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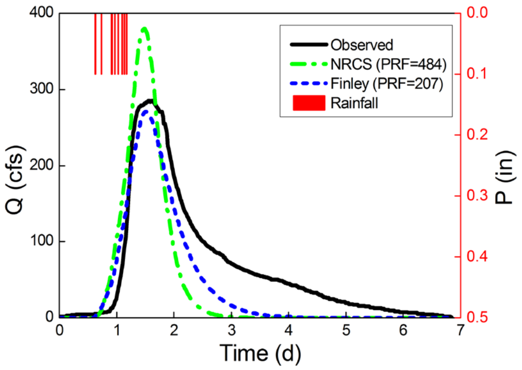
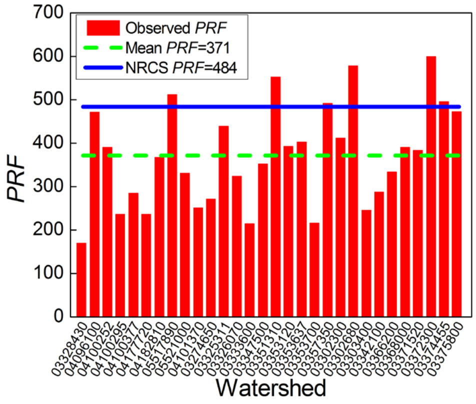
Developing Customized NRCS Unit Hydrographs (Finley UHs) for Ungauged Watersheds in Indiana





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NOTICE

ACKNOWLEDGEMENT

This report is dedicated to the memory of David Dean Finley who was its inspiration. David “The Professor” was a brilliant engineer, devoted husband, and father. David had a thirty plus year career in hydraulics, twenty of which were spent working for the State of Indiana alongside people who were glad to call him a friend as well as a greatly respected colleague.

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16. 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, referred as Finley UH to honor David Finley who inspired this study, is derived with updated parameters and the Gamma function. Validation results show that the Finley UH 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.

17. Key Words
NRCS unit hydrograph, peak rate factor, lag time, flood hydrograph prediction, geomorphic attributes, ungauged watersheds, Indiana

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EXECUTIVE SUMMARY

Introduction

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.

Findings

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.

Implementation

A customized Indiana unit hydrograph, referred to as Finley UH to honor David Finley who inspired this study, is derived with updated parameters and the Gamma function. Validation results show that the Finley UH 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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1. INTRODUCTION

Hydrologic simulations involve converting rainfall into runoff hydrographs at streams within a watershed. One of the traditional and widely used tools to convert excess rainfall, total rainfall minus losses due to infiltration, is the unit hydrograph (UH). A UH is defined as a direct runoff hydrograph resulting from one unit (usually taken as 1 inch in English units or 1 cm in SI units) of excess rainfall generated uniformly over the drainage area at a constant rate within a specified time duration (Sherman, 1932). The UH theory assumes the hydrologic system to be linear to compute the direct runoff hydrograph resulting from any amount of excess rainfall. Ideally, a UH is derived based on the observed rainfall-runoff data for multiple storm events. However, for ungauged watersheds, synthetic unit hydrographs (SUH), which are developed based on the watershed characteristics (Bhunya et al., 2011; Chow et al., 1988), are used to estimate direct runoff hydrographs. Among the many types of SUHs, the Natural Resources Conservation Service (NRCS, formerly the SCS) UH (NRCS, 2007; Mockus, 1972) is the most widely used in the United States (Folmar et al., 2007; Ojha et al., 2008). This method has been incorporated into commonly used software packages, such as HEC-HMS and TR-20, for computing direct runoff hydrographs.

According to some previous studies (Fang et al., 2005; Wilkerson & Merwade, 2010), application of NRCS UH results in inaccurate estimation of both the peak discharge and the time to peak (see Figure 1.1) for the State of Indiana. This is especially true for the northern glaciated part of the state where the peak is over estimated. On the other hand, the NRCS UH leads to under estimation of peak in the southern part of the State. As the original NRCS UH was derived by averaging many natural UHs (Mockus, 1957; Mockus, 1972), it is expected that it may not work equally well for some watersheds. However, due to its wider appeal and applicability, it is used for many engineering design projects in Indiana. Considering that NRCS UH is widely used in Indiana and that it does not always produce accurate results, there is a need to create a customized UH for Indiana watersheds. Accordingly, the overall goal of this study is to develop a customized non-dimensional UH for Indiana, referred hereafter as Finley UH to honor David Finley who inspired this study, which can provide more reliable and accurate hydrographs for engineering design and flood risk control at ungauged sites in Indiana. This broader goal is accomplished through the following objectives: (1) revisit the basic theory of NRCS UH, including its development, limitations and recent improvements; (2) derive UHs for watersheds in Indiana using historical rainfall-runoff event data and estimate the parameters of the NRCS UH; (3) relate UH parameters developed in Objective 2 to watershed characteristics by performing both statewide and regional regression analyses; and (4) develop Finley UHs using the regression expressions developed in Objective 3: and (5) compare the performance of the Finley UH with the original NRCS UH.

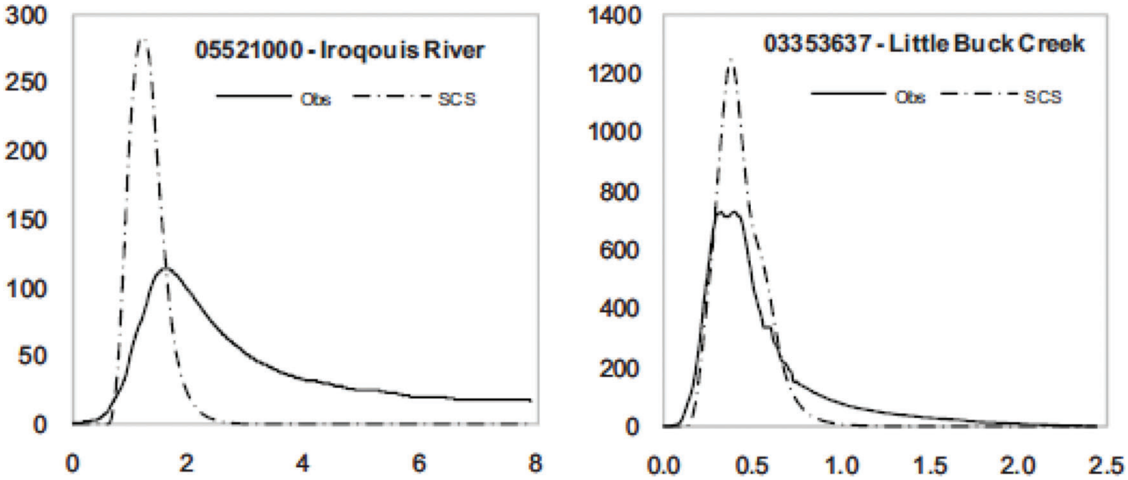


Figure 1.1 Comparison of hydrographs from NRCS method with United States Geological Survey (USGS) observed data for watersheds in Indiana. The x-axis represents time in days and the y-axis represents flow in ft^3/s (cfs).

2. REVISIT NRCS UNIT HYDROGRAPH (UH)

2.1 Basic Theory of NRCS UH

The NRCS synthetic UH was developed by Victor Mockus (1957) by using data from watersheds with different sizes and geographical locations (NRCS, 2007). The standard dimensionless UH is provided in tabular form and the schematic hydrograph is shown in Figure 2.1. The discharge in the model is expressed by the ratio of discharge q to peak discharge Q_P and the time by the ratio of time t to the time to peak T_P. If the peak discharge and the time to peak for the duration of excess rainfall are given, the UH for the given watershed can be estimated from the NRCS UH. The dimensionless UH can also be represented by the equivalent triangular UH which has the same units of time and discharge (see Figure 2.1).

According to the concept of UH, the area under the UH should be equal to one unit of direct runoff. The basic equations of the NRCS UH theory is given below.

$$Q_P = PRF\frac{AQ}{T_P} \qquad \text{(Eq. 2.1)}$$

$$T_P = T_L + \Delta D/2 \qquad \text{(Eq. 2.2)}$$

$$T_L = 0.6T_C \qquad \text{(Eq. 2.3)}$$

$$T_{in} = 1.7T_P \qquad \text{(Eq. 2.4)}$$

$$T_C = T_{in} - \Delta D \qquad \text{(Eq. 2.5)}$$

where Q_P is the peak discharge (cfs), PRF is the peak rate factor (default value is 484 in English units and 2.08 in SI units) (Mockus, 1972), A is the area of the watershed (mile^2), Q is the unit depth of excess rainfall (1 inch), T_P is time to peak (hr), T_L is the lag time (hr), ΔD is the duration of unit excess rainfall (hr), T_C is the time of concentration (hr), which is defined as the time it takes for runoff to travel from the hydraulically most distant point in the watershed to the outlet, and T_{in} is the time to the point of inflection of the hydrograph (hr).

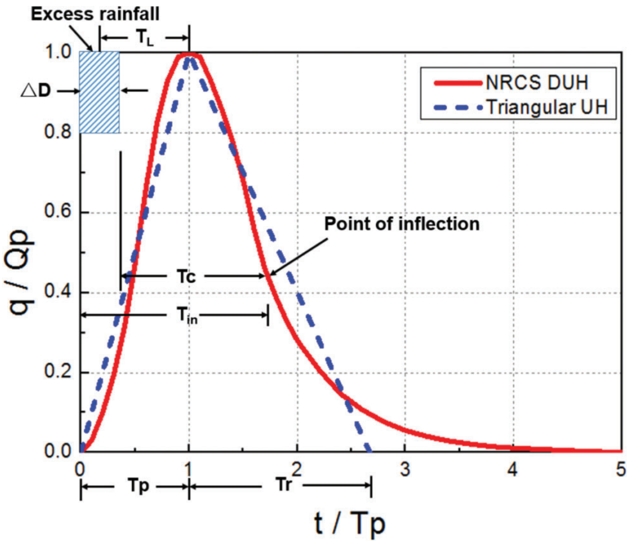


Figure 2.1 NRCS dimensionless UH and triangular UH.

By combining Eq. 2.2 to Eq. 2.5, the duration of the unit excess rainfall is recommended as either Eq. 2.6 or Eq. 2.7.

$$\Delta D = 0.2T_P \qquad \text{(Eq. 2.6)}$$

$$\Delta D = 0.133T_C \qquad \text{(Eq. 2.7)}$$

To compute the time to peak, the lag time should be estimated first. Figure 2.1 shows that the lag time is defined as the time interval between the center of mass of the excess rainfall and the peak discharge. In the 1960s, the correlation between the lag time and watershed characteristics, such as area, the longest hydraulic length, shape, slope, land use, soils, etc., were examined by using the linear regression after the log-transformation for the variables (Folmar et al., 2007; NRCS, 2007; Mockus, 1972). Based on the high R^2 value of the regression models and the sensitivity analysis on the coefficients, the final equation (Eq. 2.8) was published in the NRCS national engineering handbook in 1972.

$$T_L = \frac{L^{0.8}(S+1)^{0.7}}{1{,}900 \times Y^{0.5}} \qquad \text{(Eq. 2.8)}$$

where L is the longest flow path length (ft), $S\left(=\frac{1{,}000}{CN}-10\right)$ is the maximum potential retention (inch) and CN is the curve number, and Y is the average watershed land slope (%). L and Y can be measured or computed by using many computational methods (NRCS, 2007), and it is a convenient way to compute these two parameters by using the geographic information system (GIS) techniques if the digital elevation model (DEM) of the study area is available.

2.2 Application of NRCS UH

Although the original data that was used for the NRCS UH derivation cannot be traced, some previous studies (Folmar et al., 2007; NRCS, 2007; Welle & Woodward, 1989) have reported that it was developed from agricultural watersheds, most of which were located in the US Midwest. Since its development in the late 1950s, it has been widely used for hydrologic and hydraulic engineering design in the United States and even across the world due to its comprehensive consideration of watershed characteristics and the simplicity in use (the traditional method requires only one calculated parameter, i.e., the lag time).

Many studies including watershed specific application or comparative analysis of the NRCS UH method is published in literature. Table A.1 in Appendix presents a brief information and summary results from these studies. The results of these applications show that this average dimensionless UH has been applied for the estimation or prediction of the flood hydrograph for primarily agricultural watersheds with the drainage area less than 150 mile^2 all over the world with acceptable performance in most cases. However, the range of parameter values vary for different watersheds compared to the values proposed in the original method. Therefore, the original standard values or procedures for some parameters (e.g., *PRF*) in this method need to be updated in order to get more accurate estimates in some specific cases. On the other hand, in order to reduce the effect of the scale of the watershed and the heterogeneity in the drainage pattern and land use within the watershed to a great degree, a large basin can be divided into several hydrologically homogeneous sub-basins. Specifically, it is suggested that the drainage area of the sub-basin should not exceed 20 mile^2 and that the ratio of the largest sub-basin to the smallest should not exceed 10 when applying the NRCS UH method (NRCS, 2007).

2.3 Recent Advances in NRCS UH

According to Eq. 2.1 and Eq. 2.2, the application of NRCS UH requires estimation of two parameters: *PRF* and lag time. The procedure to determine these two parameters and the literature addressing their modification is reviewed below.

2.3.1 Estimation of Peak Rate Factor (PRF)

The *PRF* is an important parameter to determine the peak discharge, and it is determined by the shape of dimensionless UH. Based on the definition of UH and the equivalent triangular UH in Figure 2.1, the area under the triangular UH should be equal to one unit of excess rainfall over the watershed with an area of A as shown in Eq. 2.9.

$$\frac{1}{2}Q_p\left(T_p+T_r\right)=A\cdot Q \qquad \text{(Eq. 2.9)}$$

where T_r is the time to recession (hr).

Solve Eq. 2.9 for the peak discharge in cfs and Eq. 2.1 is obtained as follows.

$$Q_p=\left(645.33\times\frac{2}{1+T_r/T_p}\right)\frac{AQ}{T_p}=PRF\frac{AQ}{T_p} \qquad \text{(Eq. 2.10)}$$

where 645.33 is the unit conversion factor to get discharge from one inch rainfall occurring over an area (mile^2) in one hour, namely, $\frac{cfs\times hr}{mi^2\times in}$ and $PRF=645.33\times\frac{2}{1+T_r/T_p}$. From the review of a large number of observed UHs, NRCS suggested that $T_r=\frac{5}{3}T_p$, thus, $PRF=645.33\times0.75=484$, which is the default *PRF* of NRCS UH (NRCS, 2007; Mockus, 1972).

According to Eq. 2.10, *PRF* is an integrated parameter of the unit conversion factor, and the assumption is that 37.5% of the runoff volume occurs under the rising limb of the hydrograph. The latter factor is related to the watershed size and geomorphic characteristics hence the value of *PRF* may vary for watersheds with different conditions. The NRCS national engineering handbook from 1972 has stated that *PRF* varies from about 600 in the steep terrain to 300 in the flat and swampy area (Mockus, 1972). Considering the applicability of the standard 484 UH, the Delmarva UH with *PRF* of 284 has been developed for coastal flatlands based on the gauge records from four watersheds in the Delmarva Peninsula, USA (Woodward et al., 1980). The Delmarva UH was recommended by the NRCS as an alternative to the standard 484 UH for flat watersheds (NRCS, 2007). However, some subsequent studies (Capece et al., 1988; Capece, 1986; McCuen & Bondelid, 1983; NRCS, 2007; Sheridan et al., 2002; Welle & Woodward, 1989) have shown that the Delmarva UH based on a *PRF* of 284 may not be applicable for all coastal regions, and the value of *PRF* ranges from below 100 to more than 600 for watersheds with different storage and slope characteristics.

It is clear that applying a single *PRF*, with the value of either 484 (standard) or 284 (Delmarva), to predict the hydrograph for different watersheds is not reasonable. Then two issues need to be addressed. (1) How to derive the SUH based on the corresponding *PRF* or vice versa? (2) How to determine the *PRF* for a specific watershed that is ungauged?

The NRCS national engineering handbook provides a seven-step procedure to derive the dimensionless UH and estimate the *PRF* from measured rainfall-runoff data with TR-20 (NRCS, 2007). In the last step of the procedure, it recommends that the Gamma equation (see Eq. 2.11), which fits the shape of the standard dimensionless UH well for estimating the runoff at any time (see Figure 2.2), could be used to develop a UH. It also provides the ordinates of the UH for PRF ranging

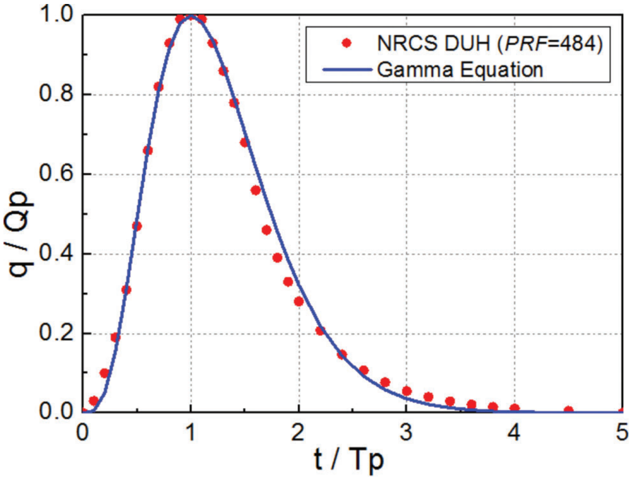


Figure 2.2 Fitting of the Gamma equation to NRCS dimensionless UH (DUH with *PRF* = 84).

from 100 to 600. The specific *PRF* is calculated from Eq. 2.12 after the corresponding UH is obtained, which means that different values of m have to be tried in Eq. 2.11 until the UH matches the shape of the observed hydrograph closely (NRCS, 2007).

$$\frac{q}{Q_P} = e^{\left(1-\frac{t}{T_P}\right)m}\left(\frac{t}{T_P}\right)^m \quad \text{(Eq. 2.11)}$$

$$PRF = \frac{645.33}{\sum DUH_{coordinates} \times \Delta T_{DUH}} \quad \text{(Eq. 2.12)}$$

where m is the Gamma equation shape factor, 645.33 is the unit conversion factor, $\sum DUH_{coordinates}$ is the summation of the dimensionless UH ordinates, and ΔT_{DUH} is the nondimensional time interval of the dimensionless UH.

It should be noted that both $PRF = \frac{Q_p T_p}{AQ}$ another form of Eq. 2.1 and Eq. 2.12) follows the same procedure to calculate the *PRF*. According to the basic concept of UH (Sherman, 1932), the area under the UH curve (direct runoff volume, V_D) should be equal to one unit of excess rainfall within the watershed (V_E) as presented below.

$$V_D = \int_0^\infty q(t)dt = Q_P T_P \cdot \int_0^\infty \frac{q(t)}{Q_P} d\left(\frac{t}{T_P}\right) \approx Q_P T_P \cdot \left(\sum DUH_{coordinates} \times \Delta T_{DUH}\right)(cfs \cdot hr) \quad \text{(Eq. 2.13)}$$

$$V_E = 645.33AQ(cfs \cdot hr) \quad \text{(Eq. 2.14)}$$

Substitute Eq. 2.13 and Eq. 2.14 into $V_D = V_E$, one can get

$$\frac{Q_P T_P}{AQ} = \frac{645.33}{\sum DUH_{coordinates} \times \Delta T_{DUH}} \quad \text{(Eq. 2.15)}$$

Eq. 2.15 provides the definition of *PRF*. Therefore, both Eq. 2.1 and Eq. 2.12 can yield the same value of *PRF*. Eq. 2.1 is a much easier way to compute the *PRF* and it can reduce the error due to the approximate integral. Since m is the only parameter in Eq. 2.11, it means that a single value of m will produce a corresponding single value of *PRF* (NRCS, 2007). The NRCS handbook provides a table to show the relationship between m and *PRF*, but it does not propose any procedures or methods to estimate this Gamma equation parameter (i.e., m). Therefore, there is some subjectivity involved in the calculation of *PRF* and UH for different watersheds.

