REGIONAL REGRESSION EQUATIONS TO ESTIMATE SYNTHETIC UNIT HYDROGRAPH PARAMETERS FOR INDIANA

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To my parents, for all their support that made this possible

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LIST OF SYMBOLS

A_w	drainage area
C	constant of channel maintenance
CDA	contributing drainage area
C_f	stream frequency
CN	curve number
D	drainage density
G	Gray’s geomorphologic parameter
H	basin relief
HKR	Hickok’s geomorphologic parameter
L_b	basin length
L_{ca}	length from the basin outlet to a point adjacent to the centroid
L_s	average grid slope
M	Murphy’s geomorphologic parameter
MCh	main channel length
Q_p	peak flow rate
R	Clark storage coefficient

R_c	circulatory ratio
R_e	elongation ratio
R_f	fineness ratio
R_{ff}	form factor
R_h	relief ratio
R_n	ruggedness number
R_p	relative relief
R_u	unity shape factor
S_b	basin shape factor
Slope	10-85% slope
t_c	Clark time of concentration
t_p	time to peak flow rate
ULC %	urban land cover
Water	% water or wetland

ABSTRACT

Jared L. Wilkerson. M.S.C.E., Purdue University, May 2009. Regional Regression Equations to Estimate Synthetic Unit Hydrograph Parameters for Indiana.
Major Professor: Venkatesh Merwade

Regression equations predicting Clark Synthetic Unit Hydrograph (SUH) parameters for time of concentration (t_c) and storage coefficient (R) are developed for small watersheds across Indiana [drainage areas = 3-38 square miles (mi^2)]. The state is partitioned into three regions: North, Central, and South, with consideration for past regionalization studies of Indiana and geomorphology. The equations are derived using multiple linear regression analysis for 30 watersheds with 90 observed rainfall-runoff events. Clark SUH parameters are optimized using Hec-HMS to match the observed rainfall-runoff events. The optimized Clark SUH parameters are related to geomorphologic parameters estimated using geographic information system (GIS) applications. An extensive list of 29 geomorphologic parameters is considered including parameters related to depression storage, slope, drainage area, basin shape, and stream network. Separate regression equations for t_c and R are developed for each region and the entire state. Values for t_c and R are predicted using the regression equations and used to model 7 new rainfall-runoff events in Hec-HMS for comparison to the NRCS SUH method.

CHAPTER 1. INTRODUCTION

Synthetic unit hydrograph methods are utilized to determine runoff hydrographs for ungauged sites. The runoff hydrograph is important in designing stormwater-management infrastructure such as culverts and detention facilities. Analysis of the hydrologic effects of bridge contractions and flood-plain assessment also rely on the use of runoff hydrographs. These runoff hydrographs are computed using design storm events based on probability of occurrence determined from references such as Bulletin 71 (Huff and Angel 1992) and National Oceanic and Atmospheric Administration (NOAA) Atlas 14 (Bonin et al. 2004). Once the proper design storm is selected, abstractions due to depression storage, interception, and infiltration must be separated from total precipitation. Typically this is done using parameters that incorporate soil types, land cover/land use, and antecedent moisture conditions. The National Resources Conservation Service (NRCS) method is the best example. A standardized curve number is applied based on antecedent moisture conditions, hydrologic soil group, and land cover/land use. The curve number is used to partition rainfall into losses and excess precipitation. The excess precipitation is then transformed into a runoff hydrograph using the traditional unit hydrograph or some other synthetic transform method.

The unit hydrograph (UH) theory was first introduced by Sherman (1932) using superposition to predict hydrographs from observed rainfall and runoff data rather than just peak discharges. The UH is the hydrograph resulting from 1 unit of excess precipitation. UHs are defined for a particular watershed and calculated as the runoff hydrograph resulting from one unit of excess precipitation. Excess precipitation is the precipitation not lost to depression storage or infiltration (Chow et al. 1988). The traditional UH however is only useful for gauged sites. Synthetic unit hydrographs (SUH) are a way to extend the use of UH theory to ungauged watersheds (Jena et al. 2006). SUHs are used to establish the UH for an ungauged watershed. Snyder (1938) was the first to develop a synthetic unit hydrograph method that tried to relate measured geomorphologic characteristics to unit hydrograph parameters. Snyder's study of watersheds in the Appalachian Mountains related values for time to peak to watershed length, distance from watershed centroid to the outlet, and a regional coefficient. Peak flow rate was computed using watershed area, time to peak, and a storage coefficient (Jena et al. 2006).

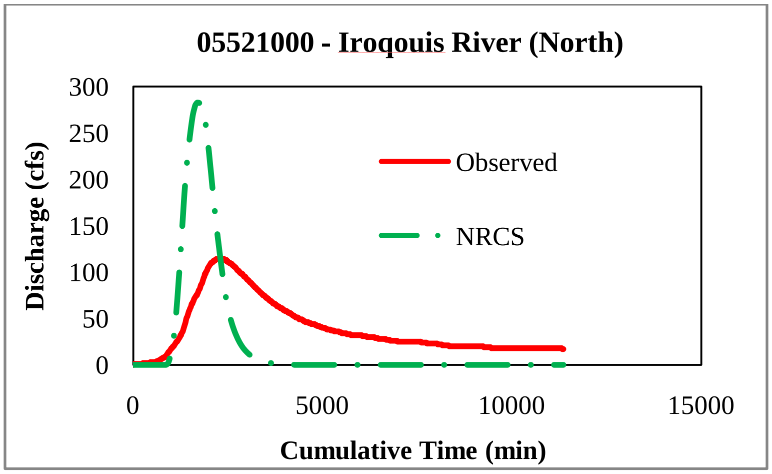
Clark (1945) developed his own SUH method that incorporated a parameter to model the watershed storage (R) and time of concentration (t_c). The Clark SUH Method incorporates the processes of attenuation and translation of runoff through the use of the time-area curve. Clark (1945) noted the translation of flow through the watershed was described by a time-area curve that expresses the fraction of watershed area contributing runoff to the watershed outlet as a function of time since the start of effective precipitation (Straub et al. 2000). A linear reservoir was used by Clark to reflect the storage effects of watersheds. Clark's method attempts to relate geomorphologic properties to watershed response using time-related parameters.

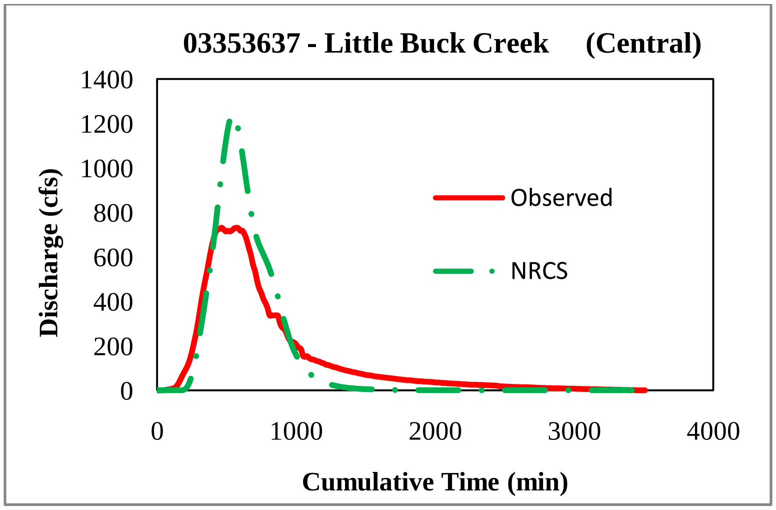
A geomorphologic unit hydrograph (GUH) was presented by Rodriquez-Itrube and Valdes (1979) and Gupta et al. (1980). Their aim was to parametrize the hydrographs in terms of geomorphology, specifically using Horton's bifurcation ratio, stream length ratio, and stream area ratio (Cleveland 2008). Jin (1992) developed a GUH utilizing a gamma distribution based on similar geomorphology as in the Rodriquez-Itrube (1979) and Gupta et al. (1980) studies.

All of these SUH studies attempt to link distance, velocity, and time to physical characteristics of watersheds to infer a unit hydrograph in the absence of observed rainfall and runoff data. Currently studies utilizing geographic information systems (GIS) have developed parallel to GUH theory by incorporating similar ideas to relate the physical characteristics of watersheds to a GUH. A study by Shamseldin and Nash (1998) argues that GUH theory is equivalent to the assumption of a generalized UH equation described by a distribution whose parameters are related by regression to appropriate watershed characteristics (Cleveland 2008). This paper presents the results using the Clark SUH method whose parameters are related to the geomorphology of Indiana.

1.2 Purpose and Approach

The application of the NRCS UH in Indiana has typically yielded accurate results for the steeper watersheds in southern Indiana, but tends to over estimate peak discharges for watersheds in the northern part of the state (Figure 1.1).





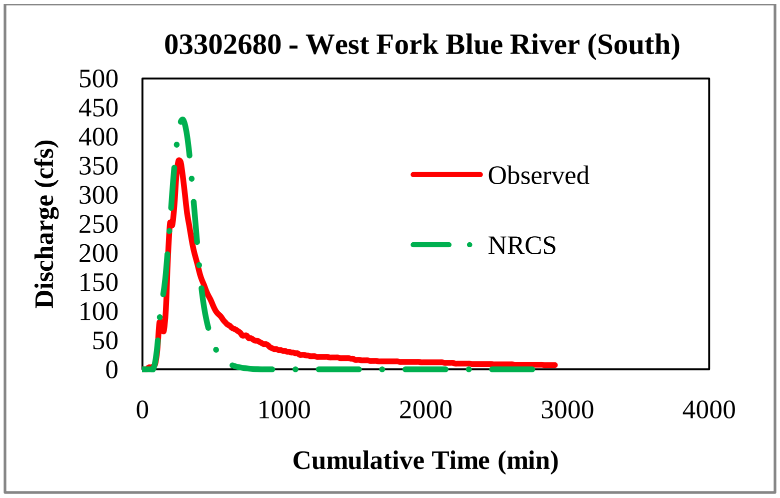


Figure 1.1. Illustration of NRCS Method for three watersheds

The assumption is that the lower gradient watersheds of northern Indiana have lower peak discharges as a result of greater watershed storage and longer travel times for runoff making it necessary to investigate the regional geomorphological characteristics throughout Indiana and how they relate to UH shape. The geomorphology of Indiana is discussed further in the next section. The NRCS UH is one of the most widely used SUHs and is incorporated in the TR-20 program. The NRCS dimensionless unit hydrograph was developed from the analysis of measured data for watersheds across the United States. The UHs were made dimensionless by dividing discharge ordinates by peak discharge and time ordinates by time to peak. NRCS (1985) curve number method is used to quantify watershed characteristics for rainfall abstractions, and to subsequently compute a runoff hydrograph for ungauged sites. The curve number approach is one of the most widely used SUH methods because of its ability to incorporate land cover/land-use characteristics. The Soil Conservation Service (now the NRCS) conducted research (SCS 1985) in which UHs for a wide variety of streams across the United States were averaged to form a composite UH that has become one of the most widely used methods for computing design runoff hydrographs.

A weakness of the NRCS method is the fixed hydrograph shape (Figure 1.2). With the NRCS, only the lag time and watershed area are used to control both the peak discharge and time base, meaning the rising and recession of the hydrograph remain the same relative to each other from one watershed to another. Alternatively the Clark SUH and traditional UH are dependent on geomorphology. The traditional UH method is very useful and flexible, but observed runoff data are necessary to establish the ordinates of the traditional UH for a given watershed. Thus, the traditional UH is not useful for application with ungauged watersheds. The Clark SUH method uses time of concentration and a storage coefficient to establish the shape of the time-area function used to establish the shape of the Clark SUH. The added flexibility of Clark SUH makes it a more capable method for relating geomorphology to hydrograph shape. Although the Clark SUH doesn’t have the flexibility of the traditional UH method, it has the advantage of being a SUH and therefore applicable to ungauged watersheds.

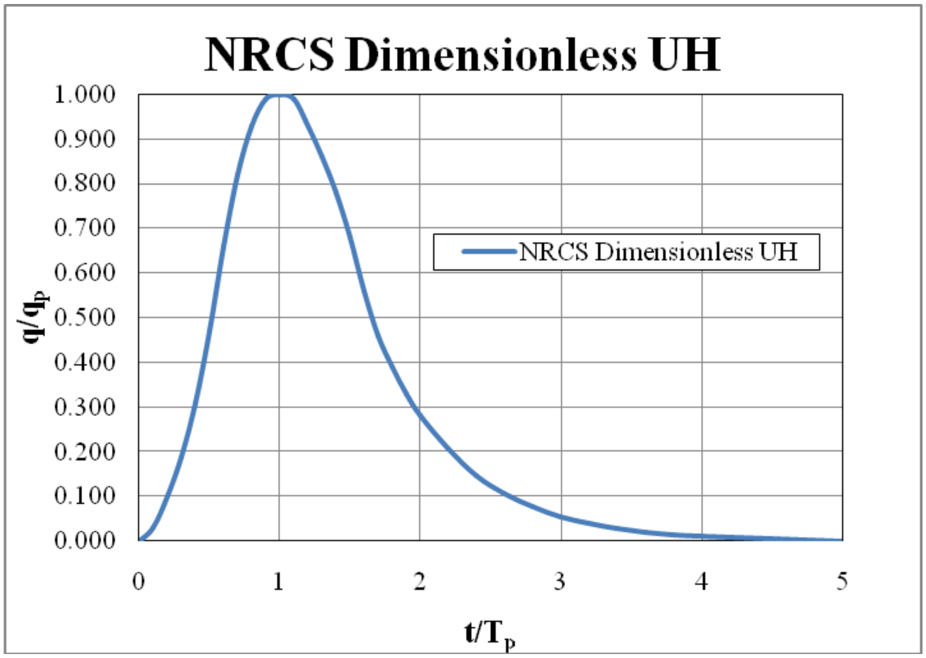


Figure 1.2. NRCS Dimensionless UH

All of the previously mentioned SUH methods attempt to extend the use of unit hydrograph theory to ungauged watersheds through the use of regional coefficients or parameters that describe watershed geomorphology. Other research attempting to more directly relate geomorphology to SUH parameters has been conducted by Hickok et al. (1959) and Gray (1961) for small watersheds in the west and midwestern United States. Research conducted by Rodriguez-Iturbe and Valdes (1979) showed how hydrograph structure is directly related to watershed geomorphology. However their research comparing GUH parameters to geomorphologic characteristics has involved using maps and instruments to measure landform and basin parameters, which may not be accurate due to human and instrument error. Because of the difficulty in measuring basin characteristics a minimum number of parameters were used in their regression models. Presently, the use of GIS software and available remote sensing and topographic information make estimating geomorphologic parameters much faster and accurate. (Jena et al. 2006). This would make GIS the preferred method for extracting watershed characteristics because a much larger list of geomorphologic characteristics could be utilized for estimating SUH parameters. Relating easily available geomorphologic characteristics using regression equations to the SUH parameters would give engineers a better way to calculate the necessary SUH parameters for both gauged and ungauged watersheds. Once the regression equations have been validated, the SUH parameters can be reliably estimated for use in the design of hydraulic structures.

CHAPTER 2. STUDY AREA AND DATA

2.1 Study Area

In an attempt to gain insight into the important geomorphologic characteristics that result in varied hydrologic responses across the state, this study was undertaken on thirty small watersheds in Indiana. Methods for estimating flood flows for larger watersheds in Indiana have been described in studies by Knipe and Rao (2004), Glatfelter (1984), and Davis (1974). The present study focused on the smallest possible watersheds with observed streamflow data. Ten watersheds from corresponding United States Geologic Survey (USGS) stream gages were selected from each of the north, central, and southern regions of the state (Figure 2.1). Indiana is located in the midwestern region of the United States, lying within 37^{o}46’- 41^{o}46’ north latitude and 84^{o}47’- 88^{o}6’ west longitude. Indiana’s elevation mainly lies between 150 and 300m (500 to 1,000 ft) above sea level. Northern Indiana is home to many natural lakes created by the last glacial period which has left the topography of this region very flat. Central Indiana features some gently rolling hills and sandstone ravines. The central region is also characterized by a patch work of fields and forests. These two regions (north and central) were covered by glacial ice during the Wisconsinan glaciations (Figure 2.2) which left behind soil comprised of sand, clay and

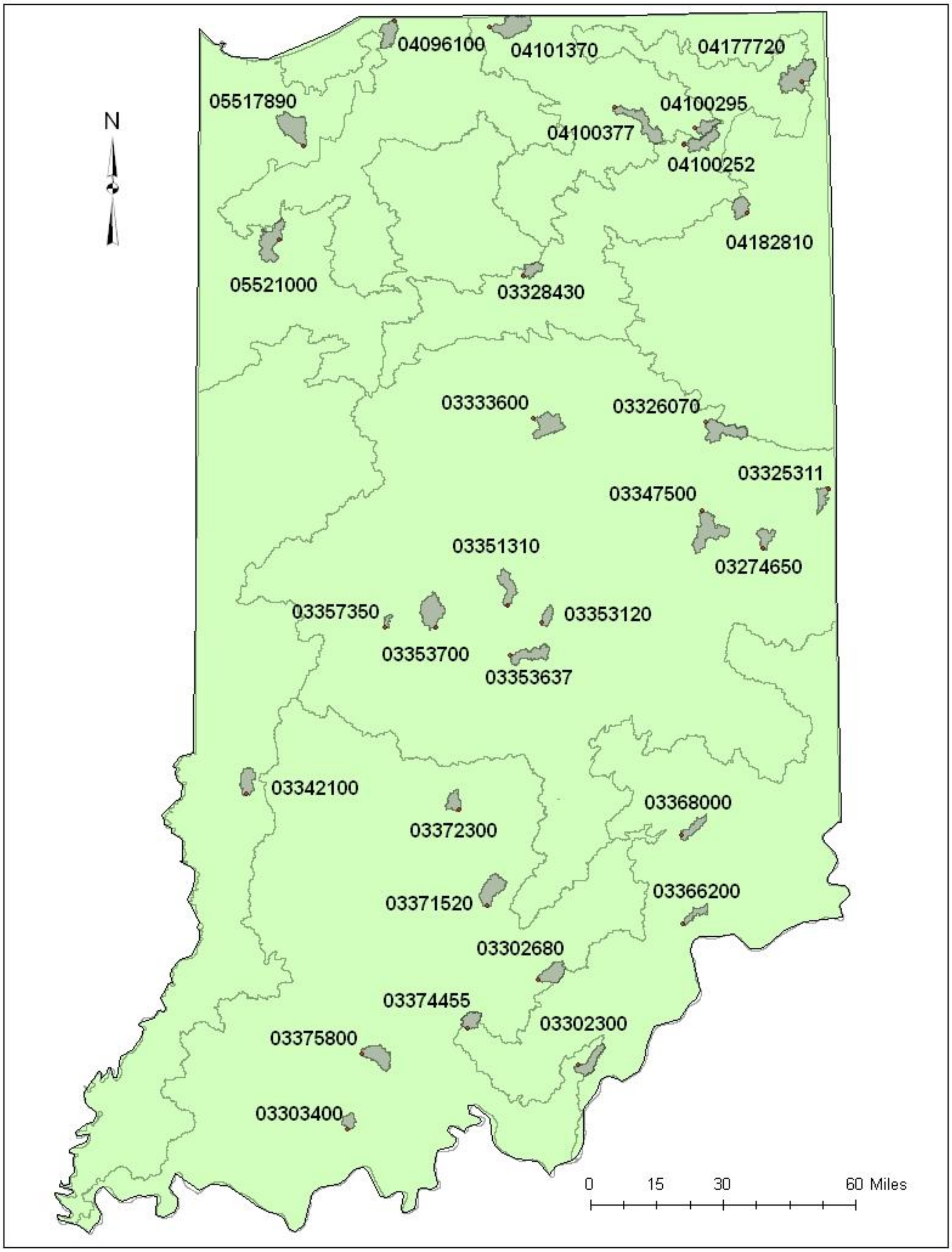


Figure 2.1. Study areas selected

gravel called glacial till. Southern Indiana is a mixture of farmland, forests, and very hilly areas (especially near Louisville, KY). Southern Indiana’s topography is more varied than the north and contains more hills and geographic variation due to the “Knobs”, a series of hills that run parallel to the Ohio River. The southern region of Indiana has been more significantly reworked by natural forces such as erosion because it has not been glaciated since the Illinoisan period. The area is also known for its karst landscape that has resulted in the creation of many caves and one of the largest limestone quarry areas in the USA. Because the northern two-thirds of the state was covered by glaciers during the Wisconsinan glaciations, southern Indiana was exposed to the forces of erosion longer and more distinct river valleys (in comparison to the rest of the state) were carved by the large amounts of melting ice once the Wisconsinan glaciations began to recede. Figure 2.2 is a digital elevation model (DEM) displaying the southern boundary of the Wisconsinan glaciations. It is visually apparent that southern Indiana has steeper slopes.

