CE 374 K – Hydrology

Runoff Processes

Daene C. McKinney
Watershed

- Watershed
  - Area draining to a stream
  - Streamflow generated by water entering surface channels
  - Affected by
    - Physical, vegetative, and climatic features
    - Geologic considerations
    - Stream Patterns
  - Dry periods
    - Flow sustained from groundwater (baseflow)
Streamflow

- **Atmospheric Water**
  - Evapotranspiration
  - Precipitation

- **Subsurface Water**
  - Infiltration
  - Groundwater

- **Surface Water**
Streamflow Hydrograph

- Centroid of Precipitation
- Basin Lag
- Peak
- Time of Rise
- Rising Limb
- Recession Limb
- Inflection Point
- Baseflow Recession
- Baseflow
- Beginning of Direct Runoff
- End of Direct Runoff
- Time
Volume of Storm Runoff

• Depends on several factors
  – Large watersheds – previous storm events
  – Small watersheds – independent of previous storm

• Rainfall available for runoff – 3 parts
  – Direct runoff
  – Initial loss (before direct runoff begins)
  – Continuing loss (after direct runoff)
Baseflow Separation

• Depletion of groundwater during this period

• Continuity equation

\[
\frac{dS}{dt} = I(t) - Q(t)
\]

\[
dS = -Q_0 e^{-\frac{(t-t_0)}{k}} dt
\]

\[
S(t) = kQ(t)
\]

\[
Q(t) = \text{flow at time } t
\]

\[
Q_0 = \text{flow at time } t_0
\]

\[
k = \text{decay constant } [T]
\]
Baseflow Separation Techniques

- **Straight – line method**
  - Draw a horizontal line segment (A-B) from beginning of runoff to intersection with recession curve
Baseflow Separation Techniques

- **Fixed Base Method**
  - Draw line segment $(A - C)$ extending baseflow recession to a point directly below the hydrograph peak
  - Draw line segment $(C - D)$ connecting a point $N$ time periods after the peak

\[ N = A^{0.2} \]
Baseflow Separation Techniques

- **Variable Slope Method**
  - Draw line segment (A-C) extending baseflow recession to a point directly below the hydrograph peak
  - Draw line segment (B-E) extending baseflow recession backward to a point directly below the inflection point
  - Draw line segment (C-E)
Loss Estimation: Phi – Index Method

• Effective (excess) rainfall
  – Rainfall that is not retained or infiltrated
  – Becomes direct runoff
  – Excess rainfall hyetograph (excess rainfall vs time)

• Losses (abstraction)
  – Difference between total and excess rainfall hyetographs

• Phi – Index
  – Constant rate of loss yielding excess rainfall hyetograph with depth equal to depth of direct runoff

\[ r_d = \sum_{m=1}^{M} (R_m - \phi \Delta t) \]

- \( r_d \) = depth of direct runoff
- \( R_m \) = observed rainfall
- \( \phi \) = Phi index
- \( M \) = # intervals of rainfall contributing to direct runoff
- \( \Delta t \) = time interval
- \( m \) = interval index
### Example – Phi Index method

<table>
<thead>
<tr>
<th>Time</th>
<th>Observed Rain (in)</th>
<th>Flow (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:30</td>
<td></td>
<td>203</td>
</tr>
<tr>
<td>9:00</td>
<td>0.15</td>
<td>246</td>
</tr>
<tr>
<td>9:30</td>
<td>0.26</td>
<td>283</td>
</tr>
<tr>
<td>10:00</td>
<td>1.33</td>
<td>828</td>
</tr>
<tr>
<td>10:30</td>
<td>2.2</td>
<td>2323</td>
</tr>
<tr>
<td>11:00</td>
<td>0.2</td>
<td>5697</td>
</tr>
<tr>
<td>11:30</td>
<td>0.09</td>
<td>9531</td>
</tr>
<tr>
<td>12:00</td>
<td></td>
<td>11025</td>
</tr>
<tr>
<td>12:30</td>
<td></td>
<td>8234</td>
</tr>
<tr>
<td>1:00</td>
<td></td>
<td>4321</td>
</tr>
<tr>
<td>1:30</td>
<td></td>
<td>2246</td>
</tr>
<tr>
<td>2:00</td>
<td></td>
<td>1802</td>
</tr>
<tr>
<td>2:30</td>
<td></td>
<td>1230</td>
</tr>
<tr>
<td>3:00</td>
<td></td>
<td>713</td>
</tr>
<tr>
<td>3:30</td>
<td></td>
<td>394</td>
</tr>
<tr>
<td>4:00</td>
<td></td>
<td>354</td>
</tr>
<tr>
<td>4:30</td>
<td></td>
<td>303</td>
</tr>
</tbody>
</table>

**Shoal Creek 1981**

- **Total Rainfall Hyetograph**
- **Direct Runoff Hydrograph**

Find: Constant rate of loss yielding excess rainfall hyetograph with depth equal to depth of direct runoff.

