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Hydrologic Modeling of Urban Development Scenarios and Low-Impact Design Systems on an Undisturbed Coastal Forested Watershed under Extreme Rainfall-Runoff Events and Hydro-Meteorological Conditions in a Changing Climate

Julianna Corbin[1], Hunter Morgan[1], Evan Patrohay[1], Ty Williams[1], Devendra Amatya[2], and Christophe J. G. Darnault[3]

AUTHORS: [1]1Student, Department of Environmental Engineering and Earth Sciences, Clemson University, 342 Computer Court, Anderson, SC 29625. [2]Research Hydrologist, Center for Forested Wetlands Research, USDA Forest Service, 3734 Highway 402, Cordesville, SC 29434. [3]Associate Professor, Department of Environmental Engineering and Earth Sciences, Clemson University, 342 Computer Court, Anderson, SC 29625.

Abstract. Watershed 80 (WS80), a reference watershed located in the USDA Forest Service Santee Experimental Forest, has been undisturbed since 1937, including from the silviculture that has historically characterized the region. Therefore, the results from this study are assumed to serve as a baseline of the developmental behavior for similar watersheds along the Southeastern Coastal Plain. The purpose of this study was first to analyze and compare the outputs of two rainfall-runoff models, the NRCS program WinTR-55 and the USGS Regional Regression Equations (RREs), with historical data gathered from WS80 to examine which model most accurately fits existing peak flow data. An accurate sense of peak flows is crucial in both the conservation and planning of sites, as proper stormwater management and infrastructure preserve the integrity of both natural resources and humanmade structures. Second, the study sought to analyze the impact of hypothetical development on design peak flow rate with up to 15% watershed imperviousness using each model. Additionally, two hypothetical scenarios of low-impact design (LID) practices such as vegetative rooftops and permeable pavements on development within the watershed were examined using the Purdue University software L-THIA. The USGS RREs overpredicted peak flows by 84% at a 5-yr return period to 12% at a 100-yr return period. WinTR-55 underpredicted peak flows by 31% at a 5-yr return period to 52% at a 100-yr return period. Increases in impervious surfaces led to subsequent increases in modeled design peak flows, with the greatest post-development change in design peak flow rate occurring within the USGS model. Although results showed that neither the USGS nor WinTR-55 models accurately predicted the design peak flow data from the watershed, USGS predictions were closer to the observed values for 50-yr or higher return periods than that from WinTR-55. Though LID practices were only applied up to a hypothetical 15% of the watershed, when fully implemented they were estimated to exert a 98% reduction in runoff which translated to a total reduction in volume by 20% and depth by 16% as compared to traditional design counterparts. This hypothesized evidence indicates the merit for using LID practices for runoff management even in situations of low imperviousness.

INTRODUCTION

In a natural setting with little impervious groundcover, vegetation and soil-intercepted precipitation reduce the momentum of overland flow. This interception increases percolation and infiltration rates, resulting in a reduction of peak levels of runoff and an increase in groundwater recharge (Kramer 2013; O'Driscoll et al. 2010; Day and Bremer 2013). Root systems function as a soil anchor, reducing soil losses and erosion while interception decreases the potential for contaminants to pollute surrounding waterbodies (O'Driscoll et al. 2010; Day and Bremer 2013). In contrast, urbanization has created well-documented changes to the hydrology of watersheds across the world due to high levels of impervious surface cover (Elaji and Ji 2020; Fang et al. 2020). Urban centers within watersheds have reduced water infiltration, reduced surface storage capacity, and increased surface runoff, and the high peak flow rates that result from

this altered hydrology often degrade streams and lead to eroded, channelized riverbeds (O'Driscoll et al. 2010). As these streams widen, their riparian buffers may be exposed to severe flooding damage, which can lead to significant losses by adjacent floodplains and wetlands (O'Driscoll et. al. 2010; Feaster et al. 2014; Saia et al. 2019).

The Charleston Metropolitan Area (CMA) is one such urban center that threatens adjacent, less-developed watersheds in coastal South Carolina. The CMA possesses a population growth rate of more than three times the national average and has experienced an average increase in urbanized area of over 250% since the 1970s, as seen in Figure 1 (Campbell et al. 2001). Surrounded in the south and the east by the Atlantic Ocean and extensive marshland, the CMA has expanded inland in the direction of the Francis Marion National Forest (FMNF), located about 60 km northeast of the city. Suburban communities with as much as 30% impervious surface coverage have been encroaching on the forest, and wooded areas along its perimeter have already been cleared (Holland et al. 2004). This fashion of urbanization threatens South Carolina as a whole, as the Environmental Protection Agency (EPA) estimates that 2,029 mi^2 of forest will be cleared for urban development statewide by the year 2050 (Kramer 2013). Given this knowledge, it is likely that the FMNF will become less isolated with time, having potential implications on the quality of ecosystem services and hydrology in and around it (O'Driscoll et al. 2010).

The forest landscapes, surrounding Santee Experimental Forest (SEF), a field research station within the FMNF managed by the United States Department of Agriculture (USDA) at the wildland-urban interface, are likely under threat due to growing urbanization in the vicinity. This coastal forest contains the headwaters of the Cooper River, one of three large rivers that drain into the Charleston Harbor. Long-term hydro-meteorological observations from the SEF have been tremendous assets to the USDA Forest Service and its collaborators and stakeholders in understanding the ecohydrological processes of coastal watersheds (Amatya and Trettin 2019). The continued encroachment of the Charleston area toward the forest makes research within the relatively undisturbed forest critical for the creation of baseline references on the processes governing water balance, storm runoff, and peak flow rate, all of which are key for water management in the region (Amatya and Trettin 2019; Callahan et al. 2012; Harder et al. 2007; La Torre Torres et al. 2011).

Watershed 80 (WS80) is one of several watersheds within the SEF (Figure 2) and is considered an important watershed for research purposes because no human disturbance has occurred within it since its founding in 1937 (https://www.srs.fs.usda.gov/charleston/santee/). Although canopy damage caused by Hurricane Hugo in 1989 has been the most significant natural disturbance to date (Hook et al. 1991), these damaged stands reportedly recovered to pre-Hugo levels by 2004 (Jayakaran et al. 2014). Therefore, where completely regenerated stands exist, ecohydrological processes in WS80 are assumed to function analogously to that of a natural coastal forested watershed. WS80 is thus often chosen as a "reference" watershed because the site is both isolated and more or less representative of the natural conditions in the surrounding Charleston area. This watershed is also being used as a control site for evaluating hydrologic effects of longleaf pine restoration ongoing on the adjacent treatment watershed (WS77) (Amatya et al. 2021a). As anthropogenic interactions often make hydrological modeling more complex, this combination of factors is of great benefit.

