Developing customized NRCS unit hydrographs for ungauged watersheds in Indiana, USA

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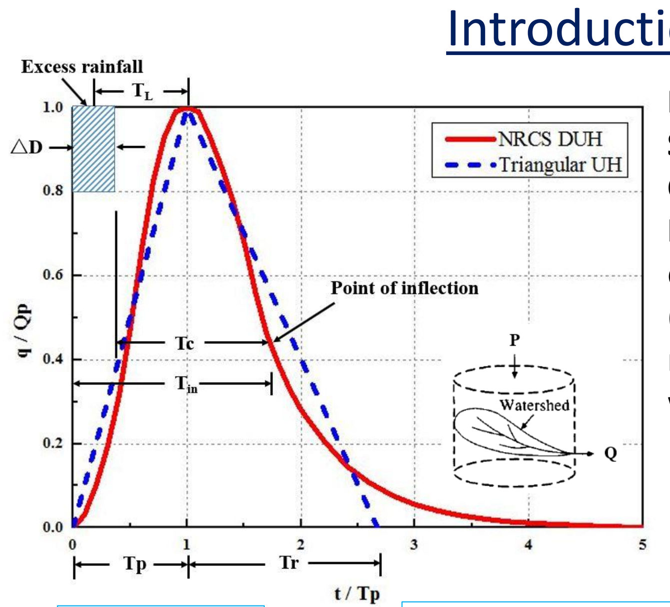
Introduction



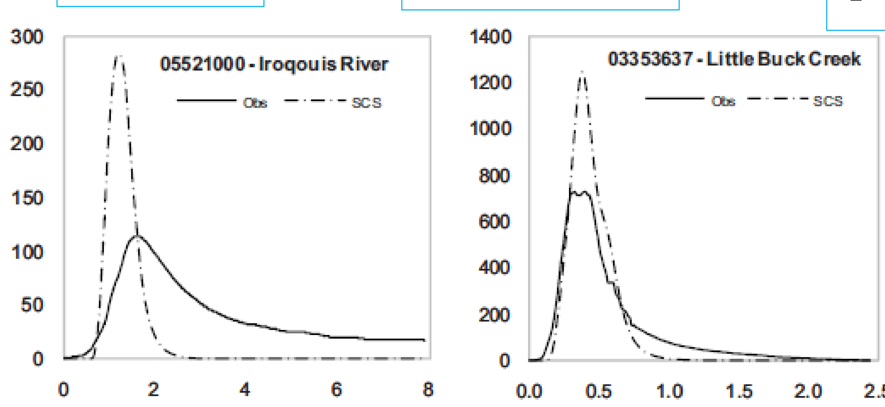
Natural Resources Conservation Service (NRCS, formerly the Soil Conservation Service, SCS) Unit Hydrograph (UH): developed by Victor Mockus (1957) and derived from many natural UHs from watersheds with different sizes and locations.

$$Q_P = PRF\frac{AQ}{T_P}$$

$$PRF = 484$$

$$T_P = T_L + \Delta D / 2$$

$$T_L = \frac{L^{0.8}(S+1)^{0.7}}{1900 \times Y^{0.5}}$$



Applications of NRCS UH method: overestimate Q_p and underestimate T_p of some watersheds in Indiana. [1]

Revisit NRCS Unit Hydrograph (UH)[2]

NRCS UH has been widely used all over the world:

- Comprehensive consideration of watershed characteristics
- Simplicity for use (i.e., lag time)

❑ Uncertainty in NRCS UH parameters (PRF & lag time)

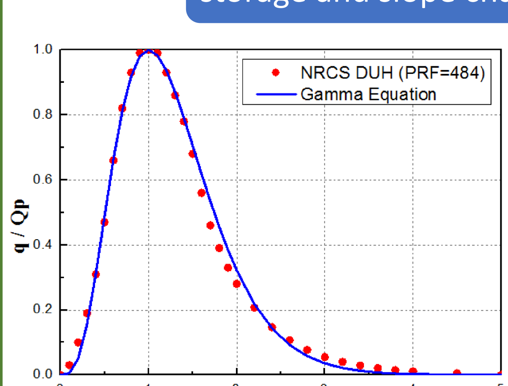
(1) Peak Rate Factor (PRF)

$$\frac{1}{2}Q_p(T_p + T_r) = A \cdot Q \Rightarrow Q_p = \left(645.33 \times \frac{2}{1 + T_r / T_p}\right)\frac{AQ}{T_p} = PRF\frac{AQ}{T_p}$$

1980: Delmarva UH with PRF of 284 was developed for coastal flatlands, which was the alternative to the standard 484 UH.

