City of Springfield

Calculation of Runoff

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Rolla, Missouri
Session Objectives

- Discuss precipitation data used in hydrologic analysis.
- Review techniques for determining runoff.
- Abstractions.
- Time of Concentration
- Critical Duration Analysis
Hydrologic Analysis

- How much rainfall runs off?
- How long does it take for the rainfall-runoff transformation and translation to the point of interest occur?
- The key input elements in hydrologic analysis are:
  - Rainfall
  - Watershed physical characteristics
Precipitation

- Rainfall frequency data are published on-line by the National Oceanic and Atmospheric Administration (NOAA). Missouri data is included in Atlas 14, Volume 8.
- Historical observed data records are also maintained by NOAA.
- Probable Maximum Precipitation estimates are available in National Weather Service Hydrometeorological Report 51 (HMR 51).
- Doppler estimates are available from the National Weather Service, 1995-present.
- Missouri Agriculture Weather, Mizzou.
- Midwestern Regional Climate Center, Illinois State Water Survey.
- Unofficial data – local networks, Weather Underground, CoCoRahs, etc.
- City of Springfield rain gage network.
Representation of Rainfall

- Total depth.
- Incremental depth or intensity per time period.
- Cumulative mass curve.
- Depth or Intensity hyetograph.
- Intensity-Duration-Frequency curves.
- Depth-Duration-Frequency curves.
- Doppler Radar Imagery.
Precipitation

Tables RO-1, Depth-Duration-Frequency and RO-2, Intensity-Duration-Frequency, provide design rainfall data.

If needed, for durations falling between tabulated values, depths/intensities can be computed using linear interpolation.
### Table RO-1

**Rainfall Depth-Duration-Frequency Relationships from Rainfall Frequency Atlas of the Midwest**  
(Huff and Angel 1992)

<table>
<thead>
<tr>
<th>Duration</th>
<th>1-year</th>
<th>2-year</th>
<th>5-year</th>
<th>10-year</th>
<th>25-year</th>
<th>50-year</th>
<th>100-year</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 min</td>
<td>0.36</td>
<td>0.45</td>
<td>0.57</td>
<td>0.67</td>
<td>0.79</td>
<td>0.88</td>
<td>0.98</td>
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<tr>
<td>10 min</td>
<td>0.63</td>
<td>0.79</td>
<td>1.01</td>
<td>1.17</td>
<td>1.38</td>
<td>1.54</td>
<td>1.72</td>
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<tr>
<td>15 min</td>
<td>0.81</td>
<td>1.02</td>
<td>1.29</td>
<td>1.50</td>
<td>1.77</td>
<td>1.98</td>
<td>2.21</td>
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<tr>
<td>30 min</td>
<td>1.11</td>
<td>1.39</td>
<td>1.77</td>
<td>2.05</td>
<td>2.43</td>
<td>2.72</td>
<td>3.03</td>
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<tr>
<td>1 hr</td>
<td>1.41</td>
<td>1.77</td>
<td>2.25</td>
<td>2.61</td>
<td>3.08</td>
<td>3.45</td>
<td>3.84</td>
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<tr>
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<td>1.74</td>
<td>2.19</td>
<td>2.78</td>
<td>3.22</td>
<td>3.80</td>
<td>4.26</td>
<td>4.74</td>
</tr>
<tr>
<td>3 hr</td>
<td>1.92</td>
<td>2.41</td>
<td>3.07</td>
<td>3.55</td>
<td>4.20</td>
<td>4.70</td>
<td>5.24</td>
</tr>
<tr>
<td>6 hr</td>
<td>2.25</td>
<td>2.83</td>
<td>3.59</td>
<td>4.16</td>
<td>4.92</td>
<td>5.51</td>
<td>6.14</td>
</tr>
<tr>
<td>12 hr</td>
<td>2.61</td>
<td>3.28</td>
<td>4.17</td>
<td>4.83</td>
<td>5.71</td>
<td>6.39</td>
<td>7.12</td>
</tr>
<tr>
<td>18 hr</td>
<td>2.82</td>
<td>3.54</td>
<td>4.50</td>
<td>5.22</td>
<td>6.17</td>
<td>6.90</td>
<td>7.69</td>
</tr>
<tr>
<td>24 hr</td>
<td>3.00</td>
<td>3.77</td>
<td>4.79</td>
<td>5.55</td>
<td>6.56</td>
<td>7.34</td>
<td>8.18</td>
</tr>
<tr>
<td>48 hr</td>
<td>3.30</td>
<td>4.14</td>
<td>5.25</td>
<td>6.07</td>
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<td>8.97</td>
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<td>7.90</td>
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<td>9.85</td>
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<td>5.21</td>
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<td>7.45</td>
<td>8.70</td>
<td>9.68</td>
<td>10.77</td>
</tr>
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<td>9.13</td>
<td>10.49</td>
<td>11.52</td>
<td>12.61</td>
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</tbody>
</table>
# IDF Rainfall Data