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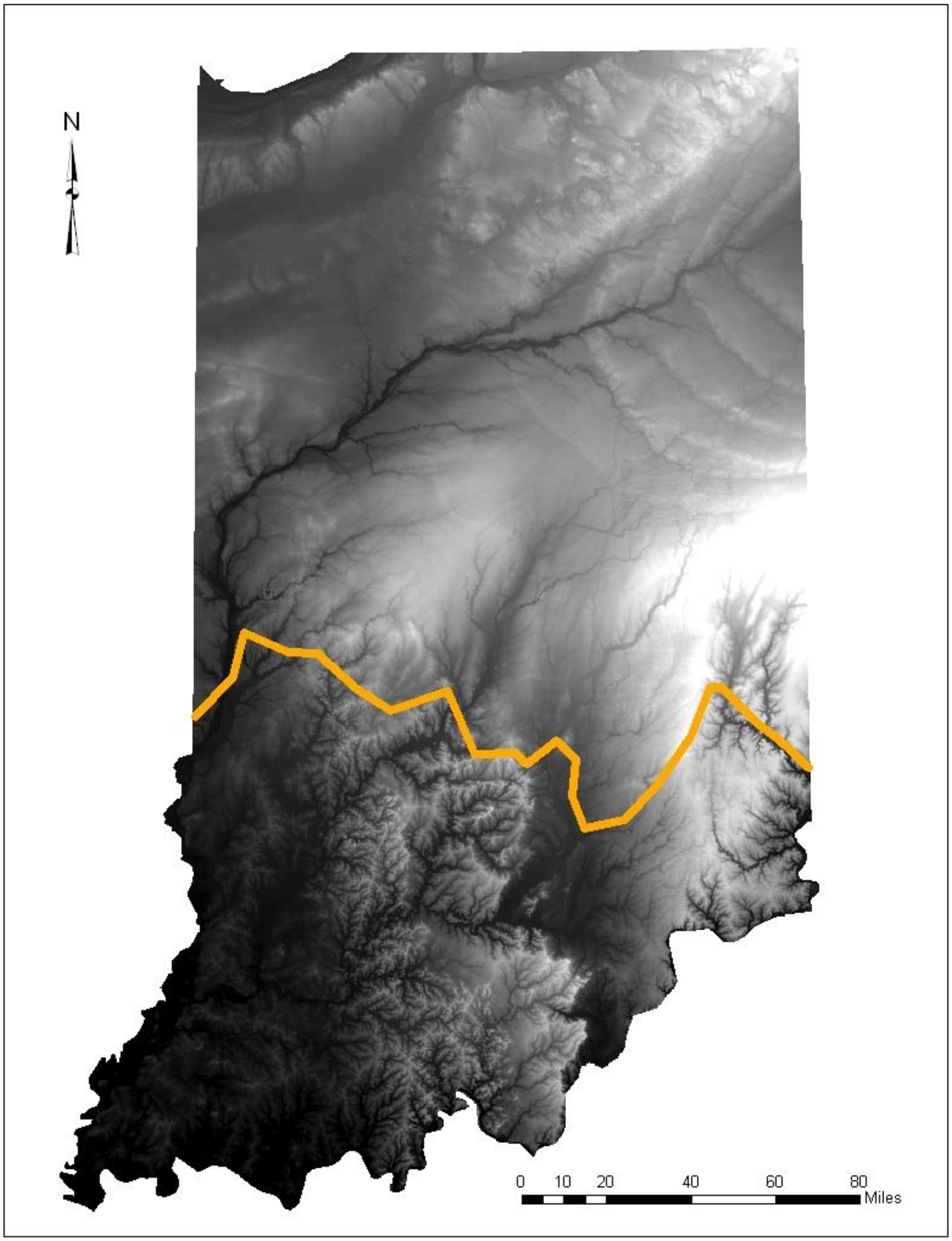


Figure 2.2. Southern border of Wisconsinan Glaciation

2.2 Data

The study areas for this research were selected from the available USGS stream gages in Indiana. Figure 2.1 shows the location of the watersheds selected for this study. The original selection criteria used included: the smallest rural watersheds (< 30 mi^2) that have available 15-minute stream flow data from at least 1995 – 2003 or more recent if available. The 2001 National Land Cover Dataset (NLCD) was used to visually inspect whether watersheds were rural. Because of the limitations of available data for gauges in northern and central Indiana the criteria was relaxed to include watersheds less than 40 mi^2. Also four of the thirty selected watersheds contain significant urban area. These watersheds fell outside the original criteria but were retained to maintain better coverage across the state. Watershed selection was also done in consultation with a past study in Indiana by Rao (2004) and Knipe (2005) which divided the state into six hydrologically similar regions. These six regions are included in Figure 2.1. Table 2.1 lists the watersheds selected for this study. The 15-minute stream flow data is available at the USGS Instantaneous Data Archive website (http://ida.water.usgs.gov/ida/).

Table 2.1. USGS stream gauges selected

Station Name	Station Number	Region	Area (mi^2)
WEESAU CREEK NEAR DEEDSVILLE, IN	3328430	North	8.9
GALENA RIVER NEAR LAPORTE, IN	4096100	North	14.9
FORKER CREEK NEAR BURR OAK, IN	4100252	North	19.2
RIMMELL BRANCH NEAR ALBION, IN	4100295	North	10.7
SOLOMON CREEK NEAR SYRACUSE, IN	4100377	North	32.5
FISH CREEK AT HAMILTON, IN	4177720	North	37.5
SPY RUN CREEK AT FORT WAYNE, IN	4182810	North	14.0
COBB DITCH NEAR KOUTS, IN	5517890	North	30.3
IROQUOIS RIVER AT ROSEBUD, IN	5521000	North	35.6
JUDAY CREEK NEAR SOUTH BEND, IN	4101370	North	38.0
WHITEWATER RIVER NEAR ECONOMY, IN	3274650	Central	10.4
LITTLE MISSISSINEWA RIVER AT UNION CITY, IN	3325311	Central	9.7
BIG LICK CREEK NEAR HARTFORD CITY, IN	3326070	Central	29.2
KOKOMO CREEK NEAR KOKOMO, IN	3333600	Central	24.7
BUCK CREEK NEAR MUNCIE, IN	3347500	Central	35.5
CROOKED CREEK AT INDIANAPOLIS, IN	3351310	Central	17.9
PLEASANT RUN AT ARLINGTON AV, INDIANAPOLIS, IN	3353120	Central	7.6
LITTLE BUCK CREEK NEAR INDIANAPOLIS, IN	3353637	Central	17.0
WEST FORK WHITE LICK CREEK AT DANVILLE, IN	3353700	Central	28.8
PLUM CREEK NEAR BAINBRIDGE, IN	3357350	Central	3.0
LITTLE INDIAN CREEK NEAR GALENA, IN	3302300	South	16.1
WEST FORK BLUE RIVER AT SALEM, IN	3302680	South	19.0
CROOKED CREEK NEAR SANTA CLAUS, IN	3303400	South	7.9
BUSSERON CREEK NEAR HYMERA, IN	3342100	South	16.7
HARBERTS CREEK NEAR MADISON, IN	3366200	South	9.3
BRUSH CREEK NEAR NEBRASKA, IN	3368000	South	11.4
BACK CREEK AT LEESVILLE, IN	3371520	South	24.1
STEPHENS CREEK NEAR BLOOMINGTON, IN	3372300	South	10.9
PATOKA RIVER NEAR HARDINSBURG, IN	3374455	South	12.8
HALL CREEK NEAR ST. ANTHONY, IN	3375800	South	21.8

CHAPTER 3. METHODOLOGY

3.1 Methodology Overview

The Clark SUH Method was selected for this study to gain some insight into how watershed storage affects runoff hydrographs. Equations for estimating the time of concentration (t_c) and storage coefficient (R) of the Clark unit-hydrograph method were developed for small rural watersheds [3-38 square miles (mi^2)] throughout Indiana. Equations were developed from rainfall-runoff data for 90 events across 30 watersheds. Data for 7 watersheds were used to verify the equations. R and t_c were determined by optimizing the rainfall-runoff data using the U.S. Army Corps of Engineers HEC-HMS software. The HEC-HMS model structure was developed using the GIS application HEC-GeoHMS. Regression relationships between watershed geomorphology, and t_c and R were determined using multiple linear regression. Equations were developed for each region separately and for the entire state.

3.2 GIS Analysis

The important computer programs used in extracting the geomorphologic parameters of the watersheds included ArcHydro and ArcGIS 9.2. The National Elevation Dataset (NED) digital elevation models (DEMs) were downloaded from USGS. For this study 30m resolution DEMs were used. The USGS National

Hydrography Dataset (NHD)stream network file clipped for Indiana was also used as an input for ArcHydro. From the DEM and NHD stream network, necessary raster files such as the flow accumulation grid and flow direction grid were created. Using ArcHydro with the DEM and stream network, the boundaries of the study watersheds were extracted. These watershed polygons were saved in geodatabases which calculated the area and perimeter.

From the ArcHydro output files used to generate the watershed polygons, the geomorphologic parameters listed and defined in Tables 3.1 and 3.2 were computed. The first nine parameters, are leased relate area and length measurements while the last nine are calculated using relief and the stream network. An additional routine within ArcHydro was used to calculate basin length, and a new feature class was created to measure the maximum straight-line length of basin from mouth to divide for the basin shape factor (S_b). Simple GIS techniques were used to extract other measurements. For example, a selection of the streams within the watershed polygon was performed to calculate the total stream length and number of streams within the watershed. This data was used to calculate the drainage density and stream frequency. The USGS Stream Stats web-based GIS interface was used to calculate additional geomorphologic characteristics: contributing drainage area (CDA), 10-85% Slope (Slope), percent of area covered by water or wetland (Water), percent of area that is urban land cover (ULC), and main channel length (MCh). Stream Stats is a web-based GIS interface that provides users with analytical tools to calculate streamflow statistics and watershed characteristics from user selected stream locations. To represent the depression storage of each watershed, the raster calculator within ArcMap was utilized to calculate the difference in the filled DEM computed during terrain processing and the raw DEM. The resulting raster has two categories: one represents raster cells that were unchanged and the other category represents the raster cells that were filled because they were sinks. Sinks are raster cells that are surrounded by cells with higher elevation leaving no route for water to "flow". The raster cells that are sinks must be "filled" so ArcHydro can calculate the raster files mentioned at the beginning of this section. Besides the Stream Stats and depression storage parameters Table 3.2 also has three composite parameters. These are named HKR (Hickok et al., 1959), Gray (Gray 1961), and Murphey (Murphey et al., 1977). These parameters are explained by the following equations.

$$HKR = \frac{A_w}{C_s \times \sqrt{D}} \tag{1}$$

$$Gray = \frac{\mathrm{L}_{\mathrm{ca}}}{\sqrt{C_s}} \tag{2}$$

$$Murphey = \frac{S_b}{A_w} \tag{3}$$

Refer to Table 3.1 for an explanation of the symbols used in these composite parameters.

Table 3.1 Definition of geomorphologic parameters

Parameters, *Symbol*	**Definition**
Drainage area, A_w	The total area projected upon a horizontal plane contributing overland flow to the stream segment of the given order and all segments of lower order.
Basin perimeter, L_p	The length measured along the divide of the drainage basin as projected on to the horizontal plane of the map.
Basin length L_b	The longest dimension of a basin parallel to the principal drainage line.
$\mathrm{L_{ca}}$, L_{ca}	The length from the basin outlet to a point adjacent to the centroid.
Form factor, R_{ff}	A dimensionless parameter defined as the ratio of basin area, A_w to the square of basin length, L_b^2
Circulatory ratio, R_c	A dimensionless parameter defined as the ratio of the basin area of a given order, A_w to the area A_p of a circle having a circumference equal to the basin perimeter, $L_{p.}$
Elongation ratio, R_e	The ratio of diameter of a circle, Dc with the same area as that of the basin, to basin length L_b
Basin shape factor, S_b	The square of maximum straight-line length of basin (from mouth to divide) divided by total area.
Unity shape factor, R_u	The ratio of the basin length, L_b to the square root of the basin area, Aw.
Basin relief, H	The maximum vertical distance between the lowest (outlet) and the highest (divide) points in the watershed.
Relief ratio, R_h	A dimensionless quantity, defined as the ratio of maximum basin relief, H to horizontal distance along the longest dimension of the basin parallel to the principal drainage line, L_b.
Relative relief, R_p	The ratio of basin relief, H to the length of the perimeter, L_p.
Drainage density, D	The ratio of the total length of all streams within a watershed to the watershed area.
Ruggedness number, R_n	Product of relief, H and drainage density, D.
Channel Maintenance, C	The ratio of the drainage area to the total of all streams in the network.
Fineness ratio, R_f	The ratio of channel lengths to the length of basin perimeter.
Stream frequency, C_f	The total number of streams per unit area.
Basin slope (%), L_s	Average grid slope computed by ArcGIS.
Main channel slope, C_s S	Slope of a line drawn along the measured profile of main channel.

Table 3.2. Definition of additional geomorphological parameters

Parameters, *Symbol*	**Definition**
10-85% Slope, *Slope*	Average of channel elevations at points 10 and 85 percent above gage
%Water/Wetland, *Water*	Percent of basin open water and herbaceous wetland from NLCD
%UrbanLC, *ULC*	Percentage of basin with urban development
Contributing DA, *CDA*	Area that contributes flow to a point on a stream
Curve Number, *CN*	Average curve number weighted by area
Main Channel Length, *MCh*	Length of longest flowline - head of stream to watershed outlet
HKR, *HKR*	$A_w/(C_s * \sqrt{D})$
Gray, *G*	$L_{ca}/\sqrt{C_s}$
Murphey, *M*	S_b / A_w
% Sinks, *Sinks*	Percentage of basin DEM (clipped by watershed polygon) filled

3.3 Rainfall-Runoff Event Selection

Rainfall-runoff events for use in this study were selected to conform as close as possible to the assumptions of the UH theory. Namely, the unit volume of surface runoff is equal to excess precipitation resulting from a storm of uniform intensity over a given duration. It is recommended by Viessman et al. (1989) that storms utilized to determine unit hydrographs should include:

- a simple structure which results in a well defined hydrograph with a distinct peak
- uniform rainfall distribution for the duration of rainfall excess
- uniform spatial distribution (of rainfall) over the entire watershed

Viessman et al. (1989) also recommend that the direct-runoff of storms selected for analysis should range from 0.5 to 1.75 in. This is because design storms used for further analysis would typically fall within this range. Storm events selected for this study were selected based on these criteria:

- Available USGS streamflow data during 1995-2006.
- The hydrographs were isolated events with well defined single peaks between March and June.

In a few cases, storms from late February were considered because of the quality of the available data. The precipitation data was also scrutinized to ensure no data was flagged as snowfall. Also, events were selected so there was little to no rainfall-runoff events five days prior and following a selected event. The objective in this approach was to minimize the effect of antecedent conditions and find the best single peaked storms. These criteria for hydrograph selection would yield the highest seasonal streamflows, with the most consistent antecedent moisture conditions, and rainfall events that covered the largest area. Precipitation data was obtained from the National Climactic Data Center (NCDC) for precipitation gauges across Indiana. Fifteen minute precipitation data was selected from the nearest precipitation gauge corresponding to the date and time of the selected streamflow hydrographs. A total of 90 rainfall-runoff events were selected, three per watershed, for calibration.

3.4 Hydrologic Modeling

Hydrologic modeling was performed with the U.S. Army Corp. of Engineer's (USACE) Hydrologic Engineering Center – Hydrologic Modeling Software (Hec-HMS). The Geospatial Hydrologic Modeling Extension (Hec-GeoHMS), a software package for use with Environmental Systems Research Institute's (ESRI) ArcMap, was used to create the hydrologic schematic of the watershed and stream network. Dividing the watersheds into subbasins was an important step in modeling. Utilizing Hec-GeoHMS, a stream threshold of 10% of the entire drainage area was selected. Thus, when an area equivalent to 10% of the watershed area drains to a point, a stream line is initiated and proceeds to the outlet. The threshold of 10% was chosen to keep the amount of subbasins per watershed at a manageable number. This resulted in approximately 3-10 subbasins per watershed. Hec-GeoHMS results were then imported to Hec-HMS for simulation and optimization. A more thorough explanation of Hec-GeoHMS can be found in the technical documentations available at the USACE’s Hydrologic Engineering Center website (http://www.hec.usace.army.mil/).

Hec-HMS requires the selection of specific processes for losses, hydrograph transform method, baseflow type, and routing. These processes are used in the hydrologic computations. The initial and constant-loss rate method was used for optimization to match effective precipitation depth to the direct-runoff depth of the observed streamflow hydrograph. Values for initial-loss and constant-loss rate were determined during Hec-HMS optimization to match effective precipitation depth to the direct runoff depth of the selected hydrographs. These values were not considered further in the analysis. Baseflow separation was performed manually before observed hydrographs were used in modeling. For the majority of storms the baseflow was estimated by extending the trend in flow throughout the entire hydrograph prior to the start of the storm. This was deemed acceptable because the events chosen were isolated and the flow returned to pre-event conditions relatively quickly. For storms that had a long recession limb before hydrographs returned to pre-event flows the straight line method was used as described by Chow et. al. (1988). Routing was modeled as a pure lag (Equation 4).

$$\mathrm{t_{lag}} = \frac{\mathrm{L}}{(\mathrm{V} * 60)} \tag{4}$$

Where t_{lag} is lag time in minutes, L is reach length in feet, and V is streamflow velocity in feet per second. This was deemed sufficient method because it minimized additional parameters for calibration and the attenuation of the hydrograph would be incorporated in the transform method chosen.

The Clark SUH method was chosen as the transform method because of its ability to incorporate the processes of translation and attenuation. Clark (1945) studied the translation of flow through a watershed and noted the time-area curve described this phenomena well. The time-area curve was defined as the fraction of watershed area contributing runoff to the outlet as a function of time since the start of effective precipitation (Straub et al. 2000). Translation is determined by using the time-area relationship described in Equation 5 (USACE, 2000).

$$\frac{A_t}{A} = \left\{ \begin{array}{c} 1.414 \left(\frac{t}{t_c}\right)^{1.5} \; for \;\; t \leq \frac{t_c}{2} \\ 1.414 \left(1 - \frac{t}{t_c}\right)^{1.5} \; for \;\; t \geq \frac{t_c}{2} \end{array} \right\} \tag{5}$$

Where A_t is the cumulative watershed area contributing runoff at time t, A is total watershed area, and t_c is time of concentration. The Clark time of concentration (t_c) bounds the time-area curve. Attenuation is modeled with the use of a storage coefficient (R) that can be represented by a simple linear reservoir as:

$$S = OR \tag{6}$$

where S is watershed storage, R is the watershed storage coefficient (in hours), and O is the outflow from the watershed. It was assumed that the storage coefficient would represent the storage effects in the watersheds of Indiana. The USACE noted the use of the ratio $R/(t_c+R)$ tends to remain constant for a region (USACE, 1990). Values for the ratio $R/(t_c+R)$ were set as 0.5-0.7 for north and central regions and 0.2-0.4 for the south. These values were comparable to those used in (Straub et al. 2000). The t_c for each subbasin was calculated using the NRCS Curve Number method for use as an initial value in optimization. Values of the Clark t_c were estimated and used as an initial value during optimization. Initial values for R were back calculated from the ratio, $R/(t_c+R)$, defined previously. These initial values were only used as a starting point for the optimization process.

3.5 Parameter Optimization

Synthetic unit hydrographs were generated for 3 rainfall-runoff events per watershed. The SUH parameters t_c and R were optimized by matching the estimated SUH to the observed streamflow for each event. The priority of the optimization was to match the peak flow rate (Q_p), time to peak (t_p), and the overall hydrograph shape. The criteria for successful optimization were: an estimated Q_p within 5% of observed values, t_p within 15 minutes of observed and similar overall hydrograph shape through graphical comparison. Of the 90 optimization trials 75 events satisfied the optimization criteria, 6 events had peak flows within 5-10% of observed and 9 events did not meet either criteria. An investigation into the unsuccessful optimizations showed Juday Creek watershed failed to produce a successful optimization. This study area was dropped from the analysis. The optimization procedure required optimization run configurations be constructed for each event. Optimization was performed using the following procedure.

1. Run configurations were created defining the basin model, meteorological model, and control specifications

2. Parameters to be optimized were selected. The Clark t_c and R in hours, initial losses in inches, and constant loss rate in inches per hour were used.

3. Initial values for all parameters were estimated and input.

Optimization was performed using a trial and error approach. Parameters outlined above were adjusted to closely match the Clark SUH to the observed hydrograph. There are six objectives functions used for optimization methods available in Hec-HMS: Peak-Weighted RMS, Percent Error Peak, Percent Error Volume, Sum of Absolute Residual, Sum of Squared Residual, Time-Weighted Error. Initially the Peak-Weighted RMS method was used, but if that did not yield good results other methods were utilized to obtain the best results.

Once optimization was complete, several checks were made to ensure the quality of the optimizations. Values of excess precipitation were compared to the resulting direct runoff calculated during optimization to ensure the values were equal. Peak flow rates and time to peak were compared to the observed to ensure values optimized sufficiently followed the observed hydrographs. Optimized Clark t_c and R were compared and averaged for all events per watershed to ensure hydrographs produced were consistent.

Hec-HMS does not calculate traditional UHs directly so an additional run configuration was created for each basin model to calculate the 5-minute UH for each watershed.

