# Developing Customized NRCS Unit Hydrographs for Ungauged Watersheds in Indiana, USA

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**Abstract**

The Natural Resources Conservation Service (NRCS, formerly the Soil Conservation Service, SCS) unit hydrograph (UH) is one of the most commonly used synthetic UH methods for hydrologic modeling and engineering design all over the world. However, previous studies have shown that the application of the NRCS UH method for some ungauged watersheds in the state of Indiana produced unrealistic flood predictions for both the peak discharge and the time to peak. The objective of this work is to customize the NRCS UH by analyzing the role of its two key parameters, namely, the peak rate factor (PRF) and the lag time, in creating the runoff hydrograph. Based on 120 rainfall-runoff events collected from 30 small watersheds in Indiana over the past two decades, the observed UHs are derived and the corresponding PRF and lag time are extracted. The observed UHs in Indiana show that the mean value of PRF is 371, which is lower than the standard PRF of 484, and the NRCS lag time equation tends to underestimate the "true" lag time. Moreover, a multiple linear regression method, especially the stepwise selection technique, is employed to relate the NRCS UH parameters to the most appropriate geomorphic attributes extracted from the study watersheds. Both the statewide and regional regression models show that the main channel slope is a major factor in determining the PRF and lag time. A customized Indiana unit hydrograph (INUH) is derived with updated parameters and the Gamma function. Validation results show that the INUH provides more reliable and accurate predictions in terms of the peak discharge and the time to peak than the original NRCS UH for the watersheds in Indiana.

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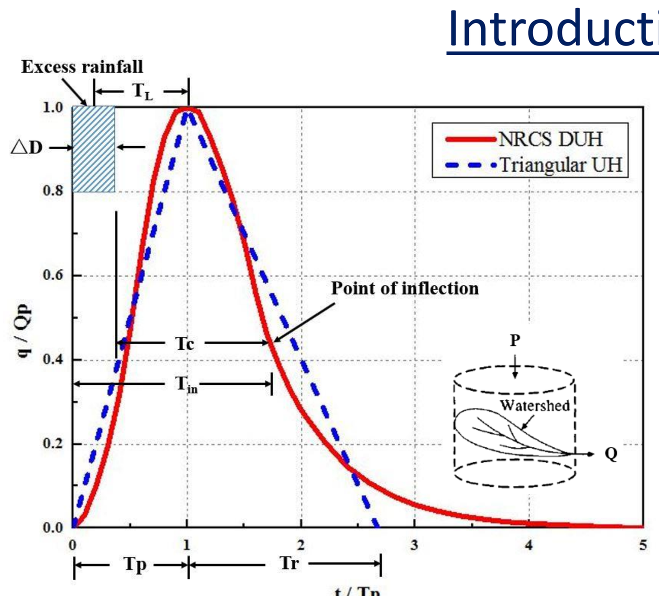
## Introduction



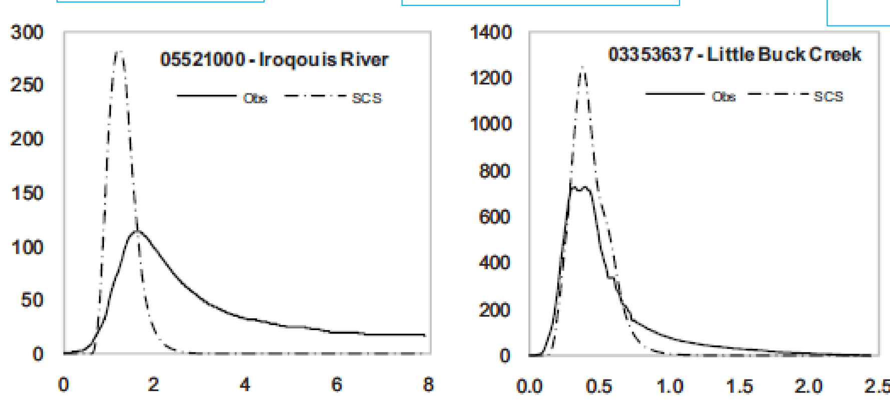

**Natural Resources Conservation Service (NRCS, formerly the Soil Conservation Service, SCS) Unit Hydrograph (UH):** developed by Victor Mockus (1957) and derived from many natural UHs from watersheds with different sizes and locations.

