OPEN CHANNEL FLOW
HW#7 assigned
Flow in channels is different than overland flow

Headwater watershed areas < 1,000 mi\(^2\)
- Small area floods / small river systems
- Flash floods of short duration

Headwater watershed areas > 1,000 mi\(^2\)
- Flood controls are “engineering” controls
  - Dams / channels / etc

Channel flow equations apply to:
- Small creeks as well as large rivers
- Magnitude of flow is the only difference
- Equations and principles apply to both small and large channels
**TYPE OF STREAMS**

- **Ephemeral streams**
  - Only contain water when there is surface runoff
  - Dry unless there is a rainfall event that produces SRO

- **Intermittent streams**
  - Dry part of the year
  - Flow when groundwater is high
  - Flow when surface runoff occurs

- **Perennial streams**
  - Flow throughout the year
  - Groundwater provides baseflow during dry periods
ORDER NUMBER (N) OF STREAMS

- System for classifying drainage networks
  - 1st order streams \( (n = 1) \)
    - Smallest “finger-tip” tributaries
  - 2nd order streams \( (n = 2) \)
    - When two 1st order streams join
  - 3rd order streams \( (n = 3) \)
    - When two 2nd order stream join
  - Etc

- Useful **only** when \( n \) is proportional to channel:
  - Dimensions
  - Size of contributing watershed
  - Stream discharge
Stream morphology

- Stream patterns and geometry influenced by:
  - Geology
  - Topography
  - Size of contributing watershed
  - Flow velocity
  - Discharge
  - Sediment transport
  - Sediment particle distribution
  - Channel geometry
  - Other geomorphological controls
STREAM MORPHOLOGY

- Streams attempt to be in “equilibrium”
  - Equilibrium between sediment and deposition

- Channel patterns
  - Sinuous
  - Meandering: for a given discharge occur on smaller slopes
  - Braided

- Sinuosity
  - Ratio of stream length to valley length
  - Sinuosity = 1 ➞ stream channel is straight
  - $1 < \text{Sinuosity} < 1.5$ ➞ channel is sinuous
  - Sinuosity $> 1.5$ ➞ channel is meandering
  - Sinuosity $> 2.1$ ➞ channel is tortuous meandering
Stream Meandering

- Present lake
- River position today
- In grandfather’s time
- Valley material deposited by the river
STREAM FEATURES

- Inner side of stream curves
  - Sand bar ridges ➔ point bars
  - Where velocity is the slowest

- Outer side of stream curves
  - Channel erosion (scour) ➔ deep pools
  - Where velocity is the highest

- If stream “equilibrium” is not achieved:
  - Scour on the outer bends continues
  - Sinuosity increases
  - Oxbow lakes may form
    - Stream flow breaks through two bends to form a cutoff
STREAM FEATURES

- Braided rivers
  - No single, well defined channel
  - Network of interconnecting streams
  - A form of meandering
  - Tend to be steeper, wider and shallower than undivided reaches carrying the same discharge

- A section of a channel is called a “reach”
STREAM SCOUR

- Scour depends on:
  - Soil / rock type in the channel
  - Vegetation in the channel
  - Flow rates in the channel

- Max permissible velocities for vegetated channels
  - 8 ft/s ➔ Bermuda grass / 0-5% slope (SCS, 1984)

- Hydraulic behavior of vegetation will change as the flow rate increases
  - Vegetation bends over and flattens out
  - Resistance to flow is reduced ➔ increased flow velocity
FLOW IN CHANNELS

Function of:
- Precipitation
- Surface runoff
- Interflow
- Groundwater flow
- Pumped inflows / outflows
- Cross sectional geometry
- Bed slope
- Bed and side roughness
- Changes in shape
- Hydraulic control structures
- Sediment transport
- Channel stability
- Antecedent moisture conditions
FLOW IN CHANNELS

- Turbulent flow
  - Steep rocky areas
  - Following storm events

- Steady uniform flow
  - Depth of flow does not change quickly with time
  - Hydraulic equations only apply to steady uniform flow
OPEN CHANNEL HYDRAULICS

- Three basic relationships
  - Continuity equation
  - Energy equation
  - Momentum equation
CONTINUITY EQUATION

Inflow – Outflow = Change in Storage

\[ Q_1 - Q_2 = \text{Change in storage rate} \]
CONTINUITY EQUATION FOR OPEN CHANNEL FLOW

- \( q = va \), where:
  - \( q \) = is the discharge (ft\(^3\)/s)
  - \( v \) = average velocity of the water (ft/s)
  - \( a \) = cross-sectional area of the stream (ft\(^2\))