1. Average values of t_c and R (from the optimizations) were used in this scenario. Representative values from the optimization were used for lag times.
2. Losses were set to zero because a UH is a direct runoff hydrograph.
3. A new meteorological model was created with a one inch pulse of rainfall of 5 minute duration. This is the definition of a 5-minute UH.
4. The results of the calculated UHs were checked to ensure a volume of 1 inch and Q_p and t_p were recorded for each.

The values of Q_p and t_p provided a basis on which to compare hydrographs of watersheds across the three regions of Indiana. These two points on the hydrograph along with the recession times would give some insight in to the shape of UH hydrographs for watersheds across the state as well.

CHAPTER 4. STATISTICAL ANALYSIS

After optimization and 5-minute UH calculations were complete, statistical analysis was performed to establish a statistically significant relationship between the geomorphology and UH shape of watershed across Indiana. This was done to assist in the selection of ideal geomorphologic parameters that might best describe the Clark SUH characteristics across the state. Three tests to determine a significant difference in the mean (between each region) were performed on all geomorphologic and hydrograph parameters. This included: Student t-test, Tukey-Kramer, and the Wilcoxon Rank Sum. Both the Student t-test and Tukey-Kramer assume a normal distribution and equal variances. In the event variables violated these assumptions, the Wilcoxon Rank Sum was included because it is nonparametric.

4.1 Student t-Test

The Student t-Test was employed to determine whether there was a statistical significance in the difference in the mean of each parameter across the three regions. The mean of each parameter measured for all 30 watersheds of each region (ten per region) were calculated. This resulted in three mean values that were compared for each parameter. A pairwise comparison of each mean was performed so each region was tested for a significant difference from the other two. Calculation of the test statistic required the use of a pooled variance:

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{(n_1 - 1) + (n_2 - 1)} \tag{7}$$

To test the hypothesis:

$$H_o: \mu_1 - \mu_2 = 0 \qquad H_a: \mu_1 - \mu_2 \neq 0$$

$$t^* = \frac{(\overline{Y}_1 - \overline{Y}_2) - 0}{s_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{8}$$

Reject H_o when $t^* > t_{1-\frac{\alpha}{2}}, v$ where $v = n_1 + n_2 - 2$

By rejecting the null hypothesis at a significance level of $\alpha = 0.05$ we can show the means are significantly different.

4.2 Tukey-Kramer Pairwise Test

The Tukey-Kramer pairwise comparison also tests the same hypothesis as the Student t-Test:

$$H_o: \mu_1 - \mu_2 = 0 \qquad H_a: \mu_1 - \mu_2 \neq 0$$

The Tukey-Kramer procedure uses the studentized range distribution. Studentized means were adjusted by dividing by an estimate of the population standard deviation. Consider r independent observations $Y_1, \ldots, Y_r$ from a normal distribution with mean μ and variance σ^2. Let *w* be the range for the observations, or the maximum observation minus the minimum observation, and assume an estimate of the variance s^2 based on v degrees of freedom and independent of the observations. The ratio of *w*/s becomes the *studentized range* denoted by (Kutner et al 2005):

$$q(r,v) = \frac{w}{s} \tag{9}$$

The distribution of q depends on r and v, and is typically tabulated for selected percentiles in many statistical textbooks (Kutner et al 2005). The Tukey test statistic is calculated as:

$$q^* = \frac{\sqrt{2}\hat{D}}{s\{\widehat{D}\}} \tag{10}$$

where $\hat{D}$ and $s^2\hat{D}$ are based on family confidence intervals and discussed in further detail by Kutner et al. (2005). H_o is concluded if $|q^*| \leq q(1-\alpha; r; n_T - r)$: otherwise, H_a is concluded. In this study comparisons were performed at a significance level of α = 0.05.

4.3 Wilcoxon Rank Sum Test

The Wilcoxon Rank Sum Test is useful for comparison when data sets do not exhibit a normal distribution that is necessary for the Student t-Test. This rank sums method was presented in a paper by Wilcoxon (1945). The method combines the samples of two tests as $n_1 + n_2$ and ranks the sorted values. A value of W is given to sum of the ranks for each sample. Depending on the size of the data set the standard distribution used for this test varies. The statistical software JMP 6.0 was utilized to calculate the test statistic and perform the analysis.

CHAPTER 5. DEVELOPMENT OF REGIONAL REGRESSION EQUATIONS

Multiple regression analysis is a useful method in developing regional parameter estimation equations (Abdulla and Lettenmaier, 1997). Regional regression equations are useful for estimating parameters at ungauged sites, and relatively straight forward for using information from gauged sites for equation development. The typical multiple regression model is of the form:

$$Y = B_1X_1 + B_2X_2 \ldots + B_nX_n \tag{11}$$

where Y is the dependent variable (in this case Clark SUH parameters), $X_1, X_2, \ldots, X_n$ are independent variables (watershed characteristics) and $B_1, B_2, \ldots, B_n$ are unknown coefficients. The unknown coefficients are determined utilizing the method of least squares (Abdulla and Lettenmaier, 1997). Stepwise selection techniques were employed to select the best number of independent variables for the regression model and specific variables that would be most useful for estimation of the Clark SUH parameters.

Several regression models were developed and investigated. SAS statistical software package was used to run stepwise regression procedures for the selection of best multiple linear regression models. The goal of stepwise regression is to take a set of independent variables and add them to the model one at a time in a certain manner until all variables have entered the model or a specific criteria has been met (Cody and Smith 2006). The criteria used in this study required all variables added to the regression were statistically significant to a level of $\alpha = 0.05$. For stepwise selection, a variable is added if it meets the significance level; as variables are added, if the significance of a previously entered variable diminishes that variable is removed. In summary variables can be added and removed throughout the process until the procedure has attempted to add all variables. It must also be noted that stepwise regression does not always select the best model, but usually an acceptable one (Draper and Smith 1981). An alternative procedure was used to select the best subsets of models with the highest r-squared values for regression equations with one, two, and eventually all variables used in the regression. This procedure did not consider the significance of each variable, but helped gain some insight into what variables consistently were used in the best regression models.

Two scenarios were used to develop five regression models for each Clark SUH parameter. Scenario 1 used all 29 watershed characteristics as possible independent variables. Scenario 2 used only the 10 geomorphologic parameters measured using the USGS Stream Stats application. The goal of Scenario 2 was to find out if a simpler list of variables could perform as well as the large list which may have some significant multicollinearity effects, that is, some variables are correlated to each other and explain the same amount of variance. The five regression models investigated were:

1. Linear Model

$$Y = B_O + B_1X_1 + B_2X_2 \ldots + B_nX_n \tag{12}$$

2. Logarithmic Model 1

$$\log(Y) = B_O + B_1 \log(X_1) + B_2 \log(X_2) \ldots + B_n \log(X_n) \tag{13}$$

3. Logarithmic Model 2 (only independent variables transformed)

$$Y = B_O + B_1 \log(X_1) + B_2 \log(X_2) \ldots + B_n \log(X_n) \tag{14}$$

4. Square Root Model 1

$$\sqrt{Y} = B_O + B_1 \sqrt{X_1} + B_2\sqrt{X_2} \ldots + B_n \sqrt{\mathrm{X_n}} \tag{15}$$

5. Square Root Model 2 (only independent variables transformed)

$$Y = B_O + B_1 \sqrt{X_1} + B_2\sqrt{X_2} \ldots + B_n \sqrt{\mathrm{X_n}} \tag{16}$$

Before models were selected to progress to the validation step, several diagnostics were performed to test whether the regression models obeyed the general assumptions of multiple linear regression. The four assumptions addressed whether: variables are normally distributed, overall model fit (linear relationship exists), independent variables are measured without error, and variance is equal across all independent variables. Once a model was selected ANOVA tables and necessary plots were developed using Excel. Normal probability plots were used to examine normality of the variables. F-test values were used to test overall significance of the entire regression model. The linear relationship of independent variables to dependent variables was tested using residual plots against predicted values. Variables were assumed to be error free because of the computational accuracy of using remote sensing and GIS datasets. Finally, equal variance across all independent variables was tested by plotting the standardized residuals of each and confirming they were randomly distributed about the x-axis. Complete ANOVA tables and regression statistics are provided in Appendix A.

CHAPTER 6. RESULTS

The statistical tests mentioned in the previous chapters were performed first on the geomorphological parameters. This was done to learn what geomorphology distinguished watersheds from region to region. The Clark SUH parameters, t_c and R, were also analyzed using the same statistical tests. From the optimized models, 5-minute UHs were calculated, as described in Section 3.5, for each watershed. The resulting Q_p and t_p were used for comparison. Finally, the best regression equations were used on 7 verification rainfall runoff events for watersheds selected from the study to represent the entire 30 watersheds best. The following sections discuss the results of the statistical analysis and regressions for each region in detail.

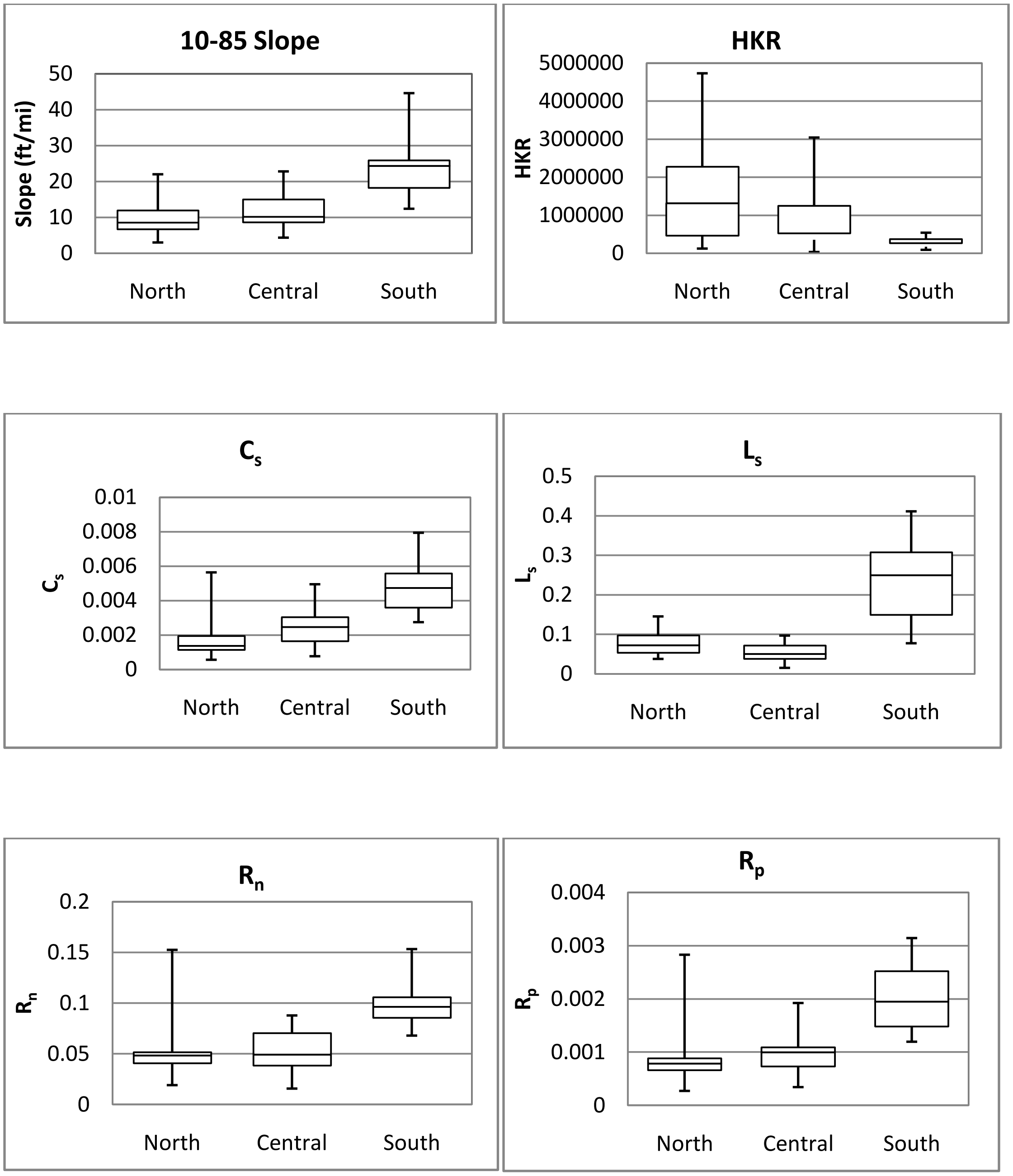
6.1 Statistical Analysis

The statistical test conducted on the geomorphologic parameters yielded results that support the geomorphology discussed in Chapter 2, namely southern Indiana is different from the north and central regions of the state. There was no significant difference between the north and central regions for any of the geomorphologic parameters dealing with slope. Significant differences in slope were observed between the southern region and each of the other two regions.

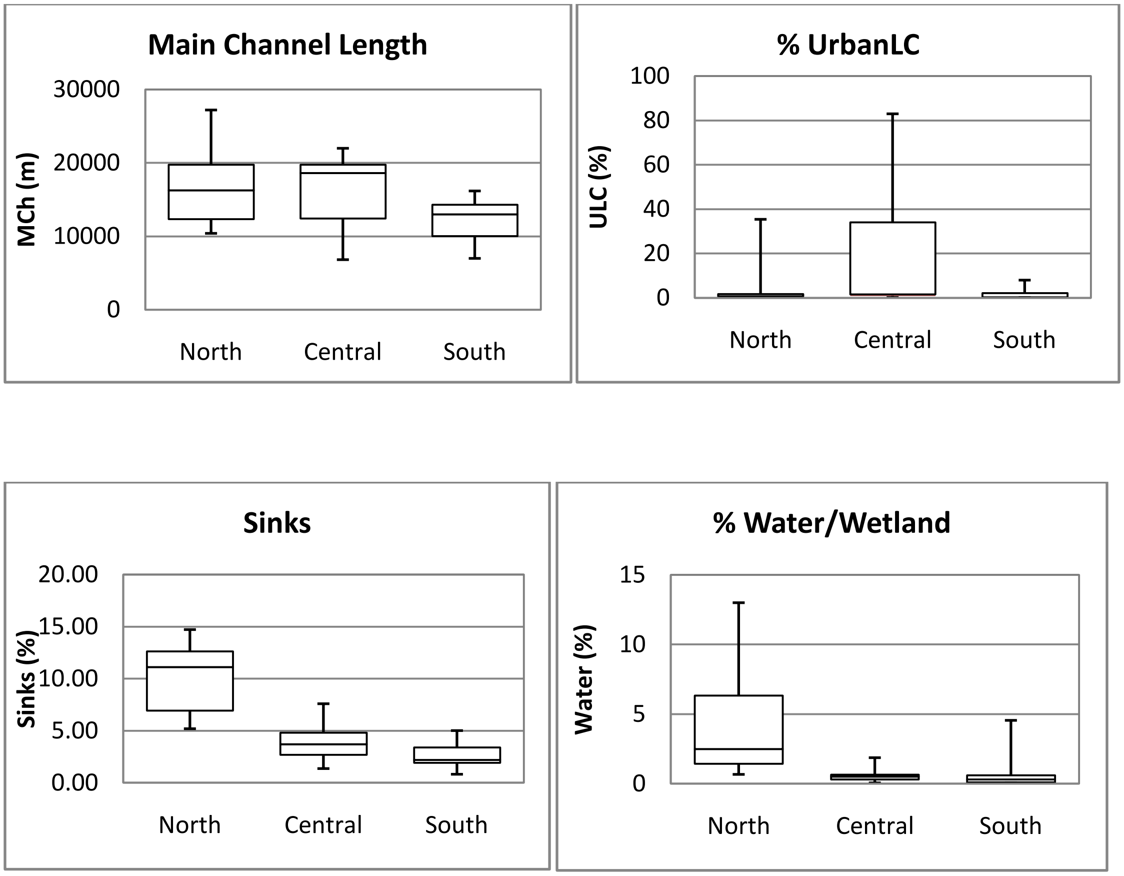
central regions. The central slopes of the and northern region are not significantly different from each other (at $\alpha = 0.05$). All parameters involving slope and relief show this relationship. The box plots showing mean values and the variation of the significantly different parameters are displayed in Figures 6.1-6.10. In other words, the central and northern region's watersheds have statistically similar slopes. The percent water/wetland parameter showed the northern region's watersheds to be statistically different from the other two regions. The northern region also showed a significantly higher percentage of sinks calculated from the DEM, which indicates more depression storage. Main channel lengths for the southern region are statistically shorter, and differ from the north and central regions. The central region was shown to be statistically different for percent of urban land cover, but this is due to the proximity of several watersheds to Indianapolis. Table 6.1 summarizes the results. Refer to Tables 3.1 and 3.2 for a description of the geomorphologic parameters.

Table 6.1. Results of statistical analysis of geomorphologic parameters

Parameter			
	Related to Slope	**Region of Difference**	**How Region Differs**
10-85 Slope	X	South	Statistically higher slopes
HKR	X	South	
Cs	X	South	
Ls	X	South	
Rn	X	South	
Rp	X	South	
Rh	X	South	
Water		North	Statistically higher % of Water/Wetlands
%ULC		Central	Statistically higher % of ULC
Main Channel		South	Statistically shorter main channel length
Sinks		North	Statistically higher % of Sinks



Figures 6.1-6.6. Box Plots displaying slope related geomorphologic parameters



Figures 6.7-6.10. Box plots displaying other significant geomorphologic parameters

In summary the watersheds of northern and central Indiana are have significantly lower slopes than the southern watersheds. However, Northern Indiana tends to have a higher percentage of water/wetland features and depression storage. Central Indiana watersheds for this study will have some effects from the urbanized land cover of Indianapolis, but because of data constraints they were kept in the study. The central region shares the lower slopes seen in the north, but has lower depression storage characteristics. Southern Indiana watersheds were shown to have higher slopes and shorter main channel lengths and the least amount of depression storage.

6.2 Clark SUH Parameter Analysis

Optimized values for t_c and R were obtained for each subbasin within each watershed. During optimization it was noted that R affected the peak flow values most, making the flows lower for higher values of R. The t_c, as one would expect, had most control on the timing of the peak. Statistical analysis showed R values increased moving north in the state, but each region was found to significantly different from the other. The southern region showed statistically smaller t_c. This would support the analysis of the geomorphological parameters where it was found that the main channel lengths were shorter and steeper resulting in higher velocities and faster travel times through the southern watersheds. Values of the Clark SUH parameters for each watershed are provided in Figure 6.11 and Table 6.2.

