Water Resources Review (Hydraulics and Hydrology)

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Water Resources Engineering

• Water Resources Engineering is that branch of civil engineering concerned with maximizing the social and economic benefit associated with the world’s water resources while minimizing the adverse environmental impacts due to modifications to the natural environment.

The Science of Hydrology

• Hydrology is that natural science that is concerned with the occurrence, properties, distribution, and movement of water in the natural and man-made environment.

The Science of Hydraulics

• Hydraulic engineering is a sub-discipline of civil engineering concerned with the flow and conveyance of fluids (water). Related to the design of pipelines, water distribution systems, drainage facilities (including bridges, dams, channels, culverts, levees, storm sewers), and canals.
Hydrologic Cycle

The Watershed or Basin

- Area of land that drains to a single outlet and is separated from other watersheds by a drainage divide.
- Rainfall that falls in a watershed will create runoff to that watershed outlet.
- All other rainfall falling outside a basin will not affect the runoff response.

Major Hydrologic Processes

- **Precipitation** (measured at rain gage)
- **Evaporation or ET** (loss to atmosphere)
  - Water budget methods, Evaporation Pans
- **Infiltration** (loss to subsurface)
- **Overland flow** (sheet flow toward stream)
- **Streamflow** (measured at stream gage)
- **Ground water flow** (Monitoring Wells)

MEASUREMENTS

<table>
<thead>
<tr>
<th>Precipitation</th>
<th>Depth (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporation or ET</td>
<td>Depth (inches)</td>
</tr>
<tr>
<td>Infiltration</td>
<td>Infiltration Rate (in/hr)</td>
</tr>
<tr>
<td>Overland flow</td>
<td>cfs</td>
</tr>
<tr>
<td>Streamflow</td>
<td>cfs</td>
</tr>
</tbody>
</table>
Hydrograph Dynamics

- Area under curve is the volume of runoff.
- Peak Flow and time to peak relate to watershed.
- Time Base is time that flow exceeds baseflow.

Hydrograph

- The total hydrologic response of a watershed to a storm event can be represented graphically through a hydrograph which represents the total flow leaving the watershed over time.

Volume of Runoff = Area x depth

Rainfall observation = 0.5 inches

Area in sq.miles

Outflow

Time Base

Time
Estimating Mean Aerial Precipitation from Point Values

- Arithmetic
- Thiessen polygon method
- Isohyetal method
- Distance Weighing

Arithmetic Mean

\[
\frac{0.55 + 0.87 + 2.33 + 5.40 + 1.89}{5} = 2.21 \text{ in.}
\]


Thiessen Polygon Method

Let \( A_1 = 10 \text{ sq. miles} \), \( A_2 = 15 \text{ sq. miles} \), \( A_3 = 20 \text{ sq. miles} \), \( A_4 = 10 \text{ sq. miles} \), \( A_5 = 13 \text{ sq. miles} \)

Then Mean Areal Precipitation:

\[
\frac{(10 \times 0.55 + 15 \times 0.87 + 20 \times 2.33 + 10 \times 5.4 + 13 \times 1.89)}{(10 + 15 + 20 + 10 + 13)} = 2.1135 \text{ inches}
\]


Isohyetal Method

Isohyets or Isopleths: Lines of equal precipitation rates

### Normal Ratio Method

\[
P^* = \frac{P_A^* \sum_{j=1}^{N} \frac{P_j}{P_{AJ}}}{N}
\]

- \(P^*\) = unknown precipitation
- \(P_A^*\) = annual precip. at sta *
- \(P_j\) = precipitation at sta. J
- \(P_{AJ}\) = annual precip. at sta. J
- \(N\) = # of stations (known precipitation)