Besides the NRCS UH method, other traditional SUH methods, such as the Snyder (1938), Clark (1945), and Taylor and Schwarz's methods (Taylor & Schwarz, 1952), are also widely used in hydrologic analysis. However, the process of manual fitting and parameter value estimation also involves great degree of subjectivity and uncertainty (Bhunya et al., 2011; Wilkerson & Merwade, 2010). Moreover, the basic concept of the UH that the total direct runoff volume of the UH should be equal to one unit is violated when some parameter values are changed (Bhunya et al., 2011; Fang et al., 2005). Due to the shape similarity between the conventional UH and the statistical distributions, some studies have explored the applicability of probability density functions (PDFs) in developing SUH since the 1950s. The Gamma function, which is recommended by the NRCS (2007), is one of the applicable distributions to derive the SUH. A brief overview of studies that use Gamma function in developing a synthetic UH is presented in Table A.2 in Appendix. Besides Gamma distribution, other distributions such as Chi-square (Montgomery & Runger, 2003), Beta (Mood et al., 1974), and Weibull (Singh, 1987; Weibull, 1939) have also been used to derive SUH by relating the time to peak and the peak discharge of the UH to the parameters of the PDF. Studies involving the use of PDFs instead of a traditional SUH have shown that they can produce equal or in some cases better flood hydrograph prediction compared to the traditional SUH methods (Bhunya et al., 2007; Bhunya et al., 2011; Ghorbani et al., 2013; Haktanir & Sezen, 1990; Jeng, 2006; Nadarajah, 2007).

Based on the above discussion, *PRF* can be related to the parameter of the Gamma function (m or α). Results from past studies (presented in Table A.2 in Appendix) also show that use of Gamma parameters can give similar results compared to SUH parameters. Additionally, Gamma parameters can be estimated by using an optimization algorithm rather than the trial-and-error method, and hence they could yield more accurate results (Fang et al., 2005). Once the *PRF* for NRCH UH is determined, its corresponding UH could also be derived with Eq. 2.11. The value of *PRF* is associated with two factors: unit conversion factor and the shape factor of the UH. The shape factor is based on the physical characteristics of watersheds.

Both the default value of *PRF* (484) and the alternative value (284) of the Delmarva UH were estimated from many natural UHs derived from the observed data (McCuen & Bondelid, 1983; Mockus, 1957; Woodward et al., 1980). However, for ungauged watersheds, one way to determine the *PRF* is to establish a quantitative relationship between the *PRF* and watershed characteristics. Based on Horton's laws of the channel networks (Horton, 1945), the peak discharge, the time to peak and the time of base of the UH can be related to the bifurcation ratio, length ratio, area ratio and the mean peak flow velocity by regression analysis (Rodríguez-Iturbe & Valdes, 1979). Some other studies have related *PRF* with drainage area and main channel slope (Sheridan et al., 2002) and mean peak discharge and mean time to peak (Fang et al., 2005). A study using data for 26 watersheds in New Jersey found that *PRF* was not significantly correlated with any single watershed characteristic obtained from the USGS StreamStats website (Horst & Gurriell, 2019), but this study tried to relate *PRF* with single watershed characteristic. It is possible that a statistically significant relationship can be derived when multiple watershed characteristics are used through multivariate regression. Accordingly, this study aims to relate *PRF* with multiple geomorphic characteristics of the watersheds of interest by using the multiple regression method.

2.3.2 Estimation of Lag Time

Lag time is the second parameter for computing the time to peak or the peak discharge in deriving the NRCS UH. Generally, it reflects the surface storage, the percentage of imperviousness, and the velocity of overland and channel flow within a watershed (Leopold, 1991). The NRCS method for computing the lag time (see Eq. 2.8) was developed based on limited sample data obtained from 16 agricultural watersheds (Folmar et al., 2007; NRCS, 2007). When it as applied to small urban basins with areas less than 3 mile^2, it was found to perform well in completely paved areas (Chow et al., 1988). However, it generally tends to underestimate the true lag time of a watershed and hence yields conservative estimate of design discharges (Folmar & Miller, 2008; Thomas Jr. et al., 2000; Wilkerson & Merwade, 2010). Some studies (Loukas & Quick, 1996; Mockus, 1957; NRCS, 2007) found that the ratio of the lag time and the time of concentration is approximately 0.6 (see Eq. 2.3), and thus lag time can be estimated using time of concentration.

According to Eq. 2.8, the lag time seems to be a unique parameter related to the watershed characteristics. Some studies (Rao & Delleur, 1974) found that the lag time depends on both watershed characteristics and rainfall characteristics (the amount of rainfall excess and the rainfall duration), and thus, it varies from storm to storm. A subsequent study (Simas, 1996) based on over forty thousand rainfall-runoff events in more than one hundred small watersheds in the USA indicated that the lag time tended to be a constant value for "bigger" storms that have either higher volume and intensity from previous 48-hour rainfall, or higher values of average runoff and peak discharge. As there was no further examination of the variation in the lag time, NRCS (2007) concluded that rainfall characteristics do not significantly affect the lag time.

Considering that the original NRCS lag time equation (Eq. 2.8) was developed based on the data from limited regions of the US, it may not work equally well for all watersheds. Considering the limitation of Eq. 2.8, the NRCS also recommends some other regression models for estimating the lag time or the time of concentration for some specific cases. By reviewing related literature, some models are presented in Table A.3 in Appendix A. The NRCS lag time equation and most models in Table A.3 show that the longest flow path distance and the average watershed slope or the stream slope play an important role in determining the lag time.

Based on the in-depth literature review presented above, it is unrealistic to produce a synthetic SUH method that can be applicable for all watersheds with different conditions because SUH was derived from limited study samples. Moreover, since the watershed characteristics change over time, past equations developed for one region may also not work equally well for the same region under current conditions. Therefore, this study aims to improve the applicability of the traditional NRCS UH method for ungauged watersheds in Indiana.

3. STUDY AREA AND DATA

Indiana, with a total area of 36,418 mile^2, is located in Midwestern region of the USA. The average altitude of Indiana is about 760 feet above sea level. The northern and central regions of Indiana are made up of till plains due to glaciation, but the southern region is characterized by valleys and rugged, hilly terrain because it has not been covered by glacial ice since the Illinoisan period and hence reshaped by natural forces. For this study, 30 study watersheds, geographically distributed across the entire state, are selected. Each watershed selected in this study has a USGS streamflow gauge at its outlet (see Figure 3.1). Unit Hydrographs for these areas are computed using 120 historical rainfall-runoff events based on the availability of the 15-minute rainfall and streamflow data from 2000–2020. To satisfy the UH assumption of uniform rainfall distribution, selected study watersheds have small areas ranging from 3 to 40 mile^2 (see Table A.4). In addition, the land use of all watersheds is primarily agricultural, with less than one percent urban cover. Basic information of all the datasets, both temporal and geospatial, used in this study are presented in Table 3.1.

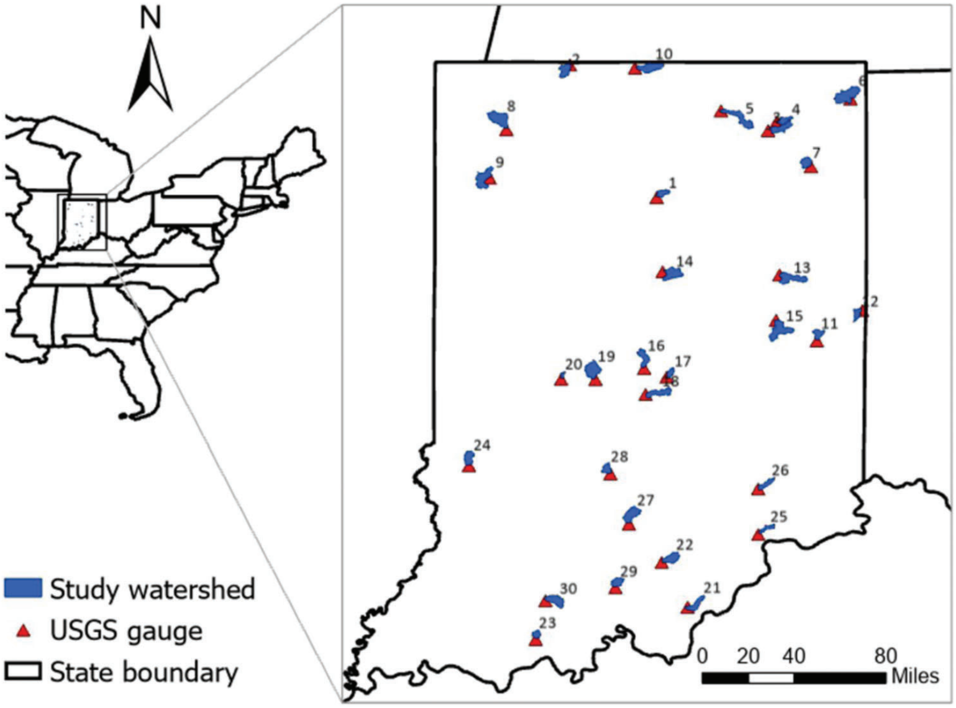


Figure 3.1 Map of study watersheds in Indiana, USA.

TABLE 3.1
Temporal and geospatial datasets used in the study

Dataset	Resolution	Source
Precipitation (rainfall)	15 min	National Oceanic and Atmospheric Administration (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)

4. METHODOLOGY

The methodology involves the following steps: (1) extraction of rainfall-runoff events for all watersheds selected in the study; (2) derivation of UHs for all watersheds using the data from the previous step and computing the peak rate factor and time to peak for each UH; (3) extraction of geomorphic attributes for each watershed using GIS data; (4) regression analysis between UH parameters and geomorphic attributes for each watershed; and (5) validation of regression equations by estimating the PRF and time to peak to compute UH for some historical events. Each step is described in detail below.

4.1 Extraction of Rainfall-Runoff from Historical Data

According to the basic theory of the UH method, the excess rainfall should have a constant intensity within the effective duration and be uniformly distributed over the entire watershed (Chow et al., 1988). Rainfall-runoff events are selected for each study area to satisfy this condition as much as possible. Specifically, a few criteria (Chow et al., 1988; Viessman et al., 1989) are established to select "good" rainfall-runoff events for this study, including (1) events are selected between April 1st to August 31st to exclude snowfall effects; (2) events are selected such that they are neither preceded nor followed by another event for at least three days to have normal antecedent moisture conditions; (3) rainfall distribution should be as uniform as possible within the duration; and (4) hydrograph has only one distinct peak during the event period. Some very small watersheds do not have any rainfall station with 15-minute interval data. For such watersheds, data from stations within 0.2° buffer are used. If the buffer includes more than one station, arithmetic mean of all stations is used as the rainfall input. A total of 120 rainfall-runoff events over the past twenty years are selected for UH analysis such that there are 2–5 events for each watershed.

4.2 Unit Hydrograph Derivation

By using the historical rainfall-runoff data obtained in 4.1, UH and dimensionless UH for each event is derived based on the basic theory of UH. First, the SCS curve number method is used to estimate the excess rainfall for each event. Next, baseflow is separated from each event hydrograph to get direct runoff hydrograph. According to NRCS national engineering handbook (NRCS, 2007), baseflow is relatively small and can be assumed constant for small watersheds. Thus, straight-line method is used to separate the baseflow from the observed streamflow. Next, UH ordinates are calculated by dividing the ordinates of direct runoff hydrograph by the equivalent depth of total direct runoff. Finally, the *PRF* and lag time for each corresponding UH are computed, respectively (see Eq. 2.1 and Eq. 2.2).

4.3 Geomorphic Data Extraction

To relate the dimensionless UH parameters (PRF and lag time) with watershed characteristics, a list of related geomorphic attributes for the study watersheds are extracted using topographic data (DEM), land cover data, and the soil data (see Table 3.1). ESRI's ArcGIS tools and custom Python tools are used in extracting 28 geomorphic attributes, which are listed and defined in Table 4.1. Attributes 1 to 9 are related to the geometric properties of a watershed. Attributes 10–19 are associated with watershed relief and stream network. Attributes 20–23, which might be relevant to the shape of UH, are obtained through USGS StreamStats (Ries et al., 2008).

4.4 Multiple Regression Analysis

Multiple regression is one of the most widely used approaches for regional hydrologic parameter estimation for ungauged watersheds (Abdulla & Lettenmaier, 1997; Folmar & Miller, 2008; Khanal, 2004). Specifically, stepwise regression (Rawlings et al., 2001) is performed in MATLAB (Higham & Higham, 2016) to develop regression models for estimating the NRCS UH parameters (*PRF* and lag time) of the watersheds in Indiana by using the most appropriate geomorphic parameters. During each step of the stepwise regression process, one independent variable is added or removed from a multilinear model based on its statistical

TABLE 4.1
List of geomorphic parameters of study watersheds

No.	Parameter	Symbol	Definition
1	Drainage area	DA	Area that contributes flow to a point on a stream
2	Basin perimeter	L_p	The length measured along the divide of the drainage basin as projected on to the horizontal plane of the map
3	Basin length	L_b	The longest dimension of a basin parallel to the principal drainage line
4	Centroid length	L_{ca}	The length from the basin outlet to a point adjacent to the centroid
5	Form factor	R_{ff}	A dimensionless parameter defined as the ratio of basin area to the square of basin length
6	Circulatory ratio	R_c	A dimensionless parameter defined as the ratio of the basin area of a given order to the area of a circle having a circumference equal to the basin perimeter
7	Elongation ratio	R_e	The ratio of diameter of a circle, Dc with the same area as that of the basin, to basin length
8	Basin shape factor	S_b	The square of straight-line length of basin (from outlet to divide) divided by total area
9	Unity shape factor	R_u	The ratio of the basin length to the square root of the basin area
10	Basin relief	H	The vertical distance between the lowest (outlet) and the highest (divide) points in the basin
11	Relief ratio	R_h	A dimensionless quantity, defined as the ratio of basin relief to the basin length
12	Relative relief	R_p	The ratio of basin relief to the length of the perimeter
13	Basin slope	L_S	Average grid slope of a basin
14	Main channel slope	C_S	Slope of a line drawn along the measured profile of main channel
15	Drainage density	D	The ratio of the total length of all streams within a watershed to the watershed area, and the stream threshold of 1% drainage area threshold is selected
16	Ruggedness number	R_n	Product of relief and drainage density
17	Channel maintenance	C	The ratio of the drainage area to the total of all streams in the network
18	Fineness ratio	R_f	The ratio of channel lengths to the length of basin perimeter
19	Stream frequency	C_f	The total number of streams per unit area
20	10%–85% slope	*Slope*	Average of channel elevations at points 10% and 85% above gage
21	Percentage of water/wetland	*Water*	Percent of basin open water and herbaceous wetland from NLCD
22	Percentage of urban land cover	*ULC*	Percentage of basin with urban development
23	Main channel length	*MCh*	Length of longest flowline—head of stream to watershed outlet
24	Curve number	*CN*	Average curve number weighted by area
25	HKR	*HKR*	$DA/\left(C_S \cdot \sqrt{D}\right)$ (Hickok et al., 1959)
26	Gray	G	$L_{ca}/\sqrt{C_S}$ (Gray, 1961)
27	Murphey	M	S_b/DA (Murphey et al., 1977)
28	Percentage of sinks in DEM	*Sinks*	Percentage of DEM that is filled to allow the water flow downstream

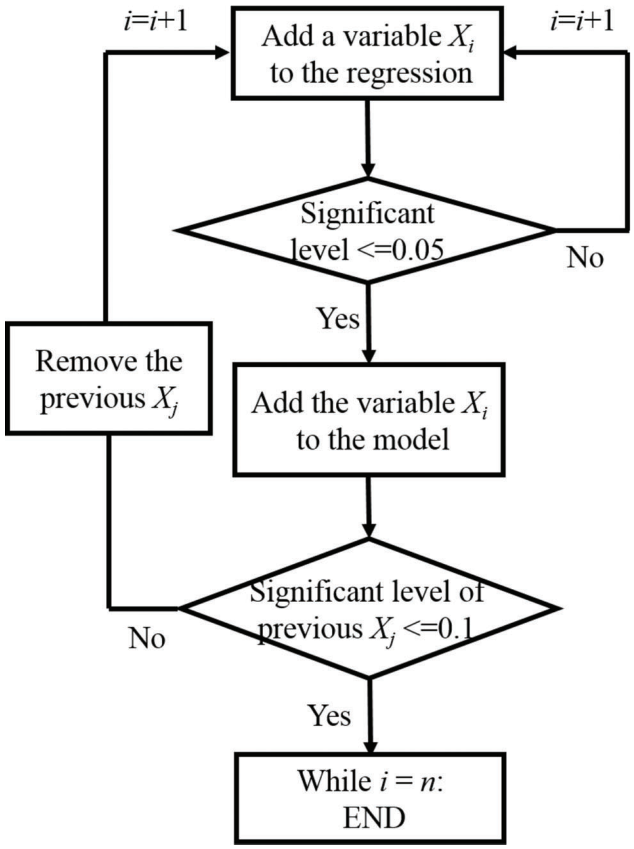


Figure 4.1 Flowchart of the stepwise regression technique.

TABLE 4.2
Types of regression models employed in the study

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_1, …, X_n are independent variables representing the geomorphic parameters, B_0, …, B_n are regression coefficients, and *log* is the logarithm with the base number, 10.

significance at $p = 0.05$. At each step, the p-value of the F-test is computed to test models with and without a potential variable. Specifically, variables are added and removed throughout the process until the procedure tests all variables. The general procedure of the stepwise regression technique is shown in Figure 4.1.

Five types of regression models, presented in Table 4.2, are used to relate the UH parameters with geomorphic attributes. The first type of regression model is a linear model, and the other four are also essentially linear models after the variable transformation. The multiple regression analysis based on the five regression models is performed in two phases in this study. In the first phase, a statewide regression analysis is conducted based on the observed data collected for all the study watersheds in Indiana. In the second phase, watersheds are separated into three groups based on the results from the first phase, including the correlation coefficient between the NRCS UH parameters and the geomorphic attributes. After both the statewide and the regional regression analysis are completed, the regression models with the highest R^2 value and lowest p-value of the F-test are selected for deriving UH.

4.5 Validation of UHs

Once the UH parameters are estimated from the regression model, one of the widely used hydrologic models, the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), is applied to validate the Finley UH at some study watersheds by comparing the resulting hydrograph with available streamflow data. For comparison, results from Finley UH are also compared with hydrographs obtained by using the original NRCS UH method. In this study, seven watersheds (see Table A.4 and Figure 3.1) with different geomorphic characteristics and geographic locations are selected for validation by using rainfall events that are not included in developing the regression models. HEC-HMS models for all watersheds are developed by using a 5% stream network threshold, and the following methods: (1) SCS curve number method for computing excess rainfall; (2) straight-line method for the baseflow separation; (3) pure lag method for the routing and (4) the Finley UH is for converting excess rainfall to direct runoff by using the *PRF* and the lag time obtained from the regression models. Finally, the performance of the original NRCS UH method and the Finley UH for Indiana is compared. Specifically, the validation hydrograph is evaluated in terms of the relative error (*RE*, see Eq. 4.1) of the peak discharge and the time to peak.

$$RE(x) = \frac{x_{sim} - x_{obs}}{x_{obs}} \times 100\% \qquad \text{(Eq. 4.1)}$$

where x_{obs} is the observed variable, and x_{sim} is the simulated variable.

5. RESULTS AND DISCUSSION

5.1 *PRF* and Lag Time for Indiana Watersheds

PRF is computed by deriving UH for all study watersheds using historical rainfall and runoff observations using Eq. 2.1. The red bars in Figure 5.1 represent the observed *PRF* for each study watershed. The mean value of the observed *PRF* is 371 which is considerably lower than the default value of 484. Specifically, among the 30 study watersheds, 24 watersheds have *PRF*s lower than 484; whereas six watersheds have *PRFs* higher than 484. These results clearly show that the default value of 484 is not applicable for many study watersheds. This explains why the default NRCS UH method results in higher peaks for many watersheds in Indiana (Wilkerson & Merwade, 2010).