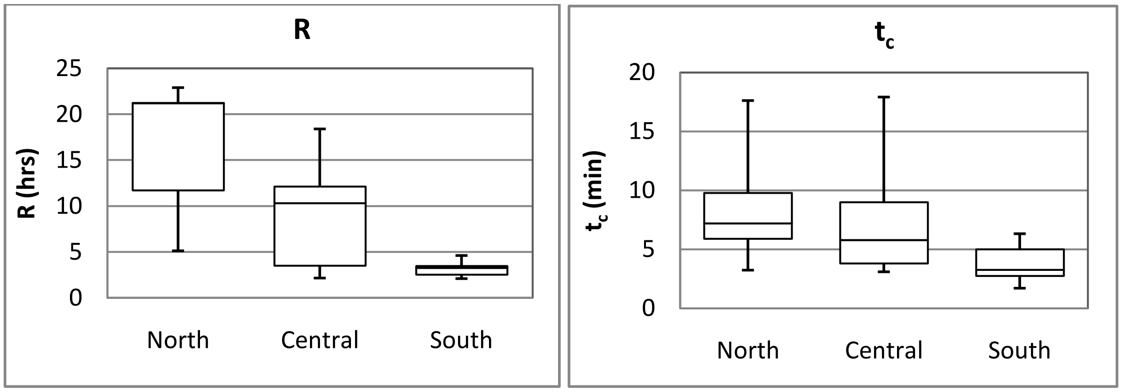


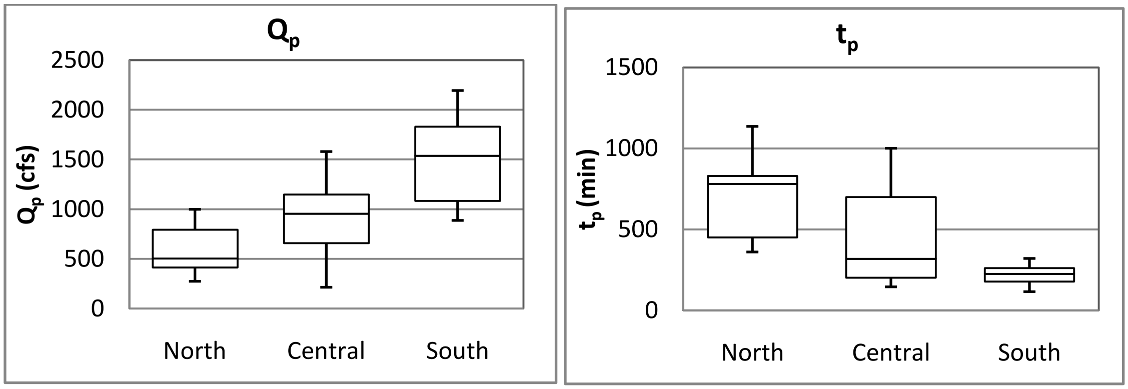
Figure 6.11. Box plot of optimized R and t_c values

Table 6.2. Summary of Optimized Clark SUH parameters

Name	**Region**	**Station No.**	**A_w (mi^2)**	**t_c (hrs)**	**R (hrs)**
WEESAU CREEK	N	03328430	8.87	3.22	21.2
GALENA RIVER	N	04096100	14.9	7.21	10.08
FORKER CREEK	N	04100252	19.2	9.77	21.23
RIMMELL BRANCH	N	04100295	10.7	5.91	11.69
SOLOMON CREEK	N	04100377	32.5	13.17	22.9
FISH CREEK	N	04177720	37.5	7.14	21.18
SPY RUN CREEK	N	04182810	14	4.4	5.12
COBB DITCH	N	05517890	30.3	7.99	19.69
IROQUOIS RIVER	N	05521000	35.6	8.2	16.75
JUDAY CREEK	N	04101370	38	10.01	19.73
Name	**Region**	**Station No.**	**A_w (mi^2)**	**t_c (hrs)**	**R (hrs)**
WHITEWATER RIVER	C	03274650	10.4	3.33	3.22
LITTLE MISSISSINEWA RIVER	C	03325311	9.67	17.9	16.73
BIG LICK CREEK	C	03326070	29.2	5.76	12.47
KOKOMO CREEK	C	03333600	24.7	10.02	18.4
BUCK CREEK	C	03347500	35.5	5.81	11.05
CROOKED CREEK	C	03351310	17.9	5.9	3.73
PLEASANT RUN	C	03353120	7.58	3.56	2.15
LITTLE BUCK CREEK	C	03353637	17	4.56	9.68
WEST FORK WHITE LICK CREEK	C	03353700	28.8	12.02	10.9
PLUM CREEK	C	03357350	3	3.08	3.41
Name	**Region**	**Station No.**	**A_w (mi^2)**	**t_c (hrs)**	**R (hrs)**
LITTLE INDIAN CREEK	S	03302300	16.1	5.18	2.62
WEST FORK BLUE RIVER	S	03302680	19	6.31	2.43
CROOKED CREEK	S	03303400	7.86	2.9	3.14
BUSSERON CREEK	S	03342100	16.7	5.79	4.26
HARBERTS CREEK	S	03366200	9.31	4.47	3.35
BRUSH CREEK	S	03368000	11.4	2.65	3.32
BACK CREEK	S	03371520	24.1	2.7	4.61
STEPHENS CREEK	S	03372300	10.9	3.6	3.49
PATOKA RIVER	S	03374455	12.8	1.69	2.09
HALL CREEK	S	03375800	21.8	2.83	2.5

6.3 Five-minute UH Analysis

The 5-minute UHs were calculated based on the optimized parameters previously computed using the method described in section 3.4. The 5-minute UH was selected as a metric to establish the difference in peak flows and travel times across the regions of Indiana. Because the individual storm events used for calibration were of varying duration and runoff volume, the 5-min UH analysis was adopted for a more direct comparison of hydrographs with equal storm duration and runoff volume. The results are consistent with the results of all previous analysis. The Q_p for the north and central regions is statistically lower than in the southern region. The box plots in Figure 6.12 & 6.13 show a trend of decreasing peak flows from the south to the north of the state. The t_p values also reinforce the trend discussed. For southern Indiana, the average t_p are statistically shorter (Figure 6.13). This analysis established the difference in hydrograph shape and thus hydrology across Indiana.



Figures 6.12 – 6.13. Box plots of 5-minute UH Q_p and t_p

6.4 Regression Models

Each of the regression models developed for individual regions contained a unique set of variables. Of the five regression models, the Logarithmic Model 1 by far performed the best for Scenario 1 and 2 (Chapter 5) within in each region. A summary of the regression results are located in Appendix C. Regressions for each region had R^2 values > 0.8 with F-test model significance < 0.008 for Log Model 1. The Log Model 1 regression for Scenario 1 (all geomorphological parameters considered for regression) performed best. Each regional equation contained a unique set of independent variables as well. The results from Scenario 2 (only Stream Stats parameters considered for regression) were not as good. The Logarithmic Model 1, again, performed best for Scenario 2, but R^2 values were 0.47 and 0.63 for the north and central regions respectively. The logarithmic Scenario 2 regression for the southern region selected no significant independent variables at $\alpha = 0.05$. One additional regression set for t_c and R was considered for comparison with regional equations. These regression equations represent the entire state containing the most simple set of variables necessary to predict t_c and R. The rationale was to see if a simpler set of regression equations for the entire state could perform as well as the region specific regression equations. The following sections discuss the regression equations in detail for each region. The discussion will include the best Scenario 1 and Scenario 2 regression models for each Clark SUH parameter (R and t_c). Refer to Appendix A for detailed regression statistics and ANOVA tables.

6.5 Regression Models – North Region

The best regression model for predicting the Clark storage coefficients (R) of Northern Indiana was represented by the Log Model 1 - Scenario 1. This regression model included urban land cover (ULC) and stream frequency (C_f) as the significant variables. Both independent variables were significant at $\alpha = 0.05$. The Linear Model – Scenario 2 regression also yielded a promising result. In Scenario 2 only the Stream Stats variables were used as possible independent variables. The 10-85% slope (Slope) and percent of water/wetland features (Water) yielded a $R^2 = 0.88$. The t_c was also best predicted by Log Model 1 – Scenario 1 and the second best model for t_c was Log Model 1 – Scenario 2. In both equations for t_c contributing drainage area (CDA) was the most significant independent variable. To summarize it seems R is best predicted with variables related to landuse/landcover, stream network, and slope. Time of concentration is more dependent on the size of the watershed. These equations are listed here in Table 6.2.

Table 6.3. Summary of best Northern Region regression equations.

Regression Model	**Transform**	**Scenario**	**R^2**
$\log(R) = 1.139 - 0.164 \log(ULC) - 0.819 \log(C_f)$	Log Model 1	1	0.86
$R = 27 – 1.665\,(\mathbf{Slope}) – 1.506\,(\mathbf{Water})$	Linear Model	2	0.88
$\log(t_c) = -3.355 + 1.677 \log(CDA) + 1.369 \log(C_f) + 0.396 \log(G)$	Log Model 1	1	0.97
$\log(t_c) = -0.254 + 0.841 \log(\mathrm{CDA}) - 0.079 \log(\mathrm{ULC})$	Log Model 1	2	0.78

All variables are log base 10-transformed except Linear Model.
Refer to Tables 3.1 and 3.2 for definitions of the independent variables

6.6 Regression Models – Central Region

The central region has represented a transition region geomorphologically. In the previous chapter it was shown that the central region shares the lower slopes seen in the north, but has depression storage characteristics more in common with the southern region. Also, the presence of watersheds with more urban land cover adds a dimension of complexity. The best regression models for t_c and R were again Log Model 1 – Scenario 1. Fineness ratio (R_f) and Slope provide the best prediction for R. Fineness ratio describes the relationship of channel lengths to basin perimeter. For the t_c prediction, urban land cover (ULC) and slope variables (L_s and H) performed best. Although both L_s and H are slope-related, their correlation coefficients were low enough to remain in the regression model together. The Scenario 2 models both displayed much less success however their inclusion of similar independent variables illustrates that slope is an important factor in the central region.

Table 6.4. Summary of best Central Region regression equations.

Regression Model	**Transform**	**Scenario**	**R^2**
$\log(R) = 1.727 - 2.722\log(R_f) - 0.932\log(Slope)$	Log Model 1	1	0.86
$\sqrt{R} = 6.189 - 0.949\sqrt{(Slope)} - 0.048\sqrt{(ULC)}$	Sqrt Model 1	2	0.82
$\log(t_c) =$ $-1.944 - 0.927\log(L_s) + 0.956\log(H) - 0.125$ $\log(ULC)$	Log Model 1	1	0.84
$\log(t_c) = 1.574 - 0.769\log(Slope)$	Log Model 1	2	0.41

All variables are log base 10 transformed except Sqrt Model 1.
Refer to Tables 3.1 and 3.2 for definitions of the independent variables

6.7 Regression Models – South Region

The regression models provided the poorest fits for the southern region. Because of the small variation among the different watersheds because of the small variation of R and t_c. Referring to the optimized R values in Table 6.2, it is clear that the storage effects of the watersheds vary little across the southern region making this variable difficult to discriminate. The regression models for R do not contain any variables relating to slope, possibly because of the consistency (small variation) in the slope across the region. The variables selected to predict R are all based on stream network and basin shape parameters. The prediction of t_c in the southern region shows a dependence on land cover/land use with the inclusion of the urban land cover and curve number parameters.

Table 6.5. Summary of best South Region regression equations.

Regression Model	Transform	Scenario	R^2
$\log(R) = 2.012 + 1.450 \log(L_{ca}) - 2.361 \log(C) + 1.215 \log(R_f)$	Log Model 1	1	0.88
$\log(t_c) = -3.283 + 0.266 \log(ULC) + 2.693 \log(CN) + 1.696 \log(R_f) - 0.568 \log(H)$	Log Model 1	1	0.95
$\log(t_c) = -3.503 + 0.179 \log(ULC) + 2.205 \log(CN)$	Log Model 1	2	0.69

All variables are log base 10 transformed.
Refer to Tables 3.1 and 3.2 for definitions of the independent variables

6.8 Regression Models – Statewide

The statewide regression equations were developed for two reasons. The first reason was to illustrate, more clearly, the important geomorphologic characteristics for Indiana overall. Second, the statewide regression models could provide a more simple set of equations utilizing a larger sample size. The larger sample size used to develop the statewide equations make them less dependent on the specific variation found in the smaller regional equations. The statewide regressions do support the findings of the statistical analysis of the geomorphologic parameters. The slopes and depression storage characteristics were identified as distinct among the regions. The prediction of R supports this by utilizing the 10-85% slope (Slope) and the percentage of sinks (Sinks). The t_c regression model incorporates similar slope and depression storage related characteristics by including the average grid slope (L_s) and percentage of water/wetland features (Water), but it also relies on basin length (L_b). The use of basin length follows conventional wisdom that some type of hydraulic length is necessary to calculate t_c.

Table 6.6. Summary of best Statewide regression equations.

Regression Model	Transform	Scenario	R^2
$\log(R) = 1.456 - 0.773 \log(Slope) + 0.382 \log(Sinks)$	Log Model 1	1	0.70
$\log(t_c) =$ $-2.176 + 0.639 \log(L_b) - 0.307 \log(L_s) + 0.160 \log(Water)$	Log Model 1	1	0.62

All variables are log base 10 transformed.
Refer to Tables 3.1 and 3.2 for definitions of the independent variables

6.9 Summary of Regression Models

The geomorphological parameters selected for the regional regressions vary greatly from region to region. Several parameters do show up frequently, namely : C_f, R_f, ULC, and Slope. For the northern region C_f is used in both regressions (t_c and R). Stream frequency (C_f) was calculated as the total number of streams per unit area. The Fineness ratio (R_f) was calculated as the ratio of channel lengths to the length of basin perimeter. The incorporation of this parameter shows that the stream network characteristics are important factors for calculating the Clark parameters within each region. The central region equations both incorporate a slope parameter which would indicate the central region is a transition region where watersheds nearer the south may exhibit higher slopes versus watersheds nearer the north. Urban land cover also has an influence on the t_c. This is to be expected because of the watersheds near Indianapolis used in this study. Equations for the southern region both include R_f which again indicates the importance of stream network characteristics. The regression equations for t_c and R across the entire state support the statistical findings of the previous sections. Slope appears to be the most important independent variable distinguishing watersheds across the state from north to south, confirming lower slopes increase the t_c and R. The Clark storage, R, is also impacted by the percentage of depression storage features. The positive correlation shows the increase in depression storage increases the Clark storage coefficient. Basin length, L_b , shows a positive correlation to t_c, which would be similar to other methods of t_c computation, where hydraulic or main channel length is an important factor. After analysis of the results from Scenario 1 and 2 the equations from the Log Model 1 – Scenario 1 were selected for validation (Table 6.6).

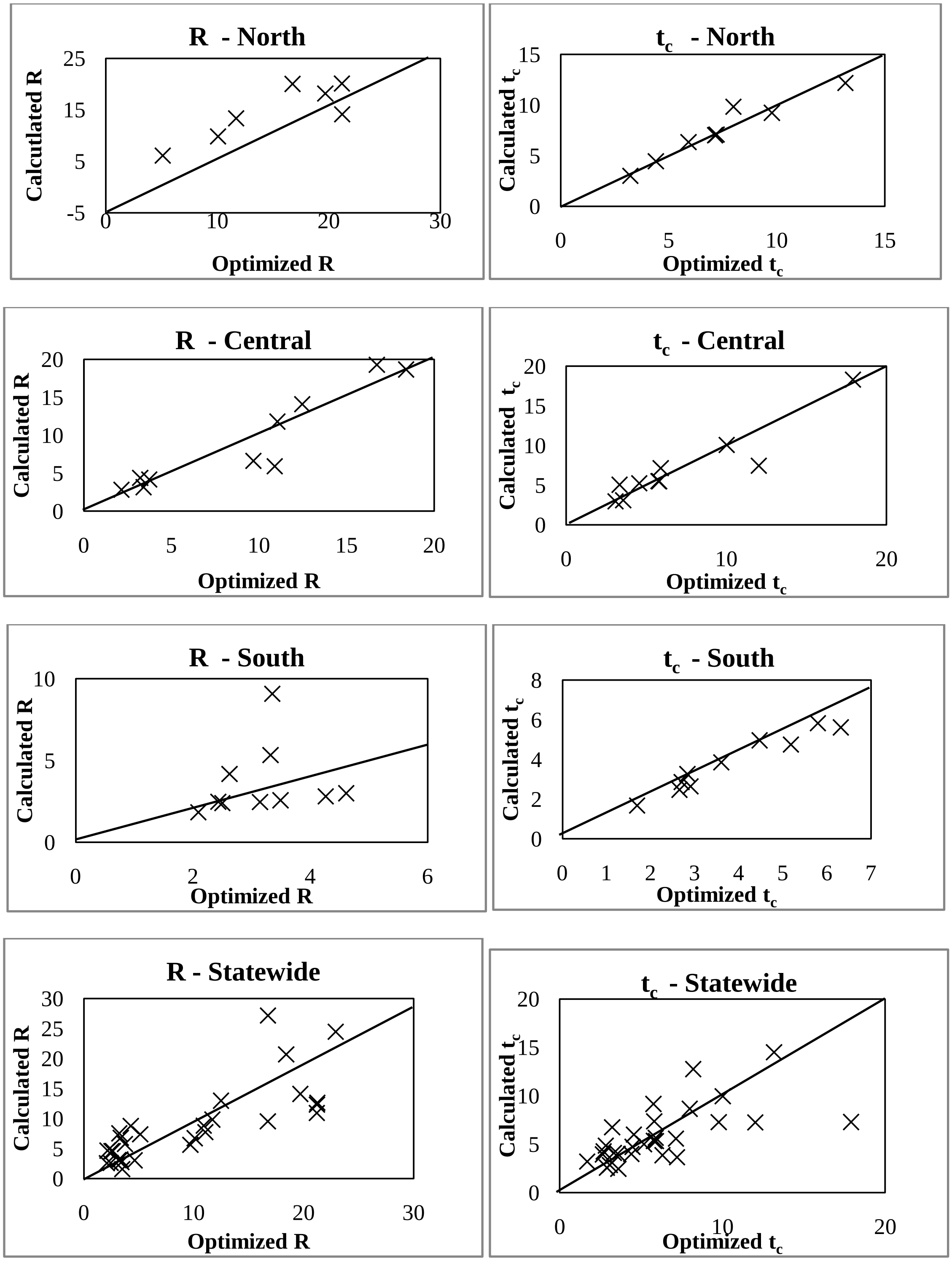
The performance of the developed regression equations was tested in two ways for this study. First, the regression equations (regionalized and statewide) were used to estimate average values of t_c and R. The average Clark parameters for all watersheds used in regression model development were compared to the optimized average values.

Plots of each are included in Figures 6.14-6.21. Overall there is a good agreement of calculated and observed values. The plot with the largest deviation from the 1:1 line was the average values for R in the southern region. This is possibly due to the small variation in the optimized average R values in the south, thus making it difficult to fit a regression to a set of closely grouped points. The regression equation for the entire state showed a higher deviation in optimized and calculated values as well. The regression models for the north and central regions performed well for both Clark parameters. This is especially important because estimating the watershed storage effects in the north was the focus of this study, since current SUH methods are not performing well for low slope watersheds.

Table 6.7. Regression equations selected for implementation

Models	**Log Model 1 - Scenario 1**
North	$\log R = 1.139 - 0.164 \log (ULC) - 0.819 \log (C_f)$
	$\log t_c = -3.355 + 1.677 \log (CDA) + 1.369 \log (C_f) + 0.396 \log (G)$
Central	$\log R = 1.727 - 2.722 \log (R_f) - 0.932 \log (Slope)$
	$\log t_c = -1.944 - 0.927 \log (L_s) + 0.956 \log (H) - 0.125 \log (ULC)$
South	$\log R = 2.012 + 1.450 \log (L_{ca}) - 2.361 \log (C) + 1.215 \log (R_f)$
	$\log t_c = -3.283 + 0.266 \log (ULC) + 2.693 \log (CN) + 1.696 \log (R_f) - 0.568 \log (H)$
Statewide	$\log R = 1.456 - 0.773 \log (Slope) + 0.382 \log (Sinks)$
	$\log t_c = -2.176 + 0.639 \log (L_b) - 0.307 \log (L_s) + 0.160 \log (Water)$

All variables are log base 10 transformed.
Refer to Tables 3.1 and 3.2 for definitions of the independent variables



Figures 6.14 – 6.21. Optimized vs Calculated R and t_c

6.10 Application of Regression Equations

Data for 7 of the 30 study watersheds were used for a application trial of a rainfall-runoff event that was not used in optimization. Watersheds selected for implementation included: Forker Creek, Rimmel Branch, and Iroqouis River from the northern region, Kokomo Creek and Little Buck Creek from the central region, and Hall creek and West Fork Blue River of the southern region. These were selected to best represent the geomorphological characteristics encountered throughout the state. Figure 6.22 is a map showing the location of each watershed and Table 6.7 lists some descriptive geomorphologic characteristics. Rainfall-runoff events were selected with the same criteria as discussed in Section 3.3.

Table 6.8. Study areas selected for implementation

Station Name	Station Number	Region	Area (mi^2)	Main Channel Length (mi)	Main Channel Slope (ft/mi)
FORKER CREEK	4100252	North	19.2	10.95	9.7
RIMMELL BRANCH	4100295	North	10.7	7.32	12.1
IROQUOIS RIVER	5521000	North	35.6	10.42	3.0
KOKOMO CREEK	3333600	Central	24.7	13.66	4.4
LITTLE BUCK CREEK	3353637	Central	17.0	12.29	14.2
WEST FORK BLUE RIVER	3302680	South	19.0	8.96	24.9
HALL CREEK	3375800	South	21.8	8.73	17.7

Hec-HMS was used as in the application of the Clark parameter regression equations. The loss method selected was initial and constant loss rate and baseflow was separated before observed hydrographs were added to Hec-HMS. Initial and constant loss rates were calculated so precipitation excess equaled direct runoff of the observed hydrograph. This was to ensure all hydrographs computed were of the same volume for proper comparison. Application differed from optimization in that three transform methods (SUH methods) were utilized.