1980-2000: subsequent studies showed that the Delmarva UH may not be applicable for all coastal regions.

2007: NRCS stated that PRF ranges from below 100 to more than 600 for watersheds with different storage and slope characteristics.



	NRCS Dimensionless UH (tabulated values)	Probability Distribution Function (Gamma Equation)
✓	Easy to use	Easy and efficient to use; more accurate and more adaptable
X	One size fits all; discrete values; subjective errors of trials	Lack of physical meaning

$$\frac{q}{Q_P} = e^{\left(1 - \frac{t}{T_P}\right)m}\left(\frac{t}{T_P}\right)^m$$

where: m = fn (PRF)

(2) Lag Time

Limitations:

- perform well in small urban basins less than 3 $mile^2$
- developed based on the data from limited areas
- developed many years ago, hence cannot be adapted to future conditions that might occur in a watershed

$$T_C = 0.0078L^{0.77}Y^{-0.385}$$ (Kirpich, 1940)

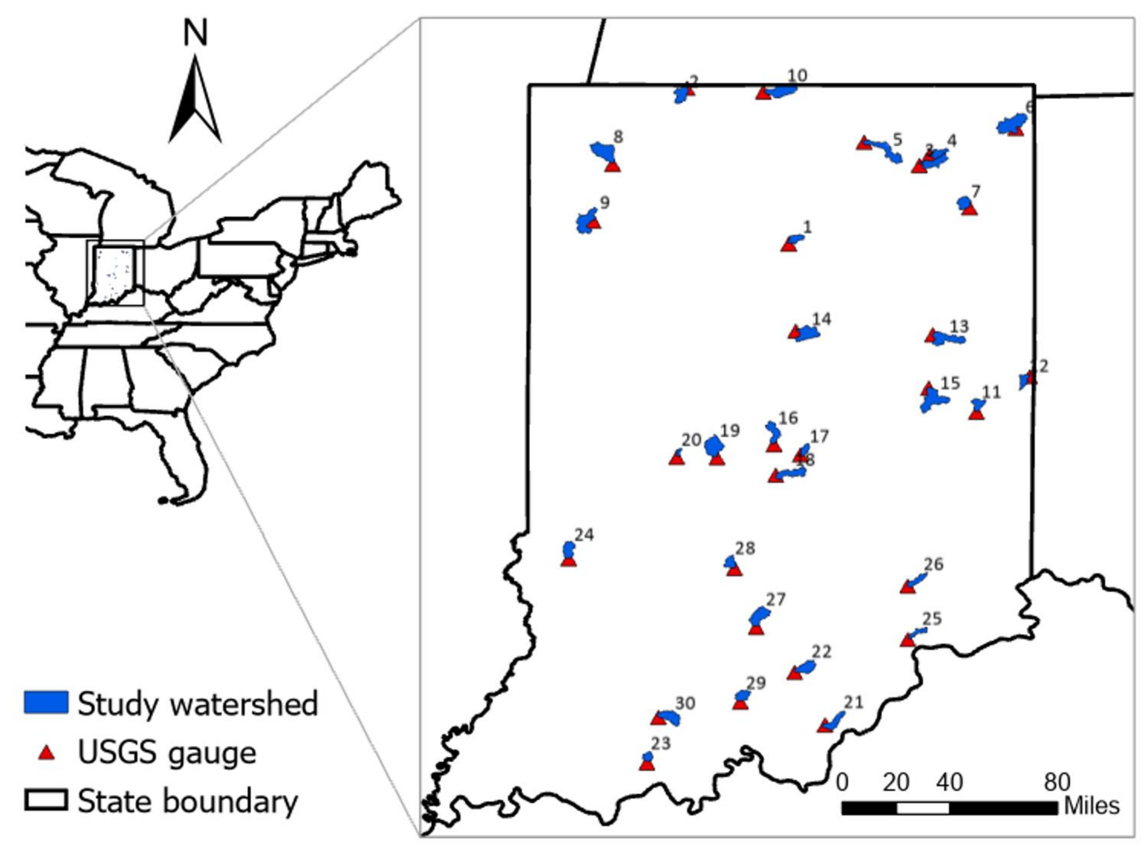
$$T_C = \left[\frac{2.2nL_C}{Y^{0.5}}\right]^{0.324}$$ (Kerby, 1959)

