Evaluation Of Calculated Peak Runoff Flow Rates At The Limitations of Different Hydrologic Methods in Knox County, Tennessee

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ABSTRACT

Determining the anticipated peak flow for a drainage crossing is critical for infrastructure design. Improper design can lead to degradation of downstream water quality, flooding of adjacent neighbors, or failure of critical infrastructure. There are many applicable hydrologic methods that may be used for a location, but the requirements for these methods may vary depending on the governing authority. For example, the Stormwater Management Manual for Knox County, Tennessee has a restriction on the applicable drainage area of the Rational method of 5 acres, which is not consistent with surrounding local, state, and federal entities. Urban Regression equations (Urban Regression) by the US Geological Survey (USGS), the Rational method, and the Natural Resources Conservation Service (NRCS) Technical Release 55 (TR-55) are common methods for determining peak flows for different rainfall events. Urban Regression equations are based upon statistical analysis of observed flow data for a specific region. The Rational method and TR-55 method are widely accepted, but the input parameters are dictated by the requirements from the respective governing authorities. USGS StreamStats is a web-based application that provides peak flow results for ungauged locations based on the USGS regression equations. This study calculated the peak flows for the 2-, 10-, and 100-year storm events for 29 drainage areas within Knox County using Urban Regression, Rational method, and TR-55 to compare the results between the different methods at a size range where the applicability of the different methods overlap between different entity requirements (20-600 acres). USGS results were used as the baseline to normalize the results from the three methods since the results can be obtained by all design engineers. The study yields similar results between the Rational method and Urban Regression for drainage areas up to 150 acres. The Rational method had similar trends to TR-55, but the TR-55 results were 1 to 1.5 times larger for the 10-year and 100-year storm events. From the results of the study, the Rational method results are consistent with other methods up to the drainage area size above 100 acres. It appears the limit of 100 acres for the Rational method is reasonable.

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CHAPTER ONE
INTRODUCTION

New development typically results in a change in land use from its natural state that can result in impacts downstream due to the alteration of the hydrologic cycle including rainfall interception, infiltration, evaporation, and transpiration (Hu and Shrestha 2020). Runoff from developments that are not properly treated, detained, or infiltrated into the ground by stormwater best management practices to mimic existing conditions may cause downstream erosion and widening of channels, loss of environmentally sensitive areas like riparian zones and wetlands, negatively impact biologic diversity, and even risk human health and safety (Bhaduri et al 2001). New development and the change in land use may increase runoff to existing drainage crossings downstream, or it may require the installation of a manmade drainage structure like a bridge or culvert in a natural conveyance. These situations need to account for the safety and sustainability of the new intended land use along with the adjacent and downstream properties impacted by the change in land use. There are many vulnerabilities to human safety that are created if drainage structures that convey stormwater runoff are not designed properly.

In Virginia, it is estimated that the highways within the state have one culvert almost every half mile of roadway, which on average have drainage areas of less than 200 acres (Hayes and Young 2005). There are many drainage crossings that require the determination of the anticipated peak flow rate for different design storms to properly design and obtain a permit to install or repair a stormwater structure such as a culvert or a bridge. Undersized structures can flood over the roadway, along with creating the potential for damage due to erosion. Incorrect peak flows can also result in oversized drainage structures which are inefficient, susceptible to erosion, and unnecessarily more expensive (Hayes and Young 2005). Erosion can contribute to poor water quality, which negatively impacts aquatic life and adds obstacles to collecting and cleaning the water for use by humans (Issaka and Ashraf 2017). The designer is tasked with determining the appropriate size and type of stormwater infrastructure to adequately convey stormwater runoff downstream efficiently, while limiting negative impacts to the upstream, downstream, and drainage conveyance areas. Improper use of the hydrologic methods

can result in errors of peak flow estimate that leads to an incorrectly sized drainage structure.

There are many hydrologic methods that can be used to determine peak storm flow, but three commonly applied methods used in East Tennessee are the USGS Urban Regression Equations, Rational method, and TR-55 method. These three methods can produce very different peak flow results for the same area of analysis and each method has its own respective limitations. Urban Regression equations were developed based on multiple regression statistical analyses from 22 drainage basins in Tennessee (Robbins 1984), but this data and the resulting regression equations are from field observed data from over 40 years ago which may not reflect our current land use conditions and climate. The Rational method is an equation for peak flow rate based on land use (Rational coefficient), rainfall intensity, and drainage area size that is relatively simple to use, but has been found to significantly underpredict estimates from a study that has compared the results to observed stream gage data (IIHR 2009). NRCS TR-55 is widely accepted and is based on land use (Curve Number), precipitation depth, and time of concentration input into a model to calculate peak flow rate based on a unit hydrograph, but per a report by Genereux (2003) many engineers do not use it since it tends to overestimate peak discharges. These methods are permitted by both the City of Knoxville and Knox County to calculate peak flow rates, although there are different unique constraints and interpretations each jurisdiction has for each method. A designer must understand the specific watershed characteristics for using these hydrologic methods, along with what regulatory authority they are permitting under and their specific interpretation of the use of these hydrologic methods since they can vary greatly.

Another common resource for calculating peak storm flow rates is USGS StreamStats web-based application. StreamStats is often one of the first resources a design engineer will check when evaluating larger drainage areas. The user can simply identify the location for analysis and select an option for a peak flow output report. StreamStats provides peak flow estimates for ungauged locations similar to the USGS regression equations, but is more advanced by including recorded supporting flow data where applicable (Ries et al., 2004). For Multivariable Rural Regression Equations (MVRR)

(Law and Tasker 2000), Knox County is in Hydrologic Area 1 which requires a minimum drainage area of 0.20 sq-mi (128 acres). For Urban Regression Equations (Robbins 1984) the minimum drainage area is 0.21 sq-mi (134.4 acres) and impervious cover for the drainage area shall be more than 10%. Due to the large minimum drainage areas, StreamStats and the USGS regression equations are not commonly used for stormwater quality best management practice design, but they are commonly used for infrastructure drainage crossing design.

Among the stormwater program and their ordinance design criteria, regulatory authorities vary widely on what methods can be applied for different sized drainage areas, along with limitations of how the methods can be used. The smallest site used for the development of the Urban Regression equations was approximately 134.4 acres (Robbins 1984). According to the TDOT Drainage Manual, it is acceptable to use the Urban Regression equations for drainage areas down to 100 acres, but the Knox County Drainage Manual limits the use of the equations to a minimum of 134 acres. According to the TDOT Drainage Manual, the Rational method is the preferred method for all drainage areas less than 100 acres, but the Knox County Drainage Manual limits the use of the Rational method to a maximum size of 5 acres and says the TR-55 method should be used for drainage areas less than 134 acres. It should be noted that these guidelines are outlined for the recommendations for determining peak flow from a drainage area when storage routing is not required. When storage routing is required, use of the TR-55 method is recommended by TDOT and Knox County. Some of the most significant differences in limitations between regulatory authorities is what drainage area size is applicable for the Rational method to be utilized. **Table 1** lists nearby regulatory authorities to Knox County and their permitted maximum drainage area sizes to utilize the Rational method.

The objective of this study is to determine if the 5-acre drainage area maximum size limitation per Knox County for the Rational method is appropriate, or if the Rational method yields peak flow results that can support its applicability up to a drainage area of 134 acres where Urban Regression becomes applicable. This study involved calculating the peak flow for the 2-yr, 10-yr, and 100-yr recurrence intervals for 29 drainage areas in

Knox County using three common hydrologic methods: the USGS Urban Regression equations (Urban Regression), the Rational method, and the NRCS Technical Release-55 method (TR-55). These recurrence intervals were selected since they are typically the most common storm events to design for water quality (2-yr), channel protection (10-yr), and flood protection (100-yr), which are the critical aspects for a regulatory review. The drainage areas range from approximately 20 to 600 acres with 3-55% impervious area so that the three methods will be applicable by one or more regulating authorities to calculate peak flows. USGS StreamStats results were used as the baseline to normalize the results from the three methods since there is no available observed data to compare to and the results are determined by the widely accepted USGS regression equations that can be obtained by all design engineers. The peak flow rate percent difference results will be evaluated to see if the data support the drainage area limitations upheld by different regulatory authorities.

Table 1: Rational Method Maximum Drainage Area for Different Jurisdictions

Agency	Rational Method Limit (acres)	Citation
Knox County	5	Knox County Stormwater Management Manual
City of Knoxville	50	City of Knoxville BMP Manual Stormwater Treatment
City of Nashville	100	City of Nashville Stormwater Management Manual
Tennessee DOT	100	TDOT Drainage Manual
North Carolina DOT	100	NCDOT Guidelines for Drainage Studies and Hydraulic Design
Virginia DOT	200	VDOT Drainage Manual
Federal Highway Administration (FHWA)	200	HEC-22

CHAPTER TWO
BACKGROUND
Stormwater Regulations

In 1987, amendments were made to the Clean Water Act, which led to the United States Environmental Protection Agency (EPA) creating what is referred to as Phase I of the National Pollutant Discharge Elimination System (NPDES) stormwater program in 1990 (TDEC 2024). Congress grants authority to the EPA to create and enforce federal stormwater regulations. Phase I required medium and large municipal separate storm sewer systems (MS4) with populations of 100,000 people or more to have an NPDES permit. An MS4 is a conveyance or multiple linked conveyances that are designed to collect and discharge stormwater to waters of the U.S., are owned by a public entity, and are not associated with wastewater conveyance. There are five (5) Phase I MS4s in Tennessee which include Knoxville, Nashville, Memphis, Chattanooga, and the Tennessee Department of Transportation (TDOT) (TDEC 2024). In 1999, Phase II regulation was implemented by the EPA which requires small MS4s to obtain NPDES permit coverage for stormwater discharge (EPA 2024). There are approximately 95 cities and counties Phase II MS4s that fall under the small MS4 general permit and these entities are required to implement a stormwater management program to help manage the discharge of stormwater for their jurisdiction. Knox County is a Phase II MS4 (Knox County 2024).