### Example

<table>
<thead>
<tr>
<th>Name</th>
<th>ISOTYPE</th>
<th>Average Range (inches)</th>
<th>Area (Sq.Miles)</th>
<th>Area x Average Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>02-0.50</td>
<td>0.375</td>
<td>3</td>
<td>1.125</td>
</tr>
<tr>
<td>A2</td>
<td>1.00-1.50</td>
<td>0.500</td>
<td>10</td>
<td>5.000</td>
</tr>
<tr>
<td>A4</td>
<td>2.00-2.50</td>
<td>1.500</td>
<td>25</td>
<td>37.500</td>
</tr>
<tr>
<td>A5</td>
<td>2.00-1.89</td>
<td>1.845</td>
<td>7</td>
<td>13.915</td>
</tr>
<tr>
<td>A6</td>
<td>3.00-4.00</td>
<td>3.000</td>
<td>15</td>
<td>45.000</td>
</tr>
<tr>
<td>A7</td>
<td>4.00-5.00</td>
<td>4.500</td>
<td>17</td>
<td>76.500</td>
</tr>
<tr>
<td>A8</td>
<td>5.00-5.40</td>
<td>5.200</td>
<td>2</td>
<td>10.400</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>68</td>
<td>133.810</td>
</tr>
</tbody>
</table>

### NWS Method

\[
P^* = \frac{\sum_{j=1}^{N} P_j W_j}{\sum W_j}
\]

- \(P^*\) = unknown precipitation
- \(P_j\) = precipitation at sta. j
- \(W_j\) = 1/D^2
- \(D^2 = X^2 + Y^2\)
- \(N\) = # stations (known precip)

The normal annual rainfall at stations A, B, C and D in a basin are 31.88, 26.61, 30.03 and 36.22 inches respectively. In the year 1975, the station D was inoperative and the stations A, B and C recorded annual precipitations of 35.87, 28.44 and 31.45 respectively.

Estimate the rainfall at station D in that year.

\[
P_D = (36.22/3)\left[\sum \frac{X^2}{31.88} + \frac{Y^2}{26.61} + \frac{Z^2}{30.03}\right] + 31.45
\]

\(= 39.12\) inches
**Return Period**

- Return period ($T_r$) is defined as the average number of years between occurrences of a hydrologic event with a specified magnitude or greater.
- Rainfall – depth and duration are important
- Exceedance probability: $1/T_r$

**Risk Calculations**

- Probability of exceedance: $1/T_r$
- Example
  - A rainfall event occurs 4 times in 100 years
    - $T_r = 25$
    - Probability of exceedance = $1/25 = 0.04$
- Risk = $1 - (1 - 1/T_r)^n$
- Theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size of storm area at a particular geographical location at a certain time of year (Hansen, 1987) – Probable Maximum Precipitation

**Design Return Period**

- Determine the hydrologic risk associated with a flood that occurs 3 times in 100 years. The life of the project is fixed as 30 years.
  - $T_r = 100/3 = 33.3$ years
  - Risk = $1 - (1 - 1/T_r)^n = 1 - (1 - 1/33.3)^{30} = 0.6$
- Selection of Design Return Period
  - Importance of the structure
  - Cost of the structure
  - Consequences of failure
- Typical Design Periods
  - Street Gutters – 2 – 5 years
  - Storm Sewers – 2 – 25 years
  - Detention Basins: 10 - 100 years
- Design return period can be found in local Drainage manuals
Evaporation Measurement

- Evaporation too measured as depth in inches
- Pan evaporation values are higher than the actual lake evaporation
  \[ E_{\text{actual}} = E_{\text{pan}} \times K \]
- \( K \) = Adjustment factor
- \( K \) ranges from 0.64 to 0.81
- Average Value = 0.7 (for the U.S.)

Rainfall Abstractions

- Abstractions – Losses
  - Collectively to that part of the rainfall that does not show up as runoff.
  - Abstractions – Interception, Surface Storage, Depression Storage, Evaporation, Transpiration, and infiltration.

Generally under design-storm conditions:
Evaporation and transpiration are negligible.