$$T_L = 0.0051W^{0.5937}Y^{-0.1505}S^{0.3131}$$ (Simas, 1996)

… …

$$T_L = L^{0.65} / 83.4$$ (Folmar, 2008)

Study Area and Data



No.	River	USGS Gauge ID	Drainage Area ($mile^2$)	Main Channel Slope (Cs)
1	Weesau Creek	03328430	9.3	0.0013
2	Galena River	04096100	17.9	0.0056
3	Forker Creek*	04100252	19.3	0.0014
4	Rimmell Branch*	04100295	11.0	0.0017
5	Solomon Creek	04100377	36.2	0.0009
6	Fish Creek	04177720	37.4	0.0020
7	Spy Run Creek	04182810	13.9	0.0024
8	Cobb Ditch	05517890	30.6	0.0012
9	Iroquois River	05521000	38.1	0.0006
10	Juday Creek	04101370	37.3	0.0011
11	Whitewater River	03274650	10.4	0.0024
12	Little Mississinewa River	03325311	9.8	0.0016
13	Big Lick Creek	03326070	29.0	0.0012
14	Kokomo Creek*	03333600	25.3	0.0008
15	Buck Creek	03347500	35.1	0.0035
16	Crooked Creek	03351310	17.9	0.0032
17	Pleasant Run	03353120	8.2	0.0026
18	Little Buck Creek	03353637	17.1	0.0027
19	West Fork White Lick Creek	03353700	28.9	0.0019
20	Plum Creek	03357350	3.0	0.0049
21	Little Indian Creek	03302300	17.1	0.0040
22	West Fork Blue River*	03302680	19.1	0.0053
23	Crooked Creek	03303400	8.0	0.0060
24	Busseron Creek	03342100	16.9	0.0032
25	Harberts Creek	03366200	9.3	0.0027
26	Brush Creek	03368000	11.3	0.0047
27	Back Creek	03371520	24.1	0.0048
28	Stephens Creek	03372300	10.8	0.0079
29	Patoka River	03374455	12.6	0.0057
30	Hall Creek	03375800	21.7	0.0035

* represents the watersheds used for validation.

Dataset	Resolution	Source
Precipitation (rainfall)	15 min	NOAA (https://www.ncdc.noaa.gov/cdo-web)
Streamflow	15 min	USGS (https://maps.waterdata.usgs.gov)
Topography	30 m	USGS Digital Elevation Model (DEM) (https://apps.nationalmap.gov/downloader/#/)
Land Cover	30 m	National Land Cover Dataset (https://www.mrlc.gov/viewer/)
Soil	1:250,000 spatial scale	Gridded Soil Survey Geographic (https://datagateway.nrcs.usda.gov/GDGOrder.aspx)