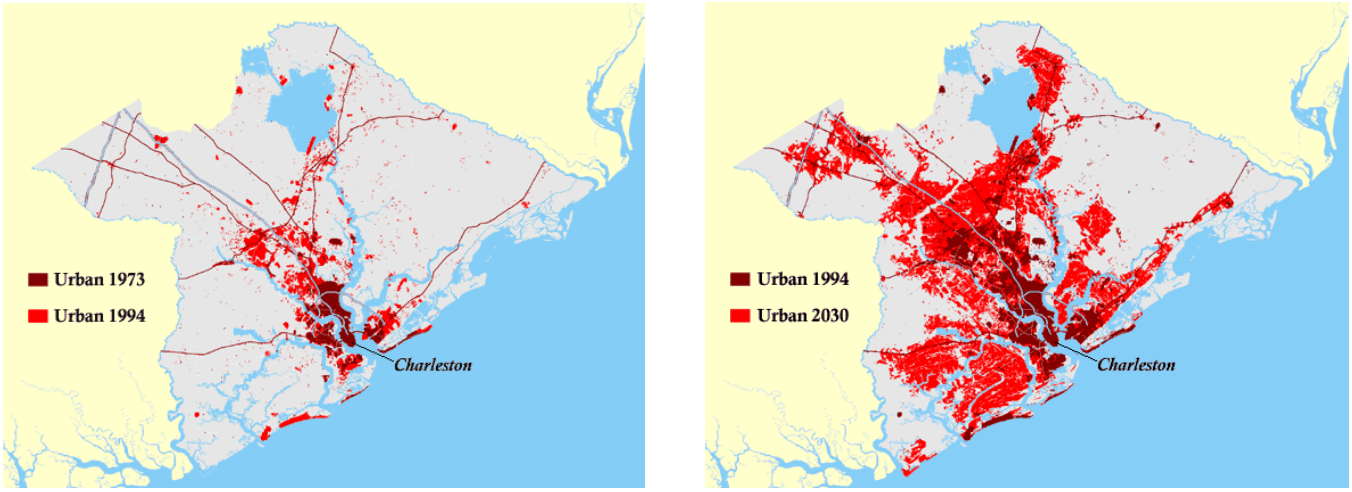

Figure 1. Projected urbanization map of the Charleston Metropolitan Area (CMA). The left figure represents recorded urban growth of 256% from 1973 to 1994. The right figure represents projected urban growth of 247% between 1994 and 2030 given current development trends. *Source*: Campbell et al., 2001.

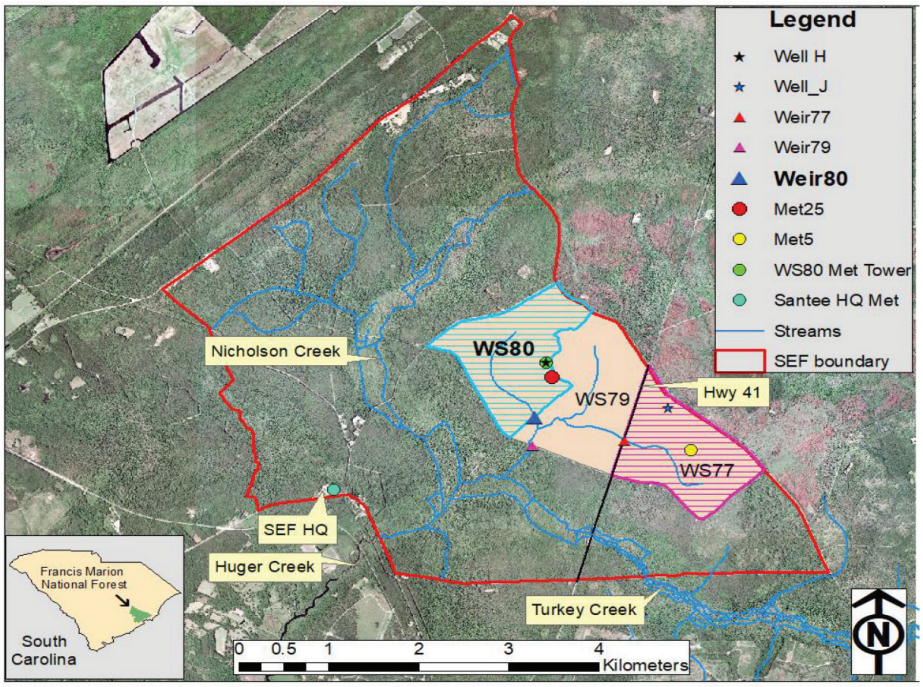

Figure 2. Map of WS80 alongside adjacent watersheds, including experimental layout. *Source*: Trettin et al., 2019.

Hydrological models are frequently used for the estimation of event-based design peak flow rates and allow engineers to determine tolerable risks of failure in infrastructure design (Hutton et al. 2015). A variety of methods have been used extensively to model the hydrology of WS80. In their application of the Soil Conservation Service (SCS) curve number method and other modified forms to obtain storm runoff volume, Walega et al. (2020) used a simpler form of the graphical peak flow rate method without flow routing on this and two other upland forest watersheds. In their study of this watershed, Amatya et al. (2021b) utilized both the Rational Method (RM) and the US Geological Survey Regional Regression Equations (USGS RREs) (Feaster et al. 2014) and determined that RM performed poorly in terms of underestimating design peak flow rate by as much as 63% for a return interval of ≥ 25 years. The reason for this high underestimation may be the result of WS80 exceeding the recommended area of 0.1 mi^2 for the use of the RM. Amatya et al. (2021b) also recommended the USGS RREs for design peak flow rate predictions on WS80, with a large surface storage, as it was found to overestimate peak flow rate for the same return period by a comparatively smaller 28%. Blair et al. (2014) also developed a modeling system based on the curve number and unit hydrograph techniques for lower coastal plain watersheds. Although Blair et al. (2014) did use the WinTR-55 with a unit hydrograph method on urbanized or semi-urbanized watersheds with proximity to the coast, it has yet to be validated to estimate design peak flow rate estimation in forested watersheds. Furthermore, to this date no comparative study exists between the empirical USGS RRE method and the more conceptually based NRCS WinTR-55 method for predicting design peak flow rates on such small forest watersheds. Often, either the data used to calibrate models for peak flow predictions or the models themselves are inadequate, limited, or too generalized. Therefore, there is a need to analyze and compare the design peak flow outputs of two models, the USGS RREs for the southern Coastal Plain (Feaster et al., 2014) and WinTR-55 (NRCS, 2009), with existing long-term meteorological and hydrological data recorded in WS80 for model validation (Amatya and Walega 2020).