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

$$PRF = 484$$

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

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




**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)

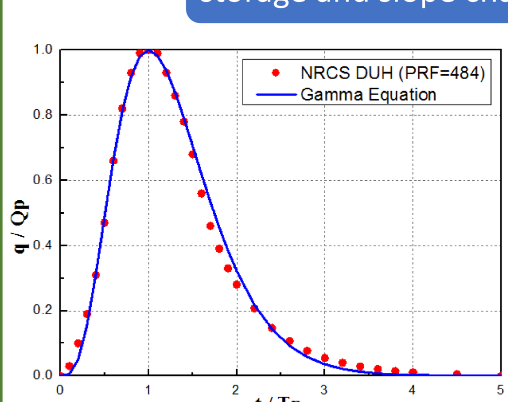
### (1) Peak Rate Factor (PRF)

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

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)

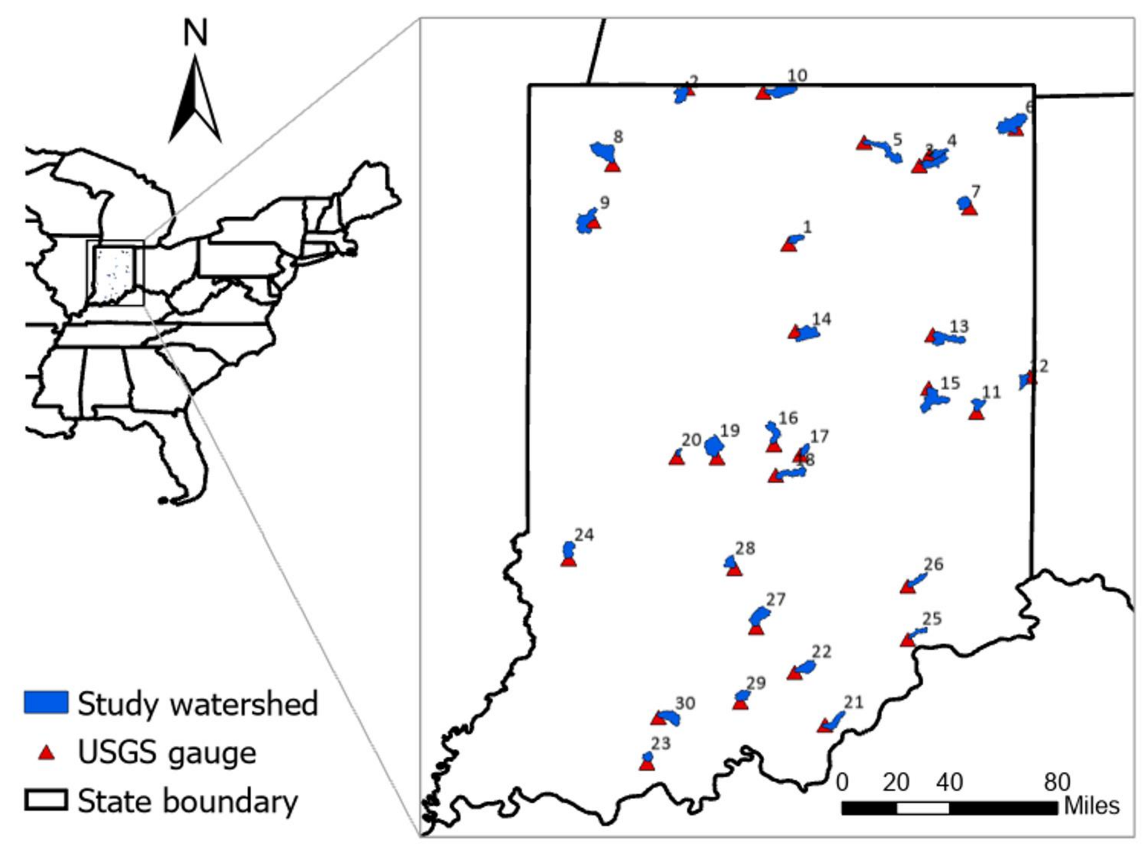
$$T_C = \left[\frac{2.2nL_C}{Y^{0.5}}\right]^{0.324}$$ (Kerby, 1959)

$$T_L = 0.0051W^{0.5937}Y^{-0.1505}S^{0.3131}$$ (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

