Expanding the Modified Rational Method for Dissimilar Drainage Areas

by

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Abstract

The Rational Method (RM) and Modified Ration Method (MRM) are some of the most used approaches to determining peak runoff flows in urban hydrology designs. The RM gained popularity for its simplicity, requiring only easy-to-acquire hydrological properties to provide quick estimates for drainage design. Yet, in highly urbanized areas, the land use in a design area is often dissimilar, limiting the user to average the runoff coefficients and use the design rainfall duration that matches the entire design area's time of concentration (T_c). The results from such limitations often fall short compared to more sophisticated, physically based approaches and tend to provide underestimated peak flow hydrographs.

This work introduces the Discretized Modified Rational Method (DMRM), an approach that provides better estimate of runoff hydrograph for dissimilar design areas while retaining the simplicity of RM-based methods. The method is a variation of the MRM that avoids combining different drainage sub-area's runoff coefficient and T_c and instead considers individual MRM-like runoff hydrographs from each sub-area. The rainfall duration is systematically varied yielding different rainfall intensities at each minute, and the sub-areas hydrographs are assumed to drain independently toward an outfall of the drainage area. Through this heuristic search, the individual hydrographs from each sub-area are combined and the one with the peak dicharge is selected for the analysis. The DMRM peak flow hydrograph is then compared to MRM, and for the tested results DMRM have presented higher peak flows.

While a comparison between RM-based results and hydrological modeling results is difficult due to the very different nature of these tools, the hydrographs from the DMRM are compared with the ones yielded by EPA SWMM 5. To perform this comparison, the sub-areas parameters used in the DMRM examples, including CN values, were also used in the SWMM input file. In addition, the DMRM hyetograph, i.e., fixed intensity short duration rain event, was also

input in SWMM. The resulting peak flow comparison between these two averages is at 6.6%, with a maximum being 18% and a minimum of 1%, with DMRM peak flows generally similar to the ones yielded by SWMM 5, which is considered a superior tool for hydrological analysis. This can indicate the importance of considering the effects of different land uses and their abstraction and time of concentration values when applying RM-based approaches.

Table of Contents

List of Figures

List of Tables

1. Introduction

With the fast-growing population, urbanization has become a worldwide phenomenon. The urban landscape is estimated to increase by 1.2 million km^2 by 2030 (Seto et al. 2012). The resulting land use and land cover changes have amplified surface runoff in specific areas, creating new challenges for urban drainage design (da Silva et al. 2023). Thus, accurately estimating urban peak runoff is a fundamental step in designing stormwater management systems for urbanized areas to prevent urban flooding with impacts to communities and the environment. The most used tool to perform peak flow estimates is the Rational Method (RM, Mulvaney 1851). A variation of this method that accounts for the evolution of the runoff flow over time, the Modified Rational Method (Poertner 1974) is also widely used by practitioners.

The selection of a hydrological models to evaluate urban flooding risks depends on various factors, among which is included the objectives of the study, data availability, size of the drainage area, among others. In nations across the globe, various stakeholders choose approaches that provide only peak flows estimates instead of hydrological modeling tools that consider more broadly the components of the hydrological cycle (Pennington, 2012; Ball et al, 2019; Wang et al, 2018). In certain cases, this choice is motivated by lack of data, access to hydrological modeling tools and resources, ease of application, or limited time and funding to perform flooding studies (Grimaldi & Petroselli, 2015; Vasconcelos et al, 2023). Thus, in the foreseeable future, simpler approaches that provide only peak flow estimates will continue to be used by practitioners, and research to improve such applications is thus needed.

This Introduction chapter is structured as follows: first, the current approaches to represent rainfall in urban hydrological modeling is presented. The second section describes the methods to quantify abstractions in urban watersheds. The following section describes the different hydrological tools to compute peak flows and hydrographs in urban watersheds. The chapter ends with a description of hydrological modeling goals and the motivation for this thesis.

1.1. Approaches to represent rainfall in urban hydrological studies

1.1.1. Field rainfall measurements

Rainfall can be field recorded with the use of sensors deployed on watersheds. During a rain event, precipitation can be measured in terms of intensity and total precipitation with the use of rain gauges. A rain gauge can be as simple as a tubular glass container that requires the user to record the depth manually or an electronic device with a tipping bucket that records the data automatically (Figure 1).

Figure 1: A rain gauge with a tipping bucket.

The intensity measurement is reported in precipitation depth over a period, often reported as inches per minute or per hour (in/min or in/hr), millimeters per minute or hour (mm/min or mm/hr). Depending on the sensor used, depth of rainfall or its intensity can be reported in different time intervals, for example, 5-minutes, 15-minute intensity (i_{15m}) and 24-hour intensity (i_{24h}). As illustrated in Figures 2 and 3, the rain event is represented as the total precipitation depth accumulated during a fixed time interval or the intensity of rainfall over time as a function of time.

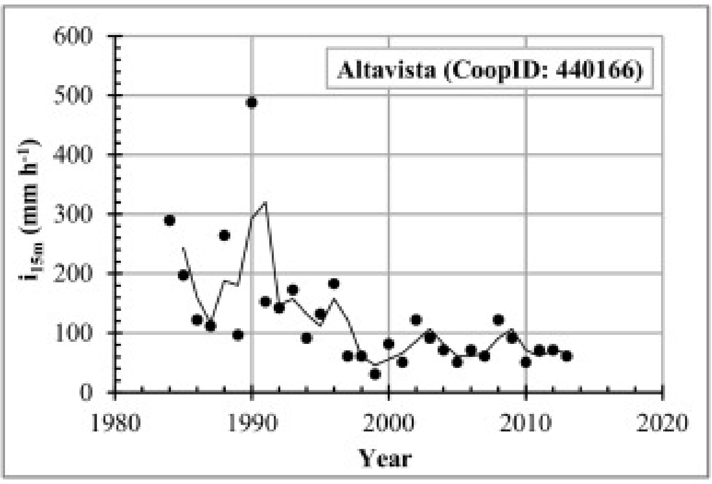


Figure 2: An example annual maximum intensity at 15-minute intervals Altavista, Virginia (Yang et al., 2021)

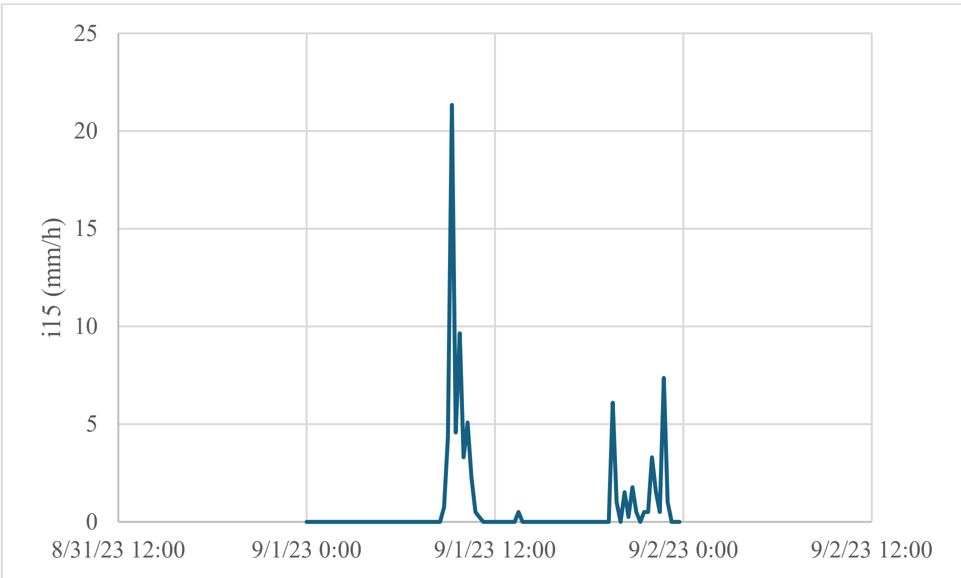


Figure 3: 15-minute rainfall intensity collected from rain gage (South Alabama Mesonet, http://chiliweb.southalabama.edu/)

The record of previous rain events is often used in urban hydrological studies, typically within hydrological models that can use actual hyetographs as input data. These datasets are obtained from independent field measurements or reputable sources, such as the National Weather Service (NWS, https://www.weather.gov/marfc/DailyPrecipitation) and NRCS National Water and Climate Center (NWCC, https://www.nrcs.usda.gov/programs-initiatives/sswsf-snow-survey-and-water-supply-forecasting-program/national-water-and).

Although actual rainfall represents real-life data and is key for hydrological modeling tools, it is not often feasible in many locations across the globe due to limited availability of records. When detailed rainfall data is available in a specific location, this data can be used in hydrological mode to evaluate the performance of the drainage system subjected to extreme rain events (Hassan et al 2024). This information in turn can be used in the design of new stormwater systems or retrofit of existing drainage infrastructure. Alternatively, data corresponding to intense rain events and useful for design purposes can be derived from long-term rainfall data gathered at a given region. This data can be expressed in terms of synthetic rainfall distributions (NRCS 1986, Huff 1967) or through intensity-duration-frequency curves that are applicable in a certain region (Al-Wagdany 2021). These other two approaches are discussed in the next sections.

1.1.2. Design rainfall with synthetic hyetographs

The synthetic rainfall hyetograph is a method to represent the design storm often used in hydrological studies, including stormwater system design (NRCS 1986, City of Birmingham 2019)

A synthetic hyetograph represents the time distribution relations for storm events and is created by analysis of observed storm events. One major difference between the synthetic hyetograph and the observed storm is that the synthetic hyetographs have smooth curves reflecting average rainfall distribution, while the observed storm does not exhibit a smooth and gradual change of intensity and often has burst characteristics.

NRCS originally designed four types of 24-hour hyetographs: Type I, IA, II, and III. Those types represent the rain distribution in different geographic locations within the United States.

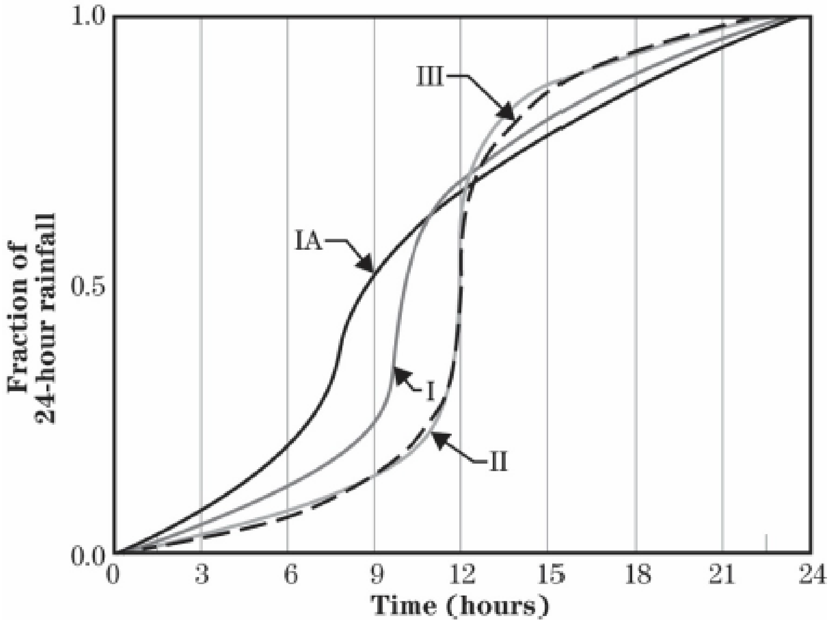


Figure 4: Plots of Type I, IA, II, and III synthetic hyetographs for 24-hour duration events (NRCS, 1986)

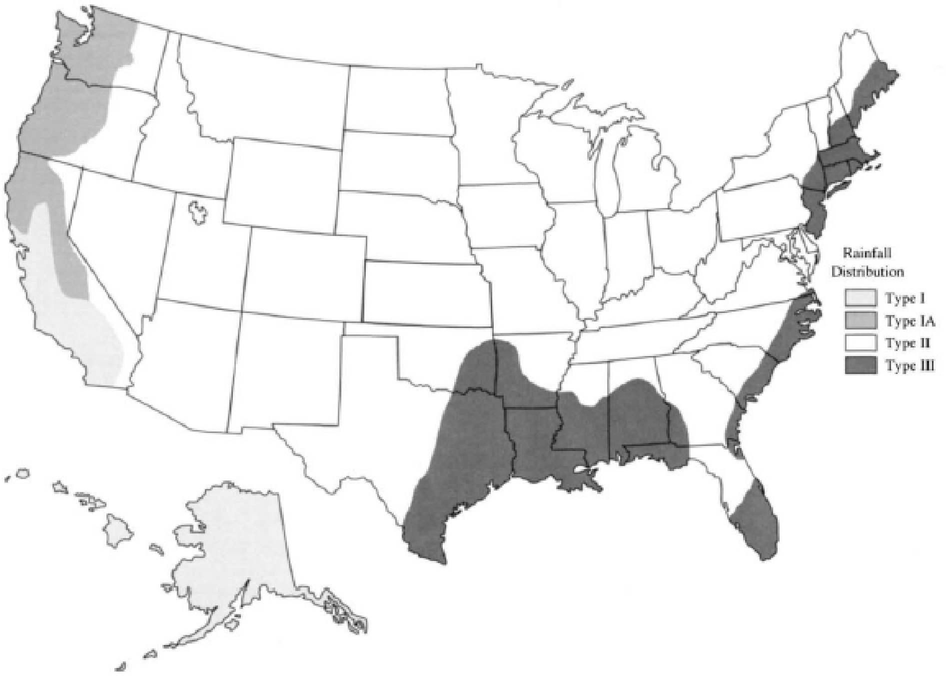


Figure 5: Location for application of the NRCS synthetic hyetographs (NRCS, 1986)

Table 1: Ratios to 24-hour Rainfall for Type II Distribution

Duration	Ratio to 24-hour rainfall
5 Minutes	0.114
10 Minutes	0.201
15 Minutes	0.270
30 Minutes	0.380
1 Hour	0.454
2 Hours	0.538
3 Hours	0.595
6 Hours	0.707
12 Hours	0.841
24 Hours	1.000

The Type I and IA distributions are for the Pacific maritime climate, Type III is for the Gulf of Mexico and Atlantic coastal areas, and Type II is for most parts of the central continental United States. Those hyetographs were derived from the information presented by Hershfield (1961) and Miller, Frederick, and Tracey (1973).

The NOAA Atlas 14 (https://hdsc.nws.noaa.gov/pfds/) has been completed for the Southwest States, California, Ohio Valley, and adjacent States, the Midwest, and the Southeast States. The WNTSC (West National Technology Support Center) National Water Quality and Quantity Team developed updated distributions for those states for use in future projects.

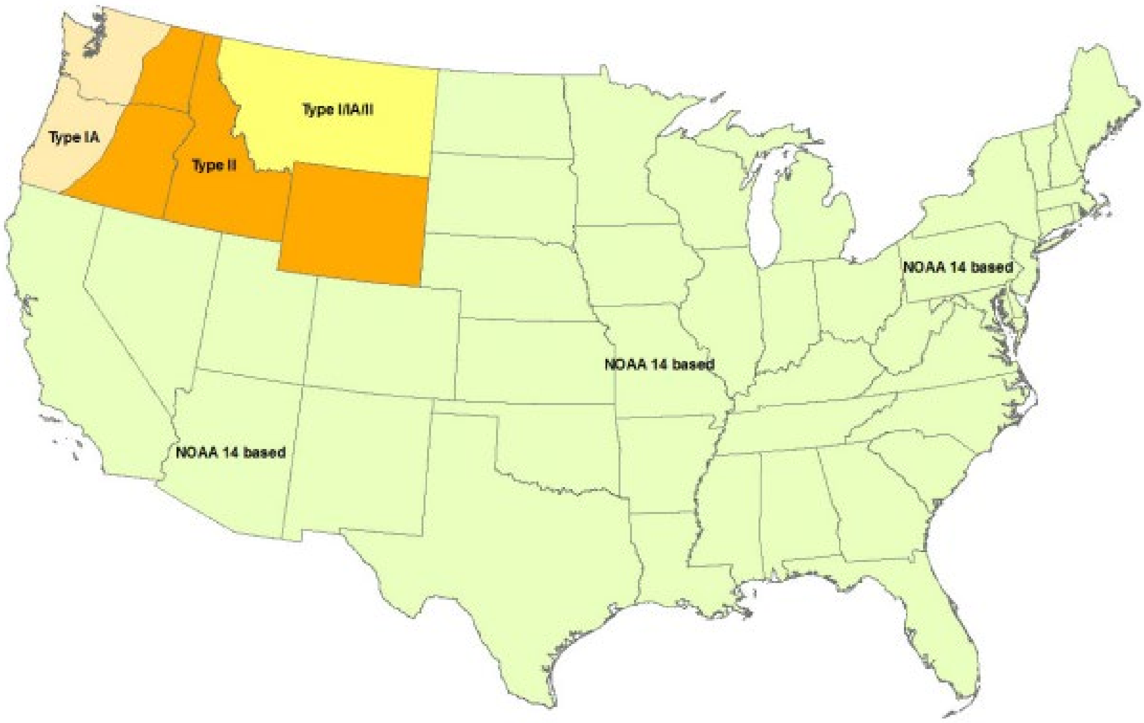


Figure 6: States with updated synthetic hydrographs as of Jan 2016 (USDA, 2019)

1.1.3. Intensity-Duration-Frequency (IDF) curve approach

An intensity-duration-frequency curve is the approach used in RM and MRM-based methods. The IDF curve is a statistical approach to describe the probability that a given average rainfall intensity will occur within a given period.

The IDF curve's construction involves utilizing long-term historical rainfall data. The maximum rainfall intensity at different time intervals for each year is obtained using the annual maxima method. The rainfall intensity for each duration and return period is then calculated using a distribution function, e.g., Gumbel, Long-Pearson III. Those data are fitted to an IDF curve using mathematical approaches, e.g., Sherman (1931) and Chow (1962).

For this work, the IDF curve is represented using Sherman’s formula:

$$I = \frac{B}{(T + D)^E}$$ Equation 1.1

Where:

I is the rain intensity (in./hr or mm/hr), T is rainfall duration time (minutes), and B, D, and E are local IDF curve parameters. On an IDF curve, the rain intensity peaks at the start and gradually decreases as the rain duration increases. When applied to RM and MRM, this results in the peak flow of an area decreasing as the T_c increases.