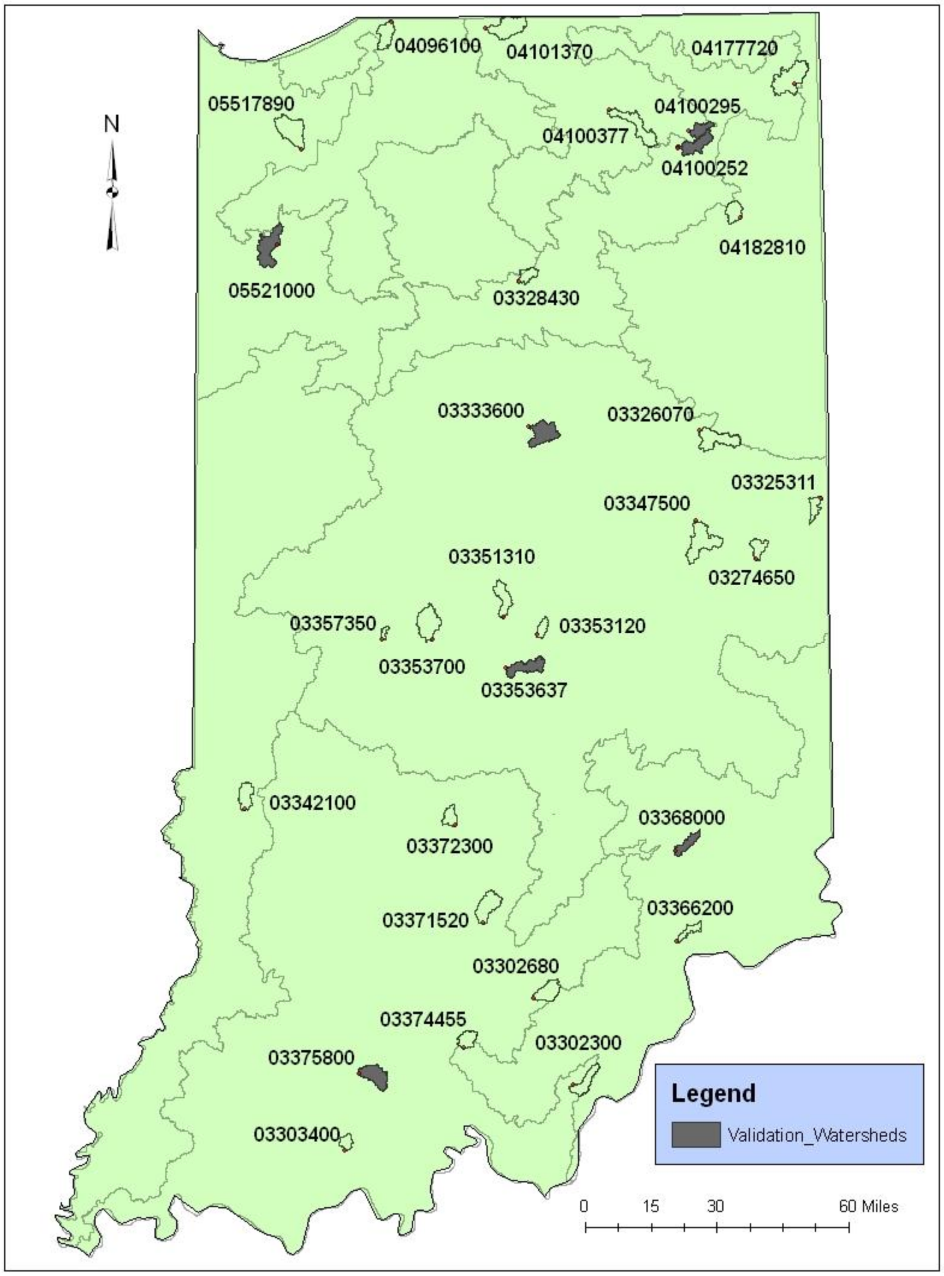


Figure 6.22. Location of validation study areas

Run 1 was performed using the Clark SUH method, where the Clark SUH parameters were estimated using the appropriate regional equations discussed previously. The second run utilized the statewide regression equation (Clark2) to estimate the Clark SUH parameters. Run 3 was computed using the standard NRCS method, where the basin lag is calculated as:

$$t_{lag} = \frac{L^{0.8}(S + 1^{0.7})}{1900\sqrt{Y}} \tag{17}$$

where t_{lag} is the lag time in hours, L is the hydraulic length of the watershed in feet, Y is watershed slope in percent, and S is maximum retention storage in inches defined as:

$$S = \frac{1000}{CN} - 10 \tag{18}$$

where CN is the curve number based on the land use and soil type. The basin lag was calculated using Hec-GeoHMS to calculate the curve number grid. The NRCS method was chosen because from experience the curve number is not sufficient for estimating the detention storage or slope effects of northern watersheds.

Results from the 7 new events are in Figures 6.23-6.29, and Table 6.8 lists summary statistics comparing the observed Q_p and t_p to each SUH method and the relative error calculated as:

$$Relative\ Error\ (Q_p) = \frac{Q_{p,observed} - Q_{p,predicted}}{Q_{p,observed}} \tag{19}$$

$$Relative\ Error\ (t_p) = \frac{t_{p,observed} - t_{p,predicted}}{t_{p,observed}} \tag{20}$$

Overall the results are very revealing about the ability of the Clark SUH to account for the storage effects in northern Indiana. Specifically, the events for Rimmel Branch, Iroquois River, Kokomo Creek, and Little Buck Creek all show the ability of the Clark regression equations to predict the Q_p and t_p. From a graphical comparison of the Forker Creek and Rimmel Branch events, it is apparent that the ability of the Clark SUH method to account for watershed storage and mirror the observed data is far superior to the NRCS method. The Forker Creek is by far the most extreme event considered from the aspect of increased storage and time of concentration. The events from the central region watersheds represent the transitional characteristics of the regions. Kokomo Creek has much lower slopes and high storage effects. Little Buck Creek is located near Indianapolis, and has geomorphology affected by urban development (45% urban land cover). In both cases (Kokomo Creek and Little Buck Creek) peak flows were estimated within 18% and 10%, and t_p was estimated within 7% and 45% respectively. Graphically in both events the Clark SUH method matched the observed data well. A comparison of the calculated R and t_c used in the application were compared to optimized values located in Table 6.9. The optimized values were only optimized for the storm events used in the application of the regression equations.

Table 6.9. Implementation Results

Name	Station No.	Run	Q_p (cfs)	Relative Error	t_p (min)	Relative Error
Forker Creek (North)	04100252	Observed	71		2250	
		Clark	112	-0.37	1620	0.39
		Clark2	229	-0.69	1080	1.08
		NRCS	529	-0.87	885	1.54
Rimmel Branch (North)	04100295	Observed	107		390	
		Clark	135	-0.21	570	-0.32
		Clark2	176	-0.39	495	-0.21
		NRCS	515	-0.79	315	0.24
Iroquois River (North)	05521000	Observed	114		2190	
		Clark	119	-0.04	2175	0.01
		Clark2	123	-0.07	2055	0.07
		NRCS	283	-0.60	1995	0.10
Kokomo Creek (Central)	03333600	Observed	285		2235	
		Clark	337	-0.15	2385	-0.06
		Clark2	315	-0.10	2400	-0.07
		NRCS	644	-0.56	2160	0.03
Little Buck Creek (Central)	03353637	Observed	732		465	
		Clark	652	0.12	675	-0.31
		Clark2	701	0.04	690	-0.33
		NRCS	1240	-0.41	540	-0.14
West Fork Blue River (South)	03302680	Observed	359		255	
		Clark	402	-0.11	435	-0.41
		Clark2	460	-0.22	375	-0.32
		NRCS	430	-0.17	285	-0.11
Hall Creek (South)	03375800	Observed	831		240	
		Clark	812	0.02	465	-0.48
		Clark2	593	0.40	555	-0.57
		NRCS	923	-0.10	405	-0.41

Clark2 - Clark parameters calculated with state regression equation

Table 6.10. Calculated and Optimized Clark values

Station Name	Station Number	Region	Calc R (hrs)	Opt R (hrs)	Calc t_c (hrs)	Opt t_c (hrs)
FORKER CREEK	4100252	North	25.9	29.3	9.2	8.7
RIMMELL BRANCH	4100295	North	13.3	14.6	6.3	2.5
IROQUOIS RIVER	5521000	North	20.0	20.3	16.5	19.0
KOKOMO CREEK	3333600	Central	18.7	22.9	10.1	5.7
LITTLE BUCK CREEK	3353637	Central	6.6	5.1	5.2	3.9
WEST FORK BLUE RIVER	3302680	South	2.5	4.4	5.6	3.0
HALL CREEK	3375800	South	2.4	3.1	3.3	3.8

Calculated values are from equations in Table 6.6

Optimized values are results from new events only

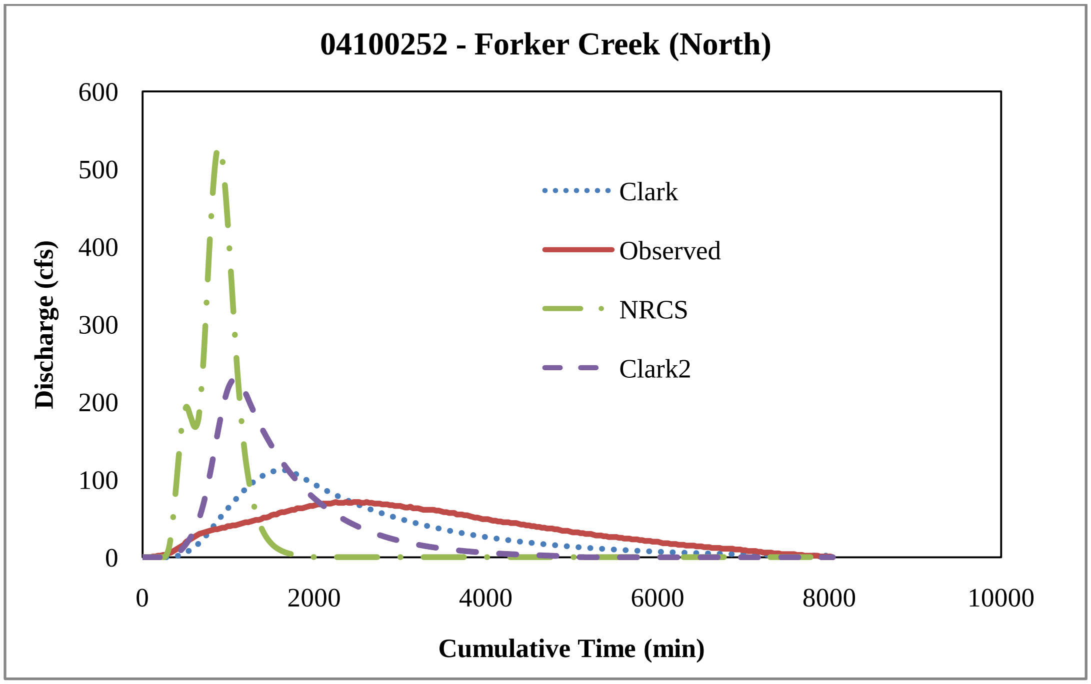


Figure 6.23. Results for 04100252 - Forker Creek

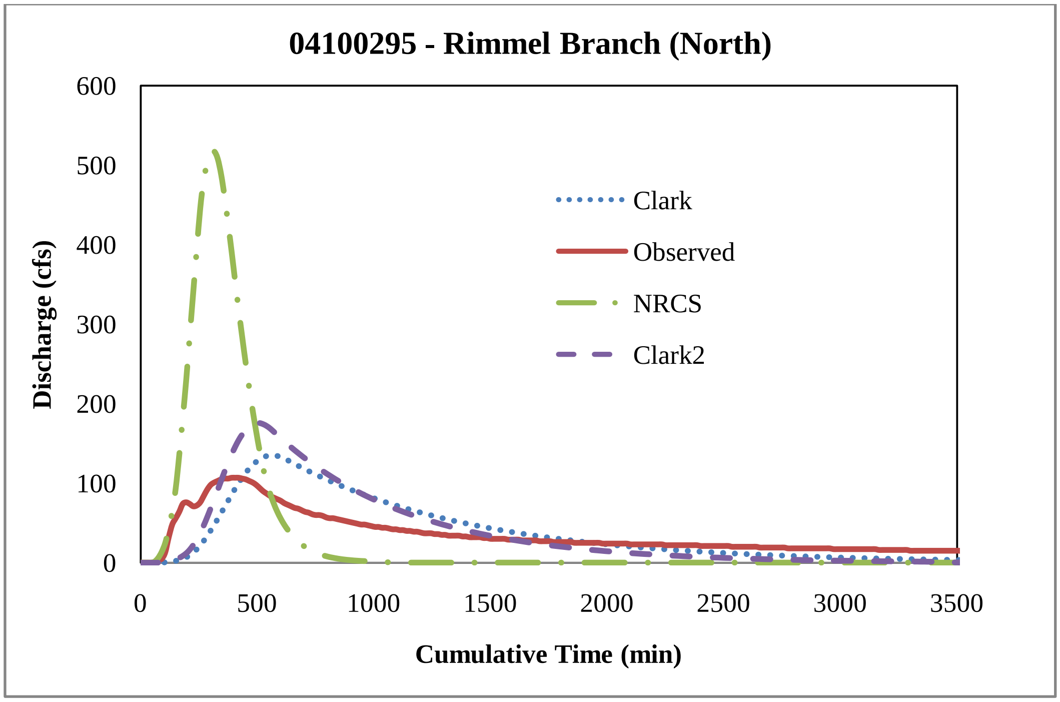


Figure 6.24. Results for 04100295 - Rimmel Branch

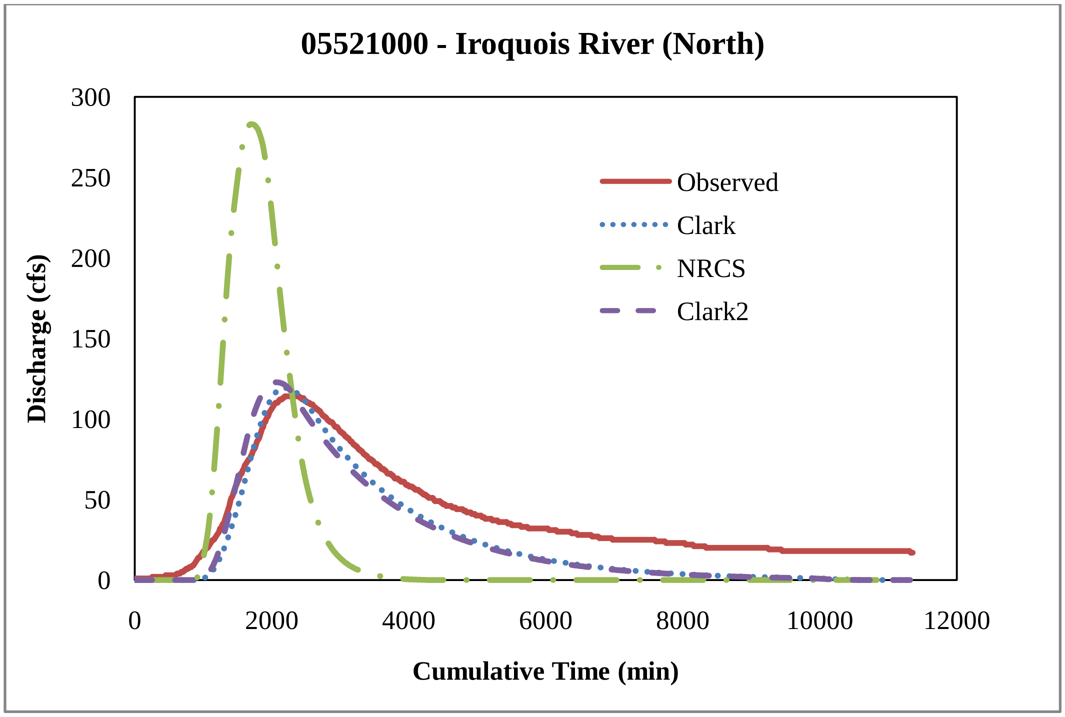


Figure 6.25. Results for 05521000 – Iroquois River

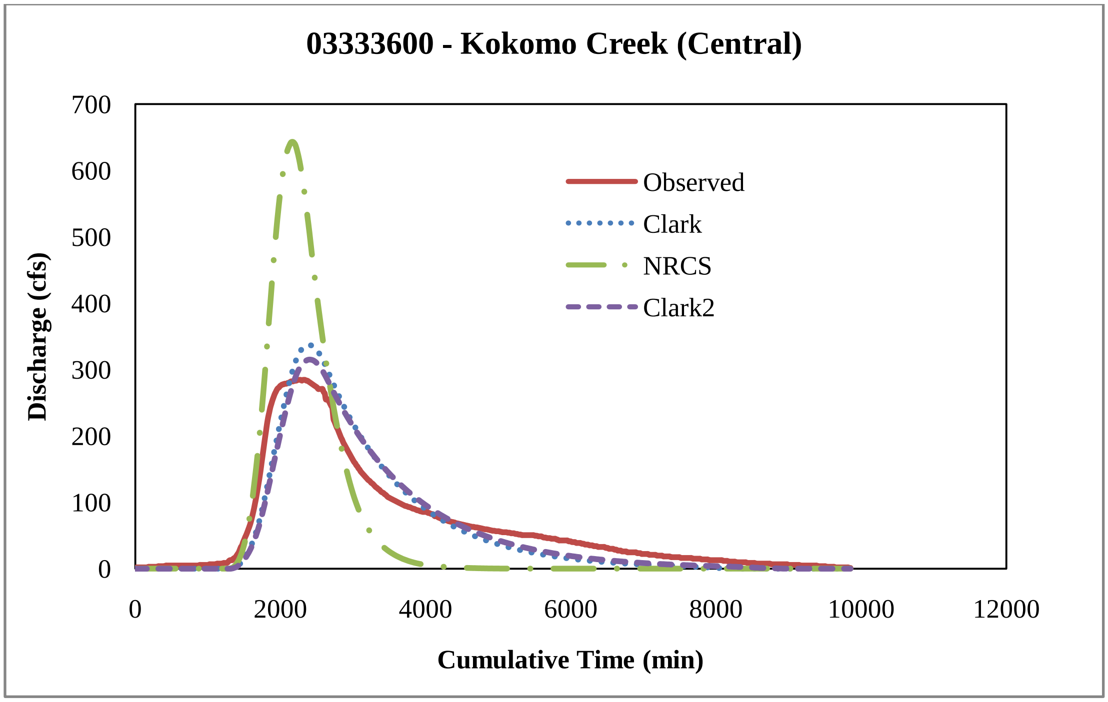


Figure 6.26. Results for 03333600 – Kokomo Creek

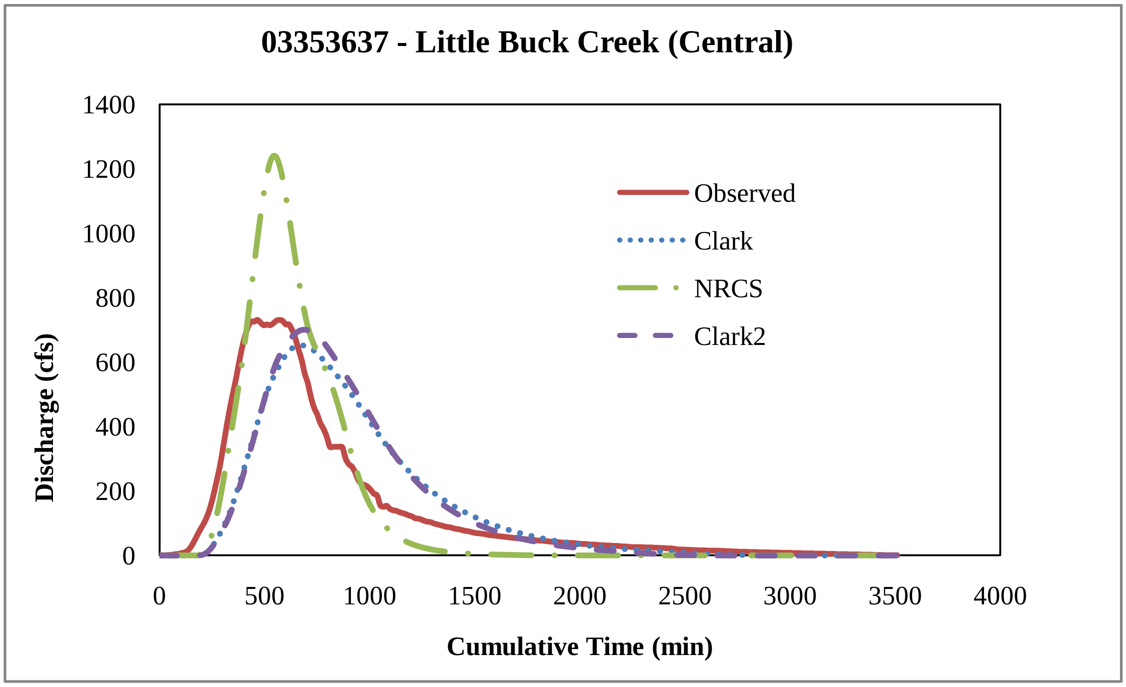


Figure 6.27. Results for 03353637 – Little Buck Creek

For the southern region (West Fork Blue River and Hall Creek) results were more varied. Both the NRCS and Clark methods performed equally well. This supports the assumption that the NRCS method is sufficient for southern Indiana. For both events in the southern watersheds Q_p was estimated well by the NRCS and regional Clark regressions (error < ± 20%). The statewide Clark estimates performed worst for the southern region. This is due to the larger variation associated with the Clark2 regression models. Peak times were difficult for both methods to match in the southern region. Overall the regional Clark estimates performed best.