The lag time computed from UH for each watershed is compared with the NRCS lag time equation and Folmar's equation (see Table A.3). Figure 5.2a shows that the NRCS equation for lag time tends to underestimate the "true" lag time for almost two-thirds of the study watersheds. This leads to underestimation of the time to peak when NRCS UH is used for some watersheds in Indiana (Wilkerson & Merwade, 2010). Moreover, Figure 5.2b shows that Folmar's equation (Folmar & Miller, 2008) leads to either overestimated or underestimated lag times for the study watersheds. Neither NRCS nor Forlmar's equation produces satisfactory estimation of the lag time for the study watersheds in Indiana. To overcome the limitation of using NRCS PRF and lag time, regression analysis is performed to develop expression for estimating these parameters using watershed characteristics. The results from regression analysis are presented in the next section.

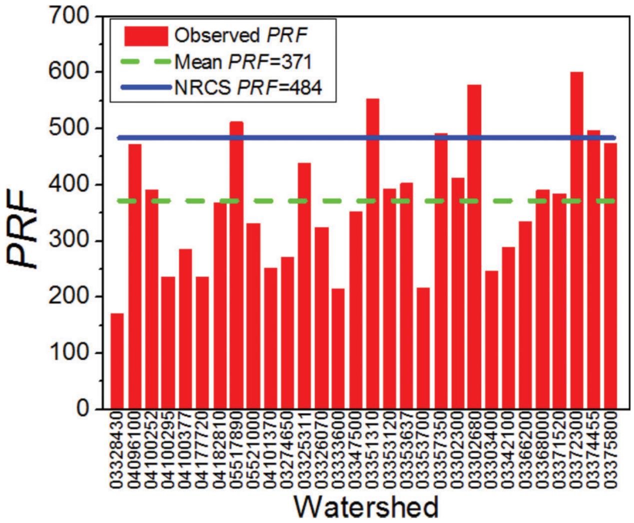
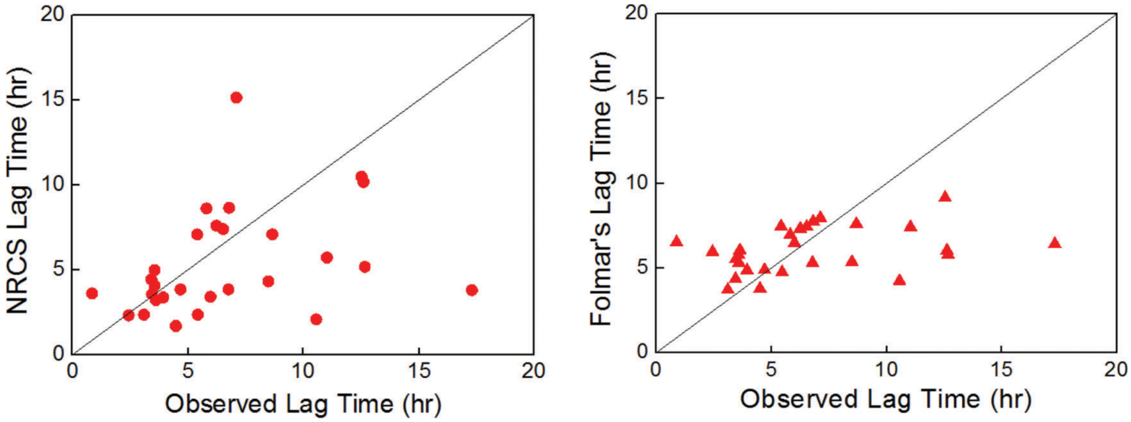


Figure 5.1 Observed *PRF* for study watersheds in Indiana.

5.2 Statewide Regression Analysis

Statewide regression analysis is performed to develop a relationship between NRCS UH parameters (*PRF* and lag time) and geomorphic attributes for all the study watersheds in Indiana by using the five linear regression models presented in Table 4.2. Results, presented in Table 5.1, show that *PRF* is closely related to the main channel slope (*Cs*). This result is consistent with the previous finding that *PRF* is dependent on to the slope characteristic of a watershed (NRCS, 2007). Even though the R^2 of the five models is less than 0.4, the low p-value of the F-test indicates that the models can explain the variability of *PRF* better than the average value, namely, $PRF = 371$.

Generally, Eq. 2.8, which follows the same form of the second regression model in Table 4.2 (also see Eq. 5.1), is used to estimate the lag time of a watershed. Linear regression after the log-transformation for the variables is employed to improve the corresponding coefficients and exponents in the original NRCS lag time equation. The performance of the original equation and the updated equation for all the study watersheds in Indiana is presented in Table 5.2. The updated equation performs slightly better than the original equation. But the low R^2 value and the high p-value indicate that neither the original equation nor the updated equation fits the observed data well. Thus, a new regression analysis for the lag time based on the recent hydrologic data and more watershed attributes is performed in this study. Table 5.3 presents the regression equations for the lag time, and the values of R^2 for the new regression equations are higher than that of the original NRCS lag time equation. The results show that the percentage of sinks is consistently used in the five models, which means the surface storage of a watershed has a significant effect on the lag time. In addition, the urban land cover (*ULC*), which is related to surface permeability, also plays an important role in Model 2 and Model 3. However, the value of



(a) NRCS lag time equation

(b) Folmar's equation (see Table A.3 in Appendix A)

Figure 5.2 Lag time comparison of observed and calculated values.

TABLE 5.1
Statewide regression equations for *PRF*

Regression Equation	Model No.	R^2	*F*-test *p*-value
$PRF = 262 + 35{,}964\ (C_S)$	1	0.33	0.001
$\log(PRF) = 2.13 + 0.32 \log(L_b) + 0.33 \log(C_S)$	2	0.37	0.002
$PRF = 932 + 216 \log(C_S)$	3	0.29	0.002
$\sqrt{PRF} = 13 + 101\sqrt{C_S}$	4	0.31	0.001
$PRF = 166 + 3{,}907\sqrt{C_S}$	5	0.32	0.001

Note: C_S = main channel slope; and L_b = basin length (m).

TABLE 5.2
Regression results for the updated NRCS lag time equation

Model	Regression Equation	R^2	*F*-test *p*-value
NRCS	$\log(T_L) = -3.28 + 0.8 \log(L) + 0.7 \log(S + 1) - 0.5 \log(Y)$	0.16	0.20
Updated	$\log(T_L) = -2.4 + 0.52 \log(L) + 1.23 \log(S + 1) - 0.28 \log(Y)$	0.19	0.13

TABLE 5.3
Statewide regression equations for lag time

Regression Equation	Model No.	R^2	*F*-test *p*-value
$T_L = 2.09 + 1.09(Sinks)$	1	0.46	<0.001
$\log(T_L) = 0.47 - 0.1 \log(ULC) + 0.52 \log(Sinks)$	2	0.39	0.001
$T_L = 1.02 - 2.36 \log(ULC) + 11.19 \log(Sinks)$	3	0.45	<0.001
$\sqrt{T_L} = 0.96 + 0.77\sqrt{Sinks}$	4	0.41	<0.001
$\sqrt{T_L} = -3.02 + 5.02\sqrt{Sinks}$	5	0.41	<0.001

Note: *Sinks* = percentage of sinks in DEM; and *ULC* = percentage of basin with urban development.

R^2 is still less than 0.5, and hence regional regression analysis is performed.

$$\log(T_L) = B_0 + B_1 \log(L) + B_2 \log(S+1) + B_3 \log(Y) \qquad \text{(Eq. 5.1)}$$

where $B_0 = \log(1/1{,}900) = -3.28$, $B_1 = 0.8$, $B_2 = 0.7$, and $B_3 = -0.5$.

5.3 Regional Regression Analysis

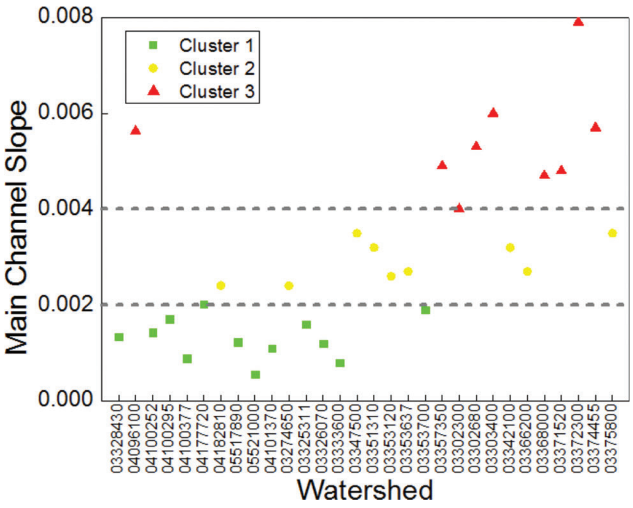


Figure 5.3 Classification of study watersheds based on main channel slope.

Since the main channel slope is consistently involved in the statewide regression equations of *PRF*, all study watersheds in Indiana are classified into three clusters based on the main channel slope for further regional regression analysis. Three clusters based on channel slope between 0 to 0.002, 0.002–0.004, and 0.004 and above are formed as shown in Figure 5.3. Regression analysis is then performed on each cluster to get equations for *PRF* (Table 5.4) and lag time (Table 5.5). The R^2 values of the regional models are higher than that of the statewide models in Tables 5.1 and 5.3. The results from regional analysis also show that the *PRF* of flat watersheds ($Cs \leq 0.004$) is related to flow length, stream network, and curve number, whereas, for steep watersheds ($Cs > 0.004$), the *PRF* is related to geomorphic and geometric attributes, including watershed relief, drainage density, and basin shape factor.

TABLE 5.4
Proposed regression equations for *PRF*

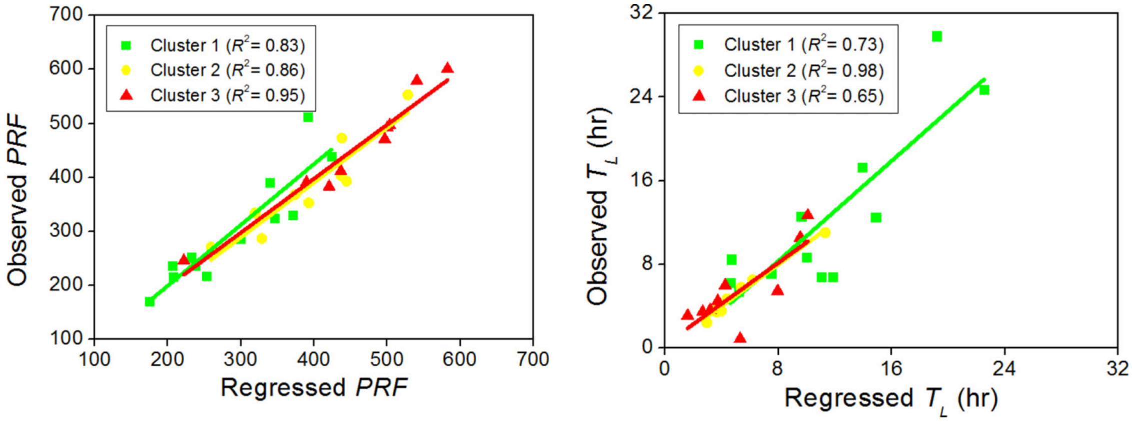
Regression Equation	Region	R^2	*F*-test *p*-value
$\log(PRF) = -2.1 - 1.8\log(L_p) + 4.3\log(L_b) - 1.5\log(L_{ca}) - 0.8\log(R_n) + 0.6\log(L_s)$	$Cs \leq 0.002$	0.83	0.025
$\sqrt{PRF} = -215.17 + 0.21\sqrt{L_b} - 0.61\sqrt{C} + 26.1\sqrt{CN}$	$0.002 < Cs \leq 0.004$	0.86	0.04
$PRF = -1{,}925 + 8{,}820R_n + 1.34C + 3{,}282M$	$Cs > 0.004$	0.95	0.001

Note: L_p = basin perimeter; L_b = basin length; L_{ca} = length from the basin outlet to a point adjacent to the centroid; R_n = ruggedness number; L_s = basin slope; C = channel maintenance; CN = curve number; $M = S_b / DA$, where S_b = basin shape factor, and DA drainage area.

TABLE 5.5
Proposed regression equations for lag time

Regression Equation	Region	R^2	*F*-test *p*-value
$\sqrt{T_L} = 28.68 + 0.022\sqrt{L_p} + 1.04\sqrt{Slope} - 3.81\sqrt{CN}$	$Cs \leq 0.002$	0.73	0.019
$T_L = -94.53 + 17.22\log(L_p) - 15.91\log(R_n)$	$0.002 < Cs \leq 0.004$	0.98	<0.001
$T_L = 42.94 - 0.53(CN)$	$Cs > 0.004$	0.65	<0.001

Note: L_p = basin perimeter; $Slope$ = 10% − 85% slope; CN = curve number; and R_n = ruggedness number.



(a) PRF (b) Lag time

Figure 5.4 Comparison of regressed parameters from regional models and observed values.

The values of R^2 of the regional models for lag time are also higher than that of the statewide models. The results show that lag time is mainly related to the basin perimeter, the channel slope, and the curve number. Visual comparisons between the regressed parameters of Finley UH from the regional regression equations for the watersheds in each cluster and the observed values are also shown in Figure 5.4. Additionally, it should be noted that the regional regression equations may not work well if they are used with variables outside the applicable ranges, which are presented in Table 5.6.

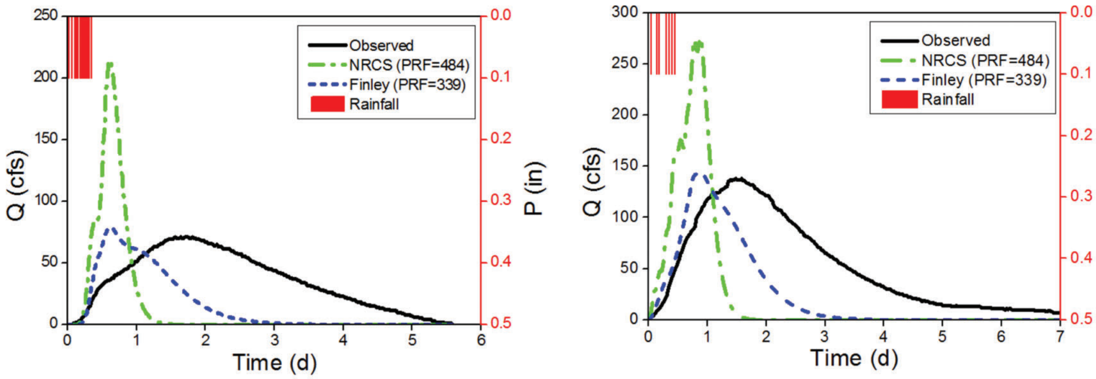
5.4 Validation of Finley UHs

Seven study watersheds with different main channel slopes located from north to south in Indiana are selected for the validation of custom (Finley) UHs that are derived based on the parameters estimated from the regression models. The performance of the original NRCS UH method and the Finley UHs are compared with the observed hydrograph as shown in Figure 5.5 and Table 5.7. The validation results of the Forker Creek (Figures 5.5 a and b), the Rimmel Branch (Figures 5.5 c and d), and the Kokomo Creek (Figures 5.5 e and f) show that the hydrographs obtained through the Finley UH matches the observed data better than the original NRCS UH in terms of the predictions of the peak discharge and the time to peak. The validation results of the other watersheds show that the performances of both the Finley and NRCS UHs are equally good since the regressed parameters are close to the default values. Specifically, the relative error of peak discharge predicted from the Finley UH is within 12%, compared with 203% from the NRCS method. The relative error of peak time predicted from

TABLE 5.6
Applicable range for geomorphic attributes in regional regression equations

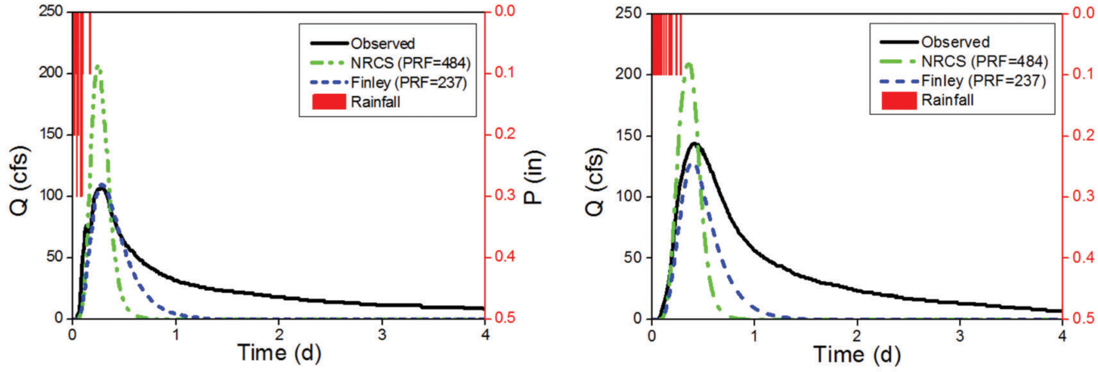
Region	Attribute	Unit	Maximum	Minimum
$Cs \leq 0.002$	L_p	m	91,260	37,440
	L_b	m	23,155	8,974
	L_{ca}	m	13,790	2,568
	R_n	/	0.053	0.016
	L_s	%	3.95	0.45
	Slope	ft/mi	12.10	3.00
	CN	/	84	71
$0.002 < Cs \leq 0.004$	L_b	m	16,573	5,520
	C	m	1,341	608
	CN	/	80	75
	L_p	m	81,540	29,340
	R_n	/	0.091	0.046
$Cs > 0.004$	R_n	/	0.084	0.153
	C	/	419	1,053
	M	1/mi^2	0.033	0.331
	CN	/	78	62

the Finley UH is within 25%, compared with 38% from the NRCS method, except for the extreme events of the Forker Creek, in which the prediction of the time-to-peak is poorer (relative error = -41% or -61%) compared with other watersheds. The large deviation might be due to the non-uniform spatial and temporal distribution of the rainfall and the complicated process of surface flow over this flat watershed. Overall, the validation results show the Finley UH provides improved simulation of runoff hydrographs at locations where NRCS predictions are poorer compared to the observed data.



(a) Forker Creek (Event-1)
(Gauge ID: 04100252)

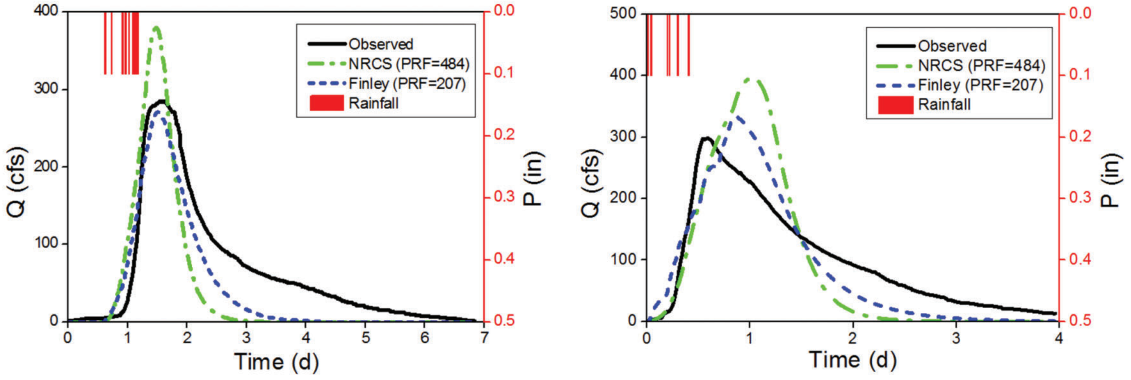
(b) Forker Creek (Event-2)
(Gauge ID: 04100252)



(c) Rimmel Branch (Event-1)
(Gauge ID: 04100295)

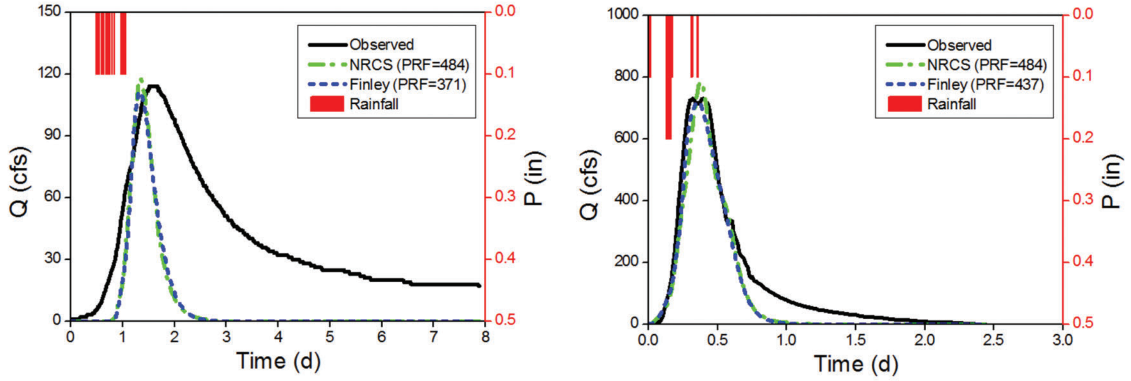
(d) Rimmel Branch (Event-2)
(Gauge ID: 04100295)

Figure 5.5 Continued to next page.