As a part of these stormwater management programs, the NPDES permit coverage grants the authority to these complying entities to regulate the stormwater runoff in their jurisdiction. Ordinances are established within these stormwater management programs which include guidance and restrictions on the types of hydrologic methods that can be used for stormwater design, along with the parameters in which the methods can be used. These restrictive parameters include but are not limited to the drainage area size and the classification of land use within that area. For this reason, stormwater management best management practices (BMPs) have been established at the federal, state, and local levels of authority. BMPs for temporary and permanent development situations help existing and future development maintain and improve the quality of our waterways.

Hydrologic Methods

Different articles and studies conclude that the various acceptable methods by a regulatory authority can yield significantly different results when evaluating the peak flow from a drainage area for a given storm event. A study in Ohio consisting of 13 urban and 2 forested watersheds ranging from 5-47 acres (with one outlier at 368 acres) compared the calculated peak flow results from NRCS TR-55, simple method, and Rational method to observed peak flow data collected. Even though there were similarities of watershed characteristics between the different sites, the observed peak flows were significantly different, leading to the conclusion that there is the potential for significant error across the different methodologies (Simpson et al. 2023). A study by USGS in Virginia compared the results of 8 watersheds in Central Virginia and peak-flow data from more than 1,000 basins across the United States. The study concluded that there was not one method that is applicable to all drainage areas for determining peak flow and there can be a significant difference in the peak flows calculated by the different methods (Hayes and Young 2005).

Urban Regression

Urban Regression equations were developed based upon multiple regression statistical analyses from 22 drainage basins in Tennessee with areas between 0.21-24.3 square miles, which also have varying amounts of impervious area between 4.7-74%. An equation for the 2-, 5-, 10-, 25-, 50-, and 100-yr recurrence intervals were developed for estimating peak flow. All the equations have drainage area (square miles), percentage imperviousness (percentage of drainage area), and the 2-year 24-hour event precipitation depth as variables, but each recurrence equation has different variations of the values of constants and exponents (Robbins 1984).

NRCS TR-55

TR-55 was developed by what is now known as the National Resources Conservation Service (NRCS) to estimate peak flow rates for small- to medium-size drainage areas with time of concentration values between 6 and 600 minutes. The TR-55 method is typically used for drainage areas less than 2,000 acres. TR-55 involves determining the drainage area, and a weighted curve number (CN) value for the area that represents the

land use and soil permeability, soil moisture, and the time of concentration of the area to estimate the peak flow using a hydrograph with a given shape and peak factor applicable to the region the site is located (Chin 2019).

Rational Method

The Rational method is based on the product of the drainage area (acres), the runoff coefficient (C, dimensionless) for the area based on the land use and slope of the area, and the rainfall intensity determined from intensity-duration-frequency (IDF) curves developed for a particular region and recurrence interval. The Rational method can be used to determine peak flow rates for a given recurrence interval but cannot be used to determine volume needed for storage routing situations (Chin 2019). This study takes a close look at the applicability of the Rational method in Knox County.

USGS StreamStats

USGS StreamStats is a web application that is a simple tool for a user to select a point of analysis and obtain data including streamflow statistics, drainage basin characteristics, and other relevant stream information. StreamStats provides locations of active and inactive gauges, and the user can select one of these gauges to obtain previously published information including peak flow rates for different storm events. There are also stream lines delineated in the map for a user to select a point of analysis that is not at an active or inactive gauge which is referred to as an ungauged location. If the user selects a point along these delineated streams of an ungauged location, StreamStats will use a Geographic Information System (GIS) program to determine drainage basin characteristics and estimate peak storm flow for the point selected with the assumption of natural flow conditions. USGS has developed equations for different locations across the country using regression analysis to statistically relate basin characteristics to peak flow statistics parameters. StreamStats determines the regression equations applicable for the location, determines what basin characteristics are needed for the equations, measures the required basin characteristics, and then inputs this information into the National Flood Frequency (NFF) program to solve the regression equations. The output results provide the user an estimate of storm peak flow for ungauged sites (Ries et al., 2004).

Rational Method Limitations

It is necessary to examine the definitions of 'small' and 'large' drainage areas. The study by Wisner et al. (1980) observed that only a slight increase in the Rational coefficient would bring the results yielded from the Rational method close to the outputs from a SWMM model when evaluating the peak flow rate at a point downstream for drainage areas of 100 acres or less. Per Hayes and Young (2005), in Virginia the regression equations were created for drainage areas ranging from 0.3 to 3,260 sq-mi and they are inappropriate to use for what they consider to be very small drainage areas, which are less than 200 acres. These values are in line with the range between different regulatory authorities for what drainage area size is permitted to utilize the Rational method.

The Rational method is approved by many regulatory agencies for varying drainage area sizes, but also receives criticism due to its assumptions that rarely match natural conditions. These assumptions include, but are not limited to: the entire drainage area is contributing to the peak runoff, which means that the storm event must be greater than or equal to the time of concentration of the drainage area (Chin 2019); there is no basin storage in the drainage area that has a meaningful impact (Hayes and Young 2005); the storm event is evenly distributed over the drainage area (Chin 2019); and all of the factors that impact precipitation not turning into runoff are included in the determination of the Rational coefficient (Chin 2019). The Rational method has been around for about 150 years and has not changed much in the designer's approach to its use even though there has been a lot more learned about hydrology (Chin 2019). Typically, it is observed that the Rational method will underestimate peak flows as the drainage area increases (Wisner et al. 1980). The study in Ohio by Simpson et al. (2023) observed that the Rational method typically underestimated peak flows compared to observed data. Chin (2019) observed that the assumption of constant rainfall intensity over any duration greater than the typically used 5-minute increment will yield underestimated peak flows. There is evidence pointing towards the Rational method underestimating peak flows compared to other methods and observed data, but what is critical for this study is at what point does the Rational method stop yielding results that are within an acceptable range.

Despite several limitations of the Rational method outlined by other studies, there is still support that runoff characteristics determined using other hydrologic computation methods for different storm events reinforce, to at least a small degree, that the Rational method peak flows can be used for the design of storm structures (Hayes and Young 2005). The main difficulty in comparing the peak flow results from the Rational method against other hydrologic models is that there is typically a subjective selection of the Rational method parameters which can be interpreted differently between designers. Also, the Rational method only gives a peak flow number and does not give the designer the flow history of a runoff event, so a strong understanding of hydrology is required to appropriately use the Rational method (Wisner et al. 1980). This study has attempted to remove subjective selection by keeping variables as consistent as possible across the different methods and outlining the tables to be used for determining variables that change based upon different watershed characteristics such as land use type, precipitation, and channel roughness.

CHAPTER THREE
METHODS
Peak Flow Calculations

Urban Regression Equations

Per Robbins (1984), the study resulted in the development of six equations based on regression analysis of the 22 observed locations. Each equation is based on variables that the designer must input for drainage area, impervious area percentage, and 2-year, 24-hour precipitation depth for their specific site. Each equation has a standard error of associated with it. This study focuses on the 2-yr, 10-yr, and 100-yr peak flows and the Urban Regression equations for these recurrence intervals are provided below.

$Q_2 = 1.76\left(\frac{A}{640}\right)^{0.74} I_{IMP}{}^{0.48}\, P_{2-24}{}^{3.01}$ 32% standard error

$Q_{10} = 11.8\left(\frac{A}{640}\right)^{0.75} I_{IMP}{}^{0.43}\, P_{2-24}{}^{2.12}$ 27% standard error

$Q_{100} = 77.0\left(\frac{A}{640}\right)^{0.75} I_{IMP}{}^{0.40}\, P_{2-24}{}^{1.10}$ 25% standard error

Q = Peak flow rate for given recurrence interval (cfs)

I_{IMP} = Impervious land cover (%)

In this study the percentage of impervious land cover was determined by downloading National Land Cover Database (NLCD) for Knox County and using ArcGIS Pro to extract the land cover types with the estimated impervious percentage for each drainage area.

A = Drainage Area (square miles)

In this study (x29) drainage areas ranging from 20-600 acres with 10-55% impervious cover were selected. USGS StreamStats was used to locate different drainage area sizes in different locations throughout Knox County, and NLCD was used to confirm that the 10-55% impervious cover requirement is met. Per Hayes and Young (2005), the basin size is the most important basin characteristic in determining peak flow. A range of

drainage area sizes were used to evaluate peak flow rate percent difference across the different drainage area size limitations by different regulatory authorities.

P2 = 2-year, 24-hr Precipitation Depth (inches)

In this study the 2-year, 24-hr rainfall depth for Knox County is 3.30 inches per the Knox County Drainage Manual. **Table 2** lists the precipitation depths used in this study and Appendix C: Rainfall Data for the Knox County Rainfall Depth **Table 11** provides the source table from Knox County.

Rational Method

There are different parameters of the Rational method that may vary between the stormwater ordinances provided by public entities. Some ordinances require a specific way to obtain the rainfall intensity value used or the time of concentration method used to obtain the rainfall intensity. Some ordinances require a correction factor to be applied to the calculated peak flow rate that increases as the recurrence interval increases in number of years. For this study, the Rational method as outlined by the Knox County Stormwater Management Manual was used. How this method was used for this study is described below.

$Q = CiA$

Q = Peak flow rate (cfs) for given recurrence interval

C = Rational coefficient (dimensionless)

For this study NLCD was used to obtain land use type, the digital elevation model (DEM) from the USGS National Map was used to determine the slopes across the drainage areas, and ArcGIS Pro was used to overlay the land use type and drainage area slopes to assign the appropriate coefficient per Knox County (Appendix A: Rational Coefficient and

Table 2: Knox County 24-Hour Rainfall Precipitation Depths

Storm Event	24-Hr Depth (in)[1]	Citation
2-yr	3.3	Knox County Stormwater Management Manual
10-yr	4.8	Knox County Stormwater Management Manual
100-yr	6.5	Knox County Stormwater Management Manual

Curve Number, **Table 7**: Rational Coefficient) which matches ST-13-1 for Rational coefficients to be used per the City of Knoxville.

i = Rainfall intensity (inches/hour)

For this study the rainfall intensity was interpolated from precipitation intensity values provided by Knox County and the calculated time of concentration. **Table 3** lists the rainfall intensity values used in this study and Appendix C: Rainfall Data, **Table 10**: Intensity-Duration-Frequency Curve Data provides the full Knox County precipitation intensity table. The same time of concentration method is to be used for Rational and NRCS TR-55 methods for consistency. See time of concentration process under NRCS TR-55 method section.

