Course Topics

1. Pumps, Turbines and Pipe networks
   – Moment of Momentum Revisited
   – Types of pumps and turbines and uses
   – Pump-pipe systems, networks

2. Open Channel Flow
   – Specific Energy and Rapid Transitions
   – Hydraulic Jumps
   – Slowly varying flow
   – Open channel control structures

3. Introduction to Surface Water Hydrology
   – Hydrologic Cycle
   – Rainfall, Runoff and Design Events

4. Hydraulic Structures
   – Dams, weirs, spillways
   – Culverts
   – Safety and Effects of Hydraulic Structures
Notre Dame as an Example, 2016
Notre Dame as Example, Yesterday
Outline of Hydrology Section

1. Introduction, Surface water processes, and Watersheds
3. Curve Numbers and Runoff
4. Site Characteristics and Time of Concentration
5. Design Rainfall
6. Introduction to Hydrographs
7. TR-55 Tabular Hydrograph Method
8. TR-55 Graphical Peak Discharge Method
9. Rational Method
What is Hydrology?

- Science dealing with the quantities, movement, properties (e.g. contaminants) and use of earth’s fresh water, and its effect on natural and human systems
  - Surface water
  - Ground water
  - Frozen (snow and ice)
  
  Examples:
  - Severity and frequency of droughts
  - Groundwater quality in agricultural areas
  - Rainfall variability
  - Soil and vegetation effects on hydrologic cycle
  - Pollution transport
- Falls under the broad heading of water resources
- Here, we will concentrate on determining the input flows for our hydraulic systems
  - Very closely linked to rainfall and runoff
  - Small regions studied here (easier)
The Hydrologic Cycle
Hydrology vs Hydraulics

• Much of hydrology is based on observations that are generalized to practice
  – What is the expected maximum rainfall over a 24 hour period?
    • For what return period? 1 year, 10 year, 100 year?
  – What will be the streamflow resulting from a given storm?
    • Peak value, time variation, relationship to total amount of rainfall
• Hydraulics tends to start from basic physical principles, then make approximations for practice
  – What will be the flow depth in a given channel for a given discharge?
    – Hydraulics tends to work with manmade systems
• Often, surface water hydrology provides inputs (max flow rate) for hydraulics (oversimplified explanation)
Important Processes for Surface Water Hydrology

• Rainfall
  – Geographic Location
  – Amount/Time/Intensity
  – Return Period

• Site Conditions
  – Size/Length
  – Gradient
  – Soil/Vegetation Type/Development/Moisture Content
Watersheds

• Areas of interest are often watersheds
  – Region that drains surface water to a given point
  – Small end: parking lot for drain design
  – Large end: Entire Mississippi basin for river at New Orleans

• Need to delineate watersheds for hydrologic analysis
  1. Identify upstream points dividing watersheds (peaks, ridges)
  2. Connect points to form watershed area

• Example
What is the watershed that drains to this location?
What is the watershed that drains to this location?

These streams are not part of the watershed.

These streams are part of the watershed.
Identify dividing lines between watersheds (peaks, ridges, saddle points)
Connect dividing lines to delineate watershed. Lines are perpendicular to contours going up valleys and run along the tops of ridges.
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TR-55 Manual

• Gives widely used engineering methods to compute both time variation of runoff and maximum runoff from small watersheds
• For unconfined flow in open channels, not sewers
• Two main methods
  1. Graphical Peak Discharge Method
  2. Tabular Hydrograph Method
• Fairly long, but do not need to print entire manual, particularly not Appendix A (soil groups)
• Very useful worksheets for computations
Do Not Use TR-55 Manual if

- Sewer flow is important for the watershed
- Complete time records of stream flow are required
- Runoff from snowmelt or rain on frozen ground are important
- Complex storage routing is in place
- The 24 hour storm is not applicable to the watershed of interest
Overall Procedure for All Surface Water Hydrology Here

1. Rainfall (inches, cm)
   – May or may not need to include time varying aspects

2. Runoff (inches, cm)
   – Less than Rainfall
   – Strongly dependent on watershed properties

3. Streamflow or Discharge (ft³/s, m³/s)
   – Design Flows
   – Function of runoff, watershed size, slope, ...
Beware of Frankenstein Units!