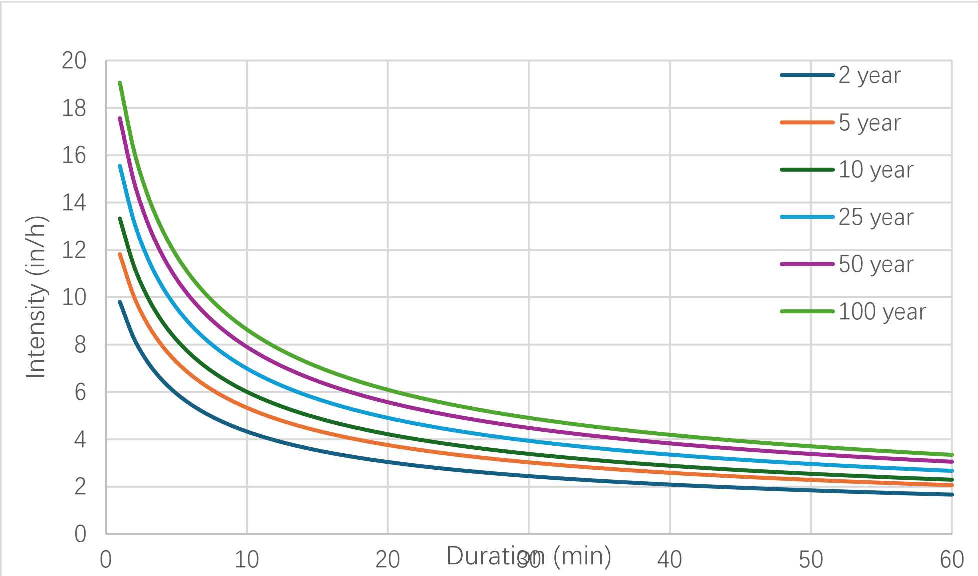


Figure 7: IDF curves for Opelika, AL (NOAA Atlas 14, 2013)

1.2. Abstractions in urban watersheds

1.2.1. Evapotranspiration in urban watersheds

Evapotranspiration (ET) describes the process of changing the water phase from solid (ice) or liquid (water) to water vapor. Its two components are open/Intercepted water evaporation and vegetation transpiration. The Penman-Monteith equation is one of the most used methods to calculate ET.

In urban watersheds, ET was once considered negligible compared to ET in neighboring rural areas because of the hydrological properties of buildings and natural underlying covers (Chandler, 1976). Thus, urban ET was often ignored or estimated empirically in many urban hydrologic studies. However, some studies show that urban ET, especially in lakes and parks, contributes to a larger magnitude of urban water balance than commercial districts and dense human settlements (Xinhao et al. 2022). With more cities adapting to green infrastructures, urban ET is becoming an important part of extended hydrological simulations. However, in this work, the simulation is event-based (e.g., rainfall within one hour), and the study is conducted in a small drainage area in which lakes or ponds are unlikely to be present. These factors limit the magnitude of the ET, as ET is influenced by the high humidity during the rain as well as the size of the catchment. Therefore, ET was not considered significant in the development of this methodology.

1.2.2. Approaches to represent infiltration in urban watersheds

Infiltration is the movement of water from the soil surface into the soil. For more developed or degraded land cover types, water typically infiltrates the soil or forms an overland flow in a rain event, moving quickly toward a stream channel. Compared to overland flow, infiltrated water will either move slowly to the surface water system, be retained in the soil, and eventually return to the vapor phase through the process of evapotranspiration or become groundwater recharge (Chow, 1988; Bedient, 2013)

Infiltration is an essential part of the rainfall hydrologic response. Many approaches were created for its calculation and are adapted in many physical-based and semi-empirical models. Within the context of hydrological modeling, the process of infiltration can be under the condition of either no surficial water ponding, saturation from above, or saturation from below (Dingman, 2015). For no ponding conditions, the water input rate is equal to the infiltration rate and is less or equal to the infiltrability. For saturation from above, the water input rate exceeds infiltrability, and the infiltration rate is equal to infiltrability. For saturation from below, the infiltration rate and infiltrability become zero.

Different mathematical formulations have been proposed to represent time-varying infiltration processes, and these are also often built in hydrological models. One method is the Green-Ampt equation, from 1911:

$$F(t) = Kt + \psi\Delta\theta ln\left[1 + \frac{F(t)}{\psi\Delta\theta}\right] \qquad \text{Equation 1.2}$$

Where:

$F(t)$ is the cumulative depth of infiltration, L, K is hydraulic conductivity, L/T, ψ is the wetting front soil suction head, L, and θ is water content, unitless.

Another traditional method to compute is the empirically based Horton equation, proposed in 1933:

$$f_t = f_c + (f_0 - f_c)e^{-kt} \qquad \text{Equation 1.3}$$

Where:

f_t is the infiltration capacity rate at time t, f_c is the constant infiltration rate after the soil has been saturated or the minimum infiltration rate, f_0 is the initial infiltration rate or maximum infiltration rate, k is the decay constant specific to the soil.

1.2.3. Approach to represent lumped abstractions in urban watersheds

In the RM-based approaches, abstractions are combined in an empirical method rather than being represented individually. These methods introduce a runoff coefficient to represent the lumped abstractions in rain events. Runoff coefficient is a dimensionless value that can be defined as the ratio of total runoff depth to total precipitation depth (Rv) or the peak runoff rate to rainfall intensity at t_c (C) (Wanielista & Yousef, 1993). Kuichling (1889) originally concluded that the percentage runoff to rainfall is nearly equal to the percentage impervious to pervious surface of the watershed, which means C=0 for a strictly pervious surface and C = 1 for a strictly impervious surface. Yet, the estimation of C is difficult to be made precisely and often depends heavily on the engineering judgment. The typical C values listed for different land uses and land cover (LCLU) today were derived from the sanitary and storm sewer design manual (ASCE & WPCF, 1960). Those values in the manual were obtained from 71 returns of a survey submitted to 380 public and private organizations. Table 2 presents values of runoff coefficients according to land use classification types present in the National Land Cover Database (2001).

Table 2: Runoff Coefficients for various land use (NLCD, 2001)

NLCD classification	NLCD classification description	C	Land use or description in the source
21	Developed, Open Space	0.4	Residential: Single-family areas (0.3-0.5)
22	Developed, Low Intensity	0.55	50% of area impervious (0.55)
23	Developed, Medium Intensity	0.65	70% of area impervious (0.65)
24	Developed, High Intensity	0.83	Business: downtown areas (0.7-0.95)
31	Barren Land	0.3	Sand or sandy loam soil, 0-5% (0.15-0.25); black or loessial soil, 0-5% (0.18-0.3); heavy clay soils; shallow soils over bedrock: pasture (0.45)
41	Deciduous Forest	0.52	Deciduous forest (Tennessee) (0.52)
42	Evergreen Forest	0.48	Forest (UK) (0.28-0.68); Forest (Germany) (0.33-0.59)
43	Mixed Forest	0.48	Forest (UK) (0.28-0.68); Forest (Germany) (0.33-0.59)
52	Shrub/Scrub	0.3	Woodland, sandy and gravel soils (0.1); loam soils (0.3); heavy clay soils (0.4); shallow soil on rock (0.4)
71	Grassland/Herbaceous	0.22	Pasture, grazing HSG A (0.1); HSG B (0.2); HSG C (0.25); HSG D (0.3)
81	Pasture/Hay	0.35	Pasturem sandy and gravel soils (0.15); loam soils (0.35); heavy clay soils (0.45); shallow soil on rock (0.45)
82	Cultivated Crops	0.4	Cultivated, sandy and gravel soils (0.2); loam soils (0.4); heavy clay soils (0.5); shallow soil on rock (0.5)

For a drainage area with multiple sub-areas, a composite C can be estimated as an area weightaverage (TxDOT, 2002):

$$C = \frac{\sum_{i=1}^{n} C_i A_i}{\sum_{i=1}^{n} A_i} \qquad \text{Equation 1.4}$$

where, i = ith sub-area, n = total number of sub-areas in the watershed, C_i = runoff coefficient for ith sub-areas, and A_i = area of ith sub-areas. Aside from estimating C based on LCLU, C can be computed from the average runoff depth to total rainfall depth ratio for individual storm events (Merz et al. 2006; Nirajan, 2012).

$$C = \frac{R}{P} \qquad \text{Equation 1.5}$$

Where, R= total runoff and P= total rainfall

1.3. Calculating runoff generation in urban areas

Hydrological tools for runoff and peak flow estimation can be classified in this thesis into three categories: physically based, semi-empirical, and lumped approaches. Physically based models imply fully and semi-distributed models that use equations based on realistic hydrologic processes (Julien and Saghafian, 1991; Sitterson et al. 2017; Vasconcelos et al. 2023). Semi-empirical models use simplified equations and physical processes to represent the hydrology in sub-catchments, and are designed to represent event-based hydrology. Lumped approaches are those that do simplify all processes of rainfall, abstraction, and surface flow markedly simplifying the processes of water flow.

1.3.1. Physically based approaches

Physically based approaches use models derived from mathematical models that describe specific processes such as rainfall, abstractions, infiltration, overland flow, etc. The spatial heterogeneity within the area is accounted for by dividing the larger area into smaller spatial units with similar characteristics. Depending on how spatial units are divided, they can be further classified into fully distributed and semi-distributed. Fully distributed models utilize gridded-based division that divides the area into the smallest spatial units regularly distributed in space (Vasconcelos et al. 2023). The area within each grid is small enough to consider that hydrological parameters within are homogeneous. An example of a fully distributed model is GSSHA (USACE 2006) which is capable of simulating processes with dissimilar time scales and tracking water fluxes between hydrological components. GSSHA's formulation includes precipitation and snowfall accumulation, an abstraction that includes interception, overland soil retention and infiltration, overland flow routing and channel routing (2D), reservoirs and lake storage, vadose zone moisture, and 2D averaged lateral groundwater flow and surface/groundwater interaction.

Semi-distributed models use sub-catchment-based division, which divides the watershed into smaller subareas. The hydrological parameters are averaged in each subarea. An example is the Storm Water Management Model (SWMM) by the U.S. EPA, which is later discussed in section 3.5. Other models that are in this category include HEC-HMS (USACE 2024) and Infoworks ICM (Autodesk 2024)

1.3.2. Semi-empirical

Semi-empirical models use simplified equations to represent water balance in catchments. One widely used simplified rainfall-runoff theory is the unit hydrograph (UH), which is the basin outflow resulting from 1.0 inch (1.0 mm) of direct runoff generated uniformly over the drainage area at a uniform rainfall rate during a specified rainfall duration (Sherman, 1932). UH assumes the hydrologic system is linear and time-invariant (Dooge, 1959), which enables complex storm hydrographs to be produced by adding up individual unit hydrographs, adjusting for rainfall volumes, and adding lag in time. The process of creating this storm hydrograph is the unit hydrograph convolution:

$$Q_n = P_n U_1 + P_{n-1} U_2 + P_{n-2} U_3 + \cdots + P_1 U_j \qquad \text{Equation 1.6}$$

Where:

Q_n= storm hydrograph ordinate, P_n= rainfall excess, U_j= unit hydrograph ordinate.

1.3.3. Lumped approaches

Lumped approaches describe complex hydrological processes using simplified approaches that lump the spatial variability and physical processes into fewer parameters. One of the most used lumped methods is the Rational Method, which is focused on the present thesis. It uses the longest time of concentration among all drainage sub-areas and then applies this well-known equation:

$$Q = C \cdot i \cdot A \qquad \text{Equation 1.7}$$

Where:

Q is the peak runoff, cfs, C is the runoff coefficient, unitless, i is the rain intensity, in/h, and A is the total watershed area, acre. The rainfall intensity is derived from Intensity-Duration-Frequency curves, in which it is assumed that the intensity decreases with the rainfall duration, and increases with the recurrence interval used in the hydrological study. The rainfall duration is selected to match the time of concentration T_c of the drainage area, and examples for this calculation are provided in various sources, including NRCS (2010).

Compared to other physically based or semi-empirical models, this method is the simplest to use, which is indicated in the worldwide application of the method. It is estimated in the Unite States, 98% of the hydrological modeling practices make direct reference to the rational method(Vasconcelos et al. 2023). It yields a quick estimate of peak runoff flows while only requiring relatively very little information from the analyst. However, this method traditionally assumes that the worst cases for peak runoff flow rate are anticipated when the entire area contributes toward the runoff generation, which means to equal the rainfall time duration to the time of concentration.

Bedient and Huber (2001), in his book Hydrology and Floodplain Analysis, stated that directly connected impervious areas (DCIA) or other land uses with a high runoff coefficient that are part of a larger catchment may contribute a higher peak flow by themselves than the whole catchment. He suggested that an additional calculation on DCIA's peak flow is necessary for such conditions to confirm that either DCIA or the entire area contributed to the worst peak flow.

$$Q = C_{DCIA} \cdot i \cdot A_{DCIA} \qquad \text{Equation 1.8}$$

Where:

C_{DCIA} is the runoff coefficient of DCIA, i is the rain intensity, and A_{DCIA} is the total area of DCIAHowever, in the book examples, only the runoff from DCIA is considered alongside with a higher rainfall intensity and smaller T_c. As a result, T_c the partial contributions of pervious areas are not considered toward the peak flow.

The Oregon Department of Transportation Hydraulic Design Manual (ODOT 2014) Section 7F 3.0 Discharges at Junctions also stated that in some instances, the peak discharge can occur when the storm duration corresponds to the T_c with a shorter time of concentration. It is recommended that the total discharge at the Tc of each tributary be calculated and compared.

For example, if Tributary n has the longest T_c, at T_{cn}:

$$Q_A = (C_f)(C_A)(i_n)(A_A) \qquad \text{Equation 1.9}$$

$$Q_B = \left(C_f\right)(C_B)(i_n)(A_B) \qquad \text{Equation 1.10}$$

$$Q_n = (C_f)(C_n)(i_n)(A_n) \qquad \text{Equation 1.11}$$

Where: Q_n is the discharge of tributary n, C_f is the adjustment factor for the design return period, C_n is the runoff coefficient of tributary n, i_n is the rain intensity at T_{cn}, A_n is the area of tributary n.

If a Tributary's T_c is longer than T_{cn} then only a portion of the drainage of that tributary will contribute to runoff. For example, if Tributary A has a longer T_c than Tributary n, at T_{cn}:

$$Q_A = (C_f)(C_A)(i_n)(\frac{T_{cn}}{T_A})(A_A) \qquad \text{Equation 1.12}$$

The combined Q_{total} at T_{cn} is:

$$Q_{total} = \sum_{i=1}^{n} Q_i \qquad \text{Equation 1.13}$$

Ponce(2014) also used the method of searching through the total discharge at each sub-areas Tc to determine the peak discharge, similar to the ODOT method. Apart from Bedient's method, this method accounts for the partial contribution for areas where T_c is unmet.

1.4. Stormwater design goals in urban areas

The above approaches and tools are typically used for stormwater-related analyses and designs. Depending on the design and the scope of work, it is essential to choose the tools that best suit the application. Below are some examples demonstrating different design goals vs. tools selected.

- Physically based models, such as SWMM 5, HEC-HMS, and GSSHA, have the advantage of yielding a more realistic water balance and being capable of performing the extended-period analysis (Vasconcelos et al. 2023); the results from those modeling tools can often be coupled with geospatial tools to provide a visualized result for a wider audience. These characteristics make it ideal for performing chronic flooding analysis in large watersheds. Many studies have made use of these tools to assess the flood risk or as a benchmark for other newly developed flood plan methods: Mapping flood risk in Wadi Al-Lith Basin, Saudi Arabia with HEC-RAS (Ibrahim H. et al. 2023) and Modeling Storm Sewer Networks and Urban Flooding in Roanoke, Virginia with SWMM and GSSHA (Conrad E. et al. 2020). Although physically based models can often provide more realistic and accurate results, they also require a large amount of input and calibration to represent the physical process.
- Semi-empirical models are a more efficient option for works that do not require a long simulation period or groundwater components that are not important. For example, using WinTR-55 for channel designs that require estimating peak discharge and runoff hydrographs.
- When peak runoff is the chief goal of a hydrological study of smaller urban drainage areas so that conveyances, such as culverts and smaller channels can be sized, lumped approaches are the fastest option. The typical Rational Method application uses Equation 1.7 for the calculation of peak flow, lumping the entire drainage area runoff coefficient C with Equation 1.4 and applying the longest T_c value. The MRM approach uses the same peak flow but assumes that the drainage area runoff grows linearly until the drainage area T_c value is reached. The lumped approaches by ODOT (2014) and Ponce (2014) consider how dissimilar drainage sub-areas should have their

contributions calculated in separate. This is similar to the DCIA approach by Bedient and Huber (2001) but considers partial contributions from pervious areas. Flow may not be justifiable. Yet, the generation of hydrographs from dissimilar sub-catchments was not explored, and the only existing approach lumps dissimilar sub-areas. The effect of applying the concept of these time-growing contributions of runoff along the lines of ODOT (2014) and Ponce (2014) and generating hydrographs that account for the dissimilarity in the design area has not been explored and consists of an open research question addressed in this work.

1.5. Summary

Among various hydrological tools to study urban watersheds, the RM is the simplest and among the most widely adopted. Yet, it combines dissimilar drainage sub-areas using composite C and the largest T_c in the drainage area, which may lead to underestimated peak flows. Moreover, the derivation of MRM-like growing hydrographs considering dissimilar drainage sub-areas has not been explored. It is assumed that the design practice of drainage systems could be improved with the separation of such sub-areas. This thesis explores the idea that peak flow may happen before all drainage sub-areas reach their T_c and provides a generalized approach for this situation to compute more representative runoff hydrograph similar to a hydrological model, yet retaining the simplicity of the Rational Method.

2. Objectives

This work aims to expand upon the Modified Rational Method to address the proposed research question of estimating peak runoff discharge using the Rational Method in a drainage area consisting of several dissimilar drainage sub-areas. Specifically, this study outlines and details the development of the Excel-based of Discretized Modified Rational Method (DMRM) tool, with the following main characteristics:

- Computation of the time of concentration for each individual drainage sub-area and application of MRM concepts
- Systematic variation of rainfall duration and computation of MRM hydrographs for each dissimilar sub-area at each minute.
- Combination of all sub-area hydrographs and search for the duration that yields the highest peak runoff value, linked to the critical rainfall duration. For that critical rainfall duration, derivation of the entire hydrographs.
- Benchmark this resulting hydrograph with the results from a semi-distributed hydrological model through a seamless integration between Excel and SWMM 5.

3. Methodology

As stated in the Objectives chapter, this thesis deals with a common situation in the determination of peak flows estimates: the existence of different land use types within the same drainage design area. These different land uses are represented as independent drainage sub-areas in the Discrete Modified Rational Method. The DMRM uses key assumptions from both RM and MRM, including:

1. The design storm has a fixed intensity which depends on the return period and the rainfall duration D, and it can be obtained from IDF curves.
2. There are a linear concentration of runoff flows within a given drainage sub-area with time.
3. This runoff flow increases due to concentration occurs until the sub-area time of concentration T_c is achieved.