- If \( q \) does not change along a channel reach, then:
  - \( q = v_1 a_1 = v_2 a_2 \), where:
    - 1 = upstream reach
    - 2 = downstream reach
MANNING’S EQUATION FOR OPEN CHANNEL FLOW

\[ v = \frac{K}{n} R^{2/3} S^{1/2} \]

- **where:**
  - \( K = \) constant, 1.49 for English units and 1.0 for SI units
  - \( v = \) velocity in ft/s or m/s
  - \( n = \) Manning’s roughness coefficient of the channel
  - \( S = \) channel bed slope (ft/ft) or (m/m)
    - Change in elevation / length of stream reach
    - Rise / run
  - \( R = \) hydraulic radius of the channel
  - \( R = \frac{A}{P}, \) where:
    - \( A = \) cross-sectional area of the channel (ft\(^2\)) or (m\(^2\))
    - \( P = \) wetted perimeter channel (ft) or (m)
<table>
<thead>
<tr>
<th>Type of Channel and Description</th>
<th>Minimum</th>
<th>Normal</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constructing Channels</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earth, winding and sluggish</td>
<td>0.025</td>
<td>0.025</td>
<td>0.030</td>
</tr>
<tr>
<td>• No vegetation</td>
<td>0.030</td>
<td>0.035</td>
<td>0.040</td>
</tr>
<tr>
<td>• Dense weeds or plants in deep</td>
<td>0.028</td>
<td>0.030</td>
<td>0.035</td>
</tr>
<tr>
<td>channels</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Earth bottom and rubble sides</td>
<td>0.030</td>
<td>0.040</td>
<td>0.050</td>
</tr>
<tr>
<td>• Cobble bottom and clean sides</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rock cuts</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Smooth and uniform</td>
<td>0.025</td>
<td>0.035</td>
<td>0.040</td>
</tr>
<tr>
<td>• Jagged and irregular</td>
<td>0.035</td>
<td>0.040</td>
<td>0.050</td>
</tr>
<tr>
<td><strong>Channels not maintained, weeds and</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>brush</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Dense weeds</td>
<td>0.050</td>
<td>0.080</td>
<td>0.120</td>
</tr>
<tr>
<td>• Same, highest stage of flow</td>
<td>0.045</td>
<td>0.070</td>
<td>0.110</td>
</tr>
<tr>
<td>• Dense brush, high stage</td>
<td>0.080</td>
<td>0.100</td>
<td>0.140</td>
</tr>
<tr>
<td><strong>Streams</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Streams on plain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Clean, straight, full stage, no</td>
<td>0.025</td>
<td>0.030</td>
<td>0.033</td>
</tr>
<tr>
<td>rills or deep pools</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Clean, winding, some pools, shoals,</td>
<td>0.033</td>
<td>0.045</td>
<td>0.050</td>
</tr>
<tr>
<td>weeds &amp; stones</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Same as above, lower stages and</td>
<td>0.045</td>
<td>0.050</td>
<td>0.080</td>
</tr>
<tr>
<td>more stones</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Sluggish reaches, weedy, deep</td>
<td>0.050</td>
<td>0.070</td>
<td>0.080</td>
</tr>
<tr>
<td>pools</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Very weedy reaches, deep pools, or</td>
<td>0.075</td>
<td>0.100</td>
<td>0.150</td>
</tr>
<tr>
<td>floodways with heavy stand of</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>timber and underbrush</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mountain streams, no vegetation in</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>channel, banks usually steep, trees</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>and brush along banks submerged at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>high stages</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Bottom: gravels, cobbles, and few</td>
<td>0.030</td>
<td>0.040</td>
<td>0.050</td>
</tr>
<tr>
<td>boulders</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Bottom: cobbles with large boulders</td>
<td>0.040</td>
<td>0.050</td>
<td>0.070</td>
</tr>
<tr>
<td><strong>Pasture, no brush</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Short Grass</td>
<td>0.025</td>
<td>0.030</td>
<td>0.035</td>
</tr>
<tr>
<td>• High grass</td>
<td>0.030</td>
<td>0.035</td>
<td>0.050</td>
</tr>
<tr>
<td><strong>Cultivated areas</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• No crop</td>
<td>0.020</td>
<td>0.030</td>
<td>0.040</td>
</tr>
<tr>
<td>• Mature row crops</td>
<td>0.025</td>
<td>0.035</td>
<td>0.045</td>
</tr>
<tr>
<td>• Mature field crops</td>
<td>0.030</td>
<td>0.040</td>
<td>0.050</td>
</tr>
<tr>
<td><strong>Brush</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Scattered brush, heavy weeds</td>
<td>0.035</td>
<td>0.050</td>
<td>0.070</td>
</tr>
<tr>
<td>• Light brush and trees</td>
<td>0.035</td>
<td>0.060</td>
<td>0.080</td>
</tr>
<tr>
<td>• Medium to dense brush, in winter</td>
<td>0.045</td>
<td>0.070</td>
<td>0.110</td>
</tr>
<tr>
<td>• Medium to dense brush, in summer</td>
<td>0.070</td>
<td>0.100</td>
<td>0.160</td>
</tr>
</tbody>
</table>

