Evaluating alternatives for the implementation of Curve Number in SWMM for an urbanized watershed

By

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Abstract

Modeling hydrological abstraction, particularly infiltration, in urbanized areas is a complex task. Without field validation data, researchers and engineers often rely on readily available methodologies on semi-empirical formulations such as the Curve Number (CN) method. Curve Number is a factor that depends on land cover, antecedent moisture conditions, and hydrologic soil groups to determine the maximum soil moisture storage capacities derived by Soil Conservation Service (SCS). Many hydrological models have implemented the CN method in their formulation, including Storm Water Management Model (SWMM). The CN method in SWMM is used to determine only the cumulative infiltration changes with cumulative rainfall during the rainfall events instead of direct runoff in the original SCS CN method. The CN method is highly suggested to apply only to the pervious area of the subcatchments with assigning the corresponding percent of impervious area of the subcatchments in SWMM. However, it is relatively complex and sophisticated to specify the percentage of impervious area by subjective assumptions and average the CN only for the rest of pervious area. This research tested two alternative ways of setting up the CN method in SWMM based on the QGIS plugin "*CurveNumberGenerator*" to find the shortcut. The model results were compared with field data collection performed at the headwater reaches of Moore's Mill Creek in Opelika and Auburn, AL. Research results indicated that the *Fully Composite CN* approach yielded better for more impervious watersheds. Regarding the *CN Cut-off* approach, a cut-off value of 90 presented the optimum results for most cases of the mixed urban areas and undeveloped areas with hydrologic soil group A/B.

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I do appreciate the help from my committee members, Dr. Fang and Dr. O'Donnell. I have taken a large number of courses and learned plenty of water resource knowledge from them. They also provided me a bunch of help when I had difficulties and questions in my study life.

I also want to thank Robson, Vitor, Gianlucca, Macabe, and Dingyu's help. Robson gave me many instructions when I had model questions. Vitor helped me to create a sweet VBA code to calculate the percentages of impervious area and weighted Curve Number values. Gianlucca, Macabe, and Dingyu accompanied me to the field respectively to collect the water depth and rainfall data.

Besides, I would also like to acknowledge the CHI (Computational Hydraulic International) for granting me the Educational License of PCSWMM (Personal Computer Storm Water Management Model). The research question was able to test with the help of powerful PCSWMM software, which has SWMM engines but with more useful tools such as SRTC (Sensitivity-based Radio Tuning Calibration) calibration tool and WDT (Watershed Delineation Tool) GIS tool.

At last, I am extremely grateful to my family. With their support, no matter in financial or in spirit, I could keep going without any worries and fears on the road of my studying abroad.

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List of Abbreviations

ASCE: American Society of Civil Engineering
CHI: Computational Hydraulic International
CN: Curve Number
HEC-HMS: Hydrologic Engineering Center – Hydrologic Modeling System
NCEI: National Centers for Environmental Information
NOAA: National Oceanic and Atmospheric Administration
NRCS: Natural Resources Conservation Service
NSE: Nash-Sutcliffe Efficiency
PCSWMM: Personal Computer Storm Water Management Model
QGIS: Quantum Geographic Information System
R^2: Coefficient of Determination
SCS: Soil Conservation Service
SRTC: Sensitivity-based Radio Tuning Calibration
SWAT: Soil & Water Assessment Tool
SWMM: Storm Water Management Model
USDA: United States Department of Agriculture
VBA: Visual Basic for Applications
WDT: Watershed Delineation Tool

1. Introduction

The hydrologic cycle is an essential component of the natural environment. The evaporation process in the surface water bodies causes precipitation and then leads to abstractions such as infiltration and transpiration. Excess rainfall creates runoff in watersheds which in turn creates surface and subsurface flow that eventually returns to surface water bodies. And then the entire process is restarted. This process is affected by urbanization, and changes to the hydrological cycle can result in adverse conditions such as stream flooding and water pollution. In order to address this kind of problems, it is necessary to develop reliable and sustainable designs that anticipate how changes to the watershed influence the local hydrology, and the hydrologic models are the tools used in this context.

Hydrologic models are used to simulate the natural process related to water movement. They can provide an understanding of a range of water resource problems for engineers and designers. Over decades, a number of hydrologic models with user-friendly interfaces have been developed and updated for engineers to solve problems. These include the HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) developed by the U.S. Army Corps of Engineers (Feldman 2000), the SWMM (Storm Water Management Model) developed by the U.S. Environmental Protection Agency (Rossman 2015), the SWAT (Soil & Water Assessment Tool) developed by U.S. Department of Agriculture, Agricultural Research Service (USDA, ARS) (Neitsch, et al. 2002), and etc. The HEC-HMS and SWMM models can estimate the peak flood discharge and simulate the runoff hydrograph at specific locations in a watershed. SWMM, the tool focused on in this research, is more commonly used in urbanized watersheds. The SWAT model is commonly used to simulate the impacts of land use and land changes on water quantity and quality in agricultural systems. In all cases, to build and run a hydrologic model, considerable data inputs are required, including precipitation, subcatchment characteristics, evaporation, and infiltration. The infiltration process is the focus of this research.

Infiltration is the process that rainfall penetrates the ground and fills the pores of the soil (Rossman 2016). Infiltration data is one of the most complex data inputs which plays a key role in runoff calculations. Currently, there are several standard infiltration methods such as Horton (Horton 1933), Green-Ampt (Green and Ampt 1911), and Curve Number (CN) (NRCS 1986) methods in SWMM. Among those methods, the Curve Number method is one of the simplest rainfall loss methods with fewer parameters. Curve Numbers are associated with soils and land uses, which higher CNs generate more runoff. In SWMM, pervious area and impervious area are provided to the users to define the fraction of impervious area by themselves. While determining whether an area in a subcatchment is impervious for certain land uses (e.g., lake, roof, parking lot) is straightforward, for mixed urban development areas (e.g., mid-intensity residential areas) or the soils with low infiltration capacity areas, in which the behavior of the soils emulate impervious surfaces regardlesss even if the areas are undevloped are not in the case. A ***Fully Composite CN*** approach considers all the areas as pervious areas and weights each curve number in each subcatchment according to its area based on the gridded CN values. However, whether the Fully Composite CN approach with setting all areas as pervious is feasible and reliable in the SWMM model is still unclear (Schoenfelder, Kacvinsky and Rossman 2007, Zhang, et al. 2007). Furthermore, whether there is a more straightforward way to calculate and identify the percent of imperviousness in a watershed is deserved to explore.

As an attempt to overcome the difficulties of determining if an area should be considered impervious or not in the infiltration calculations in SWMM, this research proposed an alternative approach, referred to as the ***CN Cut-off*** approach, to easily determine the percent of imperviousness combined with area-weighted CN only for the pervious area. The CN Cut-off approach pragmatically assumes a threshold CN value after which an area is classified as impervious irrespective of the actual land use. This new approach would be unfeasible without a satisfactory spatial resolution (i.e., 30 m x 30 m) for CN values used in this research. Moreover, a Fully Composite CN approach was also tested compared with the developed alternative approach based on the justification of the field data.

The overarching objective of this research is to assess the validity of those approaches to compute CN-based infiltration model in SWMM. Specific objectives of this research included:

1) To perform a field investigation program to collect data for SWMM model calibration.

2) To develop a SWMM model for the headwater of Moore's Mill Creek Watershed in East Alabama.

3) To assess the accuracy of Fully Composite or Cut-off based CN infiltration methods in SWMM model in terms of peak flow depth computations.

4) To provide suggestions for future research.

2. Literature Review

2. 1 Hydrological Modeling and SWMM

Models are used to represent the complex and often chaotic reality. In real world, human activities and changing environments will break the natural balance of the water cycle (Wang, Chen and Xu 2021). For instance, one of the most significant hydrological impacts of urban development is the increase in surface runoff and the flashiness of storm hydrograph (Praskievicz and Chang 2009). Hence, it is important to understand the processes of water-cycle and their responses to human activities and climate changes (Wang, Chen and Xu 2021). The hydrologic cycle is a sun-driven process whereby surface water evaporates as water vapor to the atmosphere and then precipitates back to the ground (Warren Viessman and Lewis 2014). According to Praskievicz and Chang (2009), an increase in overall surface runoff and the degradation of water quality as a result of non-point source pollution are associated with the impact of urban development. Therefore, the hydrological models should be applied to find solutions to those kinds of problems. Developing hydrological models can help engineers and researchers to study the water cycle as a crucial strategy to achieve better environmental management (Wang, Chen and Xu 2021).

Hydrological models are concerned with the movement of water which are used to simulate natural processes related to water and help engineers and researchers to evaluate and analyze the natural process such as flow rates or depth of water in streams, and are widely used tools for water resources management (Mujumdar and Kumar 2012). The hydrological models are classified as (semi-)distributed or lumped models depending on if the space derivatives are included (Mujumdar and Kumar 2012). Semi-distributed models or fully-distributed models depend on whether the runoff is calculated at every grid cell (Sitterson, et al. 2018). Spatial interpretations of the different types of hydrological models are shown in Figure 2. 1.

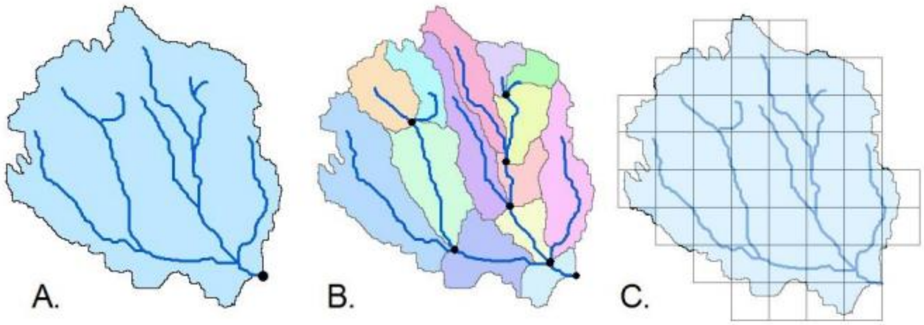


Figure 2. 1: Visualization of the Three Different Types of Runoff Models. A.: Lumped Model, B.: Semi-Distributed Model by Subcatchment, C.: Distributed Model by Grid Cell (Sitterson, et al. 2018)

A multitude of hydrological models exist today are used to estimate flood runoff, routing of flood hydrographs, and assessment of flood inundation (Mujumdar and Kumar 2012). Singh and Woolhiser (2002) have provided a summary sample table of popular hydrologic models worldwide. For instance, they explained that HEC-HMS is considered the standard model for drainage system design and quantifying the land-use change effect on flooding, and the National Weather Service River Forecast System (NWS-RFS) model is the standard model for flood forecasting in USA (Singh and Woolhiser 2002).

Hydrological models such as SWMM and PCSWMM are classified as deterministic models due to lots of physical explanations of most processes (James 2005). Deterministic models are constructed with governing equations based on conservation laws of mass and linear momentum, they are extremely useful because of the ability to provide solutions to certain water resources problems (James 2005). Moreover, with the development of high-end techniques, the geographic information system (GIS) tool which can stack, analyze, and retrieve large numbers of non-spatial and geo-databases, and the digital elevation models (DEM) tool which can analyze the digital elevation data at regular grid spacing are integrated together into a distributed hydrological model for the modeling improvement (Mujumdar and Kumar 2012). Such integration will significantly improve the modeling of various components of the hydrologic cycle and help monitor the damage estimation and mitigation of near-real-time flood events (Mujumdar and Kumar 2012).

The Storm Water Management Model (SWMM) is a hydrological, hydraulic, and water quality model for either event-based or continous simulations which was first developed in 1971 (Rossman 2015). The model is one of the most widely used hydrological models in the world and is particularly used in the context of urban stormwater management. From the start, the model was capable of event-based and continuous hydrological simulations, which typically yield more meaningful initial conditions than event-based modeling (Rossman 2016).

The SWMM model divides urban areas in subcatchments, in which hydrological processes such as rainfall, infiltration, depression storage, and overland flow are presented. The main components of a SWMM model include rain gauges, subcatchments, aquifers, junctions, outfalls, conduits, and storage units. The rain gauges, subcatchments, and aquifers are model components that belong to the Hydrology category. Junctions, outfalls, conduits, and storage units are components of the Hydraulics category. The rain gauge is the source of precipitation data to the subcatchments. The subcatchments are portions of the watershed that receive precipitation with data provided by the rain gauges, and through hydrological calculations of effective rainfall generate runoff that flow into the junctions. The aquifer is a model component that collects infiltration from subcatchments and represents shallow groundwater flows, including exfiltration into streams. Junctions are the points in the conveyance system that correspond to the start or confluence of natural and artificial conduits that route flows in the watershed toward. The outfall is the end point of the conveyance system. The conduits are channels or pipes that conveys water from such as junction to junction. The storage units correspond to ponds, lakes, or reservoirs that store or temporarily hold the surface water. Water quality processes can also be simulated by SWMM, but they are not included in the scope of the present research objectives. Figure 2. 2 shows the representation of the key elements in SWMM. Advanced implementations of SWMM in urban watersheds enable complex subcatchments and drainages (see Figure 2. 3).

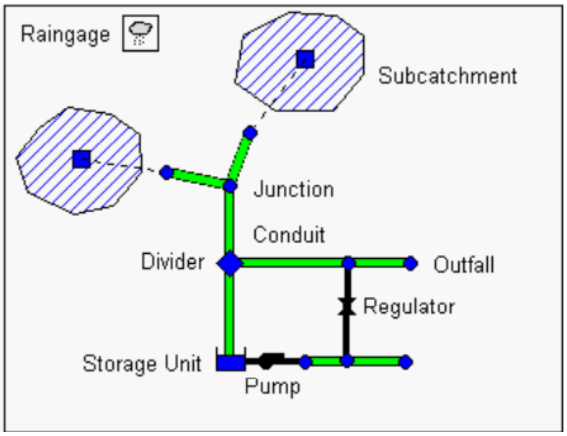


Figure 2. 2: SWMM Main Components (Rossman, 2017)

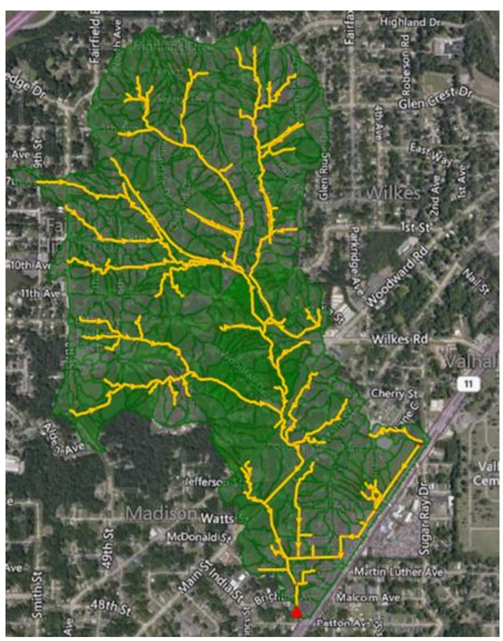


Figure 2. 3: SWMM Model of a Watershed in Jefferson County (Vasconcelos and Pachaly 2021)

2. 2 Precipitation and Rain Gauge

Precipitation can not only replenish surface water bodies, renew soil moisture for plants, and recharge aquifers, but also cause the flood problem when severe precipitation happens (Warren Viessman and Lewis 2014). Precipitated water experiences interception, evaporation, and infiltration and finally becomes surface flow which is the runoff. The precipitation plays a pivotal role in hydrological modeling which is the principal driving force in rainfall-runoff simulation (Rossman 2016). The precipitation data could be collected from either radar data or from physical rain gauge(s) installed in watersheds. Rain gauges play essential roles in providing accurate precipitation data for hydrological model simulations. Based on Skinner, et al. (2009), they compared Next Generation Radar (NEXRAD) and rain gauge precipitation measurements in South Florida, and their 4-year results revealed that NEXRAD had the tendency to overestimate small rainfall amounts and underestimate large rainfall amounts relative to the gauge network. Therefore, to get accurate model results, it is better to use the physical rain gauge data as a precipitation source or apply systematic offsets before using Radar data. However, Skinner, et al. (2009) also indicated that the rain gauges may not be able to fully capture high spatial variability rain events. In that case, radar technology may be used to catch a spatial account of rainfall.

Sadler, et al. (2017) quantified the effect of rain gauge proximity on area-averaged rainfall estimation for small urban watersheds in Virginia Beach. Their results suggested that a rain gauge within 0.5 km of the target watershed would be needed for flash-flood warning application at their research site. Since the study area in our research is not too large and the research goal is to catch the peak depth, only one rain gauge is installed to collect the rainfall data. However, installing multiple rain gauges is highly recommended if conditions permit. Because some rainfall, such as thunderstorms, may be highly localized, the single rain gauge may not be able to provide accurate rainfall data for different loggers' locations. Besides, the multiple rain gauges can avoid the risk of losing appropriate precipitation data when one of the rain gauges gets jammed by materials like leaves or bird droppings.

2. 3 Abstractions and Curve Number Hydrology

As described before, there are various abstractions (interception, depression storage, evaporation, transpiration, and infiltration) before the precipitation turns into runoff. *Interception* is the segment of gross precipitation input that gets intercepted by the aboveground objects such as vegetation until it is returned to the atmosphere through evaporation (Warren Viessman and Lewis 2014). *Depression storage* is a volume that is filled in both pervious and impervious depressed areas prior to the runoff occurrence (Rossman 2016). *Evaporation* is the process that water is transferred from the land to the atmosphere and transpiration is the evaporation counterpart for plants (Warren Viessman and Lewis 2014). *Infiltration* is the process that water penetrates into the ground and replenishes soil moisture and aquifers (Warren Viessman and Lewis 2014, Rossman 2016). Some empirical equations were invented to estimate the runoff, such as the famous SCS Curve Number method.

The Curve Number (CN) is a dimensionless empirical parameter to indicate the runoff response characteristic of the subcatchments (NRCS 1986). The Curve Number method was first developed in mid last century (1950s) by the USDA Soil Conservation Services (SCS) now renamed as Natural Resources Conservations Service (NRCS). The SCS CN method is a commonly used empirically-based methodology which is based on soils, cover, and land use (Hawkins, Ward, et al. 2009). The CN method is used to compute effective runoff depth (Q) from rainfall depth (P), maximum moisture storage capacity (S), and initial abstraction (I_a) (NRCS 1986). The SCS CN equations are:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad (2.1)$$

$$I_a = 0.2S \quad (2.2)$$

$$S = \frac{25400}{CN} - 254 \quad (2.3)$$

Where, Q is the runoff depth (mm), P is the rainfall depth (mm), S is the potential maximum retention after runoff begins (mm), and I_a is the initial abstraction (mm).

There are numerous controversies about the application and accuracy of the original SCS CN method (Hawkins, Ward, et al. 2009, Hawkins, Theurer and Rezaeianzadeh 2019, Galbetti, et al. 2022). At the same time, some researchers provided recommendations and suggestions in examining and enhancing the method with the development of CN method history. Garen and Moore (2005) talked about that the Curve Number procedure is a one or two-parameter watershed-scale event model that computes streamflow volume for a storm. They suggested that the Curve Number should not be treated as the only overland flow from the entire land unit in the model. Moreover, to correctly identify flow paths and source areas, a hydrological algorithm needs to simulate all the spatially variable processes. Praskievicz and Chang (2009) reviewed some studies using hydrological models to predict stream response to changes in precipitation amounts and delivery patterns and have used a variety of techniques to generate future scenarios. Yan and Edwards (2013) also mentioned that the SCS Curve Number runoff model has the ability to provide a way of prediction for planning stormwater systems and improving flood frequency analysis prediction. Albeit generally accepted, there are some critiques of the original TR-55 (NRCS 1986) Curve Number method. Bartlett, et al. (2016) stated that the SCS-CN method is not only restricted to certain geographic regions and land use origins but does not describe the spatial variability of runoff as well. In addition, the frequently using of the weighted curve number approach can lead to the underestimation of the total runoff (Ormsbee, Hoagland and Peterson 2020). Moreover, a significant error will be presented in the model when the accuracy of the Curve Numbers is not enough when applying the curve number method (Hawkins 1975).

SCS Curve Number method is introduced in the surface runoff chapter of SWMM Hydrology manual (Rossman 2016). In SWMM, the subcatchments are modeled as a nonlinear reservoir to generate the overland flow, as shown in Figure 2. 4, where d is the water depth and d_s is the depression storage accounting for initial abstractions. Developed urban areas are always containing a mix of land use such as commercial area, vegetations area, and residential area. Those land surface types can be divided into two primary categories: pervious area and impervious area. And each impervious area can be divided into impervious area or impervious area without depression storage.