Infiltration loss

- Rainfall volume – infiltration volume = runoff volume
- Rainfall depth – infiltration depth = runoff depth

- Methods
  1. Practical Method
  2. Horton's infiltration model
  3. \( \Phi \)-index method (crude approximation of infiltration)
  4. Soil Conservation Service Method (Runoff Method/Curve Number Method)
Horton's model for infiltration capacity

- $f(t) = f_0 + (f_c - f_0)e^{-kt}$
  - $f$: infiltration capacity [in/hr]
  - $f_0$: initial infiltration capacity [in/hr]
  - $f_c$: ultimate infiltration capacity [in/hr]
  - $k$: exponential (time) decay constant [hr$^{-1}$]

- Cumulative infiltration depth [in or cm]:
  $$F(t) = \int_0^t f_0 + (f_c - f_0)e^{-ku} \, du$$
  $$= f_0 t + \frac{f_c - f_0}{k} [1 - e^{-kt}]$$

Example

- A watershed has the following Horton parameters:
  - $f_0 = 1.5$ in/hr
  - $f_c = 0.2$ in/hr
  - $k = 0.35$ hr$^{-1}$

  a) Determine infiltration capacity at $t=10$ min, 30 min, 6 hrs.

  b) Find total depth of infiltration during a 6-hr period, assuming rainfall intensity exceeds infiltration capacity.

Solution:

<table>
<thead>
<tr>
<th>Infiltration capacity: $f(t) = 0.2 + 1.3 \cdot e^{-0.35t}$ [in/hr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$</td>
</tr>
<tr>
<td>[hr]</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>1/6</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

- Cumulative depth:
  $$F(t) = \frac{f_0 t + \frac{f_c - f_0}{k} [1 - e^{-kt}]}$$
  $$= 0.20 t + 3.71 [1 - e^{-0.35t}]$$
  $$F(6) = 4.46 \text{ inches}$$
**φ-index method**

- **Definition:**
  - a constant infiltration capacity
  - units of [in/hr] or [cm/hr]

**Common problem:**
Determine the φ-index associated with a hyetograph and a known depth of runoff

- For a given month, a 300 acre lake has 15 cfs of inflow, 13 cfs of outflow, and a total storage increase of 16 ac-ft. A USGS gage next to the lake recorded a total of 1.3 inches of precipitation for the lake for the month. Assuming that the infiltration loss as insignificant for the lake, determine the evaporation loss in inches, over the lake for the month.

**Change in Storage**
\[ \Delta S = \text{Inflow} - \text{outflow} + \text{Precipitation} - \text{Evaporation} - \text{Infiltration} \]

- **Inflow** = 15 cfs (ft³/sec) = 15 * 60 (min) * 60 (hour) * 24 (day) * 30 (month)
  = 38880000 ft³
  = 38880000 / 43560 (ft² to acre) = 892.562 acre.ft
  = 892.562 / 300 (acres-waterspread of the lake) = 2.975 ft
  = 2.975 * 12 (ft to inches) = 35.70 inches
  = 35.70 inches

- **Outflow** = 13 cfs = 30.94 inches
- **P** = 1.3 inches

- **Change in storage** \( \Delta s = 16 \text{ ac.ft} = 16 \times 12 \text{ (inches to feet) / 300 acres} \)
  = 0.64 inches (increase in storage)

\[ E = \text{Inflow} - \text{outflow} + \text{precipitation} - \text{change in storage} \]

\[ = 35.7 - 30.94 + 1.3 - 0.64 \]
\[ = 5.42 \text{ inches} \]
**SCS Runoff Curve Number Procedure**

**Runoff**
- Factors that influence the rate and volume of runoff
  - Precipitation
  - Losses (Abstractions)
  - Existing Soil Moisture
  - Nature of Surface (soil type, cover ...)

**Soil Groups**
- **Group A Soils:** High infiltration (low runoff). Sand, loamy sand, or sandy loam. Infiltration rate > 0.3 inch/hr when wet.
- **Group B Soils:** Moderate infiltration (moderate runoff). Silt loam or loam. Infiltration rate 0.15 to 0.3 inch/hr when wet.
- **Group C Soils:** Low infiltration (moderate to high runoff). Sandy clay loam. Infiltration rate 0.05 to 0.15 inch/hr when wet.
- **Group D Soils:** Very low infiltration (high runoff). Clay loam, silty clay loam, sandy clay, silty clay, or clay. Infiltration rate 0 to 0.05 inch/hr when wet.
### Antecedent Moisture

<table>
<thead>
<tr>
<th>AMC</th>
<th>Dormant Season</th>
<th>Growing Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Less than 0.5</td>
<td>Less than 1.4</td>
</tr>
<tr>
<td>II</td>
<td>0.5 - 1.1</td>
<td>1.4 - 2.1</td>
</tr>
<tr>
<td>III</td>
<td>Over 1.1</td>
<td>Over 2.1</td>
</tr>
</tbody>
</table>