In consideration of ongoing urban growth, understanding the effects that hypothetical increases in impervious areas within WS80, as a reference, have upon modeled design peak flow predictions is critical for assessing the hydrologic response and designing mitigation measures to the urban development of an undisturbed coastal forested watershed in a changing climate. As more forests in the region are developed, engineers seek to reduce negative impacts (Lockaby et al. 2013) by developing mitigation measures using low-impact design (LID). LID methods serve to reduce downstream design peak flow rates by increasing vegetative and perme-

able cover, using the natural properties of these materials to increase deposition and infiltration (Kramer 2013; Day and Bremer 2013). These systems often include bioretention and biofiltration devices, infiltration basins, media filters, porous pavement, bioswales, and other ecologically derived designs that promote the restoration of waterbodies while simultaneously reducing the design peak flow rates caused by development (Day and Bremer 2013). Integrating LID methods into existing stormwater management systems will increase their retention and infiltration effectiveness and will provide aesthetically pleasing stormwater solutions for regions such as CMA that are under pressure of increasing water-related difficulties exacerbated by climate change. Consequently, there is a need to assess the impact of LID measures upon the hydrologic response of an undisturbed coastal forested watershed to rainfall-runoff occurrences that are subject to partial urbanization and extreme hydro-meteorological events.

The first objective of this study involved comparing the design peak flow rate predictions from the empirical USGS RREs and conceptual WinTR-55 with long-term hydrological and meteorological data from an undisturbed coastal forested watershed. The goal is to understand which model most closely aligns with observed peak flow values. As WinTR-55 uses unit hydrograph techniques specifically for small watershed hydrologic analysis (NCRS 2009) it is hypothesized that this model will provide the best performance. The second objective of this study entailed measuring the hydrologic response of LID techniques, used to mitigate the hypothetical partial urbanization and resulting increases in the impervious surface area of an undisturbed coastal forested watershed, to design storms simulating extreme hydro-meteorological events associated with climate change. The goal is to assess the differences of the hydrological responses of LID techniques—specifically green roofs, bioswales, and permeable pavement—to design rainfall-runoff events in a newly developed watershed simulating the future urbanization of a forest and to detect critical rainfall events. Following the results of Kim et al. (2018), these LID practices are hypothesized to reduce the overland flow in the respective watershed areas of use by as much as 90%. This further analysis will give policymakers, developers, and city managers additional information on the stormwater management capabilities of LID techniques, even when utilized in relatively small impervious areas.

MATERIALS AND METHODS

STUDY SITE

The study site (33.15° N and 79.8° W) is a 160-ha watershed within the SEF that is bounded on three sides by roads with an artificial boundary with another small catchment at the northeast end (Harder et al. 2007). Loblolly pines, sweetgum trees, and various species of oak shade this flat region of land, with slopes not exceeding 3% and with wetland forests accounting for approximately 48% of the total 400-acre area (Amatya and Trettin, 2021). Soils in the watershed are primarily class C/D sandy loams with significantly clayey subsoils that offer moderate permeability and a high available water content. WS80 outflow is gauged using a Doppler sensor linked with a Teledyne ISCO Flowmeter at its outlet, consisting of a compound weir at its monitoring station (Amatya and Trettin, 2021). A weather station installed above the tree canopy inside the watershed monitors temperature, humidity, radiation, and wind, and a tipping bucket backed by a manual gauge in an open space near the weather tower is used to measure rainfall (Amatya and Trettin, 2021). A location map with all the monitoring stations is shown in Figure 2.

USGS REGIONAL REGRESSION EQUATIONS

Empirically developed using flood-frequency information from regionally based gauged stations, the USGS RREs serve to estimate the design peak flow rate at different return intervals. Feaster et al. (2014) developed regression equations to predict peak flows for urban and rural streams in the states of Georgia, North Carolina, and South Carolina from the data of 488 stream gauges, 340 rural gauges, 32 small rural gauges, and 116 urban gauges (spanning Piedmont, Sand Hills, and the Coastal Plain). The latter represents the hydrological region of interest in this study. These equations are presented in Table 1 (from Feaster et al. 2014).

Equations 1 through 7 in Table 1 are used to calculate design peak flow predictions based on watershed drainage area and maximum 24-hr 50-yr precipitation. In WS80, these predictions are measured as 0.609 mi^2 and 12.3 in/day based on historical climate data (Amatya et al. 2021b). It is important to note that variables like maximum precipitation are dynamic and subject to changes in weather patterns. Accordingly, if high-intensity storms continue to increase as projected in climate change models, cautious interpretation of RRE results is recommended, as the 12.3 in/day value may no longer be representative in the watershed (Saia et al. 2019). For purposes of comparison, in this study design peak flows were also calculated using the interpolated rainfall intensity value of 8.85 in/day published by the National Oceanic and Atmospheric Agency (NOAA) and derived from a weather station network located farther inland.

In addition, the RREs are meant for use in areas containing less than 10% of impervious coverage, the threshold of an "urban" watershed (O'Driscoll et al. 2010). Certain models in this study will exceed that amount of imperviousness, which may negatively impact the accuracy of predictions. The equations also work best with small drainage areas that are greater than 0.1 mi^2, indicating that WS80 with an area of 0.609 mi^2 is within the method's application limit

Table 1. USGS Regression Equations (RRE) for Estimating Design Peak Flow Rate (in cfs) in the Coastal Plain

Return Period	Peak Flow Rate in Coastal Plain	Equation Number
2	$26.3 \times A^{0.5908} \times 10^{t \times 0.0515}$	(1)
5	$40.6 \times A^{0.5958} \times 10^{t \times 0.0623}$	(2)
10	$51.8 \times A^{0.6004} \times 10^{t \times 0.0666}$	(3)
25	$67.1 \times A^{0.6067} \times 10^{t \times 0.0708}$	(4)
50	$78.4 \times A^{0.6111} \times 10^{t \times 0.0738}$	(5)
100	$90.5 \times A^{0.6154} \times 10^{t \times 0.0762}$	(6)
200	$103 \times A^{0.6201} \times 10^{t \times 0.0785}$	(7)

Note: A = drainage area (mi²), I = the 50-yr maximum precipitation (in) for a duration of 24-hr.