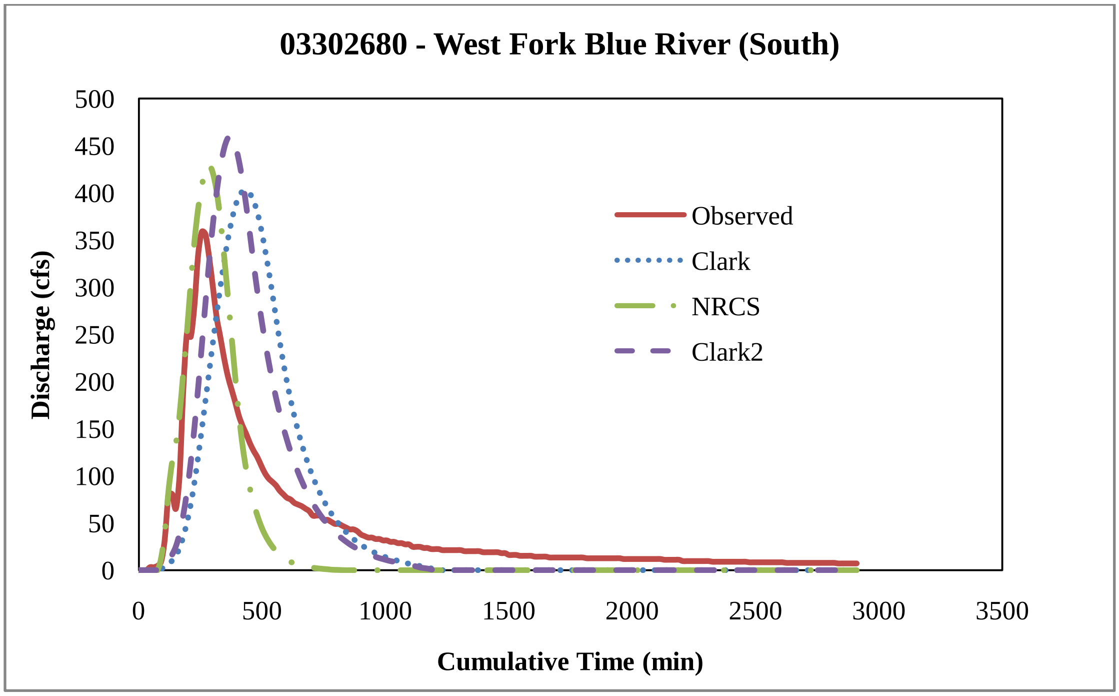


Figure 6.28. Results for 03302680 – West Fork Blue River

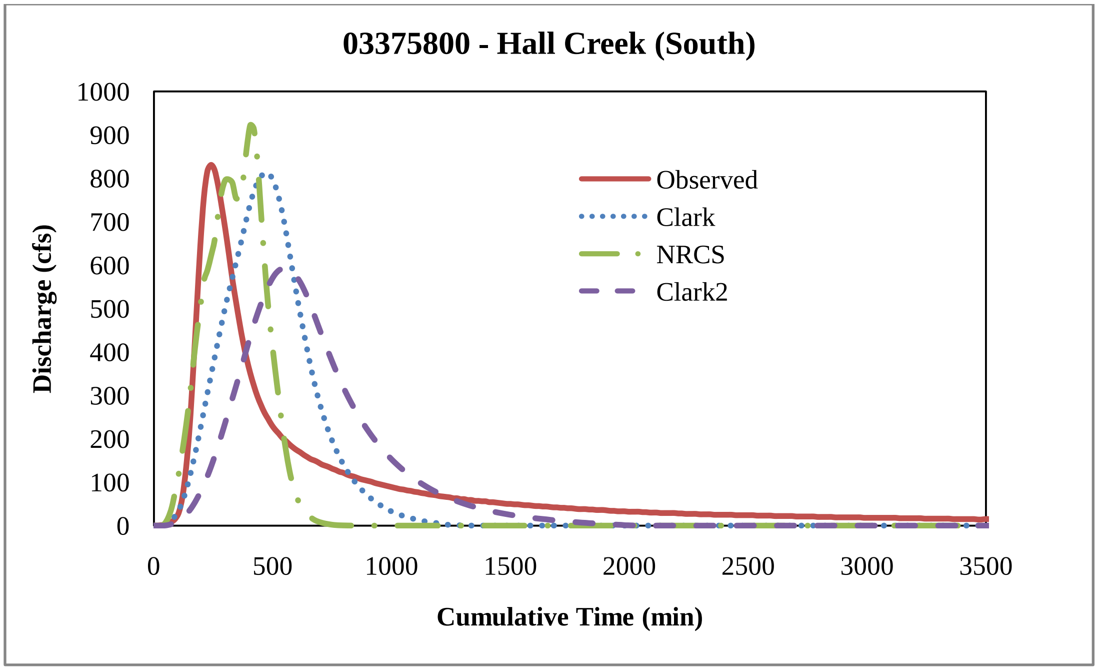


Figure 6.29. Results for 03375800 – Hall Creek

CHAPTER 7. CONCLUSIONS

From this analysis, it can be said that northern and central Indiana are geomorphologically different from the southern region. Statistical analysis has shown a significant difference in the hydrology and geomorphology of northern Indiana compared to the sourthern region. It has been shown that watersheds in southern Indiana have statistically significantly higher slopes and peak flow rates. Also, northern Indiana’s hydrology is affected by increased depression storage and lower slopes, and as a result has lower peak flows and increased times to peak. The central region appears to be a transition between the two geomorphologic extremes of the other two regions. These characteristics can be accounted for using SUH methods.

Specifically, the Clark SUH Method has been shown to account for the effects of low slopes and high depression storage using the parameters t_c and R. The Clark SUH parameters can be estimated using geomorphologic parameters extracted using GIS tools. GIS techniques can improve the accuracy and ease of geomorphologic parameter extraction. Multiple linear regression can then be utilized to establish statistically significant relationships between the geomorphologic parameters and the Clark SUH parameters t_c and R. Comparisons of the Clark and NRCS SUH methods show that the former’s flexibility to incorporate varying of geomorphology and adjust the hydrograph’s shape accordingly. In this manner the regression equations can extend the estimation of the Clark SUH parameters to ungauged watersheds of similar hydrology and geomorphology in Indiana.

The strength of these regression equations is their ease of use. Utilizing current GIS technology has become the standard in many hydrologic modeling applications. Geomorphologic parameters can be extracted accurately and quickly. Also, the regression equations can provide statistical information regarding confidence limits and measurable error of the Clark SUH parameter estimates. It is important to keep in mind, with any hydrologic method, an investigation into the results using this method is necessary before use in any design or modeling application. Comparison of this method with current established modeling methods is advised. Also, the regression equations should be applied only to watersheds with geomorphologic characteristics within the ranges used in this study

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APPENDICES

Appendix A

Table A.1. Scenario 1- Log Transformed R Regression for North Region

Regression Statistics	
Multiple R	0.93
R^2	0.86
Adj R^2	0.82
Std Error	0.10
Obs	10

ANOVA

	df	*SS*	*MS*	*F*	*Sig. F*
Regression	2	0.3427	0.1713	18.7576	0.0026
Residual	7	0.0548	0.0091		
Total	9	0.3975			

	Coefficients	*Std. Error*	*t Stat*	*P-value*
Intercept	1.139	0.034	33.759	0.000
UrbanLC	-0.164	0.035	-4.701	0.003
Cf	-0.819	0.165	-4.966	0.003

RESIDUAL OUTPUT

Obs	*Predicted Log(R)*	*Residuals*	*Std Resid.*
1	1.149	0.177	2.140
2	0.992	0.011	0.136
3	1.415	-0.088	-1.059
4	1.125	-0.057	-0.688
5	1.421	-0.061	-0.735
6	1.303	0.023	0.278
7	0.785	-0.076	-0.913
8	1.259	0.035	0.424
9	1.301	0.034	0.417

PROBABILITY OUTPUT

Percentile	*Log(R)*	*R*
5.56	0.71	5.12
16.67	1.00	10.0
27.78	1.07	11.6
38.89	1.29	19.6
50.00	1.33	21.1
61.11	1.33	21.2
72.22	1.33	21.2
83.33	1.34	21.6
94.44	1.36	22.9

Table A.2. Linear Model - Scenerio 2 R Regression for North Region

Regression Statistics	
Multiple R	0.94
R^2	0.88
Adj R^2	0.84
Std Error	2.58
Obs	9

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	2	293.665	146.832	21.987	0.002
Residual	6	40.068	6.678		
Total	8	333.733			

	Coefficients	*Std Error*	*t Stat*	*P-value*
Intercept	27.009	1.802	14.993	0.000
Slope	-1.665	0.268	-6.205	0.001
Water	1.506	0.403	3.741	0.010

RESIDUAL OUTPUT

Obs	*Predicted R*	*Residuals*	*StdResid*
1	17.16	4.04	1.80
2	9.97	0.11	0.05
3	21.74	-0.51	-0.23
4	14.47	-2.78	-1.24
5	23.73	-0.83	-0.37
6	18.35	2.83	1.26
7	6.26	-1.14	-0.51
8	19.09	0.60	0.27
9	23.99	-2.32	-1.04

PROBABILITY OUTPUT

Percentile	*R*
5.56	5.12
16.67	10.08
27.78	11.69
38.89	19.69
50.00	21.18
61.11	21.2
72.22	21.23
83.33	21.67
94.44	22.9

Table A.3. Log Model 1 – Scenerio 1 t_c Regression for North Region

Regression Statistics	
Multiple R	0.98
R^2	0.97
Adj R^2	0.95
Std Error	0.05
Obs.	9

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	3	0.398	0.133	53.126	0.0003
Residual	5	0.012	0.002		
Total	8	0.411			

	Coefficients	*Std Error*	*t Stat*	*P-value*
Intercept	-3.355	0.468	-7.169	0.001
ContDA	1.677	0.184	9.109	0.000
Cf	1.369	0.223	6.152	0.002
Gray	0.396	0.069	5.740	0.002

RESIDUAL OUTPUT

Obs.	*Pred Log(Tc)*	*Residuals*	*Std Resid*
1	0.480	0.028	0.706
2	0.851	0.007	0.171
3	0.966	0.024	0.600
4	0.802	-0.031	-0.782
5	1.086	0.034	0.849
6	0.847	0.007	0.174
7	0.648	-0.005	-0.126
8	0.993	-0.091	-2.291
9	1.218	0.028	0.697

PROBABILITY OUTPUT

Percentile	*Log(Tc)*	*Tc*
5.556	0.508	3.22
16.667	0.643	4.40
27.778	0.772	5.91
38.889	0.854	7.14
50.000	0.858	7.21
61.111	0.903	7.99
72.222	0.990	9.77
83.333	1.120	13.1
94.444	1.246	17.6

Table A.4. Log Model 1 – Scenerio 2 tc Regression for North Region

Regression Statistics	
Multiple R	0.88
R^2	0.78
Adj R^2	0.71
Std Error	0.12
Obs	9

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	2	0.320	0.160	10.620	0.011
Residual	6	0.091	0.015		
Total	8	0.411			

	Coefficients	*Std Error*	*t Stat*	*P-value*
Intercept	-0.254	0.251	-1.012	0.351
ContDA	0.841	0.186	4.522	0.004
UrbanLC	-0.079	0.044	-1.778	0.126

RESIDUAL OUTPUT

Obs	*Predicted Log(Tc)*	*Residuals*	*Std Resid*
1	0.622	-0.114	-1.069
2	0.776	0.082	0.766
3	0.976	0.013	0.126
4	0.731	0.040	0.380
5	1.073	0.046	0.436
6	1.050	-0.197	-1.850
7	0.586	0.057	0.539
8	0.973	-0.070	-0.660
9	1.104	0.142	1.332

PROBABILITY OUTPUT

Percentile	*Log(Tc)*	*Tc*
5.56	0.51	3.22
16.67	0.64	4.40
27.78	0.77	5.91
38.89	0.85	7.14
50.00	0.86	7.21
61.11	0.90	7.99
72.22	0.99	9.77
83.33	1.12	13.1
94.44	1.25	17.6

Table A.5. Log Model 1 – Scenerio 1 R Regression for Central Region

Regression Statistics	
Multiple R	0.93
R^2	0.86
Adj R^2	0.82
Std Error	0.14
Obs	10

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	2	0.884	0.442	21.932	0.0010
Residual	7	0.141	0.020		
Total	9	1.025			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	1.727	0.266	6.505	0.000
Rf	-2.722	0.792	-3.437	0.011
Slope	-0.932	0.244	-3.819	0.007

RESIDUAL OUTPUT

Obs	*Predicted Log(R)*	*Residuals*	*Std Resid*
1	0.645	-0.137	-1.092
2	1.285	-0.062	-0.493
3	1.150	-0.054	-0.429
4	1.271	-0.006	-0.051
5	1.072	-0.029	-0.231
6	0.621	-0.049	-0.395
7	0.454	-0.122	-0.973
8	0.822	0.164	1.308
9	0.773	0.264	2.109
10	0.502	0.031	0.247

PROBABILITY OUTPUT

Percentile	*Log(R)*	R
5	0.332	2.15
15	0.508	3.22
25	0.533	3.41
35	0.572	3.73
45	0.986	9.68
55	1.037	10.9
65	1.043	11.0
75	1.096	12.4
85	1.223	16.7
95	1.265	18.4

Table A.6. Square Root Model 1 – Scenerio 2 R Regression for Central Region

Regression Statistics	
Multiple R	0.83
R^2	0.69
Adj R^2	0.60
Std Error	0.65
Obs	10

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	2	6.477	3.238	7.629	0.017
Residual	7	2.971	0.424		
Total	9	9.448			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	6.189	0.990	6.250	0.000
Slope	-0.949	0.319	-2.975	0.021
UrbanLC	-0.048	0.077	-0.631	0.548

RESIDUAL OUTPUT

Obs	*Predicted √R*	*Residuals*	*Std Resid*
1	3.020	-1.225	-2.133
2	3.409	0.681	1.185
3	3.704	-0.172	-0.300
4	4.166	0.123	0.215
5	3.218	0.106	0.185
6	2.124	-0.193	-0.335
7	1.880	-0.414	-0.720
8	2.288	0.824	1.434
9	3.281	0.020	0.035
10	1.596	0.250	0.435

PROBABILITY OUTPUT

Percentile	*√R*	R
5	1.46	2.15
15	1.79	3.22
25	1.84	3.41
35	1.93	3.73
45	3.11	9.68
55	3.30	10.9
65	3.32	11.0
75	3.53	12.47
85	4.09	16.73
95	4.29	18.4

Table A.7. Log Model 1 – Scenerio 1 t_c Regression for Central Region

Regression Statistics	
Multiple R	0.92
R^2	0.84
Adj R^2	0.76
Std Error	0.12
Obs	10

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	3	0.489	0.163	10.674	0.008
Residual	6	0.092	0.015		
Total	9	0.581			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-1.944	0.685	-2.840	0.030
Ls	-0.927	0.192	-4.831	0.003
H	0.956	0.304	3.139	0.020
UrbanLC	-0.125	0.045	-2.775	0.032

RESIDUAL OUTPUT

Obs	*Predicted Log(Tc)*	*Residuals*	*Std Resid*
1	0.703	-0.180	-1.788
2	1.263	-0.010	-0.097
3	0.740	0.020	0.200
4	1.003	-0.002	-0.019
5	0.739	0.025	0.248
6	0.853	-0.082	-0.812
7	0.490	0.062	0.612
8	0.719	-0.060	-0.593
9	0.871	0.209	2.067
10	0.470	0.018	0.183

PROBABILITY OUTPUT

Percentile	*Log(Tc)*	*Tc*
5	0.489	3.08
15	0.522	3.33
25	0.551	3.56
35	0.659	4.56
45	0.760	5.76
55	0.764	5.81
65	0.771	5.9
75	1.001	10.0
85	1.080	12.0
95	1.253	17.9

Table A.8. Log Model 1 – Scenerio 2 t_c Regression for Central Region

Regression Statistics	
Multiple R	0.64
R^2	0.41
Adj R^2	0.34
Std Error	0.21
Obs	10

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	1	0.238	0.238	5.563	0.046
Residual	8	0.343	0.043		
Total	9	0.581			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	1.574	0.341	4.617	0.002
Slope	-0.769	0.326	-2.359	0.046

RESIDUAL OUTPUT

Obs	*Predicted Log(Tc)*	*Residuals*	*Std Resid*
1	0.776	-0.254	-1.301
2	0.861	0.392	2.011
3	0.950	-0.190	-0.972
4	1.083	-0.082	-0.422
5	0.823	-0.059	-0.301
6	0.663	0.108	0.553
7	0.636	-0.084	-0.432
8	0.688	-0.029	-0.148
9	0.841	0.239	1.222
10	0.530	-0.041	-0.211

PROBABILITY OUTPUT

Percentile	*Log(Tc)*	*Tc*
5	0.489	3.08
15	0.522	3.33
25	0.551	3.56
35	0.659	4.56
45	0.760	5.76
55	0.764	5.81
65	0.771	5.9
75	1.001	10.0
85	1.080	12.0
95	1.253	17.9

Table A.9. Log Model 1 – Scenario 1 R Regression for South Region

Regression Statistics	
Multiple R	0.94
R^2	0.88
Adj R^2	0.82
Std Error	0.05
Obs	10

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	3	0.095	0.032	14.941	0.003
Residual	6	0.013	0.002		
Total	9	0.108			

	Coefs	*Stand Error*	*t Stat*	*P-value*
Intercept	2.012	0.612	3.287	0.017
Lca	1.450	0.235	6.180	0.001
C	-2.361	0.370	-6.373	0.001
Rf	1.215	0.242	5.015	0.002

RESIDUAL OUTPUT

Obs	*Pred Log(R)*	*Resid*	*Std Resid*
1	0.399	0.019	0.50
2	0.435	-0.050	-1.32
3	0.438	0.059	1.57
4	0.594	0.035	0.93
5	0.522	0.003	0.08
6	0.556	-0.035	-0.92
7	0.634	0.030	0.78
8	0.595	-0.052	-1.385
9	0.338	-0.017	-0.462
10	0.390	0.008	0.214

PROBABILITY OUTPUT

Percentile	*Log(R*	*R*
5	0.320	2.0
15	0.386	2.4
25	0.398	2.5
35	0.418	2.6
45	0.497	3.1
55	0.521	3.32
65	0.525	3.35
75	0.543	3.49
85	0.629	4.26
95	0.664	4.61

Table A.10. Log Model 1 – Scenario 1 tc Regression for South Region

Regression Statistics	
Multiple R	0.98
R^2	0.95
Adj R^2	0.91
Std Error	0.05
Obs	10

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	4	0.282	0.071	25.198	0.002
Residual	5	0.014	0.003		
Total	9	0.296			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-3.283	1.437	-2.284	0.071
UrbanLC	0.266	0.028	9.381	0.000
CN	2.693	0.673	4.000	0.010
Rf	1.696	0.322	5.274	0.003
H	-0.568	0.200	-2.841	0.036

RESIDUAL OUTPUT

Obs	*Predicted Log(Tc)*	*Residuals*	*Std Resid*
1	0.677	0.037	0.948
2	0.749	0.051	1.290
3	0.421	0.041	1.042
4	0.765	-0.002	-0.060
5	0.696	-0.045	-1.149
6	0.392	0.031	0.784
7	0.456	-0.025	-0.634
8	0.586	-0.030	-0.748
9	0.224	0.004	0.090
10	0.513	-0.062	-1.563

PROBABILITY OUTPUT

Percentile	*Log(Tc*	*Tc*
5	0.228	1.69
15	0.423	2.65
25	0.431	2.7
35	0.452	2.83
45	0.462	2.9
55	0.556	3.6
65	0.650	4.47
75	0.714	5.18
85	0.763	5.79
95	0.800	6.31

Table A.11. Log Model 1 – Scenario 2 R Regression for South Region

Regression Statistics	
Multiple R	0.83
R^2	0.69
Adj R^2	0.60
Std Error	0.11
Obs	10

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	2	0.204	0.102	7.751	0.017
Residual	7	0.092	0.013		
Total	9	0.296			

	Coeff	*Stand Error*	*t Stat*	*P-value*
Intercept	-3.503	2.291	-1.529	0.170
UrbanLC	0.179	0.049	3.677	0.008
CN	2.205	1.231	1.791	0.116

RESI OUTPUT

Obs	*Predicted Log(Tc)*	*Residuals*	*Std Resid*
1	0.738	-0.024	-0.238
2	0.701	0.099	0.982
3	0.413	0.049	0.488
4	0.569	0.194	1.915
5	0.776	-0.126	-1.245
6	0.481	-0.058	-0.574
7	0.440	-0.009	-0.085
8	0.492	0.064	0.637
9	0.315	-0.087	-0.861
10	0.555	-0.103	-1.020

PROBABILITY OUTPUT

Percentile	*Log(Tc)*	*Tc*
5	0.228	1.69
15	0.423	2.65
25	0.431	2.70
35	0.452	2.83
45	0.462	2.90
55	0.556	3.60
65	0.650	4.47
75	0.714	5.18
85	0.763	5.79
95	0.800	6.31

Table A.12. Log Model 1 – Scenario 2 R Regression for State

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.84
R^2	0.70
Adj R^2	0.68
Std Error	0.21
Obs	29

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	2	2.725	1.363	30.452	0.00000
Residual	26	1.163	0.045		
Total	28	3.889			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	1.456	0.270	5.401	0.0000
Slope	-0.773	0.178	-4.348	0.0002
Sinks	0.382	0.153	2.490	0.0195

Table A.12. Log Model 1 – Scenario 2 Regression for State

RESID
OUTPUT

Obs	*Pred Log(R)*	*Resid*	*Std Resid*
1	1.237	0.089	0.437
2	0.742	0.262	1.284
3	1.108	0.219	1.073
4	1.042	0.026	0.127
5	1.416	-0.056	-0.275
6	1.088	0.238	1.166
7	0.855	-0.146	-0.716
8	1.070	0.225	1.102
9	1.520	-0.184	-0.903
10	0.870	-0.363	-1.779
11	0.893	0.331	1.623
12	1.165	-0.069	-0.340
13	1.089	0.176	0.862
14	0.983	0.060	0.296
15	0.731	-0.159	-0.781
16	0.782	-0.449	-2.203
17	0.781	0.205	1.004
18	0.951	0.087	0.426
19	0.459	0.074	0.364
20	0.653	-0.234	-1.149
21	0.514	-0.128	-0.630
22	0.410	0.087	0.427
23	0.851	-0.222	-1.087
24	0.753	-0.228	-1.120
25	0.489	0.032	0.157
26	0.600	0.064	0.315
27	0.257	0.285	1.400
28	0.330	-0.010	-0.048
29	0.608	-0.210	-1.032