**Table RO-2**

Rainfall Intensity-Duration-Frequency Relationships from Rainfall Frequency Atlas of the Midwest (Huff and Angel 1992)

<table>
<thead>
<tr>
<th>Duration</th>
<th>Intensity of Precipitation (in/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-year</td>
</tr>
<tr>
<td>5 min</td>
<td>4.32</td>
</tr>
<tr>
<td>10 min</td>
<td>3.78</td>
</tr>
<tr>
<td>15 min</td>
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<td>30 min</td>
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<td>2 hr</td>
<td>0.87</td>
</tr>
<tr>
<td>3 hr</td>
<td>0.64</td>
</tr>
<tr>
<td>6 hr</td>
<td>0.38</td>
</tr>
<tr>
<td>12 hr</td>
<td>0.22</td>
</tr>
<tr>
<td>18 hr</td>
<td>0.16</td>
</tr>
<tr>
<td>24 hr</td>
<td>0.13</td>
</tr>
<tr>
<td>48 hr</td>
<td>0.07</td>
</tr>
<tr>
<td>72 hr</td>
<td>0.05</td>
</tr>
<tr>
<td>120 hr</td>
<td>0.03</td>
</tr>
<tr>
<td>240 hr</td>
<td>0.02</td>
</tr>
</tbody>
</table>
2.0 Precipitation, cont’d

Rainfall Temporal Distributions

Huff’s Quartile Distributions:

- 1st Quartile, Duration ≤ 6 hrs
- 2nd Quartile, 6 hrs < Duration ≤ 12 hrs
- 3rd Quartile, 12 hrs < Duration ≤ 24 hrs
- 4th Quartile, 24 hrs < Duration
2.0 Precipitation cont’d

Guidelines for Storm Duration presented in Table RO-4.

A critical duration analysis is required.

- Durations are varied and the duration that produces the maximum peak discharge is considered the critical duration. Standard durations evaluated are 1-hr, 2-, 3-, 6-, 12-, and 24-hours.

- The critical duration may be different between pre- and post-project conditions.
2.0 Precipitation cont’d

- Recall that the peak discharge from a watershed occurs when the entire watershed is simultaneously contributing runoff to the point of interest (assuming uniform intensity rainfall).

- This is fairly simple with the rational method, hydrograph methods are more complex.
3.0 Rational Method

\[ Q = C_f C I A \]

where:
- \( Q \) is the flowrate in cubic feet per second
- \( C_f \) is a frequency adjustment factor
- \( C \) is the runoff coefficient
- Product of \( C_f \) and \( C \) cannot exceed 1.0
- \( i \) = Rainfall intensity in inches per hour
- \( A \) = Contributing area in acres
  - Entire watershed
  - Directly connected Impervious area

\( 1 \text{ ac-in/hr} = 1.008 \text{ cu-ft/sec}, \) no units conversion needed.
Rational Method