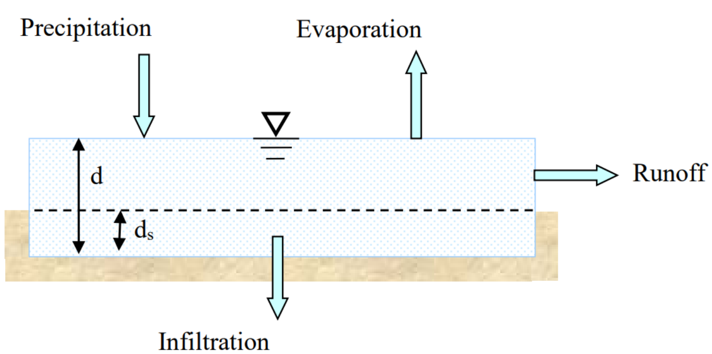


Figure 2. 4: Nonlinear Reservoir Model of a Subcatchment (Rossman, Storm Water Management Model Reference Manual Volume I – Hydrology (Revised) 2016)

With the CN tables developed by SCS and published in TR-55, and the knowledge of soil type and land use, the single CN value can be identified (Feldman 2000). For a watershed that consists of multiple soil types and land uses, a composite CN could be calculated by using equation (2.4). If the CN are composite values for directly-connected impervious area and open space, no further accounting for the impervious area is required which refers to the Fully Composite CN approach (Feldman 2000). However, in SWMM, the CN method is suggested to only be applied to the pervious area, so it is necessary to estimate the imperviousness of the subcachments. The percent of imperviousness of a subcatchment can be measured precisely from aerial photos or land use maps (Rossman 2016). However, this kind of work could be very tedious, and if done manually through observation adds a degree of subjectivity. As is further elaborated, in order to simplify the estimation of the percent of imperviousness in SWMM subcatchments, this research proposes an approach called the *CN Cut-off* strategy that calculates the percent of imperviousness based solely on the gridded CN values through the QGIS plugin "*CurveNumberGenerator*" (Siddiqui 2020) and Excel Visual Basic for Application (VBA) code.

$$CN_{composite} = \frac{\sum A_i CN_i}{\sum A_i} \tag{2.4}$$

Where $CN_{composite}$ is the composite CN used for runoff volume computations, i is the index of watersheds subdivisions of uniform land use and soil type, CN_i is the CN for subdivision i, and A_i is the drainage area of subdivision i.

To apply the SCS Curve Number method in SWMM when approximating runoff, Rossman (2016) indicates that the percent impervious area of the subcatchments could be set to 0, the pervious area depression storage should be set equal to the initial abstraction depth, and the pervious area roughness coefficient should be set to 0 to prevent the delay in runoff flow. However, when the overland roughness is set as 0.1 to allow SWMM to produce realistic runoff hydrograph, the total runoff volume will drop a lot due to increased time for ponded water to infiltrate through the overland surface. Therefore, to get a realistic hydrograph, the overland roughness should not be set equal to 0, and keep in mind that it will probably underestimate the runoff. This research is going to test the model performance when setting the typical overland roughness based on tabulated values with modified composite Curve Number method in SWMM model for continuous simulations.

2. 4 Infiltration Computation in SWMM

When it comes to infiltration, there are several different methods provided in SWMM Hydrology manual (Rossman 2016) to estimate it. The most famous infiltration method is the Horton's method which is empirical in nature developed by Horton in the early 1930s. Horton proposed an exponential equation (2.5) to predict the infiltration based on the multiple observation of field measurements (Rossman 2016). Horton's method applies only to events where rainfall intensity consistently exceeds the infiltration capacity.

$$f_p = f_\infty + (f_0 - f_\infty)e^{-k_d t} \tag{2.5}$$

Where f_p is the infiltration capacity (depth/time) into soil, f_∞ is the minimum or equilibrium value of f_p (at t = ∞), f_0 is the maximum or initial value of f_p (at t = 0), t is the time from the beginning of the storm, and k_d is decay coefficient (a constant). Another method provided by SWMM is the Green-Ampt method, originally proposed in 1911, which is based on Darcy's Law and Richards Equation. The governing equation (2.6) is shown below where infiltration capacity is a function of hydraulic conductivity K_s, the capillary suction head along the wetting front ψ_s, the depth of ponded water at the surface d, and the depth of the saturated layer below the surface L_s (Rossman 2016). The three key parameters are relatively hard to measure especially for the suction head (ψ_s).

$$f_p = K_s[\frac{d+L_s+\psi_s}{L_s}] \tag{2.6}$$

The newest infiltration method provided by SWMM is the Curve Number method which is based on the SCS Curve Number method for evaluation of rainfall excess (Rossman 2016). The SWMM Curve Number method is different from the original SCS Curve Number that it only accounts for infiltration losses instead of lumps all lost due to interception, depression storage, and infiltration together. The other abstractions are modeled separately in SWMM. To apply the Curve Number method in SWMM, only two parameters are required: the Curve Number and the drying time. The drying time is related to a soil's saturated hydraulic conductivity the same parameter in the Green-Ampt method. Different researchers used the Curve Number method as their infiltration model. Yan and Edwards (2013) referenced Shi, et al. (2007) who recommended using the Curve Number model when hydrological and meteorological data were insufficient. In this research, likewise, because of insufficient infiltration data, and the Curve Number method is the least parameters required infiltration model, it is used as the infiltration model in SWMM in this study.

2. 5 Flood and Urban Drainage Infrastructure in Watersheds

A flood is an overflow of water that submerges normally dry land and may last days or weeks (NOAA n.d.). There are multiple types of floods. A river flood occurs when water levels beyond the top of riverbanks. A coastal flood is an inundation with seawater on normally dry land areas along the coast such as Hurricane Harvey caused the serious flood problem in Houston in August 2017. An inland flood could be caused by steady rainfall over several days or a short and intense period of rainfall. The clogged drainages could also cause an inland flood when rainfall runoff cannot be channeled properly into the drainage systems (Earth Eclipse 2022). A flash flood happens when high-intensity heavy or excessive rainfall precipitates in the low-lying areas within six hours, caused mainly by severe thunderstorms, and sometimes can be caused by the failure of a dam or levee (NOAA n.d.).

Within an urban watershed, it is anticipated the existence of urban drainages infrastructure systems such as sewers, culverts, and trenches. Nevertheless, the drainage infrastructure could still fail and cause the flood because of design issues, construction issues, severe rain events, or increased urbanization. To alleviate the flood problems, the engineering design of drainage considers technical factors and cost, but flooding risks are never eradicated. Drainage infrastructures should be added to the hydrological model to better simulate the urban watershed response. Meierdiercks, et al. (2010) found that drainage networks play a significant role in determining urban hydrologic response through their research results. Their results also indicated that drainage density and presence of stormwater ponds affect peak discharge more significantly in the subbasins including storm pipes, surface channels, street gutters, and storm management ponds than the percent of impervious or land use type of the sub-basins. Another research about drainage systems in an urban area (Campeche District, in Santa Catarina State, south of Brazil) found that a drainage system can decrease the susceptibility to urban flooding in approximately 27% of their research region (Caprario, et al. 2019). In their conclusion part, they stated that the model analyses show that converting impervious upstream portions of the sub-basin to 100% pervious only reduces a little peak flow. An urban watershed in Albany County, NY (Meierdiercks, Kolozsvary, et al. 2017) found that the drainage network properties and slope are the dominant controls on run-off volumes for water quantity. Therefore, it is essential to represent the urban drainage infrastructure in SWMM models as close as the reality, such as the one presented in this research.

2. 6 Model Calibration and Validation

Prior to any hydrological model evaluation and use, it is important for modelers to clearly understand the ultimate objective of model application and available data (Ahmadisharaf, et al. 2019). The different goals can alter the calibration parameters. In the case of this research, the objective was to represent the peak depth between the simulation result and the observed data. Therefore, the computed peak depth is plotted against the observed peak depth for several different rainfall events (James 2005). In terms of calibration and validation, Ahmadisharaf, et al. (2019) reviewed existing approaches for model calibration, validation, and uncertainty analysis. It also provided recommendations to establish baseline modeling practices to obtain a satisfactory watershed model. Finally, numerical models will be influenced by the initial conditions such as the soil moisture, water level in ponds, and flows in conduits, which are often unknown. Thus, a procedure referred to as a model warm-up is used, whereby the model is allowed to run with data prior to the time of interest in the analysis. A warm-up procedure is recommended to reduce model dependence on unknown initial conditions (Ahmadisharaf, et al. 2019).

Model calibration often entails an iterative process for changing parameters in the simulation until a satisfactory agreement between simulations and observations is achieved. In urban runoff quantity modeling of peak flow, the computed versus observed points should fit on a 45 degrees line with little scatter for a good calibration (James 2005). Moriasi, et al. (2007) and Moriasi, et al. (2015) suggested that if daily, monthly, or annual coefficient of determination (R^2) > 0.6, Nash-Sutcliffe efficiency (NSE) > 0.5, and percent bias (PBIAS) <= $\pm$15% for watershed-scale models, the model performance can be judged “satisfactory” for flow simulations. In this research study, (Moriasi, Arnold, et al. 2007) & (Moriasi, Gitau, et al. 2015)’s model evaluation criteria are used as guidance and reference on model performance. James (2005) introduced sensitivity analysis in PCSWM modeling as the modeling calibration and validation reference. The model evaluation statistics equations are shown below (Moriasi, Gitau, et al. 2015).

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]^2 \quad 0\ to\ 1 \tag{2.7}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad -\infty\ to\ 1 \tag{2.8}$$

$$PBIAS = \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} \times 100 \quad -\infty\ to\ \infty \tag{2.9}$$

Where, O are observed values, P are predicted values, and the optimal value is 1 for R^2 and NSE, and 0 for PBIAS.

Once the hydrological model is calibrated, another independent data set should be run to evaluate and verify the reliability of the calibrated obtained parameters of the model. That process is called model validation, ensuring credibility and confidence in model results. Model validation is the extension of model calibration, which tests the optimum parameters against a new set of observations (James 2005). Because the created model in this research is not going to use to solve the real problems at this stage, the validation process is skipped in this research study.

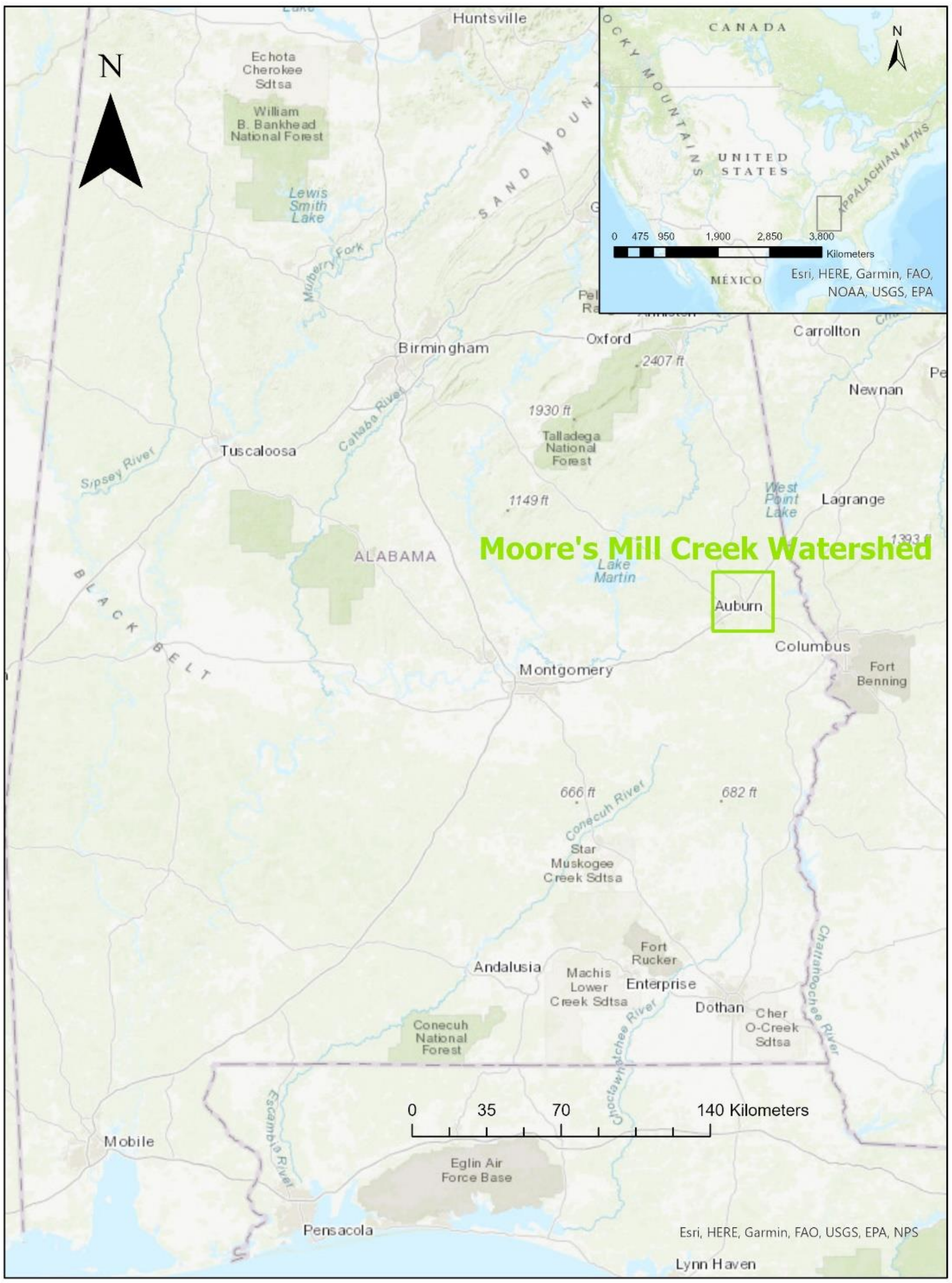
3. Methodology

Models can provide insights to the engineers about reasonable design ideas. Nevertheless, as stated by British statistician George E. Box, “All models are wrong, though some may be said to be useful.” To improve model reliability, field investigations are needed to support calibration and validation tasks of models (James 2005). As is further elaborated, this research combines fieldwork and numerical modeling to test alternative and practical approaches that assigning Curve Number (CN) values to subcatchments in the SWMM model. Infiltration-based CN method is the most popular method among the present infiltration methods such as Horton method, Green-Ampt method, and Richards’ equation to compute effective rainfall in hydrological models. Yet, CN assignments can be laborious and has uncertainties associated with the land use and soil characteristics. With the development of geospatial databases, the computation and assignment of CN within hydrological models has been simplified, but it is still uncertain that what approach is the best to compute CN to represent the peak flow depth.

As explained earlier in this thesis, one goal is to assess the accuracy of the Fully Composite approach to validate the approach’s feasibility of assuming the whole SWMM subcatchment as pervious and adjusting CN accordingly. The other goal is to assess the accuracy of the CN Cut-off approach when assigning imperviousness based solely on CN values. In this context, the accuracy is assessed by comparing modeled peak flow depths against measured values at different subcatchments within the Moore’s Mill Creek watershed, in Lee County, Alabama. This chapter describes the steps taken for the field monitoring of the studied area, and the effort to perform the hydrological modeling setup and calibration.

3. 1 Study Area

The research watershed is located at the headwater of the Moore's Mill Creek, a second-order stream where is located within Lee County. The creek flows from northeast to southwest starts from Opelika through East Auburn, Chewacla State Park and ends at the confluence with Chewacla Creek. The entire watershed occupies an area near 30 km^2 (see Figure 3. 1).



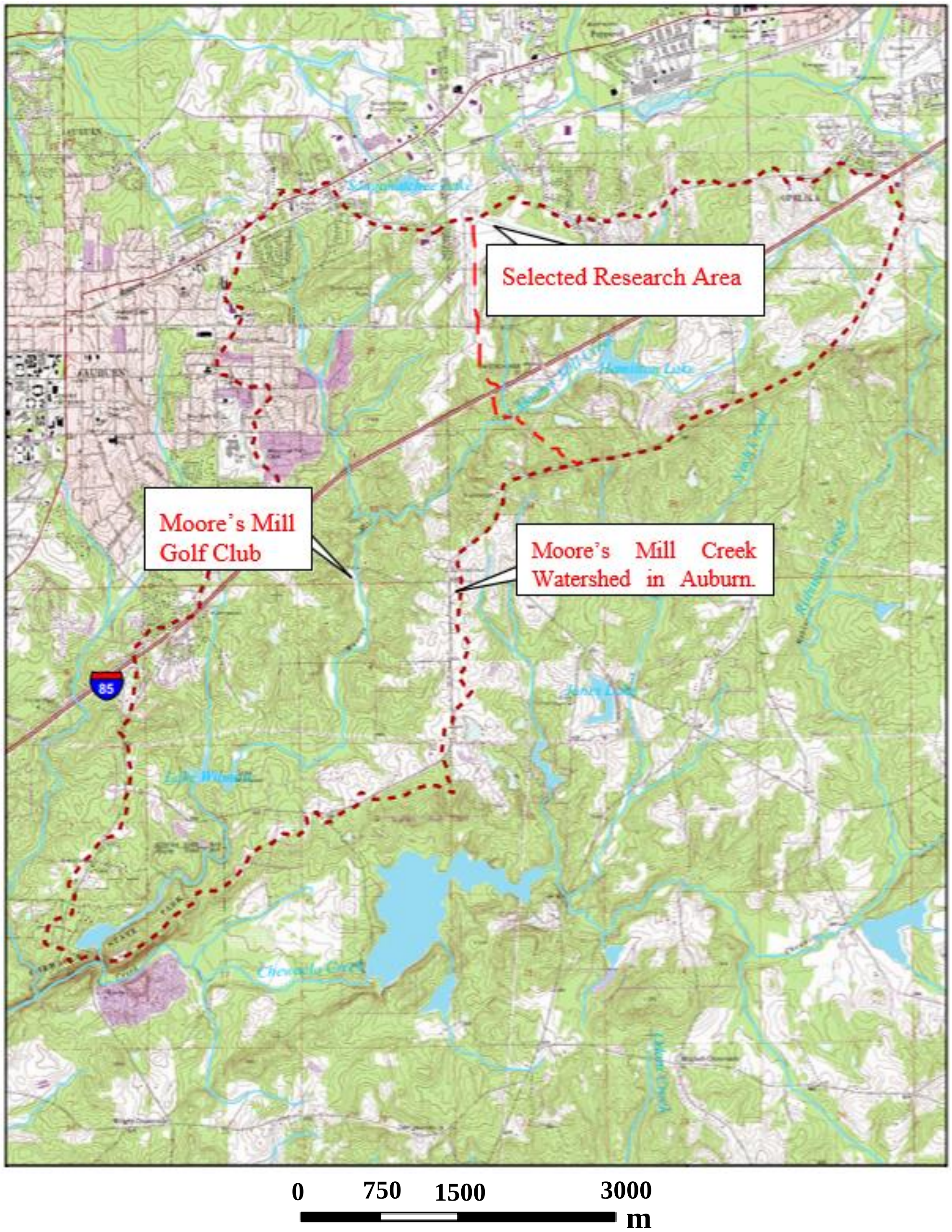


Figure 3. 1: Upper: General Location of Moore's Mill Creek Watershed; Below: Specific location of Moore's Mill Creek Watershed (Acer Engineering 2008)

In terms of environmental quality, Moore's Mill Creek was included on the 303 (d) list of impaired streams in 2000 for siltation according to an existing assessment of the Moore's Mill Creek Watershed performed in 2008 (Acer Engineering 2008). Within this watershed, the area selected for this study is in the northeastern part covering essentially the part of the watershed located in Opelika, and a small portion in the eastern part of Auburn (see Figure 3.1: Selected Research Area). The research sub-basin size is about 10 km^2 which is one-third of the entire basin area.