(Amatya et al. 2021b). The equations are also not appropriate where humanmade structures significantly alter stream flow (Feaster et al. 2014). In such a case, the weir located in WS80 is assumed as nonsignificant.

WINTR-55

WinTR-55, more formally Windows Technical Release 55 (SCS, 1986), is a single-event, small watershed hydrology analysis program that was utilized to produce various storm runoff design peak flow volumes and peak flow rates necessary for the design of stormwater management structures (USDA 2004a). The software is limited to user-inputted curve numbers specific to 10 subbasins (maximum 25 mi² area), including their area land use and rainfall distribution.

To initiate predevelopment simulations on the WS80 watershed, an existing SEF 10 m digital elevation model (DEM) dataset was used in ArcGIS to produce a topography map upon which subbasin delineation could occur. The watershed was separated into two subbasins of areas 80.4 and 77.6 hectares, respectively. The drainage area values obtained from the watershed delineation using ArcGIS software were used as input parameters, in addition to the composite curve number obtained from back-calculations informed by observed storm event data (Epps et al. 2013). These back-calculated curve numbers were further adjusted for a dry, wet, and medium antecedent condition (Epps et al. 2013). However, the medium antecedent condition curve number is used as the input for both the current model with a natural condition and the subsequent models of proposed developed scenarios (USDA 2004a, 2004b). The percentage of land fully developed will have a curve number of 98 (Mishra et al. 2011), and the remaining percentage of land will retain the back-calculated curve number previously developed by the research team at SEF (Epps et al. 2013).

In the design peak flow rate calculation method, WinTR-55 uses Manning's kinematic solution to compute the travel time of water as a sheet flow on the watershed, as shown below.

$$T = \frac{0.007(nL)^{0.8}}{P^{0.5}s^{0.4}} \tag{8}$$

where T is the time of concentration [hours]; n is Manning's coefficient [-]; L is the length of slope [ft]; P is the 2-yr, 24-hr rainfall [in]; and s is the slope [ft/ft].

Manning's Equation is used to calculate the velocity of water when it flows in a channel pattern, which is then converted to travel time. This travel time aids in the determination of when the peak flow occurs. These are represented in Equations 9 and 10, respectively.

$$V = \frac{1.49r^{2/3}s^{1/2}}{n} \tag{9}$$

where V is the water velocity [ft/s]; r is the hydraulic radius [ft]; s is the slope [ft/ft]; and n is the Manning's coefficient [-].

$$T = \frac{L}{3600V} \tag{10}$$

where T is the time of concentration [hours]; L is the length of slope [ft]; and V is the water velocity [ft/s].

Using a 3-yr data set, the curve numbers for WS80 and the Upper Debidue Creek watershed were calculated by Epps et al. (2013). The study found that runoff was most closely associated with the elevation of the water table at the time of precipitation, and that curve numbers adjusted for the existing conditions offer the most accurate prediction of the

outflow of the watershed. Having this curve number for the study watershed allowed for a more efficient calculation of the runoff in the WinTR-55 model. Using the curve number previously derived (Epps et al. 2013), the time of concentration (Tc), the areas of the subbasins derived in GIS calculations, and the modeling parameters established at the onset of the study, multiple WinTR-55 models were constructed. The design standard curve number of 98 for impervious surfaces was coded for the simulated development area. A curve number of 67 obtained through the average of three back-calculations and the Tc of around 3 hrs were used as inputs to the software for both pre- and post-development conditions. Though WinTR-55 has the capability to calculate Tc based on land use data, the Tc was manually calculated for the simulated development area using the following calculations for developed conditions:

$$T_C = \frac{68630^{0.8}\left(\frac{1000}{98}-9\right)^{0.7}}{1140\times 0.5^{0.5}} = 1.66\ hours \qquad (11)$$

The time of concentration for pre-development conditions and undeveloped areas in urbanization calculations was decidedly an average of Amatya et al. (2021b), who found the time of concentration to be around 2.2 hours, and the calculations of this study, which calculated a 4-hr time of concentration.

An additional factor of consideration was the dimensional unit hydrograph, also called the peak rate factor (PRF). Although the default factor of 484 is considered too large for areas near the coast, the PRF can range from 600 for steeply sloped land to 100 in flat, boggy swamp lands (Blair et al. 2014). Areas similar to those examined in this study have a peak rate factor of closer to 230 (McCuen et al. 1983). Since the selectable factors are in increments of 50, a peak rate factor of 250 was used in this study for both the pre- and post-development models.

MODELING PARAMETERS

For a consistent comparison of the modeling methods, a standard set of parameters was established. Accordingly, 0%, 5%, 10%, and 15% imperviousness scenarios for urbanization were simulated to evaluate design peak flow rates for storms of 2-, 5-, 10-, 25-, 50-, 100-, and 200-yr return periods. The result is a set of pre-development baseline data detailing the early stages of watershed urbanization, analogous to the situation occurring in areas surrounding the FMNF (O'Driscoll et al. 2010). Coastal structures are designed for a lifespan of between 50 and 100 years, especially where the cost of failure from a storm merits a stronger structure. Conversely, a lifespan of between 10- and 25-yr return periods are used to inform the design of smaller structures (Schall et al. 2012). In addition, it is anticipated that these criteria will provide information on the potential impacts of the "threshold of urbanization," often considered as a 10% impervious area of a developed watershed (O'Driscoll et al. 2010). In its current, undeveloped condition, WS80 is considered as 0% impervious, though a one-lane dirt road that runs along its border could realistically skew this number to approximately 1% imperviousness.