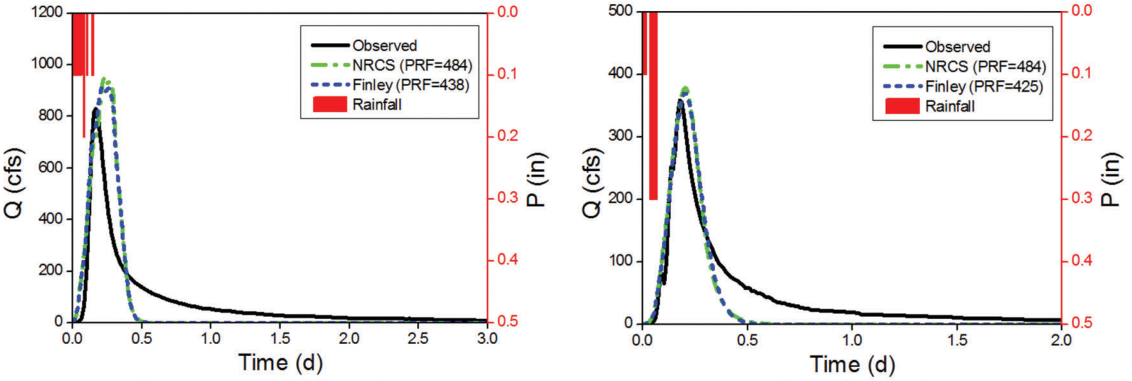
(e) Kokomo Creek (Event-1)
(Gauge ID: 03333600)

(f) Kokomo Creek (Event-2)
(Gauge ID: 03333600)



(g) Iroquois Creek
(Gauge ID: 05521000)

(h) Little Buck Creek
(Gauge ID: 03353637)



(i) West Fork Blue River
(Gauge ID: 03302680)

(j) Hall Creek
(Gauge ID: 03375800)

Figure 5.5 Validation hydrographs for study watersheds in Indiana.

TABLE 5.7
Comparison of peak discharge and time to peak from NRCS and Finley UH

Validation Watershed	Observed Peak Discharge (cfs)	Simulated Peak Discharge		Observed Time to Peak (hr)	Simulated Time to Peak	
		NRCS	Finley UH		NRCS	Finley UH
Forker Creek (Event-1)	71.0	214.9 (203%)	79.3 (12%)	37.5	14.8 (-61%)	14.8 (-61%)
Forker Creek (Event-2)	138.0	276.1 (100%)	144.9 (5%)	35.5	21.0 (-41%)	21.0 (-41%)
Rimmel Branch (Event-1)	107.0	207.5 (94%)	109.6 (2%)	6.5	6.0 (-8%)	6.8 (4%)
Rimmel Branch (Event-2)	144.0	208.8 (45%)	129.2 (-10%)	9.8	8.5 (-13%)	9.5 (3%)
Kokomo Creek (Event-1)	284.5	379.8 (33%)	270.9 (-5%)	37.3	35.5 (-5%)	36.3 (-3%)
Kokomo Creek (Event-2)	298	396.3 (33%)	333.8 (12%)	14.0	25.0 (79%)	20.8 (48%)
Iroquois River	114.0	117.9 (3%)	111.6 (-2%)	36.5	32.5 (-11%)	32.0 (-12%)
Little Buck Creek	731.5	785.1 (7%)	721.6 (-1%)	7.8	9.0 (16%)	8.5 (10%)
Hall Creek	831.0	953.0 (15%)	912.5 (10%)	4.0	5.5 (38%)	5.0 (25%)
West Fork Blue River	358.7	378.3 (5%)	370.1 (3%)	4.3	4.8 (12%)	4.8 (12%)

Note: The number in parenthesis is the relative error (see Eq. 4.1) of the variable of interest.

6. CONCLUSIONS

Accurate prediction of hydrographs is critical for engineering design and flood prevention. Given the limitations of the widely used original NRCS UH method for Indiana, basic theory and recent advances of this method have been comprehensively reviewed in this study. Considering the complexity of a hydrologic system associated with different watershed characteristics, statewide and regional regression models, based on the recent observed rainfall-runoff data and geomorphic properties, are developed to derive customized, referred as Finley, UHs for the ungauged watersheds in Indiana. The following conclusions are drawn from this study.

1. Derivation of unit hydrographs for the 30 study watersheds using data from last 20 years show that the mean value of the *PRF* is 371, which is lower than the default *PRF* of 484. Additionally, the lag time obtained from the derived UHs is higher than the lag time estimated by the NRCS lag time equation.
2. 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 urban land cover. Regional regression analysis, where regions are created based on the channel slope, shows that the *PRF* of flat watersheds depends on the flow length and the stream network, whereas the *PRF* for steep watersheds depends on the ruggedness and basin shape. The lag time is primarily related to the channel slope, the basin relief, and the curve number.
3. Validation results indicate that the performance of custom UH is better compared with the original NRCS UH method for the watersheds in Indiana in terms of the predictions of peak discharge and time to peak.

Although the Finley UH can improve the performance of the original NRCS UH method to some extent, it is important to note that the NRCS UH is derived based on some specific assumptions and hence the method itself has inherent limitations. Based on the validation hydrographs, neither NRCS nor the Finley UHs produce good prediction of the recession limb of the hydrograph. In addition, the prediction accuracy of the time-to-peak time still needs to be improved especially for flat watersheds. Specifically, it is noted that the runoff process resulting from the rainfall over a watershed surface includes overland flow and channel flow (Chow et al., 1988). The UH parameters should contain the time it takes for both the flow types and each of them is governed by different physical principles of continuity and momentum. However, the application of these principles is only limited in some simplified situations.

The regression models developed in this study do not satisfy the homogeneity principle of dimensional analysis, which should be based on a more comprehensive understanding of the runoff process and its interaction with the geomorphic conditions of the watershed. Additionally, it should be noted that the regional regression equations might be only applicable for the value ranges of the corresponding attributes for relatively small rural watersheds. This study primarily focuses on modifying the NRCS UH method, but the general idea can also be employed to enhance the performance of other traditional SUH approaches or develop new rainfall-runoff models. Overall, the Finley UH overcomes the limitation of the application of the original NRCS UH method for some watersheds in Indiana, and more studies for the other areas of the United States need to be performed for the further and wider applications of the customized NRCS UH.

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APPENDICES

Appendix A. Tables

Appendix B. Introduction to Graphical User Interface (GUI) for Applications of Indiana NRCS Unit Hydrograph (Finley Unit Hydrograph)

APPENDIX A. TABLES

Table A.1 Summary of applications of NRCS UH method

Location	Watershed Characteristics	Results
Six watersheds in Iowa, Illinois, and Ohio, USA	Drainage Area: 5.42–39.3 mile^2 Length of main channel: 4.45–18.1 mile Average slope of main channel: 0.22%–0.98%	Three SUH methods (NRCS, Gray's, and Snyder's) were employed to the hydrograph prediction for comparison. The NRCS and Gray's SUH methods performed better on the prediction than Snyder's method, but the variation of predictions still existed due to the assumption of these methods (Hanson & Johnson, 1964).
Six watersheds in the Canterbury area, New Zealand	Drainage Area: 0.85–201.16 mile^2 Length of main channel: 1.43–24.48 mile Average slope of main channel: 1.6%–15.8%	Three SUH methods (NRCS, Common's, and Snyder's) were applied to the hydrograph prediction for comparison. Snyder's method performed best for the peak discharge prediction in the study watersheds (Hoffmeister & Weisman, 1977).
Four watersheds in Delmarva Peninsula, USA	Drainage Area: 5–60 mile^2 Average watershed slope: 2%–5% Land use: Agricultural coastal plain	The average Delmarva UH with the *PRF* of 284 gave better estimates than the standard NRCS UH, which yielded higher peak discharges than the measured values (McCuen & Bondelid, 1983; Welle & Woodward, 1989; Woodward et al., 1980).
One watershed in Hubei province, China	Drainage Area: 9.73 mile^2 Land use: Forested, hilly, and agricultural area Curve number: 84	It was the first application of the NRCS model (curve number and UH method) in Hubei, China. The results showed that peak discharge matched the measured value very well (Mu, 1992).
Seven watersheds in Utah, USA	Drainage Area: 13–39 mile^2 Average watershed slope: 6.32%–14% Land use: Arid and semiarid area	Two-thirds of Utah watersheds had *PRF* values much smaller than the standard value, which indicated that the NRCS UH method may overestimate the peak flow for some watersheds in Utah (Shammet, 1995).
Eight experimental watersheds in the southeastern US	Drainage Area: 2.6–49.9 mile^2 Land use: Agricultural coastal plain and flatwoods area	The mean *PRF* for the eight watersheds ranged from 174 to 476, which indicated that a single SUH was not applicable for watersheds in

Location	Watershed Characteristics	Results
		coastal regions of the southeastern US (Sheridan et al., 2002).
Seventeen experimental watersheds in different parts of Turkey	Drainage Area: 0.13–38 mile^2 Average watershed slope: 0.3%–30% Length of main channel: 0.8–11 mile Curve number: 67–88	The new suggested *PRF* value for the watersheds across Turkey was between 447 to 768, and the mean value is 607. The new suggested ratio of time to recession and time to peak was between 0.45 and 2.23, and the mean value is 1.34. However, the corresponding value of the standard NRCS UH method is 484 and 1.67, respectively (Istanbulluoglu et al., 2004).
Ninety watersheds in central Texas, the US	Drainage Area: 0.33–116 mile^2 Length of main channel: 0.46–45.07 mile Slope of main channel: 8.67–83.64 ft/mile	It was found that the mean *PRF* for the study watersheds in Texas is 370 with a standard deviation of 76 (Fang et al., 2005).
Eight watersheds in Ogun-Osun river basin, Nigeria	Drainage Area: 17.76–7876.48 mile^2 Length of main channel: 7.33–372.82 mile Slope of main channel: 0.07%–0.59% Mean curve number: 75	The NRCS UH, Gray’s method, and Snyder’s method were adopted to compute the peak discharge for the study area. The difference between the results obtained from these three methods varied from each other. The results for the larger watershed have a higher variance (Salami et al., 2009; Salami et al., 2017).
Seven small watersheds in Indiana, USA	Drainage Area: 10.96–38.14 mile^2 Land use: Agricultural land Curve number: 71–79	The NRCS UH method yielded high peak flows and short time to peaks for the northern region in the state of Indiana (Wilkerson & Merwade, 2010).
One watershed in Maghalaya, India	Drainage Area: 135.135 mile^2 Curve number: 50 Length of main channel: 32.19 mile	The NRCS UH method overestimated the peak discharge, underestimated the rising limb, and closely matched with the recession limb of the hydrograph (Bhunya et al., 2011).
Six watersheds in Makkah metropolitan area, Saudi Arabia	Drainage Area: 28–139 mile^2 Curve number: 83–93 Length of main channel: 10–30 mile	Since the NRCS UH method incorporated several characteristics of the area of interest, it was applied to the ungauged watersheds in the southwestern Saudi Arabia (Dawod & Koshak, 2011).
Two watersheds in Barak basin, India	Drainage Area: 135 mile^2 and 158 mile^2 Average watershed slope: 28% and 9.8%	For the study watersheds without landcover data, the NRCS UH method

Location	Watershed Characteristics	Results
	Length of main channel: 32.69 mile and 30.40 mile	was applied with Kirpich formula, which gave a similar peak discharge and time to peak compared with the geomorphological instantaneous unit hydrograph results (Choudhury & Nongthombam, 2012).
One experimental watershed at Tombstone of Arizona, USA	Drainage Area: 2.7 mile^2 Land use: semi-arid and rangeland area	Eleven rainfall-runoff events were selected and simulated in HEC-HMS using the kinematic wave method and the NRCS UH method, respectively. The results showed that the NRCS method consistently underestimated the peak discharge and overestimated the time to peak, and the former method was more accurate than the latter one for the study watershed (Syed et al., 2012).
One watershed in East Azarbayjan province, Iran	Drainage Area: 29.42 mile^2 Average watershed slope: 11% Length of main channel: 10.56 mile	The NRCS UH method could estimate the peak value and time to peak, but the result did not match the actual time of base (Ghorbani et al., 2013).
Slonka watershed in the Malopolska province, Poland	Drainage Area: 3.38 mile^2 Length of main channel: 4.5 mile Land use: Agricultural lands and forests Curve number: 50–69	Flow hydrographs obtained using NRCS UH method were characterized by the long time to peak, low peak flows, and a flattened curve, which is not standard in the mountain rivers such as the Słonka (Pietrusiewicz et al., 2014).
Boukhalef watershed in northwestern Morocco	Drainage Area: 18.66 mile^2 Average watershed slope: 10.4% Land use: Semi-rural land, followed by forest and urban area Mean curve number: 74.88	The NRCS UH method in HEC-HMS was employed to predict the design peak flow with different return periods in an ungauged watershed (Khaddor et al., 2017).
Two watersheds in Indonesia	Drainage Area: 90.54 mile^2 and 469.6 mile^2 Average watershed slope: 10%–20%	By conducting simulations in HEC-HMS, it did not necessarily yield better results to use varied *PRF* values in the watershed model but make the model more complete compared to the result with the standard *PRF* of 484 (Cahyono & Adidarma, 2019).
Five sub-basins in upper Ciliwung watershed, Indonesia	Drainage Area: 1.03–6.46 mile^2 Length of main channel: 191–5,476 mile Average watershed slope: 9.5%–46% Land use: Rural and urban area	The performances of the NRCS UH method and the Kinematic wave method in HEC-HMS were employed for the hydrograph simulation in the

Location	Watershed Characteristics	Results
	Curve number: 76–83	same study watersheds. The results showed that the former method was more suitable for rural areas (Sharaswati et al., 2019).
Seven sub-basins in Marshyangdi river watershed, Nepal	Drainage Area: 120–349 mile^2 Average watershed slope: 29° Land use: Snow (29.6%), forest (23.5%), grass land (19.0%), barren area (12.7%) and agricultural area (10.3%)	The NRCS curve number method and dimensionless UH method in HEC-HMS were employed to simulate the streamflow for each sub-basin of Marshyangdi watershed, which yielded satisfactory and acceptable results (Paudel et al., 2019).
One watershed in Sichuan province, China	Drainage Area: 136.68 mile^2 Length of main channel: 30.45 mile Land use: Forest (92%), bare land (4%) and water (2%)	The NRCS UH method in HEC-HMS was adopted to simulate the flash flood hydrographs in the mountainous watershed in China (Tu et al., 1992).
One watershed in the St. Louis Metropolitan, USA	Drainage Area: 105.7 mile^2 Length of main channel: 39.7 mile Land use: Agricultural area (60%–58%) and developed area (26%–29%)	The NRCS UH method in HEC-HMS was employed in the case study to examine the impact of land use changes on the peak discharges (Hu & Shrestha, 2020).
One watershed in the upper Vistula river catchment, Poland	Drainage Area: 33.2 mile^2 Land use: Forests (73%), meadows and pastures (14%), and agricultural area (7%)	The NRCS UH, Snyder's method, and EBA4SUB were employed to determine the runoff hydrograph for comparison. The third model was suggested to be an alternative to the traditional ones due to the lower relative error of the peak flow estimation (Młyński et al., 2020).

Table A.2 History course for use of Gamma function in SUH derivation

Progress	Equations
The Gamma function was employed to quantify the proportional relationship between Q and $t^x e^{-yt}$ (Edson, 1951).	$$Q = \frac{CAy(yt)^x e^{-yt}}{\Gamma(x+1)}$$ Q = discharge in cfs at time t in days. C = 242/9, unit conversion factor. A = drainage area in mile^2. x, y = constants for the UH. $\Gamma(x+1)$ = Gamma function of x+1.
The instantaneous UH was expressed in the form of Gamma function based on the concept model of n-linear reservoirs with the same storage coefficient K (Dooge, 1959; Nash, 1959). K and n can be estimated by the regression model related	$$q = \frac{1}{K\Gamma(n)}\left(\frac{t}{K}\right)^{n-1} e^{-t/K}$$ q = direct runoff depth per unit time per unit effective rainfall.