I: Drier than normal  
II: Average conditions (normal)  
III: Wetter than normal

### Runoff Curve Number

- Runoff Curve Number CN is a basin parameter with a range of 0 - 100.
- The value of CN depends on the hydrologic soil group, the soil cover type and condition, the percentage impervious areas in the watershed and the antecedent moisture condition of the soil.
- If the watershed is composed of several subareas with different CNs, a weighted average (based on area) or composite CN can be obtained for the whole watershed.

### Runoff Curve Numbers for Urban Areas

<table>
<thead>
<tr>
<th>Curve types and Hydrologic conditions</th>
<th>Curve Numbers for Hydrologic soil groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curve type</td>
<td>A</td>
</tr>
<tr>
<td>Fully developed urban areas (no vegetation established)</td>
<td></td>
</tr>
<tr>
<td>Open space (lawn, parks, golf courses, construction, etc.)</td>
<td></td>
</tr>
<tr>
<td>Poor condition (grass cover ≤ 30%)</td>
<td>88</td>
</tr>
<tr>
<td>Fair condition (grass cover 30% to 70%)</td>
<td>89</td>
</tr>
<tr>
<td>Good condition (grass cover &gt; 70%)</td>
<td>89</td>
</tr>
<tr>
<td>Image area - Paved streets, alleys, driveways, etc.</td>
<td>88</td>
</tr>
<tr>
<td>Street属 centered in grass or (including right-of-way)</td>
<td>98</td>
</tr>
<tr>
<td>Street属 centered in paved streets (including right-of-way)</td>
<td>98</td>
</tr>
<tr>
<td>Curve (including right-of-way)</td>
<td>86</td>
</tr>
<tr>
<td>Divided to divided right-of-way</td>
<td>72</td>
</tr>
<tr>
<td>Watershed located in water body</td>
<td>63</td>
</tr>
<tr>
<td>Watershed located in park (pavement area only)</td>
<td>70</td>
</tr>
<tr>
<td>Watershed located in any A, B, C, D (within or outside of park)</td>
<td>88</td>
</tr>
<tr>
<td>Watershed located in urban area (within or outside of park)</td>
<td>88</td>
</tr>
<tr>
<td>Watershed located in any A, B, C, D (within or outside of park)</td>
<td>88</td>
</tr>
</tbody>
</table>

This table is for AMC condition II

### SCS runoff CN Equation

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

- \( R(t) \) and \( P(t) \) are cumulative  
- If \( P < I_a \) then \( R(t) = 0.0 \)

\( I_a \): Initial Abstractions = 0.2 \( S \)

\( S = \frac{1000}{C N} - 10 \) basin retention
Agricultural Lands

<table>
<thead>
<tr>
<th>Curve type</th>
<th>Hydrologic condition</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasture, grassland or range—continuous</td>
<td>Poor</td>
<td>98</td>
<td>76</td>
<td>54</td>
<td>36</td>
</tr>
<tr>
<td>Forest for growing</td>
<td>Fair</td>
<td>86</td>
<td>64</td>
<td>42</td>
<td>24</td>
</tr>
<tr>
<td>Good</td>
<td>—</td>
<td>80</td>
<td>61</td>
<td>41</td>
<td>21</td>
</tr>
<tr>
<td>Meadow—continuous grass, protected from grazing and generally covered by hay</td>
<td>Poor</td>
<td>94</td>
<td>72</td>
<td>50</td>
<td>32</td>
</tr>
<tr>
<td>Forest for growing</td>
<td>Fair</td>
<td>82</td>
<td>60</td>
<td>38</td>
<td>20</td>
</tr>
<tr>
<td>Good</td>
<td>—</td>
<td>76</td>
<td>57</td>
<td>37</td>
<td>17</td>
</tr>
<tr>
<td>Pond—uncontrolled runoff with brush</td>
<td>Poor</td>
<td>88</td>
<td>66</td>
<td>44</td>
<td>26</td>
</tr>
<tr>
<td>Forest for growing</td>
<td>Fair</td>
<td>80</td>
<td>58</td>
<td>38</td>
<td>20</td>
</tr>
<tr>
<td>Good</td>
<td>—</td>
<td>74</td>
<td>55</td>
<td>35</td>
<td>15</td>
</tr>
<tr>
<td>Wood—grass cover laminated or wood furnishing</td>
<td>Poor</td>
<td>72</td>
<td>50</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Forest for growing</td>
<td>Fair</td>
<td>64</td>
<td>44</td>
<td>24</td>
<td>14</td>
</tr>
<tr>
<td>Good</td>
<td>—</td>
<td>58</td>
<td>40</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Farmstead—buildings, barns, documents, and open cultivated land</td>
<td>Poor</td>
<td>70</td>
<td>48</td>
<td>28</td>
<td>18</td>
</tr>
<tr>
<td>Forest for growing</td>
<td>Fair</td>
<td>62</td>
<td>42</td>
<td>22</td>
<td>12</td>
</tr>
<tr>
<td>Good</td>
<td>—</td>
<td>56</td>
<td>38</td>
<td>18</td>
<td>8</td>
</tr>
</tbody>
</table>