L-THIA

Long-Term Hydrologic Impact Analysis (L-THIA) is a web-based tool that was developed to evaluate both the impact of urbanization on runoff volume and the potential runoff reduction by LID practices if implemented anywhere in the United States. It is meant to be an easy-to-use program that can assist decision-makers in evaluating the effects of LID, thereby supporting quicker and more effective watershed management (Hunter et al. 2010). It was selected by the authors for this reason, as it allowed the modeling of LID practices from the perspective of policymakers and stakeholders. The model calculates the SCS curve number (CN) for a given location, calculated from user inputs of land use and soil group data, and uses rainfall data to calculate the resulting runoff volume. When an LID practice is selected, L-THIA adjusts the CN using the corresponding reduction in percent imperviousness and calculates a new runoff volume (Hunter et al. 2010). Thus, pre- and post-development scenarios based on the utilization of specific LID practices can be generated. In this study, L-THIA was used to study how a combination of vegetated roofs, bioswales, and permeable pavement on WS80 would change estimated runoff volumes if 15% of the watershed was developed and both 50% and 100% of this developed area was built using LID infrastructure. These criteria represent common methods of LID (Kramer 2013; Day and Bremer 2013), and this percentage development represents the maximum imperviousness analyzed in this study. The L-THIA lot-level function was used, where specific LID methods chosen by the user are adapted to fit a half-acre lot (Hunter et al. 2010).

RESULTS

USGS REGIONAL REGRESSION EQUATION RESULTS

Design peak flow rate results calculated using the USGS RREs for all design return periods and percent imperviousness considered are shown in Table 2.

Simulations using the USGS equations showed that WS80 would experience a design peak flow of approximately 84 $ft^3 \cdot sec^{-1}$ at a 2-yr return period, 577 $ft^3 \cdot sec^{-1}$ at a 100-yr return period, and a maximum of 700 $ft^3 \cdot sec^{-1}$ at a 200-yr return period under nondevelopment conditions with 0% imperviousness (Table 2). The design peak flow rate increased markedly with each uptick in percent imperviousness, with flows eventually topping 153 $ft^3 \cdot sec^{-1}$ and 774 $ft^3 \cdot sec^{-1}$ for a

Table 2. Simulated Design Peak Flow Rates by Return Period and Percent Imperviousness

	Peak Flow (Q) [cfs]						
Percent Imperviousness	**2 years**	**5 years**	**10 years**	**25 years**	**50 years**	**100 years**	**200 years**
0%	84	176	254	369	468	577	700
5%	103	204	285	401	501	607	724
10%	126	235	320	439	535	638	748
15%	153	272	360	478	572	670	774

Table 3. Percentage Changes in Design Peak Flow Rate over 0–15% Imperviousness

Return Period	**Change in Peak Flow over 0–15% Imperviousness**
2-year	182%
5-year	154%
10-year	142%
25-year	130%
50-year	122%
100-year	116%
200-year	110%

2-yr and 200-yr storm, respectively, at 15% impervious area. Differences between nondevelopment and 15% development conditions are represented by percent changes in Table 3.

The peak flows of smaller return-period storms are substantially more severe than they are for larger return-period storms on a percentage basis, as seen in Table 3. Even a relatively minor impervious cover of 15% means that small return-period storms exhibit a 1.5-fold greater impact than predevelopment conditions in WS80. Because small return-period storms are by nature more common, these results mean that most storms passing through the watershed may cause nearly twice the damage around the threshold of urbanization. However, although large return-period storms are more uncertain based on rainfall record length, their large magnitudes alone may have a huge impact when they occur.

WINTR-55 RESULTS

Table 4 shows the peak outflow rates calculated by WinTR-55. These flow rates rise with respect to both the percent imperviousness modeled and the magnitude of the return-period storm as expected. As the impervious acreage increased in the context of the same modeled rain event, the peak flow values grew by 182% at the 2-yr storm to 116% at the 200-yr storm. Similarly to the USGS RREs, this increase implies that smaller and more frequent storms reflect the largest-observed change between an undisturbed and undeveloped watershed and a watershed that has experienced development. Further, these results affirm the sharp differences in hydrologic activity that small alterations in impervious cover are capable of causing.

DISCUSSION

COMPARISON OF MODELS

A comparison of the model results and observed data is shown in Figure 3 below. In this graph, predicted design peak flow rate outputs for up to a 100-yr return period from WinTR-55 and the USGS RREs are compared with observed design peak flow rate data reported by Amatya et al. (2021b) for WS80 under pre-development conditions. The USGS RREs were applied using 24-hr 50-yr precipitation intensity from both the measured value of 12.3 in/day on WS80 (Amatya et al. 2021b) as well as the NOAA-published value of 8.85 in/day, which was used by Walega et al. (2020) for this watershed. The percent overprediction and underprediction (percent error) for both models is presented in Table 5. These were calculated by taking the difference between the modeled design peak flow rates and the measured peak flow rates on WS80, then dividing by the measured peak flow rates.

Table 4. Simulated Design Peak Flow Rates by Return Period and Percent Imperviousness, Calculated by WinTR-55

	Peak Flow (Q) [cfs]						
Percent Imperviousness	**2 years**	**5 years**	**10 years**	**25 years**	**50 years**	**100 years**	**200 years**
0%	35	66	96	146	188	247	352
5%	43	75	106	158	201	262	368
10%	53	86	119	172	217	278	388
15%	64	99	133	188	234	297	410

Table 5. Percent Differences in Model Predictions of Design Peak Flow Rates

Return Period	**USGS Overprediction**	**WinTR-55 Underprediction**
5-year	84%	31%
10-year	60%	39%
25-year	42%	44%
50-year	28%	49%
100-year	12%	52%

Figure 3 shows that the design peak flow rates predicted by the USGS equations using the 24-hr 50-yr rainfall intensity from WS80 agree closest with the observed data, indicating that it is the highest-performing model. The USGS equations using the 24-hr 50-yr rainfall intensity data published by NOAA was the next-best-performing model. Though the same equations were used in both models, the latter model predicted peak flows to nearly half that of the former, indicating the significant degree of influence of these equations upon 50-yr 24-hr rainfall intensity values. As such, hydrologists and engineers interested in their use should proceed with caution. The NOAA rainfall intensity value of 8.85 in/day is skewed much less than the WS80 value of 12.3 in/day because recent high return-period storms such as Hurricane Joaquin (2015), Hurricane Matthew (2016), and some other tropical storms (2008) were not considered in the NOAA data, as the value was based on interpolated analysis of data only through 2004. Variations in 50-yr 24-hr intensity values may exhibit widely divergent consequences in model outputs, in addition to the uncertainties that derive from the dynamic nature of the variable. These models are followed in accuracy by WinTR-55, which performs better at lower return-period storms (Figure 3, Table 5). This improved performance is perhaps due to the association of high return-period storms with high intensities, which cause ground saturation and alter the PRF.