Progress	Equations
to the watershed characteristics (Nash, 1960; Wu, 1963).	K, n = parameters defining the shape of IUH. Compared with the equation above (Edson, 1951), $K = 1/y$ and $n = x+1$.
The two-parameters Gamma distribution was used to fit the SUH (Croley, 1980), and related the values from the hydrograph (Aron & White, 1982). It could be derived that $\frac{q(t)}{Q_P} = e^{(1-t/T_P)\alpha}\left(\frac{t}{T_P}\right)^{\alpha}$ is exactly the same as Eq. 2.12 recommended by NRCS (NRCS, 2007), where $\alpha = m$. When $\alpha = m = 3.7$, the values given by this equation are very close to the dimensionless hydrograph ordinates given by NRCS, which was, however, developed using graphical techniques based on observed rainfall-runoff events.	$f(t) = \frac{t^{\alpha}e^{-t/\beta}}{\beta^{\alpha+1}\Gamma(\alpha+1)} = \frac{q(t)}{645.33A}$ $T_P = \alpha\beta$ $f(T_P) = \frac{\alpha^{\alpha+1}e^{-\alpha}}{T_P\Gamma(\alpha+1)} = \frac{Q_P}{645.33A}$ $\phi(\alpha) = \frac{\alpha^{\alpha+1}e^{-\alpha}}{\Gamma(\alpha+1)} = \frac{Q_P T_P}{645.33A}$ $f(t)$ = direct runoff depth per unit time per unit effective rainfall, namely q in the equation above. α = dimensionless parameter. β = parameter with the dimension of time. Compared with the equation above (Nash, 1959), $\alpha = n-1$ and $\beta = K$. ϕ = dimensionless function of the gamma parameter α.
Based on previous methods, some other attempts to calculate the Gamma function parameter α from ϕ were conducted and vice versa.	$\alpha = 0.045 + 0.5\phi + 5.6\phi^2 + 0.3\phi^3$ (McCuen, 1989) $\alpha = 2 + 6.5\left(\frac{Q_P T_P}{V}\right)^{1.92}$ (Haan et al., 1994) V = total volume of effective rainfall. $\alpha = 0.09 + 0.164\phi + 6.19\phi^2$ (Singh, 1998) $\alpha = \frac{1}{6} + 2\pi\phi^2$ (Singh, 2000) $\alpha = 5.53\phi^{1.75} + 0.04\ (0.01 < \phi < 0.35)$ $\alpha = 6.29\phi^{1.998} + 0.157\ (\phi \geq 0.35)$ (Bhunya et al., 2003)
The relationship between the *PRF* in the NRCS UH and the Gamma function parameter ϕ was constructed, and it shows that the *PRF* is directly related to ϕ, and different UH are corresponding to different values of *PRF* (Singh, 2000).	$\phi = \frac{PRF}{645}$
The two-parameter Gamma function and the equations from Bhunya et al. (2003) were employed to develop regional UH of ninety watersheds in Texas and the relationship between	$\phi = \frac{Q_P T_P}{645.33A} = \frac{PRF}{645.33}$ $Q_P = 46.99A^{0.910}L^{-0.219}{L_S}^{0.707}$

Progress	**Equations**
the *PRF* and the Gamma function parameters α was also identified (Fang et al., 2005).	$T_P = 2.65A^{0.134}L^{-0.089}{L_S}^{-0.317}$ (for $A < 10$ mile^2) $T_P = 34.82A^{0.431}L^{-0.491}{L_S}^{-0.970}$ (for $A > 10$ mile^2) L = length of main channel (mile) L_S = slope of main channel (ft/mile)

Table A.3 Other equations for computing lag time or time of concentration

Study Area	**Equation for T_L or T_C**
Seven rural watersheds in Tennessee (Kirpich, 1940)	$T_C = 0.0078L^{0.77}Y^{-0.385}$ (in min) L = length of channel, ft Y = average watershed slope, ft/ft
Small mountainous watersheds in California (Rowe & Thomas, 1942)	$T_C = 60(11.9L^3/H)^{0.385}$ (in min) L = length of the longest watercourse, mile H = elevation difference between divide and outlet, ft
Laboratory experiments for overland flow on the roadway and turf surfaces (Izzard & Hicks, 1946)	$T_C = \frac{41.025(0.0007i+c)L^{0.33}}{{L_S}^{0.333}i^{0.667}}$ (in min) i = rainfall intensity, in/h c = retardance coefficient L = length of flow path, ft Ls = slope of flow path, ft/ft
A very small watershed with flow lengths less than 1,000 ft (Kerby, 1959)	$T_C = \left[\frac{2.2nL_C}{Y^{0.5}}\right]^{0.324}$ (in min) n = Manning's channel roughness coefficient Lc = length of channel, ft Y = average watershed slope, ft/ft
Nighty flood events from several British watersheds with areas ranging from 4.8 to 859 mile^2 (Nash, 1960)	$T_L = 27.6A^{0.3}Y^{-0.3}$ (in hr) A = watershed area, mile^2 Y = average watershed slope, parts per 10,000
Seventeen small watersheds in Indiana (Wu, 1963)	$T_L = 780A^{0.94}{L_0}^{-1.47}{L_S}^{-1.47}$ (in hr) A = watershed area, mile^2 L_0 = main channel length, mile Ls = average slope of stream, ft/mile
Small watersheds in Texas and Ohio (Mockus, 1972)	$T_C = 2.4A^{0.6}$ (in hr) applicable in Texas

Study Area	Equation for T_L or T_C
	$T_C = 0.9A^{0.6}$ (in hr) applicable in Ohio A = watershed area, mile^2
84 small rural watersheds with drainage areas less than 0.8 mile^2 in the USA (Papadakis & Kazan, 1987)	$T_C = 0.66L^{0.5}n^{0.52}Ls^{-0.31}i^{-0.38}$ (in min) L = length of the longest waterway, ft n = Manning's channel roughness coefficient Ls = slope of the flow path, ft/ft i = intensity of the excess rainfall, in/h
168 small watersheds, most of which are agricultural areas, with areas ranging from 0.243 to 3,490 acres across the USA (Simas, 1996)	$T_L = 0.0051W^{0.5937}Y^{-0.1505}S^{0.3131}$ (in hr) W = watershed width, ft Y = average watershed slope, ft/ft S = maximum potential retention
52 agricultural and forested watersheds with areas less than 20 mile^2 located in nine states of the USA (Folmar & Miller, 2008)	$T_L = L^{0.65}/83.4$ (in hr) L = length of the longest waterway, m

Note: The various methods in the table above may use different units in order to maintain the form of equations as published by the author.

Table A.4 List of study watersheds in Indiana, USA

No.	River	USGS Gauge ID	Drainage Area (mile^2)	Main Channel Slope
1	Weesau Creek	03328430	9.3	0.0013
2	Galena River	04096100	17.9	0.0056
3	Forker Creek[1]	04100252	19.3	0.0014
4	Rimmell Branch[1]	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[1]	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[1]	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[1]	03353637	17.1	0.0027
19	West Fork White Lick Creek	03353700	28.9	0.0019

No.	River	USGS Gauge ID	Drainage Area (mile^2)	Main Channel Slope
20	Plum Creek	03357350	3.0	0.0049
21	Little Indian Creek	03302300	17.1	0.0040
22	West Fork Blue River[1]	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[1]	03375800	21.7	0.0035

[1] Represents the watersheds used for validation.

APPENDIX B. INTRODUCTION TO GRAPHICAL USER INTERFACE (GUI) FOR APPLICATIONS OF INDIANA NRCS UNIT HYDROGRAPH (Finley Unit Hydrograph)

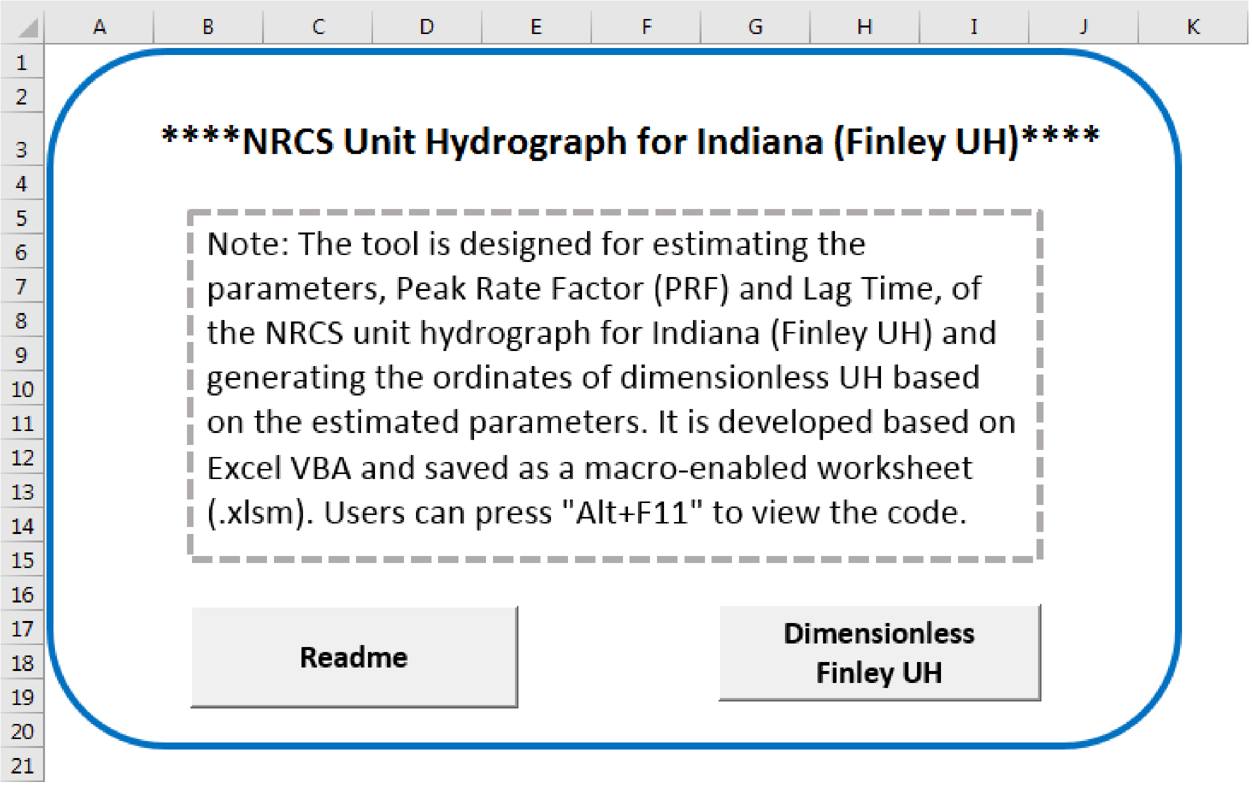
B.1 Introduction

This document is associated with the technique report *Developing Customized NRCS Unit Hydrographs for Ungauged Watersheds in Indiana* and works as a general guide for the applications of Finley Unit Hydrograph (UH) by using the graphical user interface (GUI) developed based on Excel VBA or Python. To simplify the application process, 2,052 watersheds with a mean area of 17 mile^2 are delineated for the whole state of Indiana using the Arc Hydro tools in ArcGIS. Then the UH parameters (*PRF* and Lag Time) of each delineated watershed are estimated based on the regional regression equations presented in the report mentioned above. Therefore, the UH parameters given a specific point within Indiana are obtained from the values corresponding to the nearest drainage point of the delineated watershed. The following sections will describe the features of these two GUIs in detail. Also, these two GUIs are available at GitHub (see the link below).

https://github.com/huan1441/GUIs-for-Indiana-NRCS-Unit-Hydrograph

B.2 GUI based on Excel VBA for applications of Finley UH

This version of GUI is an Excel file that contains three spreadsheets (see Figure B.1), which are "Welcome," "Finley UH Parameters" (see Table B.1), and "Finley UH." The tool is designed for estimating the parameters (*PRF* and Lag Time) of Finley UH and generating the ordinates of dimensionless UH based on the estimated parameters. It is developed based on Excel VBA and saved as a macro-enabled worksheet (*.xlsm). Interested users can press "Alt+F11" to view the Basic code in the Excel file.


****NRCS Unit Hydrograph for Indiana (Finley UH)****

Note: The tool is designed for estimating the parameters, Peak Rate Factor (PRF) and Lag Time, of the NRCS unit hydrograph for Indiana (Finley UH) and generating the ordinates of dimensionless UH based on the estimated parameters. It is developed based on Excel VBA and saved as a macro-enabled worksheet (.xlsm). Users can press "Alt+F11" to view the code.

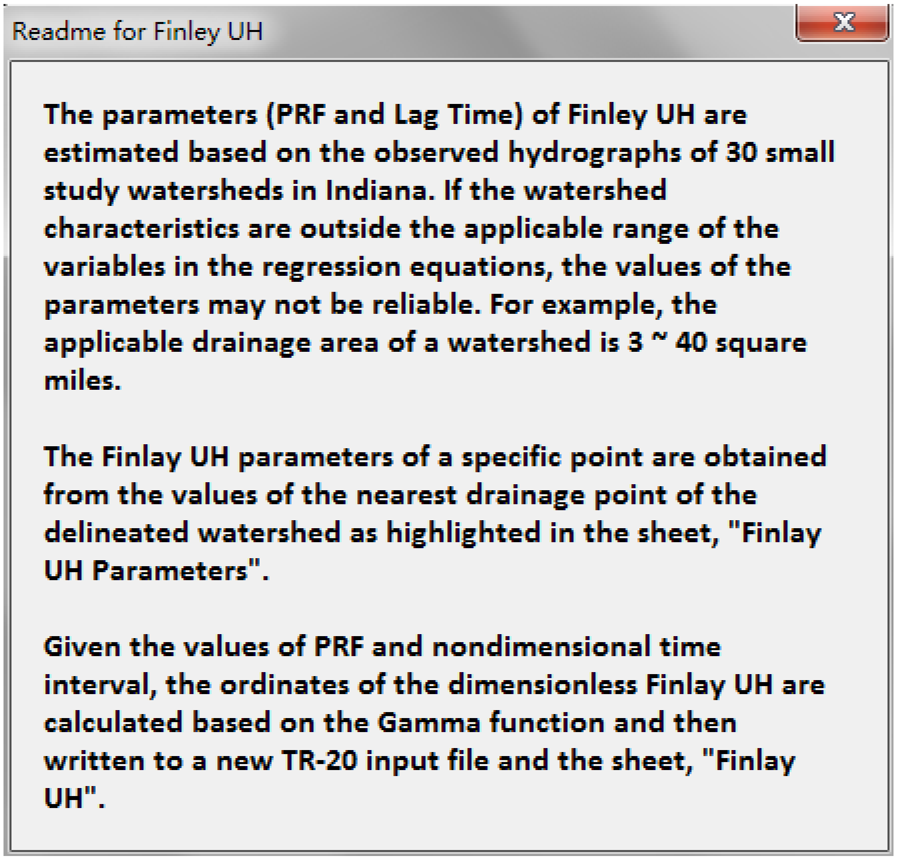
Figure B.1 Excel spreadsheets for applications of Finley UH.

Table B.1 Data structure in the spreadsheet “Finley UH Parameters”

North Latitude (°)	West Longitude (°)	*PRF*	Lag Time (hours)	Variable (1)	Variable (2)	Variable (…)
41.7655	86.6564	327	5.21	–	–	–
41.6865	86.8439	313	6.85	–	–	–
41.7290	86.9141	286	7.41	–	–	–
41.6865	86.8442	751	4.83	–	–	–
41.6788	87.0634	324	4.44	–	–	–
–	–	–	–	–	–	–

There are two buttons in the “Welcome” spreadsheet, namely, “Readme” and “Dimensionless Finley UH”. Once users click on the left button, an interface (see Figure B.2) will pop up to show a brief introduction to the tool. It stated that the parameters (*PRF* and Lag Time) of Finley UH are estimated based on the observed hydrographs of 30 small study watersheds in Indiana. If the watershed characteristics are outside the applicable range of the variables in the regression equations, the values of the parameters may not be reliable. For example, the applicable drainage area of a watershed is 3 ~ 40 mile^2. The Finley UH parameters of a specific point are obtained from the values of the nearest drainage point of the delineated watershed as highlighted in the spreadsheet, Finley UH Parameters. Given the values of *PRF* and nondimensional time interval, the ordinates of the dimensionless Finley UH are calculated based on the Gamma function and then written to the spreadsheet, “Finley UH,” and the contact email. After clicking on the right button in the “Welcome” spreadsheet, an interface (see Figure B.3) will pop up for the input of the location of a site of interest and the nondimensional time interval, and then the Finley UH parameters of the given point are obtained from the values of the nearest drainage point of the delineated watershed, which will be highlighted in red in the spreadsheet “Finley UH Parameters.” And then users can get the ordinates of a dimensionless Finley UH based on the estimated parameters through the GUI as well as in a new TR-20 input file under the working directory and the spreadsheet “Finley UH” for further applications.

Additionally, this GUI includes some basic error-checking features. For example, after clicking on the “Run” button, if the given latitude or longitude of an outlet is falling outside of Indiana or users did not enter anything or accidentally entered the non-numerical characters, the GUI will pop up a message window to remind users to reenter the correct information.

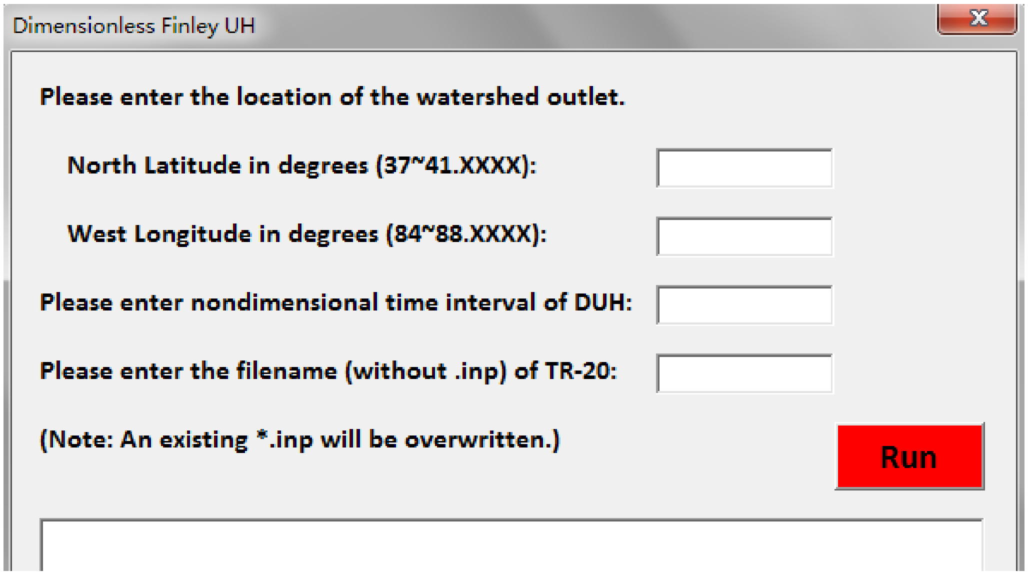


The parameters (PRF and Lag Time) of Finley UH are estimated based on the observed hydrographs of 30 small study watersheds in Indiana. If the watershed characteristics are outside the applicable range of the variables in the regression equations, the values of the parameters may not be reliable. For example, the applicable drainage area of a watershed is 3 ~ 40 square miles.

The Finlay UH parameters of a specific point are obtained from the values of the nearest drainage point of the delineated watershed as highlighted in the sheet, "Finlay UH Parameters".

Given the values of PRF and nondimensional time interval, the ordinates of the dimensionless Finlay UH are calculated based on the Gamma function and then written to a new TR-20 input file and the sheet, "Finlay UH".

Figure B.2 Readme interface of GUI based on Excel VBA.



Please enter the location of the watershed outlet.

North Latitude in degrees (37~41.XXXX):

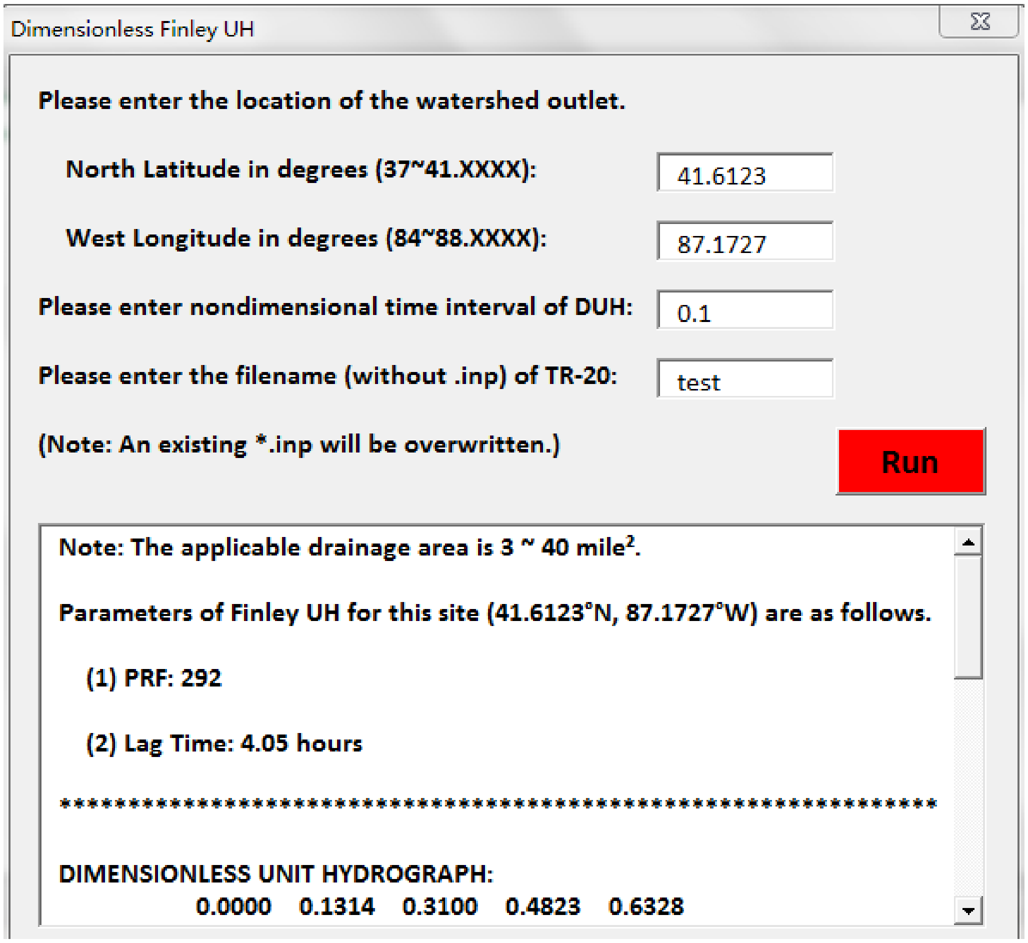
West Longitude in degrees (84~88.XXXX):

Please enter nondimensional time interval of DUH:

Please enter the filename (without .inp) of TR-20:

(Note: An existing *.inp will be overwritten.)