1. Average runoff condition, and $\beta = 0.25$.
2. Poor: <50% ground cover or highly eroded.
3. Fair: 50 to 75% ground cover and not highly eroded.
4. Good: >75% ground cover and not highly eroded.

Graphical Solution of Runoff equation

Antecedent Curve Numbers

<table>
<thead>
<tr>
<th>CN for AMC II</th>
<th>CN for AMC I</th>
<th>CN for AMC III</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>95</td>
<td>87</td>
<td>99</td>
</tr>
<tr>
<td>90</td>
<td>78</td>
<td>98</td>
</tr>
<tr>
<td>85</td>
<td>70</td>
<td>97</td>
</tr>
<tr>
<td>80</td>
<td>63</td>
<td>94</td>
</tr>
<tr>
<td>75</td>
<td>57</td>
<td>91</td>
</tr>
<tr>
<td>70</td>
<td>51</td>
<td>87</td>
</tr>
<tr>
<td>65</td>
<td>45</td>
<td>83</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>79</td>
</tr>
</tbody>
</table>

SCS CN method

- Advantages
  - Simple to use
  - Produces runoff directly
  - Includes land use effects
  - Incorporates AMC

- Disadvantages
  - Inductive
  - Method assumes $f$ approaches 0 instead of $f_c$
Composite CN

\[
\text{Composite CN} = \frac{CN_1 \times A_1 + CN_2 \times A_2 + CN_3 \times A_3}{(A_1 + A_2 + A_3)}
\]

Composite curve numbers

- Determine the composite for a watershed with 40\% residential (1/4-acre lots), 25\% open space good condition, 20\% commercial and business (85\% impervious) and 15\% industrial (72\% impervious) with soil groups C, D, C, D respectively.

- Solution:

<table>
<thead>
<tr>
<th>Land use (%)</th>
<th>Soil Group</th>
<th>Curve Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 %</td>
<td>C</td>
<td>83</td>
</tr>
<tr>
<td>25 %</td>
<td>D</td>
<td>80</td>
</tr>
<tr>
<td>20 %</td>
<td>C</td>
<td>94</td>
</tr>
<tr>
<td>15 %</td>
<td>D</td>
<td>93</td>
</tr>
</tbody>
</table>

Table (next slide)

- Composite
  - \[CN = 0.40(83) + 0.25(80) + 0.20(94) + 0.15(93) = 85.96 = 86\]
  - For the same watershed, calculate cumulative runoff and incremental runoff for three hours with precipitation of 2 inches in the first hour, 3 inches in the second hour and 1 inch in third hour.