A = Drainage Area (acres)

A 1.25 correction factor was applied to the 100-yr event, but no correction factor is required for the 2-yr or 10-yr event per the Knox County stormwater management manual. See selection process of drainage areas under Urban Regression section.

NRCS TR-55 Method

The TR-55 method can be modeled in many different softwares including but not limited to HEC-HMS, Autodesk Storm and Sanitary Analysis, and HydroCAD. In this study the Autodesk Hydraflow Extension was used. The analysis location in the United States will dictate what rainfall distribution and peaking factor should be used in the model. Per the Knox County Stormwater Management Manual, a Type II rainfall distribution and peak factor of 484 were used in the model for all the study locations. Curve Numbers (CN) and time of concentrations were determined for each drainage area and input into separate models to determine peak flow.

CN = Curve Number

In this study the NLCD was used to obtain land use type, NRCS Web Soil Survey was used to obtain hydrologic soil group, and ArcGIS Pro was used to overlay the land use type and hydrologic soil group to assign the appropriate Curve Number per the Knox County (Appendix A: Rational Coefficient and Curve Number, **Table 8**: Curve Number) which provides values required by the City of Knoxville.

Table 3: Knox County Rainfall Intensity

	Precipitation Frequency (in/hr) by Return Period[1]		
Minutes	2-yr	10-yr	100-yr
5	4.60	6.25	8.60
10	3.70	5.25	7.49
15	3.19	4.60	6.60
20	2.82	4.10	6.02
25	2.48	3.70	5.50
30	2.22	3.34	5.03
35	2.02	3.06	4.62
40	1.86	2.82	4.24
45	1.73	2.62	3.93
50	1.62	2.46	3.67
55	1.53	2.32	3.45
60	1.45	2.20	3.26

A = Drainage Area (acres)

See selection process of drainage areas under Urban Regression section.

P2, P10, and P100: 24-hr Precipitation Depths

TDOT Drainage Manual has slightly different values than the CoK and Knox County (Appendix C: Rainfall Data, **Table 11**: Rainfall Depths for Hypothetical Storm Events). In this study the CoK and Knox County values will be used since it was established by the local authorities. See **Table 2** for precipitation depths used in this study.

Time of Concentration

The time of concentration is the time that it takes runoff to travel from the most hydraulicly remote point in the drainage area to the determined point of analysis downstream. This may not always be the greatest length of flow path for runoff in the drainage area. The land use and slope at the top of the watershed may impact where the most hydraulicly remote point will be and it is up to engineering judgement by the designer to determine appropriately.

Sheet (Overland) Flow

In this study the Kinemetic Wave (Simplification) equation was used since it is based upon 2-year 24-hour storm depth (P2), which keeps consistency with the P2 value being used in the Urban Regression equations.

Tc = Time of concentration (minutes)

S = Slope of flow per segment (ft/ft)

In this study the USGS National Map was used to download digital elevation models (DEM) to calculate the slope for the respective area.

L = Length of flow per segment (ft)

In this study the DEM was used to calculate the length for the respective areas.

n = Manning's Roughness Coefficient (dimensionless)

In this study guidance from the Knox County stormwater management manual was used for overland flow (Appendix D: Manning's Roughness Coefficient, **Table 12**: Manning's Roughness Coefficients for Overland Flow).

$$T_c = \frac{0.007(nL)^{0.8}}{{P_2}^{0.5} S^{0.4}}$$

Per 3.1.3.5, a maximum length of sheet flow of 100 feet for over unpaved surfaces and 50 feet over paved surfaces will be used. Sheet flow values were checked with the maximum sheet flow length per McCuen and Spiess (1995) to ensure that the sheet flow time of concentration value is not over-estimated. For some situations where the topography, site conditions, and McCuen Spiess equations indicated greater lengths of sheet flow, the Section 3.1.3.5 was violated. This approach was kept consistent for each drainage area.

USDA NRCS Part 630 Hydrology National Engineering Handbook

Chapter 15 Time of Concentration:

Eq. 15-9

$$l = \frac{100\sqrt{S}}{n}$$

Shallow Concentrated Flow

$(Unpaved)\ V = 16.135S^{0.5}$ (ft/s) $(Paved)\ V = 20.328S^{0.5}$ (ft/s)

$$T_c = \frac{L}{V} * \frac{1\,min}{60s} \quad (minutes)$$

Channel Flow

$$V = \frac{1.49}{n} R_h^{0.67} S_c^{0.5} \qquad T_c = \frac{L}{V} * \frac{1\,min}{60s} \quad (minutes)$$

The hydraulic radius (Rh) is the flow area (square feet) divided by the wetted perimeter (feet) in the channel. The dimensions of the average channel cross section were determined using contours extracted from the DEM in ArcGIS Pro and an assumption was made for the initial hydraulic radius. After calculating the final peak flow for the 2-yr event for the Rational method, iterations were performed for routing the calculated peak flow through the channel dimensions and Manning's coefficient in the Hydraulic Engineering Toolbox software until the final hydraulic radius (and therefore final time of concentration and corresponding peak flow values) matched the model. The Manning's Coefficient for channels was selected from the TDOT drainage manual which can be found in Appendix D Manning's Roughness Coefficient, **Table 13**: Manning's

Roughness Coefficients for Manmade Channels or **Table 14**: Manning's Roughness Coefficients for Natural Streams. Without visiting the site and obtaining a detailed survey, it can be difficult to determine the transition point from shallow concentrated flow to channel flow. The transition point to channel flow was estimated based upon where the blue streamline was present on the USGS Map and/or where tight channel definition in contours was present for the DEM.

Time of concentration is a difficult watershed characteristic to determine. This is especially true for urban environments where there may be underground pipe networks and other manmade structures that require a significant breakdown of the time of concentration path to get to an accurate determination. Per Simpson et al. (2023), the urban features such as underground pipe networks prohibit the use of time of concentration methods such as the Kirpach equation, Kerby-Hathaway equation, NRCS velocity method, etc. This study is not intended to be the most accurate prediction of peak flow for these individual drainage areas studied, but is intended to use real watershed characteristics to compare the results from the three different methods. The time of concentration values calculated are reasonable for their drainage area size and shape for comparison between the methods, but further attention to the time of concentration path should be given for evaluating structures in these areas. Per Wisner et al. (1980), a lack of knowledge of pipe routing is not significant for small watersheds.

Data Collection

Study Location

Locations were selected from different parts of Knox County as much as practical to try and best obtain variations in watershed characteristics. There are 22 total study locations, but seven locations were used for one or more drainage area sizes by selecting a point of analysis upstream or downstream of the original point. **Figure 1** shows the study locations. The intent of this research is not to determine the exact peak flow calculation for the points of analyses, but to use real landscape characteristics to evaluate the differences in estimated flow between the Urban Regression, Rational, and TR-55 methods. The TR-55 method should be used to account for evaluations that require storage routing. Urban Regression and Rational methods do not account for storage, so

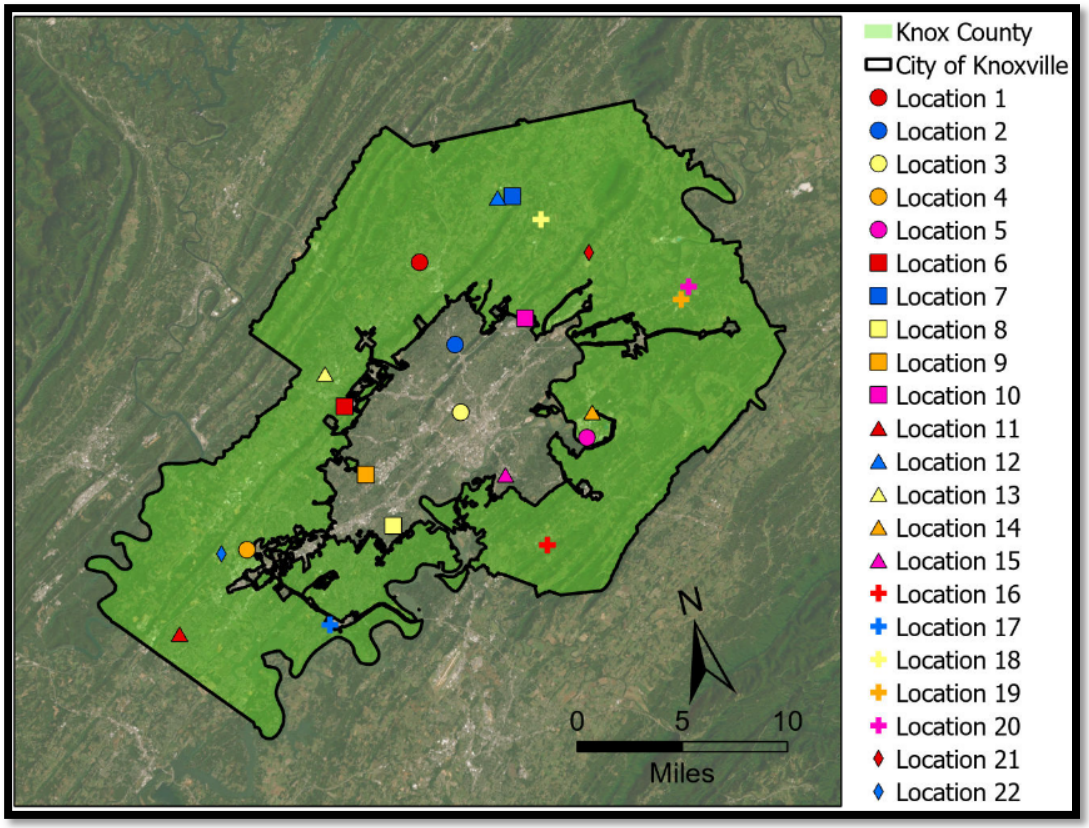

Figure 1 – Study Location Map

storage routing is not included in this study since it cannot be accurately compared between the different methods.