The sub-basin presents mixed with the urban area which is the Tiger town region, a shopping center, and the natural vegetation area. Three prominant land use types are identified as open space, commercial/industrial, and residential. The predominant hydrologic soil group is B class at the study watershed and with some C class at the airport region (Soil Survey Staff, NRCS, USDA 2015). The predominant soil types are Pacolet sandy loam series (Soil Survey Staff, NRCS, USDA 2015). Moreover, the sub-basin includes lakes such as Hamilton Lake (~0.87 km^2) and Orr Estates Lake (~0.18 km^2). The area of percent urban development area is about 43% based on USGS (United States Geological Survey) StreamStats Report (U.S. Geological Survey 2022). The elevation range of the sub-basin is from 187m to 239m based on the NLCD DEM file (United States Department of Agriculture n.d.). Because the Moore's Mill Creek watershed is only about 320 km away from the Gulf of Mexico, it receives an approximately 1400 mm of rainfall during one year (Acer Engineering 2008). The climate is humid subtropical.

3. 2 Field Work

3. 2. 1 Stream measurements

The HOBO U20L Water level logger was used to monitor the water depth changing in the stream, lake, well, and a wide range of underwater environments. It can measure and record the pressure during the selected interval. To calibrate the model results, five HOBO U20L Water Level loggers were deployed at 5 locations inside the streams (Capps Way, Hamilton Bridge, Bent Creek Road, Lakeshore Drive, and Champions Blvd) within the research watershed (see Figure 3. 2). Another

HOBO U20L Water Level logger worked as a barometric reference was installed at the Lakeshore Drive where located at the center point of the entire watershed. A picture of a HOBO level logger and the data shuttle used to retrieve the information in the sensor is shown in Figure 3. 3.

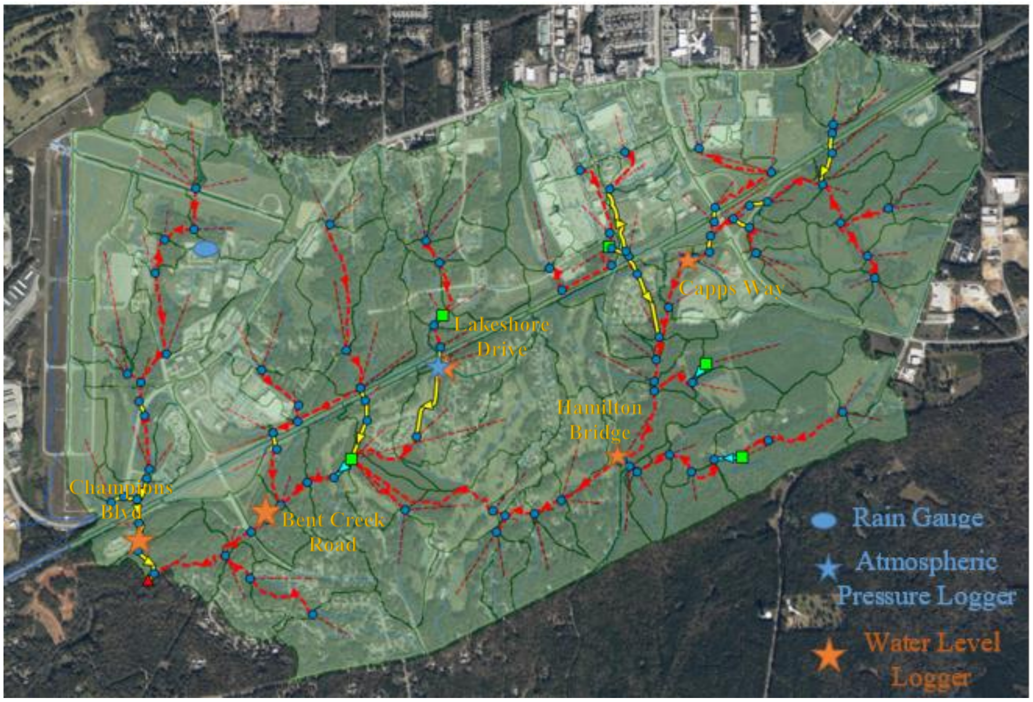


Figure 3. 2: Level Loggers and Rain Gauge Distribution Map

Figure 3. 3: Onset HOBO Water Level (13ft / 3.96m) Logger-U20L and Data Shuttle

The water level loggers use a reference water level barometric compensation logger which records only absolute pressure, and HOBOware software developed by the ONSET Company to automatically convert the pressure readings into water level readings. The typical error of Water

Level Accuracy of the HOBO U20L (13ft/3.96m) is ±0.1% FS (Full Scale), 0.4 cm (0.013ft) water (Onset Computer Corporation 2014-2018). The frequency of the loggers was set as 15 minutes for all the level loggers. Based on the HOBO U20L Water Level Logger Manual (Onset Computer Corporation 2014-2018), barometric pressure readings are consistent across a region (within 15 km), the barometric reference was also used for another four locations to calculate the water depth using the software HOBOware. Figure 3. 4 instructs how the data shuttle is coupled with the level logger.

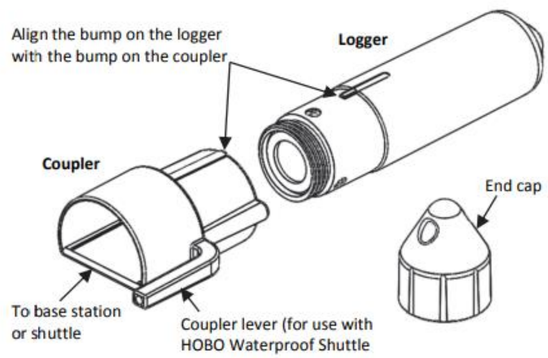


Figure 3. 4: Logger and Coupler Instruction (Onset Computer Corporation 2014-2018)

To improve the model representations of the watershed behavior, field surveys were made to determine the conduits' type and size across the streets and roads. A tape measure was used to measure the dimensions of the culverts (Figure 3. 5). The groundwater contributions to the base flow were added manually in the PCSWMM model, as aquifer components were not presented in the modeling. Thus, the baseline flows needed to be estimated from field surveys as constant inflows added into the model. To calculate the baseline flows at water level loggers' locations, the width of the stream and the velocity of the stream were measured by tape measure and global water flow current meter (Model: FP211-S, 0.1 FPS) (see Figure 3. 6) which is an accurate water velocity instrument for measuring flows in open channels and partially filled pipes, respectively. The loggers' deployed locations are Champions Blvd (Figure 3. 7: a), Bent Creek Road (Figure 3. 7:

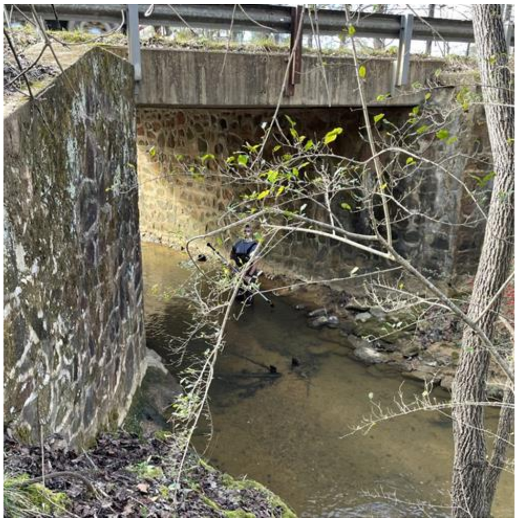
b), Hamilton Bridge (Figure 3. 7: c), Lakeshore Drive (Figure 3. 7: d), and Capps Way (Figure 3. 7: e). The stream depth collection period was from December 22nd, 2021 to April 27th, 2022. However, the effective period was only from December 22nd, 2021 to January 26th, 2022.

Figure 3. 5: Left: Champions Blvd Culvert Cross-section (6.10m x 1.78m); Right: Lakeshore Drive Culvert Cross-section (~ 1.524m x 0.991m)

Figure 3. 6: Using the Global Flow Probe to Measure the Stream Velocity

a. Champions Blvd Logger Location and Cross-section

b. Bent Creek Road Logger Location and Cross-section



c. Hamilton Bridge Logger Location and Cross-section

d. Lakeshore Drive Logger Location and Cross-section

e. Capps Way Logger Location and Cross-section

Figure 3. 7: Level Logger Locations and Cross-sections (a, b, c, d, e)

3. 2. 2 Meteorological Data Collection

At the beginning, two remote rain gauges (8.7 km and 12.5 km away from the watershed) operated by the City of Auburn (HOBOlink 2021) were used as the source of the precipitation data. However, they could not always provide reliable rainfall data based on the observed water depths. In the case of that, the rainfall events couldn't be matched up with the observed water depth. Therefore, it was decided to install a rain gauge within the research watershed to increase the accuracy of the precipitation data in PCSWMM model.

Before installing the rain gauge in the field, the first thing needed to do was to calibrate the rain gauge. The Onset Data Logging Rain Gauge RG3 User's Manual (Onset Computer Corporation 2005-2018) gave the instructions for calibration processes that a cup of 437 ml water was used to drop into the rain gauge to receive 100 tips to prove the rain gauge was calibrated. Each bucket tip is counted as 0.01 inches (0.0254 cm) of rainfall for the tipping-bucket rain gauge model of RG3. If the number of tips of water is higher or lower than 100 tips, the two screws under the rain gauge need to be adjusted either counterclockwise or clockwise to decrease or increase the tips to 100.

After the rain gauge was calibrated, our research group installed it at the off-campus lab (3410 Skyway Drive near the Auburn airport, see Figure 3. 2) which was located at northwestern of the research watershed (Figure 3. 8). For this research, the precipitation period was selected from December 18th, 2021 to January 26th, 2022 for the model simulation test.

Figure 3. 8: Off-Campus Lab Rain Gauge

Evaporation is the process by which water is transferred from the land and water masses of the earth to the atmosphere. Evaporation is particularly significant over large bodies of water such as lakes, reservoirs, and the ocean. In this research study watershed, there are several lakes inside of it. Therefore, evaporation plays a key role in the model simulations. PCSWMM provides users the function to compute the evaporation directly from temperatures in climate files. Hargreaves's method (Hargreaves and Samani, 1985) is used to compute daily evaporation rates from the daily maximum-minimum air temperature record and the site's latitude (Rossman 2015). The governing equation is in eq. (3.1). The climate files were obtained from the National Oceanic and Atmospheric Administration National Centers for Environmental Information (NCEI n.d.).

$$E = 0.0023\,(\frac{R_a}{\lambda})T_r^{\frac{1}{2}}(T_a + 17.8) \tag{3.1}$$

Where, E is evaporation rate (mm/day), R_a is water equivalent of incoming extraterrestrial radiation ($MJm^{-2}d^{-1}$), T_r is average daily temperature ranges for a period of days (degree C), T_a is average daily temperature for a period of days (degree C), and λ is latent heat of vaporization ($MJkg^{-1}$) which is equal to ($2.50 – 0.002361T_a$).

3. 3 Numerical Modeling

PCSWMM (Personal Computer Storm Water Management Model) is a commercial version of SWMM which was developed by Computational Hydraulics International (CHI). PCSWMM uses SWMM computational engine and couples it with pre- and post- process tools to help in the data input and analysis tasks. These powerful tools include geographic information system (GIS) tools, a watershed delineation tool (WDT), and Sensitivity-based Radio Tuning Calibration (SRTC) tool. In terms of Model creations, there are several steps: a) Data gathering: the digital elevation model (DEM) data is collected to generate the watershed delineation in PCSWMM; b) Model set up: organize the parameters and components in PCSWMM; c) Model calibration: use the SRTC tool to validate some model parameters; d) Model validation: use a different group of rain events to verify the calibrated model. The flowchart in Figure 3. 9 shows the overall strategy of this research project. The main steps are:

1. Collect the DEM data from the online sources (USDA Geospatial Data Gateway).
2. Run the Watershed Delineation Tool (WDT) in PCSWMM software.
3. Use the QGIS plugin to calculate Curve Number Layer by importing the Subcatchments layer generated from the PCSWMM into the QGIS.
4. Calculate the area-weighted CN and percent of impervious if applicable by using the Excel and VBA program.
5. Determine running the Fully Composite CN approach (Set percent of impervious area to 0, and average the CN values for each of subcatchments based on the percent of the area of

CN features taken at each of the subcatchment) or running the CN Cut-off approach (Count the CN values larger than the threshold value as impervious area and average the CN values for the rest of the CN features inside of the subcatchment).

6. Compare the simulation results with the observed results.
7. Determine if the model needs the calibration or not.
8. Check and compare the calibrated results versus field data.

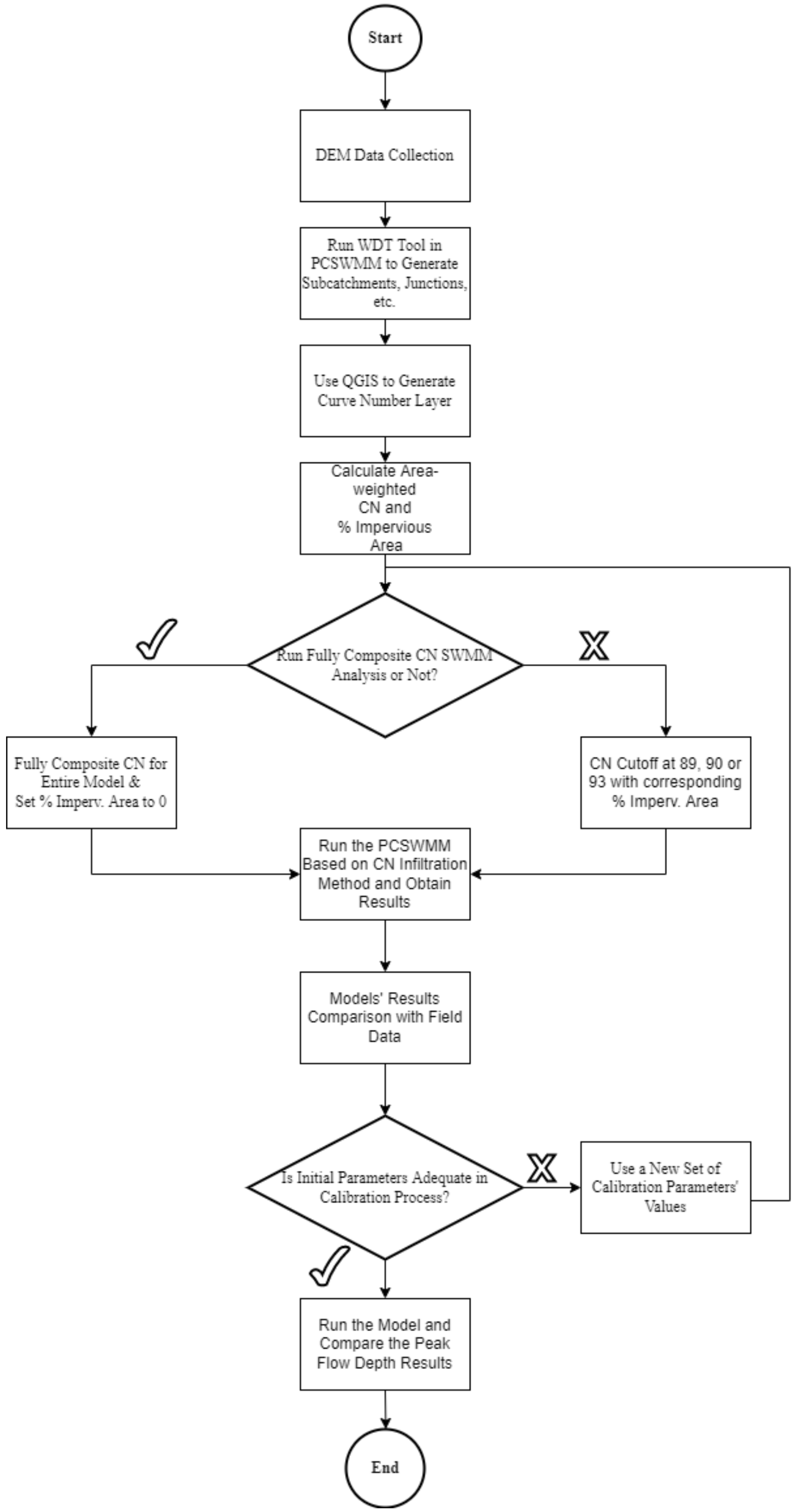


Figure 3. 9: Flowchart of the Implementation and Assessment of Fully Composite or CN Cut-off Approaches within SWMM

3. 3. 1 DEM Data Collection

The DEM (Digital Elevation Model) provides the SWMM model with elevation data at regular grid spacing. The PCSWMM model requires DEM to run the Watershed Delineation Tool (WDT). The USDA's Geospatial Data Gateway (USDA 2022) provides DEM data for digital elevation models for most regions across the United States, including this study's region of interest. It offers a variety of elevation options such as 1m, 2m, 10m, and 30m. The DEM elevation data was pulled from the Geospatial Data Gateway for the headwater of Moore's Mill watershed in Opelika, AL. One-meter Bare Earth DEM data was selected because of its precision and ease of merging and resampling. Because large sized TIF files would slow the PCSWMM, ArcMap was used to merge and resample the TIF (DEM) file from 1 x 1 pixel to 5 x 5 pixels to reduce the TIF file size. Therefore, the actual resolution of the DEM used in this model is 5m by 5m.

3. 3. 2 Watershed Delineation Tool (WDT)

Once the DEM data was acquired, the PCSWMM was used to simulate the hydrologic impact and performance at headwater of Moore's Mill watershed. Below are the steps to generate the watershed automatically based on the WDT in PCSWMM.

Step 1: A SWMM 5 project in PCSWMM was created.

Step 2: The resampled DEM TIF file was inserted into the PCSWMM to run the WDT.

Step 3: The outfall location was confirmed and located inside the DEM map.

Step 4: The DEM TIF file, outfall location, and target discretization of 10 ha were input into the WDT dialog box and the WDT was run. This generated the subcatchments, nodes, and conduits automatically (see Figure 3. 10).

Step 5: The Manning's roughness N for impervious area was set as 0.011 (Smooth asphalt), Manning's N for pervious area was set as 0.15 (Short, prairie), 0.4 (Light underbrush), and 0.8 (Dense underbrush) for different surface criteria (Table 3. 1).

The depth of depression storage on impervious area was set as 2 mm, depth of depression storage on pervious area was set as 5 or 8 mm for initial use of all the subcatchments (Table 3. 2).

Step 6: The data generated by the WDT were then compared with data provided by the USGS (United States Geological Survey) StreamStats "*IDENTIFY A STUDY AREA Basin Delineated*", and the discrepancies were adjusted in the PCSWMM WDT delineation of subcatchments and conduits.

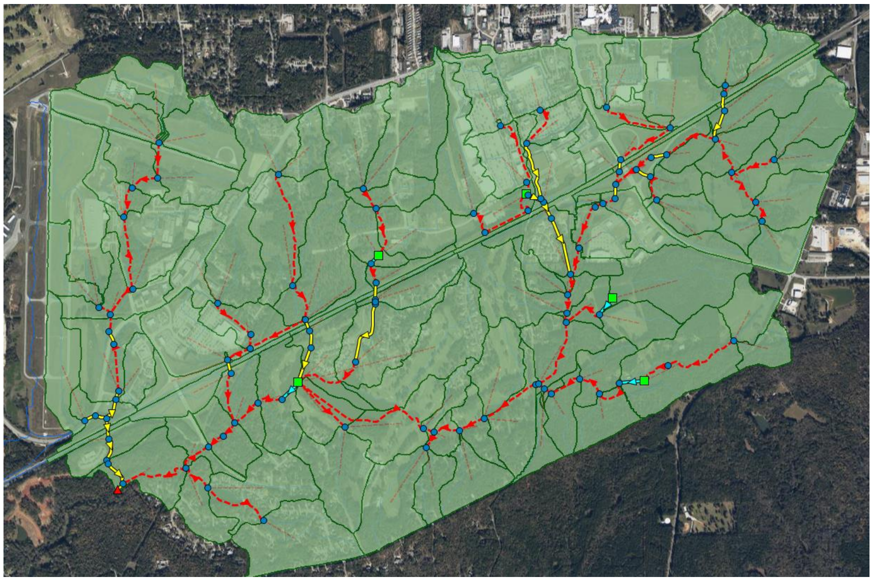


Figure 3. 10: WDT Based Subcatchments, Conduits, and Junctions

Table 3. 1: Manning's n – Overland Flow (McCuen 1996)

Surface	Manning's n
Smooth asphalt	0.011
Grass	
Short prairie	0.15
Dense	0.24
Woods	
Light underbrush	0.4
Dense underbrush	0.8

Table 3. 2: Depression Storage Reference Table (ASCE 1992)

Surface	Depression storage (mm)
Impervious surfaces	1.25 - 2.5
Lawns	2.5 - 5
Pasture	5
Forest litter	8

3. 3. 3 Junctions and Conduits Setup

The junctions' elevations were automatically calculated by using the Elevation from the DEM tool in the PCSWMM Nodes tab. The *Transect Creator* tool under the Conduits tab was used to generate and assign the transects automatically for the conduits based on the DEM file (for this research, the Transect spacing was set as 100 m, and the Transect length was set to 20 – 100 m, the Station spacing was set to 1 m, and the Transect use filter was set to 1).