Solution:

\[S = \frac{1000}{86} - 10 = 1.63\]
Ia = 0.2(S) = 0.2(1.63) = 0.33 inches

Steps
- Calculate cumulative precipitation
- Calculate cumulative runoff (use SCS curve number equation)
- Calculate incremental runoff

Runoff = \(\frac{(2-0.2\cdot1.63)^2}{(2+0.8\cdot1.63)} = 0.85\)

<table>
<thead>
<tr>
<th>Time</th>
<th>Cumulative rainfall</th>
<th>Cumulative Runoff</th>
<th>Incremental runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 inches</td>
<td>0.85 inches</td>
<td>0.85</td>
</tr>
<tr>
<td>2</td>
<td>5 inches</td>
<td>3.46 inches</td>
<td>2.61</td>
</tr>
<tr>
<td>3</td>
<td>6 inches</td>
<td>4.40 inches</td>
<td>0.94</td>
</tr>
</tbody>
</table>

### Watershed Response

- An initial understanding of a watershed can be developed by first examining the nature of the watershed response by measuring and characterizing the evapotranspiration and stream flow leaving the watershed.

### Determining Streamflow

The streamflow from a particular watershed can be measured at a particular gauging station by measuring the stage at the station and then converting the stage to an associated discharge using a rating curve.

### Influent Streams

(Arid and semi-arid regions)
Components of the storm hydrograph

- Storm hydrograph divided into
  - Direct runoff
  - Baseflow

Net rainfall = gross rainfall - infiltration

Baseflow separation

- Method 1:
  - Baseflow = constant, equal to lowest discharge before storm.

- Method 2:
  - Extend baseflow recession to under peak, then to the inflection point on the falling limb.

Example

- Consider the hyetograph and direct runoff hydrograph below.
  - The ϕ-index for the storm is 0.5 in/hr.
  a) Plot the excess rainfall hyetograph on the hydrograph
  b) Determine the total volume of runoff
  c) Determine the watershed area in [ac-ft]
The volume is determined from the hydrograph.

\[ V = (Q_1 + Q_3 + Q_5 + \ldots + Q_{25}) \times 2 \times 3600 \text{ [ft}^3] \]

- Volume = 32.76 \times 10^6 \text{ ft}^3
- Volume = 32.76 \times 10^6 \text{ ft}^3 \times (2.3 \times 10^{-5} \text{ ac/ft}^2)
- Volume = 750 \text{ ac-ft}

- Area of watershed:
- Depth of excess rain = 3.5 \text{ in} (from hyetograph)
\[
\text{Area} = \frac{\text{volume}}{\text{depth}} = \frac{750 \text{ ac-ft}}{3.5 \text{ in} \times 1/12 \text{ ft/in}} \\
\approx 750 \text{ ac-ft}
\]

Gross Rainfall = Depression Storage + Evaporation + infiltration + rainfall excess

Rainfall Excess = Gross Rainfall - Losses

In general, HYDROGRAPH can be divided into two parts: Direct Runoff Hydrograph DRH and Baseflow

DRH may include some interflow, whereas Baseflow is considered mostly from Contribution from groundwater
Definitions

• Lag Time (t_{lag}): The time from the center of mass of the rainfall excess to the peak of the hydrograph
• Time of rise or peak (T_{p}): The time from the start of rainfall excess to the peak of the hydrograph
• Time of Concentration (t_{c}): the time for wave (water) to propagate from the most distant point in the watershed to the outlet. One estimate is the time from the end of the rainfall excess to the inflection point of the hydrograph
• Time base (T_{b}): the total duration of the Direct Runoff hydrograph

Unit Hydrograph (UH)

• A concept proposed by Sherman in 1932
• Widely used in Hydrology
• Many Runoff Models use this approach (e.g. HEC-HMS)
• Inductive Models (derived from rainfall – runoff data collected)
• Direct runoff hydrographs can be generated if UH are available.

Unit Hydrograph

• Definition:
  – The storm hydrograph that results from 1 unit (1” or 1 cm) of rainfall excess (runoff) that occurs uniformly over a watershed during a duration T.
  – Derivation of the UH
  – Application of the UH
  – Translation or Transformation of the UH

Unit Hydrograph Assumptions

• The runoff is assumed to be due to overland flow.
• The runoff is uniformly distributed in time (runoff must be of short duration).
• The runoff is uniformly distributed in space (the area must not be too large).
• The watershed response is linear (linear superposition may be used).
• The watershed characteristics do not change with time.
• The unit volume under the UH is equal to 1.0
Derivation of the UH