However, there are some assumptions on the traditional implementation of RM and MRM that are not adopted in the DMRM approach:

1. The most critical rainfall duration D does not match the largest time of concentration among the drainage sub-areas. As a result, the most critical rainfall duration can occur when not the entire drainage area is contributing to the runoff generation.
2. A composite runoff coefficient, calculated with Equation 1.4, is representative of the most conservative peak flow estimates.

In addition, DMRM introduces additional assumptions that are not included in the original RM or MRM approaches:

1. The runoff concentration within each drainage sub-area depends on the local T_c and is not influenced by the concentration of a different sub-area with different land use.
2. Each drainage sub-area drains independently to the design area outlet. In other words, after the overland flow is completed in a drainage sub-area, these inflows reach the drainage outlet without interfering with another sub-area overland flow.
3. The most relevant mechanism for the computation of a sub-area time of concentration is the sheet flow. This means that the time associated with shallow concentrated, or channel flows are considered much smaller and thus neglected.

The most important implication of the DMRM assumptions is that the critical duration of rainfall duration that yields the largest peak flow is unknown because the rate and the magnitude of runoff concentration within sub-areas varies. The proposed Discretized Modified Rational Method (DMRM) applies these assumptions to systematically derive runoff hydrographs from drainage areas with non-uniformity in their land use. The DMRM varies the duration of the design storm and its corresponding rainfall intensity, resulting in multiple hydrographs of each drainage sub-area for different rain durations and rainfall intensity. Hydrographs of the same duration are then combined to create hydrographs for the whole drainage area of varying duration. The method then searches for the storm duration that yields the highest peak flow, computing the associated combined hydrograph and the runoff volume.

To attain this goal, the following key steps needs to be performed:

1. Sub-division of the drainage area according to the land use, slope, and any other criteria that the analyst deems relevant.
2. Computation of T_c of each one of these sub-areas.
3. Systematically varying the rainfall duration and applying the corresponding intensity to all sub-areas, deriving hydrographs to each one of them, similarly to what is done in the MRM.
4. Combine all individual sub-areas hydrographs into total runoff hydrographs, determining the peak flow and calculating the runoff volume.
5. Determine the critical rainfall durations by selecting the largest runoff peak flow, and the largest runoff volume.

The subsequent sections of the methodology present these steps that are required for the DMRM in detail.

3.1 Sub-areas division

One key difference between DMRM and MRM is that it breaks down the whole drainage area into several small sub-areas and independently applies MRM calculation steps to those individual sub-areas. Because the MRM only calculates using the average of the whole sub-areas, those sub-areas must have similar properties within their corresponding areas. Here, the sub-areas were divided considering the two main characteristics:

- Morphology and roughness characteristics: Area, surface slope, Manning roughness, and flow path length.

- Runoff generation parameters. Sub-area runoff coefficient (C) and the curve number (CN) of the sub-area.

Figure 8 represents an example of sub-area division of a football field, in which the different colors correspond to different sub-areas in the whole drainage area, located in the south of the figure near the south edge of sub-area 5. Areas 1, 2, and 4 correspond to pervious area, whereas areas 3 and 5 correspond to paved areas. These areas were separated according with the different flow path lengths, slopes and roughness. The DMRM and the MRM are applied to this area in Chapter 4, Results.

Figure 8: Site division of sub-areas. All runoff is conveyed to the rectangular detention facility in the south edge of the drainage area.

3.2 Time of concentration calculation

Each sub-area needs to have its own time of concentration T_c computed for DMRM. In a traditional MRM application, the largest T_c would be adopted and the rainfall duration D would match this T_c. However, for the DMRM, the T_c is computed for each area so that sets of hydrographs for each sub-area can be derived. Whereas there are several different approaches to compute T_c, only two methods are considered in this thesis: The Lag Method and the Velocity Method (NRCS 2010) for overland flows.

3.2.1. Lag Method

One method used for T_c computation is the Lag Method developed by Mockus (1961), which is suited for a wide range of conditions to determine the time of concentration. Lag (L) is the delay between the runoff beginning and the time runoff reaches maximum. Research (Mockus 1957; Simas 1996) shows that the watershed Lag under average natural watershed conditions is approximately $0.6T_c$. Thus, the time of concentration is obtained by multiplying the SCS method for lag by 0.6.

The computation process is represented in Equation 3.1.

$$T_c = \frac{l^{0.8}(S+1)^{0.7}}{1140Y^{0.5}} \qquad \text{Equation 3.1}$$

Where:

T_c is the time of concentration, h. L is the flow length, ft. Y is the average watershed land slope, %. S is the maximum potential retention, in, $S = \frac{1000}{cn\prime} - 10$ and cn is the retardance factor. Because the retardance factor is approximately the same as the curve number (NRCS, 2010), CN was used instead of the retardance factor in calculating maximum potential retention. Flow length L in the lag method is defined as the longest path where water flows from the sub-area to the sub-area outlet. The land slope used in the above equation is the average land slope of the sub-area and not the slope of the longest flow path.

3.2.2. Velocity Method

The other method of T_c is the Velocity Method developed by Welle and Woodward (1986). This method assumes that the time of concentration is the summation of the flow path segments' travel time. These segments consist of three types of flow: sheet flow, shallow concentrated flow, and open channel flow. Compared to sheet flow, shallow concentrated and open channel flow travel time is much shorter, thus neglected for simplicity. The time of concentration is calculated using only the sheet flow component, represented in equation 3.2.

$$T_c = \frac{0.007(nl)^{0.8}}{(P_2)^{0.5}S^{0.4}} \qquad \text{Equation 3.2}$$

Where:

n is Manning's roughness coefficient, l is the sheet flow length, ft, P_2 is the 2-year, 24-hour rainfall, in, and S is the slope of the land surface, ft/ft. If a drainage sub-area has both pervious and impervious fractions, the Manning roughness coefficient that is relevant for the analysis is corresponding to the pervious areas. This is the case because the roughness for impervious areas is much lower than the corresponding value pervious areas, and thus does not control T_c.

For better estimation, the sheet flow length is limited to equation 3.3 (McCuen and Spiess 1995):

$$l_s = \frac{100\sqrt{S}}{n} \qquad \text{Equation 3.3}$$

Where:

l_s = limiting length of flow, ft, n is Manning's roughness coefficient.

For many cases, the kinematic method will give a slightly shorter time of concentration compared to the lag method. Table 3 represents the T_c computed with Lag and Kinematic Method for three different areas.

Table 3: Examples of resulting T_c values from the Lag and Velocity methods for the sub-areas presented in Figure 8:

Area (Acres)	**Runoff Coefficient**	**Slope**	**CN**	**Manning n pervious**	**Relevant flow length (ft)**	**T_c Lag (min)**	**T_c Kin (min)**
5.23	0.18	0.198	69	0.4	598	6	12
4.41	0.1	0.01	61	0.15	552	33	12
0.89	0.96	0.01	98	0.011	120	3	2
2.23	0.1	0.01	61	0.15	486	30	12
0.36	0.96	0.03	98	0.011	650	6	6

3.3. Rain intensity

As discussed in the Introduction, there are various critical rainfall approaches depending on the engineering application and data availability. For example:

- Actual extreme events

- Synthetic hyetographs (e.g., NRCS 1986)
- IDF curves

The selection of these approaches depends on the actual engineering needs and data availability.

Like the RM and MRM, DMRM also uses the IDF curves for computing rainfall intensity. The rain intensity (I) depends on the rain duration (D). The values for D are systematically varied, applied to each drainage sub-area, and the resulting hydrographs derived and combined. There are various forms to express IDF curves, and for the tool developed in the context of the thesis, the formulation by Sherman (1931) was adopted.

$$I = \frac{B}{(D + E)^F} \qquad \text{Equation 3.4}$$

Where:

I is the rain intensity, in, D is the rainfall duration, minute and B, E, and F are local IDF curve parameters. As an example, IDF parameters B, E, and F for the drainage area in Figure 8 (i.e., Birmingham, AL) is shown in Table 4:

Table 4: IDF parameters for Birmingham, AL

Return Period (years)	B	E	F
2	1471.75	22.51	1.68
5	1406.23	26.93	1.55
10	653.11	24.17	1.34
25	422.73	22.56	1.19
50	364.31	21.89	1.12
100	115.52	12.91	0.84

3.4 Sub-area hydrograph calculation with MRM

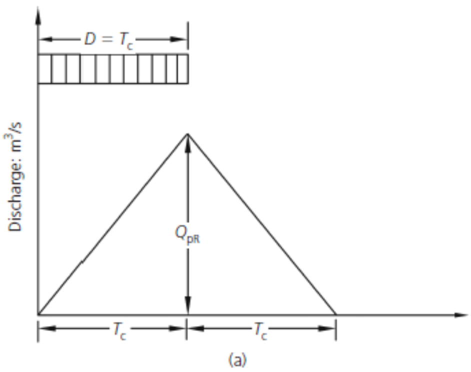
As explained earlier, the Modified Rational Method is an extension to the Rational Method that approximates a direct runoff hydrograph by creating either a triangular or trapezoidal-shaped hydrograph depending on rain duration (D) and the time of concentration T_c (Poertner (1974). According with the D and T_c values, there are three possible types of hydrographs as shown in Figure 9:

1. When D is equal to T_c (case a), the resulting hydrograph is triangular, with its peak flow

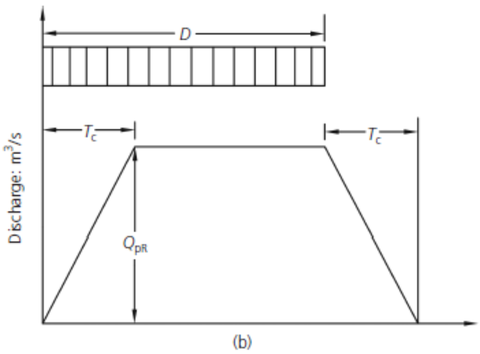
Q_{Pr}= C·I·A at t=D=T_c. The runoff flow rate increases and decreases linearly from and to 0 over a total time equal to twice the T_c of the drainage area or sub-area.

2. When D is longer than T_c (case b), the resulting hydrograph is of trapezoidal shape, with its peak flow Q_{pR}= C·I·A at t=T_c. The rainfall intensity derived from the IDF curve is not corresponding to T_c but with the rainfall duration D. The discharge value increases from 0 to Q_{pR} linearly and stay at its maximum until the rain stops (t=D), then decreases to 0 at t=T_c+D
3. When D is shorter than T_c (case c), the resulting hydrograph is of trapezoidal shape, with its peak flow Q_{pD}= C·I·A·(T_c/D) at t=D. The rainfall intensity derived from the IDF curve is not corresponding to T_c but with the rainfall duration D. The discharge value increases from 0 to Q_{pD} linearly and stays at its maximum until the time of concentration is reached (t=T_c), then decreases to 0 at t=T_c+D

(a)



(b)



(c)

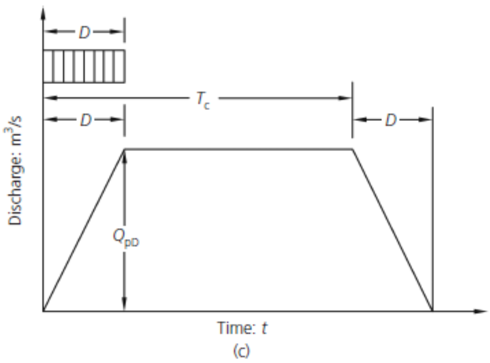


Figure 9: Types of hydrographs computed by the Modified Rational Method according to the rainfall duration D and the drainage area T_c (Dhakal et al., 2013)

To determine the worst-case scenario for the combined runoff from all drainage sub-areas, the MRM hydrograph was calculated from D=1 min to D=60 min at 1-minute interval. This creates 60 hydrographs for each sub-area. Then the runoff from each hydrograph is added up to create a hydrograph for the whole drainage area. For example, let's consider three sub-areas with time of concentrations equal to 5, 20 and 9 minutes. If the MRM hydrographs are generated for the rainfall duration D equal to 10 minutes, the result will be as presented in Figure 10. The DMRM approach will create a combined hydrograph by summing the individual components of these three hydrographs as indicated in Equation 3.5.

$$Q(10) = Q_1(10) + Q_2(10) + Q_3(10) \qquad \text{Equation 3.5}$$

By varying the rainfall duration D it is possible to determine which value will result in the maximum peak flow from the summation of all individual sub-areas hydrographs.

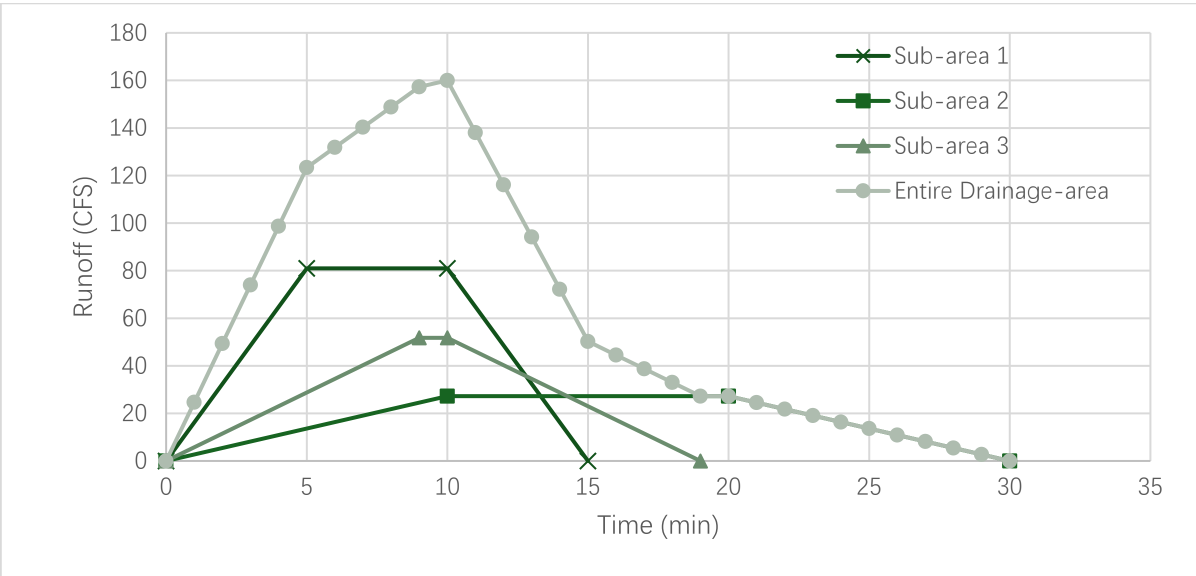


Figure 10: An example of combining MRM's hydrographs for a 10-minute duration of rainfall event.

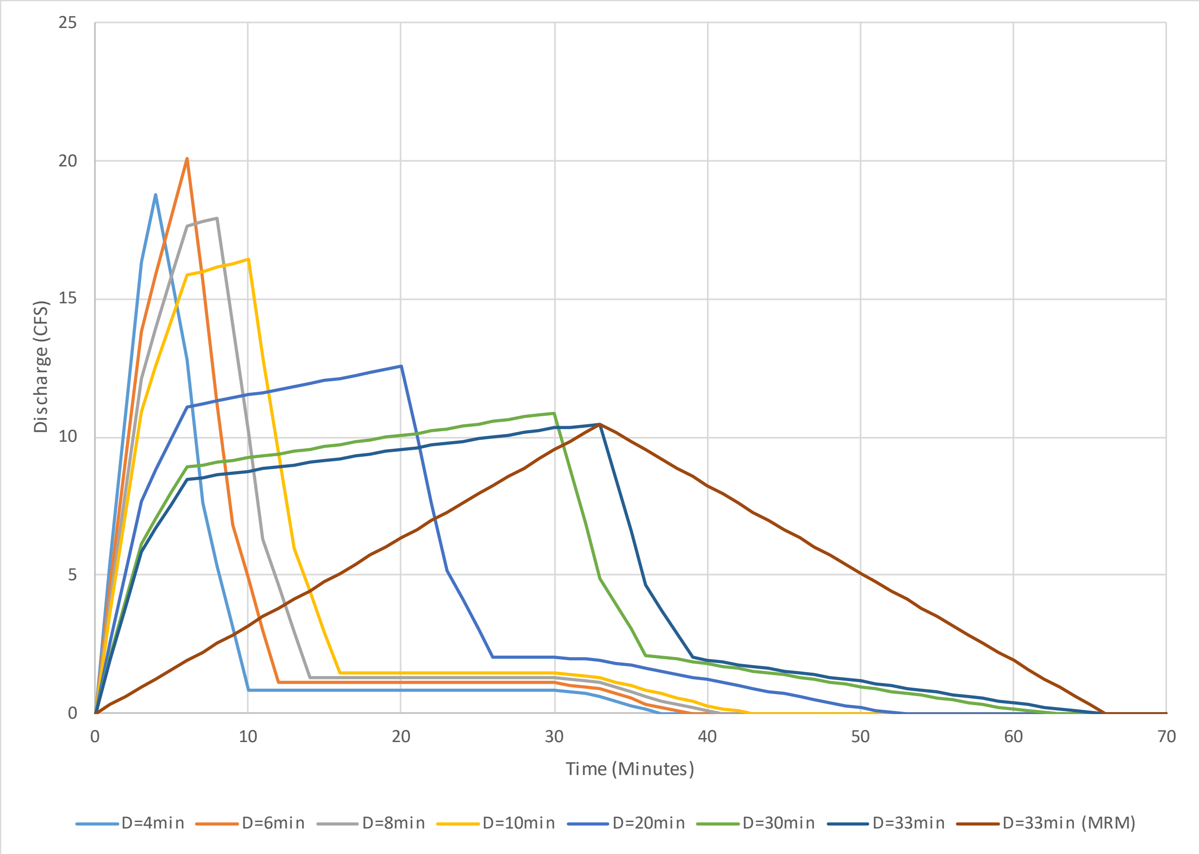


Figure 11: An example of combined hydrographs at different duration

Figure 11 shows the combined hydrographs at various durations. The peak flow occurred at D=6 minutes, and the entire area's time of concentration is at 33 minutes where the DMRM and MRM peak discharge is equal.