- No direct runoff until after 9:30
- And little precip after 11:00

**Basin area A = 7.03 mi²**
Example – Phi Index Method (Cont.)

• Estimate baseflow (straight line method)
  – Constant = 400 cfs
Example – Phi Index Method (Cont.)

- Calculate Direct Runoff Hydrograph
  - Subtract 400 cfs

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Rainfall</th>
<th>Streamflow</th>
<th>Time</th>
<th>Direct Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>in</td>
<td>cfs</td>
<td>1/2 hr</td>
<td>cfs</td>
</tr>
<tr>
<td>24-May</td>
<td>8:30 PM</td>
<td>0.15</td>
<td>203</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9:00 PM</td>
<td>0.26</td>
<td>246</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9:30 PM</td>
<td>1.33</td>
<td>283</td>
<td>428</td>
<td>770,400</td>
</tr>
<tr>
<td></td>
<td>10:00 PM</td>
<td>2.2</td>
<td>828</td>
<td>1</td>
<td>1,923</td>
</tr>
<tr>
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<td>10:30 PM</td>
<td>2.08</td>
<td>2323</td>
<td>2</td>
<td>5,297</td>
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<tr>
<td></td>
<td>11:00 PM</td>
<td>0.2</td>
<td>5697</td>
<td>3</td>
<td>9,131</td>
</tr>
<tr>
<td></td>
<td>11:30 PM</td>
<td>0.09</td>
<td>9531</td>
<td>4</td>
<td>10,625</td>
</tr>
<tr>
<td>25-May</td>
<td>12:00 AM</td>
<td>11025</td>
<td></td>
<td>5</td>
<td>7,834</td>
</tr>
<tr>
<td></td>
<td>12:30 AM</td>
<td>8234</td>
<td></td>
<td>6</td>
<td>3,921</td>
</tr>
<tr>
<td></td>
<td>1:00 AM</td>
<td>4321</td>
<td></td>
<td>7</td>
<td>1,846</td>
</tr>
<tr>
<td></td>
<td>1:30 AM</td>
<td>2246</td>
<td></td>
<td>8</td>
<td>1,402</td>
</tr>
<tr>
<td></td>
<td>2:00 AM</td>
<td>1802</td>
<td></td>
<td>9</td>
<td>830</td>
</tr>
<tr>
<td></td>
<td>2:30 AM</td>
<td>1230</td>
<td></td>
<td>10</td>
<td>313</td>
</tr>
<tr>
<td></td>
<td>3:00 AM</td>
<td>713</td>
<td></td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3:30 AM</td>
<td>394</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4:00 AM</td>
<td>354</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4:30 AM</td>
<td>303</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total** 7.839E+07 Volume of direct runoff

\[
r_d = \frac{V_d}{A} = \frac{7.839 \times 10^7 \text{ ft}^3}{7.03 \text{ mi} \times 5280^2 \text{ ft}^2} = 4.80 \text{ in}
\]

Depth of direct runoff
Example – Phi Index Method (Cont.)

• Neglect all precipitation intervals that occur before the onset of direct runoff (before 9:30)

• Select $R_m$ as the precipitation values in the 1.5 hour period from 10:00 – 11:30

$$r_d = \sum_{m=1}^{M} (R_m - \phi \Delta t) = \sum_{m=1}^{3} (R_m - \phi 3 \times 0.5)$$

\[4.80 = (1.33 + 2.20 + 2.08 - \phi \times 3 \times 0.5)\]

$\phi = 0.54$ in

$\phi \Delta t = 0.54 \times 0.5 = 0.27$ in
Example – Phi Index Method (Cont.)
SCS Curve Number Method

• SCS Curve Number (CN) method
  – estimates excess precipitation as a function of
    • cumulative precipitation
    • soil cover
    • land use, and
    • antecedent moisture

• Developed for small basins (< 400 sq. mi.)
• Classify soils into four types
• Simple to use
• Converts basin storage into something simpler and more manageable (a “curve number” CN)
Losses – SCS Method

- Total rainfall separated into 3 parts:
  - Direct runoff
  - Continuing Loss
  - Initial Loss

- SCS Assumption

\[
\frac{\text{Actual Storage}}{\text{Potential Storage}} = \frac{\text{Actual Runoff}}{\text{Potential Runoff}}
\]

\[
\frac{(P - I_a) - P_e}{S} = \frac{P_e}{P - I_a}
\]

- Solve for Rainfall Excess

\[
P_e = \frac{(P - I_a)^2}{P - I_a + S}
\]

\[
P = \text{Total Rainfall}
\]

\[
P_e = \text{Excess Rainfall (Runoff)}
\]

\[
I_a = \text{Initial Loss}
\]

\[
F_a = \text{Continuing Loss}
\]

\[
S = \text{Maximum Watershed Storage}
\]
SCS Method (Cont.)

