \[6000 + 2.0 + 1.1\]

= \[6003.1\text{ ft MSL}\]