Manning’s Roughness Coef. (n)
FACTORS AFFECTING MANNING’S N

A. Surface Roughness
B. Vegetation
C. Channel Irregularity
D. Channel Alignment
E. Silting and Scouring
F. Obstruction
G. Size and Shape of the Channel
H. Stage and Discharge
I. Seasonal Change
J. Suspended Material and Bedload.
Natural channels often have a main channel and an overbank section.
Most flow occurs in main channel; however during flood events overbank flows may occur.

In this case the channel is broken into cross-sectional parts and the sum of the flow is calculated for the various parts.
FLOW IN COMPOUND CHANNELS

\[ V_i = \frac{1.49}{n_i} S^{1/2} \left( \frac{A_i}{P_i} \right)^{2/3} \]

\[ Q = \sum_{i=1}^{n} V_i A_i \]

In determining R only that part of the wetted perimeter in contact with an actual channel boundary is used.
ENERGY EQUATION (BERNOULLI’S)

\[\frac{v_1^2}{2g} + y_1 + z_1 + \frac{p_1}{\gamma} = \frac{v_2^2}{2g} + y_2 + z_2 + \frac{p_2}{\gamma} + h_{L,1-2}\]

- **Velocity head**: \(\frac{v_1^2}{2g}\)
- **Elevation head**: \(y_1\)
- **Pressure head**: \(\frac{p_1}{\gamma}\)
- **Energy loss between sections 1 and 2**: \(h_{L,1-2}\)

**Symbols:**
- \(v\): Velocity
- \(g\): Gravitational acceleration
- \(\gamma\): Specific weight of fluid
- \(y\): Elevation
- \(z\): Pressure
- \(h\): Energy loss
- \(L\): Length
In open channel flow (as opposed to pipe flow) the free water surface is exposed to the atmosphere so that $p/\gamma$ is 0, leaving:

\[
\frac{v_1^2}{2g} + y_1 + z_1 = \frac{v_2^2}{2g} + y_2 + z_2 + h_{L,1-2}
\]
SPECIFIC ENERGY

\[ \frac{v^2}{2g} + y = E \]  
(Eqn. 4.6)

E is the specific energy.
\( q = vy \) Where \( q \) is the flow per unit width.

Eqn. 4.6 becomes:

\[
\frac{q^2}{2gy^2} + y = E \quad \text{(Eqn. 4.8)}
\]
*Note q is constant.
CRITICAL DEPTH, $y_c$

- The depth of flow corresponding to the minimum $E$ is the critical depth, $y_c$

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

or

$$\frac{v}{\sqrt{gy_c}} = 1$$
Froude Number, $F$

\[ \frac{v}{\sqrt{gy_c}} \]

is known as the Froude Number, $F$

- If $F = 1$, $y = y_c$ and flow is critical.
- If $F < 1$, $y > y_c$ and flow is subcritical.
- If $F > 1$, $y < y_c$ and flow is supercritical.
- $F$ is independent of the slope of the channel, $y_c$ dependent only on $Q$. 
Froude Number

\[ F = \frac{V}{\sqrt{gd_h}} \]

- For non-rectangular channels
- \( d_h \) is the hydraulic depth, defined as the area divided by the top width, \( t \). \( d_h = A/t \).
- Table 4.9 contains the properties of typical non-rectangular channels.
WHAT IS UNIFORM FLOW?

- If flow characteristics at a point are unchanging with time the flow is said to be **steady**.
- If flow properties are the same at every location along the channel, the flow is **uniform**.
- The energy line, water surface and channel bottom are all parallel in uniform flow.
In natural flow situations flow is generally non-steady and non-uniform.

In designing most channels steady, uniform flow is assumed with the channel design being based on some peak or maximum discharge.