PROBABILITY
OUTPUT

Percentile	*Log(R)*	*R*
1.724	0.320	2.09
5.172	0.332	2.15
8.621	0.386	2.43
12.069	0.398	2.5
15.517	0.418	2.62
18.966	0.497	3.14
22.414	0.508	3.22
25.862	0.521	3.32
29.310	0.525	3.35
32.759	0.533	3.41
36.207	0.543	3.49
39.655	0.572	3.73
43.103	0.629	4.26
46.552	0.664	4.61
50.000	0.709	5.12
53.448	0.986	9.68
56.897	1.003	10.08
60.345	1.037	10.9
63.793	1.043	11.05
67.241	1.068	11.69
70.690	1.096	12.47
74.138	1.223	16.73
77.586	1.265	18.4
81.034	1.294	19.69
84.483	1.326	21.18
87.931	1.326	21.2
91.379	1.327	21.23
94.828	1.336	21.67
98.276	1.360	22.9

Table A.13. Log Model 1 – Scenario 2 tc Regression for State

Regression Statistics	
Multiple R	0.79
R^2	0.62
Adj R^2	0.58
Std Error	0.17
Obs	29

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	3	1.147	0.382	13.732	0.00002
Residual	25	0.696	0.028		
Total	28	1.843			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-2.176	0.859	-2.533	0.018
Lb	0.639	0.214	2.984	0.006
Ls	-0.307	0.092	-3.325	0.003
Water	0.106	0.053	2.021	0.054

Table A.13. Log Model 1 – Scenario 2 Regression for State

RESID
OUTPUT

Obs	*Pred Log(Tc)*	*Resid*	*Std Resid*
1	0.669	-0.161	-1.023
2	0.738	0.120	0.762
3	0.877	0.113	0.715
4	0.797	-0.025	-0.161
5	1.037	0.082	0.523
6	0.801	0.053	0.337
7	0.696	-0.052	-0.332
8	0.932	-0.029	-0.185
9	0.933	0.312	1.979
10	0.532	-0.009	-0.058
11	1.004	0.249	1.579
12	0.954	-0.193	-1.225
13	1.042	-0.041	-0.259
14	0.779	-0.015	-0.093
15	0.925	-0.154	-0.976
16	0.700	-0.149	-0.944
17	0.841	-0.182	-1.152
18	0.829	0.251	1.594
19	0.407	0.081	0.515
20	0.651	0.064	0.404
21	0.520	0.280	1.773
22	0.420	0.042	0.267
23	0.765	-0.003	-0.017
24	0.864	-0.213	-1.353
25	0.669	-0.246	-1.559
26	0.575	-0.144	-0.910
27	0.349	0.207	1.312
28	0.355	-0.127	-0.807
29	0.564	-0.112	-0.709

PROBABILITY
OUTPUT

Percentile	*Log(Tc)*	*Tc*
1.724	0.228	1.69
5.172	0.423	2.65
8.621	0.431	2.7
12.069	0.452	2.83
15.517	0.462	2.9
18.966	0.489	3.08
22.414	0.508	3.22
25.862	0.522	3.33
29.310	0.551	3.56
32.759	0.556	3.6
36.207	0.643	4.4
39.655	0.650	4.47
43.103	0.659	4.56
46.552	0.714	5.18
50.000	0.760	5.76
53.448	0.763	5.79
56.897	0.764	5.81
60.345	0.771	5.9
63.793	0.772	5.91
67.241	0.800	6.31
70.690	0.854	7.14
74.138	0.858	7.21
77.586	0.903	7.99
81.034	0.990	9.77
84.483	1.001	10.02
87.931	1.080	12.02
91.379	1.120	13.17
94.828	1.246	17.6
98.276	1.253	17.9

Appendix B

The entries in Table B.1 are the extracted geomorphologic parameters

Table B.1. Extracted Geomorphologic Parameters

Station Name	Station No.	Region	Lp (m)	Lb (m)	Lca (m)	Rff (m^2/m^2)	Ap (m)	Rc (m^2/m^2)	Re (m/m)	Sb (m^2/m^2)
WEESAU CREEK	03328430	N	37440	8974	4483	0.328	111548101	0.236	0.646	1.44
GALENA RIVER	04096100	N	36420	9413	4776	0.300	105552952	0.252	0.618	1.39
FORKER CREEK	04100252	N	71820	16365	7971	0.186	410469889	0.121	0.486	3.63
RIMMELL BRANCH	04100295	N	45120	10790	4834	0.238	162005099	0.171	0.550	3.18
SOLOMON CREEK	04100377	N	91260	23155	13790	0.131	662752587	0.106	0.408	5.86
FISH CREEK	04177720	N	86580	10999	2568	0.796	596520902	0.162	1.007	0.73
SPY RUN CREEK	04182810	N	34620	7216	3434	0.681	95377213	0.372	0.931	1.26
COBB DITCH	05517890	N	59220	16801	8814	0.289	279079097	0.293	0.607	2.73
IROQUOIS RIVER	05521000	N	83760	14577	4654	0.359	558295131	0.137	0.676	0.65
JUDAY CREEK	04101370	N	61260	16906	9195	0.260	298637601	0.249	0.576	2.76
WHITEWATER RIVER	03274650	C	37320	5520	4203	0.967	110834195	0.266	1.110	0.62
LITTLE MISS RIVER	03325311	C	42180	14125	4514	0.125	141580569	0.177	0.400	4.24
BIG LICK CREEK	03326070	C	72120	16996	7684	0.246	413906207	0.172	0.560	3.46
KOKOMO CREEK	03333600	C	57960	13021	5932	0.385	267329728	0.244	0.700	0.66
BUCK CREEK	03347500	C	81540	16305	8135	0.332	529092880	0.167	0.650	1.85
CROOKED CREEK	03351310	C	56520	15897	8410	0.181	254211275	0.180	0.480	4.11
PLEASANT RUN	03353120	C	29340	8451	3916	0.280	68503178	0.292	0.597	2.42
LITTLE BUCK CREEK	03353637	C	65280	16573	8535	0.190	339117963	0.153	0.491	3.60
WEST FRK LICK CRK	03353700	C	57900	14867	7123	0.336	266776537	0.278	0.654	2.41
PLUM CREEK	03357350	C	19140	5780	2716	0.232	29152404	0.266	0.543	2.57
LITTLE INDIAN CRK	03302300	S	54960	15505	6664	0.179	240372041	0.179	0.478	3.24
WEST FORK BLUE RIV	03302680	S	44280	12159	6584	0.329	156029144	0.311	0.647	2.55
CROOKED CREEK	03303400	S	28560	6593	3283	0.472	64909298	0.316	0.775	1.77
BUSSERON CREEK	03342100	S	42060	11146	5626	0.335	140776136	0.296	0.653	2.22
HARBERTS CREEK	03366200	S	44460	13021	6672	0.134	157300252	0.144	0.413	5.86
BRUSH CREEK	03368000	S	45120	13154	5695	0.171	162005099	0.183	0.467	4.87
BACK CREEK	03371520	S	54240	14200	7462	0.310	234115337	0.267	0.628	2.07
STEPHENS CREEK	03372300	S	34200	8979	3786	0.349	93077072	0.302	0.666	2.02
PATOKA RIVER	03374455	S	34800	8586	4028	0.442	96371583	0.338	0.750	1.49
HALL CREEK	03375800	S	50160	13516	6803	0.308	200219125	0.281	0.626	2.07

Table B.1 Extracted Geomorphologic Parameters (Continued)

Station Name	Station No.	Region	Ru	H (m)	Rh (m)	Rp (m/m)	D (m/m^2)	Rn (m^2/m^2)	C (m)	Rf (m/m)
WEESAU CREEK	03328430	N	1.75	32.71	0.0036	0.0009	0.0013	0.044	743.9	0.947
GALENA RIVER	04096100	N	1.83	103.03	0.0109	0.0028	0.0015	0.153	675.5	1.080
FORKER CREEK	04100252	N	2.32	49.53	0.0030	0.0007	0.0011	0.053	938.0	0.738
RIMMELL BRANCH	04100295	N	2.05	35.79	0.0033	0.0008	0.0014	0.049	725.5	0.845
SOLOMON CREEK	04100377	N	2.76	46.75	0.0020	0.0005	0.0008	0.040	1181.3	0.651
FISH CREEK	04177720	N	1.12	56.32	0.0051	0.0007	0.0009	0.052	1083.3	1.027
SPY RUN CREEK	04182810	N	1.21	37.51	0.0052	0.0011	0.0013	0.050	756.9	1.353
COBB DITCH	05517890	N	1.86	45.68	0.0027	0.0008	0.0008	0.039	1180.7	1.169
IROQUOIS RIVER	05521000	N	1.67	22.77	0.0016	0.0003	0.0008	0.019	1192.2	0.764
JUDAY CREEK	04101370	N	1.96	54.04	0.0032	0.0009	0.0009	0.047	1139.2	1.066
WHITEWATER RIVER	03274650	C	1.02	43.68	0.0079	0.0012	0.0014	0.061	715.7	1.103
LITTLE MISS RIVER	03325311	C	2.82	30.50	0.0022	0.0007	0.0012	0.036	847.8	0.699
BIG LICK CREEK	03326070	C	2.02	30.52	0.0018	0.0004	0.0009	0.027	1147.0	0.860
KOKOMO CREEK	03333600	C	1.61	19.88	0.0015	0.0003	0.0008	0.016	1265.2	0.889
BUCK CREEK	03347500	C	1.74	61.88	0.0038	0.0008	0.0007	0.046	1341.2	0.806
CROOKED CREEK	03351310	C	2.35	59.30	0.0037	0.0010	0.0012	0.073	809.3	1.002
PLEASANT RUN	03353120	C	1.89	27.77	0.0033	0.0009	0.0016	0.046	607.8	1.122
LITTLE BUCK CREEK	03353637	C	2.30	69.43	0.0042	0.0011	0.0011	0.076	919.6	0.867
WEST FRK LICK CRK	03353700	C	1.73	63.33	0.0043	0.0011	0.0008	0.052	1212.8	1.057
PLUM CREEK	03357350	C	2.08	36.80	0.0064	0.0019	0.0024	0.088	418.9	0.967
LITTLE INDIAN CREEK	03302300	S	2.36	89.38	0.0058	0.0016	0.0010	0.093	966.2	0.811
WEST FORK BLUE RIVER	03302680	S	1.74	105.39	0.0087	0.0024	0.0009	0.100	1053.1	1.042
CROOKED CREEK	03303400	S	1.46	73.25	0.0111	0.0026	0.0015	0.107	686.7	1.047
BUSSERON CREEK	03342100	S	1.73	58.55	0.0053	0.0014	0.0012	0.068	861.5	1.150
HARBERTS CREEK	03366200	S	2.73	53.14	0.0041	0.0012	0.0013	0.069	772.4	0.662
BRUSH CREEK	03368000	S	2.42	64.67	0.0049	0.0014	0.0013	0.084	771.7	0.851
BACK CREEK	03371520	S	1.80	102.50	0.0072	0.0019	0.0010	0.103	991.3	1.162
STEPHENS CREEK	03372300	S	1.69	105.48	0.0117	0.0031	0.0015	0.153	688.2	1.194
PATOKA RIVER	03374455	S	1.50	109.34	0.0127	0.0031	0.0011	0.126	870.9	1.076
HALL CREEK	03375800	S	1.80	100.40	0.0074	0.0020	0.0009	0.091	1107.0	1.013

Table B.1. Extracted Geomorphologic Parameters (Continued)

Station Name	Station No.	Region	Cf (#stream/km^2)	Ls (m/m)	Cs (m/m)	HKR	Gray	Murphey	Area (mi^2)	Slope (ft/mi)
WEESAU CREEK	03328430	N	1.40	0.0797	0.0013	537497	122528	0.0547	9.3	6.54
GALENA RIVER	04096100	N	1.54	0.1451	0.0056	122647	63645	0.0521	17.9	22.00
FORKER CREEK	04100252	N	1.11	0.1315	0.0014	1062599	210546	0.0729	19.3	9.69
RIMMELL BRANCH	04100295	N	1.99	0.0892	0.0017	435886	116916	0.1149	11.0	12.10
SOLOMON CREEK	04100377	N	0.50	0.0501	0.0009	2703877	461578	0.0835	36.2	3.56
FISH CREEK	04177720	N	0.61	0.0999	0.0020	1570751	57148	0.0076	37.4	11.30
SPY RUN CREEK	04182810	N	1.33	0.0634	0.0024	405275	70007	0.0356	13.9	14.60
COBB DITCH	05517890	N	0.62	0.0651	0.0012	2283199	251328	0.0334	30.6	7.14
IROQUOIS RIVER	05521000	N	0.75	0.0376	0.0006	4731264	197203	0.0085	38.1	3.00
JUDAY CREEK	04101370	N	0.74	0.0421	0.0011	2239535	274632	0.0372	37.3	7.46
WHITEWATER RIVER	03274650	C	2.00	0.0747	0.0024	335124	86660	0.0211	10.4	10.90
LITTLE MISS RIVER	03325311	C	1.32	0.0156	0.0016	465812	114169	0.1697	9.8	8.47
BIG LICK CREEK	03326070	C	0.77	0.0392	0.0012	1968810	219686	0.0487	29.0	6.48
KOKOMO CREEK	03333600	C	0.57	0.0149	0.0008	3042327	214859	0.0102	25.3	4.35
BUCK CREEK	03347500	C	0.62	0.0898	0.0035	917363	137144	0.0210	35.1	9.48
CROOKED CREEK	03351310	C	1.03	0.0379	0.0032	413484	149795	0.0897	17.9	15.30
PLEASANT RUN	03353120	C	2.50	0.0402	0.0026	189329	76727	0.1211	8.2	16.60
LITTLE BUCK CREEK	03353637	C	0.94	0.0636	0.0027	584256	164202	0.0692	17.1	14.20
WEST FORK LICK CRK	03353700	C	0.71	0.0612	0.0019	1363031	163532	0.0325	28.9	8.97
PLUM CREEK	03357350	C	6.58	0.0967	0.0049	32102	38636	0.3313	3.0	22.80
LITTLE INDIAN CREEK	03302300	S	1.60	0.2573	0.0040	331831	104908	0.0751	17.1	18.90
WEST FORK BLUE RIVER	03302680	S	1.15	0.2080	0.0053	299473	90741	0.0525	19.1	24.90
CROOKED CREEK	03303400	S	2.48	0.2613	0.0060	89751	42403	0.0862	8.0	30.80
BUSSERON CREEK	03342100	S	1.25	0.0990	0.0032	387783	100183	0.0532	16.9	12.40
HARBERTS CREEK	03366200	S	2.07	0.0772	0.0027	230432	127468	0.2580	9.3	18.00
BRUSH CREEK	03368000	S	1.52	0.1293	0.0047	176310	83362	0.1644	11.3	25.60
BACK CREEK	03371520	S	1.04	0.2418	0.0048	408086	107458	0.0331	24.1	23.80
STEPHENS CREEK	03372300	S	1.74	0.4110	0.0079	92956	42513	0.0718	10.8	44.60
PATOKA RIVER	03374455	S	1.81	0.3592	0.0057	169077	53393	0.0457	12.6	26.00
HALL CREEK	03375800	S	0.98	0.3226	0.0035	540448	115631	0.0368	21.7	17.70

B.1. Extracted Geomorphologic Parameters (Continued)

Station Name	Station No.	Region	CDA (mi^2)	% ULC (%)	Water (%)	CN	MCh (mi)	Sinks (%)	t_c (hrs)	R (hrs)
WEESAU CREEK	03328430	N	9.3	0.16	0.69	77	7.4	11.9	3.2	21.2
GALENA RIVER	04096100	N	16.6	0.90	13.00	62	8.4	7.02	7.2	10.1
FORKER CREEK	04100252	N	19.3	0.01	7.21	77	10.9	12.2	9.8	21.2
RIMMELL BRANCH	04100295	N	11.0	0.04	5.05	78	7.3	12.8	5.9	11.7
SOLOMON CREEK	04100377	N	36.2	0.62	1.76	77	16.9	10.3	13.2	22.9
FISH CREEK	04177720	N	36.1	1.16	6.74	84	9.8	14.7	7.1	21.2
SPY RUN CREEK	04182810	N	13.9	35.40	2.36	80	6.5	6.1	4.4	5.1
COBB DITCH	05517890	N	30.6	1.95	2.63	78	12.7	5.2	7.9	19.7
IROQUOIS RIVER	05521000	N	38.1	0.44	1.31	71	10.4	13.6	8.2	16.8
JUDAY CREEK	04101370	N	33.3	16.60	0.67	79	13.1			
WHITEWATER RIV	03274650	C	10.4	0.52	0.54	79	7.3	3.7	3.3	3.2
LITTLE MISS RIV	03325311	C	9.8	0.12	0.58	80	8.9	2.5	17.9	16.7
BIG LICK CREEK	03326070	C	29.0	2.02	0.91	82	12.0	7.6	5.8	12.5
KOKOMO CREEK	03333600	C	25.3	0.78	1.87	79	13.7	2.2	10.0	18.4
BUCK CREEK	03347500	C	35.1	0.98	0.29	78	12.3	5.5	5.8	11.1
CROOKED CREEK	03351310	C	17.9	52.80	0.66	77	11.1	3.2	5.9	3.7
PLEASANT RUN	03353120	C	8.2	83.00	0.27	79	5.4	5.1	3.6	2.2
LITTLE BUCK CRK	03353637	C	17.1	44.80	0.37	76	12.3	3.7	4.6	9.7
WEST FRK LCK CRK	03353700	C	28.9	1.77	0.49	78	12.4	4.0	12.0	10.9
PLUM CREEK	03357350	C	3.0	1.52	0.06	78	4.2	1.4	3.1	3.4
LITTLE INDIAN CRK	03302300	S	17.1	7.96	0.51	71	10.0	3.0	5.2	2.6
WEST FRK BLU RI	03302680	S	19.1	2.30	0.07	75	8.9	2.3	6.3	2.4
CROOKED CREEK	03303400	S	8.0	0.08	0.62	74	4.3	1.9	2.9	3.1
BUSSERON CRK	03342100	S	16.9	0.31	2.83	77	6.4	4.3	5.8	4.3
HARBERTS CRK	03366200	S	9.3	6.06	4.55	75	8.4	5.0	4.5	3.4
BRUSH CREEK	03368000	S	11.3	0.12	0.28	76	7.8	2.1	2.7	3.3
BACK CREEK	03371520	S	24.1	0.11	0.14	73	9.9	3.5	2.7	4.6
STEPHENS CREEK	03372300	S	10.8	1.51	0.08	63	5.2	1.6	3.6	3.5
PATOKA RIVER	03374455	S	12.6	0.08	0.08	66	6.2	0.8	1.7	2.1
HALL CREEK	03375800	S	21.7	0.21	0.34	79	8.7	2.0	2.8	2.5

Appendix C

The entries in Tables C.1 – C.6 are the summary of the stepwise selection technique for all transform models and scenarios.