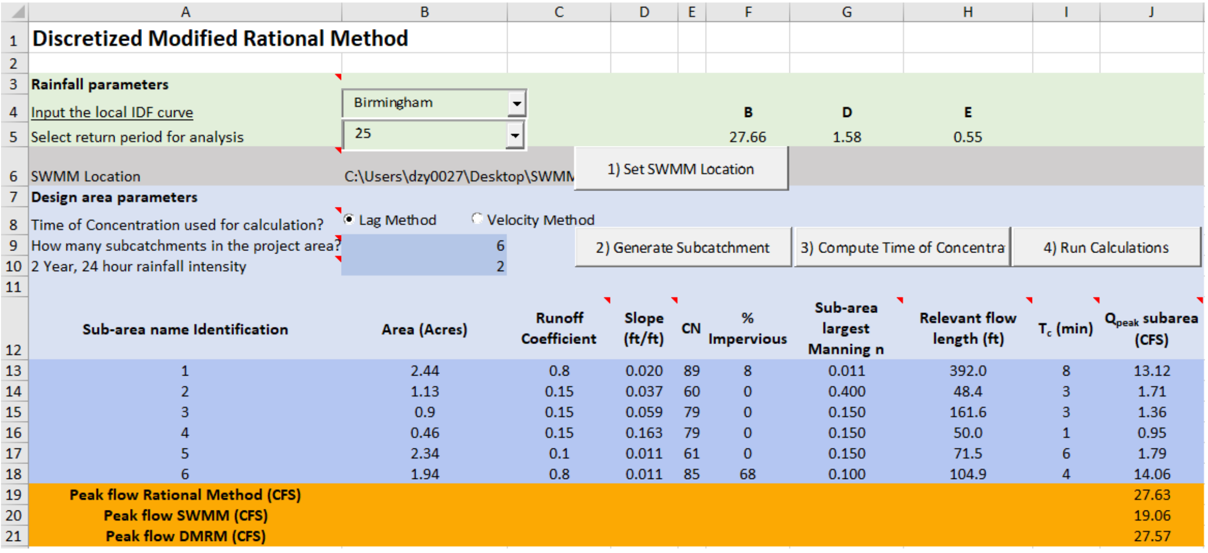
3.5 Using the Excel VBA implementation of DMRM

The calculations described above were implemented into an Excel spreadsheet tool using a code built in Visual Basic for Applications. The tool has two goals:

1. Perform all the systematic calculations to determine the worst peak flow scenario for all drainage areas using the MRM and DMRM approaches
2. To create, run, and retrieve the results of a SWMM 5 input file that was created using the same data input for DMRM analysis. The SWMM 5 run is performed seamlessly, without the user needing to use SWMM 5 interface. The SWMM 5 results can be used

to benchmark the solutions obtained with the DMRM.

The IDF curve needed for rain intensity calculations was generated by selecting the location and return period from a drop box, as shown in Figure 12. With this information, the tool has the information of the IDF curve parameters to be used in the calculations.



Discretized Modified Rational Method

Rainfall parameters

Input the local IDF curve — Birmingham

Select return period for analysis — 25

B	D	E
27.66	1.58	0.55

SWMM Location — C:\Users\dzy0027\Desktop\SWMM — 1) Set SWMM Location

Design area parameters

Time of Concentration used for calculation? — Lag Method — Velocity Method

How many subcatchments in the project area? — 6

2 Year, 24 hour rainfall intensity — 2

2) Generate Subcatchment — 3) Compute Time of Concentra — 4) Run Calculations

Sub-area name Identification	Area (Acres)	Runoff Coefficient	Slope (ft/ft)	CN	% Impervious	Sub-area largest Manning n	Relevant flow length (ft)	T_c (min)	Q_{peak} subarea (CFS)
1	2.44	0.8	0.020	89	8	0.011	392.0	8	13.12
2	1.13	0.15	0.037	60	0	0.400	48.4	3	1.71
3	0.9	0.15	0.059	79	0	0.150	161.6	3	1.36
4	0.46	0.15	0.163	79	0	0.150	50.0	1	0.95
5	2.34	0.1	0.011	61	0	0.150	71.5	6	1.79
6	1.94	0.8	0.011	85	68	0.100	104.9	4	14.06
Peak flow Rational Method (CFS)									27.63
Peak flow SWMM (CFS)									19.06
Peak flow DMRM (CFS)									27.57

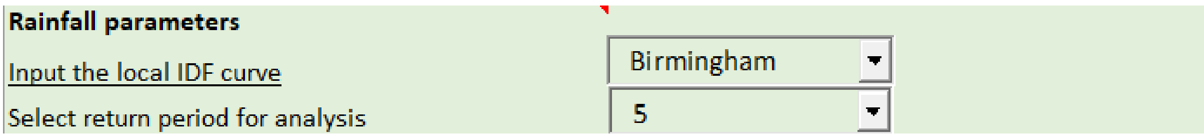


Figure 12: IDF parameters

The Excel tool needs to have the information about where the SWMM5.DLL is located, as this information is needed for the code to send the input files, run SWMM analysis and retrieve results for benchmarking of DMRM results. This SWMM.DLL file is copied within the installation folder of the Excel tool, so the user needs to inform the folder in the computer from within the is running the Excel tool. This information is input in Excel, after which the used needs to click the "Set SWMM Location" button, as exemplified in Figure 13.

Figure 13: Selecting the folder location of the SWMM 5 for the analysis.

Once the drainage area is divided into sub-areas, the number of the sub-areas, 2-year, 24-hour rainfall intensity and time of concentration method is typed into the design area parameters section to generate sub-area tabs, as presented in Figure 14. The user then needs to select the "generate sub-area" button in Excel, which will create the dark blue section in which the sub-areas parameters will be input. After the parameters are input representing all the drainage subareas, and after the T_c calculation method is selected, the user can press the button to compute each individual sub-area T_c values.

Area (Acres)	Runoff Coefficient	Slope	CN	% Impervious	Manning n pervious	Relevant flow length (ft)
25	0.5	0.02	69	40	0.035	100
12	0.1	0.01	61	30	0.03	300
10	0.96	0.003	90	90	0.011	150

Figure 14: Design area parameters for T_c and runoff computation.

Finally, the last step is to click the "Run Calculations" button, and the Excel the tool will generate the IDF curve for the drainage area for the selected recurrence interval, then apply MRM to each sub-area and automatically generate the critical runoff hydrograph and the volume hydrograph for the drainage area. Those results will be presented in the "Result from analysis" sheet. The SWMM 5 analysis is performed for the same hyetograph (i.e., same fixed rainfall intensity and duration) that resulted in the peak runoff flow applying DMRM. The results from these calculations are exemplified in Figure 15.

Time (min)	Peak Flow SWMM (CFS	Peak Flow ADRM (CFS	Peak Flow MRM (CFS)
1	0.04	6.403472801	3.45375
2	2.555	12.28188364	6.9075
3	4.467	18.16029447	10.36125
4	7.34	23.26633159	13.815
5	11.016	25.41984644	17.26875
6	15.011	27.57336128	20.7225
7	19.064	23.02662919	24.17625
8	12.542	19.00495907	27.63
9	6.606	13.12654823	24.17625
10	4.373	8.020511111	20.7225
11	3.513	5.866996268	17.26875
12	2.781	3.713481426	13.815
13	2.442	1.856740713	10.36125
14	2.278	0	6.9075
15	2.123	0	3.45375
16	1.877	0	0
17	1.691	0	0
18	1.628	0	0
19	1.485	0	0
20	1.345	0	0
21	1.239	0	0
22	1.199	0	0
23	1.097	0	0
24	1.008	0	0
25	0.936	0	0
26	0.91	0	0
27	0.842	0	0
28	0.782	0	0
29	0.727	0	0

DMRM result		
Critical peak flow	27.5734	cfs
Critical rain duration peak flov	6	minutes
Total volume runoff	35006.8	ft^3
Max duration	60	minutes
MRM result		
Critical peak flow	27.63	cfs
Critical rain duration peak flov	8	minutes
Total volume runoff	13158.8	ft^3
SWMM result		
Critical peak flow	19.064	cfs
Critical rain duration peak flov	7	minutes
Total volume runoff	8243.7	ft^3

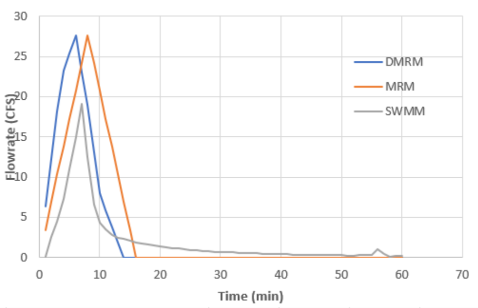


Figure 15: Results from the Excel tool VBA code presenting DMRM, MRM and SWMM 5 results.

3.6 Approach to perform DMRM benchmarking with SWMM 5

As pointed earlier in this thesis, the assumptions used by hydrological models and approaches such as RM or DMRM are significantly different. Thus, in order to enable a comparison between DMRM and SWMM 5 results, several adjustments were needed in SWMM to produce comparable results. Initially, all the sub-areas that were created for DMRM analysis were also created in SWMM as subcatchments. Regarding the parameters for these subcatchments, the following was assumed:

a) Percentage impervious is not a parameter used for RM, MRM, or DMRM but this needs to be informed as a modeling parameter in SWMM. Thus, this was added as a required parameter for the Excel tool.

b) The runoff coefficient is not used in SWMM, though there is a correlation between C and the percent impervious. It was assumed that C was equal to the percent impervious of a subcatchment.

c) It was assumed that impervious areas in SWMM modeling have relatively small Manning numbers when compared to the pervious areas. Thus, the Manning number of pervious areas, which is provided as a parameter in the Excel tool DMRM method, was used as the Manning for the pervious areas and that typically controlled each SWMM subcatchment draining time.

d) SWMM does not have a single abstraction, which is the key characteristic of runoff coefficient. Instead, SWMM adopts time-varying infiltration methods such as CN. The curve number for each subcatchment is one of the parameters provided in the Excel file data input. SWMM abstraction was thus set to CN, while the additional parameters for this abstraction (i.e., conductivity and drying time) is not essentially needed for event-based simulation, can optionally be changed in the Excel tool.

e) Whereas SWMM typically is provided with a time-varying hyetographs to perform its hydrological analysis, a comparison with DMRM would only be feasible if the same rainfall was considered. Thus, a fixed rainfall intensity with duration and intensity matching the critical rainfall duration determined in DMRM calculations is also introduced in SWMM as hyetograph.

4. Results and Discussion

4.1. Simple Drainage Area Studies

The simple case study represents a 10-acre drainage area with six different percentages of impervious varies from 0, 20%, 40%, 60%, 80% and 100% at four different slopes at 0.5%, 1%, 2%, and 5%. Figure 16 shows an example of a case area that is 50% impervious.

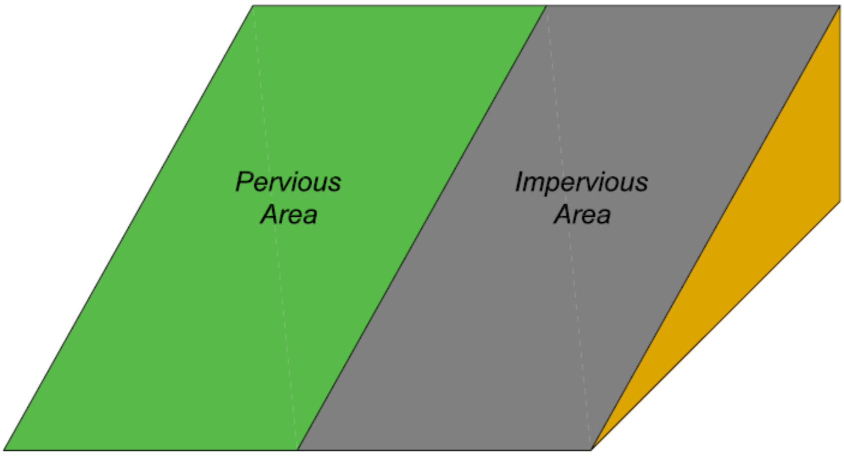


Figure 16: A 50% impervious simple drainage area

For pervious areas, it is assumed that the land cover type is lawns, heavy soil, and for impervious areas, it is assumed that the land cover is Asphaltic and concrete. It is further assumed that the flow length for both pervious and imperious areas is 300 ft. Based on these assumptions, the land properties required for DMRM and T_c computation were selected. Table 5 shows the values used for the simple area studies, and Figure 17 represents the IDF curve used for runoff computation.

For each of the imperviousness (I) and Slope (S) combinations, the runoff hydrograph, critical runoff peak (Q_C), and critical rain duration (T_{Cr}) were calculated using DMRM and MRM. The results were then collected and compared for simple area study in Tables 6 to 9 and Figures 18 and 19.

Table 5: Values used for simple area study

	Pervious Area	Impervious Area
Runoff Coefficient	0.15	0.95
CN	39	98
Manning Roughness	0.035	0.015

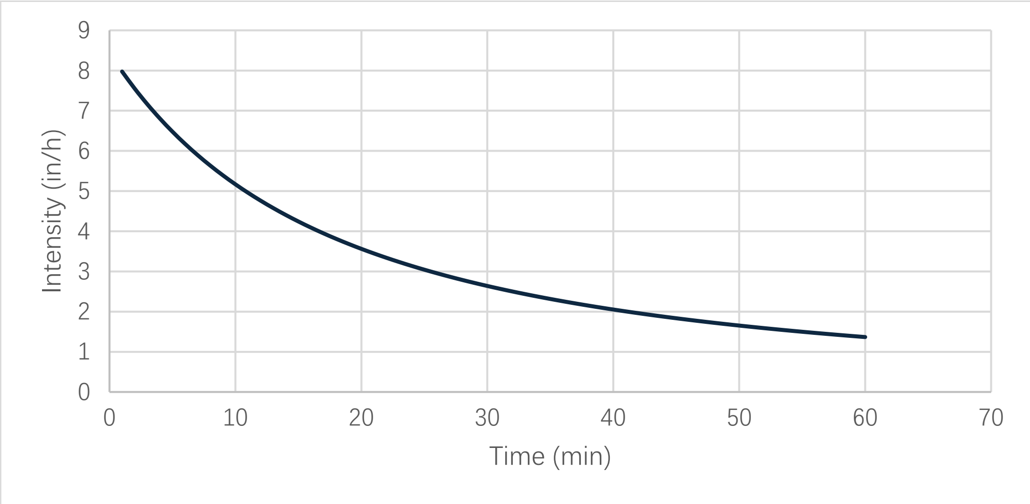


Figure 17: IDF curve used in simple area study

Table 6: Results of Simple Area Study (Lag Method)

DMRM					
%Impervious	Slope	0.5%	1.0%	2.0%	5.0%
I=0	Q_c (cfs)	3.77	4.59	5.49	7.11
	T_{Cr} (min)	51	36	26	16
I=20%	Q_c (cfs)	13.95	15.97	18.72	21.18
	T_{Cr} (min)	8	6	4	3
I=40%	Q_c (cfs)	26.33	30.04	35.36	39.57
	T_{Cr} (min)	8	6	4	3
I=60%	Q_c (cfs)	38.71	44.10	52.00	57.95
	T_{Cr} (min)	8	6	4	3
I=80%	Q_c (cfs)	51.09	58.17	68.65	76.33
	T_{Cr} (min)	8	6	4	3
I=100%	Q_c (CFS)	63.47	72.24	85.29	94.71
	T_{Cr} (min)	8	6	4	3

Table 6: Results of Simple Area Study (Lag Method, continued)

MRM					
%Impervious	**Slope**	0.5%	1.0%	2.0%	5.0%
I=0	Q_c (CFS)	3.77	4.59	5.49	7.11
	T_{Cr} (min)	51	36	26	16
I=20%	Q_c (CFS)	7.80	9.48	11.34	14.70
	T_{Cr} (min)	51	36	26	16
I=40%	Q_c (CFS)	11.82	14.38	17.20	22.28
	T_{Cr} (min)	51	36	26	16
I=60%	Q_c (CFS)	15.85	19.27	23.06	29.87
	T_{Cr} (min)	51	36	26	16
I=80%	Q_c (CFS)	19.87	24.16	28.91	37.46
	T_{Cr} (min)	51	36	26	16
I=100%	Q_c (CFS)	63.47	72.24	85.29	94.71
	T_{Cr} (min)	8	6	4	3

Table 7: Peak Runoff %Difference (Lag Method)

Slope	I=0	I=20%	I=40%	I=60%	I=80%	I=100%
0.5%	0	44%	55%	59%	61%	0
1.0%	0	41%	52%	56%	58%	0
2.0%	0	39%	51%	56%	58%	0
5.0%	0	31%	44%	48%	51%	0

Table 8: Results of Simple Area Study (Velocity Method)

DMRM					
%Impervious	**Slope**	0.5%	1.0%	2.0%	5.0%
I=0	Q_c (cfs)	10.02	11.41	12.32	14.95
	T_{Cr} (min)	8	6	5	3
I=20%	Q_c (cfs)	21.29	22.45	24.92	28.31
	T_{Cr} (min)	6	4	3	2
I=40%	Q_c (cfs)	34.02	38.16	42.37	48.13
	T_{Cr} (min)	6	4	3	2
I=60%	Q_c (cfs)	46.77	53.87	59.82	67.94
	T_{Cr} (min)	6	4	3	2
I=80%	Q_c (cfs)	59.50	69.58	77.26	87.76
	T_{Cr} (min)	6	4	3	2
I=100%	Q_c (cfs)	72.24	85.29	94.71	107.57
	T_{Cr} (min)	6	4	3	2

Table 8: Results of Simple Area Study (Velocity Method, contined)

MRM					
%Impervious	**Slope**	0.5%	1.0%	2.0%	5.0%
I=0	Q_c (cfs)	10.02	11.41	12.32	14.95
	T_{Cr} (min)	8	6	5	3
I=20%	Q_c (cfs)	20.71	20.71	23.57	27.83
	T_{Cr} (min)	8	8	6	4
I=40%	Q_c (cfs)	31.40	31.40	35.74	42.20
	T_{Cr} (min)	8	8	6	4
I=60%	Q_c (cfs)	42.09	42.09	47.91	56.56
	T_{Cr} (min)	8	8	6	4
I=80%	Q_c (cfs)	52.78	52.78	60.07	70.93
	T_{Cr} (min)	8	8	6	4
I=100%	Q_c (cfs)	72.24	85.29	94.71	107.57
	T_{Cr} (min)	6	4	3	2

Table 9: Peak Runoff %Difference (Velocity Method)

Slope	I=0	I=20%	I=40%	I=60%	I=80%	I=100%
0.5%	0	3%	8%	10%	11%	0
1.0%	0	8%	18%	22%	24%	0
2.0%	0	5%	16%	20%	22%	0
5.0%	0	2%	12%	17%	19%	0