As shown in the predicted design peak flow rates using the default PRF in Figure 4, the USGS RREs utilizing the on-site rainfall intensity data performed the best. This superior performance was likely due to the utilization of recent data that was consistent with observed design peak flow rates and regional, rural stream gauges in the derivation of the model (Feaster et al. 2014). Nonetheless, the model did overpredict by roughly 100 ft3·sec-1 or 84% compared to the observed data for low return-period storms (Table 5) until a 100-yr return-period storm where the gap begins to narrow to about 12%. This discrepancy was possibly due to a skew in intensity value, of 12.3 in/day, from recent tropical storms and hurricanes. The WinTR-55 model, however, fell below the observed values by roughly 100 $ft^3 \cdot sec^{-1}$ for a 25-yr storm, which caused a severe underprediction of 52% that grew to over a 250 $ft^3 \cdot sec^{-1}$ of separation for a 100-yr storm (Table 5). The USGS model with on-site data overpredicts by 28% or less for 50-yr and larger return periods. This overprediction is considered acceptable because liberal estimates for the design of water management and road infrastructure are often favored to offset the consequences of a structural failure from more conservative estimates, which are often much higher than any overdesign costs (Amatya et al. 2021b). Neither model was considered sufficiently accurate for predicting design peak flow rates for all return periods; thus, a more expansive study with multi-site data and enhanced

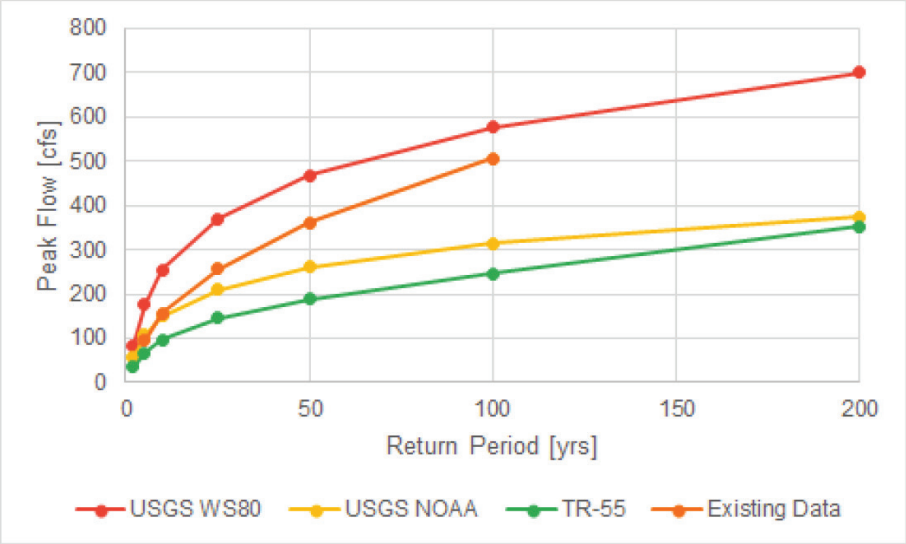

Figure 3. Comparison of models at pre-development.

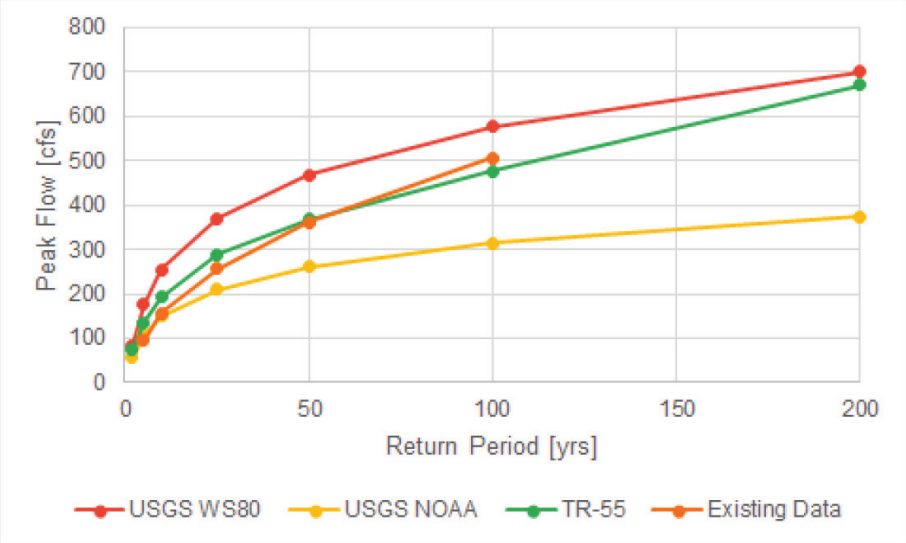

Figure 4. Comparison of models at pre-development at default PRF.

model parameters is merited in the future, as was also noted by Amatya et al. (2021b). The overprediction of observed design peak flow rates by the USGS model with on-site data for small return periods (Table 5) also may be due to wetland areas of the watershed possessing a high water storage capacity that would be less responsive to smaller design events until filled with considerable rainfall. In all models, however, this data from a return of 200 years is largely uncertain since rainfall records do not encompass that period.

If the default PRF value of 484 is used in WinTR-55, its predictions much more closely match the observed flood-frequency data, as seen in Figure 4. Although previous studies (Blair et al. 2014; McCuen et al. 1983) infer that this number is not representative of coastal regions, our results indicate that such is not always the case, as the observed design peak flow rates are due to the occurrence, in recent years, of more extreme, high-intensity precipitation events. We therefore suggest that hydrologists and engineers exercise caution

when using WinTR-55 on low-gradient coastal landscapes to predict design peak flow rates with suggested PRFs that are lower than the default value for both recent and future climate scenarios.