• Many formulas in hydrology will only work in one specific set of (often strange) units. For example:
  – Time in days
  – Area in Acres, or Square Miles
  – Distance in feet, or inches
  – Volumes in acre-feet
  – Rainfall rates in inches/hour

• If equations are computed in the wrong set of units, they will not make sense

• **Write down on your formula sheets, the proper units for each equation, where applicable.**
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Runoff

• Divided into surface runoff (fast), groundwater runoff (slow) (also interflow – usually small)
• Here, we will look largely at surface runoff to streams, channels, and rivers
• Amount and time variation of surface runoff-produced streamflow is often the design input for hydraulics
  – Surface runoff reduced by interception, depression storage, soil-moisture replenishment, groundwater infiltration
• Surface runoff collects in streams, other channels
  – Often develop stage (water level) –discharge curves to obtain records of stream flow
    • e.g. Sharp crested weir has strong elevation-discharge relationship
Relationships between Rainfall and Runoff

- Need a method to estimate runoff for ungauged sites (most) – amount and time variation
  - SCS (Soil Conservation Service, now Natural Resources Conservation Service) methods
  - Dependent on
    - Land Use,
    - Antecedent Soil Moisture,
    - Soil Type, ABCD – sand/gravel (A) through clay (D)
    - Rainfall Amount
  1. Gives Curve Number: Runoff is simple function of Precipitation and Curve Number
  2. Combine with Synthetic Unit Hydrograph to get predicted hydrograph from given storm

- Useful for sites where basin response time scale is similar to or larger than storm time scales
  - If basin response time is very small, use different methods
Runoff Magnitudes

- SCS Procedures use data-driven methods to find amount of runoff compared to amount of rainfall

- Need to know:
  - Catchment properties: Uses, soil types, antecedent moisture
  - Storm Characteristics: rainfall amounts in given time periods
  - Runoff can be quite nonlinear compared to rainfall
Antecedent Moisture Conditions and Soil Groups

• Often use AMC II (average moisture for general design)
  • Runoff less for low soil moisture, greater for higher soil moisture
• Runoff higher for low infiltration rate (C-D), runoff lower for easy infiltration to groundwater (A-B)

<table>
<thead>
<tr>
<th>Antecedent Moisture Condition (AMC)</th>
<th>Soil Conditions</th>
<th>Hydrologic Soil Group</th>
<th>Descriptions of the Hydrologic Soil Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMC I</td>
<td>Low moisture; soil is dry</td>
<td>A</td>
<td>Soils with high infiltration rate, even when wet; mostly sand and gravel</td>
</tr>
<tr>
<td>AMC II</td>
<td>Average moisture; common for design</td>
<td>B</td>
<td>Soils with moderate rate of infiltration when wet; coarse to fine texture</td>
</tr>
<tr>
<td>AMC III</td>
<td>High moisture; heavy rain in last few days</td>
<td>C</td>
<td>Soils with slow infiltration rate when wet; moderately fine to fine texture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>Soils with low infiltration rate when wet; clay or soil with high water table</td>
</tr>
</tbody>
</table>
## Some SCS Runoff Curve Numbers for AMC II

<table>
<thead>
<tr>
<th>Cover Description</th>
<th>% Impervious</th>
<th>Hydrologic Soil Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cover Type and Hydrologic Condition</strong></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Open space (parks, cemeteries, etc.):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor condition (grass cover &lt; 50%)</td>
<td>68</td>
<td>79</td>
</tr>
<tr>
<td>Fair condition (grass cover 50%–75%)</td>
<td>49</td>
<td>69</td>
</tr>
<tr>
<td>Good condition (grass cover &gt; 75%)</td>
<td>39</td>
<td>61</td>
</tr>
<tr>
<td>Impervious areas (parking lots, etc.)</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Urban districts:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial and business</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Industrial</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>Residential areas (by average lot size):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/8 acre or less (town houses)</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>1/4 acre</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>1/3 acre</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>1/2 acre</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>1 acre</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>2 acre</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Newly graded areas (no vegetation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural land or open land (good condition)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fallow land (crop residue)</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>Row crops (contoured)</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Small grain crops (contoured)</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>Pasture, grassland, or range</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Meadow (mowed for hay)</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Woods–grass combination (orchards)</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Woods</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>
Curve Numbers and Runoff

- Curve Number (0-100) gives a measure of the tendency toward runoff (higher gives more runoff)
- Find Soil-moisture deficit $S$ (inches) at beginning of runoff
- If Cumulative Rainfall $P$ (inches) large enough, runoff occurs
- Procedure to estimate CN from Figs. 2-2, 2-3, 2-4, Table 2, TR-55

\[
S = \frac{1000 - 10 \times CN}{CN}
\]