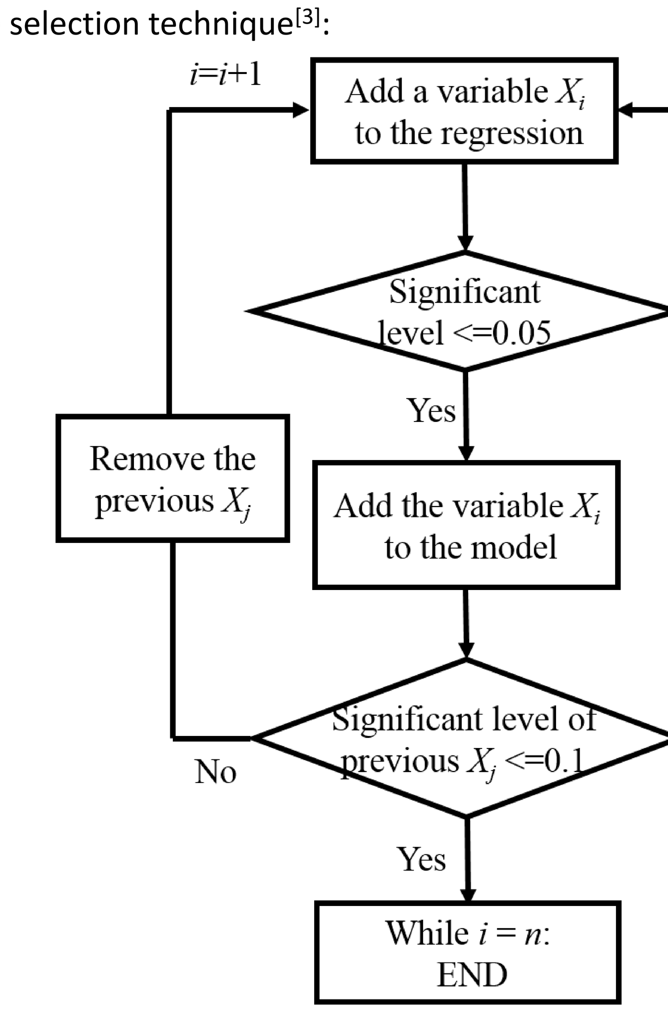
- In order to avoid the effect of snowfall, all the events are selected between April 1st to August 31st.
- Considering the consistent soil moisture conditions, the selected flood event is neither preceded nor followed by another event for at least three days.
- The rainfall distribution should be as 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<br>• Basin perimeter ($L_p$)<br>• Basin length ($L_b$)<br>• Centroid length ($L_{ca}$)<br>• Form factor<br>• Circulatory ratio<br>• Elongation ratio<br>• Basin shape factor<br>• Unity shape factor | • Basin relief<br>• Relief ratio<br>• Relative relief<br>• Basin slope<br>• Main channel slope (*Cs*)<br>• Drainage density<br>• Ruggedness # ($R_n$)<br>• Channel maintenance<br>• Fineness ratio ($R_f$)<br>• Steam frequency | • 10-85% slope (*Slope*)<br>• % Water / Wetland<br>• % Urban land cover (*ULC*)<br>• Main channel length | • Curve number (*CN*)<br>• HKR<br>• Gray<br>• Murphey<br>• % 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 | $Y = B_0 + B_1\sqrt{X_1} + B_2\sqrt{X_2}\cdots + B_n\sqrt{X_n}$ |

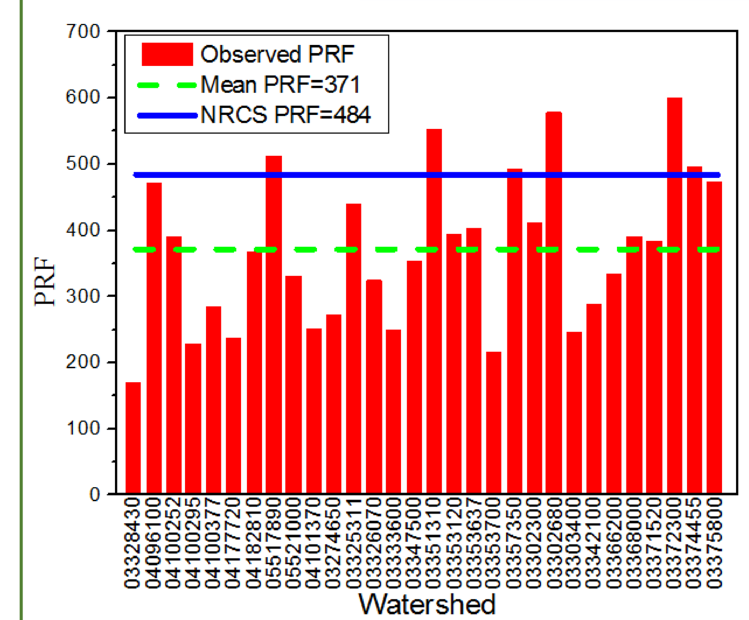
Note: *Y* is the dependent variable (PRF or lag time), $X_i$ are independent variables representing the geomorphic parameters, $B_i$ and are regression coefficients.