Assumptions

- Frequency of peak discharge is the same as the rainfall intensity.
- Duration of peak intensity rainfall is at least as long as the time of concentration of the watershed.
- There is no appreciable storage in the watershed.
Rational Method

More assumptions

- The runoff coefficient “C” represents uniform, average conditions within the watershed.
- Rainfall is uniformly distributed in time and space over the watershed.
- Applicable to watershed areas less than 200 acres per ASCE guidelines. A more practical limit is around 40 acres.
“The misunderstanding that the time of concentration equals duration of the rainfall rather than the rainfall intensity averaging time has resulted in the development of detention/retention sizing methodologies that are likely to significantly underestimate storage volumes.” From “Urban Surface Water Management”, S. Walesh, 1989
3.3 Time of Concentration

- Two components
- Overland flow, Kerby-Hathaway Equation

\[ t_o = 0.83 \left( \frac{N_k L}{S^{0.5}} \right)^{0.47} \]
3.3 Time of Concentration

The time it takes for the hydraulically most remote point in the watershed to contribute runoff to the point of interest.

Two components –
- Overland flow, shallow laminar flow, sheet flow
- Channel flow, turbulent, accumulated flow
Kerby-Hathaway Equation

\[ t_o = \text{overland flow time, minutes.} \]
\[ N_k = \text{roughness coefficient} \]
\[ L = \text{overland flow length, ft.} \]
\[ S = \text{slope of overland flow element, ft./ft.} \]

- \( L = 200 \text{ ft. maximum for undeveloped} \)
- \( L = 150 \text{ ft. maximum for developed} \)
Time of Concentration

Channel flow time, Kirpich Equation

\[ t_t = 0.0078 \left( \frac{L}{S^{0.5}} \right)^{0.77} \]
Kirpich Equation

\[ t_t = \text{travel time in minutes} \]
\[ L = \text{travel distance in ft.} \]
\[ S = \text{slope in ft./ft.} \]
Time of concentration

- Hydrograph Methods
  - \( t_c = t_o + t_t \)

- For Rational Method, typically use only the Kirpich Equation
4.0 Hydrograph Methods

Recommended models

- HEC-1
- HEC-HMS
- Hydraflow, Hydrology Studio
- TR-20*
- TR-55*

*Only versions that allow user input of rainfall distributions and perform acceptable channel and reservoir routing
Definitions

- Abstractions – interception, depression storage, infiltration, evapotranspiration.
- Excess precipitation - rainfall that is not taken up by abstractions – Runoff!
- Unit hydrograph - the hydrograph resulting from 1” of uniformly distributed, uniform intensity, excess precipitation.
Model Requirements

- SCS Curve Number method for abstractions
- Hydrograph transformations include kinematic wave and SCS dimensionless unit hydrograph transformations
  - Kinematic wave preferred for urban areas
- Channel Routing
  - Kinematic wave
  - Muskingum-Cunge
- Reservoir Routing
  - Modified Puls
  - Level Pool
SCS Curve Number

SCS Curve Number Technique for Abstractions

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

- **Q** = Runoff in inches
- **P** = Precipitation, inches
- **S** = Maximum potential watershed retention, inches
Maximum potential watershed retention in inches is computed as:

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

Where CN is the curve number.
Curve Numbers

Table RO-8 and RO-9

Table Values vs. Actual Impervious Area Values:

- Sampled older lots (constructed in 1970’s, 1980’s) ¼ acre in size, % impervious ranged from 28% to 36%.
- Sampled newer lots (constructed in last 10 years) ¼ acre in size, % impervious ranged from 40% to 48%