- Experiments showed
  \[ I_a = 0.2S \]

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

\[ S = \frac{1000}{CN} - 10 \]  
(American Units; 0 < CN < 100)

\[ S = \frac{25400}{CN} - 254CN \]  
(SI Units; 30 < CN < 100)
SCS Method (Cont.)

- $CN$ depends on previous (antecedent) rainfall
- Normal conditions, AMC(II)
- Dry conditions, AMC(I)
  \[ CN(I) = \frac{4.2CN(II)}{10 - 0.058CN(II)} \]
- Wet conditions, AMC(III)
  \[ CN(III) = \frac{23CN(II)}{10 + 0.13CN(II)} \]

<table>
<thead>
<tr>
<th>AMC Group</th>
<th>5-day antecedent rainfall (in)</th>
<th>Dormant season</th>
<th>Growing season</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>&lt; 0.50</td>
<td>&lt; 1.4</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>0.5 -- 1.1</td>
<td>1.4 -- 2.1</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>&gt; 1.1</td>
<td>&gt; 2.1</td>
<td></td>
</tr>
</tbody>
</table>
SCS Method (Cont.)

- $CN$ depends on soil conditions

<table>
<thead>
<tr>
<th>Group</th>
<th>Minimum Infiltration Rate (in/hr)</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.3 – 0.45</td>
<td>High infiltration rates. Deep, well drained sands and gravels</td>
</tr>
<tr>
<td>B</td>
<td>0.15 – 0.30</td>
<td>Moderate infiltration rates. Moderately deep, moderately well drained soils with moderately coarse textures</td>
</tr>
<tr>
<td>C</td>
<td>0.05 – 0.15</td>
<td>Slow infiltration rates. Soils with layers, or soils with moderately fine textures</td>
</tr>
<tr>
<td>D</td>
<td>0.00 – 0.05</td>
<td>Very slow infiltration rates. Clayey soils, high water table, or shallow impervious layer</td>
</tr>
</tbody>
</table>
Example - SCS Method (1)

- Rainfall: 5 in.
- Area: 1000-acres
- Soils:
  - Class B: 50%
  - Class C: 50%
- Antecedent moisture: AMC(II) - Normal
- Land use
  - Residential
    - 40% with 30% impervious cover
    - 12% with 65% impervious cover
  - Paved roads: 18% with curbs and storm sewers
  - Open land: 16%
    - 50% fair grass cover
    - 50% good grass cover
  - Parking lots, etc.: 14%
Example (SCS Method 1, Cont.)

<table>
<thead>
<tr>
<th>Land use</th>
<th>Hydrologic Soil Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Residential (30% imp cover)</td>
<td>20 72 14.40</td>
</tr>
<tr>
<td>Residential (65% imp cover)</td>
<td>6 85 5.10</td>
</tr>
<tr>
<td>Residential (65% imp cover)</td>
<td>6 90 5.40</td>
</tr>
<tr>
<td>Roads</td>
<td>9 98 8.82</td>
</tr>
<tr>
<td>Open land: good cover</td>
<td>4 61 2.44</td>
</tr>
<tr>
<td>Open land: Fair cover</td>
<td>4 69 2.76</td>
</tr>
<tr>
<td>Parking lots, etc</td>
<td>7 98 6.86</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>50</strong></td>
</tr>
</tbody>
</table>

\[ CN = 40.38 + 43.40 = 83.8 \]
Example (SCS Method 1 Cont.)

- **Average AMC**
  
  \[
  CN = 83.8 \quad S = \frac{1000}{CN} - 10
  \]

  \[
  S = \frac{1000}{83.8} - 10 = 1.93 \text{ in}
  \]

  \[
  P_e = \frac{(P - 0.2S)^2}{P + 0.8S} = \frac{(5 - 0.2*1.93)^2}{5 + 0.8*1.93} = 3.25 \text{ in}
  \]

- **Wet AMC**

  \[
  P_e = \frac{(P - 0.2S)^2}{P + 0.8S} = \frac{(5 - 0.2*0.83)^2}{5 + 0.8*0.83} = 4.13 \text{ in}
  \]
Example (SCS Method 2)