- Separate the baseflow to determine the storm hydrograph
- Determine the volume of the storm hydrograph in depth (e.g. inches) by dividing the total runoff by the watershed area
- Divide the ordinates of the storm hydrograph by the depth
- Determine the duration by examining the rainfall excess hyetograph

Application of the UH

- Divide the runoff hyetograph into time increments equal to D
- Multiply the runoff amount for the first increment by each ordinate of the UH to produce the first incremental hydrograph
- Lag the computations by one time increment and repeat step 2 for each runoff increment
- Sum the individual incremental hydrographs to get the composite storm hydrograph

Given a 3 hr unit hydrograph is given in the following table. Find the direct runoff hydrograph resulting from a storm occurred for 9 hours with rainfall excess 2 inches, 3 inches and 1 inch in consecutive 3 hrs incrementally.

<table>
<thead>
<tr>
<th>Time (hrs)</th>
<th>First 3hrs RF (2 inches)</th>
<th>Second 3hrs RF (3 inches)</th>
<th>Third 3hrs (1 inch)</th>
<th>Total Response (cfs)</th>
</tr>
</thead>
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</tr>
<tr>
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<td>100</td>
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<td>2750</td>
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<td>450</td>
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<td>100</td>
<td>100</td>
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<td>15</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>100</td>
</tr>
</tbody>
</table>

Time(hr) 0 1 2 3 4 5 6 7 8
UH (cfs) 0 50 100 300 450 350 250 150 100

Time (hrs) 9 10 11
UH 50 25 0
Transformation of UH

1. Subtract both curves
2. Shift Curve by time $T$
3. Lag UHs by $D$ and sum
4. Subtract both curves
5. Scale new UH by multiplying by $D/T$

Transformation of UH

<table>
<thead>
<tr>
<th>Time</th>
<th>1st 2-hr</th>
<th>2nd 2-hr</th>
<th>3rd 2-hr</th>
<th>4th 2-hr</th>
<th>S-hyd</th>
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<td>100</td>
<td>250</td>
<td>350</td>
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Effective Rain Hyetographs

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<th>Time (hr)</th>
<th>In/hr</th>
<th>(Ft/sec)/inch</th>
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</tr>
<tr>
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<tr>
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</tr>
<tr>
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<td></td>
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<tr>
<td>8</td>
<td>0</td>
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</tr>
</tbody>
</table>

3 Hr Unit hydrograph

5 Hr Unit hydrograph
Effective rain in first three hours $R_1$ inches
Effective rain in second three hours $R_2$ inches

Losses

$\frac{\text{Ft}^3/\text{sec}}{\text{inch}} = \frac{\text{Volume}}{\text{Area}}$

Divide the ordinates by the Runoff depth

$\frac{x}{3}$

Direct runoff hydrograph (DRO) For the rainfall pattern

Field Data

Rainfall Hyetograph - Losses ($\Phi$-Index) = Effective Rainfall (Find Storm duration $D$ hours)

Storm Hydrograph - Base flow = DRH (Direct Runoff Hydrograph)

Divide each ordinate of DRH by Effective Rainfall depth to get the Dhr UH

Developing a DRH for a given storm by convolution

Deriving a $nD$ hr UH from the given Dhr UH (where $n$ is an integer)

Deriving a $T$ hr UH from a given Dhr UH using S curve procedure

When no data is available?

Synthetic UH

Total Runoff hydrograph = DRO + Baseflow
**TIME OF CONCENTRATION (TOC)**

- Time of Concentration is often defined as the time required for stormwater to flow from hydrologically most remote point in the basin (watershed) to the basin (watershed) outlet.

- Time required for all parts of a basin to contribute to discharge at outlet simultaneously

- Flow will reach at the time equal to time of concentration

**Time of Concentration (TOC)**

- **Lumped Approach** — **ONE EQUATION FOR WATERSHED**
  - Kirpich Equation
  - SCS Lag Method

- **Disaggregated Approach** — **SPLIT INTO TWO/THREE**
  - Overland Flow
    - Kinematic Wave Equation
    - SCS Nomograph Method
  - Gutter Flow
    - SCS Nomograph Method
  - Channel/Pipe Flow
    - Manning’s Equation