After that, the *Transect objects* were selected and the *Average transects intersecting each conduit* were chosen as the Channel representation method and the choice of Assign conduit name to transect was ticked. Eventually, the tab of Analyze was hit and all the conduits had their geometries of cross-sections based on the DEM. According to Denver's Urban Drainage and Flood Control District (UDFCD, 2007), the maximum flow path length should not exceed 150m. Therefore, the Set Flow Length/Width tool, under the Subcatchments tab, was used to set all the flow path lengths under 150 m. Manning's n for concrete pipes was set as 0.015 and for natural channels was set as 0.05 based on the ASCE Manual of Practice No.60 (ASCE 1982). Figure 3. 11 presents the open street map with junctions and reaches.

Figure 3. 11: Map with Junctions (blue dots) and Reaches (red and yellow lines) for the Model of Moore's Mill

SWMM uses the explicit Euler method to calculate the flow at every junctions and a discrete implementation of the Saint-Venant equations (i.e., link-node) as shown in equation 3.2 series (Rossman 2017). The update of flow conditions at junctions is done through the continuity equation, presented in equation 3.3. Figure 3. 12 illustrates the calculation elements used by SWMM.

$$Q^{t+\Delta t} = \frac{Q^t + \Delta Q_{inertia} + \Delta Q_{pressure}}{1 + \Delta Q_{friction}} \quad (3.2)$$

Where,

$$\Delta Q_{inertia} = 2\overline{U}(\bar{A}^{t+\Delta t} - \bar{A}^t) + \overline{U}^2 \frac{A_2 - A_1}{L} \Delta t \quad (3.2a)$$

$$\Delta Q_{pressure} = -g\bar{A}\frac{H_2-H_1}{L}\Delta t \qquad (3.2b)$$

$$\Delta Q_{friction} = g\eta^2\frac{|\bar{U}|\Delta t}{\bar{R}^{4/3}} \qquad (3.2c)$$

Where,

U = flow velocity, equal to Q/A;

Δt = time step;

A = flow cross-sectional area;

Q = flow rate;

g = acceleration of gravity;

R = the hydraulic radius of the flow cross-section;

H = hydraulic head of water in the conduit (conduit invert elevation + conduit water depth);

L = conduit length

A1 = flow area at the upstream end of the conduit;

A2 = flow area at the downstream end of the conduit;

H1 = hydraulic head at the upstream end of the conduit;

H2 = hydraulic head at the downstream end of the conduit.

$$H^{t+\Delta t} = H^t + \frac{\frac{\Delta t}{2}(\sum Q^t + \sum Q^{t+\Delta t})}{(A_{SN}+\sum A_{SL})^{t+\Delta t}} \text{ for non-outfall nodes} \qquad (3.3a)$$

$$H^{t+\Delta t} = H_{outfall} \text{ for outfall nodes} \qquad (3.3b)$$

Where,

As = node assembly surface area;

A_{SN} = node's storage surface area;

A_{SL} = the surface area contributed by a connecting link.

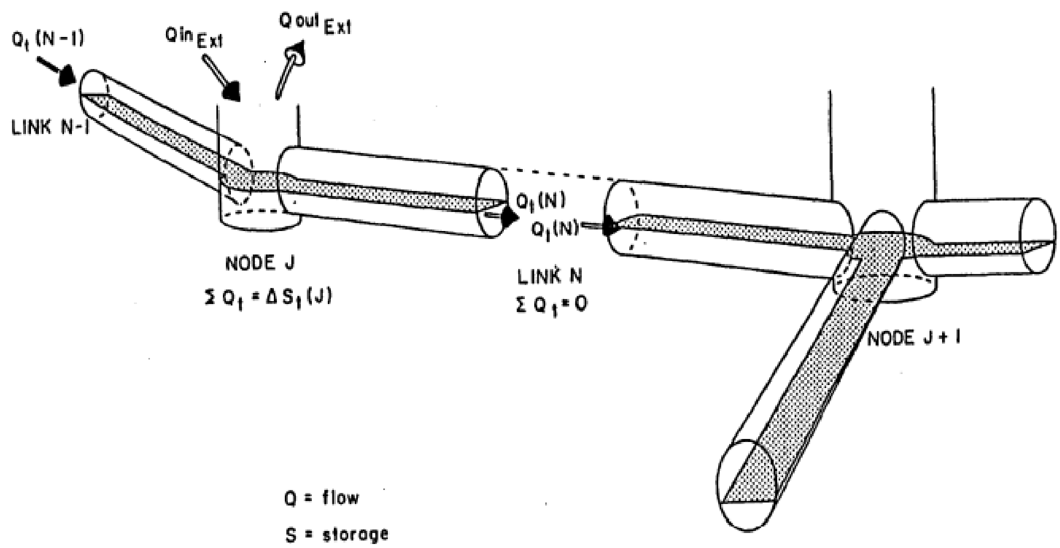


Figure 3. 12: Node-link Representation of a Conveyance Network in SWMM (Roesner, Aldrich and Dickinson 1992)

3. 3. 4 Setting Storage Units to Represent the Lakes and Detention Basin

Storage Units are drainage system nodes that provide storage volume which can represent storage facilities such as reservoirs or lakes (Rossman, 2015). Because the WDT tool cannot generate the storage units automatically, the junctions located at the lakes or detention basins were converted as storage units manually. In Figure 3. 13, the five green squares are the storage units (lakes or detention basins) in this PCSWMM model. The properties of the storage units are shown in Table 3. 3.

Table 3. 3: Storage Units Attribute Table in PCSWMM model

Storage Unit Name	Invert Elev. (m)	Rim Elev. (m)	Depth (m)	Initial Depth (m)	Surface Area (m^2)	Types of Outlets
Detention Basin	211.15	218.15	7.00	1	1150	1.5m x 1.5m Box Orifice
Hamilton Lake	195.08	197.33	2.25	2	89000	10m x 1m Weir
Lake_3	208.00	209.47	1.47	1.16	26650	2m x 1m Weir
Lake_4	214.50	215.99	1.49	1.46	19500	2m x 1m Weir
Orr Estates Lake	208.40	210.30	1.90	1.51	19440	0.2m Diameter Circular Orifice and 1m x 1m Weir

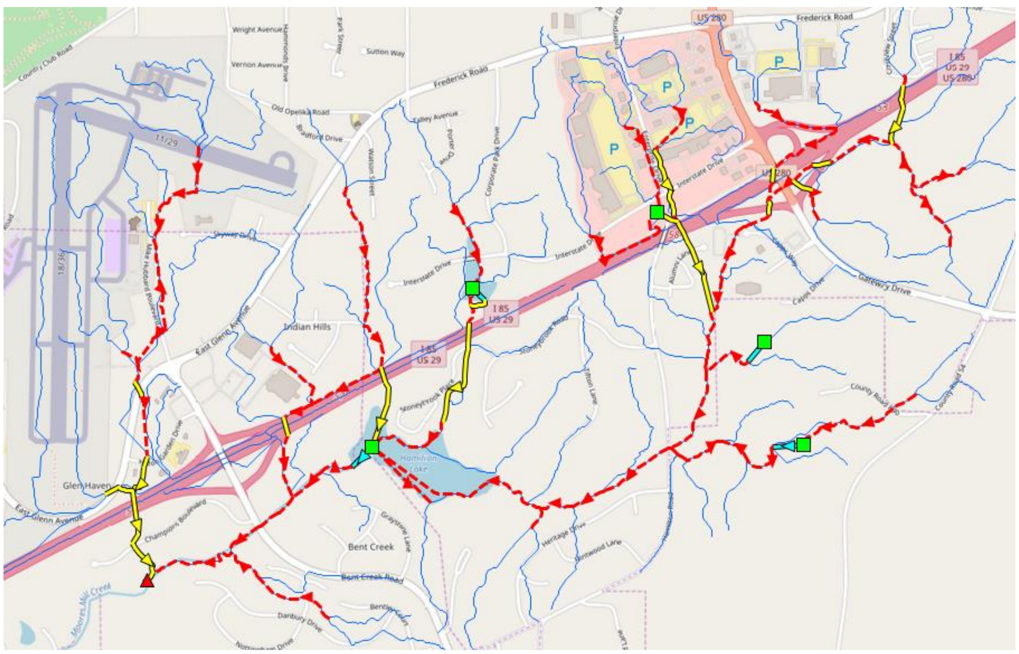


Figure 3. 13: Map of Storage Units Locations (green squares)

<u>3. 3. 5 Generating Curve Number Layer using QGIS</u>

As pointed earlier, the assignment of CN for each subcatchment can be difficult and tedious in terms of spatial averaging, uncertainties associated with the land use and soil characteristics, and the amount of work to input all those data into the models. The Fully Composite CN and the proposed CN Cut-off approaches in this research consist in alternatives to avoid this issue. These approaches rely on a relatively high-density spatial distribution of CN data. This is possible in this research because of the high-resolution dataset of land cover from the NLCD (Dewitz, J., and U.S. Geological Survey 2021) and the spatial data of hydrological soil groups (Soil Survey Staff, NRCS, USDA 2015). Through a comparison with field data, this study performs an assessment of the accuracy of Fully Composite CN and CN Cut-off approaches.

In the PCSWMM, the subcatchments layer was exported as a Shapefile file and was imported into the geospatial software Quantum Geographic Information System (QGIS). In order to carry out the necessary functions for CN calculation, a "*Curve Number Generator*" plugin was installed within QGIS. The "*CurveNumberGenerator*" is a QGIS plugin that can generate the Curve Number layer for the given Area of Interest within the contiguous United States (Siddiqui 2020). The algorithm uses the National Land Cover Database (Dewitz, J., and U.S. Geological Survey 2021) and Soil Survey Geographic Database (Soil Survey Staff, NRCS, USDA 2015) as reference tables. By intersecting the two datasets together, a combined land use and soil layer were generated. Then, by joining a lookup table (See Appendix B) that provid unique relationship between land use, soil, and Curve Number, the final output of CN values was calculated (Siddiqui 2020).

Before the plugin function, "*CurveNumberGenerator*," was set to run, the subcatchment layer was set as the area boundary, and the "Output Curve Number Layer" was selected. After running this process, the Curve Number layer within the subcatchment was generated as shown in

Figure 3. 14. Then, the field calculator in the attribute table was opened by creating a new field called the "AreaCN" and clicking the $area under the Geometry tab, the area geometry of each feature was calculated. Next, the "Union" function in Geoprocessing Tools under the vector tab was used to union the Subcatchments layer and the CN layer together. Lastly, the area of each new row of the Union layer was calculated by using the filed calculator in the attribute table. By

importing the columns of Subcathments name, CN values, area of each Subcatchments, and area of each CN feature into Excel, the area-weighted average CN (Fully Composite CN) values could be calculated. Detailed calculation information is provided in the next section 3. 3. 6 Area-weighted CN Calculations.

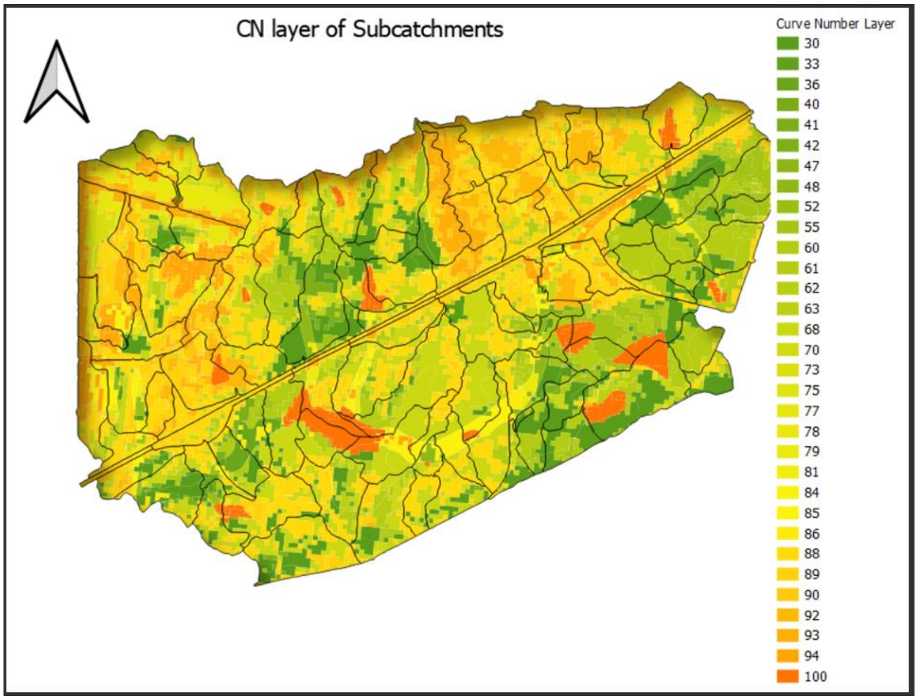


Figure 3. 14: Map of CN Layer within Subcatchments

In terms of the CN Cut-off approaches, the generated CN layer will be selected based on the CN values to generate the new layers which the Curve Number values will be cut off at 93, 90, and 89. That means areas with CN values above a threshold (93, 90, and 89) are considered as impervious, and the CN values are averaged only using subcatchments below the cut-off value. The specific values for CN Cut-off were chosen based on the data in Table 3. 4 (highlight rows): percentage of CN features of cut-off CN layers compared with fully CN layer. In the table, the fully CN (equivalent to Fully Composite approach) has the 100% features of the Curve Number layer.

Through the CN equals 95 to 100, it takes only 5 % of the features in the attribute table of the CN layer. However, when CN is less than 93, the percent of the features dropped to 86.3%, meaning 13.7% of the features are considered impervious in the CN Cut-off approach. Therefore, the first CN Cut-off value was chosen at CN equal to 92. By using the same strategy, the other CN Cut-off values were chosen at CN equal to 89 and 88, in which the percent features dropped to 77.6% and 65.6%, respectively, creating further increases in the impervious areas to be considered in the SWMM model. The CN Cut-off approaches varied only on the number of impervious features resulting from the selected cut-off value. After the cut-off CN layers were generated (Figure 3. 15, Figure 3. 16, and Figure 3. 17), a GIS "Union" function was applied with the subcathments layer in QGIS to provide the data on CN values and imperviousness being used in the SWMM model.

Table 3. 4: Alternatives for CN Cut-off Criteria in Moore's Mill Watershed

QGIS Select Features				
Method	**# of features**	**Difference**	**Sum**	**% Features**
Fully CN	2430	0	0	100.0
CN <100	2308	122	122	95.0
CN <99	2308	0	122	95.0
CN<98	2308	0	122	95.0
CN<97	2308	0	122	95.0
CN<96	2308	0	122	95.0
CN<95	2308	0	122	95.0
CN<94	2260	48	170	93.0
CN<93	2097	163	333	86.3
CN<92	1969	128	461	81.0
CN<91	1969	0	461	81.0
CN<90	1886	83	544	77.6
CN<89	1595	291	835	65.6
CN<88	1175	420	1255	48.4

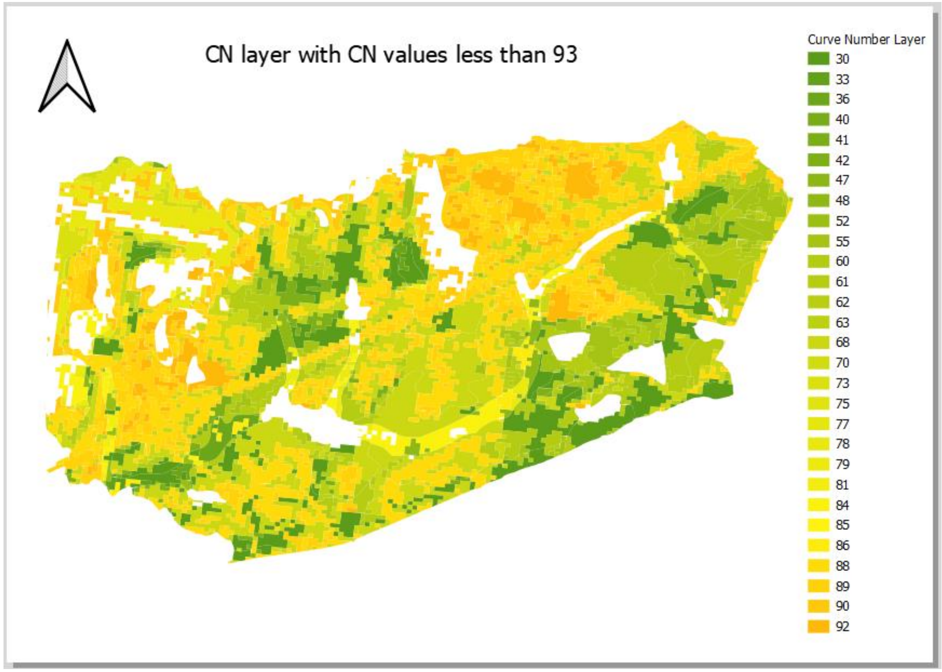


Figure 3. 15: Map of CN Layer with CN values less or equal to 92

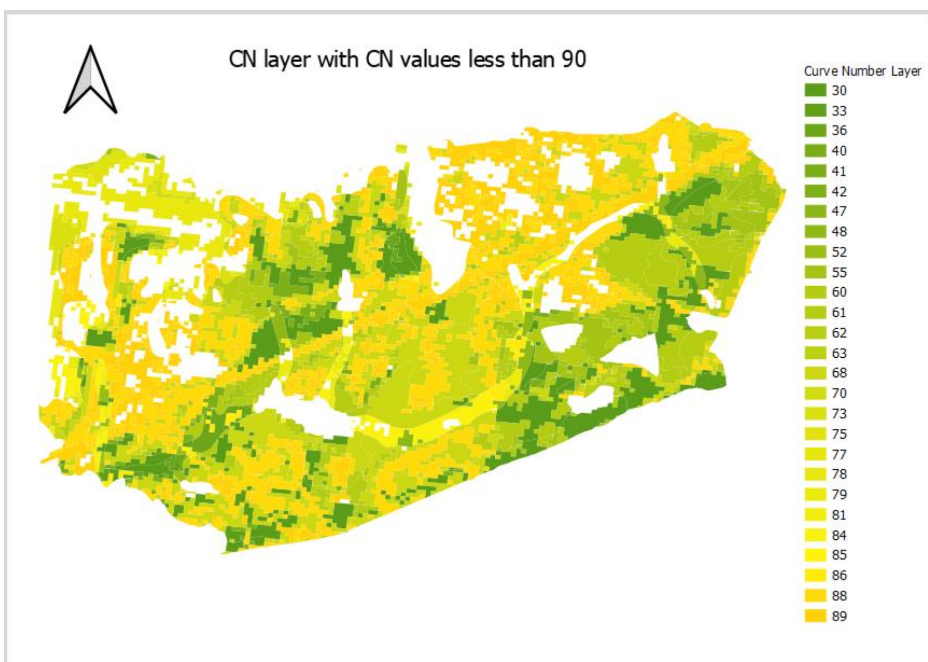


Figure 3. 16: Map of CN Layer with CN values less or equal to 90

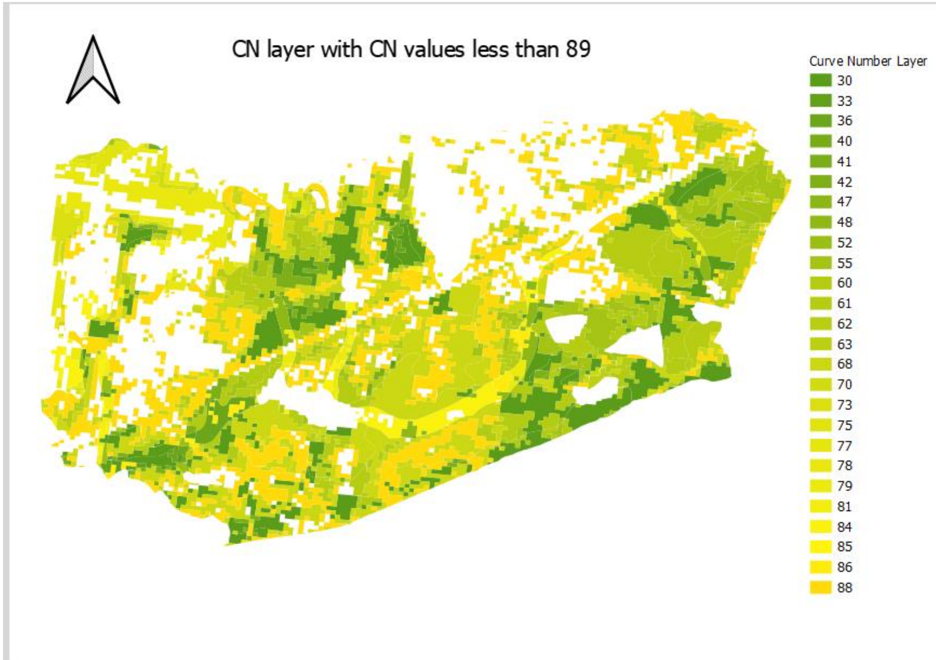


Figure 3. 17: Map of CN Layer with CN values less or equal to 89

3. 3. 6 Area-weighted CN Calculations

The Fully Composite method means that all areas in subcatchments are considered pervious, but CN values are averaged among land uses that are impervious and pervious. In order to calculate the Area-weighted CN for the Fully Composite method, the first thing is to acquire the area of subcatchments and the area of each CN feature. Because QGIS allows the user to select the relevant columns in the entire attribute table, several proper columns (Subcatchments NAME, Area of Subcatchments, Area of Each CN Feature) were selected, copied, and pasted into a Microsoft Excel to simplify the calculation columns. Percent of each CN could be calculated by using the area of each CN feature divided by the area of each subcatchment. Then the CN values of each row were multiplied by the corresponding percent of CN to get the partial CN values. Lastly, by inserting a Pivot table in Microsoft Excel, the sum of the Partial CN was calculated, which is the Fully Composite CN values based on the subcatchments Name.

