Evolution of the Colorado Urban Hydrograph Procedure (CUHP)

Ben Urbonas, P.E., D.WRE
History of Colorado Unit Hydrograph Procedure

1969 - Wright Water Engineers developed the original hand calculating procedure published in the Urban Storm Drainage Criteria Manual.

1972 - First computer version written by Ben Urbonas & Stewart McGuire, URS/Ken R. White Co. This was the first version of the one used today.
- Biggest challenge was to develop a numerical procedures to shape the unit hydrograph.)
1. Defined as runoff hydrograph shape **from 1-inch of runoff** that occurs uniformly **over unit of time**
2. Tributary area shape and characteristics determine the hydrograph shape
Possible Catchment Shape
1968 CUHP
Basic Equations in the USDCM

\[ t_p = C_t \left( L L_{ca} \right)^{0.3} \]

- \( t_p = \text{time to peak} \) of the unit hydrograph from midpoint of unit rainfall in hours
- \( L = \text{length along runoff flow path} \) to upstream limits of the catchment, in miles
- \( L_{ca} = \text{length along runoff flow path} \) to a point adjacent to the centroid of the catchment, in miles
- \( C_t = \text{coefficient reflecting time to peak} \)

\[ q_p = \frac{640 C_p}{t_p} \]

- \( q_p = \text{unit peak rate of runoff} \), in cfs per square mile
- \( C_p = \text{coefficient related to peak rate of runoff} \)

Guidance for selection of \( C_t \) and \( C_p \) coefficients was limited and required much user judgment. It was based on 1 to 3 runoff events in Harvard Gulch.
1977 - UDFCD adopts mainframe version of CUHP

Program modified for UDFCD use by Gary Walkovitz, URS Company

Also, modified to permit (by Ben Urbonas):
  a. Use of Horton’s Equation for infiltration rates,
  b. Vary infiltration rates by storm event,
  c. Overriding of default unit hydrograph shape,
  d. Generation output to file for interface with HEC FFA.
1979 - Major update and revision

Based on UDFCD/USGS rainfall/runoff data analysis
Calibrated to data for areas > 90 and < 2000 acres

CUHP was calibrated and revised using rainfall/runoff data:
* 8 different urban catchment conditions
* periods of data record ranged from 10 to 12 years
1979 CUHP Revision Approach

• In 1969 UDFCD contracted with USGS to collect paired Rainfall Runoff Data at 29 urban catchments of various characteristics

• In 1978 began to analyze paired Rainfall/Runoff data
  • Test data for errors and integrity (started with 29 catchments)
    • Cross-plot runoff volume vs. rainfall volume
    • Discard catchments that showed clear errors (only 8 remained)
      (e.g., runoff volume greater than rainfall volume)

• Process data through HEC-1 to develop unit hydrograph for each storm
  • Find average unit hydrograph for each catchment
  • Take off values for unit peak runoff, time to peak, W50%, W75%

• Search for relationships between Catchment parameters and above values

• Seek to relate UH parameters to Catchment parameters
Finding the New $C_t$

\[
\left( \frac{LL_{ca}}{\sqrt{S}} \right)
\]
The 1979 update for the first time provided quantitative guidance for selecting of $C_t$ and $C_p$ coefficients, relating them to imperviousness and area.
Waterway Slope is Now a Part of Updated CUHP

A need to **adjust steep slopes** was introduced
Weighted Waterway Slope

When the flow line slope varies along the drainageway, calculate a length-weighted:
1. Segment waterway into similar reaches
2. Correct the steep reach slopes using the correction coefficient in USDCM
3. Find weighted slope using the following equation:

\[
S = \left( \frac{L_1 \cdot S_1^{0.24} + L_2 \cdot S_2^{0.24} + \cdots + L_n \cdot S_n^{0.24}}{L_1 + L_2 + \cdots + L_n} \right)^{4.17}
\]

\(S\) = weighted catchment waterway slope in ft/ft
\(S_1, S_2, \ldots, S_n\) = slopes of individual reaches in ft/ft (after adjustments for steep slopes)
\(L_1, L_2, \ldots, L_n\) = lengths of corresponding reaches
1979 Version CUHP
Basic Time to Peak Equations

\[ T_p = 60 \, t_p + 0.5 \, t_u \]

\( T_p \) = time from beginning of unit rainfall to peak of hydrograph, in minutes
\( t_u \) = unit rainfall duration, in minutes

\[ C_p = P \cdot C_t \cdot A^{0.15} \]

\( C_p \) = unit hydrograph peaking coefficient
\( C_t \) = time to peak coefficient
\( P \) = peaking parameter
\( A \) = catchment area in square miles
1979 Version CUHP

Basic Equations that Did Not Change
Unit Peak Runoff and Peak Runoff

\[ q_p = \frac{640 \ C_p}{t_p} \]

\( q_p \) = unit peak rate of runoff, in cfs per square mile
\( C_p \) = coefficient related to peak rate of runoff

\[ Q_p = q_p \ A \]

\( Q_p \) = peak of the unit hydrograph, in cfs
\( A \) = area of catchment, in square miles
Unit Hydrograph
New Calibrated $C_t$ Coefficient

Equation and Coefficients of Curves

$$C_t = aI_a^2 + bI_a + c$$

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Unit Hydrograph
New Calibrated $C_p$ Coefficient

\[ C_p = PC_t A^{0.15} \]

\[ P = \text{peaking parameter from Figure} \]

\[ C_t = \text{coefficient} \]

\[ A = \text{catchment area, in square miles} \]
Unit Hydrograph
Calibrated UH widths at 50 & 75% of $Q_p$
Did not Change

\[ W @ 50\% = \frac{500}{q_p} \]

\[ W @ 75\% = \frac{260}{q_p} \]
Unit Hydrograph
Points that define UH shape and shaping it.