Methodology

Rainfall-runoff event data collection and UH derivation

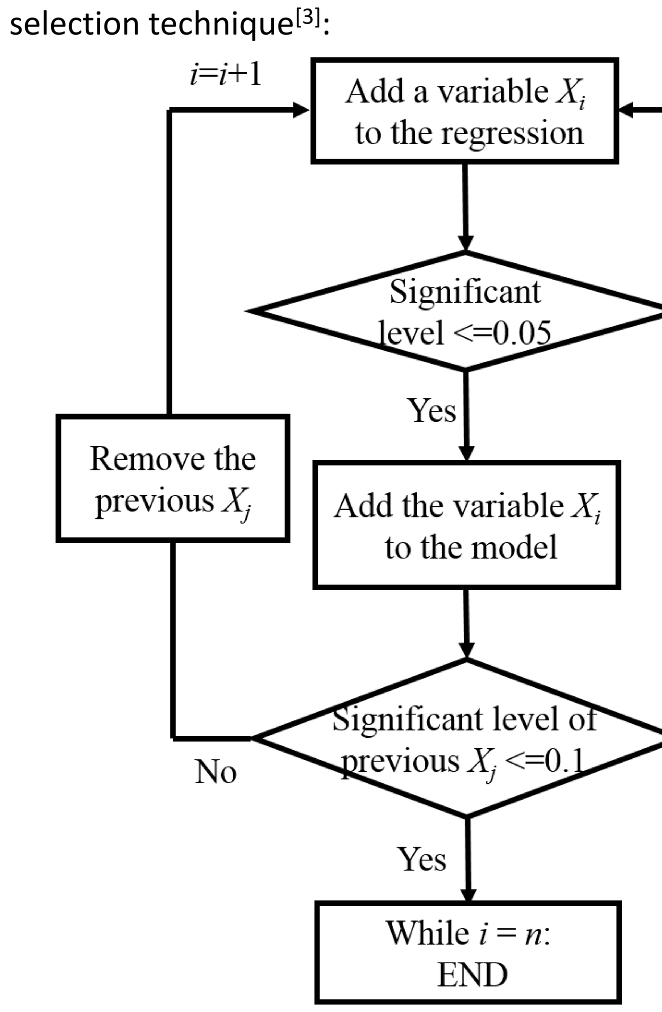
- In order to avoid the effect of snowfall, all the events are selected between April 1st to August 31st.
- Considering the consistent soil moisture conditions, the selected flood event is neither preceded nor followed by another event for at least three days.
- The rainfall distribution should be as uniform as possible within the duration.
- The hydrograph has only one distinct peak during the event period.
- UHs are derived based on 120 rainfall-runoff events in past twenty years and observed PRFs and lag times are calculated accordingly.

Geomorphic data extraction (28 parameters)

Geometric attributes (9)	Watershed relief & Stream network (10)	StreamStats (4)	Other (5)
• Drainage area • Basin perimeter (L_p) • Basin length (L_b) • Centroid length (L_{ca}) • Form factor • Circulatory ratio • Elongation ratio • Basin shape factor • Unity shape factor	• Basin relief • Relief ratio • Relative relief • Basin slope • Main channel slope (*Cs*) • Drainage density • Ruggedness # (R_n) • Channel maintenance • Fineness ratio (R_f) • Steam frequency	• 10-85% slope (*Slope*) • % Water / Wetland • % Urban land cover (*ULC*) • Main channel length	• Curve number (*CN*) • HKR • Gray • Murphey • % Sinks of basin DEM (*Sinks*)

Multiple regression analysis

Stepwise selection technique[3]:



No.	Regression Model
1	$Y = B_0 + B_1X_1 + B_2X_2 \cdots + B_nX_n$
2	$\log(Y) = B_0 + B_1\log(X_1) + B_2\log(X_2) \cdots + B_n\log(X_n)$
3	$Y = B_0 + B_1\log(X_1) + B_2\log(X_2) \cdots + B_n\log(X_n)$
4	$\sqrt{Y} = B_0 + B_1\sqrt{X_1} + B_2\sqrt{X_2} \cdots + B_n\sqrt{X_n}$
5	$Y = B_0 + B_1\sqrt{X_1} + B_2\sqrt{X_2} \cdots + B_n\sqrt{X_n}$