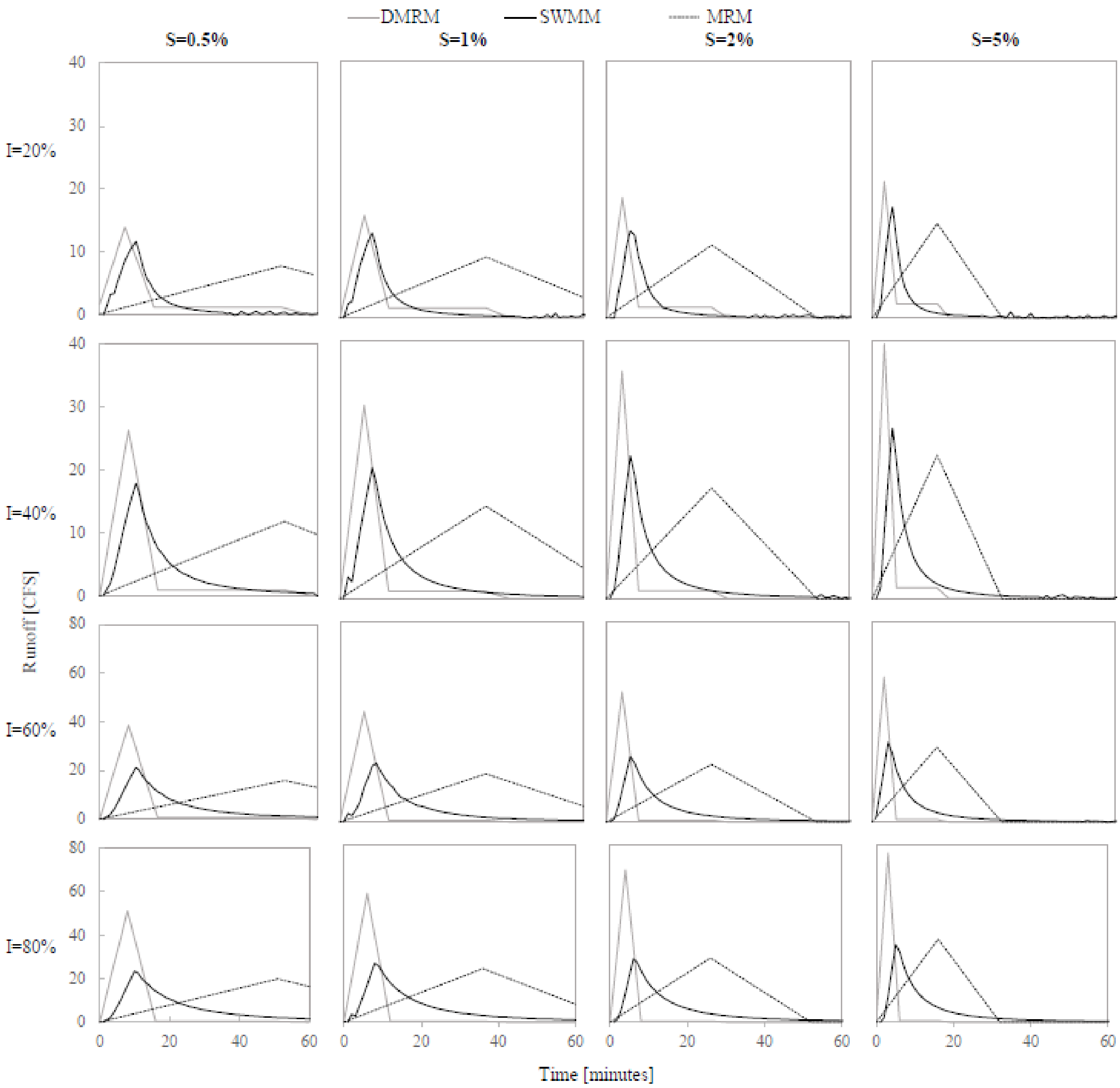


Figure 18: Hydrographs from simple area study (Tc from Lag Method)

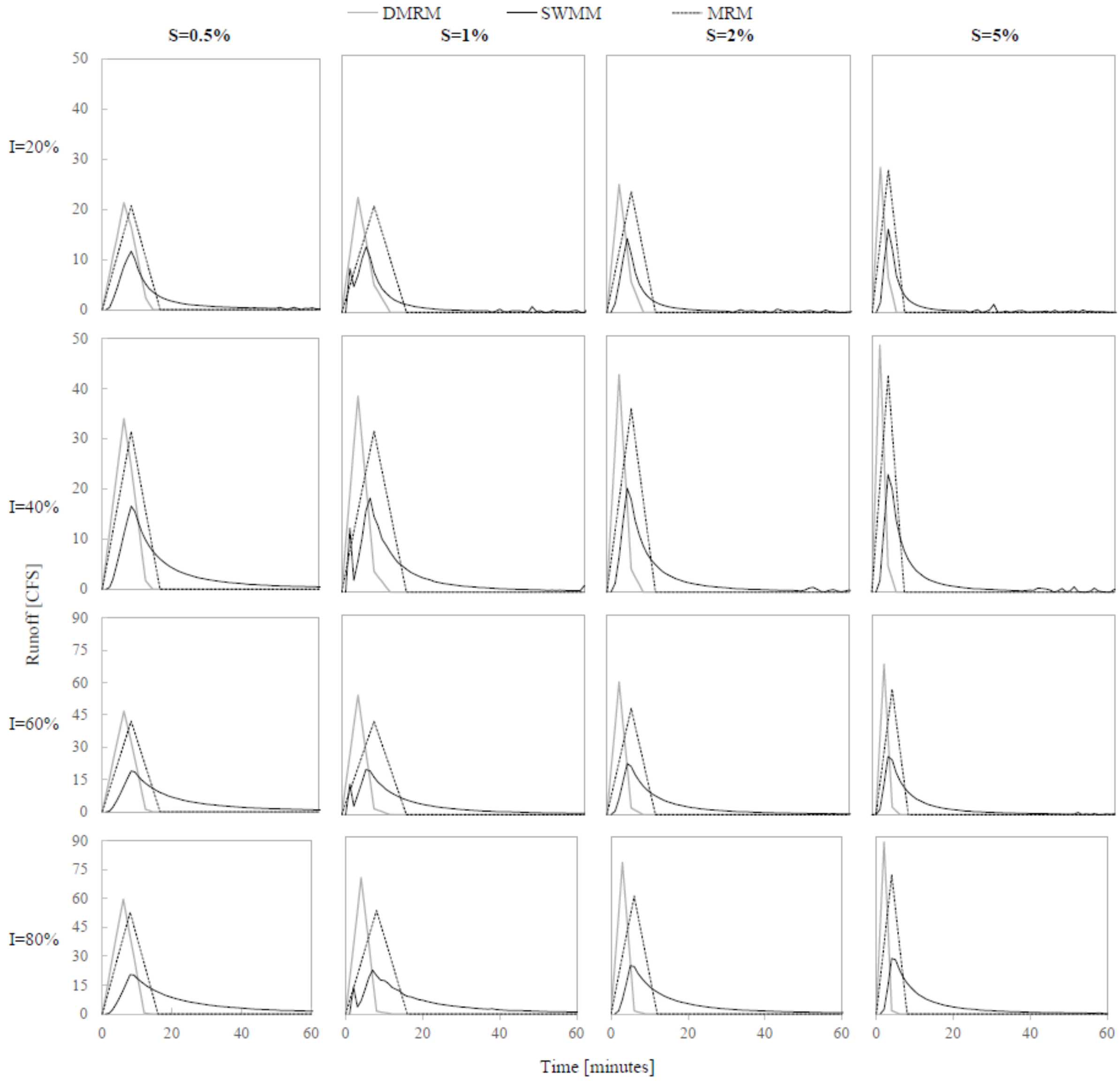


Figure 19: Hydrographs from simple area study (Tc from Velocity Method)

As expected, for the area with 0% and 100% imperviousness, the DMRM and MRM produced the same results because of the same T_c.

For other cases (I=20% to I=80%), the result from DMRM and MRM shows a substantial difference in critical runoff and critical rain duration. Under the same conditions, the DMRM favors the shorter T_c of the impervious area and reaches a faster peak, while the MRM only peaks as the longest T_c is reached for the pervious area.

Figures 18 and 19 show three hydrographs for I=20% to I=80% areas: (1) combined critical hydrograph at the critical rainfall duration (T_{Cr}) from DMRM, (2) SWMM produced hydrograph using the same rainfall hyetograph at the critical duration of DMRM, and (3) MRM triangular hydrograph at the longest T_C with total drainage area. DMRM predicts a higher Q_c and shorter T_{Cr} for both cases than MRM. The difference between DMRM and MRM increases as imperviousness increases due to a larger area contributing to the shorter time of concentration. As the slope increases, the difference between the two methods decreases in Q_c and T_{Cr}. This is resulted from decreased T_c for both pervious and impervious areas.

Comparing the results between Lag Method and Velocity method, the Lag Method showed a longer T_c for both pervious and impervious areas while for the Velocity method, the T_c difference between pervious and impervious is much smaller due to they both have a much shorter T_c. Despite the difference in T_c computation, the DMRM is producing larger peak flow at a shorter duration for all cases.

The results from the simple area study match the assumption that peak runoff can occur before the time of concentration of the entire drainage area is reached.

4.2. Realistic Case Studies

4.2.1. Soccer Field

To further evaluate the project, two real-life locations were selected to check the function of the SWMM tool. The first site is a football field located in Birmingham, AL. Figure 20 is the aerial view of the site. The site is divided into five sub-areas according to the slope, land cover and other parameters mentioned in the Sub-areas division section.

Figure 20: Birmingham site of a soccer field with parking lot and forested area. All runoff is conveyed to the rectangular detention facility in the south edge of the drainage area.

The site consists of two football fields that have a very low slope and are fully covered by grass. These areas are considered 100% pervious and have a low runoff coefficient; those areas have the longest T_c. The forest area on the left has a higher slope, a slightly higher runoff coefficient, and a longer flow path. The forest area has a longer t_c compared to the football fields. The other two sub-areas are the parking lot and the driveway. Those areas are fully covered by asphalt and are 100% impervious, have the largest runoff coefficient and the shortest T_c.

For realistic sites, the soil type and the hydrological group of the sub-areas were determined using the NRCS Web Soil Survey (WSS), the slope and area were computed with Google Earth data, and the hydrological parameters were determined using the runoff coefficient, CN and manning roughness table listed in NEH Chapter 15 Time of Concentration.

This site consists of three soil types: 79% Choccolocco-Sterrett association (Hydrologic Soil Group B/C), 17.3% Nauvoo-Sunlight complex (Hydrologic Soil Group B) and 3.7% Nauvoo loam (Hydrologic Soil Group B/C). In average, the soild on the site are moderately drained.

Table 10: Football field Sub-areas parameters

Sub-Area	Area (Acres)	Runoff Coefficient	Slope	CN	% Impervious	Highest Manning n	Relevant flow length (ft)
1	5.23	0.18	0.198	69	10	0.4	598.22
2	4.41	0.1	0.01	61	0	0.15	552.79
3	0.89	0.96	0.01	98	100	0.011	120
4	2.23	0.1	0.01	61	0	0.15	486
5	0.36	0.96	0.03	98	100	0.011	650

Table 10 shows the key parameters of those sub-areas. For the football field, all the analyses were based on Birmingham's local 25-year return period IDF intensity. The resulting hydrographs and critical runoff from SWMM, DMRM, and MRM are shown in Figure 21, 22 and Table 11, 12 below:

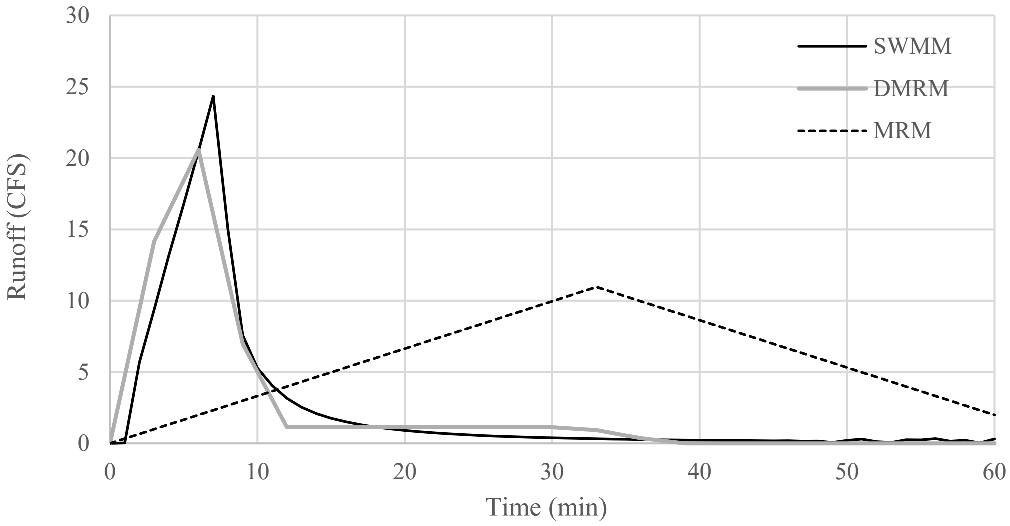


Figure 21: Hydrographs of Football Field (T_c computed from Lag Method)

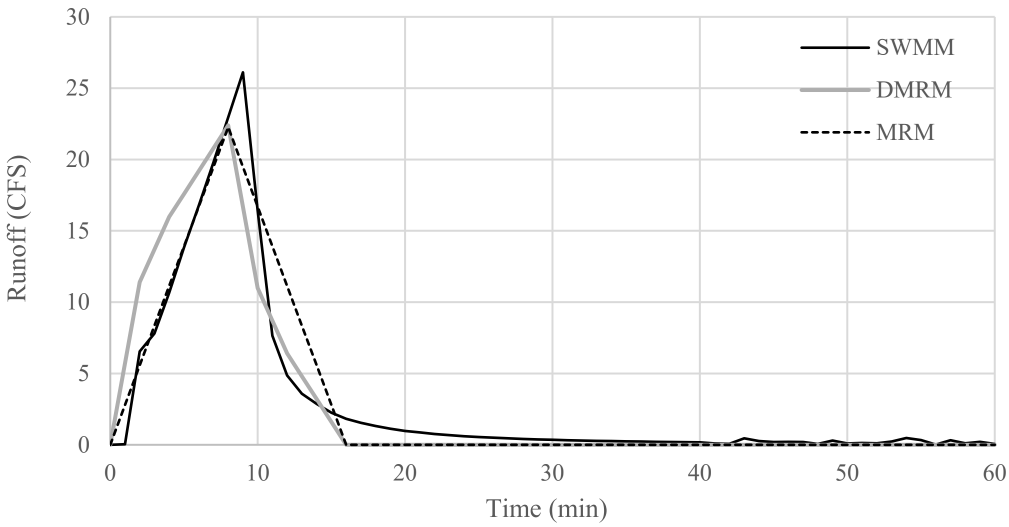


Figure 22: Hydrographs of Football Field (T_c computed from Velocity Method)

Table 11: Critical Runoff and Duration (Lag Method)

Runoff Method	Critical peak flow (cfs)	Total runoff volume (ft^3)	Critical rain duration (min)
SWMM	24.35	9530.61	7
DMRM	20.57	9169.20	6
MRM	10.96	21391.92727	33

Table 12: Critical Runoff and Duration (Velocity Method)

Runoff Method	Critical peak flow (CFS)	Total runoff volume (ft^3)	Critical rain duration (min)
SWMM	26.11	11280	9
DMRM	22.39	10748.00	8
MRM	22.27	10606	8

As shown in the aerial view and Table 10 the study site consists of highly pervious and impervious areas. It is expected that in five different areas, the DMRM hydrograph should represent five distinctive runoff increase/decrease rates that are defined by the t_c of the five sub-areas.

The hydrographs from Figure 21 conform to the previous expectations. The DMRM hydrograph has five Runoff increase/decrease rate changes at the sub-area t_c, with the peak runoff occurring at 6 minutes which is the t_c of Area 1 (Forest area) and Area 5 (Driveway). The MRM hydrograph peaked at the longest duration of 33 minutes, which is the t_c of Area 2 (Large Football field)

Interestingly, the hydrograph generated from SWMM closely follows the trend of DMRM hydrograph with a roughly 1-minute delay and a slightly higher peak (3.78 cfs)

4.2.2. Jay and Susie Gogue Performing Arts Center

The second realistic site is the Jay and Susie Gogue Performing Arts Center located in Auburn, AL. Differing from the Football site, the Gogue Performing Arts Center is considerably more developed, and the three Sub-areas do not show a wide difference in t_c, with the longest t_c of 22 minutes and the shortest of 11 minutes. This should result in similar results between MRM and DMRM. All the analysis performed on this site were based on Auburn, 25-year return period IDF intensity. The soil type for this site is entirely Marvyn loamy sand (Hydrological Group B); the soils in the site in general are well drained.