(a) GUI based on Excel VBA for estimation of Finley UH parameters and ordinates.



Please enter the location of the watershed outlet.

North Latitude in degrees (37~41.XXXX): 41.6123

West Longitude in degrees (84~88.XXXX): 87.1727

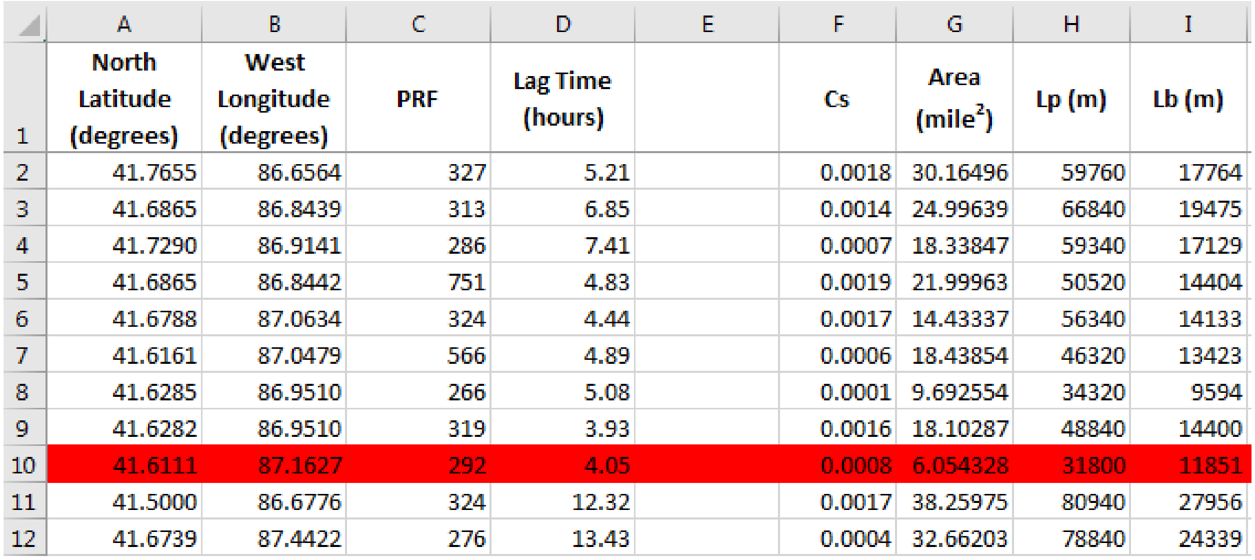
Please enter nondimensional time interval of DUH: 0.1

Please enter the filename (without .inp) of TR-20: test

(Note: An existing *.inp will be overwritten.)

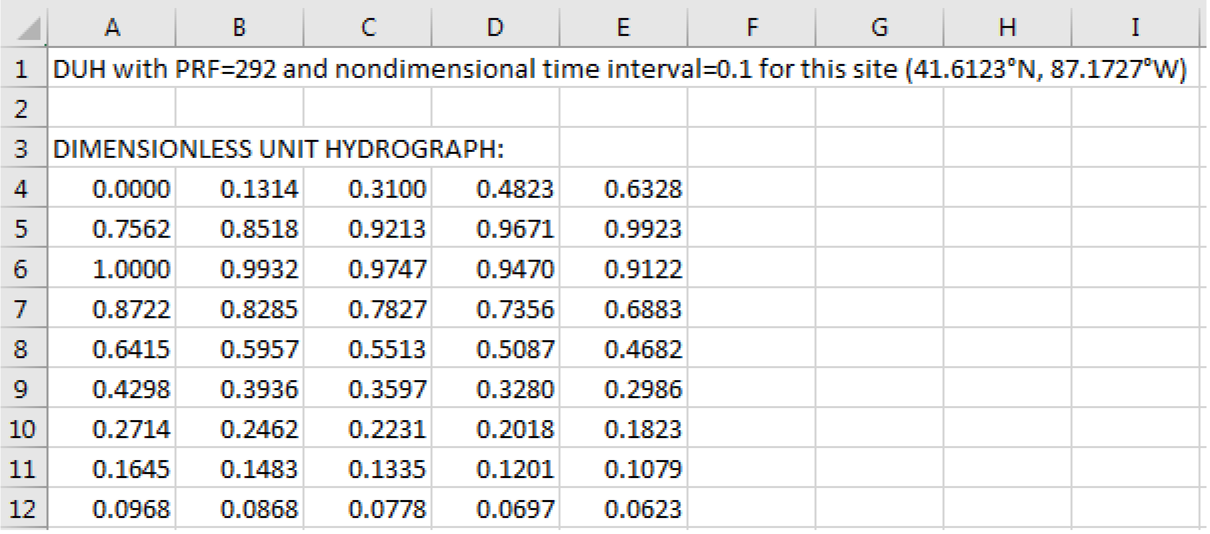
```
Note: The applicable drainage area is 3 ~ 40 mile².

Parameters of Finley UH for this site (41.6123°N, 87.1727°W) are as follows.

  (1) PRF: 292

  (2) Lag Time: 4.05 hours

*****************************************************************

DIMENSIONLESS UNIT HYDROGRAPH:
          0.0000   0.1314   0.3100   0.4823   0.6328
```

(b) Example results obtained in the GUI based on Excel VBA.



	A	B	C	D	E	F	G	H	I
1	North Latitude (degrees)	West Longitude (degrees)	PRF	Lag Time (hours)		Cs	Area (mile^2)	Lp (m)	Lb (m)
2	41.7655	86.6564	327	5.21		0.0018	30.16496	59760	17764
3	41.6865	86.8439	313	6.85		0.0014	24.99639	66840	19475
4	41.7290	86.9141	286	7.41		0.0007	18.33847	59340	17129
5	41.6865	86.8442	751	4.83		0.0019	21.99963	50520	14404
6	41.6788	87.0634	324	4.44		0.0017	14.43337	56340	14133
7	41.6161	87.0479	566	4.89		0.0006	18.43854	46320	13423
8	41.6285	86.9510	266	5.08		0.0001	9.692554	34320	9594
9	41.6282	86.9510	319	3.93		0.0016	18.10287	48840	14400
10	41.6111	87.1627	292	4.05		0.0008	6.054328	31800	11851
11	41.5000	86.6776	324	12.32		0.0017	38.25975	80940	27956
12	41.6739	87.4422	276	13.43		0.0004	32.66203	78840	24339

(c) Highlights in red in the spreadsheet "Finley UH Parameters."



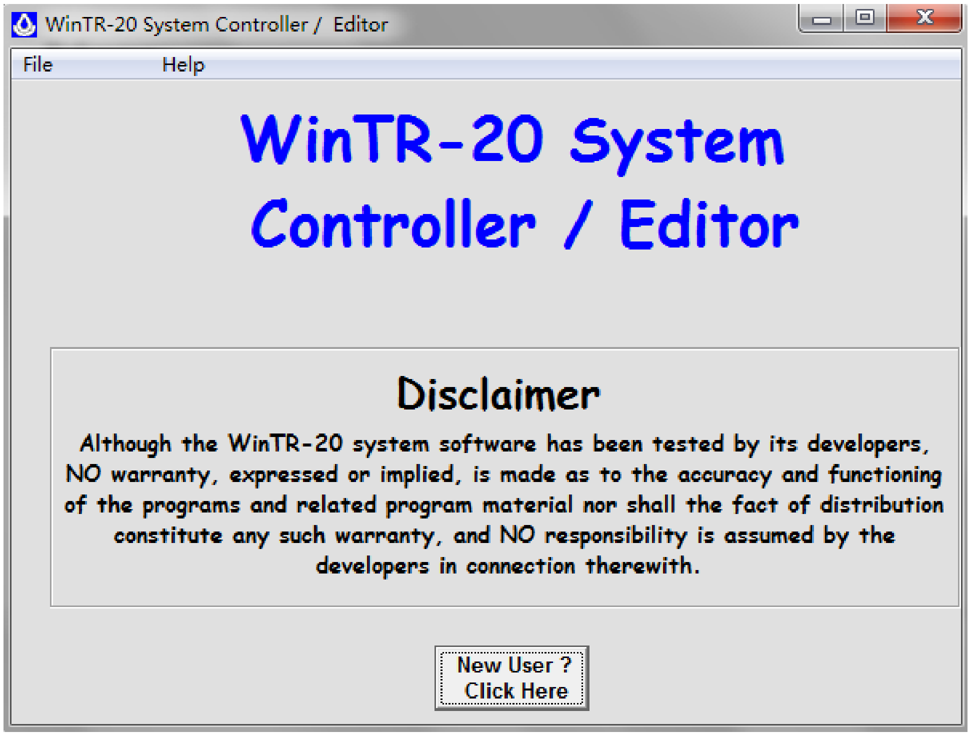
	A	B	C	D	E	F	G	H	I
1	DUH with PRF=292 and nondimensional time interval=0.1 for this site (41.6123°N, 87.1727°W)								
2									
3	DIMENSIONLESS UNIT HYDROGRAPH:								
4	0.0000	0.1314	0.3100	0.4823	0.6328				
5	0.7562	0.8518	0.9213	0.9671	0.9923				
6	1.0000	0.9932	0.9747	0.9470	0.9122				
7	0.8722	0.8285	0.7827	0.7356	0.6883				
8	0.6415	0.5957	0.5513	0.5087	0.4682				
9	0.4298	0.3936	0.3597	0.3280	0.2986				
10	0.2714	0.2462	0.2231	0.2018	0.1823				
11	0.1645	0.1483	0.1335	0.1201	0.1079				
12	0.0968	0.0868	0.0778	0.0697	0.0623				

(d) Output ordinates of dimensionless UH in spreadsheet "Finley UH."

Figure B.3 GUI based on Excel VBA for generating dimensionless Finley UH.

B.3 GUI based on Python for applications of Finley UH in TR-20

This version of GUI is an executable file (*.exe) developed based on Python and can be used with the TR-20 software. This software is a surface hydrologic model applied for single storm events at a watershed scale and the WinTR-20 (hereinafter referred to as TR-20) is developed for running in the Windows system of a personal computer. The main window of TR-20 is shown in Figure B.4 and the features related to the applications of NRCS UH are shown in Figure B.5.



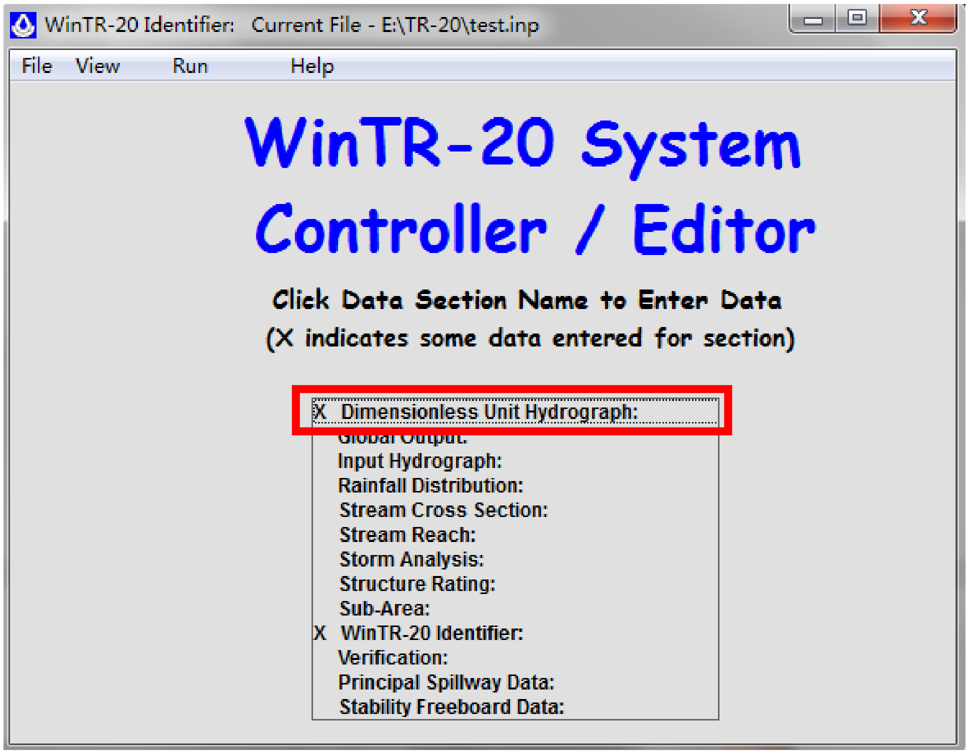
WinTR-20 System Controller / Editor

Disclaimer

Although the WinTR-20 system software has been tested by its developers, NO warranty, expressed or implied, is made as to the accuracy and functioning of the programs and related program material nor shall the fact of distribution constitute any such warranty, and NO responsibility is assumed by the developers in connection therewith.

Figure B.4 Main window of TR-20.

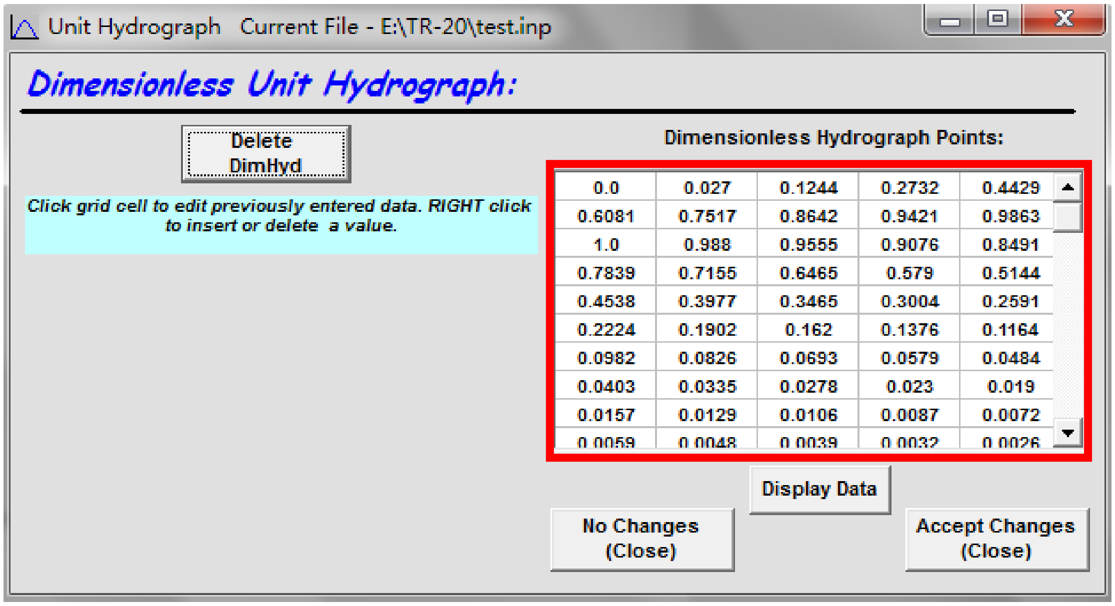
After a new TR-20 file is created, the dimensionless UH section in the main menu (see Figure B.5a) is used to edit or enter information for a dimensionless UH. Any data entered here will be used in lieu of the standard dimensionless unit hydrograph with *PRF* = 484. If the NRCS standard dimensionless UH is desired, then no data should be entered through this window. Otherwise, the sequential dimensionless UH points with a customized *PRF* should be filled in the cells in the red box manually (see Figure B.5b) after clicking on the first section in the main menu. The updated dimensionless UH can be displayed as shown in Figure B.5c.



WinTR-20 System Controller / Editor

Click Data Section Name to Enter Data
(X indicates some data entered for section)

(a) Main menu of controller/editor of TR-20.

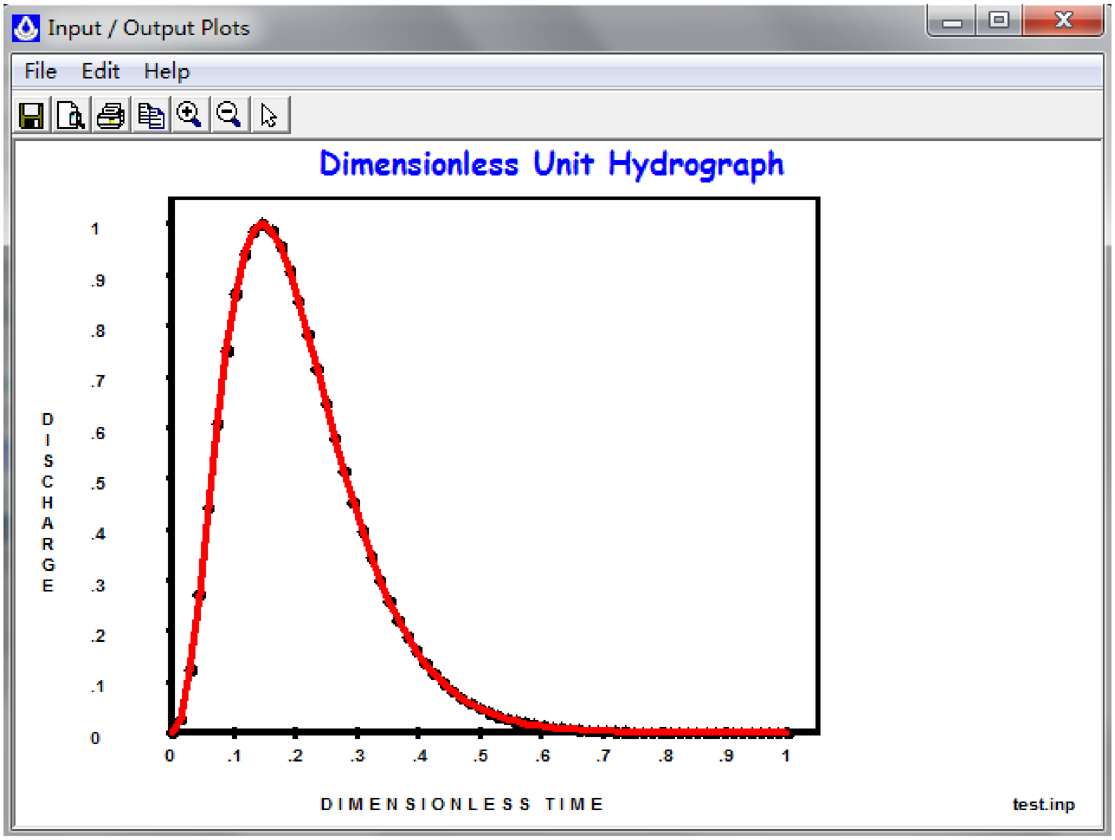


Click grid cell to edit previously entered data. RIGHT click to insert or delete a value.