Site Selection

Drainage areas were also selected with a range of percent imperviousness with a maximum of 55%. Drainage areas greater than 55% are within the limits of the hydrologic methods, but were unable to have an accurate time of concentration path estimated without a detailed field investigation. In **Figure 2**, the data are aligned in increasing drainage area size on the y-axis and the order of corresponding location number on the x-axis. Each point is represented by a unique marker indicating the impervious percentage to show the spread of the data for a wide range. **Table 4** summarizes the different watershed characteristics for each location.

National Land Cover Database

The National Land Cover Database (NLCD) was developed by USGS in association with the Multi-Resolution Land Characteristics Consortium (MRLC). Areas of interest can be downloaded by the public that outline the land use as defined by different classifications (Appendix B: Land Cover Classification and Description, **Table 9**: Landcover Classification and Description). By comparing the definitions, in **Table 5** each NLCD land cover type was converted to the most similar land cover type for SCS Curve Number (Appendix A: Rational Coefficient, **Table 7** and Curve Number, **Table 8**). The Knox County Rational coefficient table did not have specific land cover type definitions, but each land use type was matched to the appropriate SCS curve number land cover description and type. This was more obvious for the different vegetative covers from NLCD, but the landcover types of low intensity, medium intensity, and high intensity development required estimating impervious cover percentage.

USGS StreamStats

All of the locations of study are ungauged sites within Knox County. The output report generated by StreamStats consists of four different sections which include a description of the analysis, the basin characteristics, peak-flow statistics parameters, and peak-flow statistics flow report. The description of the analysis section includes the region ID, coordinates, time the analysis was performed, and a map of the basin.

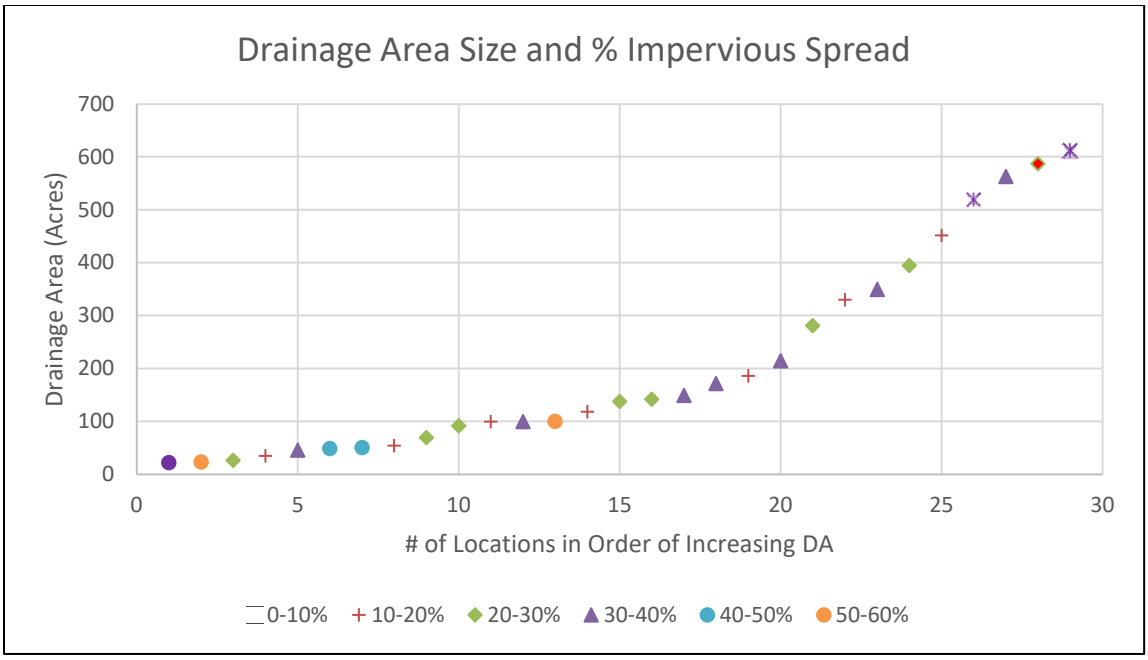

Figure 2 – Percent Imperviousness and Drainage Area Size Spread

Table 4: Watershed Characteristics

ID	Lat.	Long.	DA[1] (acres)	Imp.[2] (%)	S (ft/ft)	L (ft)	ToC[3] (min.)	C[4]	CN[5]
1A	36.09338	-83.94346	137.40	26.64	0.0505	4477	21.71	0.40	71
1B	36.08984	-83.93999	281.18	26.12	0.0430	6863	24.43	0.39	71
2	36.02913	-83.92648	171.30	31.92	0.0205	5070	24.29	0.43	82
3	35.98276	-83.93507	100.08	53.54	0.0408	4016	19.22	0.45	81
4	35.92388	-84.13807	21.98	48.13	0.0708	1250	13.27	0.43	79
5	35.94584	-83.83579	50.17	44.44	0.0167	3660	25.44	0.50	80
6	36.00502	-84.02986	48.40	46.24	0.1354	1957	12.19	0.50	84
7	36.11961	-83.85030	611.77	9.72	0.0081	8504	42.04	0.48	78
8A	35.90436	-84.02350	23.14	54.92	0.0268	1546	21.10	0.49	85
8B	35.91731	-84.01271	349.00	35.64	0.0171	7935	35.15	0.41	75
8C	35.92004	-84.00340	562.64	32.17	0.0162	11,171	39.85	0.39	73
9	35.95592	-84.02552	26.27	27.46	0.0532	1410	13.62	0.36	70
10	36.03567	-83.86351	53.99	14.90	0.0536	2855	17.69	0.44	77
11	35.87858	-84.20967	149.12	31.75	0.0655	4525	17.35	0.37	72
12A	36.13067	-83.86710	34.55	18.91	0.0239	2051	23.46	0.44	74
12B	36.12704	-83.86581	91.41	21.21	0.0201	3436	27.84	0.46	78
12C	36.12157	-83.86272	142.11	26.89	0.0174	5755	32.70	0.46	80
13	36.03055	-84.03955	99.68	31.87	0.0338	4141	20.87	0.39	73
14	35.96268	-83.82633	69.12	19.85	0.0220	3048	21.63	0.34	77
15	35.93774	-83.90482	45.48	34.07	0.0285	1930	20.96	0.44	83
16	35.88004	-83.88928	451.30	18.86	0.0471	9449	27.26	0.36	73
17	35.86064	-84.08406	214.36	33.69	0.0378	5770	22.15	0.36	73
18	36.09950	-83.83109	99.32	18.31	0.0647	4261	17.35	0.35	67
19A	36.02163	-83.73655	185.86	18.20	0.0201	6755	30.37	0.41	79
19B	36.02357	-83.73103	330.18	14.02	0.0173	8636	35.10	0.38	78
20	36.03100	-83.72243	118.05	9.95	0.0466	5703	20.16	0.39	78
21	36.06978	-83.79807	519.11	3.41	0.0513	9442	27.75	0.33	67
22A	35.92531	-84.15989	394.53	27.43	0.0378	8307	24.50	0.36	74
22B	35.92181	-84.16540	586.68	25.50	0.0302	10835	30.47	0.36	74

[1] Drainage Area
[2] Percent imperviousness of the drainage area
[3] Time of Concentration calculated using NRCS TR-55 methodology
[4] Weighted Rational Coefficient
[5] Weighted Curve Number

Table 5: NLCD Conversion to Curve Number and Rational Coefficient Descriptions

NLCD Land Cover Type	NLCD Description	SCS CN Description	SCS CN Cover Type	Rational Land Use
Developed, Open Space	<20% impervious)	20% avg. imp. area	Res. Dist. 1 acre	Res. 1 acre
Developed, Low Intensity	(20-49% impervious)	38% avg. imp. area	Res. Dist. 1/4 acre	Res. 1/4 acre
Developed, Medium Intensity	(50-79% impervious)	65% avg. imp. area	Res. Dist. 1/8 acre	Res. 1/8 acre
Developed, High Intensity	(80-100% impervious)	85% avg. imp. area	Urban District Comm. & Business	Commercial
Barren Land	less than 15% Veg.	N/A	Dirt	Dist. Area
Deciduous Forest	>20% of veg. cover is decid. trees > 5 m	N/A	Wood or forest land	Forest
Evergreen Forest	>20% of veg. cover is evergreen trees > 5m	N/A	Wood or forest land	Forest
Mixed Forest	>20% of veg. cover is trees 5 meters or taller	N/A	Wood or forest land	Forest
Shrub/Scrub	>20% of veg. cover is shrubs >5 m	N/A	Wood or forest land	Forest
Grassland/ Herbaceous	>80% vegetation not subject to mgt.	N/A	Meadow	Meadow
Pasture/Hay		N/A	Pasture	Pasture
Cult. Crops		N/A	cultivated land	Farmland
Woody Wetlands	>20% of veg. cover is forest	N/A	Wood or forest land	Forest
Herbaceous Wetlands	>80% vegetation herbaceous	N/A	Meadow	Meadow

This information helps to document not only where and what the analysis was performed for, but what regression equations will be applicable (**Figure 3**). The basin characteristics section shows the 2-year climate factor (dimensionless), contributing drainage area size (sq-mi), and the main channel slope (feet/mile) determined by the GIS resources in StreamStats (**Figure 4**). The Peak-Flow Statistics Parameters section compares these determined basin characteristics values to the range of values permitted by the limitations of the regression equation determined to be appropriate (**Figure 5**). All of the 29 sites in this study were calculated by the Multi-Variable Rural Regression (MVRR) equations for Hydrologic Region 1 which appear as [MultiVariable Area 1] in the Peak-Flow Statistics of the output report. The Peak-Flow statistics Flow Report shows the calculated peak flow rate values for different storm frequencies along with the range of error (**Figure 6**).