When calculating the Area-weighted CN for the CN Cut-off approaches and the percent of imperviousness, the percent of CNs was calculated at first. By inserting a Pivot table, the sum of percent CNs was put in the VALUES, and the Subcathments Name and CN value were put in the Rows. The sum of percent CN based on each CN value was shown in the Pivot table. Then, a VBA (Visual Basic for Application) program with Microsoft Excel was developed to calculate the cut-off CN values and percent of impervious areas. The VBA code details are presented in the Appendix A of this thesis.

3. 3. 7 Setting the CN-Based Infiltration Method Model

Within PCSWMM, under the Project tab, in the Simulation Options, the infiltration method was changed from the default Horton method to the Curve Number method. When applying the Fully Composite CN approach, the Fully Composite CN values were copied and pasted from the Excel file into the PCSWMM subcatchments attribute table. Moreover, to avoid double counting the infiltration through both high composite CNs and impervious areas, the percent of impervious was changed from the default value (25%) to 0 % for all subcatchments. Regarding the CN Cut-off approaches, the composite CN Cut-off values and the percent of the impervious areas were copied and pasted into the Subcatchments table. Then, the model was ready to run after the natural rainfall and evaporation information were imported to PCSWMM.

3. 3. 8 Model Calibration and Results Comparison

Model calibration is used to improve the model performance. In this study, several parameters were considered: Depression storage, Manning's roughness for impervious areas, and Manning's roughness for pervious areas. These values were calibrated by checking the empirical table according to past research studies (ASCE 1992, McCuen 1996). Other parameters in the calibration process, such as subcatchments slope, and subcatchments drying time were calibrated by applying the SRTC (Sensitivity-based Radio Tuning Calibration) tool in PCSWMM. Notably, CN itself was not calibrated as these values were informed by the calculations performed with the QGIS data, which diverges from the approach used in past SWMM studies (Alfredo, Montalto and Goldstein 2010, Swathi, et al. 2019) using CN infiltration method.

The CN Cut-off at 90 approach was used to apply the model calibrations because it was the closest model to the actual representation. Moreover, the calibrated parameters were also used for the other CN Cut-off models and the Fully Composite model. A warm-up period was also applied when running the calibration process to reduce the model dependence at initial conditions. The watershed responses are crucial to the conclusions by comparing the model calibration results with the grading criteria for model performance (NSE and R^2).

4. Results and Discussion

4. 1 Watershed Properties at Five Level Loggers' Locations

Table 4. 1 presents the percent of imperviousness in StreamStats (Ries, et al. 2008, U.S. Geological Survey 2022) based on the NLCD 2011 and the percent of imperviousness for three CN Cut-off approaches at five research sub-watersheds. The area comparisons between the PCSWMM model watershed delineation and StreamStats watershed delineation of those watersheds are shown in Table 4. 1 *Area* section. The watershed area is very close between the PCSWMM model and StreamStats. The average CN values at five different research watersheds for different models are included in Table 4. 1 *Area-weighted average CN* section. The average CN values are dropping from the Fully Composite CN approach to CN Cut-off at 89 approach, as would be expected given that the Fully Composite CN approach considers all areas, including impervious areas with high CN, in the computation of the average CN value. Conversely, as we move from the Fully Composite into the lowest CN Cut-off value approaches, the average CN for the pervious areas increases, indicating more infiltration capacity for the pervious fraction.

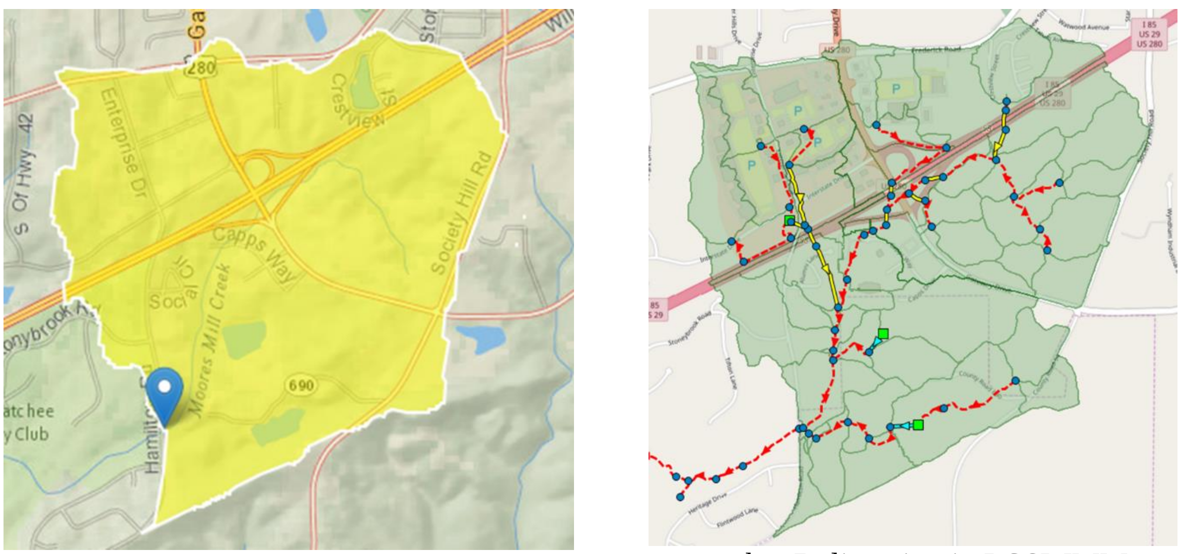
Table 4. 1: % Imperviousness and CN Values in Watersheds

Watershed	Area (km^2)		% of Imperviousness				Area-weighted average CN			
	Area in model	Area in StreamStats	StreamStats (NLCD 2011)	CN Cut-off 93	CN Cut-off 90	CN Cut-off 89	Fully Composite	CN Cut-off 93	CN Cut-off 90	CN Cut-off 89
Capps Way	1.666	1.719	21.1	5.2	13.3	28.1	74	71	70	68
Hamilton Road	3.945	4.070	21.0	9.6	17.4	31.4	72	69	68	66
Bent Road	7.641	7.780	17.8	8.8	15.3	26.2	72	70	69	67
Lakeshore Drive	0.713	0.709	14.6	10.3	15.1	24.3	71	68	66	64
Champions Blvd	1.624	1.517	28.0	22.7	34.0	46.1	82	79	76	74

The watershed delineations at five locations about StreamStats and PCSWMM are shown in Figure 4.1 – 4.5, indicating the slight differences of the watershed delineation between the two applications. The Capps Way location is most upstream, low-density residential, some commercial, some ponds, and half of the forested areas in the watershed which average CN is 70 for CN Cut-off at 90 approach. The Hamilton Road location is mid-point, including a commercial area (Tiger town), some ponds, and forest areas in the watershed. It receives the water from both vegetation area and urban area, and it is the downstream site of the Capps Way. The average CN at upstream site is 68 for CN Cut-off at 90 approach at Hamilton Road. The Bent Creek Road location is downstream, which adds some low-density areas and more ponds. A dam at Hamilton Lake, which is upstream of Bent Creek Road, can hold water during storm events. The average CN upstream of this site is 69 for CN Cut-off at 90 approach at Bent Creek Road. The Lakeshore Drive is a tributary to Moore's Mill Creek, which primarily drains forested, residential areas with a pond (Orr Estates Lake). The average CN upstream is 66 for CN Cut-off at 90 approach at Lakeshore Drive. The Champions Blvd is another tributary to Moore's Mill Creek, which has poorly drained soils airport without a big pond. The average CN upstream is 76 at CN Cut-off at 90 approach, with the highest CN values among those five watersheds.

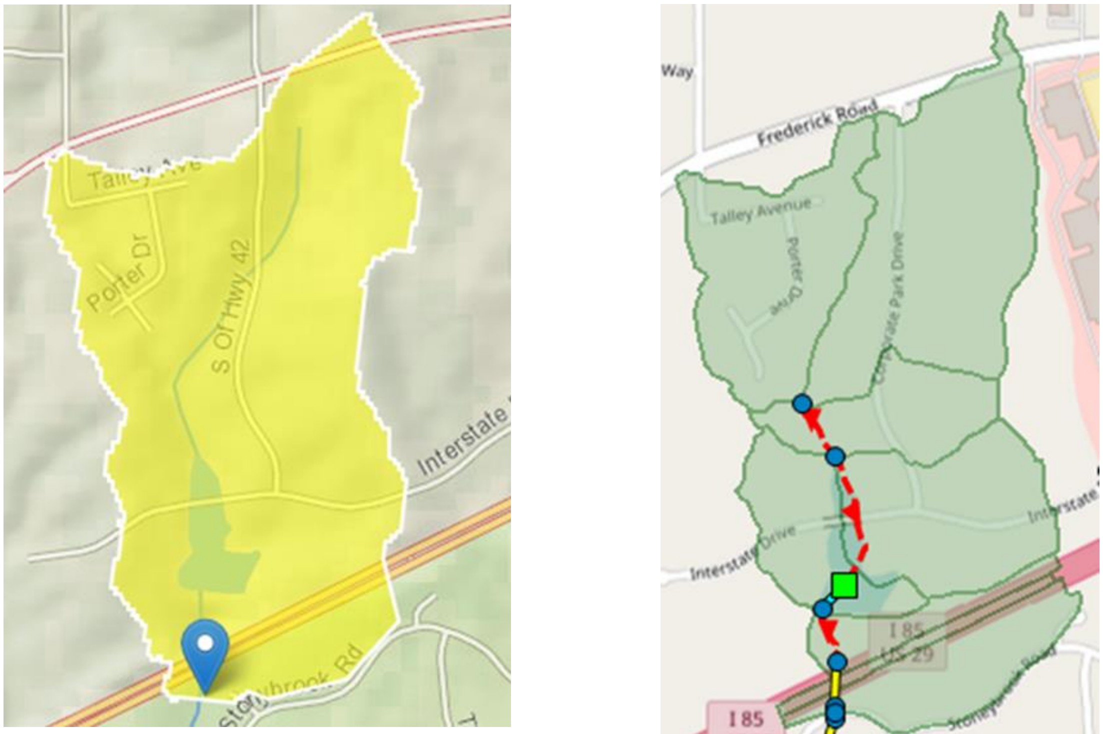
a. Delineation in USGS StreamStats
b. Delineation in PCSWMM

Figure 4. 1: Capps Way Watershed Delineations



a. Delineation in USGS StreamStats
b. Delineation in PCSWMM

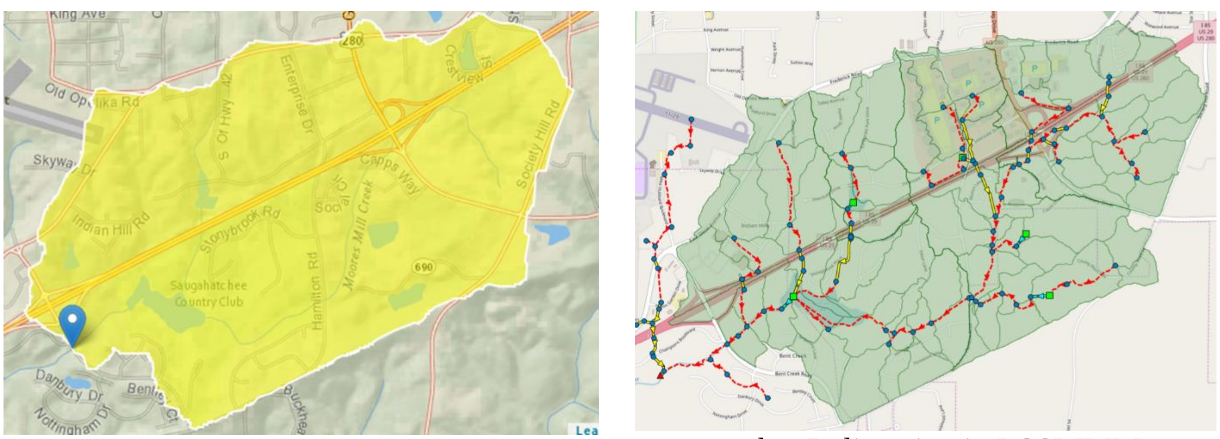
Figure 4. 2: Hamilton Road Watershed Delineation



a. Delineation in USGS StreamStats

b. Delineation in PCSWMM

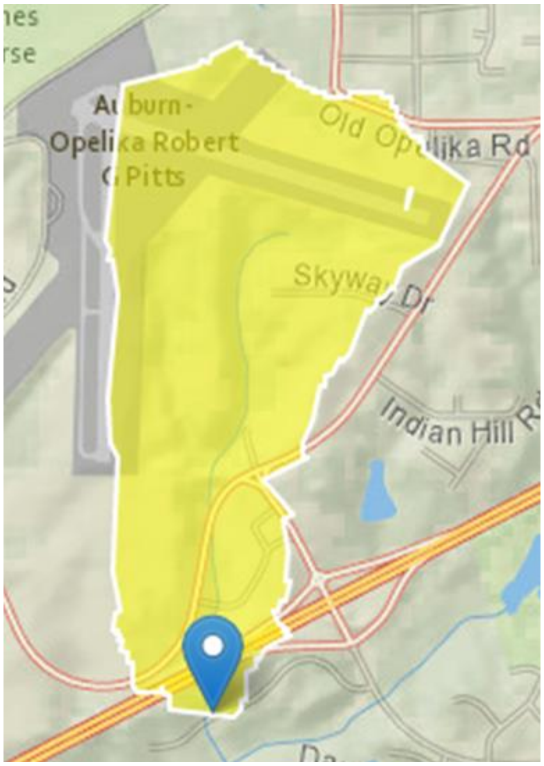
Figure 4. 3: Lakeshore Drive Watershed Delineation



a. Delineation in USGS StreamStats

b. Delineation in PCSWMM

Figure 4. 4: Bent Creek Road Watershed Delineation



a. Delineation in USGS StreamStats

b. Delineation in PCSWMM

Figure 4. 5: Champions Blvd Watershed Delineation

4. 2 Flow Depth Hydrographs: Measurements and Modeling Results

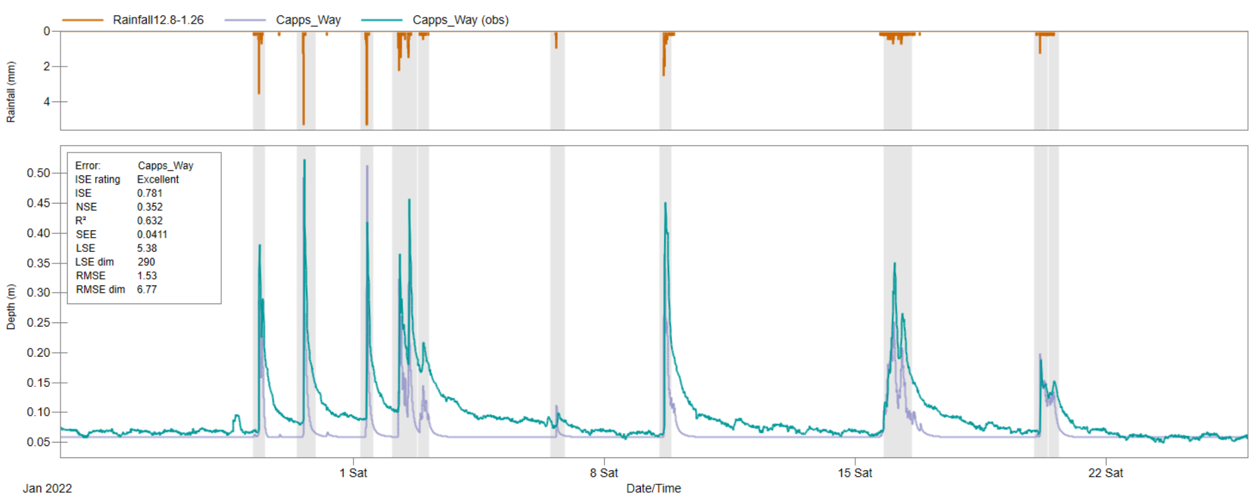


Figure 4. 6: Capps Way Measured Depth Hydrographs and CN Cut-off at 90 Approach Results

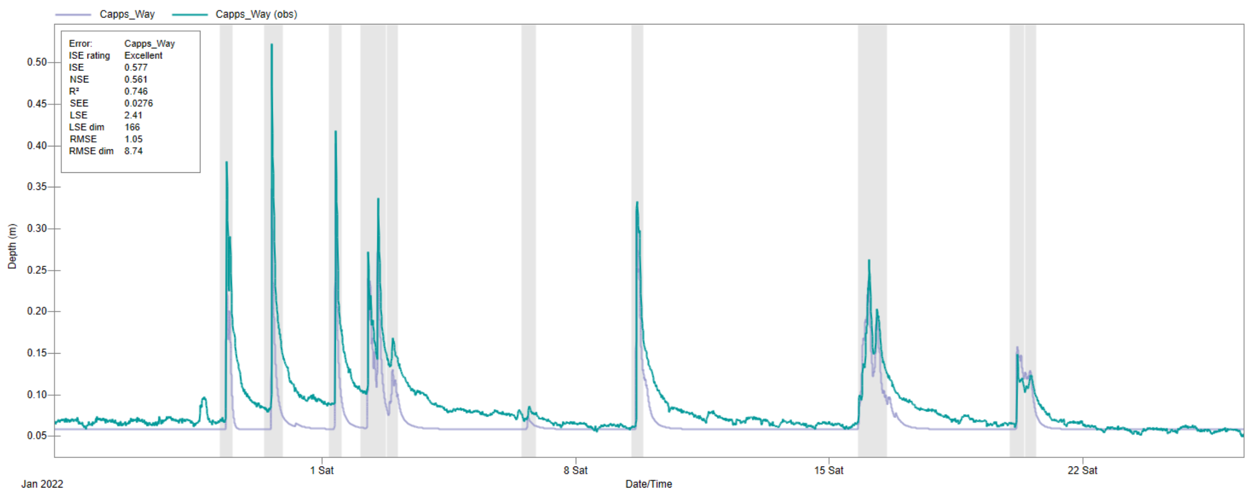


Figure 4. 7: Capps Way Measured Depth Hydrographs and Fully Composite CN Approach Results

Figures 4. 6 and 4. 7 show the hydrographs at Capps Way comparing the results from the CN Cut-off at 90 and the Fully Composite approaches. From the visual inspection, the Fully Composite CN approach presented a slightly better hydrograph performance than the CN Cut-off at 90 approach. Both models had a rapid flow depth drop compared to the observed field data in the recession limb. Interestingly, the CN Cut-off at 90 approach sometimes underestimates or overestimates the flow depth. This common problem is attributed to the lack of groundwater representation in the model. Based on the last two rainfall events, the Fully Composite CN approach had good performance when the rain event was light, but consistently under-predicted the flow depth at this cross-section of Moore's Mill Watershed.