ASSESSMENT OF LID SCENARIOS ON DESIGN PEAK FLOW RATES

Through L-THIA, users may implement LID practices based on the percentage of existing impervious cover that is transitioned to LID to assess its impacts on design peak flow rates. Here, the changes in runoff under conditions of 15% imperviousness were examined when both 50% and 100% of this developed area was constructed using the LID infrastructure. It should be noted that WS80 is only 0.609 mi^2 in area, with 15% representing a mere 0.091 mi^2 or 58 acres. Therefore, the effects of changes to overall watershed hydrology and design peak flow rate based on such a small area are significant only if high percentages of the developed area utilize LID, as shown in Table 6 for 50% LID and 100% LID.

The data in Table 6 represent the predicted runoff depth and volume in the watershed. While L-THIA did not provide peak flow data as the other models in this study did, it still provides a picture of how development impacts the amount of runoff in a watershed. The use of 50% LID reduces the total runoff volume from 0.24 to 0.21 acre-ft and the runoff depth from 4.84 to 4.28 inches, as shown in Figure 5. Though the runoff depth in the developed portion of the watershed is reduced by nearly half from 8.38 to 4.69 inches, the comparably small area means any development using 50% LID or less does not translate to large reductions in total watershed runoff. However, the use of 100% LID reduces runoff by 98%, with a decrease from 8.38 to 0.09 inches in the developed portion of the watershed, as shown in Table 6. With such a considerable reduction, even though only a small portion of the watershed is developed, overall runoff volume is reduced to 0.17 acre-ft and depth to 3.59 inches, equivalent to a 20% and 16% reduction respectively. Therefore, it is recommended that any hypothetical development on the watershed possess as much LID implemented area as possible. These data suggest that as development encroaches, a significant reduction in added runoff is only possible through the use of high percentages of LID-implemented areas.

To be more beneficial to policymakers and stakeholders, L-THIA is kept rather simplified and only uses hydrologic soil group, land use, and weather data (Hunter et al. 2010). In addition, groundwater table depth, which in a coastal watershed like WS80 may influence runoff (Harder et al. 2007), is not considered. Lot-level dimensions are also standardized and may not necessarily reflect those of local Charleston-area ordinances. Therefore, conclusions derived from L-THIA modeling scenarios, even though it is interesting to analyze them to see where they lead, will have to be used with caution.

CONCLUSIONS

In terms of peak flow results, USGS RRE indicated an overprediction between 12% and 84%, and WinTR-55 indicated an underprediction by as much as 52% over a 100-yr return period. Neither model accurately matched the historical design peak flow data for all return periods on WS80. Although the USGS model with on-site rainfall intensity data performed relatively better for 50-yr or higher return periods than the USGS model with NOAA data and WinTR-55, a study of additional models or a second comparison with enhanced modeling parameters, including rainfall intensity in the USGS models and the peak rate factor and runoff derivation method in WinTR-55, is recommended. To enhance predictions of design peak flow rate in the low-gradient landscape for all return periods, the observed design peak flow rate data from a single site like WS80 may have to be combined with similar long-term data from multiple sites in the region influenced by recent large storms. For instance, the surprisingly accurate WinTR-55 results derived using the default PRF value of 484 at the WS80 site suggest that more data covering recent large events from other similar sites in the Coastal Plain is needed to increase confidence in model parameters. In addition, SCS-CN-based runoff prediction used in Win-TR55 could be evaluated

Table 6. Predicted Reductions in Runoff Volume and Depth from Utilization of LID Methods

	No Development	Development without LID	With 50% LID	With 100% LID
Total Annual Vol. [ac-ft]	0.21	0.24	0.21	0.17
Total Avg. Annual Runoff Depth [in]	4.20	4.84	4.28	3.59
Avg. Runoff Depth on Developed 15%	N/A	8.38	4.69	0.09

using recently modified versions of SCS-CN–based runoff computation methods (Blair et al. 2014; Walega et al. 2020) to enhance peak flow prediction on low-gradient coastal forests. Finally, when used on a mere 15% of WS80, LID reduced the watershed runoff volume and depth by 20% and 16%, respectively, indicating its promise when fully implemented. Therefore, the implementation of LID combined with the L-THIA modeling software represents a powerful tool for mitigating runoff caused by urban encroachment into the forests of the Coastal Plain.

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REFERENCES

Amatya DM, Harrison CA, Trettin CC. 2016. Hydrometeorologic assessment of October 2015 extreme precipitation event on Santee Experimental Forest watersheds, South Carolina. Journal of South Carolina Water Resources 3(1):19–30.

Amatya DM, Trettin CC. 2019. Long-term ecohydrologic modeling: a case study from the Santee Experimental Forest, South Carolina. Journal of South Carolina Water Resources 6(1):46–55.

Amatya DM, Hamidi D, Trettin CC, Dai Z. 2021a. Simulating Hydrology of current stands and post-longleaf pine restoration in coastal South Carolina. In: Proceedings, 7th ICRW, General Technical Report 254, USDA Forest Service Southern Research Station, Ashville, NC.

Amatya DM, Tian S, Marion D, Caldwell P, Laseter S, Youssef MA, Grace JM, Chescheir GM, Panda S, Ouyang Y, Sun G, Vose JM. 2021b. Estimates of precipitation IDF curves and design discharges for road-crossing drainage structures: a case study in four small, forested watersheds in the Southeastern U.S. Journal of Hydrologic Engineering 26(4):05021004. doi:10.1061/(ASCE)HE.1943-5584.0002052

Amatya, DM, Trettin, CC. 2021. Santee Experimental Forest, Watershed 80: streamflow, water chemistry, water table, and weather data. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2021-0043.

Amatya DM, Walega A. 2020. Long-term Data–the key for evaluating runoff peak discharge estimation tools and parameters for watersheds on forest lands. Advancement Civil Engineering & Technology 4(2).

Blair A, Sanger D, White D, Holland AF, Vandiver L, Bowker C, White S. 2014. Quantifying and Simulating Stormwater Runoff in Watersheds. Hydrological Processes 28(3):559–569.

Callahan TJ, Vulava VM, Passarello MC, Garrett CG. 2012. Estimating groundwater recharge in lowland watersheds. Hydrological Processes 6(19):2845–2855.

Campbell CE, Passmore S, Allen J. 2001. Charleston urban growth model used to identify resources at risk. Proceedings of the 21st Annual ESRI International User Conference, July 9–13, 2001.