The basin characteristic values determined do not always fall within the acceptable ranges from the limitations outlined for the regression equation. MVRR in Hydrologic Region 1 is applicable for drainage area sizes of 0.20 sq-mi (128 acres) or up to 9,000 sq-mi and watersheds with less than 10% impervious area (Law and Tasker 2000). It should be noted that the StreamStats outputs for locations with a drainage area size less than 0.20 sq-mi are out of range and the calculated peak flows are based on extrapolation. For locations that have peak flow statistics parameters outside the acceptable range of the regression equation utilized per the peak flow statistics section, a warning message will display in the output report that the peak flow results were extrapolated along with a highlight in orange for the characteristic that is out of range (**Figure 7**).

Statistics

The peak flow values for each method were normalized since it is not the value of the peak flows, but the amount of percent difference between the methods that are of interest. The peak flow value provided by USGS StreamStats was used as the baseline for comparison to the other methods. Without the availability of actual observed data to compare to, the StreamStats values were a reasonable baseline for comparison since it is a publicly available result that any designer can obtain, and the results are determined by

Location 1 A StreamStats Report

Region ID: TN
Workspace ID: TN20240815111431100000
Clicked Point (Latitude, Longitude): 36.09338, -83.94346
Time: 2024-08-15 07:14:52 -0400

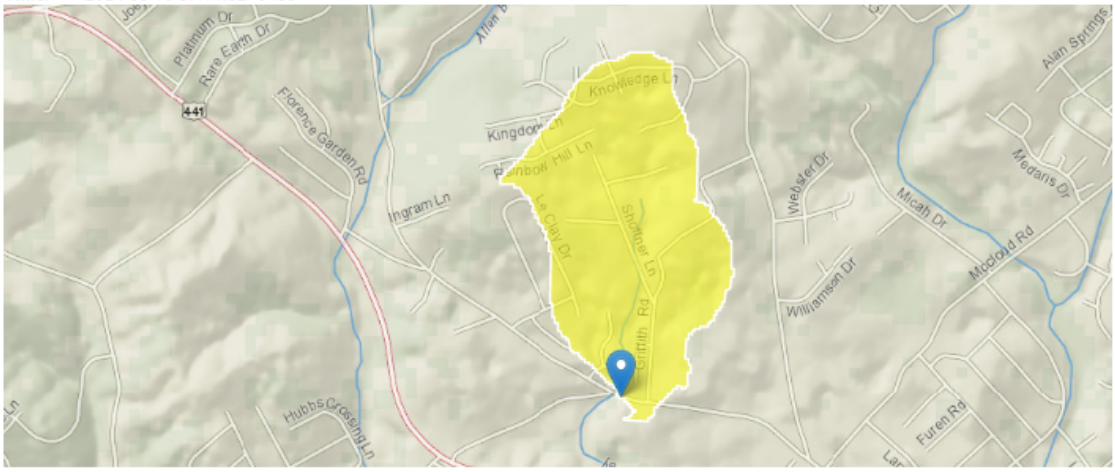

Figure 3 – Location 1A Description of Analysis

> Basin Characteristics

Parameter Code	Parameter Description	Value	Unit
CLIMFAC2YR	Two-year climate factor from Lichy and Karlinger (1990)	2.235	dimensionless
CONTDA	Area that contributes flow to a point on a stream	0.21	square miles
CSL10_85	Change in elevation divided by length between points 10 and 85 percent of distance along main channel to basin divide - main channel method not known	187.74	feet per mi

Figure 4 – Location 1A Basin Characteristics

> Peak-Flow Statistics

Peak-Flow Statistics Parameters [MultiVariable Area 1]

Parameter Code	Parameter Name	Value	Units	Min Limit	Max Limit
CONTDA	Contributing Drainage Area	0.21	square miles	0.2	9000
CSL10_85	Stream Slope 10 and 85 Method	187.74	feet per mi	3.29	950
CLIMFAC2YR	Tennessee Climate Factor 2 Year	2.235	dimensionless	2.06	2.32

Figure 5 – Location 1A Peak Flow Statistics Parameters

Peak-Flow Statistics Flow Report [MultiVariable Area 1]

PIL: Lower 90% Prediction Interval, PIU: Upper 90% Prediction Interval, ASEp: Average Standard Error of Prediction, SE: Standard Error, PC: Percent Correct (other -- see report)

Statistic	Value	Unit	PIL	PIU	ASEp	Equiv. Yrs.
50-percent AEP flood	35.4	ft^3/s	18.8	66.7	39.2	1.7

Statistic	Value	Unit	PIL	PIU	ASEp	Equiv. Yrs.
20-percent AEP flood	59.4	ft^3/s	31.6	112	38.2	2.6
10-percent AEP flood	78.3	ft^3/s	40.8	150	40.1	3.4
4-percent AEP flood	105	ft^3/s	52.6	210	42.7	4.3
2-percent AEP flood	126	ft^3/s	60.8	261	45.2	4.9
1-percent AEP flood	151	ft^3/s	70	326	47.9	5.3
0.2-percent AEP flood	213	ft^3/s	89	510	55.2	5.8

Peak-Flow Statistics Citations

Law, G.S., and Tasker G.D.,2003, Flood-Frequency Prediction Methods for Unregulated Streams of Tennessee, 2000: U.S. Geological Survey Water-Resources Investigations Report 03-4176, 79p. (http://pubs.usgs.gov/wri/wri034176/)

Figure 6 – Location 1A Peak Flow Statistics Flow Report

Peak-Flow Statistics

Peak-Flow Statistics Parameters [MultiVariable Area 1]

Parameter Code	Parameter Name	Value	Units	Min Limit	Max Limit
CONTDA	Contributing Drainage Area	0.18	square miles	0.2	9000
CSL10_85	Stream Slope 10 and 85 Method	145.97	feet per mi	3.29	950
CLIMFAC2YR	Tennessee Climate Factor 2 Year	2.234	dimensionless	2.06	2.32

Peak-Flow Statistics Disclaimers [MultiVariable Area 1]

One or more of the parameters is outside the suggested range. Estimates were extrapolated with unknown errors.

Figure 7 – Location 20 StreamStats Output Error Message

the widely accepted USGS regression equations. StreamStats also yielded the lowest peak flow values of all the methods for all of the analyses so we can easily compare the order of magnitude that the other methods are greater than this likely underestimated peak flow.

Mean and Standard Deviation

The watershed characteristics observed were evaluated in IBM Statistical Package for the Social Sciences (SPSS). The mean is the average, or the approximate center point of the data for a given variable. Standard deviation is the measure of variation, or how wide the values spread in our collected data. Higher standard deviation results in more distinct data values. Typically, data points with standard deviation values over 3 are considered outliers (Akritas 2016). SPSS was used to provide descriptive statistics for the watershed characteristics and the percent difference calculated to easily see the range in values for the data collected and to determine if there were any outliers that should be omitted from the analysis.

Linear Regression

The percent difference calculated was evaluated in Microsoft Excel. Linear regression is a statistical analysis that can help understand the relation between explanatory variables and a response by creating a linear equation where the slope indicates the change in average mean value of the dependent variable as the independent variable changes (Akritas 2016). The explanatory variable (x) is the drainage area size from the 29 different points of analyses. The response variable (y) is the percent difference in peak flow rate for a specific method and storm event, which is calculated by the method of interest peak flow rate subtracted by the StreamStats peak flow rate and this value is then divided by the StreamStats peak flow rate and written in percent form. Microsoft Excel was used to graph the values of percent difference for all three methods for the 2-, 10-, and 100-year storm events. Each method for each storm event has a trendline, equation, and R-squared value. The intent is that the equation generated from the data will be used to predict a response based upon a given value of the explanatory variable. Not all data created equations will accurately predict a response variable. The R-squared value is the percentage of the total response variation explained by the explanatory variable. The

higher the R-squared value, the better the predictive power of the regression model (Akritas 2016). The p-value is provided for each trendline. P-values <.05 are considered to be statistically significant and p-values >.05 are not statistically significant.

CHAPTER FOUR
RESULTS
Data Plots

2-Year Storm Event

For the 2-year storm event, in **Figure 8** it is observed that TR-55 and Urban Regression percent differences slightly decrease with increasing drainage area size with slopes of -0.0007 and -0.0021 respectively. The Rational method percent differences slightly increase with a slope of 0.0009. The TR-55 and Rational method differences appear similar in value, with the Rational method being less than TR-55 until the upper end of the drainage area size from this study of approximately 600 acres where they are approximately equal. Urban Regression percent differences are lower than TR-55 and Rational method by an order of magnitude of about 1 to 2.5 times smaller. Urban Regression percent difference compared to the baseline StreamStats results significantly decreases with increasing drainage area size.

For the fit of the trendline to the data, the TR-55 method has the least percent difference explained with an R-squared value of 0.0126 and a p value of .562. The Rational method has more percent difference explained than TR-55 with an R-squared value of 0.1326 and a p-value of .052. Urban Regression has the most percent difference explained with R-squared values of 0.2932 and a p-value of .002. Due to the TR-55 and Rational methods having p-values greater than .05, the trendlines are determined to not be statistically significant. Caution should be used when drawing conclusions about the data from these trendlines. Urban Regression trendline is considered to be significant.

10-Year Storm Event

For the 10-year storm event, in **Figure 9** it is observed that TR-55 and Rational method percent differences slightly increase with increasing drainage area size with similar slopes of 0.0008 and 0.0011 respectively, except the TR-55 method is higher than the Rational method by an order of magnitude of about 1.5.