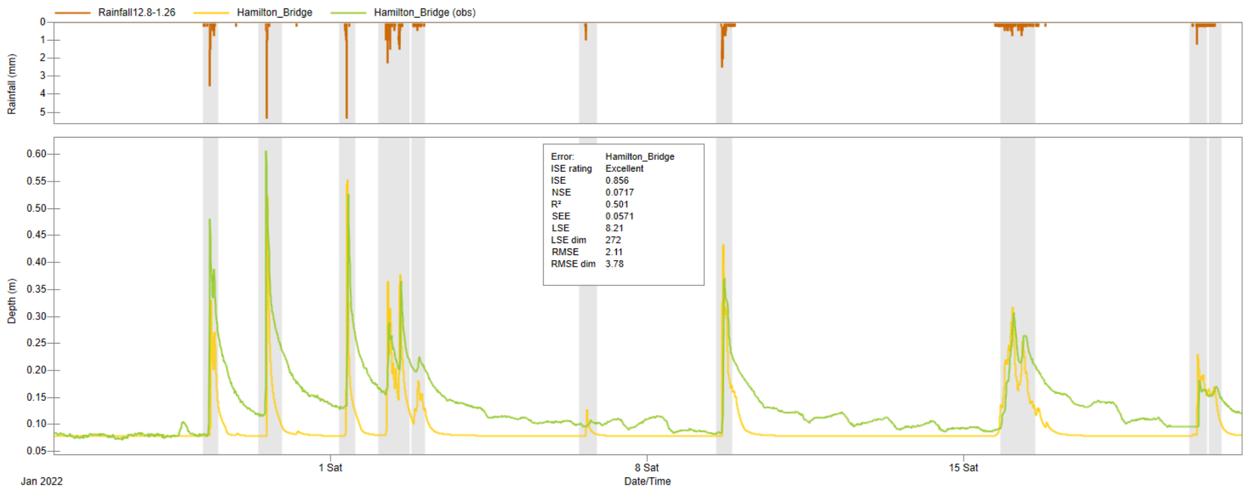


Figure 4. 8: Hamilton Rd. Measured Depth Hydrographs and CN Cut-off at 90 Approach Results

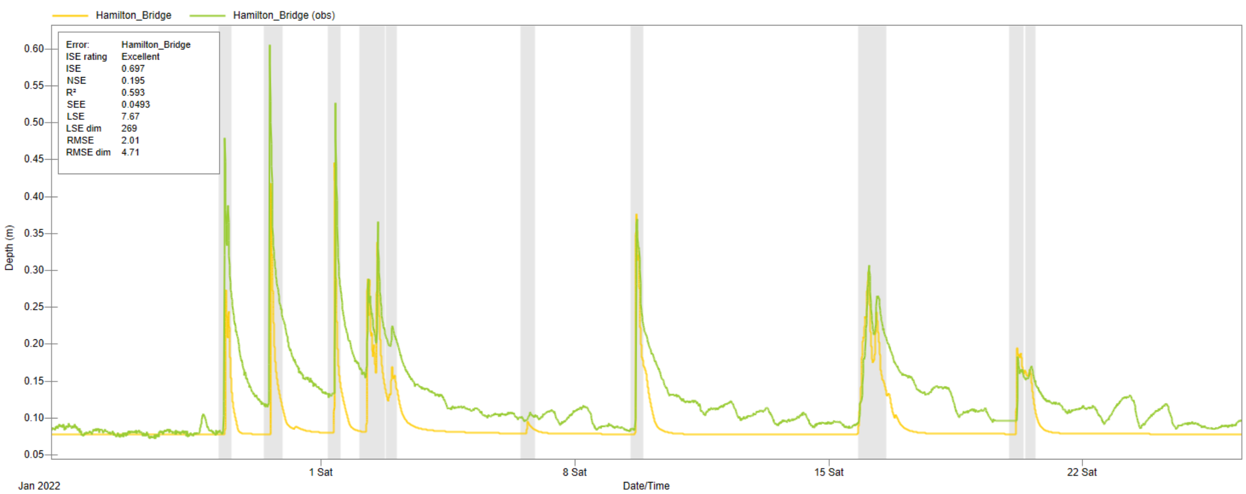


Figure 4. 9: Hamilton Rd. Measured Depth Hydrographs and Fully Composite CN Approach Results

The performance of hydrographs at Hamilton Road in CN Cut-off at 90 approach and the Fully Composite approach was similar to the Capps Way watershed. Likewise, the Fully Composite CN approach had good simulation performance at the last three small rainfall events but still underestimated the flow depth at the first several significant rainfall events. Furthermore, the not well-represented recession curve problem still existed at this location. Since Hamilton Road is located downstream of Capps Way and two more tributaries were added into this location from the two lakes, the same difficulties in Capps Way reappeared here. The CN Cut-off at 90 approach had the similar performance when compared with Capps Way model results. As it was shown ahead, the recession curves affected prominently the NSE of the modeled hydrographs.

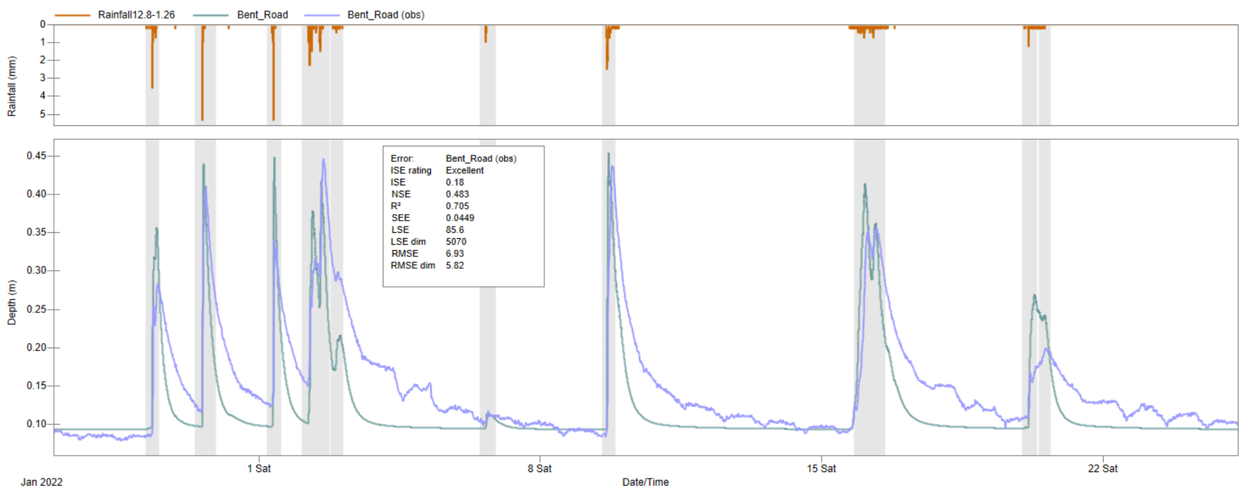


Figure 4. 10: Bent Creek Road Measured Depth Hydrographs and CN Cut-off at 90 Approach Results

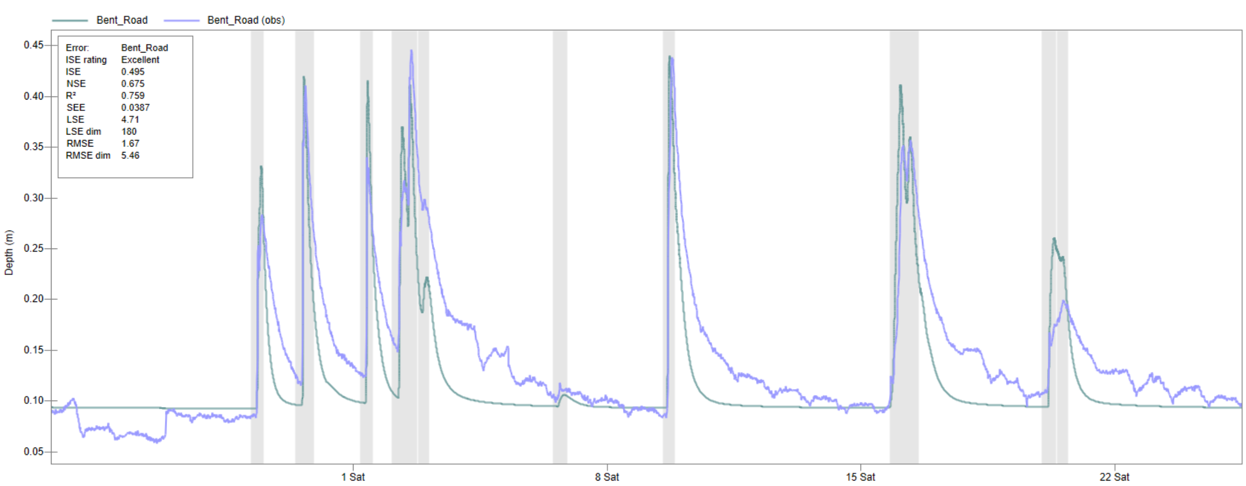


Figure 4. 11: Bent Creek Road Measured Depth Hydrographs and Fully Composite CN Approach Results

By inspecting the hydrographs at Bent Creek Road presented in Figures 4.10 and 4.11, one notices that the two SWMM models had similar simulation performances. While peak depths are fair in both models, the recession limb prediction issue still exists. The problem is even more severe for the modeling results for Lakeshore Drive, presented in Figures 4.11 and 4.12. It is speculated that the poor result could result from the small size of the watershed, low CN value, and the proximity of a retention pond to the site.

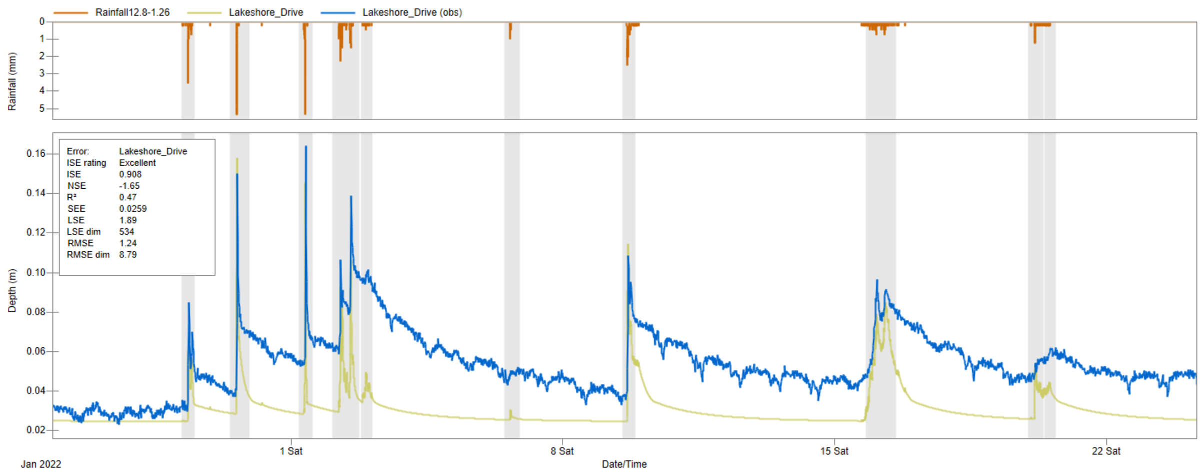


Figure 4. 12: Lakeshore Drive Measured Depth Hydrographs and CN Cut-off at 90 Approach Results

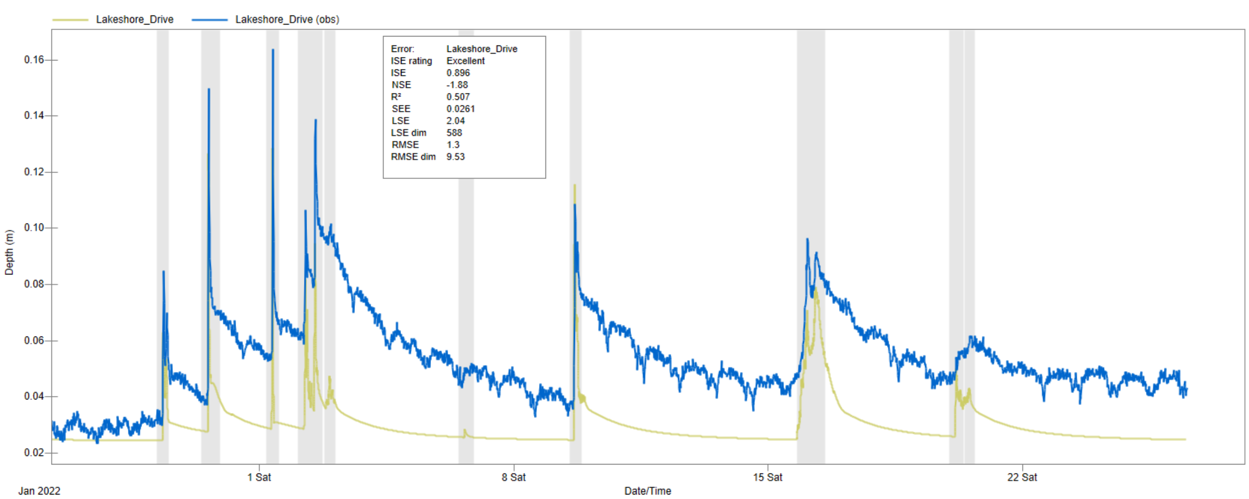


Figure 4. 13: Lakeshore Drive Measured Depth Hydrographs and Fully Composite CN Approach Results

The results from these four watersheds differ from the result obtained in Champions Blvd, shown in Figures 4.14 and 4.15. Based on the error performance (R^2 and NSE), both models at Champions Blvd are satisfactory according to Moriasi, Gitau, et al. (2015). The Fully Composite approach underestimated the flow depth at the first three rain events at Champions Blvd. The CN Cut-off at 90 approach overestimated the flow depth at the first three rain events. Moreover, the Fully Composite approach had a better simulation performance than the CN Cut-off at 90 approach. More importantly, the discrepancy with the recession limb is limited in the present model. This recession limb is attributed to the higher level of imperviousness, and overall large CN values in this watershed. Moreover, some soils in this area are also from the hydrologic soil group D, with a bit of infiltration capacity and large CN.

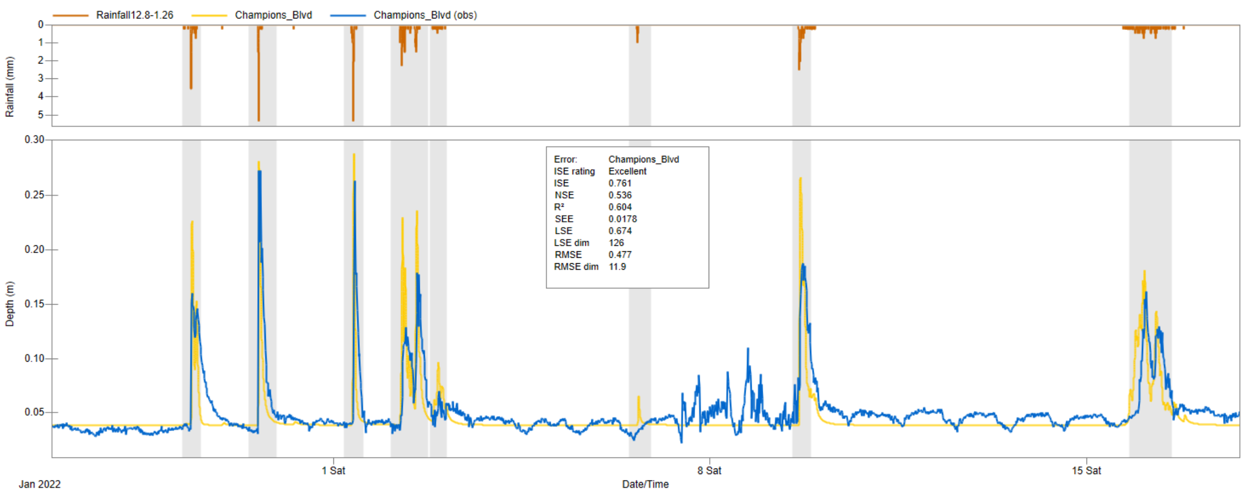


Figure 4. 14: Champions Blvd Measured Depth Hydrographs and CN Cut-off at 90 Approach Results

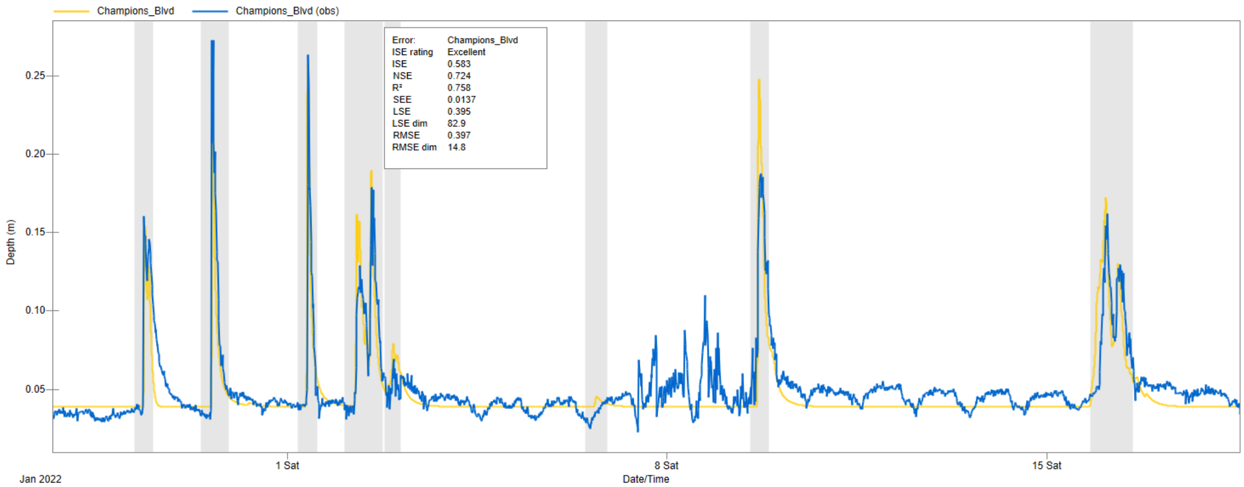


Figure 4. 15: Champions Blvd Measured Depth Hydrographs and Fully Composite CN Approach Results

4. 3 Modeling Results Peak Depth Comparison

As pointed out, the proposed approaches to represent infiltration and assigning impervious fractions affected the models' infiltration behavior. The Fully Composite approach had the highest average CN in the watersheds but no impervious fractions for the SWMM computations. The approach with the lowest cut-off at CN = 89 yielded the highest proportion of impervious areas and the smallest area-averaged CN for the pervious fraction.

The net result is noticeable in the observed vs. modeled peak flows shown in Figures 4.16 to 4.20. All graphs present four plots of peak flow depths comparison at every five locations for the Fully Composite and the three CN Cut-off approaches tested. The points scatter in general, moving from the right to the left side of the graphs with the change from the Fully Composite CN approach to the CN Cut-off approaches (93>90>89). The change means that the computed peak flow depths change from underestimations to overestimations compared with the field data. Except for Champions Blvd, the Fully Composite CN method underestimated most of the peak flow depth for most events, and the CN Cut-off at 89 Model overestimated the peak flow depth. The CN Cut-off at 90 approach, in general, gave the best model simulations (such as NSE = 0.864, R^2 = 0.865 at Capps Way), even though for the Lakeshore Drive watershed, the CN Cut-off at 93 approach was also good. The results obtained at Champions Blvd for the Fully Composite approach were the best, with the cut-off approaches yielding overestimations of the peak flow depths.