Day CA, Bremer KA. 2013. Modeling urban hydrology: a comparison of new urbanist and traditional neighborhood design surface runoff. International Journal of Geosciences 4(5):891–897.

Elaji A, Wei J. 2020. Urban runoff simulation: how do land use/cover change patterning and geospatial data quality impact model outcome? Water 12:2715. doi:10.3390/w12102715

Epps TH, Hitchcock DR, Jayakaran AD, Loflin DR, Williams TM, Amatya DM. 2013. Curve number derivation for watersheds draining two headwater streams in lower Coastal Plain South Carolina, USA. Journal of the American Water Resources Association 49(6):1284–1295.

Feaster TD, Gotvald AJ, Weaver JC. 2014. Washington: methods for estimating the magnitude and frequency of floods for urban and small, rural streams in Georgia, South Carolina, and North Carolina, 2011. (ver. 1.1, March 2014): U.S. Geological Survey Scientific Investigations Report 2014–5030. doi:10.3133/sir20145030

Fang Z, Song S, He C, Liu Z, Qi T, Zhang J, Li J. 2020. Evaluating the impacts of future urban expansion on surface runoff in an alpine basin by coupling the LUSD-urban and SCS-CN models. Water 12:3405. doi:10.3390/w12123405

Harder SV, Amatya DM, Callahan TJ, Trettin CC, Hakkila J. 2007. Hydrology and water budget for a forested Atlantic Coastal Plain Watershed, South Carolina. Journal of the American Water Resources Association 43(3):1–13.

Holland AF, Sanger DM, Gawle CP, Lerberg SB, Santiago MS, Riekerk GHM, Zimmerman LE, Scott GI. 2004. Linkages between tidal creek ecosystems and the landscape and demographic attributes of their watersheds. Journal of Experimental Marine Biology and Ecology 298:151–178.

Hook DD, Buford MA, Williams TM. 1991. Impact of Hurricane Hugo on the South Carolina Coastal Plain Forest. Journal of Coastal Research 8:291–300.

Hunter JG, Engel BA, Quansah JE. 2010. Web-based low impact development decision support tool for watershed planning. In: Proceedings of the International Low Impact Development Conference 2010, San Francisco, California, USA, April 11–14, 2010, Volume 1 of 2, 484–495.

Hutton D, Kaye NB, Martin WD, III. 2015. Analysis of climate change and 24-hour storm depths for a range of return periods across South Carolina. Journal of South Carolina Water Resources 2(1):70–79.

Jayakaran AD, Williams TM, Ssegane H, Amatya DM, Song B, Trettin CC. 2014. Hurricane impacts on a pair of coastal forested watersheds: implications of selective hurricane damage to forest structure and streamflow dynamics. Hydrology and Earth System Sciences 18:1151–1164.

Kim J, Lee J, Song Y, Han H, Joo J. 2018. Modeling the runoff reduction effect of low impact development installations in an industrial area, South Korea. Water 10(8):967.

Kramer MG. 2013. Our built and natural environments: a technical review of the interactions among land use, transportation, and environmental quality. Washington, DC: US Environmental Protection Agency.

La Torre Torres I, Amatya DM, Callahan TJ, Sun G. 2011. Seasonal rainfall-runoff relationships in a lowland forested watershed in the southeastern U.S.A. Hydrological Processes 25:2032–2045.

Lockaby G, Nagy C, Vose JM, Ford CR, Sun G, McNulty S, Caldwell P, Cohen E, Meyers JM. 2013. Forests and water. In: Wear DN, Greis JG, eds., The southern forest futures project: technical report (Gen. Tech. Rep. SRS-GTR-178), 309–339. Asheville, NC: USDA-Forest Service, Southern Research Station.

McCuen RH, Bondelid TR. 1983. Estimating unit hydrograph peak rate factors. Journal of Irrigation and Drainage Engineering 109(2): 238–250.

Mishra SK, Singh VP. Soil Conservation Service Curve Number (SCS-CN) Methodology. In: Springer, Dordrecht, 2011, p. 90.

Natural Resources Conservation Service (NRCS). 2009. Small Watershed Hydrology WinTR-55 User Guide.

O'Driscoll M, Clinton S, Jefferson A, Manda A, McMillan S. 2010. Urbanization effects on watershed hydrology and in-stream processes in the southern United States. Water 2(3):605–648.

Saia SM, Suttles KM, Cutts BB, Emanual RE, Martin KL, Wear DN, Coulston JW, Vose JM. 2019. Applying climate change risk management tools to integrate streamflow projections and social vulnerability. Ecosystems 23(1):67–83.

Schall JD, Thompson PL, Zerges SM, Kilgore RT, Morris JL. 2012. Hydraulic design of highway culverts. 3rd ed. Hydraulic Design Series No. 5 (FHWA-HIF-12-026). Washington, DC; Federal Highway Administration (FHWA), U.S. Department of Transportation.

SCS TR-55. 1986. Urban Hydrology for Small Watersheds.

Trettin CC, Amatya DM, Gaskins AH, Miniat CF, Chow A, Callahan T. 2019. Watershed response to longleaf pine restoration–application of paired watersheds on the Santee Experimental Forest. In: Latimer JS, Trettin CC, Bosch DD, Lane CR, eds., Working Watersheds and Coastal Systems: Research and Management for a Changing Future—Proceedings of the Sixth Interagency Conference on Research in the Watersheds. July 23–26, 2018, Shepherdstown WV, 194–201. e-Gen. Tech. Rep. SRS-243. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station.

USDA. 2004a. Part 630 Hydrology. National Engineering Handbook. Chapter 10. Estimation of Direct Runoff from Storm Rainfall. Washington, DC: United States Department of Agriculture (USDA) Soil Conservation Service.

USDA. 2004b. Part 630 Hydrology. National Engineering Handbook. Chapter 9. Hydrologic Soil-Cover Complexes. Washington, DC: United States Department of Agriculture (USDA) Soil Conservation Service.

Walega A, Amatya DM, Caldwell P, Marion D, Panda S. 2020. Assessment of storm direct runoff and peak flow rates using improved SCS-CN models for selected forested watersheds in the southeastern United States. Journal of Hydrology: Regional Studies 27. doi:10.1016/j.ejrh.2019.100645