- Given $P$, CN = 80, AMC(II)
- Find: Cumulative abstractions and excess rainfall hyetograph

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Cumulative Rainfall (in)</th>
<th>Cumulative Abstractions (in)</th>
<th>Cumulative Excess Rainfall (in)</th>
<th>Excess Rainfall Hyetograph (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$P$</td>
<td>$I_a$</td>
<td>$F_a$</td>
<td>$P_e$</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4.65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>5.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>5.36</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Example (SCS Method – 2)

• Calculate storage

\[ S = \frac{1000}{CN} - 10 = \frac{1000}{80} - 10 = 2.50 \text{ in} \]

• Calculate initial abstraction

\[ I_a = 0.2S = 0.2 \times 2.5 = 0.5 \text{ in} \]

• Initial abstraction removes
  - 0.2 in. in 1\textsuperscript{st} period (all the precip)
  - 0.3 in. in the 2\textsuperscript{nd} period (only part of the precip)

• Calculate continuing abstraction from SCS method equations

\[ F_a = \frac{S(P - I_a)}{(P - I_a + S)} = \frac{2.5(P - 0.5)}{(P + 2.0)} \]

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Cumulative Rainfall (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>P</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.9</td>
</tr>
<tr>
<td>3</td>
<td>1.27</td>
</tr>
<tr>
<td>4</td>
<td>2.31</td>
</tr>
<tr>
<td>5</td>
<td>4.65</td>
</tr>
<tr>
<td>6</td>
<td>5.29</td>
</tr>
<tr>
<td>7</td>
<td>5.36</td>
</tr>
</tbody>
</table>
Example (SCS method –2, Cont.)

- Cumulative abstractions can now be calculated

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Cumulative Rainfall (in)</th>
<th>Cumulative Abstractions (in)</th>
<th>$F_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$</td>
<td>$I_a$</td>
<td>$F_a$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.9</td>
<td>0.5</td>
<td>0.34</td>
</tr>
<tr>
<td>3</td>
<td>1.27</td>
<td>0.5</td>
<td>0.59</td>
</tr>
<tr>
<td>4</td>
<td>2.31</td>
<td>0.5</td>
<td>1.05</td>
</tr>
<tr>
<td>5</td>
<td>4.65</td>
<td>0.5</td>
<td>1.56</td>
</tr>
<tr>
<td>6</td>
<td>5.29</td>
<td>0.5</td>
<td>1.64</td>
</tr>
<tr>
<td>7</td>
<td>5.36</td>
<td>0.5</td>
<td>1.65</td>
</tr>
</tbody>
</table>

$$F_a = \frac{2.5(P - 0.5)}{(P + 2.0)}$$

$F_a (2 \text{ hr}) = \frac{2.5(0.9 - 0.5)}{(0.9 + 2.0)} = 0.34 \text{ in}$
Example (SCS method 2, Cont.)

- Cumulative excess rainfall can now be calculated
- Excess Rainfall Hyetograph can be calculated

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Cumulative Rainfall (in)</th>
<th>Cumulative Abstractions (in)</th>
<th>Cumulative Excess Rainfall (in)</th>
<th>Excess Rainfall Hyetograph (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$</td>
<td>$I_a$</td>
<td>$F_a$</td>
<td>$P_e$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.2</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.9</td>
<td>0.5</td>
<td>0.34</td>
<td>0.06</td>
</tr>
<tr>
<td>3</td>
<td>1.27</td>
<td>0.5</td>
<td>0.59</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>2.31</td>
<td>0.5</td>
<td>1.05</td>
<td>0.76</td>
</tr>
<tr>
<td>5</td>
<td>4.65</td>
<td>0.5</td>
<td>1.56</td>
<td>2.59</td>
</tr>
<tr>
<td>6</td>
<td>5.29</td>
<td>0.5</td>
<td>1.64</td>
<td>3.15</td>
</tr>
<tr>
<td>7</td>
<td>5.36</td>
<td>0.5</td>
<td>1.65</td>
<td>3.21</td>
</tr>
</tbody>
</table>
Example (SCS method 2, Cont.)

Rainfall (in)  | Time (hour) |
--- | --- |
0.0 | 0 |
0.5 | 1 |
1.0 | 2 |
1.5 | 3 |
2.0 | 4 |
2.5 | 5 |
3.0 | 6 |
3.5 | 7 |

Excess Rainfall

Rainfall Hyetographs
Time of Concentration

• Different areas of a watershed contribute to runoff at different times after precipitation begins

• Time of concentration
  – Time at which all parts of the watershed begin contributing to the runoff from the basin
  – Time of flow from the farthest point in the watershed