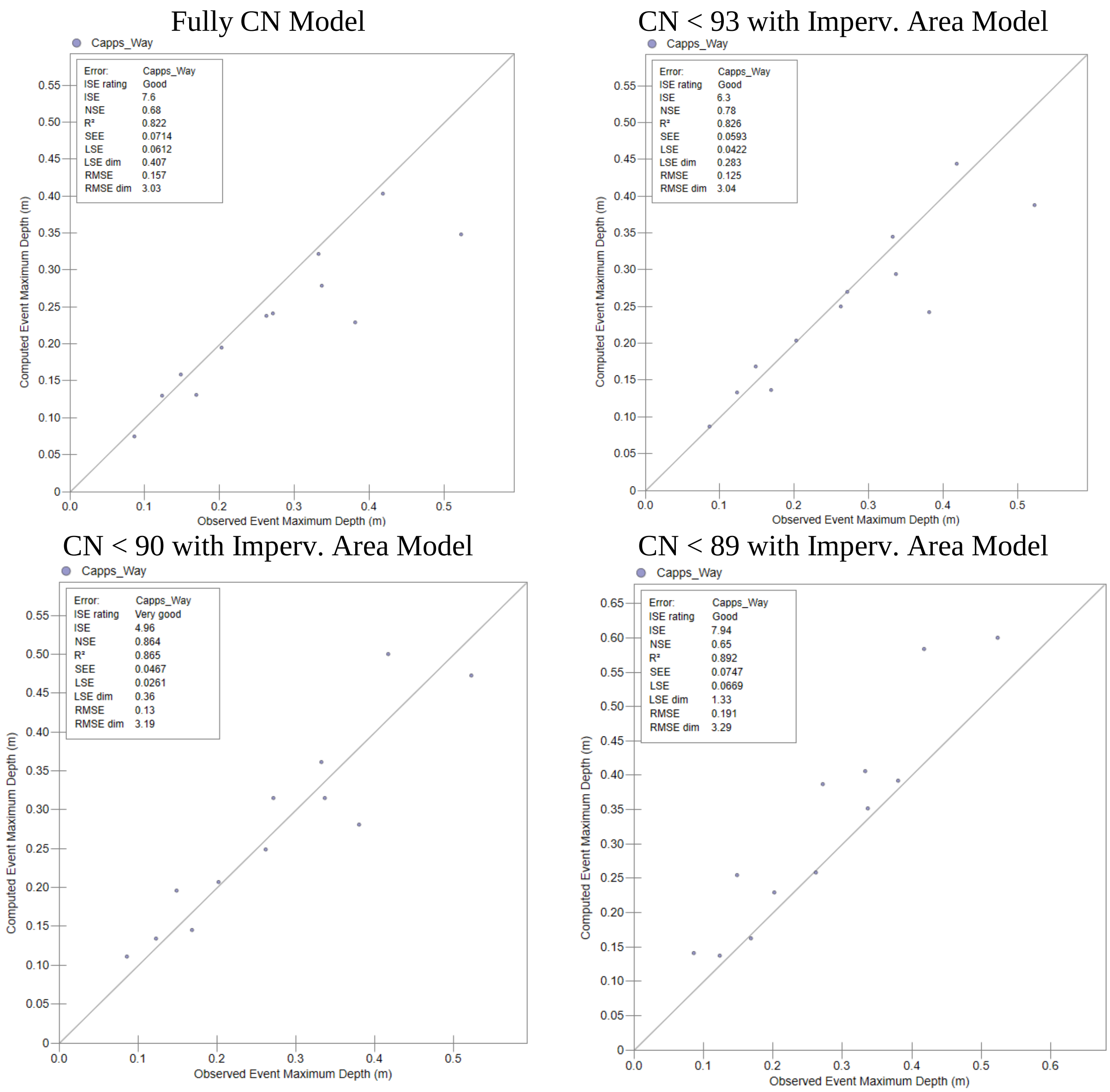


Figure 4. 16: Capps Way Peak Flow Depth Comparison

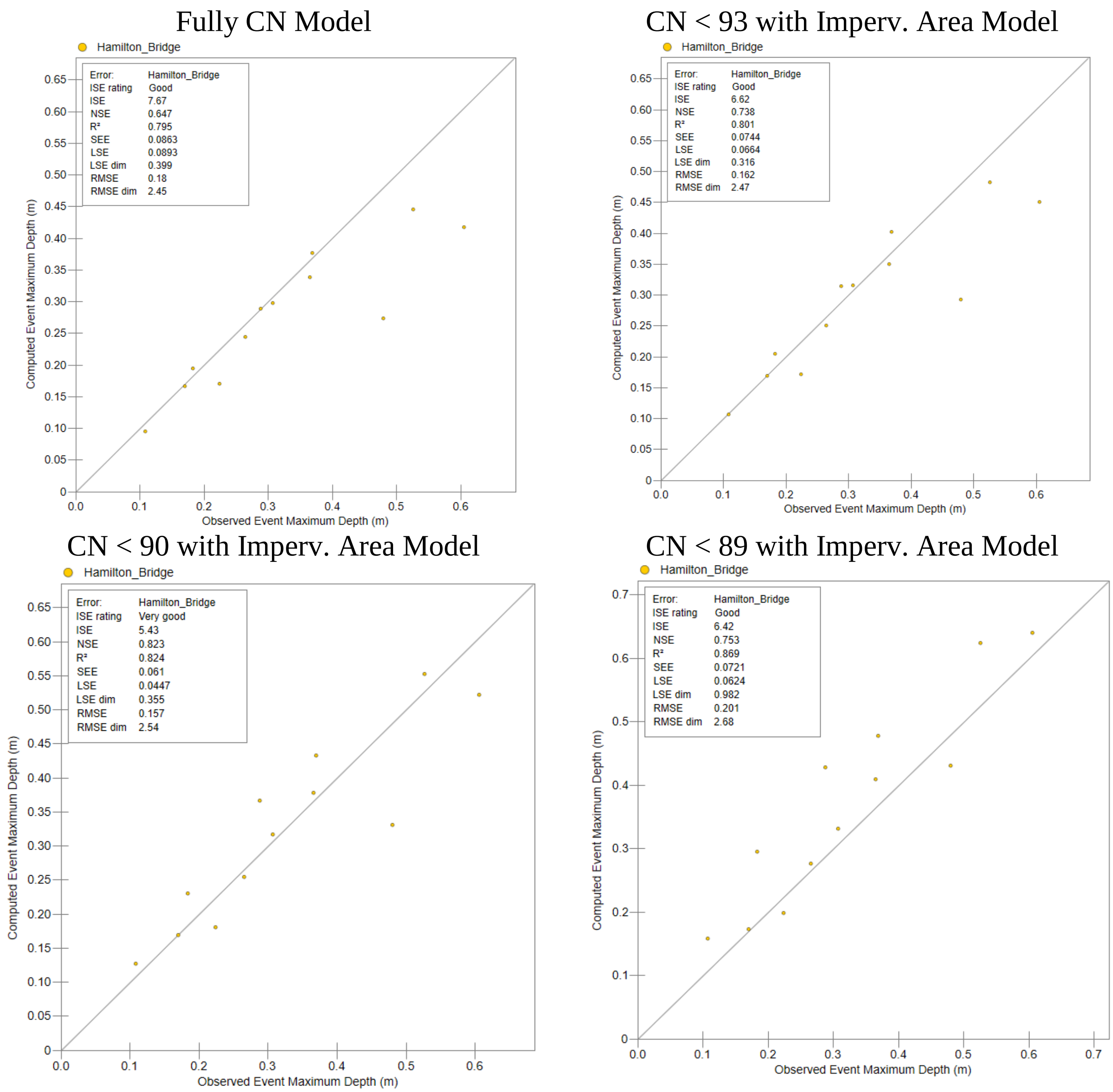


Figure 4. 17: Hamilton Rd. Peak Flow Depth Comparison

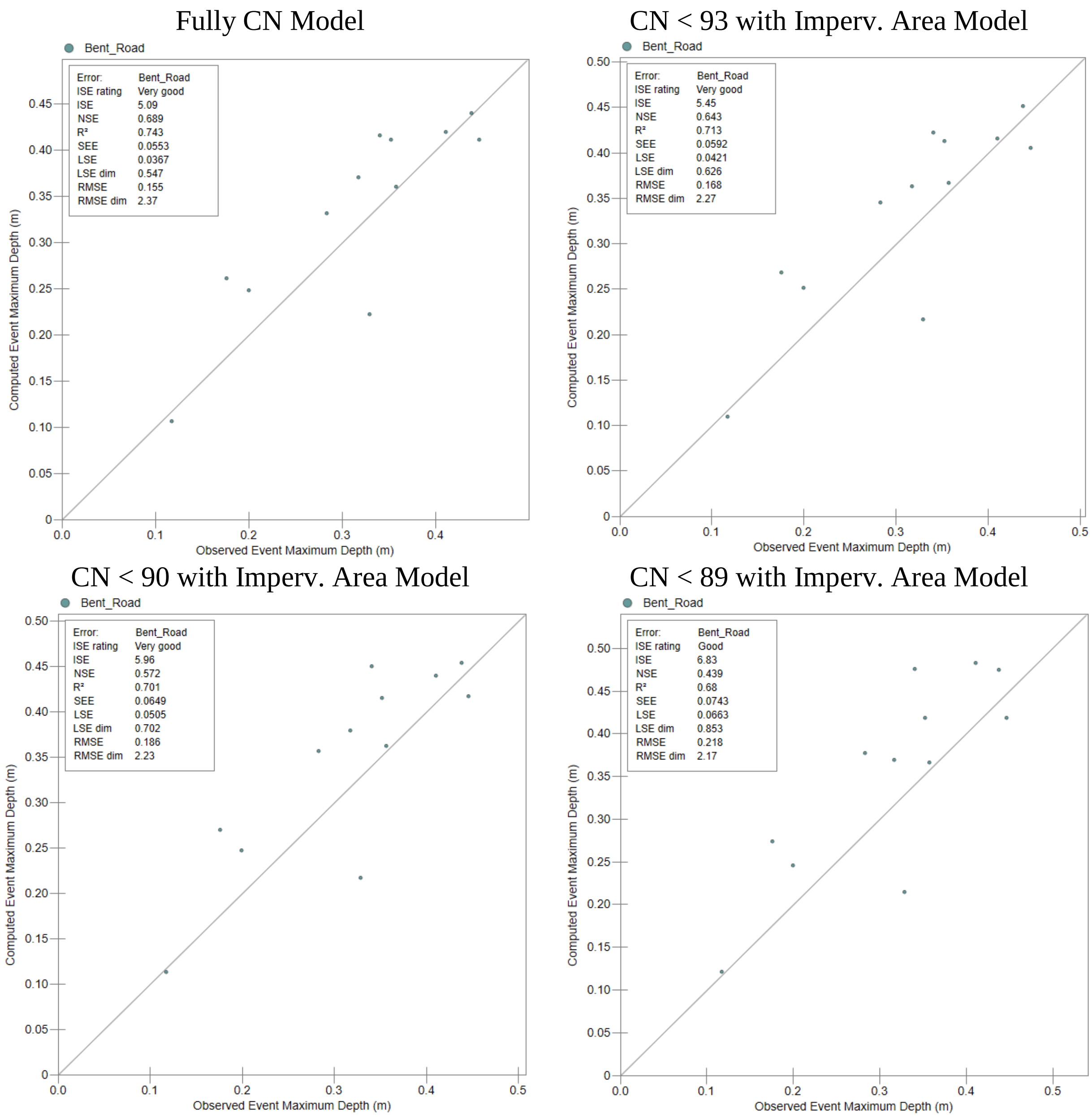
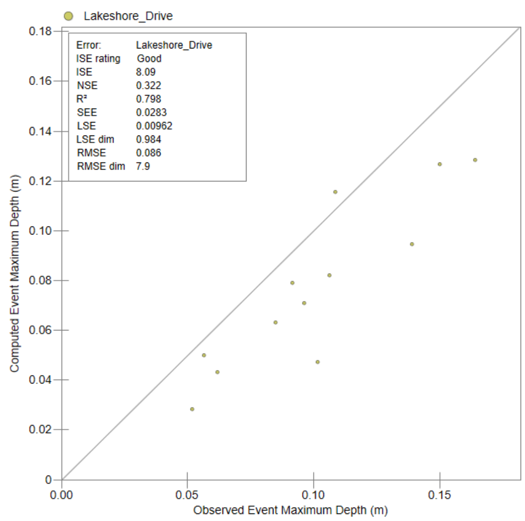
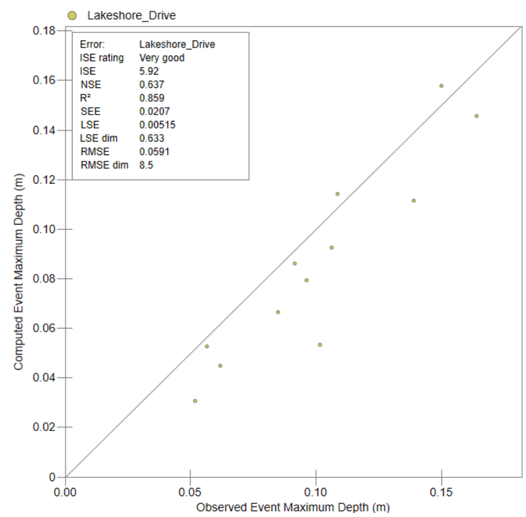


Figure 4. 18: Bend Creek Rd. Peak Flow Depth Comparison

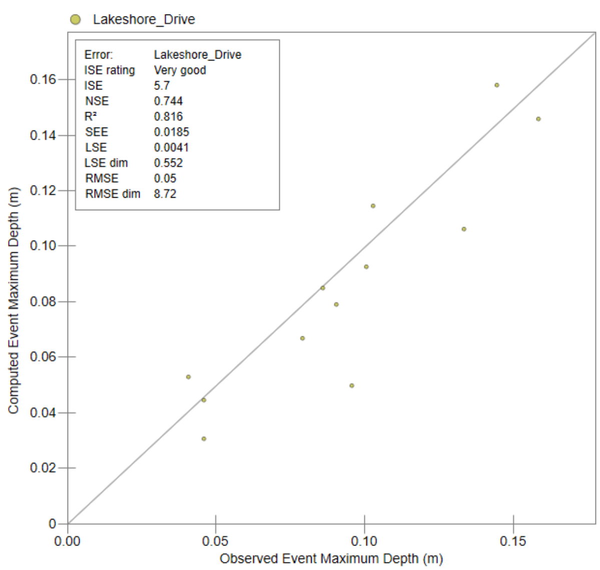
Fully CN Model



CN < 93 with Imperv. Area Model



CN < 90 with Imperv. Area Model



CN < 89 with Imperv. Area Model

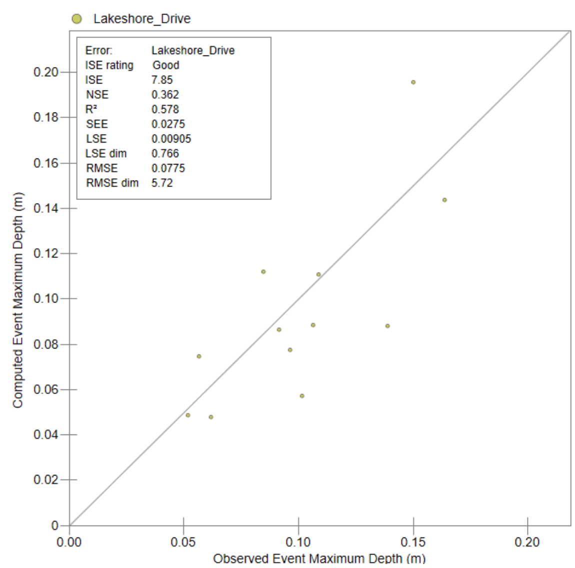
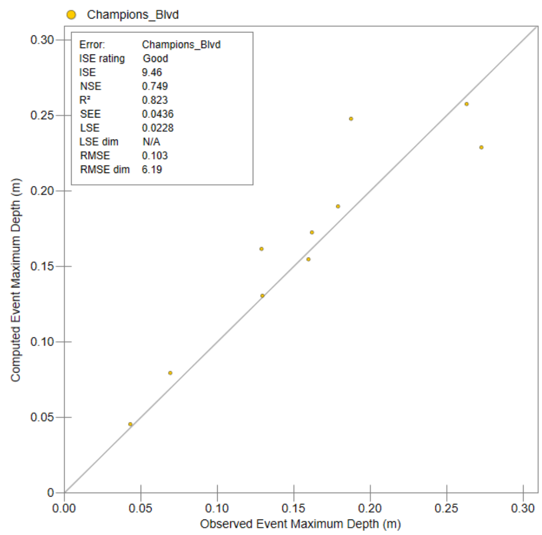
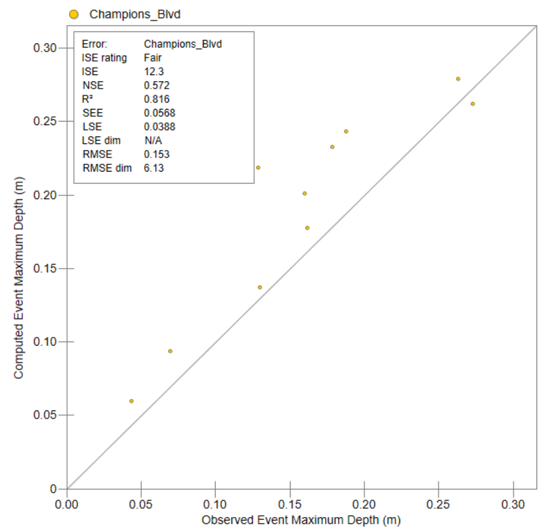


Figure 4. 19: Lakeshore Dr. Peak Flow Depth Comparison

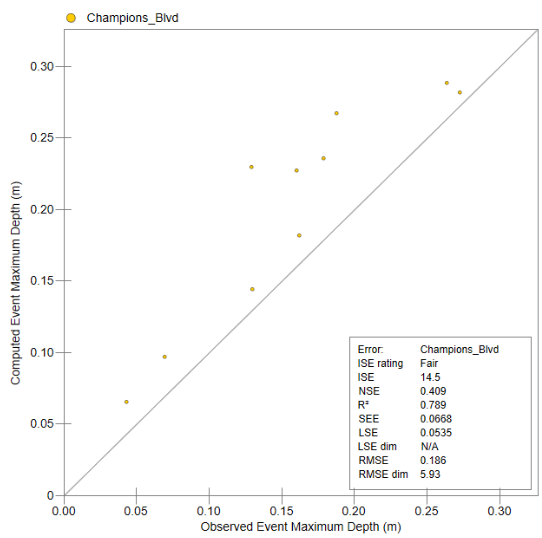
Fully CN Model



CN < 93 with Imperv. Area Model



CN < 90 with Imperv. Area Model



CN < 89 with Imperv. Area Model

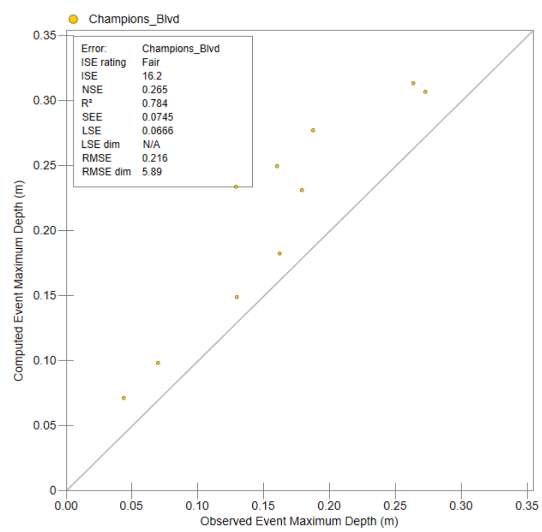


Figure 4. 20: Champions Blvd Peak Flow Depth Comparison

4. 4 Modeling Error Performance in Peak Depth Comparison

The highest Nash-Sutcliffe Efficiency (NSE) is in the CN Cut-off at 90 approach at Capps Way, which is 0.864; the second-highest NSE is in the CN Cut-off at 90 approach at Hamilton Road (0.823). Capps Way and Hamilton Road had similar water source combinations, and the CN Cut-off at 90 approach had the best NSE performance. At Lakeshore Drive, only the lake and some roads were the sources of impervious areas, and the CN Cut-off at 93 had the best NSE performance at this location. At Bend Creek Road and Champions Blvd, the Fully Composite model had the best NSE performance in peak depth comparison.

Table 4. 2: NSE Dataset Results Summary in Peak Depth Comparison

Location	Strategy for CN value assignments			
	Fully Composite	CN Cutoff<93	CN Cutoff<90	CN Cutoff<89
Capps Way	0.680	0.780	0.864	0.650
Hamilton Road	0.647	0.738	0.823	0.753
Bent Creek Rd.	0.689	0.643	0.572	0.439
Lakeshore Dr.	0.322	0.637	0.586	0.362
Champions Blvd	0.749	0.572	0.409	0.265

Table 4. 3: R^2 Dataset Results Summary in Peak Depth Comparison

Location	Strategy for CN value assignments			
	Fully Composite	CN Cutoff<93	CN Cutoff<90	CN Cutoff<89
Capps Way	0.822	0.826	0.865	0.892
Hamilton Road	0.795	0.801	0.824	0.869
Bent Creek Rd.	0.743	0.713	0.701	0.680
Lakeshore Dr.	0.798	0.859	0.835	0.578
Champions Blvd	0.823	0.816	0.789	0.784

The highest coefficient of determination (R^2) is in the CN Cut-off at 89 approach at Capps Way, which is 0.892. The CN Cut-off at 89 approach also had the highest R^2 value at Hamilton Road. The CN Cut-off at 93 approach had the highest R^2 value at Lakeshore Drive. The Fully

Composite approach had the highest R^2 value at both Bent Creek Road and Champions Blvd, which agreed with the NSE performance.