Figure 23: Jay and Susie Gogue Performing Arts Center

Table 13: Gogue Performing Arts Center parameters

Sub-Area	Area (Acres)	Runoff Coefficient	Slope	CN	% Impervious	Highest Manning n	Relevant flow length (ft)
1	3.47	0.7	0.019	85	50	0.011	505
2	7.72	0.62	0.036	60	60	0.2	669
3	2.54	0.36	0.025	49	5	0.259	400

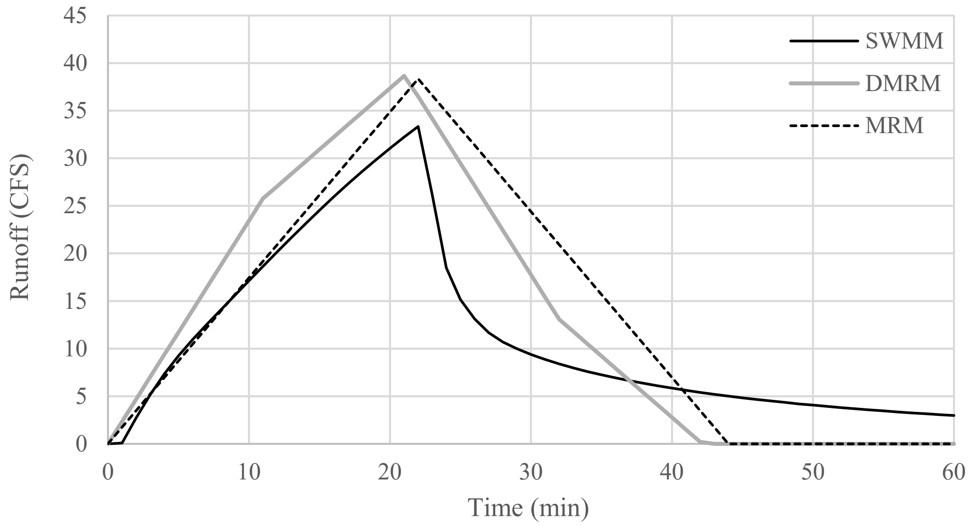


Figure 24: Hydrographs of Gogue Performing Arts Center (T_c computed from Lag Method)

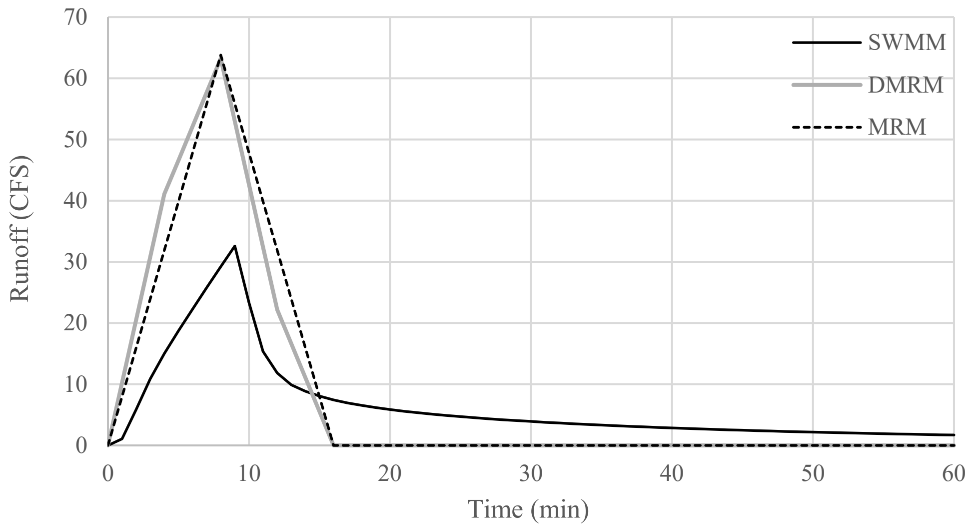


Figure 25: Hydrographs of Gogue Performing Arts Center (T_c computed from Velocity Method)

Table 14: Critical Runoff and Duration (Lag Method)

Runoff Method	Critical peak flow (cfs)	Total runoff volume (ft^3)	Critical rain duration (min)
SWMM	33.34	48215.79	22
DMRM	38.65	48949.04363	21
MRM	38.35	50569.70455	22

Table 15: Critical Runoff and Duration (Velocity Method)

Runoff Method	Critical peak flow (cfs)	Total runoff volume (ft^3)	Critical rain duration (min)
SWMM	32.59	28650	9
DMRM	63.23	30351	8
MRM	63.79	30380	8

As expected, for the Lag Method, all three methods produced very similar critical runoff, with the DMRM reaching its peak flow at 21 minutes while SWMM and MRM peaks at the slightly longer T_c of 22 minutes. For Velocity Method, MRM and DMRM peak flow is very close, but SWMM peak flow is much lower, due to the very short duration.

The Lag Method hydrographs show that the peak flow from all three methods is very close to each other, with MRM 0.3 cfs lower than DMRM and SWMM 3.31 cfs lower than DMRM. Because of the same critical rain duration, the DMRM and MRM hydrograph is very similar to each other for Velocity Method. The SWMM hydrograph has a similar shape to the DMRM but at half the magnitude.

4.2.3. Redevelopment of Campus Tennis Ball Field

The last realistic site study is a comparison between the old tennis ball field and the new practice field developed on the same site. The soil types for both sites are 96.8% Pacolet sandy loam (Hydrological soil group B) and 3.2% Marvyn loamy sand (Hydrological soil group B). The old site had more pervious surfaces, such as grass and tennis ball fields, as well as a low slope. In comparison, the newly developed site is less pervious due to the large building areas and sloped roofs. Because of these differences, the result should show a larger and faster peak flow for the new site.

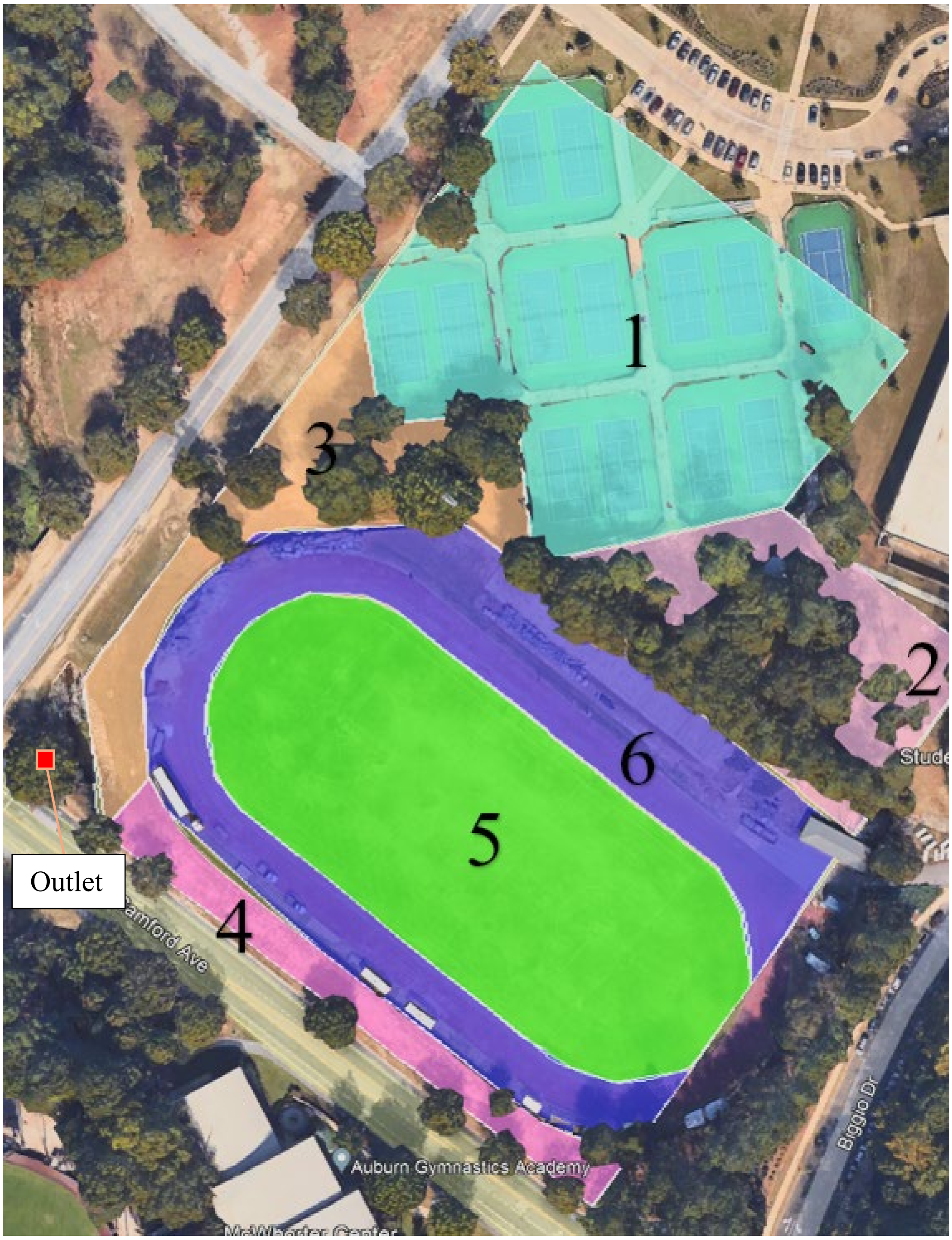


Figure 26: Old Tennis Ball Site

The characteristics of the sub-areas considered in the peak flow calculations for the pre-development conditions are presented in Table 16. The resulting pre redevelopment hydrographs computed with the Excel-VBA tool are presented in Figure 27 (Tc computed with the Lag Method) and Figure 28 (Tc computed with the Velocity Method). Tables 17 and 18 present the corresponding results for the critical rainfall duration considering each approach for time of concentration, as well as the total runoff volume

Table 16: Old Tennis Ball Site Parameters

Sub-Area	Area (Acres)	Runoff Coefficient	Slope	CN	% Impervious	Highest Manning n	Relevant flow length (ft)
1	2.44	0.8	0.02	89	8	0.011	392
2	1.13	0.15	0.04	60	0	0.4	251
3	0.9	0.15	0.06	79	0	0.15	246
4	0.46	0.15	0.16	79	0	0.15	50
5	2.34	0.1	0.01	61	0	0.15	526
6	1.94	0.8	0.01	85	68	0.1	542

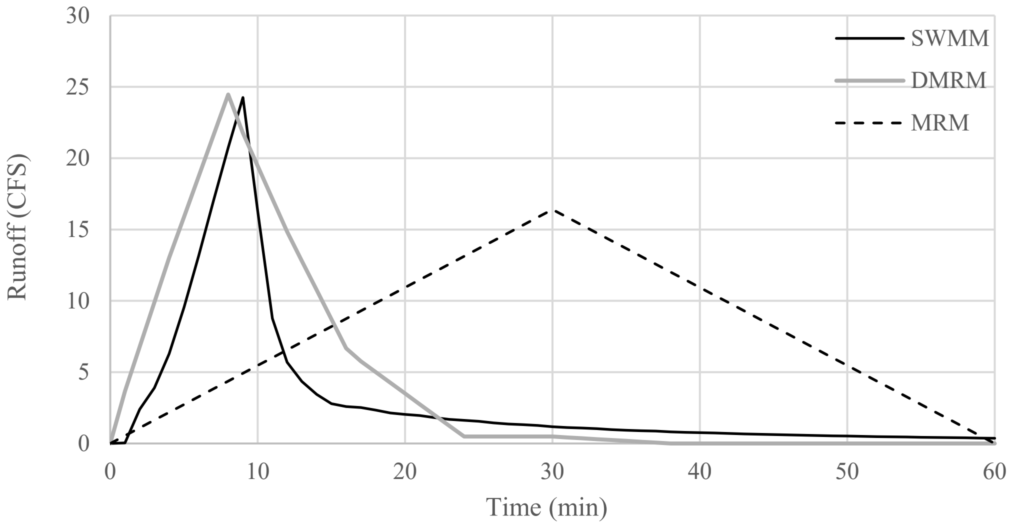


Figure 27: Hydrographs of the before re-development site (T_c from Lag Method)

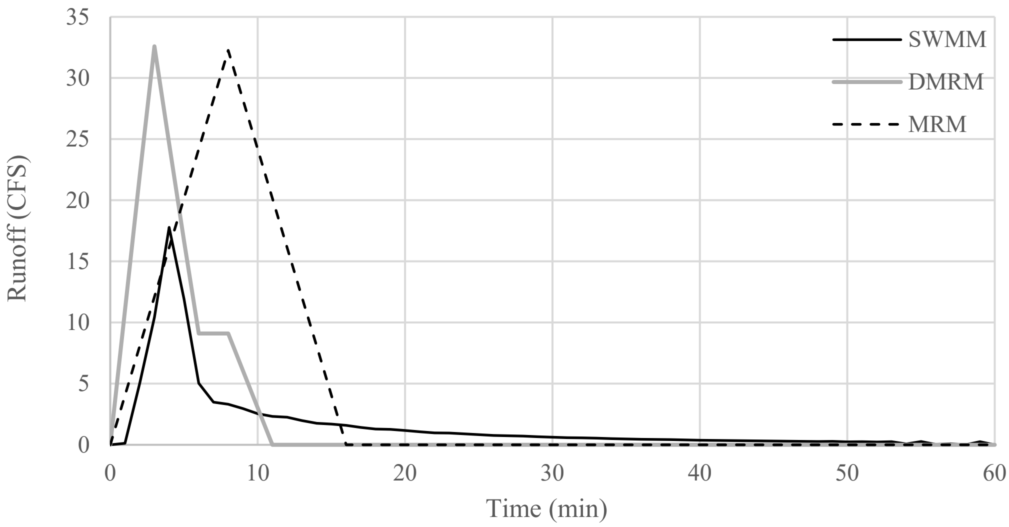


Figure 28: Hydrographs of the before re-development site (T_c from Velocity Method)

Table 17: Critical Runoff and Duration (Lag Method)

Runoff Method	Critical peak flow (cfs)	Total runoff volume (ft^3)	Critical rain duration (min)
SWMM	24.25	12293.37	9
DMRM	24.46	15349.32864	8
MRM	16.40	29503.6	49

Table 18: Critical Runoff and Duration (Velocity Method)

Runoff Method	Critical peak flow (cfs)	Total runoff volume (ft^3)	Critical rain duration (min)
SWMM	17.79	6529.7	4
DMRM	32.59	8599.3	3
MRM	32.26	15364	8

As discussed before, the new development for this site, illustrated in Figure 29, appears to have created significant increases in peak flows and a much faster time of concentration, mainly due to the newly added paved surfaces and the sloped roof. The SWMM and DMRM methods produced similar hydrographs for both new and old sites, while the MRM gives a much lower peak flow and longer critical duration because of the long time of concentration of the grassed subarea. The characteristics of the redeveloped drainage subareas are presented in Table 19, with the corresponding hydrographs shown in Figures 30 and 31 for the two tested time of concentration formulas. The critical rainfall duration and total runoff volumes are summarized in Tables 20 and 21.

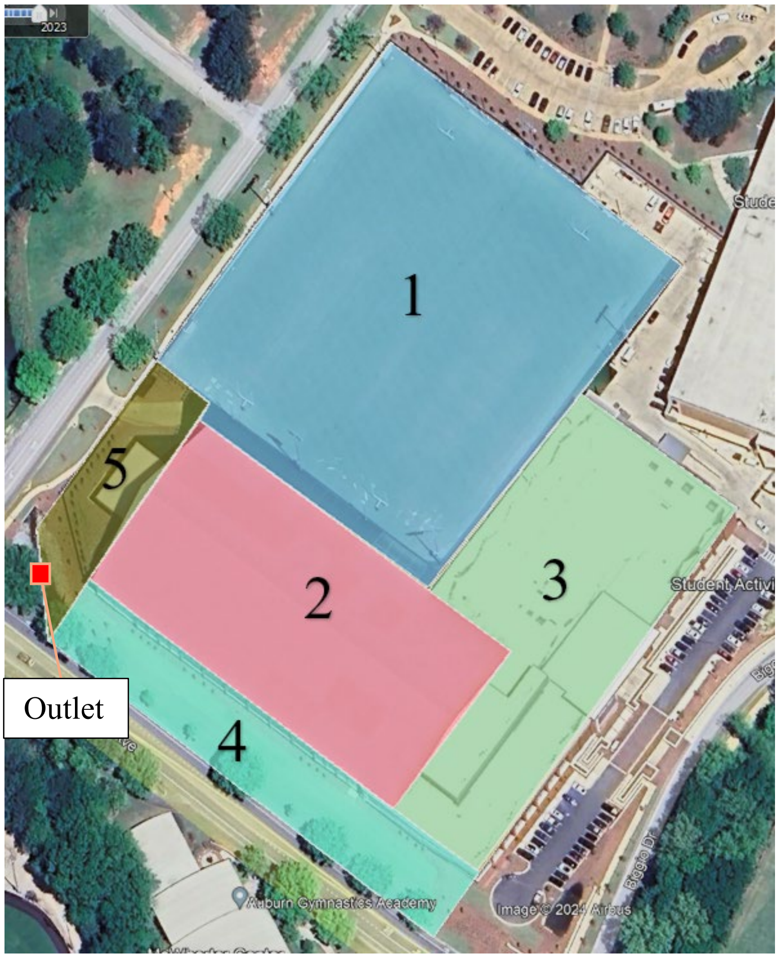


Figure 29: New Developed Site

Table 19: New Developed Site Parameters

Sub-Area	Area (Acres)	Runoff Coefficient	Slope	CN	% Impervious	Highest Manning n	Relevant flow length (ft)
1	3.9	0.1	0.03	61	0	0.15	582.44
2	2	0.96	0.30	98	100	0.011	105.8
3	1.81	0.96	0.01	98	100	0.011	482
4	1	0.15	0.09	69	10	0.4	69.26
5	0.48	0.4	0.06	82	25	0.1	74.91

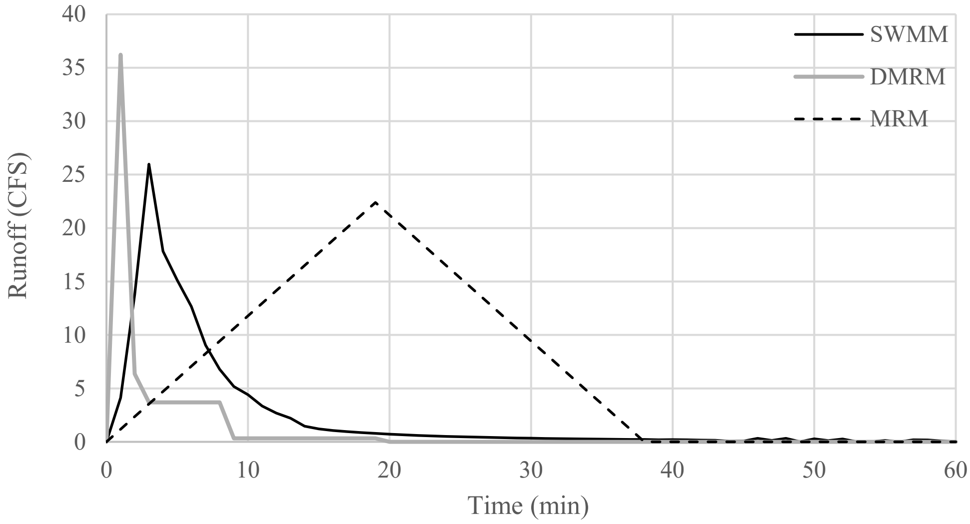


Figure 30: Hydrographs of the new site (T_c from Lag Method)

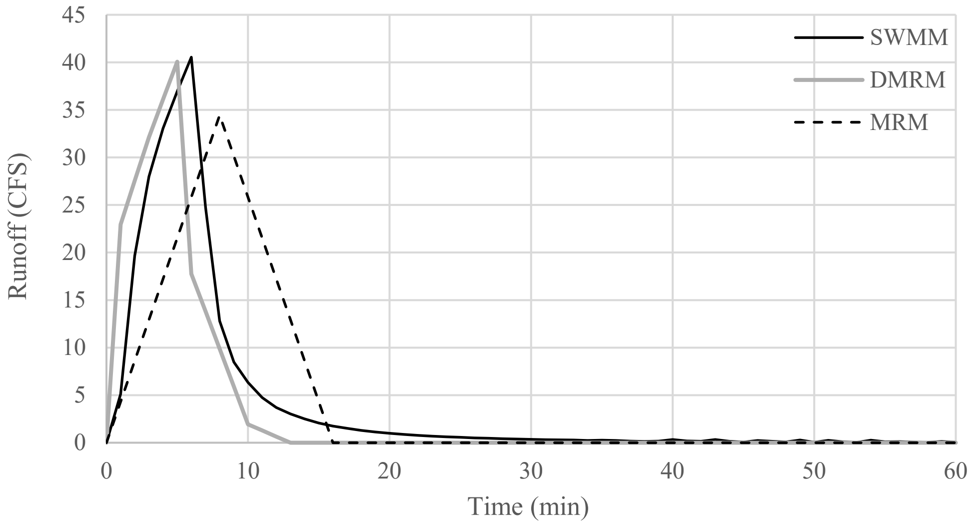


Figure 31: Hydrographs of the new site (T_c from Velocity Method)

Table 20: Critical Runoff and Duration (Lag Method)

Runoff Method	**Critical peak flow (cfs)**	**Total runoff volume (ft^3)**	**Critical rain duration (min)**
SWMM	25.98	8762.34	3
DMRM	36.22	4096.023731	1
MRM	22.39	25489.24737	19

Table 21: Critical Runoff and Duration (Velocity Method)

Runoff Method	**Critical peak flow (cfs)**	**Total runoff volume (ft^3)**	**Critical rain duration (min)**
SWMM	40.54	15118	6
DMRM	40.06	12600	5
MRM	34.44	16402	8

Table 22 presents the percentage difference in peak discharge between the DMRM and SWMM hydrographs for both time of concentration methods. For the first site, the difference between Lag and Velocity is the smallest at 1%; for the third site, the difference is the largest at 44%.