EFFECTIVE RAINFALL = 1 INCH IN $t_u$

1. $0.35 \times (\text{WIDTH} @ 50\%)$ OR $0.6 \times T_p$, WHICHEVER IS LESS

2. $0.45 \times (\text{WIDTH} @ 75\%)$ OR $0.424 \times T_p$ IF $0.6 \times T_p$ FOR (1) IS USED

ADJUST RECESSION LIMB UNTIL A UNIT HYDROGRAPH VOLUME IS ACHIEVED ($\pm 5\%$)

ASSUMED SHAPE

FINAL SHAPE
1979 Calibrated CUHP Recorded vs. Calculated Peak Flows

Recorded Peak Flow - cfs

Calculated Peak Flow - cfs

Acceptable Data

Questionable Data Points

1980 - 1981 Data
- H.G. @ C.C.Q. BLVD.
- H.G. @ H.P.
- Sanderson G. Trib.
Now that we have a calibrated Unit Hydrograph, let’s **CALIBRATE DESIGN STORMS**

Goal: Match peak/volume return period of design storm to that of storm hydrograph.
1979 Comparison of 30 minute Depths
73 years of Data, NOAA Atlas, UDFCD Manual

- Rainfall Depth in Inches
- Return Period in Years

Note: Practically no pattern relating rainfall to antecedent precipitation.
Original Pre-1979 Design Storm Procedure

1. User picked off 5-minute through 2-hour rainfall depths from isopluvial maps in USDCM
2. Plot a depth-duration curve
3. Segregated the values into 5-minute depths
4. Rearrange the 5-minute incremental depths into a “logical” temporal arrangement by placing the highest depth increment at 30 or 35 minutes from start of storm (depending on return period).
UDFCD Design Storm Analysis for 1979 Update

1. Calibrated CUHP model using recorded simultaneous rainfall/runoff data for a variety of land uses using the catchments used in developing updated CUHP
2. Used the calibrated CUHP to process three large storms with 5-minute data for each of the 73 years of historical rainfall data
3. Picked off the largest 73 runoff peaks and volumes
4. Performed Log-Pearson Type III frequency analysis
5. Results became the basis for comparing peaks and volumes between existing and new design storms
Post 1979 UDFCD Design Storms

1. Developed using 73 years of rainfall to model runoff peaks using calibrated unit hydrograph model

2. **2-hour duration** front-loaded **design storm pattern** was selected after studying 73 years of storm patterns
   • 3- and 6-hour duration storms were also developed for use with large catchments

3. **Design storm distributions were adjusted to produce runoff peaks** that best match runoff peaks at all return periods
Redesigned Design Storm Peaks vs. Runoff Peak Statistics (250 ac & 40% Imp.)
Redesigned Design Storm Peaks vs. Runoff Peak Statistics (90 ac & 97% Imp.)
History of Colorado Unit Hydrograph Procedure

1984 - Program converted to run of PCs by Young S. Yoon and Niem-Sheng Hsu, Boyle Engineering Corporation to:

• Write storm hydrograph file for use with UDSWM2-PC,
• Permit an estimate of hydrographs for small drainage areas using time of concentration to compare results of Rational Method.
2005 - Excel user interface developed by John-Michael O’Brien, UDFCD intern and John O’Brien, Wright Water Engineers to execute the C-language version of the software and to interface with EPA SWMM 5.0 software.

This included the “Converter” to translate older versions of CUHP and UDSWM input to run under the rewritten CUHP and EPA’s SWMM 5.0.
2005 Model Conceptual Relationships for Directly Connected Imperviousness

Runoff Areas:

- **DCIA** = directly (hydraulically) connected impervious
- **UIA** = unconnected impervious
- **RPA** = receiving pervious
- **SPA** = separate pervious
CUHP Runoff Calculations

CUHP calculates excess precipitation for each unit time step (e.g., 5-minute steps)

1. First calculated runoff from impervious areas
2. Splits by connected/unconnected ratios
3. Adds connected impervious portion to total runoff
4. Transfers unconnected runoff to the receiving pervious area and adds runoff depth to rainfall depth. Calculates runoff form receiving pervious area. Adds to total runoff
5. Calculates runoff from separate pervious area and adds to total runoff
CUHP Produces Storm Runoff Hydrograph

Steps to generate runoff hydrograph
1. Develop Unit Hydrograph based on:
   – Catchment area, shape, slope, imperviousness
2. Convert design rainfall into runoff for each time increment based on:
   – Imperviousness, soil/groundcover type, connected/unconnected character of catchment
3. Multiply unit hydrograph by runoff at each time increment of runoff
4. Sum all the resultant mini storm hydrographs to obtain design hydrograph
Convolution of Unit Hydrograph, Runoff Hyetograph into Storm Hydrograph

\[
\text{Unit Hydrograph} \ast \text{Hyetograph} = \sum \text{Mini hydrographs}
\]

Final storm hydrograph
(Sum of mini hydrographs)

Mini hydrographs
Finding the Storm Hydrograph:

Cross-multiply excess precipitation at each time step by ordinates of the Unit Hydrograph

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QUESTIONS?