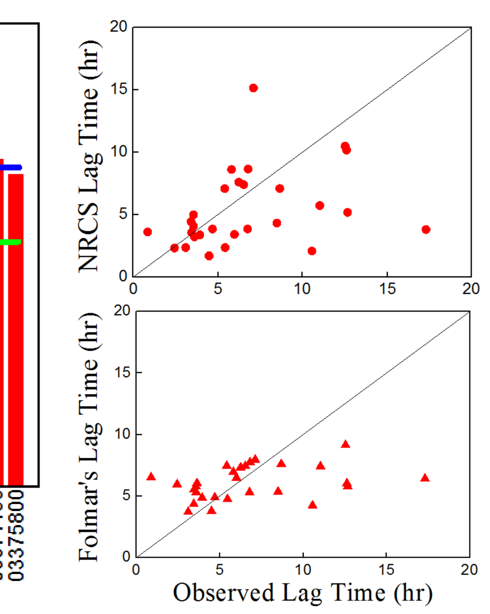
### Validation

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

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

## Results and Discussion

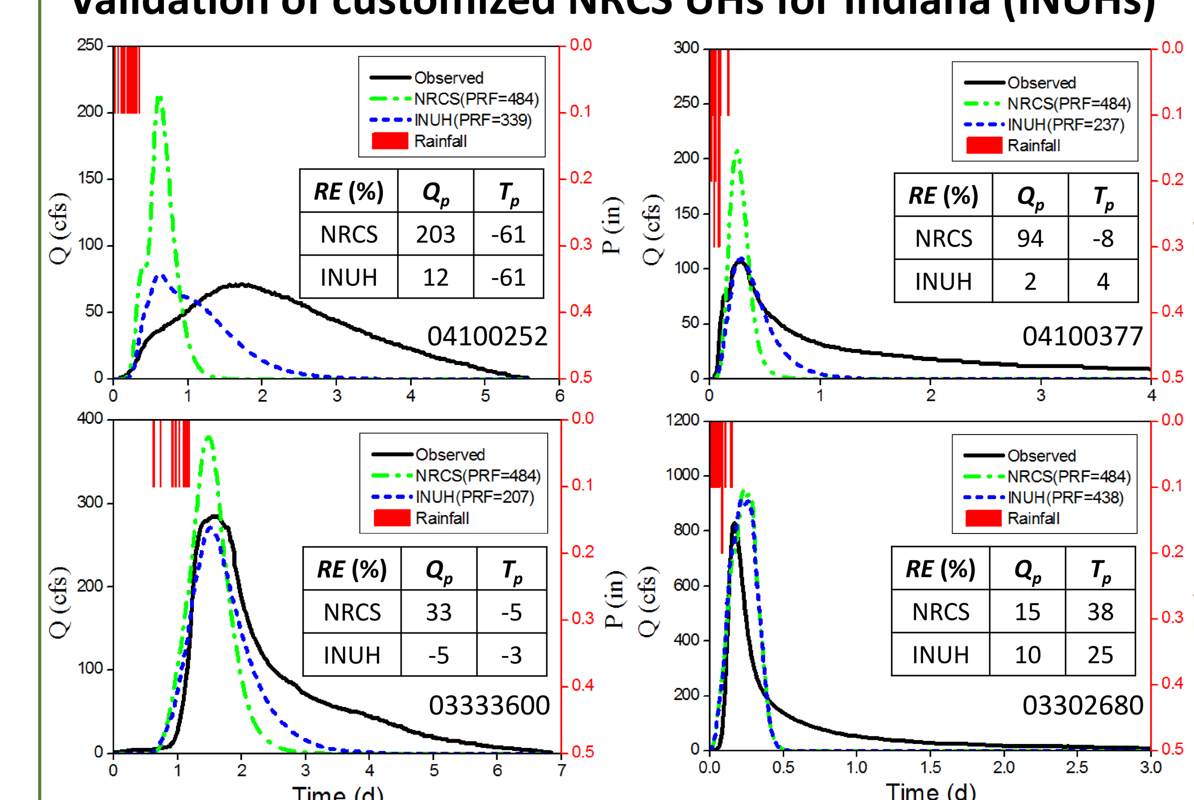



### Statewide and regional regression models

| 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 R² 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.