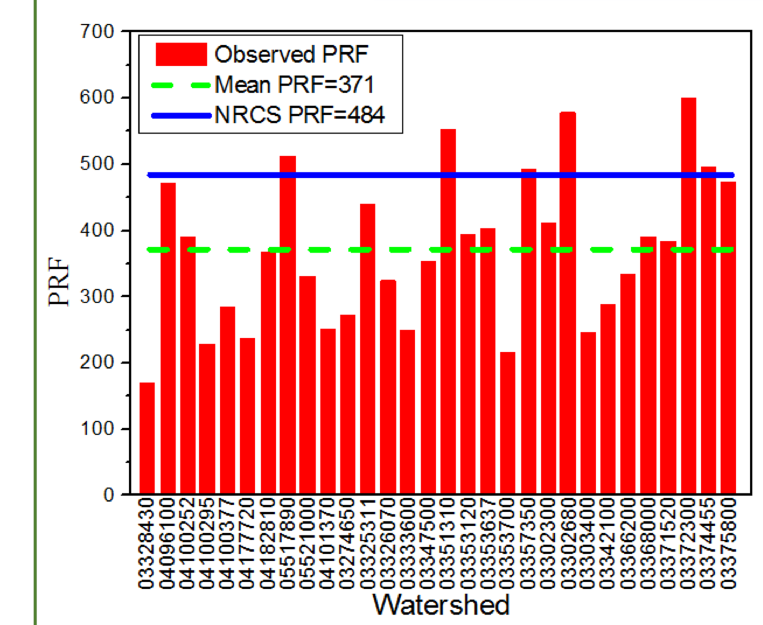
Note: *Y* is the dependent variable (PRF or lag time), X_i are independent variables representing the geomorphic parameters, B_i and are regression coefficients.

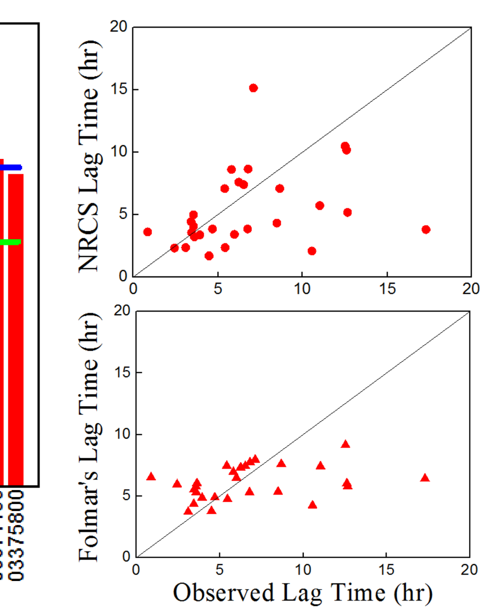
Validation

$$RE(x) = \frac{x_{sim} - x_{obs}}{x_{obs}} \times 100\%$$

where: *x* is the peak discharge or the time to peak.