Dimensionless Hydrograph Points:

0.0	0.027	0.1244	0.2732	0.4429
0.6081	0.7517	0.8642	0.9421	0.9863
1.0	0.988	0.9555	0.9076	0.8491
0.7839	0.7155	0.6465	0.579	0.5144
0.4538	0.3977	0.3465	0.3004	0.2591
0.2224	0.1902	0.162	0.1376	0.1164
0.0982	0.0826	0.0693	0.0579	0.0484
0.0403	0.0335	0.0278	0.023	0.019
0.0157	0.0129	0.0106	0.0087	0.0072
0.0059	0.0048	0.0039	0.0032	0.0026

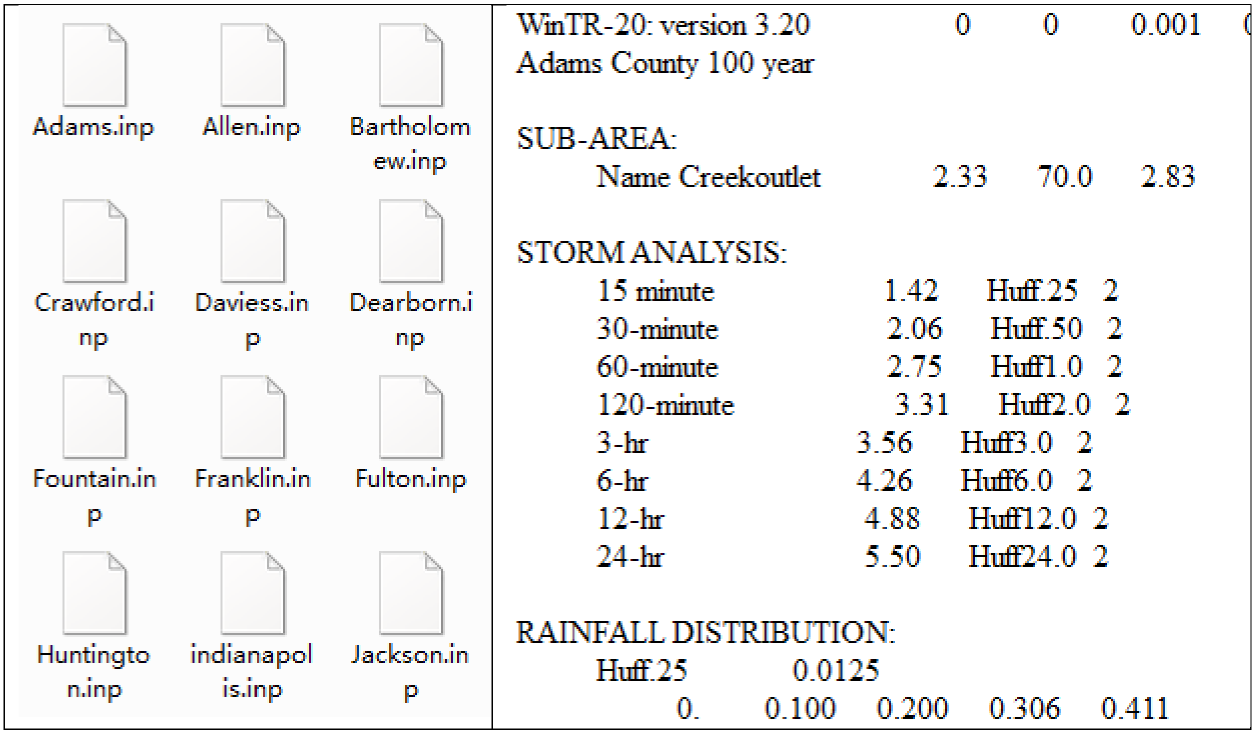
(b) Ordinates of dimensionless UH with a customized *PRF*.



(c) Plot of dimensionless UH.

Figure B.5 Features related to NRCS UH in TR-20.

It is suggested to use the GUI with the TR-20 input files from the INDOT, namely, 96 *.inp template files (see Figure B.6), which are used for the 100-year peak flow calculation and include the 100-year precipitation data from the NOAA website for a location at the center of each county in Indiana (These files can be downloaded from https://www.in.gov/indot/engineering/files/TR-20-Input-Files.zip). The GUI and these input files are intended as tools to provide convenience in the hydraulic design of hydrographs.



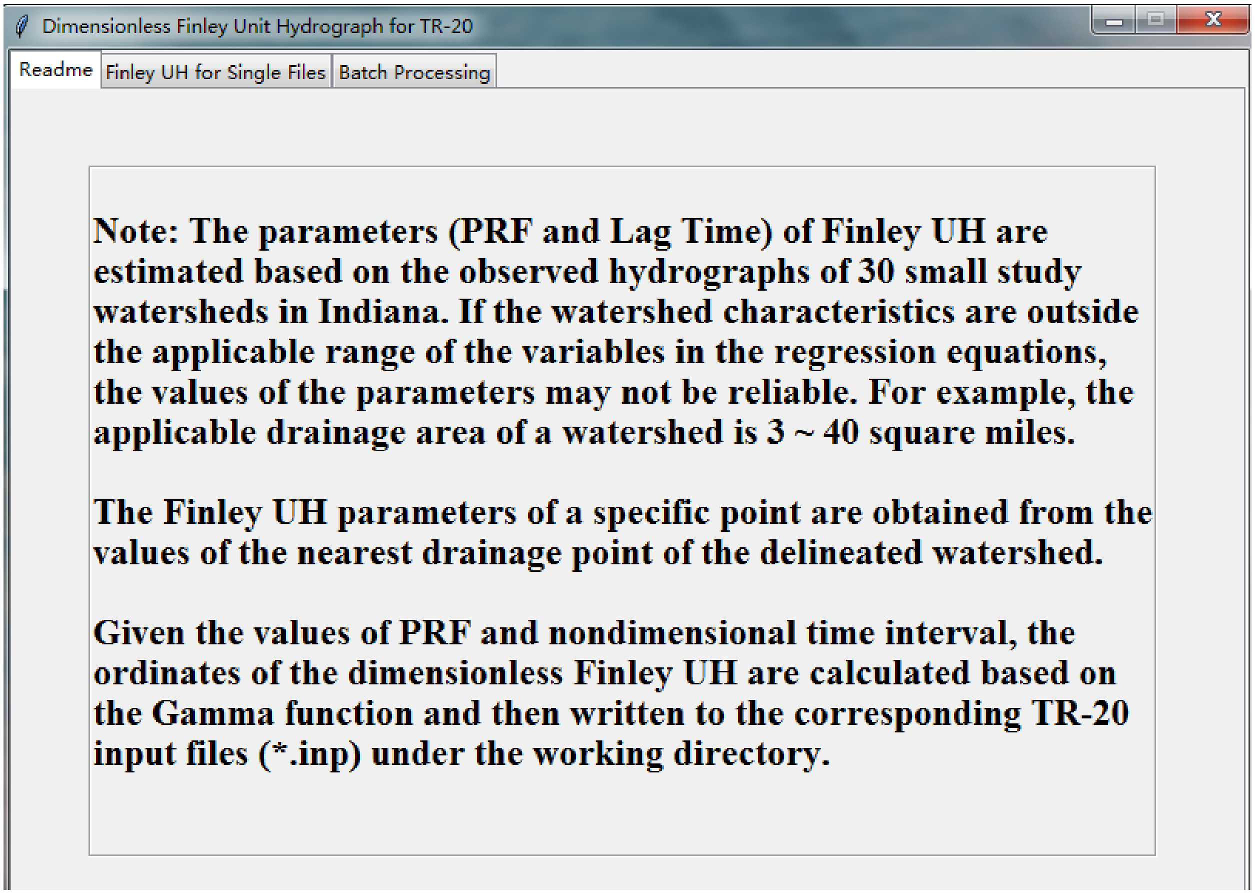
```
WinTR-20: version 3.20            0       0       0.001
Adams County 100 year

SUB-AREA:
        Name Creekoutlet          2.33     70.0     2.83

STORM ANALYSIS:
        15 minute               1.42     Huff.25   2
        30-minute               2.06     Huff.50   2
        60-minute               2.75     Huff1.0   2
        120-minute               3.31     Huff2.0   2
        3-hr                   3.56     Huff3.0   2
        6-hr                   4.26     Huff6.0   2
        12-hr                   4.88     Huff12.0  2
        24-hr                   5.50     Huff24.0  2

RAINFALL DISTRIBUTION:
        Huff.25          0.0125
                0.      0.100     0.200     0.306     0.411
```

(a) TR-20 input files for each county in Indiana

(b) File contents

Figure B.6 Screenshots of TR-20 input files of INDOT.

The GUI based on Python is a one-stop tool that consists of three tabs (see Figure B.7). In Tab 1, it is a Readme interface which is the same as that in the GUI based on Excel VBA. In Tab 2 (“Finley UH for Single Files”) and Tab 3 (“Batch Processing”), users can estimate the Finley UH parameters by entering the latitude and longitude of watershed outlets. And then users can get the ordinates of a dimensionless UH for one single TR-20 file and multiple files in Tabs 2 and 3, respectively, based on the estimated parameters and the given TR-20 filenames. A new TR-20 input file will be created if it does not exist in the working directory. Different from the GUI based on Excel VBA, users also need to enter the filename of a TR-20 file for single-file processing (see Figure B.7b) or the filename of a CSV file for batch (multiple-file) processing (see Figure B.7c). After clicking on the “Run” button in Tab 2 or Tab 3, the GUI can help to insert the customized dimensionless UH ordinates into the TR-20 input files automatically rather than typing them into the cells manually (see Figure B.5b). Similarly, if users did not enter anything or the TR-20 file or the CSV file is not existing in the working directory, the GUI will pop up a message window to remind users to reenter the filename. If the input information is reasonable, the GUI will output the dimensionless UH ordinates in the scrolled text window in Tab 2 as well as inserting into the TR-20 input files under the current directory. An example of processing a single TR-20 input file (*Adams.inp*) by using the GUI is shown in Figure B.8 and an example for batch processing is shown in Figure B.9.

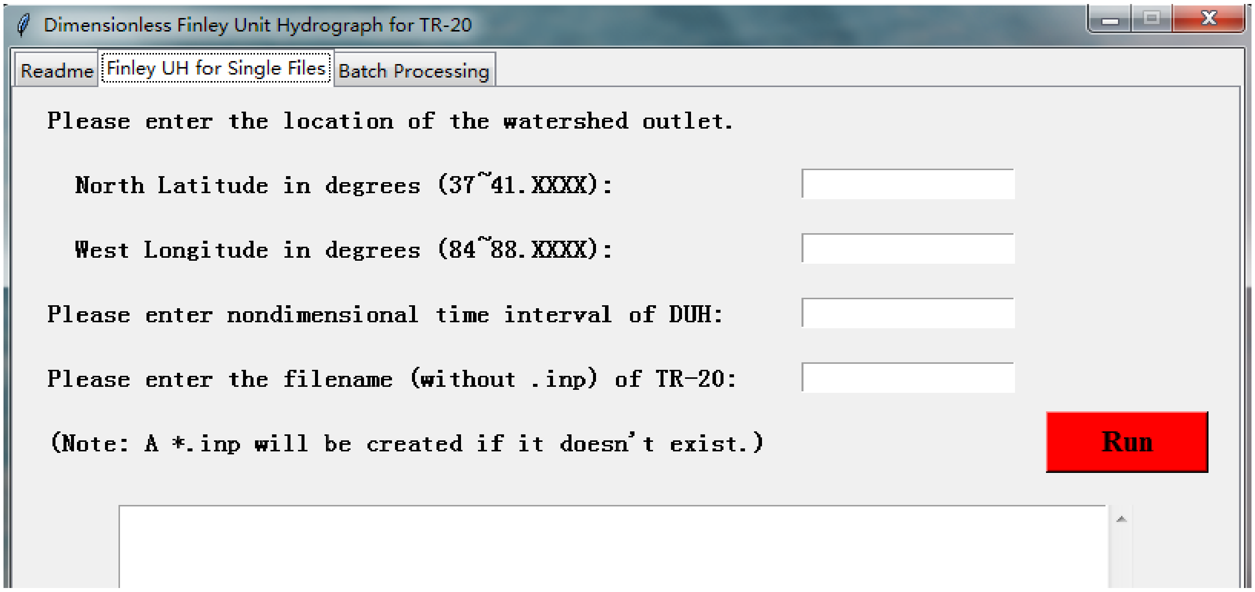


Note: The parameters (PRF and Lag Time) of Finley UH are estimated based on the observed hydrographs of 30 small study watersheds in Indiana. If the watershed characteristics are outside the applicable range of the variables in the regression equations, the values of the parameters may not be reliable. For example, the applicable drainage area of a watershed is 3 ~ 40 square miles.

The Finley UH parameters of a specific point are obtained from the values of the nearest drainage point of the delineated watershed.

Given the values of PRF and nondimensional time interval, the ordinates of the dimensionless Finley UH are calculated based on the Gamma function and then written to the corresponding TR-20 input files (*.inp) under the working directory.

(a) Tab 1 for readme interface



Please enter the location of the watershed outlet.

North Latitude in degrees (37~41.XXXX):

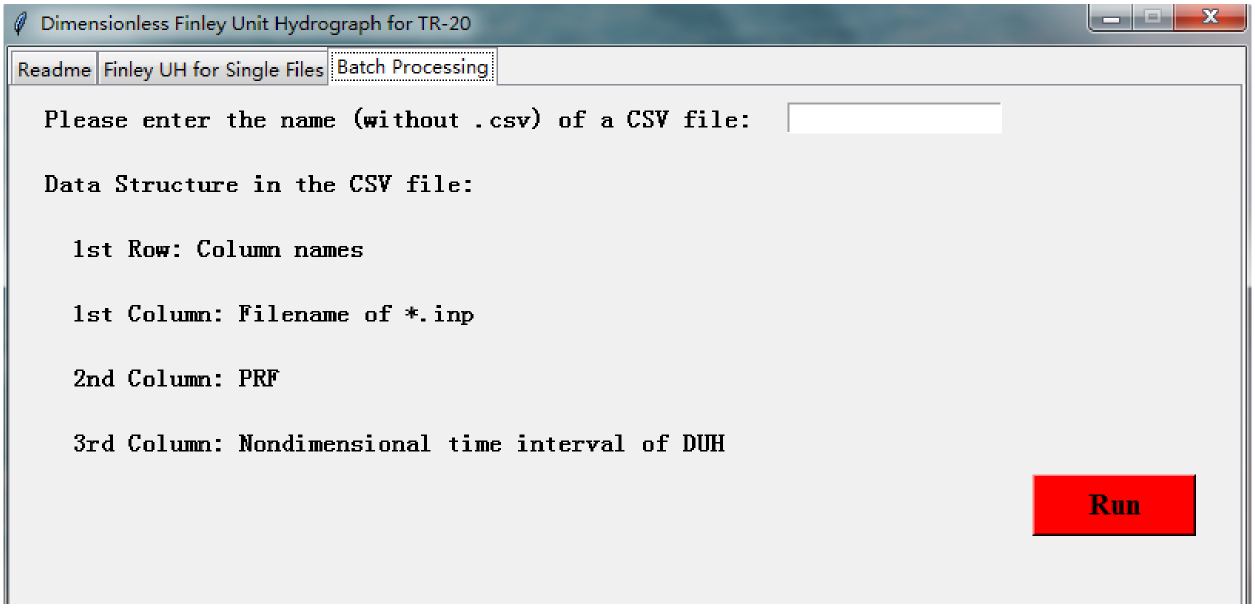
West Longitude in degrees (84~88.XXXX):

Please enter nondimensional time interval of DUH:

Please enter the filename (without .inp) of TR-20:

(Note: A *.inp will be created if it doesn't exist.)

(b) Tab 2 for single-file processing



Please enter the name (without .csv) of a CSV file:

Data Structure in the CSV file:

1st Row: Column names

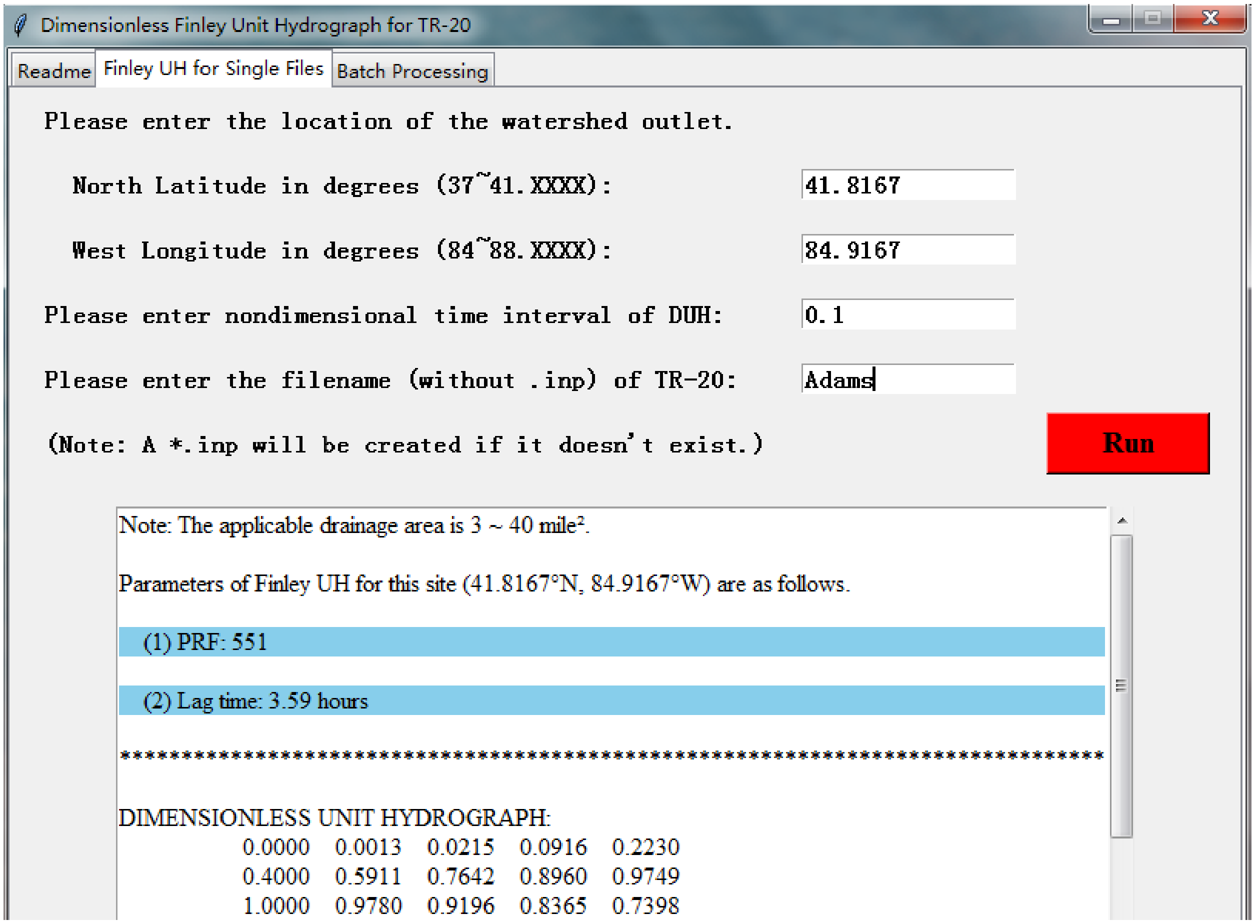
1st Column: Filename of *.inp

2nd Column: PRF

3rd Column: Nondimensional time interval of DUH

(c) Tab 3 for batch processing

Figure B.7 GUI based on Python for generating dimensionless Finley UH for TR-20 file.



Please enter the location of the watershed outlet.