Table C.1. Stepwise selection results for Linear Model R

					Variables				
Region	Transform	Variables	R^2	p-value	Dependant	Independent			
N	Linear Model 1	All	0.88	0.15	R	Slope	Water		
C	Linear Model 1	All	0.86	0.05	R	Slope	Rf		
S	Linear Model 1	All	None	0.15	R	None			
Statewide	Linear Model 1	All	0.74	0.15	R	HKR	Cs	Water	ULC
Statewide	Linear Model 1	StreamStats	0.65	0.15	R	Slope	ULC	Water	DA
N	**Linear Model 1**	**StreamStats**	**0.88**	**0.15**	**R**	**Slope**	**Water**		
C	Linear Model 1	StreamStats	0.64	0.15	R	Slope			
S	Linear Model 1	StreamStats	None	0.15	R	None			

Table C.2. Stepwise selection results for Logarithmic Model R

					Variables				
Region	Transform	Variables	R^2	p-value	Dependant	Independent			
N	Log Model 2	All	0.59	0.05	R	Lp			
C	Log Model 2	All	0.91	0.05	R	Slope	Rf		
S	Log Model 2	All	None	0.05	R	None			
N	**Log Model 1**	**All**	**0.86**	**0.05**	**R**	**ULC**	**Cf**		
C	**Log Model 1**	**All**	**0.86**	**0.05**	**R**	**Rf**	**Slope**		
S	**Log Model 1**	**All**	**0.88**	**0.05**	**R**	**Lca**	**C**	**Rf**	
Statewide	Log Model 1	All	0.79	0.05	R	Slope	ULC	Cf	C
Statewide	Log Model 2	All	0.75	0.05	R	Slope	ULC	Water	
Statewide	Log Model 1	StreamStats	0.72	0.05	R	Slope	ULC	Water	
Statewide	Log Model 2	StreamStats	0.75	0.05	R	Slope	ULC	Water	
N	Log Model 2	StreamStats	0.54	0.05	R	Slope			
C	Log Model 2	StreamStats	0.71	0.05	R	Slope			
S	Log Model 2	StreamStats		0.05	R	None			
N	Log Model 1	StreamStats	0.47	0.05	R	MCh			
C	Log Model 1	StreamStats	0.63	0.05	R	Slope			
S	Log Model 1	StreamStats	None	0.05	R	None			

Table C.3. Stepwise selection results for Square Root Model R

					Variables					
Region	Transform	Variables	R^2	p-value	Dependant	Independent				
N	Sqrt Model 2	All	1.00	0.1	R	Slope	GridSlope	Ls	Lp	C
C	Sqrt Model 2	All	0.89	0.15	R	Slope	Rf			
S	Sqrt Model 2	All	None		R	None				
N	Sqrt Model 1	All	0.98	0.1	R	ULC	Cf	DA	H	
C	Sqrt Model 1	All	0.89	0.15	R	Slope	Rf			
S	Sqrt Model 1	All	None		R	None				
Statewide	Sqrt Model 2	All	0.76	0.15	R	HKR	Water	Slope	ULC	
Statewide	Sqrt Model 1	All	0.76	0.15	R	Slope	Water	HKR	ULC	
Statewide	Sqrt Model 2	StreamStats	0.71	0.15	R	Slope	ULC	Water		
Statewide	Sqrt Model 1	StreamStats	0.72	0.15	R	Slope	Water	ULC		
N	Sqrt Model 2	StreamStats	0.80	0.15	R	Slope	ULC			
C	Sqrt Model 2	StreamStats	0.69	0.15	R	Slope				
S	Sqrt Model 2	StreamStats	None	0.15	R	None				
N	Sqrt Model 1	StreamStats	0.67	0.15	R	Slope				
C	**Sqrt Model 1**	**StreamStats**	**0.82**	**0.15**	**R**	**Slope**	**ULC**			
S	Sqrt Model 1	StreamStats	None	0.15	R	None				

Table C.4. Stepwise selection results for Linear Model t_c

					Variables					
Region	Transform	Variables	R^2	p-value	Dependant	Independent				
N	Linear Model 1	All	0.95	0.15	t_c	HKR	Water	M		
C	Linear Model 1	All	0.97	0.15	t_c	GridSlope	ULC	Water	CN	Rn
S	Linear Model 1	All	0.26	0.15	t_c	ULC				
All	Linear Model 1	All	0.72	0.15	t_c	HKR	Ru	Sb	Re	Rff
All	Linear Model 1	StreamStats	0.43	0.15	t_c	Slope	CN			
N	Linear Model 1	StreamStats	0.58	0.15	t_c	CDA				
C	Linear Model 1	StreamStats	0.30	0.15	t_c	Slope				
S	Linear Model 1	StreamStats	0.26	0.15	t_c	ULC				

Table C.5. Stepwise selection results for Log Model t_c

					Variables						
Region	Transform	Variables	R^2	p-value	Dependant	Independent					
N	Log Model 2	All	0.78	0.05	t_c	CDA	Rf				
C	Log Model 2	All	0.83	0.05	t_c	Ls	ULC	H			
S	Log Model 2	All	0.50	0.05	t_c	ULC					
N	**Log Model 1**	**All**	**0.97**	**0.05**	$\mathbf{t_c}$	**CDA**	**Cf**	**G**			
C	**Log Model 1**	**All**	**0.84**	**0.05**	$\mathbf{t_c}$	**Ls**	**H**	**ULC**			
S	**Log Model 1**	**All**	**0.95**	**0.05**	$\mathbf{t_c}$	**ULC**	**CN**	**Rf**	**H**		
All	Log Model 1	All	0.62	0.05	t_c	Slope	Lb	Lca			
All	Log Model 2	All	0.80	0.05	t_c	Slope	Ru	Re	Lca	CDA	Rp
All	Log Model 1	StreamStats	0.54	0.05	t_c	Slope	Water				
All	Log Model 2	StreamStats	0.54	0.05	t_c	Slope	CN				
N	Log Model 2	StreamStats	0.84	0.1	t_c	CDA	Slope	CN			
C	Log Model 2	StreamStats	0.30	0.05	t_c	ULC					
S	Log Model 2	StreamStats	0.50	0.05	t_c	ULC					
N	**Log Model 1**	**StreamStats**	**0.78**	**0.05**	$\mathbf{t_c}$	**CDA**	**ULC**				
C	**Log Model 1**	**StreamStats**	**0.41**	**0.05**	$\mathbf{t_c}$	**Slope**					
S	**Log Model 1**	**StreamStats**	**0.69**	**0.05**	$\mathbf{t_c}$	**ULC**	**CN**				

Table C.6. Stepwise selection results for Sqrt Model t_c

					Variables						
Regio	Transform	Variables	R^2	p-value	Dependant	Independent					
N	Sqrt Model 2	All	0.98	0.15	t_c	HKR	CN	Rc	ULC		
C	Sqrt Model 2	All	1.00	0.15	t_c	Ls	ULC	H	Water	Rc	MCh
S	Sqrt Model 2	All	0.37	0.15	t_c	ULC					
N	Sqrt Model 1	All	0.91	0.15	t_c	HKR	CN	Lp			
C	Sqrt Model 1	All	0.92	0.15	t_c	Ls	ULC	H	Water		
S	Sqrt Model 1	All	0.39	0.15	t_c	ULC					
All	Sqrt Model 2	All	0.63	0.15	t_c	HKR	Ru	Lca			
All	Sqrt Model 1	All	0.63	0.15	t_c	HKR	Ru	Lca			
All	Sqrt Model 2	StreamStats	0.51	0.15	t_c	Slope	CN				
All	Sqrt Model 1	StreamStats	0.52	0.15	t_c	Slope	CN				
N	Sqrt Model 2	StreamStats	0.58	0.15	t_c	CDA					
C	Sqrt Model 2	StreamStats	0.30	0.15	t_c	Slope					
S	Sqrt Model 2	StreamStats	0.37	0.15	t_c	ULC					
N	Sqrt Model 1	StreamStats	0.62	0.15	t_c	CDA					
C	Sqrt Model 1	StreamStats	0.37	0.15	t_c	Slope					
S	Sqrt Model 1	StreamStats	0.39	0.15	t_c	ULC					

Appendix D

Correlation tables for all variables in Tables D.1. – D.3.

Table D.1. Correlation Matrix for North Region Variables

	Aw	*Lp*	*Lb*	*Lca*	*Rff*	*Ap*	*Rc*	*Re*	*Sb*	*Ru*	*Tc*	*R*	*Qp*	*tp*
Aw	1.00													
Lp	0.84	1.00												
Lb	0.53	0.74	1.00											
Lca	0.23	0.44	0.92	1.00										
Rff	0.27	-0.04	-0.59	-0.70	1.00									
Ap	0.82	0.99	0.72	0.43	-0.01	1.00								
Rc	-0.34	-0.75	-0.60	-0.38	0.41	-0.75	1.00							
Re	0.23	-0.12	-0.65	-0.76	0.99	-0.09	0.47	1.00						
Sb	0.02	0.32	0.78	0.91	-0.69	0.31	-0.43	-0.77	1.00					
Ru	-0.11	0.28	0.77	0.87	-0.91	0.27	-0.56	-0.96	0.90	1.00				
Tc	0.54	0.76	0.68	0.42	-0.32	0.75	-0.63	-0.34	0.21	0.37	1.00			
R	0.62	0.75	0.66	0.44	-0.29	0.73	-0.70	-0.32	0.27	0.37	0.51	1.00		
Qp	0.47	0.10	-0.07	-0.12	0.67	0.10	0.51	0.64	-0.18	-0.52	-0.11	-0.27	1.00	
tp	0.78	0.84	0.58	0.25	-0.09	0.82	-0.60	-0.10	0.00	0.14	0.87	0.65	-0.01	1.00

	H	*Rh*	*Rp*	*D*	*Rn*	*C*	*Rf*	*Cf*	*Ls*	*Cs*	*Tc*	*R*	*Qp*	*tp*
H	1.00													
Rh	0.88	1.00												
Rp	0.88	0.96	1.00											
D	0.36	0.65	0.69	1.00										
Rn	0.95	0.95	0.97	0.62	1.00									
C	-0.32	-0.62	-0.64	-0.99	-0.58	1.00								
Rf	0.22	0.49	0.42	0.36	0.28	-0.35	1.00							
Cf	0.14	0.41	0.47	0.92	0.42	-0.92	0.17	1.00						
Ls	0.76	0.70	0.67	0.53	0.77	-0.55	0.07	0.44	1.00					
Cs	0.90	0.99	0.98	0.67	0.97	-0.63	0.45	0.45	0.71	1.00				
Tc	-0.19	-0.43	-0.38	-0.70	-0.31	0.73	-0.63	-0.57	-0.40	-0.39	1.00			
R	-0.29	-0.59	-0.59	-0.73	-0.49	0.72	-0.66	-0.67	-0.23	-0.63	0.51	1.00		
Qp	-0.18	-0.10	-0.23	-0.34	-0.30	0.32	0.64	-0.40	-0.35	-0.13	-0.11	-0.27	1.00	
tp	0.01	-0.27	-0.30	-0.79	-0.19	0.81	-0.47	-0.73	-0.18	-0.27	0.87	0.65	-0.01	1.00

Table D.1. Correlation Matrix for North Region Variables (Continued)

	DA	*Slope*	*CDA*	*ULC*	*Water*	*Sinks*	*CN*	*MCh*	*HKR*	*G*	*M*	*Tc*	*R*	*Qp*	*tp*
DA	1.00														
Slope	-0.49	1.00													
CDA	1.00	-0.52	1.00												
ULC	-0.28	0.29	-0.28	1.00											
Water	-0.15	0.82	-0.18	-0.20	1.00										
Sinks	0.21	-0.38	0.20	-0.50	-0.09	1.00									
CN	0.09	-0.36	0.10	0.27	-0.49	0.26	1.00								
MCh	0.71	-0.57	0.73	-0.39	-0.21	-0.03	0.04	1.00							
HKR	0.82	-0.75	0.84	-0.27	-0.47	0.26	-0.04	0.59	1.00						
G	0.48	-0.68	0.51	-0.29	-0.42	-0.06	0.03	0.92	0.54	1.00					
M	-0.52	0.08	-0.51	-0.20	0.09	0.02	-0.04	0.07	-0.43	0.29	1.00				
Tc	0.75	-0.54	0.76	-0.34	-0.17	0.28	-0.28	0.63	0.90	0.58	-0.21	1.00			
R	0.59	-0.77	0.60	-0.70	-0.33	0.52	0.18	0.65	0.61	0.57	-0.16	0.51	1.00		
Qp	0.31	0.03	0.31	0.69	-0.23	-0.39	0.56	0.02	0.10	-0.09	-0.49	-0.11	-0.27	1.00	
tp	0.89	-0.43	0.89	-0.49	0.04	0.34	-0.19	0.60	0.84	0.39	-0.47	0.87	0.65	-0.01	1

Table D.2. Correlation Matrix for Central Region Variables

	Aw	*Lp*	*Lb*	*Lca*	*Rff*	*Ap*	*Rc*	*Re*	*Sb*	*Ru*	*Tc*	*R*	*Qp*	*tp*
Aw	1.00													
Lp	0.94	1.00												
Lb	0.75	0.87	1.00											
Lca	0.81	0.91	0.89	1.00										
Rff	-0.05	-0.16	-0.55	-0.27	1.00									
Ap	0.92	0.98	0.82	0.87	-0.18	1.00								
Rc	-0.40	-0.68	-0.76	-0.68	0.44	-0.68	1.00							
Re	0.03	-0.12	-0.53	-0.24	0.99	-0.13	0.48	1.00						
Sb	-0.14	0.09	0.50	0.30	-0.77	0.07	-0.57	-0.84	1.00					
Ru	-0.21	0.01	0.45	0.14	-0.87	-0.01	-0.55	-0.94	0.91	1.00				
Tc	0.15	0.12	0.38	0.02	-0.31	0.03	-0.16	-0.35	0.27	0.45	1.00			
R	0.52	0.52	0.57	0.28	-0.27	0.46	-0.40	-0.26	0.02	0.24	0.74	1.00		
Qp	0.38	0.32	0.29	0.54	0.09	0.26	0.11	0.13	0.07	-0.25	-0.28	-0.41	1.00	
tp	0.29	0.37	0.39	0.12	-0.19	0.35	-0.50	-0.21	0.02	0.30	0.65	0.77	-0.56	1.00

	H	*Rh*	*Rp*	*D*	*Rn*	*C*	*Rf*	*Cf*	*Ls*	*Cs*	*Tc*	*R*	*Qp*	*tp*
H	1.00													
Rh	0.34	1.00												
Rp	0.30	0.79	1.00											
D	-0.24	0.55	0.82	1.00										
Rn	0.58	0.73	0.90	0.64	1.00									
C	0.20	-0.54	-0.73	-0.94	-0.63	1.00								
Rf	0.06	0.55	0.42	0.36	0.34	-0.40	1.00							
Cf	-0.24	0.54	0.82	0.96	0.58	-0.80	0.26	1.00						
Ls	0.51	0.76	0.70	0.38	0.66	-0.21	0.25	0.50	1.00					
Cs	0.38	0.61	0.84	0.69	0.83	-0.56	0.20	0.72	0.78	1.00				
Tc	-0.16	-0.52	-0.41	-0.42	-0.49	0.37	-0.54	-0.39	-0.59	-0.55	1.00			
R	-0.23	-0.71	-0.71	-0.68	-0.73	0.72	-0.75	-0.55	-0.53	-0.68	0.74	1.00		
Qp	0.54	0.08	-0.02	-0.30	0.16	0.20	0.60	-0.40	0.07	-0.02	-0.28	-0.41	1.00	
tp	-0.26	-0.55	-0.60	-0.48	-0.59	0.49	-0.82	-0.41	-0.43	-0.38	0.65	0.77	-0.56	1.00

Table D.2. Correlation Matirix for Central Region (Continued)

	DA	*Slope*	*CDA*	*U LC*	*Water*	*Sinks*	*CN*	*MCh*	*HKR*	*G*	*M*	*Tc*	*R*	*Qp*	*tp*
DA	1.00														
Slope	-0.69	1.00													
CDA	1.00	-0.69	1.00												
ULC	-0.31	0.47	-0.31	1.00											
Water	0.38	-0.72	0.38	-0.26	1.00										
Sinks	0.55	-0.35	0.55	0.11	-0.07	1.00									
CN	0.14	-0.46	0.14	-0.49	0.27	0.46	1.00								
MCh	0.86	-0.74	0.86	-0.24	0.58	0.28	-0.08	1.00							
HKR	0.67	-0.78	0.67	-0.40	0.88	0.18	0.35	0.72	1.00						
G	0.78	-0.77	0.78	-0.18	0.73	0.40	0.17	0.92	0.84	1.00					
M	-0.73	0.76	-0.73	0.05	-0.49	-0.50	-0.03	-0.74	-0.56	-0.69	1.00				
Tc	0.16	-0.55	0.16	-0.38	0.33	-0.23	0.21	0.34	0.29	0.29	-0.07	1.00			
R	0.52	-0.80	0.52	-0.53	0.65	0.01	0.32	0.68	0.74	0.68	-0.33	0.74	1.00		
Qp	0.38	0.01	0.38	0.45	-0.11	0.44	-0.31	0.28	-0.03	0.25	-0.49	-0.28	-0.41	1.00	
tp	0.31	-0.60	0.31	-0.44	0.45	-0.11	0.28	0.40	0.37	0.31	-0.18	0.65	0.77	-0.56	1.00

Table D.3. Correlation Matrix for South Region

	Aw	*Lp*	*Lb*	*Lca*	*Rff*	*Ap*	*Rc*	*Re*	*Sb*	*Ru*	*Tc*	*R*	*Qp*	*tp*
Aw	1.00													
Lp	0.74	1.00												
Lb	0.60	0.98	1.00											
Lca	0.71	0.94	0.93	1.00										
Rff	-0.03	-0.67	-0.80	-0.66	1.00									
Ap	0.74	1.00	0.96	0.91	-0.64	1.00								
Rc	0.16	-0.54	-0.67	-0.51	0.95	-0.53	1.00							
Re	0.04	-0.62	-0.76	-0.62	1.00	-0.59	0.97	1.00						
Sb	-0.35	0.29	0.47	0.38	-0.87	0.25	-0.91	-0.90	1.00					
Ru	-0.17	0.52	0.67	0.53	-0.97	0.49	-0.98	-0.99	0.95	1.00				
Tc	0.12	0.24	0.30	0.35	-0.30	0.21	-0.16	-0.28	0.19	0.23	1.00			
R	0.15	0.16	0.12	0.19	-0.12	0.16	-0.13	-0.10	0.08	0.06	0.07	1.00		
Qp	0.85	0.68	0.56	0.58	-0.04	0.68	0.08	0.01	-0.28	-0.10	-0.26	-0.12	1.00	
tp	0.32	0.41	0.33	0.37	-0.18	0.44	-0.24	-0.17	-0.01	0.14	0.02	0.68	0.16	1.00

	H	*Rh*	*Rp*	*D*	*Rn*	*C*	*Rf*	*Cf*	*Ls*	*Cs*	*Tc*	*R*	*Qp*	*tp*
H	1.00													
Rh	0.66	1.00												
Rp	0.73	0.99	1.00											
D	-0.42	0.26	0.21	1.00										
Rn	0.74	0.87	0.91	0.30	1.00									
C	0.47	-0.21	-0.15	-0.99	-0.24	1.00								
Rf	0.54	0.61	0.61	-0.03	0.57	0.06	1.00							
Cf	-0.37	0.31	0.23	0.80	0.18	-0.80	-0.31	1.00						
Ls	0.84	0.82	0.86	0.01	0.89	0.06	0.52	0.02	1.00					
Cs	0.56	0.83	0.85	0.47	0.93	-0.42	0.56	0.29	0.72	1.00				
Tc	-0.24	-0.42	-0.38	-0.24	-0.40	0.22	-0.14	-0.22	-0.46	-0.31	1.00			
R	-0.38	-0.37	-0.40	0.22	-0.21	-0.25	0.28	-0.16	-0.39	-0.10	0.07	1.00		
Qp	0.53	-0.09	-0.06	-0.85	-0.07	0.83	0.15	-0.74	0.21	-0.27	-0.26	-0.12	1.00	
tp	-0.25	-0.39	-0.44	-0.11	-0.30	0.08	0.06	-0.16	-0.18	-0.43	0.02	0.68	0.16	1.00

Table D.3. Correlation Matrix for South Region (Continued)

	DA	*Slope*	*CDA*	*ULC*	*Water*	*Sinks*	*CN*	*MCh*	*HKR*	*G*	*M*	*Tc*	*R*	*Qp*	*tp*
DA	1.00														
Slope	-0.42	1.00													
CDA	1.00	-0.42	1.00												
ULC	-0.11	-0.23	-0.11	1.00											
Water	-0.30	-0.50	-0.30	0.39	1.00										
Sinks	0.13	-0.61	0.13	0.46	0.83	1.00									
CN	0.34	-0.75	0.34	-0.08	0.35	0.49	1.00								
MCh	0.70	-0.53	0.70	0.46	-0.01	0.40	0.39	1.00							
HKR	0.87	-0.71	0.87	0.02	0.06	0.36	0.60	0.68	1.00						
G	0.54	-0.80	0.54	0.43	0.50	0.75	0.67	0.81	0.77	1.00					
M	-0.62	-0.10	-0.62	0.45	0.69	0.48	0.18	0.02	-0.36	0.28	1.00				
Tc	0.17	-0.34	0.17	0.51	0.38	0.53	0.28	0.27	0.23	0.38	0.06	1.00			
R	0.16	-0.05	0.16	-0.21	0.31	0.58	0.17	0.00	0.12	0.19	0.06	0.07	1.00		
Qp	0.83	-0.39	0.83	-0.17	-0.44	-0.15	0.21	0.67	0.72	0.41	-0.53	-0.26	-0.12	1.00	
tp	0.34	-0.39	0.34	0.15	0.44	0.66	0.16	0.23	0.48	0.48	-0.02	0.02	0.68	0.16	1.00

Appendix E

Table E.1. Ranges of geomorphologic parameters for use in regression equations

				Range	
Region	Dependent	Independent	Units	Min	Max
North	R				
		ULC	%	0.01	35.4
		C_f	#streams/km^2	0.5	1.99
	t_c				
		CDA	mi^2	9.3	38.1
		C_f	#streams/km^2	0.5	1.99
		G		122647	461578
Central	R				
		R_f	m/m	0.699	1.12
		Slope	ft/mi	4.35	22.8
	t_c				
		L_s	m/m	0.0149	0.0967
		H	m	19.88	69.43
		ULC	%	0.12	83
South	R				
		L_{ca}	m	3283	7462
		C	m	686.7	1107
		Rf	m/m	0.662	1.194
	t_c				
		ULC	%	0.08	7.96
		CN		63	79
		R_f	m/m	0.662	1.194
		H	m	53.14	109.34
Statewide	R				
		Slope	ft/mi	3	44.6
		Sinks	%	0.82	14.72
	t_c				
		L_b	m	5520	23155
		L_s	m/m	0.0149	0.411
		Water	%	0.06	13