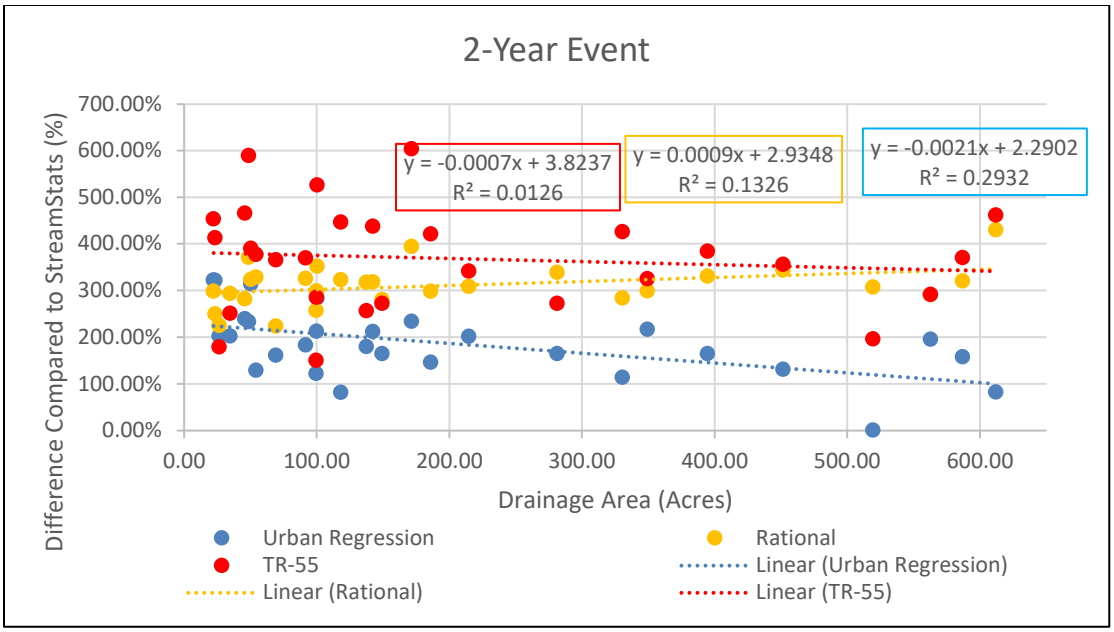

Figure 8 – 2-Year Storm Event: Method % Difference vs. Drainage Area

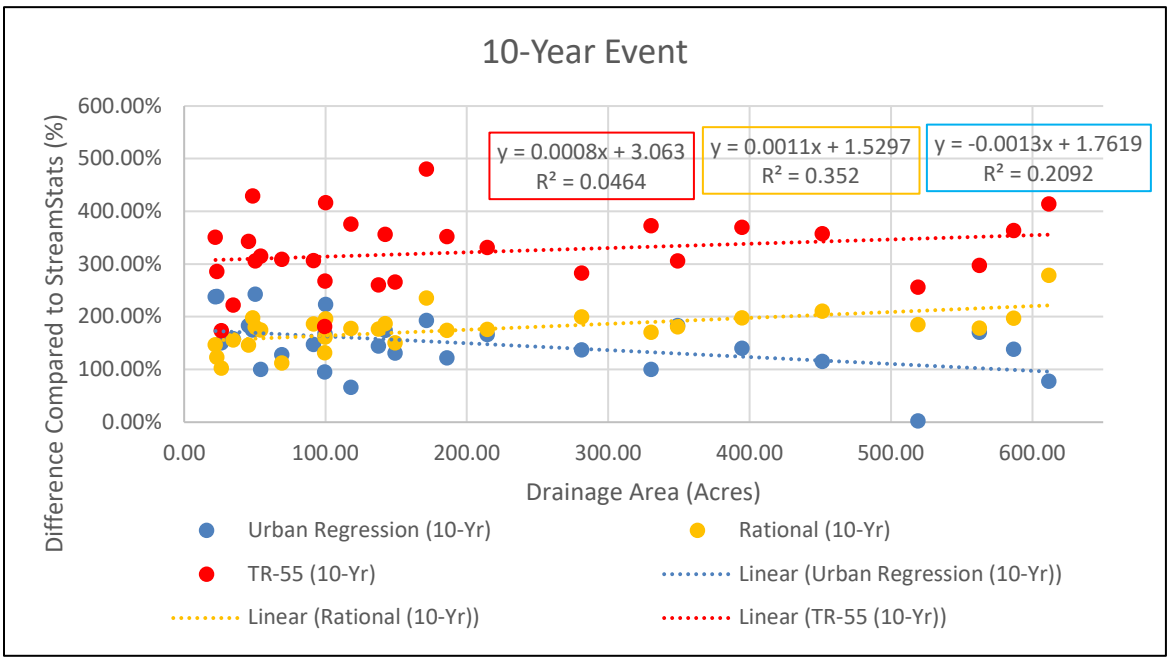

Figure 9 – 10-Year Storm Event: Method % Difference vs. Drainage Area

Urban Regression percent differences slightly decrease with increasing drainage area size with a slope of -0.0013. Urban Regression percent differences are very similar to the Rational method for drainage area sizes from 0 to 200 acres, but as drainage area size increases the Urban Regression reduces in percent differences while the Rational method increases.

Compared to the 2-year storm event, the significance of the trendlines improved for the Rational and TR-55 methods. For the Rational method trendline the R-squared value increased to 0.352 and the p-value decreased to <.001. For the TR-55 method trendline the R-squared value increased to 0.0464 and the p-value decreased to .262. For the Urban Regression trendline the R-squared value decreased to 0.2092 and the p-value increased to .013. Since the p-value for the Rational method trendline is less <.05, it is determined to be statistically significant. Although the p-value for the Urban Regression trendline slightly increased, it is still <.05 and is determined to be significant. Due to the TR-55 p-value having improved, but still greater than .05, the trendline is determined to not be significant and caution should be used when drawing conclusions about the data from this trendline.

100-Year Storm Event

For the 100-year storm event, from **Figure 10** it is observed that TR-55 and Rational method percent differences slightly increase with increasing drainage area size with the same slope of 0.0015, except the TR-55 method is higher than the Rational method by an order of magnitude of about 0.9. This is similar to the 10-year storm event, although the magnitude of how much greater the TR-55 percent difference is compared to the Rational method is less than that of the 10-year event. Urban Regression percent differences are very similar to the Rational method for drainage area sizes from 0 to 150 acres, but as drainage area size increases the Urban Regression reduces in percent difference while the Rational method increases.

Compared to the 10-year storm event, the significance of the trendlines improved for the Rational and TR-55 methods. For the Rational method trendline the R-squared value increased to 0.5052 and the p-value remained at <.001. For the TR-55 method trendline the R-squared value increased to 0.2686 and the p-value decreased to .004. For the

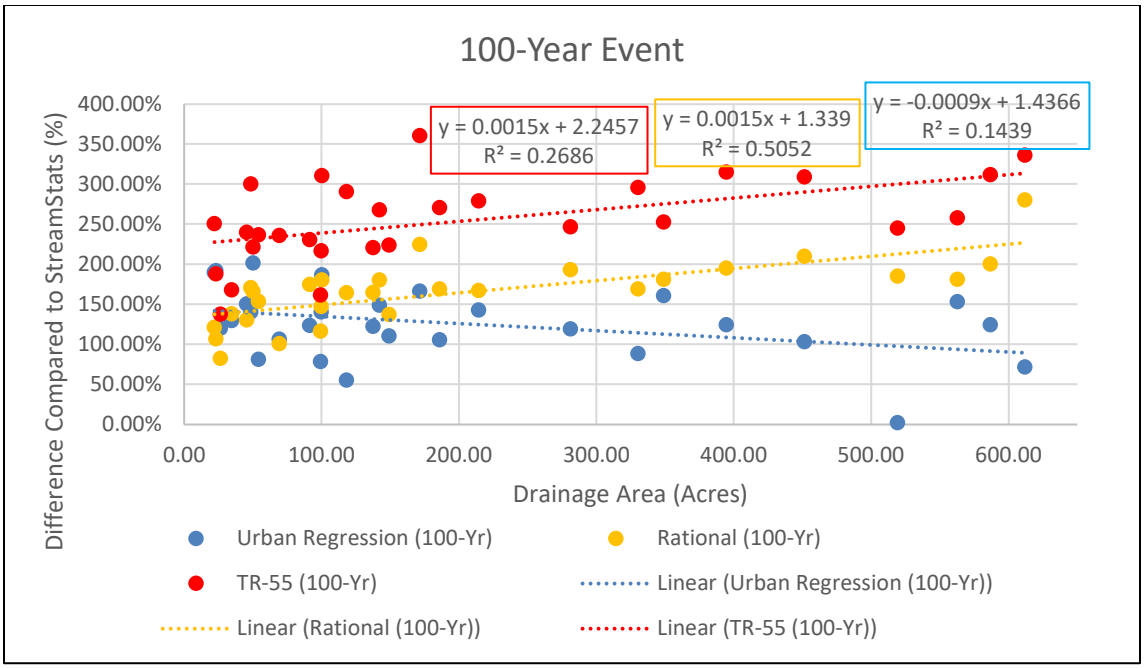

Figure 10 – 100-Year Storm Event: Method % Difference vs. Drainage Area

Urban Regression trendline the R-squared value decreased to 0.1439 and the p-value increased to .042. Since the p-value for the Rational and TR-55 method trendlines are less <.05, they are determined to be statistically significant. Although the p-value for the Urban Regression trendline slightly increased, it is still <.05 and is determined to be significant.

Descriptive Statistics

SPSS was used to provide the descriptive statistics output from the statistical analysis including minimum, maximum, mean, and standard deviation (**Table 6**). The watershed characteristics of drainage area size, percent impervious area, channel slope, channel length, time of concentration, Rational coefficient, and Curve Number show a wide range in values indicating the drainage areas have unique characteristics compared to one another. Rational method percent difference on average were between the values of Urban Regression and TR-55 with similar drop in average compared to TR-55 with less frequent larger storm events. TR-55 has the greatest range and most percent difference compared to TR-55 and Rational method, which is consistent with **Figures 8-10**.