If $P > 0.2S$

\[
R = \frac{(P - 0.2S)^2}{P + 0.8S}
\]

Otherwise

$R = 0$
Simple Runoff Examples

1. If we have a storm that provides 1 inch of rain for a meadow with Soil Group A and AMC II, what runoff will it produce?
2. Do the same thing for a residential area with 1/8 acre lots and soil group D
Example 1

• For a meadow with soil group A and AMC II, the curve number is CN=30 (quite low)
• Gives S = 23.3 inches (very high)
• P= 1 inch
• 0.2*S = 4.6 inches
• Since P<0.2*S, Runoff R=0
• No direct runoff from this storm, but after some time, the groundwater base flow will increase
Example 2

• For a residential area with 1/8 acre lots, AMC II, and soil group D, CN=92 (high runoff)
• Gives $S = 0.86$ inches (low)
• $P = 1$ inch
• $0.2*S = 0.174$ inches
• Since $P > 0.2*S$

Runoff $R = 0.41$ inches

• If we double precipitation to 2 inches, we find $R = 1.24$ inches

• *So runoff is very nonlinear*
Why is Runoff Nonlinear?

• When rain first starts, it is very easy for water to infiltrate into the ground, get trapped on leaves, and just make things wet
  – Initial rainfall does not lead to runoff

• After some time, it is harder for rainfall to make its way into groundwater, etc., and runoff begins
  – Some rainfall still makes it to GW etc

• After a long time, saturated conditions mean that all additional rainfall leads to runoff
SCS Runoff with CN and Rainfall

Runoff does not begin until a certain amount of rainfall has occurred.

Curves on this sheet are for the case $I_a = 0.2S$, so that

$$R = \frac{(P - 0.2S)^2}{P + 0.8S}$$

All additional rainfall becomes runoff here.

Runoff does not begin until a certain amount of rainfall has occurred.
Curve Numbers When Table 2-2 Assumptions do not Apply

- When assumptions do not apply (e.g. different % impervious), can make modified CN
- Follow Fig 2-2 flow chart
- Ex: Type B Soil, ½ acre lots, 35% connected impervious, good condition, 5 inches rainfall – does not fit assumptions of Table 2-2
  - Find CN for open space, type B
  - Use Fig 2-3 to find CN for 35% impervious
  - Equations in Appendix F
When Table 2-2 Assumptions do not Apply (cont.)

• Sometimes impervious area is not all “connected”
  – Not continuous along drainage path

• May need to use Fig. 2-4
  – Type B soil; good condition open area; 22% impervious; unconnected impervious area is 50% of total impervious area

• Follow flow chart, Fig. 2-2
Overall Runoff from Composite Watersheds

• For regions with more than one type of land cover/land use, make Overall CN from individual CN

• Area Weighted
  – Can use Worksheet 2, TR-55

• Example: A catchment has 10 acres of previous example, and 10 acres Soil type C, residential ¼ acre lots, 38% impervious

• For some purposes (Tabular Hydrograph Method), you will have to divide overall watershed into subareas, and compute composite CN for each
How to Find the Amount of Runoff Generated During Various Portions of a Storm

- Say we have a storm hyetograph, site conditions
- We can now find the total runoff produced
- To use unit hydrographs, need the time variation of runoff produced
- How?
Runoff Time Variation

• Simple solution to problem of runoff time variation

1. At each time $t_j$, find cumulative runoff from cumulative precipitation up to that time, $R_j$

2. Runoff generated during that time interval of $t_{j-1}$ to $t_j$ is the difference between runoffs $dR_j = R_j - R_{j-1}$

3. These $dR_j$ values are inputs into the unit hydrograph for that watershed
Runoff Time Variation Example

- Say we have an urban industrial district with soil group B, AMC II
- Rainfall is

<table>
<thead>
<tr>
<th>Time (hrs)</th>
<th>Rainfall (inches/hour)</th>
<th>Cumulative Rainfall (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>2-4</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>4-6</td>
<td>0.5</td>
<td>1.6</td>
</tr>
<tr>
<td>6-8</td>
<td>0.3</td>
<td>2.2</td>
</tr>
<tr>
<td>8-10</td>
<td>0.3</td>
<td>2.8</td>
</tr>
<tr>
<td>10-12</td>
<td>0.1</td>
<td>3.0</td>
</tr>
<tr>
<td>12-14</td>
<td>0.05</td>
<td>3.1</td>
</tr>
</tbody>
</table>