North Latitude in degrees (37~41.XXXX): 41.8167

West Longitude in degrees (84~88.XXXX): 84.9167

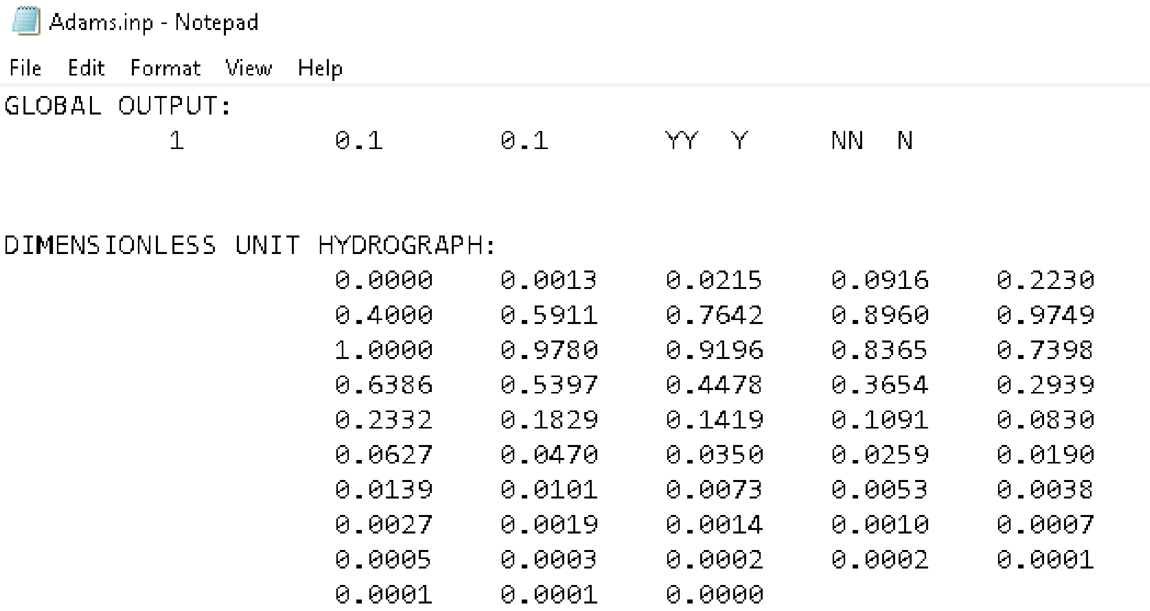
Please enter nondimensional time interval of DUH: 0.1

Please enter the filename (without .inp) of TR-20: Adams

(Note: A *.inp will be created if it doesn't exist.)

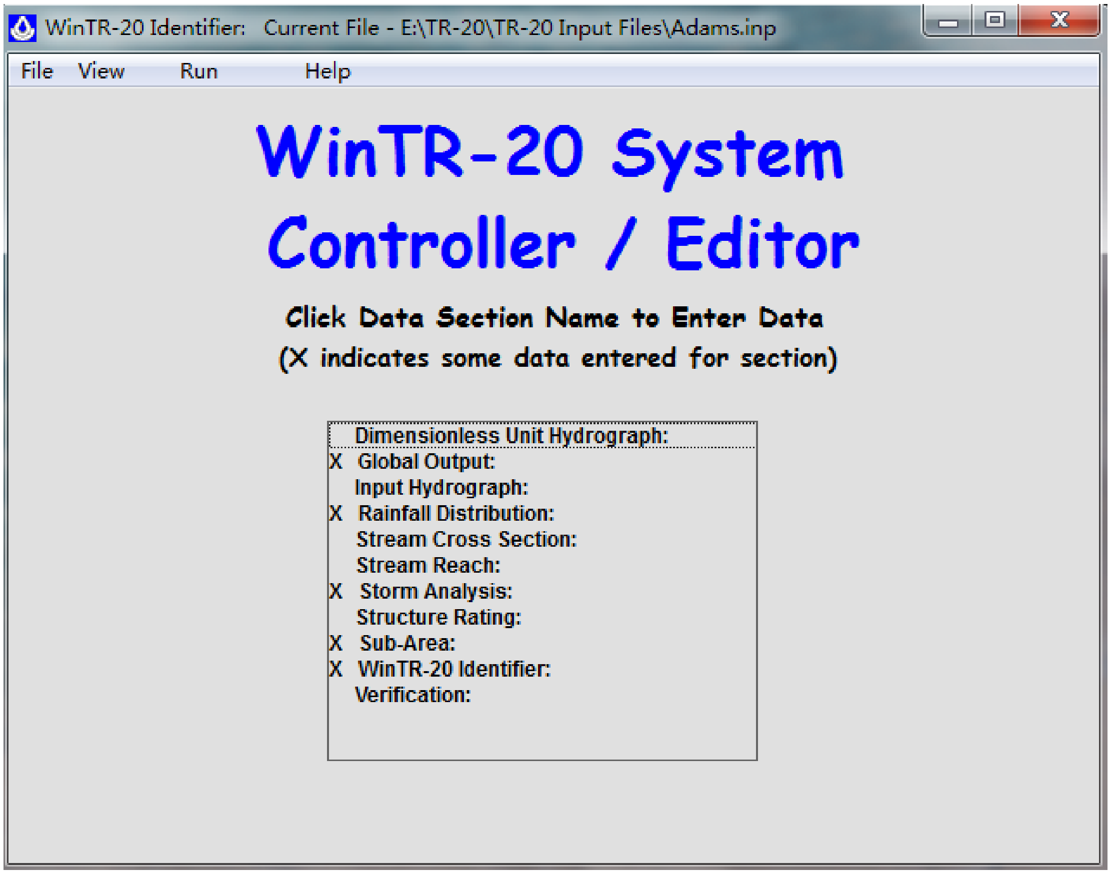
```
Note: The applicable drainage area is 3 ~ 40 mile².

Parameters of Finley UH for this site (41.8167°N, 84.9167°W) are as follows.

  (1) PRF: 551

  (2) Lag time: 3.59 hours

********************************************************************************

DIMENSIONLESS UNIT HYDROGRAPH:
             0.0000   0.0013   0.0215   0.0916   0.2230
             0.4000   0.5911   0.7642   0.8960   0.9749
             1.0000   0.9780   0.9196   0.8365   0.7398
```

(a) Input and output in GUI for single-file processing



```
GLOBAL OUTPUT:
          1         0.1         0.1         YY  Y       NN  N


DIMENSIONLESS UNIT HYDROGRAPH:
                    0.0000      0.0013      0.0215      0.0916      0.2230
                    0.4000      0.5911      0.7642      0.8960      0.9749
                    1.0000      0.9780      0.9196      0.8365      0.7398
                    0.6386      0.5397      0.4478      0.3654      0.2939
                    0.2332      0.1829      0.1419      0.1091      0.0830
                    0.0627      0.0470      0.0350      0.0259      0.0190
                    0.0139      0.0101      0.0073      0.0053      0.0038
                    0.0027      0.0019      0.0014      0.0010      0.0007
                    0.0005      0.0003      0.0002      0.0002      0.0001
                    0.0001      0.0001      0.0000
```

(b) Output of dimensionless UH ordinates in the TR-20 input file



WinTR-20 System

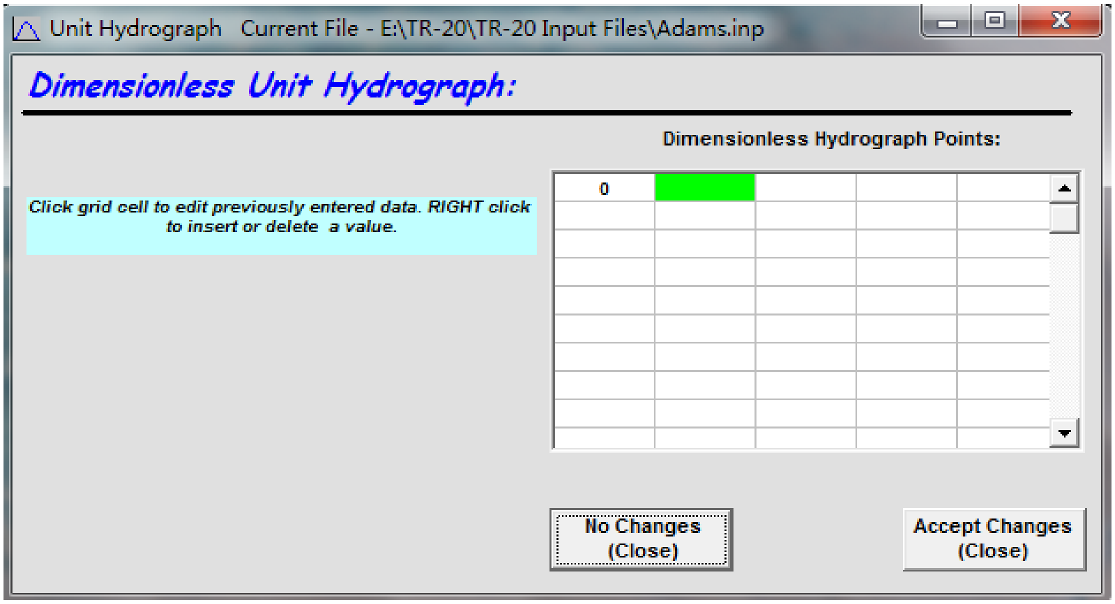
Controller / Editor

Click Data Section Name to Enter Data

(X indicates some data entered for section)

Dimensionless Unit Hydrograph:
X Global Output:
Input Hydrograph:
X Rainfall Distribution:
Stream Cross Section:
Stream Reach:
X Storm Analysis:
Structure Rating:
X Sub-Area:
X WinTR-20 Identifier:
Verification:

(c) Main menu of the original TR-20 file



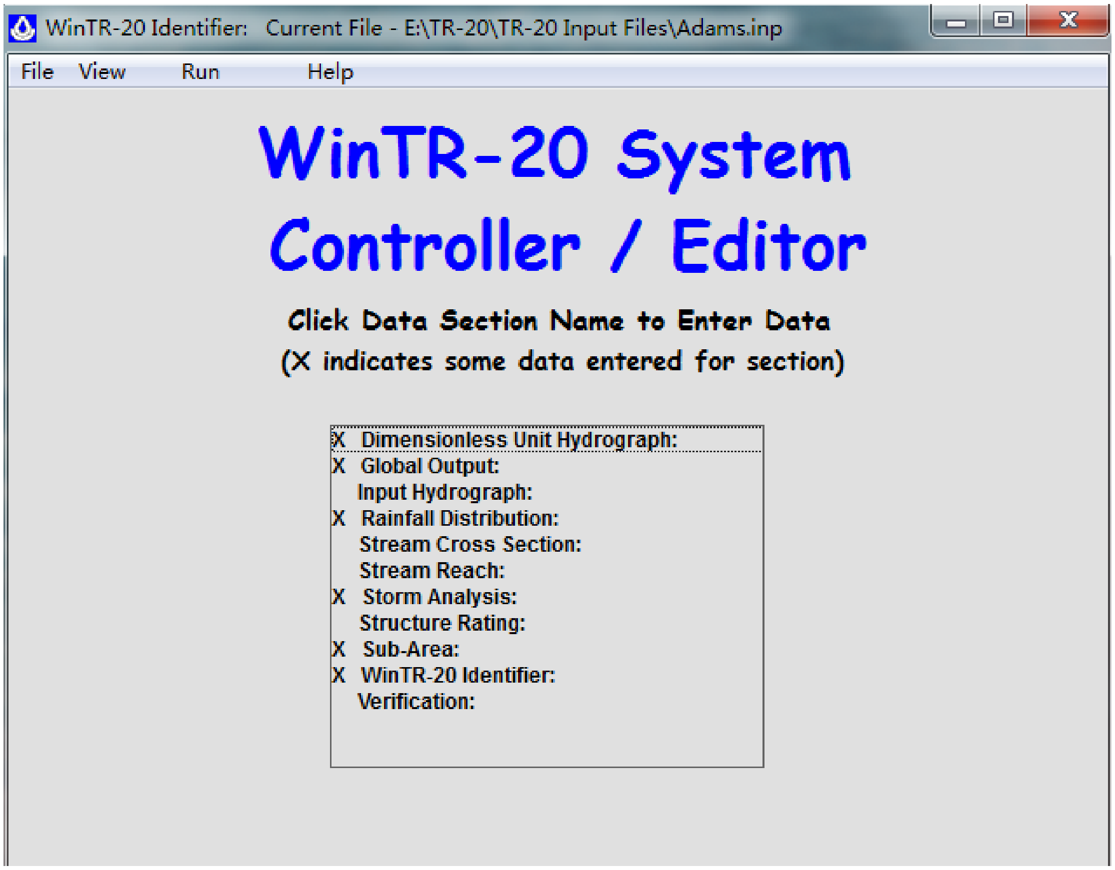
Unit Hydrograph Current File - E:\TR-20\TR-20 Input Files\Adams.inp

Dimensionless Unit Hydrograph:

Dimensionless Hydrograph Points:

Click grid cell to edit previously entered data. RIGHT click to insert or delete a value.

(d) Dimensionless UH window of the original TR-20 input file



WinTR-20 Identifier: Current File - E:\TR-20\TR-20 Input Files\Adams.inp

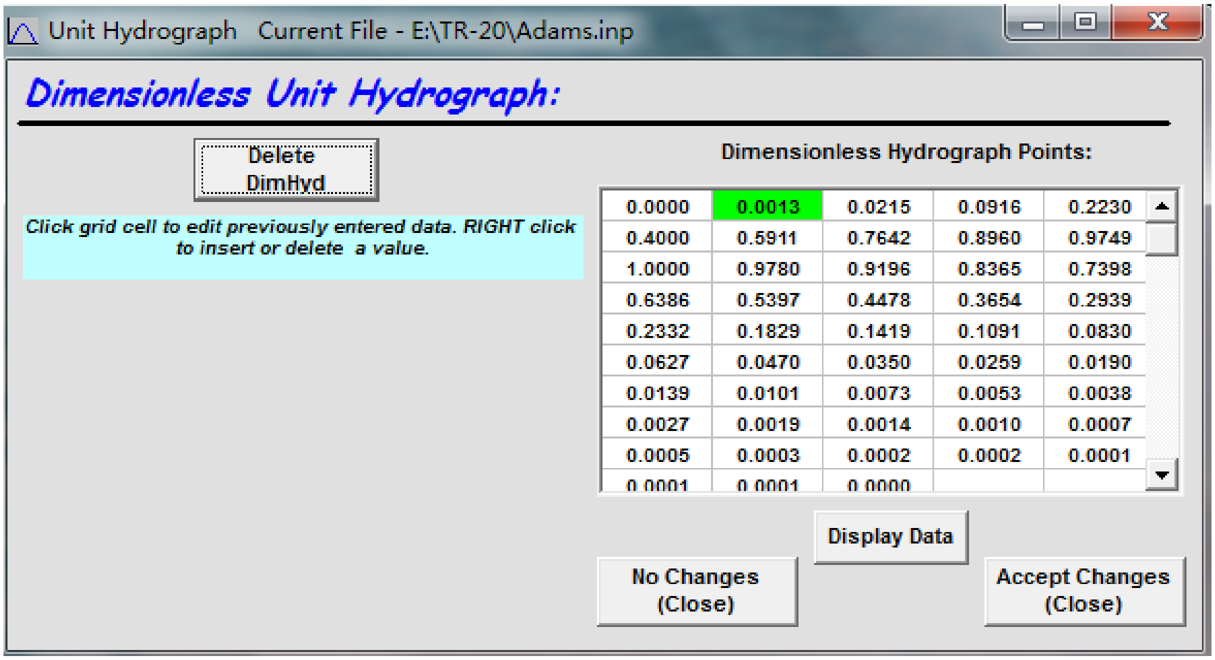
WinTR-20 System Controller / Editor

Click Data Section Name to Enter Data

(X indicates some data entered for section)

X Dimensionless Unit Hydrograph:
X Global Output:
Input Hydrograph:
X Rainfall Distribution:
Stream Cross Section:
Stream Reach:
X Storm Analysis:
Structure Rating:
X Sub-Area:
X WinTR-20 Identifier:
Verification:

(e) Main menu of the modified TR-20 input file



Unit Hydrograph   Current File - E:\TR-20\Adams.inp

Dimensionless Unit Hydrograph:

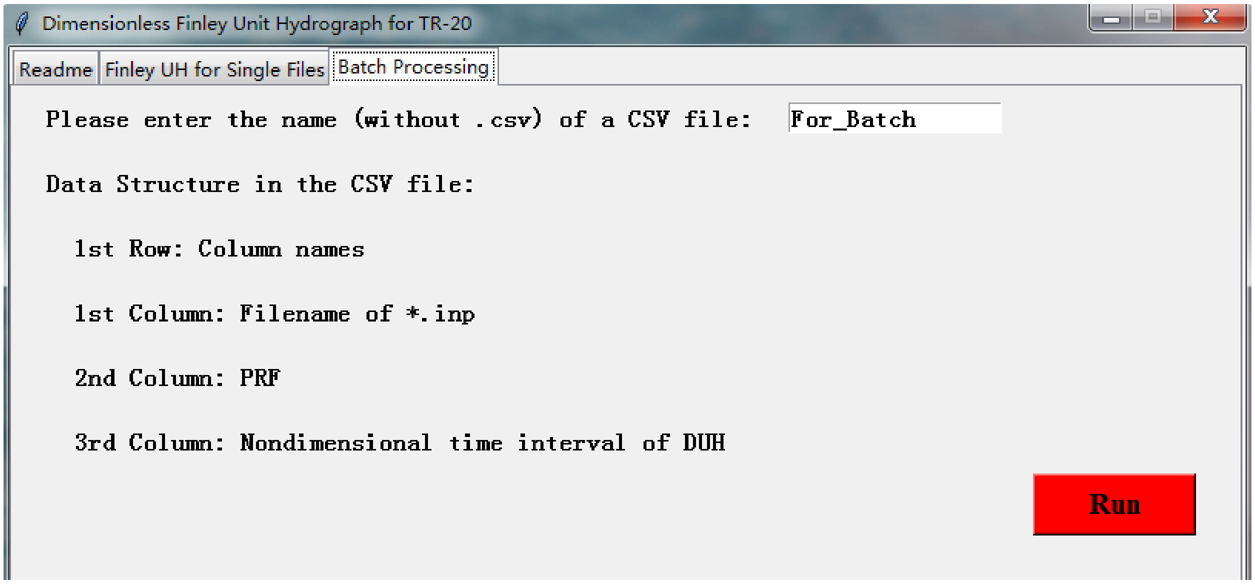
Click grid cell to edit previously entered data. RIGHT click to insert or delete a value.

Dimensionless Hydrograph Points:

0.0000	0.0013	0.0215	0.0916	0.2230
0.4000	0.5911	0.7642	0.8960	0.9749
1.0000	0.9780	0.9196	0.8365	0.7398
0.6386	0.5397	0.4478	0.3654	0.2939
0.2332	0.1829	0.1419	0.1091	0.0830
0.0627	0.0470	0.0350	0.0259	0.0190
0.0139	0.0101	0.0073	0.0053	0.0038
0.0027	0.0019	0.0014	0.0010	0.0007
0.0005	0.0003	0.0002	0.0002	0.0001
0.0001	0.0001	0.0000		

(f) Dimensionless UH window of the modified TR-20 input file

Figure B.8 Example-1 for single-file processing (*Adams.inp*).



Dimensionless Finley Unit Hydrograph for TR-20

Please enter the name (without .csv) of a CSV file: For_Batch

Data Structure in the CSV file:

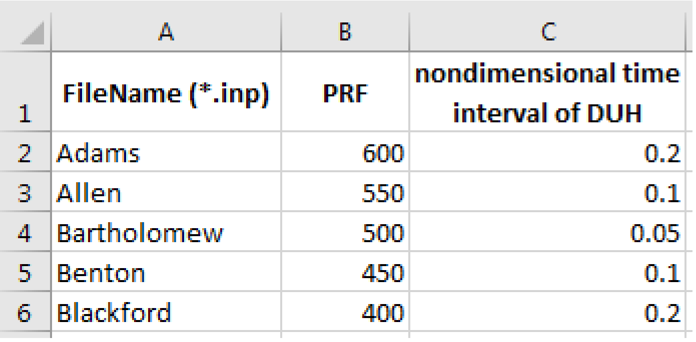
1st Row: Column names

1st Column: Filename of *.inp

2nd Column: PRF

3rd Column: Nondimensional time interval of DUH

(a) Input in GUI for batch processing



	A	B	C
1	**FileName (*.inp)**	**PRF**	**nondimensional time interval of DUH**
2	Adams	600	0.2
3	Allen	550	0.1
4	Bartholomew	500	0.05
5	Benton	450	0.1
6	Blackford	400	0.2

(b) Data structure of the CSV file (*For_Batch.csv*)

Figure B.9 Example-2 for batch processing.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

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