Table 22: Result Comparison between DMRM and SWMM

Site	%Difference Lag Method	%Difference Velocity Method
Football Field	18%	17%
Gogue Performing Arts Center	14%	48%
Old Tennis Field	1%	45%
New Practice Field	28%	1%

Although the SWMM simulation does not include T_c, the rainfall hyetograph depends on the critical duration related to the sub-area T_c. According to the Iowa Department of Natural Resources Manual Chapter 3 - Storm Water Hydrology, the Lag method should be selected for areas that are more rural in character and have long hydraulic lengths. For sites 2 and 3, the site consists of a lot of pervious space and a relatively low slope. The results from these sites are in favor of the Lag Method. Site 4 mostly consists of impervious land covers such as roofs and paved space, whereas the Velocity Method produces much better results at only a 1% difference. For Site 1, although there is a large portion of wooded area on the left. The slope of that area is steep at 19.8%, resulting in a faster Tc, and the two methods produce similar results.

Those results are in line with the Iowa state manual, suggesting that for better estimates, the Lag Method should be used for mostely rural areas and the Velocity Method should be used in highly urbanlized areas where fast T_c is expected.

5. **Conclusion**

Despite its various limitations, Rational Method-based approaches continue to be one of the most used hydrological tools to provide peak flow estimates due to their simplicity, intuitiveness, and relatively low data requirements. Yet, these peak flow estimates may be severely impacted when there are different types of land use in the drainage area with corresponding large differences in the overland flow velocity and time of concentration. Currently, when various land use types are present in a drainage area, the practice is to average runoff coefficients and to select the time of concentration of the entire drainage area. This work has shown that this approach can lead to the underestimation of peak flow in some cases. Earlier studies have acknowledged this issue (ODOT, 2014; Ponce, 2014; Bedient, 2013), but have not presented a generalized equation to consider these dissimilar land uses in applying the RM or in deriving hydrographs.

Based on this existing limitation of the RM, this thesis expanded upon the MRM and proposed the DMRM method. The method does not assume that the critical rainfall duration is known a priori, and separates the runoff contributions of various drainage sub-areas generating various MRM-type hydrographs for each rainfall duration. By computing the peak runoff from all tested rainfall, the critical rainfall duration and the related critical hydrograph are determined. This is all obtained with the same data requirements of the traditional RM, and while manual computational can be cumbersome, the method has been implemented in an Excel-based tool using Visual Basic for Applications code.

The results from simple drainage areas with two land uses show that the hydrograph generated from MRM and DMRM are identical for a uniform catchment. When the drainage area is dissimilar, i.e., the impervious percentage (I) from 20% to 80%. DMRM yields larger peak flows that accumulate more rapidly when compared to MRM. The largest peak flow differences were 220% for cases with areas with high impervious fraction (~80%) and lower surface slope (S=0.5%). Conversely, the smallest differences were observed when the impervious fraction was lower (20%) and steep surface slope (S=5%).

The method is then further evaluated using four realistic drainage areas selected for their various degrees of land use dissimilarity, with the third area being a before/after development comparison. The results follow the trend from simple drainage area studies, showing a large difference for sites with high levels of dissimilar land use. The area with the closest similarity between DMRM and MRM was the one with less dissimilar land cover (i.e., no 100% impervious sub-areas), indicating that DMRM is more applicable for dissimilar land use types with full impervious sub-areas.

The Excel tool created for this thesis also generates an input file with the same sub-catchment characteristics and rainfall hyetograph for SWMM for benchmarking the DMRM results. The DMRM hydrographs for most cases followed the trend of SWMM hydrographs showing a very similar result. However, for cases that have sub-catchments with very short Tc , the hydrograph from DMRM and SWMM starts to deviate, possibly due to the infiltration and storage model used in SWMM.

It is difficult to present a comparison of DMRM with real world peak flows since the rainfall used in the method is very simplified. Yet, future investigations could further evaluate and benchmark the hydrograph results from the DMRM. For instance, future research could compare the DMRM hydrographs with the ones generated by WinTR-55. While WinTR-55 hyetograph is synthetic and time-varying, the rainfall depth could be averaged over time so that could be introduced in the DMRM, and then the resulting runoff could be comparable. Other future research could expand upon SWMM 5 comparisons and obtain in what conditions peak flow results from lumped approaches deviated most from the hydrological modeling estimates.

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7. Appendix VBA Code

```
Private Sub ComboBox1_Change()



Dim jj As Integer, kk As Integer, y As Integer

Dim Parameters(3) As Double



jj = Sheets("IDF Parameters").Cells(1, Columns.Count).End(xlToLeft).Column



 If ComboBox2.Value <> "User input" Then

   For jj = 1 To jj

       If Sheets("IDF Parameters").Cells(1, jj) = ComboBox2.Value Then

       kk = jj

       End If

   Next jj
```

```
    y = ComboBox1.Value

    Parameters(1) = Sheets("IDF Parameters").Cells(y, kk + 1)

    Parameters(2) = Sheets("IDF Parameters").Cells(y, kk + 2)

    Parameters(3) = Sheets("IDF Parameters").Cells(y, kk + 3)




    Cells(5, 6) = Application.WorksheetFunction.Round(Parameters(1), 2)

    Cells(5, 7) = Application.WorksheetFunction.Round(Parameters(2), 2)

    Cells(5, 8) = Application.WorksheetFunction.Round(Parameters(3), 2)


  Else: Range("F5:H5") = 0

  End If


End Sub


Private Sub ComboBox2_Change()


Dim jj As Integer, kk As Integer, y As Integer
```

```
Dim Parameters(3) As Double


jj = Sheets("IDF Parameters").Cells(1, Columns.Count).End(xlToLeft).Column


 If ComboBox2.Value <> "User input" Then
   For jj = 1 To jj
       If Sheets("IDF Parameters").Cells(1, jj) = ComboBox2.Value Then
       kk = jj
       End If
   Next jj



   y = ComboBox1.Value
   Parameters(1) = Sheets("IDF Parameters").Cells(y, kk + 1)
   Parameters(2) = Sheets("IDF Parameters").Cells(y, kk + 2)
   Parameters(3) = Sheets("IDF Parameters").Cells(y, kk + 3)
```

```
   Cells(5, 6) = Application.WorksheetFunction.Round(Parameters(1), 2)
   Cells(5, 7) = Application.WorksheetFunction.Round(Parameters(2), 2)
   Cells(5, 8) = Application.WorksheetFunction.Round(Parameters(3), 2)

  Else: Range("F5:H5") = 0
  End If

End Sub

Private Sub CommandButton1_Click()
Dim S As Integer, i As Integer
Dim CarryOn As Variant
CarryOn = MsgBox("Do you want to clear the current subcatchments?", vbYesNo,
"SWMMtools for Excel")
If CarryOn = vbYes Then
 Range("A13:J999").Clear

S = Cells(9, 2)
For i = 1 To S
Cells(i + 12, 1) = i
```

```
Next i

Cells(S + 13, 1) = "Peak flow rational method (CFS)"

Cells(S + 14, 1) = "Peak flow SWMM method (CFS)"

Range("A12:J12").Interior.Color = RGB(217, 225, 242)

Range("A13" & ":J" & S + 12).Interior.Color = RGB(180, 198, 242)

Range("A" & S + 13 & ":J" & S + 15).Interior.Color = RGB(252, 169, 3)

End If

End Sub

Private Sub CommandButton2_Click()

  Dim S As Integer, i As Integer

  Dim C As Double

  Dim l As Double, y As Double, SL As Double, t As Double, n As Double
```

```
  Dim Run As Variant

  S = Cells(9, 2)


  If OptionButton1.Value = True Then

    'compute Tc with lag method

    Lag

  End If


  If OptionButton2.Value = True Then

    'compute Tc with kinematic method

    kinematic

  End If



End Sub
```

```
Private Sub CommandButton3_Click()

Dim diaFolder As FileDialog


'Open the file dialog


Set diaFolder = Application.FileDialog(msoFileDialogFolderPicker)

diaFolder.AllowMultiSelect = False

diaFolder.Title = "Please select folder"

diaFolder.Show

Cells(6, 2) = diaFolder.SelectedItems(1)

Set diaFolder = Nothing

End Sub



Private Sub CommandButton4_Click()

  Dim S As Integer, ii As Single, jj As Integer, kk As Integer, t As Integer

  Dim C As Double

  Dim l As Double, y As Double, SL As Double, n, Qr As Double

  Dim Run As Variant

  Dim Tc() As Single, Qpd() As Single, Q() As Double, Max(2) As Double, V() As Double
```

```
  Dim Parameters(3) As Double

  Dim VOL As Double, MSWMM As Double, TSWMM As Integer

  S = Cells(9, 2)

   Sheets("Input File").Range("A55:N99999").Clear


'ADRM


Sheets("Hydrograph").Range("A2:BI999").Clear

Sheets("Result from analysis").Range("A2:G999").Clear



    Parameters(1) = Cells(5, 6)

    Parameters(2) = Cells(5, 7)

    Parameters(3) = Cells(5, 8)


  Sheets("MRM").Cells(1, 1) = "time"

  Sheets("MRM").Cells(1, 2) = "intensity"


  For t = 1 To 60

    I = Parameters(1) / ((t + Parameters(2)) ^ Parameters(3))
```

```
    Sheets("MRM").Cells(t + 1, 1) = t

    Sheets("MRM").Cells(t + 1, 2) = l

  Next t
```