Verify the percent impervious area!
Limits on Curve Numbers

<table>
<thead>
<tr>
<th>HSG</th>
<th>Minimum</th>
<th>Central</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>25</td>
<td>51-68</td>
<td>77</td>
</tr>
<tr>
<td>B</td>
<td>48</td>
<td>62-77</td>
<td>86</td>
</tr>
<tr>
<td>C</td>
<td>65</td>
<td>70-84</td>
<td>91</td>
</tr>
<tr>
<td>D</td>
<td>73</td>
<td>77-88</td>
<td>94</td>
</tr>
</tbody>
</table>

FROM TR-55 Table 2-2c
Antecedent Runoff Condition

- The ARC (formerly the Antecedent Moisture Condition) is a confidence interval relationship for Curve Numbers.
  - ARC-I represents the 90% condition
  - ARC-III represents the 10% condition
Curve Number Hydrology, State of the Practice, ASCE, 2009
Curve Number Hydrology, State of the Practice, ASCE, 2009
SCS Curve Number Technique

- Hydrologic Soil Groups, NRCS has updated some mapping and the hydrologic soil groups have changed from previously mapped.
- Areas disturbed during construction have soil structure altered, therefore the infiltration characteristics have been altered.
SCS Curve Numbers

Based on

- Hydrologic Soil Group (HSG)
- Hydrologic condition
- Land cover type
- Antecedent Runoff Conditions (previously Antecedent Moisture Conditions)
4.2 Kinematic Wave Method

- Element Representation
  - Overland Flow Plane
  - Collector Channel
  - Main Channel

- Roughness Coefficients Table RO-12
4.3 SCS Unit Hydrograph

The unit hydrograph peak flowrate is a function of area and time to peak

\[ q_p = 484 \frac{A}{T_p} \]

- \( q_p \) = unit hydrograph peak cfs/inch
- \( A \) = area in square miles
- \( T_p \) = time to peak, hours
SCS Dimensionless Unit Hydrograph

$q$ = DISCHARGE AT TIME $t$
$q_p$ = PEAK DISCHARGE
$Q_a$ = ACCUMULATED VOLUME AT TIME $(t)$
$Q$ = TOTAL VOLUME
$t$ = A SELECTED TIME
$T_p$ = TIME FROM BEGINNING OF RISE TO THE PEAK

OR $Q_a/Q$

$\frac{q}{q_p}$
SCS Unit Hydrograph

Time to Peak

\[ T_p = \frac{\Delta D}{2} + 0.6t_c \]

- \( \Delta D \) = Duration of excess rainfall (should be approximately 0.133 \( t_c \)), hours
- \( t_c \) = time of concentration, hours
- 0.6 \( t_c \) is defined as the basin lag
Runoff is computed by multiplying the ordinates of the unit hydrograph by the depth of excess precipitation. Multiple periods of excess rainfall are lagged appropriately and summed for the composite runoff hydrograph.
4.4 Channel Routing

- Kinematic Wave
- Muskingum-Cunge
5.0 Alternative Methods

USGS Urban Regression Equations

Limitations

- Watersheds relatively unaffected by storage or diversions
- Areas of 0.25 to 40 square miles
- BDF of 0 to 12
- Percent impervious 1% to 40%
Urban Regression Equations

Based on Impervious Percentage
\[ Q_2 = 224 \, A^{0.793} \, I^{0.175} \]

Basin Development Factor
\[ Q_2 = 801 \, A^{0.747} \, (13 - \text{BDF})^{-0.400} \]
6.0 Offsite and Adjacent Runoff

- Offsite upstream
  - Assume fully developed per current City Zoning.
  - For flood control assume without detention unless otherwise approved by the City.
  - Possible exception is a watershed with a regional basin or one known to operate properly that is under control of the City.
6.0 Offsite and Adjacent Runoff

- Verify impacts on adjacent properties:
  - Particularly on flood stages, both upstream and downstream.
  - Discharges at potentially erosive velocities.
  - Location of discharge compared to pre-project conditions.
  - Diversions.
Summary

- Rainfall
- Abstractions
- Time of Concentration
- Rational Method
- Hydrograph Methods
- Regression Equations
QUESTIONS?