Table 6: Descriptive Statistics

	Minimum	Maximum	Mean	Standard Deviation
Drainage Area (Acres)	21.98	611.77	205.80	187.68
% Impervious	3.41	54.92	27.78	12.94
Slope (ft/ft)	0.0081	0.1354	0.0385	0.0252
Channel Length (feet)	1,250	11,171	5,336	2,948
Time of Concentration (min.)	12.19	42.04	24.48	7.53
Rational Coefficient	0.33	0.50	0.41	0.05
Curve Number	67	85	76	5
Urban Regression 2-Yr Peak Flow (% Difference)	1.15	322.88	185.59	73.13
Rational Method 2-Yr Peak Flow (% Difference)	224.06	430.46	311.21	44.40
SCS-TR 55 2-Yr Peak Flow (% Difference)	150.82	603.99	368.64	111.45
Urban Regression 10-Yr Peak Flow (% Difference)	2.81	243.42	149.17	53.86
Rational Method 10-Yr Peak Flow (% Difference)	103.17	279.41	176.07	35.50
SCS-TR 55 10-Yr Peak Flow (% Difference)	174.33	480.86	322.91	70.31
Urban Regression 100-Yr Peak Flow (% Difference)	2.00	201.39	125.42	43.85
Rational Method 100-Yr Peak Flow (% Difference)	82.28	280.19	165.18	40.13
SCS-TR 55 100-Yr Peak Flow (% Difference)	137.58	360.66	254.48	52.63

CHAPTER FIVE
DISCUSSION

Observations across the data obtained for the 2-, 10-, and 100-year storm events yield that the percent difference between the three methods ranged from 1 to 4 times greater than the StreamStats peak flow results. This difference in magnitude is significant, but the StreamStats value does not represent the true peak flow value. In this study, the StreamStats results are based on the Multi-Variable Rural Regression equations for Hydrologic Area 1 in Tennessee, which is another method for determining peak flows outside the three methods evaluated in this study. It is more important to evaluate the difference between the three different methods that are being compared to StreamStats. It should be noted that for some locations, these different methods were used for drainage area sizes and percent imperviousness outside of what different regulatory authorities permit. This was intended to see if the percent differences for these methods increased at these threshold limits.

For Urban Regression we would expect to see significant percent difference from other methods for drainage areas less than 100 acres since this is the minimum drainage area size permitted by the regression study size and the equations have to be extrapolated to calculate smaller areas than 0.21 sq-mi (134.4 acres). This study in Knox County, Tennessee found that Urban Regression percent differences were actually closest to TR-55 and Rational method percent differences from StreamStats for smaller drainage areas under 100 acres and with increasing drainage area size Urban Regression reduced in percent differences towards the StreamStats calculated value, while the other methods increased in percent differences. This divergence of Urban regression percent differences with increasing drainage area size is likely due to the strong relationship that the rural and urban regression equations have with drainage area as compared to the other input values. In addition to drainage area size, rural regression equations also rely on climate factor and channel slope which do not change, and urban regression equations rely on 2-year 24-hour precipitation depth, percent imperviousness, and channel slope which do not change.

For the TR-55 method, it is expected that the peak flow values will be the largest compared to the other methods. For the Rational method, it is expected to see significant percent differences from other methods with increasing drainage area size, especially above 200 acres, which is the typical maximum allowed by a regulatory authority. This study in Knox County, Tennessee has results that indicate that on average Urban Regression is typically the smallest, Rational method is in the middle, and TR-55 is the largest. A study in North Carolina by Genereaux (2003) for an approximately 40-acre drainage area also found USGS results to be the smallest, Rational method to be in the middle, and TR-55 to be the largest peak flow values. This North Carolina study concluded that the assumption of a large peak in the rainfall hyetograph leads directly to a large peak discharge estimate. Another study in Nebraska by Hotchkiss and McCallum (1995) evaluated four drainage areas less than 2 square miles, and compared the calculated peak flow rates of USGS Regression, TR-55 and Rational method to recorded peak flows by stream gauge including historical data. This Nebraska study found that Rational method was the best hydrologic method estimate up to the 5-year storm event, but was not similar for the 25-year event. USGS regression was determined to be the most accurate peak flow estimate for this study overall.

In this Knox County study, it should be noted that the Urban Regression trendline is significant for the 2-, 10-, and 100-year storm events, the Rational method trendline is close to significance for the 2-year storm event, but is significant for the 10- and 100-year storm events, and the TR-55 method trendline is only significant for the 100-year storm event. For the 10- and 100-year storm events, the Urban Regression percent differences are similar to the Rational method for smaller drainage areas of 150 acres or less, and the percent differences significantly increase between these two methods with increasing drainage area size above 150 acres. It should be noted that the Urban Regression results for drainage areas less than 100 acres are extrapolated per the drainage area size limitations outlined in the study that produces these equations (Robbins 1984). It should also be noted that for the 2-, 10- and 100-year storm events, the Urban Regression equations report by Robbins (1984) determined a percent error for the equations as 32%, 27%, 25% respectively. Since Urban regression equations are based on observed field

data, and the fact that Urban Regression peak flow results are accepted by multiple regulatory authorities that have jurisdiction for different types of projects in Knox County, these results support that the Rational method peak flow values are in range of an acceptable hydrologic method and therefore the Rational method should also be considered as an acceptable method for determining peak flow for the 0 to 150 acre drainage area size.

For all three storm events in this study, the TR-55 trendline slope is very similar to the Rational method trendline slope, but only the 100-year event yields trendlines that are statistically significant for both methods. For the 100-year event the trendline slope for TR-55 and Rational method are identical (.0015), but TR-55 is larger by an order of magnitude of approximately 0.9. The TR-55 percent differences compared to the Rational method indicates the TR-55 method yields higher peak flow rates than the Rational method on average. This is consistent with a study in Iowa sponsored by the Iowa Highway Research Board (2009) that evaluated drainage areas of 200 acres or less and the calculated peak flows were compared to observed flow in stream gauges and for urban land uses. This study concluded that the TR-55 method on average overpredicted peak flow and that the Rational method significantly underestimates peak flows based on the stream gauge data (IIHR 2009). Likely, the true peak flow value for these storm events lies between the results of these two methods.

It should be noted that not only are the slopes similar for the Rational and TR-55 method trendlines, the trendlines increase in statistical significance for lower frequency higher intensity storm events. TR-55 method has trendlines with the lowest R-squared values and p-values >.05 yielding trendlines that are not statistically significant for the 2- and 10- year storm events, but for the 100-year event the p-value drops significantly below .05 with a significant increase in R-squared to 0.2686 making the 100-yr storm event trendline statistically significant. Rational method has a steadily increasing R-squared values of .1326, .3520, and .5052 for 2- 10- and 100-years storm events respectively. Rational method trendlines p-value for the 2-year event is borderline significant at 0.05, but is very significant for the with p-value <0.01 for the 10- and 100-year storm events. This increase in statistical significance and goodness of fit of the trendline for less

frequent higher intensity storm events for the Rational method and TR-55 method may be because the drainage area size becomes the most influential dependent variable for the calculated peak flow value which increases the explanation in the percent differences. Rainfall intensity and precipitation depth do increase for the less frequent storm events, but the magnitude of the drainage area size is greater and more likely to influence the reduction in percent difference from the trendline. The Rational coefficient and curve number remain the same between different storm events, so they do not explain the reduction in percent difference for less frequent storm events.

Without knowing the true peak flow values from observed field data, this study cannot confirm which hydrologic method is most accurate for determining peak flows. What can be confirmed is that the results indicate that the order of magnitude difference in percent differences for the 100-year storm event between the Rational method and TR-55 method is consistent with either the Rational method underestimating the peak flow value if TR-55 is determined to be closest to the true peak flow value, TR-55 is overestimated if the Rational method is determined to be closest to the true peak flow value, or the true peak value lies between the results of the two methods and both statements are true. This study can also confirm that the Rational method yields peak flow values within range of Urban Regression for drainage area sizes between 0 to 150 acres, which is significant since Urban Regression is an acceptable method for peak flow calculations for this drainage area range for several regulatory authorities for drainage areas greater than 100 acres.

If a design engineer evaluated the same point of analysis using Urban Regression and TR-55 for a drainage area of 100 to 150 acres, the engineer could be in compliance with the regulatory authority guidance by using either method if all other conditions of limitations of the methods were met. Even though these calculations would be in compliance, the peak flow estimates using either the Urban Regression or TR-55 methods are likely to be very different by up to a magnitude of 1.0 or more per the findings in this study. The Rational method results in similar percent differences to Urban Regression for drainage areas of 0 to 150 acres for the 10-year and 100-year storm events, and is consistently between the Urban Regression and TR-55 values which is consistent with

findings from other studies. Since the Urban Regression equations are empirically based on observed field studies, and the Rational method is close in value to Urban Regression and similar in trend to the TR-55 method for the 100-year storm event, the use of the Rational method should be made applicable for drainage areas up to the lower limitations of the Urban Regression equations (134.4 acres in Region 1) when storage routing is not required.

This drainage area limitation for the Rational method would be close to the 100-acre limit established by TDOT, and consistent with the 200-acre limit established by FHWA and VDOT. At the very least, the Rational method is a widely accepted hydrologic method for calculating peak flows that could be used to check peak flow estimates from the Urban Regression and TR-55 methods. Since TR-55 is said to be a high estimate and Rational method is said to a be a low estimate, the designer could calculate both and use this range to show the anticipated function of the system over this range of possible outcomes instead of assuming one peak flow rate which is unlikely to represent the true peak flow value. Another option would be to perform additional studies to apply a correction factor to the Rational coefficients or the overall Rational equation as proposed in the Iowa study to reduce biases in the data they observed (IIHR 2009). Hydrology is a science driven by many variables which yields significant differences in results. Without additional field data, a range of scenarios may be more appropriate than a single estimate to help account for differences between hydrologic methods.

To design a better study to evaluate the different hydrologic methods, field data is required in order to establish a baseline of actual observed peak flow rates. Initially this study sought out to use any stream gauge data within Knox County, Tennessee to include in the locations of study, but there are no stream gauges within Knox County with a drainage area less than 15 sq-mi (9,600 acres). The next step should be to find gauges in east Tennessee, west North Carolina, southwest Virginia, and/or south West Virginia to investigate if enough stream gauges with drainage areas of 600 acres or less can be found and used as a baseline. These locations would be most similar to terrain, climate, and geology to Knox County. After this expanded regional study or if this study is unable to be completed, additional gauge stations or a similar monitoring systems could be setup at

different locations throughout Knox County to begin data collecting. Location selection could be similar to this study for choosing different locations across the County that will have a wide spread of different watershed characteristics. An existing channel could be modified at the point of analysis to be manmade channel section that could funnel the channel to a flume at the outlet point where measurement devices could be installed. The manmade channel section would help to limit turbulence through a consistent Manning's n value, allow for simple measurement of area of flow if the depth was determined, and have different mechanisms setup at various heights in the channel to determine velocity of flow over a period of time to determine peak flow rate. This option would be expensive and require a lot of time to be able to gather enough data for different storm events. Additional research could help identify cheaper ways to evaluate the flow characteristics or the locations could be used for other items of study for different stream data to help split the costs of research equipment and monitoring.