Results and Discussion

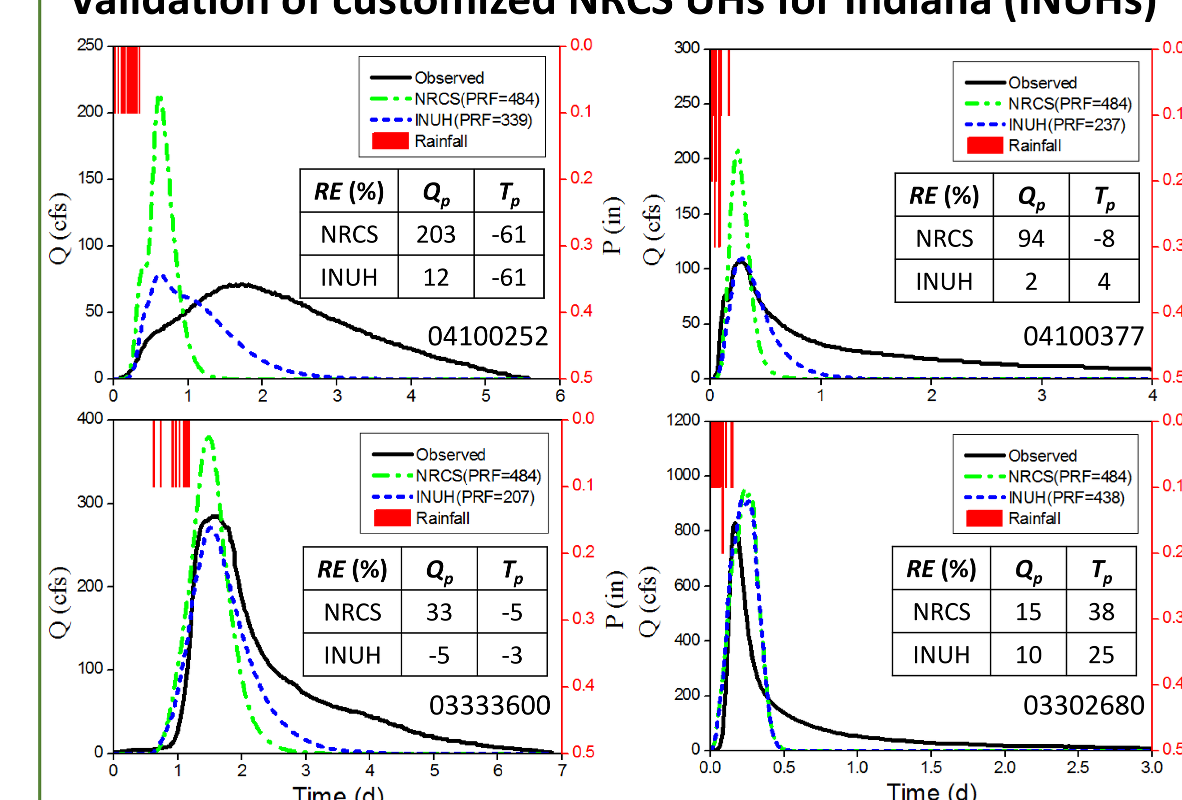




Statewide and regional regression models

Regression equation	Region	R^2	F-test (p-value)
PRF=fn (Cs); T_L=fn(Sinks, ULC)	Statewide	< 0.5	< 0.003
PRF=fn (L_p, L_{ca}); T_L=fn(L_p, Slope, CN)	*Cs* ≤ 0.002	> 0.7	< 0.025
PRF=fn (L_b, C, CN); T_L=fn(L_p, R_n)	0.002 < *Cs* ≤ 0.004	> 0.8	< 0.04
PRF=fn (S_b, R_f); T_L=fn(CN)	*Cs* > 0.004	> 0.7	< 0.001

Validation of customized NRCS UHs for Indiana (INUHs)



Conclusions

- The PRF and the lag time are two key parameters to derive the NRCS UH. The application of Gamma function on the synthetic UH derivation and flood prediction proved to be superior to the traditional empirical methods. The relationship between the Gamma function parameter and PRF was identified.
- 120 rainfall-runoff events are collected from 30 small watersheds in Indiana. UHs are derived based on the observed data. The mean value of observed PRF is 371, which is lower than the default PRF 484. The NRCS lag time equation tends to underestimate the “true” lag time.
- The statewide regression analysis shows that the PRF is related to the main channel slope, and the lag time is related to the percentage of sinks and the urban land cover. Furthermore, the regional regression analysis is performed according to the main channel slope of a watershed. Regional regression models have higher R^2 than statewide models. The regional regression analysis shows that the PRF of a flat watershed depends on the flow length and the stream network, while for a steep watershed, the model for PRF includes basin shape factor and fineness ratio terms. The lag time is mainly related to the channel slope and the curve number.
- Validation results show that the performance of INUH is better compared with the original NRCS UH method for the watersheds in Indiana when the parameters (PRF & lag time) are estimated through regression equations developed in this study.

References

[1] Wilkerson, J., Merwade, V. (2010). Incorporating surface storage and slope to estimate Clark unit hydrographs for ungauged Indiana watersheds. Journal of Hydrologic Engineering, 15(11), 918-930.

[2] NRCS. (2007). Part 630, Hydrology National Engineering Handbook.

[3] Rawlings, J. O., Pantula, S. G., Dickey, D. A. (2001). Applied regression analysis: a research tool. Springer Science & Business Media.