![Rainfall Graph](attachment:image.png)
Cumulative Runoff

- From Chart, CN = 88
- $S = 1.36$ inches
- From cumulative rainfall, find cumulative runoff from

If $P > 0.2S$

$$R = \frac{(P - 0.2S)^2}{P + 0.8S}$$

Otherwise

$R = 0$

No runoff from first rainfall interval
Incremental Runoff

• Incremental Runoff found from difference in runoffs produced between two successive time intervals

• These are the inputs for a unit hydrograph

• These are not the time variation of actual discharge in a stream
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Time of Concentration

• One of the most important factors of synthetic unit hydrographs is the \textit{Time of Concentration}, $T_c$
  – Time for runoff to reach design point from most distant location in watershed
  – Three phases: add together to get total time
    1. Sheet flow (very shallow over planar surface)
    2. Shallow concentrated flow (gutter)
    3. Open-channel flow (stream)
  – Or, single empirical equation based on flow length, watershed slope, and land use/soil type
  – \textit{All have Frankenstein combinations of units: be extremely careful}
Sheet Flow

- Very shallow depths only (<~0.1 ft)
  - Flow across parking lot, grass, etc.
  - Usually confined to first 100 feet or so

\[
T_{t_1} = \left[ 0.007(nL)^{0.8} \right] / \left( P_2^{0.5} S_0^{0.4} \right)
\]

\( T_{t_1} \)  time in hours

\( n \)  Manning's sheet flow roughness

\( L \)  Flow length in feet

\( P_2 \)  2-year, 24-hr rainfall (inches)

\( S_0 \)  Dimensionless slope (.01 etc)

<table>
<thead>
<tr>
<th>Surface Description</th>
<th>Range of n Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete, bare soil</td>
<td>0.011</td>
</tr>
<tr>
<td>Grass</td>
<td></td>
</tr>
<tr>
<td>short grass</td>
<td>0.15</td>
</tr>
<tr>
<td>dense grass</td>
<td>0.24</td>
</tr>
<tr>
<td>Bermuda grass</td>
<td>0.41</td>
</tr>
<tr>
<td>Range (natural)</td>
<td>0.13</td>
</tr>
<tr>
<td>Fallow, no residue</td>
<td>0.05</td>
</tr>
<tr>
<td>Cultivated soils</td>
<td></td>
</tr>
<tr>
<td>residue cover &lt;20%</td>
<td>0.06</td>
</tr>
<tr>
<td>residue cover &gt;20%</td>
<td>0.17</td>
</tr>
<tr>
<td>Woods</td>
<td></td>
</tr>
<tr>
<td>light underbrush</td>
<td>0.4</td>
</tr>
<tr>
<td>dense underbrush</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Shallow Concentrated Flow

• When sheet flow converges to a more consolidated flow in lower areas
  – Gutters, etc.

\[ V = 16.1345S_0^{0.5} \text{ Unpaved} \]
\[ V = 20.3282S_0^{0.5} \text{ Paved} \]

\( V \) Flow velocity in ft/s
\( S_0 \) Dimensionless slope
\( T_{t_2} = \frac{L_{t_2}}{V} \)

\( L_{t_2} \) distance in feet
\( T_{t_2} \) in seconds if \( L_{t_2} \) in feet

You will be given lengths, slopes, etc., for any problems
Channel Flow

• Exactly as before – use units of feet for bankfull depth

• Need to specify some general flow depth – does not change with flow rate

$$V = \frac{1.49}{n} R_{h}^{2/3} S_{0}^{1/2}$$

- $V$ in ft/s
- $R_{h}$ in ft
- $S_{0}$ dimensionless slope
- $T_{t_3} = \frac{L_{t_3}}{V}$
- $L_{t_3}$ in ft
- $T_{t_3}$ in seconds
Overall Time of Concentration

- Total time of Concentration
  \[ T_c = T_{t1} + T_{t2} + T_{t3} \]
- Make sure that units are the same when adding
- Worksheet 3
Alternate Time of Concentration

- For small watersheds (<2,000 acres)
- Based on regression of data

\[
T_c = \frac{L^{0.8} (S + 1)^{0.7}}{(1140 \times (100S_0)^{0.5})}
\]

- \(T_c\) in hours
- \(L\) Length in ft from most distant point in watershed
- \(S\) Soil moisture deficit calculated from Curve Number CN (NOT SLOPE!!)
- \(S_0\) Average slope