'Tc(1) to Tc(S) is time of concentration for each subcatchment, Tc(S+1) is the longest time of concentration

```
ReDim Tc(S + 1)

ReDim Qpd(S, 60)
```

```
For ii = 1 To S

   Tc(ii) = Application.WorksheetFunction.Round(Cells(ii + 12, 9), 0)

        If Tc(ii) > Tc(S + 1) Then Tc(S + 1) = Tc(ii)




      For jj = 1 To 60

         Qpd(ii, jj) = Cells(ii + 12, 2) * Cells(ii + 12, 3) * Sheets("MRM").Cells(jj + 1, 2)

      Next jj
```

```
Next ii

ReDim V(60, 60 + Tc(S + 1))

ReDim Q(60, 60 + Tc(S + 1))

For ii = 1 To 60

    For jj = 1 To 60 + Tc(S + 1)

        For kk = 1 To S

            If ii <= Tc(kk) And jj <= ii Then
```

```
Q(ii, jj) = Q(ii, jj) + Qpd(kk, ii) * jj / Tc(kk)

ElseIf ii <= Tc(kk) And jj > ii And jj <= Tc(kk) Then

Q(ii, jj) = Q(ii, jj) + Qpd(kk, ii) * ii / Tc(kk)

ElseIf ii <= Tc(kk) And jj > Tc(kk) And jj <= Tc(kk) + ii Then

Q(ii, jj) = Q(ii, jj) + Qpd(kk, ii) * ii / Tc(kk) - Qpd(kk, ii) * (jj - Tc(kk)) / Tc(kk)

End If

If ii > Tc(kk) And jj <= Tc(kk) Then

Q(ii, jj) = Q(ii, jj) + Qpd(kk, ii) * jj / Tc(kk)

ElseIf ii > Tc(kk) And jj > Tc(kk) And jj <= ii Then
```

```
    Q(ii, jj) = Q(ii, jj) + Qpd(kk, ii)

    ElseIf ii > Tc(kk) And jj > ii And jj <= Tc(kk) + ii Then

    Q(ii, jj) = Q(ii, jj) + Qpd(kk, ii) - Qpd(kk, ii) * (jj - ii) / Tc(kk)

    End If

Next kk

    Sheets("Hydrograph").Cells(jj + 1, ii + 1) = Q(ii, jj)

    V(ii, jj) = V(ii, jj - 1) + (Q(ii, jj) + Q(ii, jj - 1)) * 30

      If Q(ii, jj) > Max(0) Then

        Max(1) = ii
```

```
            Max(0) = Q(ii, jj)

        End If

   Next jj

      If V(ii, 60 + Tc(S + 1)) > V(ii - 1, 60 + Tc(S + 1)) Then Max(2) = ii

      Sheets("Hydrograph").Cells(62 + Tc(S + 1), ii + 1) = V(ii, 60 + Tc(S + 1))

Next ii

For ii = 1 To 60 + Tc(S + 1)
```

```
    Sheets("Hydrograph").Cells(ii + 1, 1) = ii

Next ii

    Sheets("Hydrograph").Cells(62 + Tc(S + 1), 1) = "Total Volume"

For ii = 1 To 60

    Sheets("Result from analysis").Cells(ii + 1, 3) = Q(Max(1), ii)

Next ii

Sheets("Result from analysis").Cells(2, 9) = Max(0)

Sheets("Result from analysis").Cells(3, 9) = Max(1)
```

```
Sheets("Result from analysis").Cells(4, 9) = V(Max(1), 60 + Tc(S + 1))

Sheets("Result from analysis").Cells(5, 9) = Max(2)

'Max(0) is peak flow, Max(1) is the duration when peak flow occurs, Max(2) is the duration when peak volume occures V(Max(3)) is the peak volume graph

'Subcatchments
   ii = Sheets("Input file").Cells(Rows.Count, 1).End(xlUp).Row
   Sheets("Input File").Cells(ii + 2, 1) = "[SUBCATCHMENTS]"
   Sheets("Input File").Range("A" & ii + 3 & ":I" & ii + 3) = Array(";;Name      ", "Rain Gage       ", "Outlet", "Area", "%Imperv", "Width", "%Slope", "CurbLen", "SnowPack")
   Sheets("Input File").Range("A" & ii + 4 & ":I" & ii + 4) = Array(";;--------------", "----------------", "----------------", "--------", "--------", "--------", "--------", "--------", "----------------")
   For jj = 1 To S

         Sheets("Input File").Cells(ii + 4 + jj, 1) = "S" & jj
```

```
            Sheets("Input File").Cells(ii + 4 + jj, 2) = "RainGage        "
            Sheets("Input File").Cells(ii + 4 + jj, 3) = "J" & jj
            Sheets("Input File").Cells(ii + 4 + jj, 4) = Cells(12 + jj, 2)
            Sheets("Input File").Cells(ii + 4 + jj, 5) = Cells(12 + jj, 6)
            If Cells(12 + jj, 2) * 43560 / Cells(12 + jj, 8) < 300 Then
              Sheets("Input File").Cells(ii + 4 + jj, 6) = Cells(12 + jj, 2) * 43560 / Cells(12 + jj, 8)
            Else: Sheets("Input File").Cells(ii + 4 + jj, 6) = 300
            End If
            Sheets("Input File").Cells(ii + 4 + jj, 7) = Cells(12 + jj, 4) * 100
            Sheets("Input File").Cells(ii + 4 + jj, 8) = 0


    Next jj


    ii = ii + 4 + S


'Subareas
    Sheets("Input File").Cells(ii + 2, 1) = "[SUBAREAS]"
    Sheets("Input File").Range("A" & ii + 3 & ":H" & ii + 3) = Array(";;Subcatchment  ", "N-Imperv  ", "N-Perv    ", "S-Imperv  ", "S-Perv    ", "PctZero   ", "RouteTo   ", "PctRouted ")
    Sheets("Input File").Range("A" & ii + 4 & ":H" & ii + 4) = Array(";;--------------", "---------
```

```
-------", "----------------", "--------", "--------", "--------", "--------", "--------")

For jj = 1 To S

        Sheets("Input File").Cells(ii + 4 + jj, 1) = "S" & jj
            If Cells(jj + 12, 6) <> 100 Then
                Sheets("Input File").Cells(ii + 4 + jj, 2) = Cells(jj + 12, 7)
                Sheets("Input File").Cells(ii + 4 + jj, 3) = 0.015

            Else
                Sheets("Input File").Cells(ii + 4 + jj, 2) = Cells(jj + 12, 7)
                Sheets("Input File").Cells(ii + 4 + jj, 3) = Cells(jj + 12, 7)
            End If

Next jj

 Sheets("Input File").Range("D" & ii + 5 & ":F" & ii + 4 + S) = 0.0001
```

```
Sheets("Input File").Range("G" & ii + 5 & ":G" & ii + 4 + S) = "OUTLET    "

ii = ii + 4 + S

'Infiltration

Sheets("Input File").Cells(ii + 2, 1) = "[INFILTRATION]"

Sheets("Input File").Range("A" & ii + 3 & ":D" & ii + 3) = Array(";;Subcatchment   ", "CurveNum  ", "          ", "DryTime   ")

Sheets("Input File").Range("A" & ii + 4 & ":D" & ii + 4) = Array(";;--------------", "----------------", "----------------", "--------")

For jj = 1 To S

        Sheets("Input File").Cells(ii + 4 + jj, 1) = "S" & jj

        Sheets("Input File").Cells(ii + 4 + jj, 2) = Cells(jj + 12, 5)

Next jj

Sheets("Input File").Range("C" & ii + 5 & ":C" & ii + 3 + jj) = 0.2

Sheets("Input File").Range("D" & ii + 5 & ":D" & ii + 3 + jj) = 6.5
```

```
    ii = ii + 4 + S

'Junctions

    Sheets("Input File").Cells(ii + 2, 1) = "[JUNCTIONS]"

    Sheets("Input File").Range("A" & ii + 3 & ":F" & ii + 3) = Array(";;Name          ", "Elevation
", "MaxDepth  ", "InitDepth ", "SurDepth  ", "Aponded   ")

    Sheets("Input File").Range("A" & ii + 4 & ":F" & ii + 4) = Array(";;--------------", "----------
------", "----------------", "--------", "--------", "--------")



    For jj = 1 To S


        Sheets("Input File").Cells(ii + 4 + jj, 1) = "J" & jj


    Next jj


    Sheets("Input File").Cells(ii + 5 + S, 1) = "OUTJ"

    Sheets("Input File").Range("B" & ii + 5 & ":B" & ii + 5 + S) = 1

    Sheets("Input File").Range("C" & ii + 5 & ":F" & ii + 6 + S) = 0
```

```
Sheets("Input File").Cells(ii + 6 + S, 2) = "0"

ii = ii + 5 + S


'Outfalls
Sheets("Input File").Cells(ii + 2, 1) = "[OUTFALLS]"
Sheets("Input File").Range("A" & ii + 3 & ":F" & ii + 3) = Array(";;Name          ", "Elevation     ", "Type      ", "Stage Data      ", "Gated   ", "Route To        ")
Sheets("Input File").Range("A" & ii + 4 & ":F" & ii + 4) = Array(";;--------------", "----------------", "----------------", "--------", "--------", "--------")

Sheets("Input File").Cells(ii + 5, 1) = "OUT"
Sheets("Input File").Cells(ii + 5, 2) = "-1"
Sheets("Input File").Cells(ii + 5, 3) = "FREE      "
Sheets("Input File").Cells(ii + 5, 4) = "                "
Sheets("Input File").Cells(ii + 5, 5) = "NO      "
Sheets("Input File").Cells(ii + 5, 5) = "                "

ii = ii + 5
```

```
'Conduits

    Sheets("Input File").Cells(ii + 2, 1) = "[CONDUITS]"

    Sheets("Input File").Range("A" & ii + 3 & ":I" & ii + 3) = Array(";;Name           ", "From Node       ", "To Node         ", "Length    ", "Roughness ", "InOffset  ", "OutOffset ", "InitFlow  ", "MaxFlow   ")

    Sheets("Input File").Range("A" & ii + 4 & ":I" & ii + 4) = Array(";;--------------", "----------------", "----------------", "--------", "--------", "--------", "--------", "--------", "--------")



    For jj = 1 To S

        Sheets("Input File").Cells(ii + 4 + jj, 1) = "C" & jj

        Sheets("Input File").Cells(ii + 4 + jj, 2) = "J" & jj

    Next jj

    Sheets("Input File").Range("C" & ii + 5 & ":C" & ii + 4 + S) = "OUTJ"

    Sheets("Input File").Range("D" & ii + 5 & ":D" & ii + 5 + S) = 100

    Sheets("Input File").Range("E" & ii + 5 & ":E" & ii + 5 + S) = 0.001

    Sheets("Input File").Range("F" & ii + 5 & ":I" & ii + 5 + S) = 0

    Sheets("Input File").Cells(ii + 5 + S, 1) = "OUTC"

    Sheets("Input File").Cells(ii + 5 + S, 2) = "OUTJ"
```

```
    Sheets("Input File").Cells(ii + 5 + S, 3) = "OUT"

    ii = ii + 5 + S

'Xsections
    Sheets("Input File").Cells(ii + 2, 1) = "[XSECTIONS]"
    Sheets("Input File").Range("A" & ii + 3 & ":H" & ii + 3) = Array(";;Link           ", "Shape
", "Geom1           ", "Geom2     ", "Geom3     ", "Geom4     ", "Barrels   ", "Culvert   ")
    Sheets("Input File").Range("A" & ii + 4 & ":H" & ii + 4) = Array(";;--------------", "---------
-------", "----------------", "--------", "--------", "--------", "--------", "--------")

     For jj = 1 To S
       Sheets("Input File").Cells(ii + 4 + jj, 1) = "C" & jj

     Next jj

    Sheets("Input File").Cells(ii + 5 + S, 1) = "OUTC"
```

```
    Sheets("Input File").Range("B" & ii + 5 & ":B" & ii + 5 + S) = "CIRCULAR     "

    Sheets("Input File").Range("C" & ii + 5 & ":C" & ii + 5 + S) = 20

    Sheets("Input File").Range("D" & ii + 5 & ":F" & ii + 5 + S) = 0

    Sheets("Input File").Range("G" & ii + 5 & ":G" & ii + 5 + S) = 1


    ii = ii + 5 + S


'IDF

    jj = Sheets("IDF Parameters").Cells(1, Columns.Count).End(xlToLeft).Column

    For jj = 1 To jj

        If Sheets("IDF Parameters").Cells(1, jj) = ComboBox2.Value Then

        kk = jj

        End If

        Next jj




  If ComboBox1.Value = True Then

    y = ComboBox1.Value

    Parameters(1) = Sheets("IDF Parameters").Cells(y, kk + 1)
```

```
    Parameters(2) = Sheets("IDF Parameters").Cells(y, kk + 2)

    Parameters(3) = Sheets("IDF Parameters").Cells(y, kk + 3)

  Else: MsgBox ("Please select return period")

  Exit Sub

  End If



    ii = Sheets("Input file").Cells(Rows.Count, 1).End(xlUp).Row

    jj = Cells(9, 2)

    Sheets("Input File").Cells(ii + 2, 1) = "[TIMESERIES]"

    Sheets("Input File").Range("A" & ii + 3 & ":D" & ii + 3) = Array(";;Name     ", "Date      ",
"Time      ", "Value     ")

    Sheets("Input File").Range("A" & ii + 4 & ":D" & ii + 4) = Array(";;--------------", "---------
-------", "----------------", "--------")

    Sheets("Input File").Range("A" & ii + 5 & ":A" & ii + 65) = "IDF"

    l = Parameters(1) / ((Max(1) + Parameters(2)) ^ Parameters(3))



  For t = 1 To Max(1) + 1



    If t < 61 Then

    Sheets("Input File").Cells(ii + 4 + t, 3) = "0:" & (t - 1)
```

```
  Else
  Sheets("Input File").Cells(ii + 4 + t, 3) = "1:00"
  End If
  Sheets("Input File").Cells(ii + 4 + t, 4) = l
Next t


l = 0


For t = Max(1) + 2 To 61


  If t < 61 Then
  Sheets("Input File").Cells(ii + 4 + t, 3) = "0:" & (t - 1)
  Else
  Sheets("Input File").Cells(ii + 4 + t, 3) = "1:00"
  End If
  Sheets("Input File").Cells(ii + 4 + t, 4) = l
Next t


ii = ii + 65
```

```
'ReportTagsMap

    Sheets("Input File").Cells(ii + 2, 1) = "[REPORT]"

    Sheets("Input File").Range("A" & ii + 3) = Array(";;Reporting Options")



    Sheets("Input File").Cells(ii + 4, 1) = "SUBCATCHMENTS"

    Sheets("Input File").Cells(ii + 5, 1) = "NODES"

    Sheets("Input File").Cells(ii + 6, 1) = "LINKS"



    Sheets("Input File").Range("B" & ii + 4 & ":B" & ii + 6) = "ALL"



    Sheets("Input File").Cells(ii + 8, 1) = "[TAGS]"

    Sheets("Input File").Cells(ii + 10, 1) = "[MAP]"

    Sheets("Input File").Cells(ii + 11, 1) = "DIMENSIONS"

    Sheets("Input File").Range("B" & ii + 11 & ":E" & ii + 11) = Array("-100", "-100", "600",
"500")

    Sheets("Input File").Range("A" & ii + 12 & ":B" & ii + 12) = Array("Units     ", "Feet")



    ii = ii + 12



'Coordinates
```

```
Sheets("Input File").Cells(ii + 2, 1) = "[COORDINATES]"

Sheets("Input File").Range("A" & ii + 3 & ":C" & ii + 3) = Array(";;Node          ", "X-Coord
", "Y-Coord           ")

Sheets("Input File").Range("A" & ii + 4 & ":C" & ii + 4) = Array(";;--------------", "---------
-------", "----------------")


For jj = 1 To S

  Sheets("Input File").Cells(ii + 4 + jj, 1) = "J" & jj

Next jj


Sheets("Input File").Cells(ii + 5 + S, 1) = "OUTJ"

Sheets("Input File").Cells(ii + 6 + S, 1) = "OUT"


For jj = 1 To S

  Sheets("Input File").Cells(ii + 4 + jj, 2) = 50 + 100 * (jj - 1)

Next jj


Sheets("Input File").Cells(ii + 5 + S, 2) = 100 * S / 2

Sheets("Input File").Cells(ii + 6 + S, 2) = 100 * S / 2
```

```
    For jj = 1 To S
      Sheets("Input File").Cells(ii + 4 + jj, 3) = 200
    Next jj

    Sheets("Input File").Cells(ii + 5 + S, 3) = 250
    Sheets("Input File").Cells(ii + 6 + S, 3) = 300

    ii = ii + 7 + S

'Polygons
    Sheets("Input File").Cells(ii + 2, 1) = "[Polygons]"
    Sheets("Input File").Range("A" & ii + 3 & ":C" & ii + 3) = Array(";;Node          ", "X-Coord
", "Y-Coord           ")
    Sheets("Input File").Range("A" & ii + 4 & ":C" & ii + 4) = Array(";;--------------", "---------
-------", "----------------")

     For jj = 1 To S

          Sheets("Input File").Cells(ii + 1 + 4 * jj, 1) = "S" & jj
          Sheets("Input File").Cells(ii + 2 + 4 * jj, 1) = "S" & jj
```

```
        Sheets("Input File").Cells(ii + 3 + 4 * jj, 1) = "S" & jj

        Sheets("Input File").Cells(ii + 4 + 4 * jj, 1) = "S" & jj

    Next jj

    For jj = 1 To S
        Sheets("Input File").Range("B" & ii + 1 + 4 * jj & ":B" & ii + 4 + 4 * jj) = Application.Transpose(Array(((jj - 1) * 100), (jj * 100), (jj * 100), ((jj - 1) * 100)))
    Next jj

    For jj = 1 To S
        Sheets("Input File").Range("C" & ii + 1 + 4 * jj & ":C" & ii + 4 + 4 * jj) = Application.Transpose(Array("0", "0", "100", "100"))
    Next jj

    ii = ii + 4 + 4 * S

'Symbols
    Sheets("Input File").Cells(ii + 2, 1) = "[SYMBOLS]"
```

```
  Sheets("Input File").Range("A" & ii + 3 & ":C" & ii + 3) = Array(";;Gage         ", "X-Coord
", "Y-Coord          ")

  Sheets("Input File").Range("A" & ii + 4 & ":C" & ii + 4) = Array(";;--------------", "---------
-------", "----------------")

  Sheets("Input File").Range("A" & ii + 5 & ":C" & ii + 5) = Array("RainGage         ", "0",
"500")


  ii = ii + 5




 File

 Runswmm

 Read

 Rational

 Plot



 For ii = 1 To 180

  Sheets("Result from analysis").Cells(ii + 1, 1) = ii

  Sheets("Result from analysis").Cells(ii + 1, 2) = Sheets("outflow").Cells(2 * ii, 2)

  If Sheets("Result from analysis").Cells(ii + 1, 2) > MSWMM Then
```

```
  MSWMM = Sheets("Result from analysis").Cells(ii + 1, 2)

  TSWMM = ii

  End If

 Next


 For ii = 1 To 180

  VOL = VOL + (Sheets("Result from analysis").Cells(ii + 1, 2) + Sheets("Result from analysis").Cells(ii + 2, 2)) * 30

 Next


 Sheets("Result from analysis").Cells(13, 9) = MSWMM

 Sheets("Result from analysis").Cells(14, 9) = TSWMM

 Sheets("Result from analysis").Cells(15, 9) = VOL


 VOL = 0


 For ii = 1 To 60

 VOL = VOL + (Sheets("Result from analysis").Cells(ii + 1, 4) + Sheets("Result from analysis").Cells(ii + 2, 4)) * 30
```

```
  Next

  Sheets("Result from analysis").Cells(10, 9) = VOL

End Sub

Sub kinematic()

Dim t As Double, n As Double, l As Double

Dim P As Double, S As Double

Dim i As Integer

P = Cells(10, 2)

For i = 1 To Cells(9, 2)
```

```
    n = Cells(i + 12, 7)

    S = Cells(12 + i, 4)

    l = Application.WorksheetFunction.Min(Cells(i + 12, 8).Value, 100 * S ^ (0.5) / n)

    Cells(i + 12, 8) = l

    t = (0.007 * (n * l) ^ 0.8) / (P ^ (0.5) * S ^ (0.4))

    Cells(12 + i, 9) = Application.WorksheetFunction.Round(t * 60, 0)

Next i

End Sub


Sub Lag()

Dim t As Double, l As Double, cn As Double

Dim y As Double, S As Double

Dim i As Integer


For i = 1 To Cells(9, 2)

    l = Cells(12 + i, 8)

    cn = Cells(12 + i, 5)

    y = Cells(12 + i, 4) * 100

    S = (1000 / cn) - 10

    t = (l ^ 0.8 * (S + 1) ^ 0.7) / (1140 * y ^ 0.5)
```

```
    Cells(12 + i, 9) = Application.WorksheetFunction.Round(t * 60, 0)

    Next i


End Sub









Sub File()


  Dim cellValue As Variant

  Dim inpFilePath As String

  Dim ii, jj As Integer

  Dim lastRow, lastCol As Long

  inpFilePath = Cells(6, 2) & "\pre-dev_input.inp"

  'determine size of each line and number of lines

  lastCol = Sheets("Input File").UsedRange.SpecialCells(xlCellTypeLastCell).Column

  lastRow = Sheets("Input File").UsedRange.SpecialCells(xlCellTypeLastCell).Row
```

```
cellValue = ""
'open file for writing
Open inpFilePath For Output As #1
'read worksheet contents line by line
ii = 0
jj = 0
For ii = 1 To lastRow
  For jj = 1 To lastCol
      If jj = lastCol Then
      'last cell does not have trailing tab
          cellValue = cellValue + Trim(Sheets("Input File").Cells(ii, jj).Text) 'trims leading and trailing spaces
      Else
      'prints all cells in a row separated by a tab in a line fo text
          cellValue = cellValue + Trim(Sheets("Input File").Cells(ii, jj).Text) + "  " 'trims leading and trailing spaces
      End If
  Next jj
  Print #1, cellValue
  'clears text line for next row
```

```
    cellValue = ""
  Next ii
  Close #1

End Sub

Sub Runswmm()

Dim Run As Variant
Dim swmmPath, outFilePath As String
swmmPath = Cells(6, 2)
Run = Shell(swmmPath & "\runswmm.exe" & " " & swmmPath & "\pre-dev_input.inp" & " "
& swmmPath & "\pre-dev_input.rpt")
```

```
End Sub


Sub Read()

Dim textline As String

Dim outFilePath As String

Dim ii As Single

Sheets("SWMM output").Range("A:T").Clear

outFilePath = Cells(6, 2) & "\pre-dev_input.rpt"

Open outFilePath For Input As #2


'bug 3/31/20: code reads file before SWMM is finished, resulting in an incomplete file.

'Fix with loop that checks size of output file and continues when size stops increasing.


'Loop to wait on SWMM

'Dim kk As Long

'Dim checkSize(1000000000) As Long

'kk = 0

'For kk = 1 To 1000000000

'    checkSize(kk) = LOF(2)

'    If checkSize(kk) = checkSize(kk - 1) Then
```

```
'        Exit For
'    End If
'Next

'bug 3/31/20: loop to read length of SWMM file was crashing
'temporary fix: wait five seconds before reading file

Application.Wait (Now + TimeValue("0:00:05"))

'reads each line of text and trims leading and trailing spaces
ii = 1
Do While Not EOF(2)
    Line Input #2, textline

    Worksheets("SWMM output").Cells(ii, 1).Value = textline
    'Debug.Print textline
    ii = ii + 1
Loop
```

```
Close #2

'selects column A and separates each word into individual cells for every row
Worksheets("SWMM output").Activate
Worksheets("SWMM output").Range("A:A").Select
Selection.TextToColumns DataType:=xlDelimited, _
ConsecutiveDelimiter:=True, Space:=True
'makes flow data general number format
Worksheets("SWMM output").Range("C:C").Select
Selection.NumberFormat = "General"
Worksheets("User input").Activate
End Sub

Sub Rational()
Dim S As Integer, y As Integer, i As Integer
Dim t As Double, Q As Double, mt As Double, A As Double, C As Double
Dim B As Double, D As Double, E As Double
S = Cells(9, 2)
Dim j As Integer, k As Integer
```

```
    j = Sheets("IDF Parameters").Cells(1, Columns.Count).End(xlToLeft).Column

    For j = 1 To j

        If Sheets("IDF Parameters").Cells(1, j) = ComboBox2.Value Then

        k = j

        End If

        Next j




    y = ComboBox1.Value

    B = Sheets("IDF Parameters").Cells(y, k + 1)

    D = Sheets("IDF Parameters").Cells(y, k + 2)

    E = Sheets("IDF Parameters").Cells(y, k + 3)

For S = 1 To S

    If Cells(S + 12, 9) > mt Then mt = Cells(S + 12, 9)

    t = Cells(S + 12, 9)

    Cells(S + 12, 10) = Application.WorksheetFunction.Round(B / ((t + D) ^ E) * Cells(S + 12,
2) * Cells(S + 12, 3), 2)

    A = A + Cells(S + 12, 2)

    C = C + Cells(S + 12, 3) * Cells(S + 12, 2)
```

```
Next S
    C = C / A
    Q = Application.WorksheetFunction.Round(B / ((mt + D) ^ E) * A * C, 2)
    Cells(S + 12, 10) = Q
    Cells(S + 14, 10) = Application.WorksheetFunction.Round(Sheets("Result from analysis").Cells(2, 9), 2)


    For i = 1 To mt
        Sheets("Result from analysis").Cells(i + 1, 4) = Q / mt * i
    Next i


    For i = mt To 60
        Sheets("Result from analysis").Cells(i + 1, 4) = Application.WorksheetFunction.Max(Q - (Q / mt * (i - mt)), 0)
    Next i


    Sheets("Result from analysis").Cells(8, 9) = Q
    Sheets("Result from analysis").Cells(9, 9) = mt


End Sub
```

```
Sub Plot()

Dim i As Double, j As Double, k As Single

Dim Max As Double, S As Double

S = Cells(9, 2)

i = 1

Do

  i = i + 1

Loop Until Sheets("SWMM output").Cells(i, 4) = "OUTC"

i = i + 5

j = i + 359

k = 1

For i = i To j

   Sheets("Outflow").Cells(k, 2) = Sheets("SWMM output").Cells(i, 4)

   If Sheets("SWMM output").Cells(i, 4) > Max Then Max = Sheets("SWMM output").Cells(i,
4)

   k = k + 1

Next i


Cells(S + 14, 10) = Application.WorksheetFunction.Round(Max, 2)
```

```
End Sub
```