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APPENDICES

APPENDIX A: RATIONAL COEFFICIENT AND CURVE NUMBER

Table 7: Rational Coefficient[1]

	Runoff Coefficient (C) by Hydrologic Soil Group and Ground Slope											
	A			B			C			D		
Land Use	**<2%**	**2-6%**	**>6%**	**<2%**	**2-6%**	**>6%**	**<2%**	**2-6%**	**>6%**	**<2%**	**2-6%**	**>6%**
Forest	0.08	0.11	0.14	0.10	0.14	0.18	0.12	0.16	0.20	0.15	0.20	0.25
Meadow	0.14	0.22	0.30	0.20	0.28	0.37	0.26	0.35	0.44	0.30	0.40	0.50
Pasture	0.15	0.25	0.37	0.23	0.34	0.45	0.30	0.42	0.52	0.37	0.50	0.62
Farmland	0.14	0.18	0.22	0.16	0.21	0.28	0.20	0.25	0.34	0.24	0.29	0.41
Res. 1 acre	0.22	0.26	0.29	0.24	0.28	0.34	0.28	0.32	0.40	0.31	0.35	0.46
Res. 1/2 acre	0.25	0.29	0.32	0.28	0.32	0.36	0.31	0.35	0.42	0.34	0.38	0.46
Res. 1/3 acre	0.28	0.32	0.35	0.30	0.35	0.39	0.33	0.38	0.45	0.36	0.40	0.50
Res. 1/4 acre	0.30	0.34	0.37	0.33	0.37	0.42	0.36	0.40	0.47	0.38	0.42	0.52
Res. 1/8 acre	0.33	0.37	0.40	0.35	0.39	0.44	0.38	0.42	0.49	0.41	0.45	0.54
Industrial	0.85	0.85	0.86	0.85	0.86	0.86	0.86	0.86	0.87	0.86	0.86	0.88
Commercial	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.89	0.89	0.90
Streets: ROW	0.76	0.77	0.79	0.80	0.82	0.84	0.84	0.85	0.89	0.89	0.91	0.95
Parking	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97
Disturbed Area	0.65	0.67	0.69	0.66	0.68	0.70	0.68	0.70	0.72	0.69	0.72	0.75

[1] *Stormwater Management Manual*, Volume 2, Knox County, TN, United States, January 2008, Chapter 3 Stormwater Hydrology, Accessed: January 14, 2024. [Online]. Available: https://www.knoxcounty.org/stormwater/volume2.php

Table 8: Curve Number[1]

Cover Description	Cover Type and Hydrologic Condition	Average Percent Impervious Area	Curve numbers for Hydrologic Soil Groups			
			A	B	C	D
Cultivated land:	without conservation treatment		72	81	88	91
	with conservation treatment		62	71	78	81
Pasture or range land:	poor condition		68	79	86	89
	good condition		39	61	74	80
Meadow	generally mowed for hay		30	58	71	78
Wood or forest land:	thin stand, poor cover		45	66	77	83
	good cover		25	55	70	77
Open space (lawns, parks, golf course, cemeteries, etc.)	poor condition (grass cover <50%)		68	79	86	89
	fair condition (grass cover 50% to 75%		49	69	79	84
	good condition (grass cover > 75%)		39	61	74	80
Impervious areas:	paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:	paved; curbs and storm drains (excluding right-of-way)		98	98	98	98
	paved; open ditches (including right-of-way)		83	89	92	93
	gravel (including right-of-way)		76	85	89	91
	dirt (including right-of-way)		72	82	87	89
Urban Districts:	commercial and business	85%	89	92	94	95
	industrial	72%	81	88	91	93
Residential Districts:	1/8 acre or less (town houses)	65%	77	85	90	92
	1/4 acre	38%	61	75	83	87
	1/3 acre	30%	57	72	81	86
	1/2 acre	25%	54	70	80	85
	1 acre	20%	51	68	79	84
	2 acres	12%	46	65	77	82
Developing urban areas and newly graded areas (pervious areas only, no vegetation)			77	86	91	94

APPENDIX B: LAND COVER CLASSIFICATION AND DESCRIPTION

Table 9: Landcover Classification and Description[1]

Class/Value	Classification Description
Water	**Open Water** - areas of open water, generally with less than 25% cover of vegetation or soil.
	Perennial Ice/Snow - areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cove
Developed	**Developed, Open Space** - areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
	Developed, Low Intensity - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.
	Developed, Medium Intensity - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
	Developed High Intensity - highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.
Barren	**Barren Land (Rock/Sand/Clay)** - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
Forest	**Deciduous Forest** - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
	Evergreen Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
	Mixed Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.

Table 9 Continued: Landcover Classification and Description[1]

Class/Value	Classification Description
Shrubland	**Dwarf Scrub** - Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation.
	Shrub/Scrub - areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
Herbaceous	**Grassland/Herbaceous** - areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
	Sedge/Herbaceous- Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra.
	Lichens - Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation.
	Moss - Alaska only areas dominated by mosses, generally greater than 80% of total vegetation.
Planted/Cultivated	**Pasture/Hay** - areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
	Cultivated Crops - areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
Wetlands	**Woody Wetlands** - areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
	Emergent Herbaceous Wetlands - Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

[1] National Land Cover Database, United States Geological Survey, Earth Resources Observation and Science Center, September 11, 2018, Accessed: January 14, 2024. [Online]. Available: https://www.usgs.gov/centers/eros/science/national-land-cover-database

APPENDIX C: RAINFALL DATA

Table 10: Intensity-Duration-Frequency Curve Data[1]

ARI (years)		24-Hour Precipitation Frequency Estimates (inches/hour) by Return Periods					
Hours	**Minutes**	**2-year**	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**
0.083	5	4.60	5.55	6.25	7.30	7.90	8.60
0.170	10	3.70	4.60	5.25	6.20	6.80	7.49
0.250	15	3.19	3.98	4.60	5.45	6.00	6.60
0.330	20	2.82	3.50	4.10	4.90	5.45	6.02
0.420	25	2.48	3.12	3.70	4.45	4.95	5.50
0.500	30	2.22	2.80	3.34	4.03	4.53	5.03
0.580	35	2.02	2.55	3.06	3.67	4.14	4.62
0.670	40	1.86	2.35	2.82	3.38	3.80	4.24
0.750	45	1.73	2.18	2.62	3.14	3.53	3.93
0.830	50	1.62	2.04	2.46	2.94	3.30	3.67
0.920	55	1.53	1.92	2.32	2.77	3.10	3.45
1.00	60	1.45	1.82	2.20	2.62	2.93	3.26

Table 11: Rainfall Depths for Hypothetical Storm Events[1]

Rainfall Depths for Hypothetical Storm Events	
Storm Event	**24-Hr Depth (in)**
1-year	2.5
2-year	3.3
5-year	4.1
10-year	4.8
25-year	5.5
100-year	6.5

[1] *Stormwater Management Manual*, Volume 2, Knox County, TN, United States, January 2008, Chapter 3 Stormwater Hydrology, Accessed: January 14, 2024. [Online]. Available: https://www.knoxcounty.org/stormwater/volume2.php

APPENDIX D: MANNING'S ROUGHNESS COEFFICIENT

Table 12: Manning's Roughness Coefficients for Overland Flow[1]

Surface Description	n
Smooth surfaces (concrete, asphalt, gravel or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated soils:	
Residue cover (less than or equal to 20%)	0.06
Residue cover (greater than 20%)	0.17
Grass:	
Short grass prairie	0.15
Dense grasses	0.24
Bermuda grass	0.41
Range (natural)	0.13
Woods:	
Light underbrush	0.40
Dense underbrush	0.80

Table 13: Manning's Roughness Coefficients for Manmade Channels[2]

Description	Minimum	Normal	Maximum
Earth, straight and uniform			
Clean, recently completed	0.016	0.018	0.020
Clean, after weathering	0.018	0.022	0.025
Gravel, uniform section, clean	0.022	0.025	0.030
With short grass, few weeds	0.022	0.027	0.033
Earth, winding and sluggish			
No vegetation	0.023	0.025	0.030
Grass, some weeds	0.025	0.030	0.033
Dense weeds or aquatic plants in deep channels	0.030	0.035	0.040
Earth bottom and rubble sides	0.025	0.030	0.035
Stony bottom and weedy sides	0.025	0.035	0.045
Cobble bottom and clean sides	0.030	0.040	0.050
Channels not maintained, uncut weeds and brush			
Dense weeds as high as flow depth	0.050	0.080	0.120
Clean bottom, brush on sides	0.040	0.050	0.080
Same, highest stage of flow	0.045	0.070	0.110
Dense brush, high stage	0.800	0.100	0.140

Table 14: Manning's Roughness Coefficients for Natural Streams[2]

Description	Minimum	Normal	Maximum
Minor Streams (top width at flood stage <100 ft), Streams on Plain			
Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
Same as above, but more stones and weeds	0.030	0.035	0.040
Clean, winding, some pools and shoals	0.033	0.040	0.045
Same as above, but some weeds and stones	0.035	0.045	0.050
Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055

[1] *Stormwater Management Manual*, Volume 2, Knox County, TN, United States, January 2008, Chapter 3 Stormwater Hydrology, Accessed: January 14, 2024. [Online]. Available: https://www.knoxcounty.org/stormwater/volume2.php

[2] *Drainage Manual*, Tennessee Department of Transportation, September 7, 2021, Chapter 4 Hydrology, Accessed: January 14, 2024. [Online]. Available: https://www.tn.gov/tdot/roadway-design/design-standards/drainage-manual.html

VITA

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