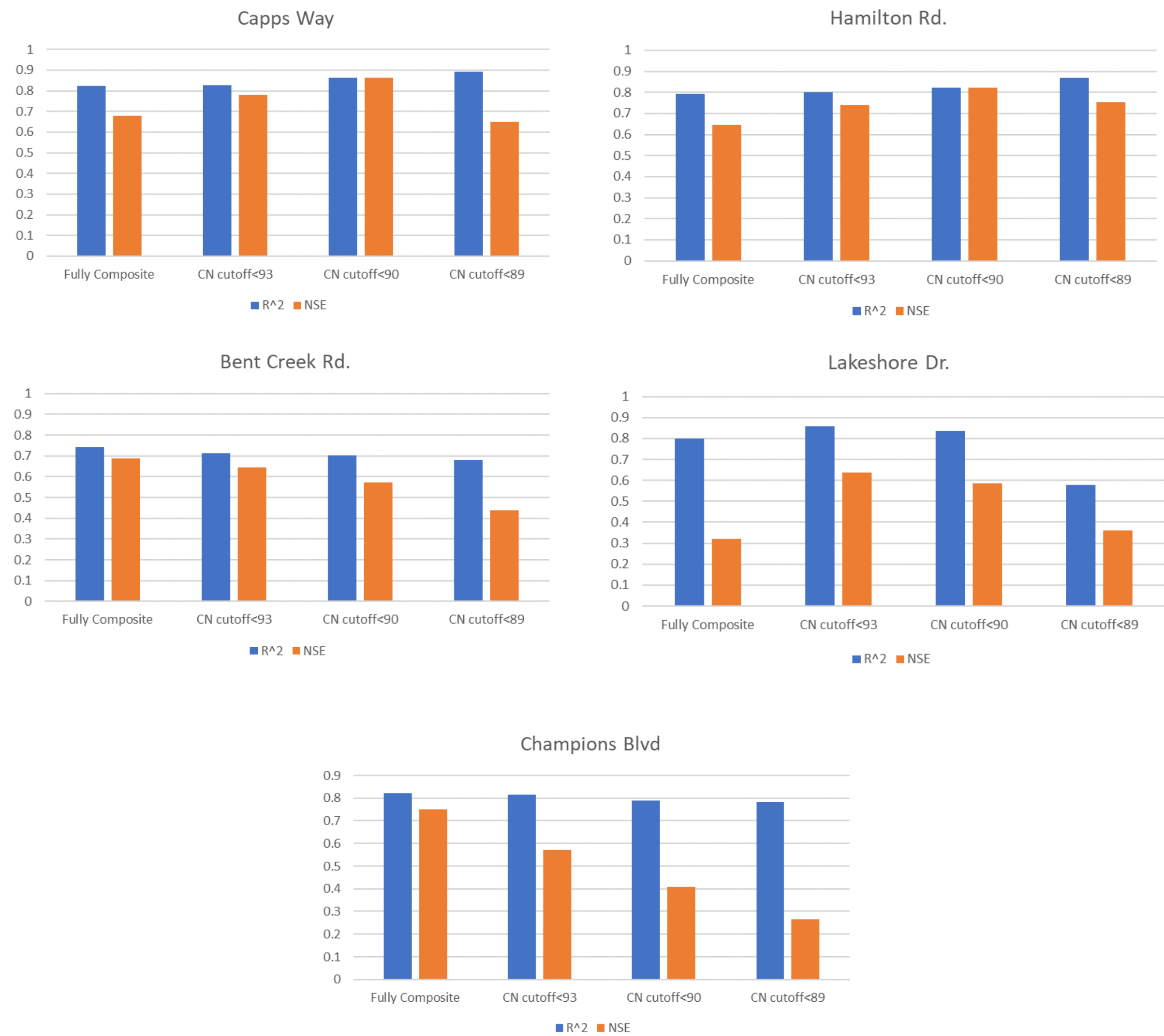


Figure 4. 21: Model Error Performance at Five Water Level Logger Locations

Looking at the model error performance histograms in Figure 4.21, the CN Cut-off at 90 approach gave the best all-around performance at Capps Way and Hamilton Road. The CN Cut-off at 93 approach gave the best all-around performance at Lakeshore Drive, and the Fully Composite CN approach gave the best all-around performance at Champions Blvd.

4. 5 Limits and Shortcomings

The field work and the modeling approach used in this research have important limitations, which are listed below.

1. Only one rain gauge was installed in the field, so the precipitation data may not be entirely accurate at some locations;
2. Some level loggers were washed out by the stream and may malfunction at some stage, and thermal artifacts (Moore, et al. 2016) may also have affected some field measurements;
3. No groundwater elements were added to the model, so the recession curve could not be well represented for most watersheds;
4. Insufficient dimension information of drainage infrastructures at some locations in the watershed and lack of the collection system geometry might have impacted the response of the watersheds to rain events;
5. No validation process was performed to verify the accuracy of the model;
6. Care must be taken in generalizing the findings of this study as the performance of CN Cut-off approaches depend on the watershed characteristics. If a similar study is performed in a watershed with a different type of land use and soil groups, different cut-off values could perform better than the CN Cut-off at 90, which was determined the best for Moore's Mill Creek.

5. Conclusion and Recommendation

Hydrological models have been widely applied to design and manage water resources, including stormwater management in urban watersheds. The accuracy and quality of the data input in these models are of paramount importance so that the model predictions are helpful and represent well watersheds. Infiltration is a critical component of hydrological models, and the Curve Number, due to its simplicity and data availability, is one of the most adopted methodologies to compute this type of abstraction. The CN methodology is also presented in the EPA SWMM 5 model, albeit slightly adapted to represent continuous hydrological simulation. Despite the relative simplicity of CN infiltration, these values can be unclear to certain types of land uses, and tedious in the case of a large number of subcatchments in a SWMM model.

This research evaluated the performance of alternative approaches to assign CN values to SWMM subcatchments, using CN values to determine whether a subcatchment area should be considered impervious. The traditional Fully Composite approach and proposed CN Cut-off approaches were evaluated using the headwater watersheds of Moore’s Mill Creek Watershed in East Alabama. In the field investigation, five watersheds within Moore’s Mill Creek were considered, with monitoring of rainfall, atmospheric pressure, and stream flow depth. The model calibration goal in SWMM was to represent the peak flow depths. A vital component of the work was the source of the gridded CN data from the QGIS plugin “*CurveNumberGenerator*” (Siddiqui 2020) and the automatic computation of area-average CNs from the gridded results within each subcatchment from the Microsoft Excel (Pivot Table and VBA program).

The comparison between models and field measurements of the streamflow depths indicated that the models were able to represent the rapid rise of flow depths following rain events. However, the recession limb was not well modeled in most cases, possibly due to the lack of groundwater representation in the SWMM models. Regrading the peak flow depths, the tendency for the modeled peak flows increased as the model approaches changed from Fully Composite to the CN Cut-off at 89. For the watersheds with the lowest average CN values, i.e., less urban development or hydrologic soil groups A/B, the Cut-off approach using CN = 90 yielded the best predictions for the peak flow depth. On the other hand, the Fully Composite approach yielded the best results for Champions Blvd, comparatively more spartan than the CN Cut-off approaches, which could be applied to other watersheds that are highly developed, whereas the Cut-off approaches to less urbanized watersheds. The poorer performance of the Fully Composite approach for Lakeshore Dr. watershed indicates a potential issue if lakes/reservoirs are near the monitoring station or if they constitute a sizable portion of the watershed. In such cases, the CN Cut-off approaches are recommended. However, these preliminary recommendations need to be confirmed by subsequent investigations in other watersheds adopting these approaches.

Again, this research did not include groundwater in the SWMM model, thus effects of these approaches to computing CN on the interactions between groundwater and surface water have not been explored. The performance of the method regarding other hydrological parameters, such as flow rate or velocity, was not tested. Finally, the performance of the modeling approaches to computing CN in watersheds that have extensive use of green infrastructure practices was not evaluated in this work. These are open research questions that need to be addressed in future research.

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Appendix A

CN Calculations Example in CN Cut-off at 90 Approach:

Excel screenshot

CNCutoff90

	A	B	I	J	K	L
1	Row Labels	Sum of %CN	Name	%impervious	fixed CN	%imperv
2	S1	100.00%	S1	20.57%	83	20.57
3	0	20.57%	S10	52.61%	86	52.61
4	60	1.57%	S100	0.00%	78	0.00
5	61	6.08%	S101	4.84%	65	4.84
6	68	8.83%	S102	0.00%	64	0.00
7	84	0.05%	S103	0.00%	55	0.00
8	88	45.26%	S104	0.00%	71	0.00
9	89	17.64%	S105	1.76%	73	1.76
10	S10	99.96%	S106	3.09%	78	3.09
11	0	52.61%	S107	12.63%	88	12.63
12	68	5.74%	S108	1.91%	89	1.91
13	70	1.37%	S109	11.12%	88	11.12
14	78	0.59%	S11	27.33%	74	27.33
15	88	7.53%	S12	68.85%	48	68.85
16	89	32.11%	S13	0.64%	59	0.64
17	S100	99.86%	S14	37.43%	75	37.43
18	0	0.00%	S15	23.14%	83	23.14
19	30	6.54%	S16	30.55%	69	30.55
20	61	0.07%	S17	50.23%	78	50.23
21	68	32.27%	S18	9.74%	83	9.74
22	88	60.98%	S19	31.39%	77	31.39
23	S101	100.07%	S2	0.84%	79	0.84
24	0	4.84%	S20	0.00%	47	0.00
25	30	15.55%	S21	22.68%	71	22.68
26	36	3.94%	S22	45.57%	89	45.57
27	42	1.25%	S23	36.64%	85	36.64
28	52	4.70%	S24	25.82%	78	25.82
29	60	2.76%	S25	11.16%	83	11.16
30	68	37.62%	S26	24.04%	87	24.04
31	88	23.93%	S27	0.00%	57	0.00
32	89	5.48%	S28	41.79%	80	41.79
33	S102	100.00%	S29	0.00%	49	0.00
34	0	0.00%	S3	18.02%	87	18.02
35	30	27.00%	S30	55.57%	89	55.57

*The screenshot shows only part of the entire CN calculations in Excel.

VBA code:

```
Private Sub CalculateCNButton_Click()

    'Declaring variables
    Dim nSub As Integer
    Dim percentImpervious(), CN() As Double
    Dim ii, jj, kk, nRows, countRows As Integer
    Dim nameSub As String
    Dim isFinished As Boolean
    Dim result, sumImp As Double

    'Why not?
    ReDim percentImpervious(50)
    ReDim CN(50)

    'There are 109 sub-catchments in our watershed
    'Change this value in case there are more (or less)
    nSub = 109
    nRows = 2
    jj = 0
    kk = 0
    countRows = 2
    isFinished = False

    'I am reading just the first character of the cell
    nameSub = Left(Cells(nRows, 1).Text, 1)

    'I am reading cells until the first character of the read cell is an "S"
    Do While nameSub <> "S"
        nRows = nRows + 1
        nameSub = Left(Cells(nRows, 1).Text, 1)
    Loop

    'nameSub is = "S"
    'for loop from 0 to subcatchments
    For ii = 1 To nSub '(includes last number)
        'We will write the name of this subcatchment at column I
        Cells(countRows, 9).Value = Cells(nRows, 1).Value

        'While loop to test the cell content
        Do While isFinished = False
            'I am reading the next line
            nRows = nRows + 1
            nameSub = Left(Cells(nRows, 1).Text, 1)
```

*Continuous in next page

```
    'Test if the first character is zero
    If nameSub = "0" Then
        'I wanna paste the value into the J column: AVOID INSERTING CN VALUES
        'LOWER THAN 10 STARTING WITH ZERO
        Cells(countRows, 10).Value = Cells(nRows, 2)
    'Testing if the sub-catchment is over
    ElseIf (nameSub = "S" Or nameSub = "") Then
        'I have reached the bottom of my sub-catchment, go to the next one
        isFinished = True
    'is it a number?
    Else
        'We have a number as our first character, this means we will need to
        'perform some sort of calulations
        CN(jj) = Cells(nRows, 1).Value
        percentImpervious(jj) = Cells(nRows, 2).Value
        jj = jj + 1 'I wanna count how many values I am reading
    End If
Loop


            'Calculate stuffs
            For kk = 0 To jj - 1
                'Multiply my CN by the percentImpervious
                result = result + (CN(kk) * percentImpervious(kk))
                sumImp = sumImp + percentImpervious(kk)
            Next kk

            'Print the output value into column K
            If sumImp > 0 Then
                Cells(countRows, 11).Value = result / sumImp
                countRows = countRows + 1
            Else
                Cells(countRows, 11).Value = 0
                countRows = countRows + 1
            End If

            'Reset my variables
            ReDim percentImpervious(50)
            ReDim CN(50)
            jj = 0
            kk = 0
            result = 0
            sumImp = 0
            isFinished = False
        Next ii

    End Sub
```

Appendix B

CN look up Table

Grid_Code	CN	Grid_Code	CN	Grid_Code	CN	Grid_Code	CN	Grid_Code	CN
11A	100	24A	88	43A	36	73A	74	95A	80
11B	100	24B	92	43B	60	73B	74	95B	80
11C	100	24C	93	43C	73	73C	74	95C	80
11D	100	24D	94	43D	79	73D	74	95D	80
11	100	24	94	43	79	73	74	95	80
12A	100	31A	70	51A	33	74A	79		
12B	100	31B	81	51B	42	74B	79		
12C	100	31C	88	51C	55	74C	79		
12D	100	31D	92	51D	62	74D	79		
12	100	31	92	51	62	74	79		
21A	52	32A	70	52A	33	81A	40		
21B	68	32B	81	52B	42	81B	61		
21C	78	32C	88	52C	55	81C	73		
21D	84	32D	92	52D	62	81D	79		
21	84	32	92	52	62	81	79		
22A	81	41A	45	71A	47	82A	62		
22B	88	41B	66	71B	63	82B	74		
22C	90	41C	77	71C	75	82C	82		
22D	93	41D	83	71D	85	82D	86		
22	93	41	83	71	85	82	86		
23A	84	42A	30	72A	47	90A	86		
23B	89	42B	55	72B	63	90B	86		
23C	93	42C	70	72C	75	90C	86		
23D	94	42D	77	72D	85	90D	86		
23	94	42	77	72	85	90	86		

**QGIS plugin "CurveNumberGenerator" uses the lookup table to convert NLCD Land Use and NRCS Hydrologic Soil Groups to Curve Number. Grid code numbers 11-95 are represented for NLCD land use types shown in the legend of Figure B. 1 and grid code letters A-D are represented for NRCS HSG shown in the legend of Figure B. 2.*

NLCD Land Cover Map of Study Watershed

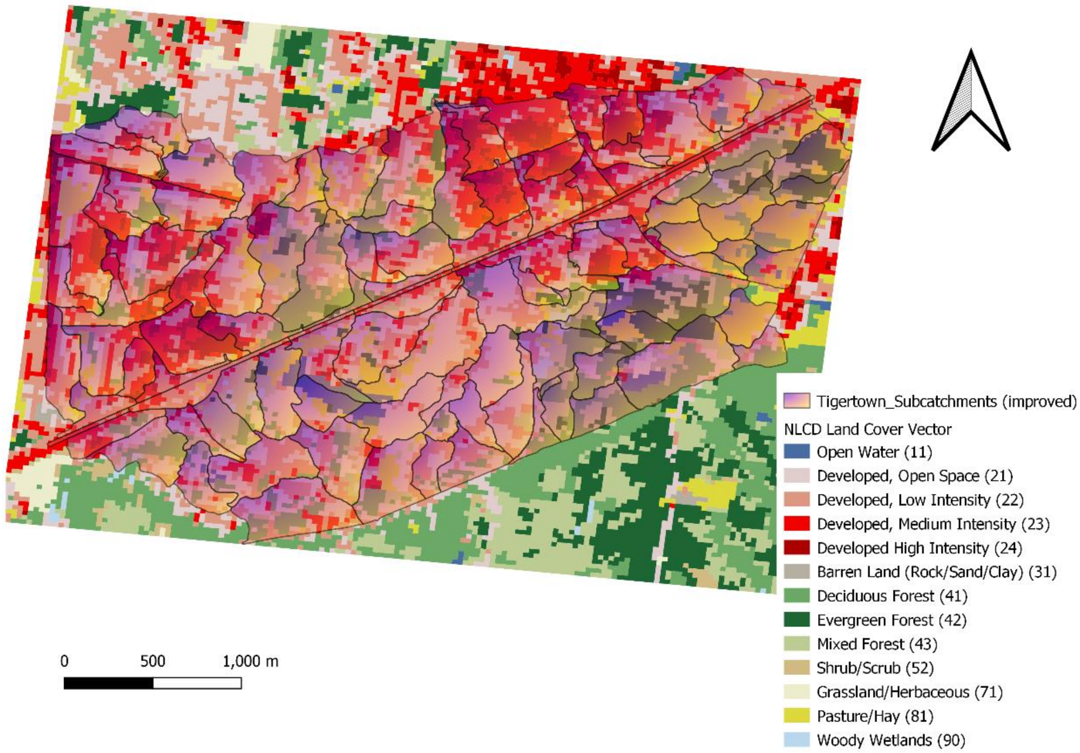

Figure B. 1: NLCD Land Cover Map

SSURGO Soil Layer Map of Study Watershed

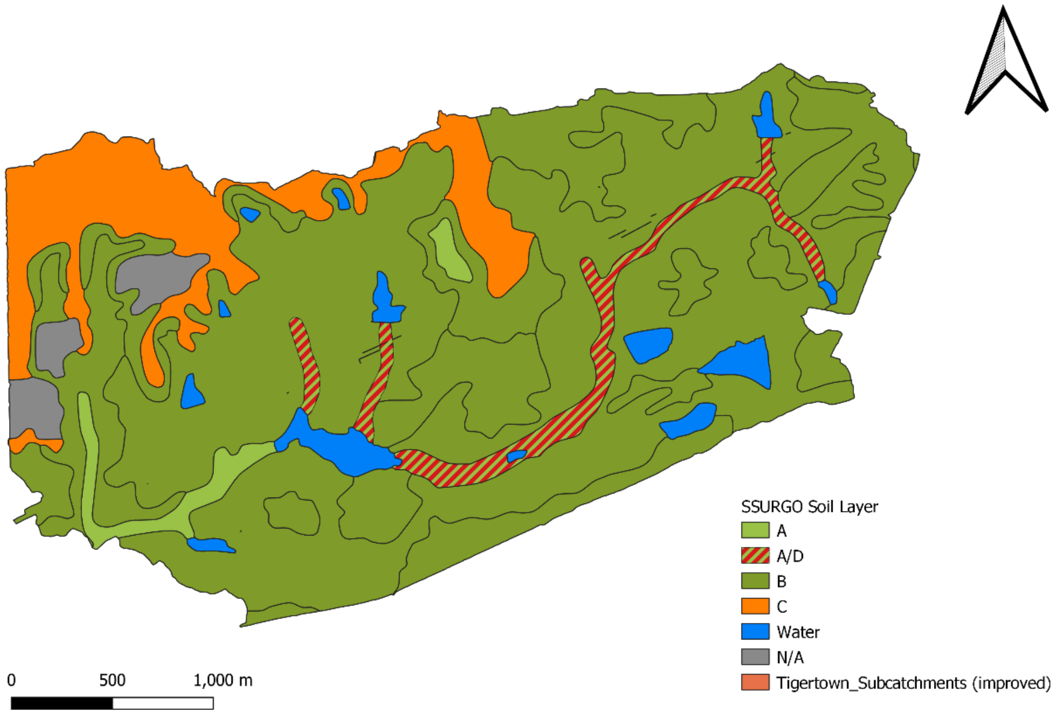

Figure B. 2: SSURGO Soil Layer Map