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Research Paper

Assessing the Accuracy of HydroCAD for Pre-Development Runoff in Wooded Coastal Watersheds

Briar Ownby-Connolly[1], Matthew Connolly[2], Randy Chambers[3], Landon Knapp[4,5], William Strosnider[1]

[1]Baruch Marine Field Laboratory, University of South Carolina, Georgetown, South Carolina, United States

[2]Landtech Resources Inc., Williamsburg, Virginia, United States

[3]Keck Environmental Lab, William & Mary, Williamsburg, Virginia, United States

[4]South Carolina Sea Grant Consortium, Charleston, South Carolina, United States

[5]Geology Department, College of Charleston, Charleston, South Carolina, United States

Correspondence
Briar Ownby-Connolly
Baruch Marine Field Laboratory
University of South Carolina, Georgetown, SC 29440, United States

Email: briarcoc@gmail.com

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Urbanization increases stormwater runoff that, without proper management, leads to eroded channels and impaired downstream water quality and habitats. To simplify pre- and post-development calculations of stormwater runoff, Technical Release 55 (TR-55) was established by the United States Department of Agriculture in 1986 and adopted for use by engineering firms nationwide. The commonly applied HydroCAD stormwater modeling software utilizes TR-55, which is meant to help engineers ameliorate pressures from increased runoff due to urbanization, guiding Best Management Practice (BMP) design. We evaluated this conventional modeling method using 2 field sites to test limitations of TR-55 within HydroCAD. In-situ stream flow velocities, rainfall data, soil samples, and topographic surveys were used to compare model results with site data and observations. We identified hydrologic soil groups as the most influential parameter, where misclassified soil groups, specifically for undeveloped wooded areas, led to current standard practices that underestimate infiltration. As a result, the HydroCAD model overestimated pre-development peak discharge rates (Q_p) by approximately 710% and 240% at our 2 field sites. Due diligence in corroborating soil mapping was crucial, as uncorrected model outcomes can cause deleterious downstream effects via undersized BMPs. The large error rate observed indicates that the standard assumptions of TR-55 within HydroCAD should be revisited not only in undeveloped wooded areas, but in other prevalent land cover types.

Keywords HydroCAD, hydrologic soil groups; stormwater management, TR-55, urbanization

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1. Introduction

Increases in impervious surface from development subsequently increase rates of stormwater runoff draining into receiving channels and downstream watersheds (Canters et al. 2006; Wang et al. 2017, 2023). Since land conversion and development continue apace in the United States, the impact of increasing impervious surface due to urbanization is a critical issue (Roberts et al. 2009) leading to extensive erosion of receiving channels, habitat degradation, and water quality impairments downstream (Bedi et al. 2015). Urbanizing watersheds are susceptible to erosion from stormwater runoff as greater discharges strip away sediment, often deepening receiving channels to accommodate increased velocities and volumes of runoff (Dindinger et al. 2020). Common mitigation measures, or Best Management Practices (BMPs), include ponds meant to slow rates of discharge into receiving channels to limit the pace of erosion (Hancock et al. 2010; Cronshey et al. 1986).

Stormwater retention ponds sizing determines the discharge rates entering receiving channels and thus strongly influences channel geomorphology and water quality (Cronshey et al. 1986). To support the design process, Technical Release 55 (TR-55), a method established by the United States Department of Agriculture (USDA) in 1986, models pre- and post-development peak discharges (Cronshey et al. 1986; Ormsbee et al. 2020). TR-55 is an embedded functionality within HydroCAD stormwater modeling software, providing simplified procedures to estimate stormwater runoff volumes, peak discharge hydrographs, and storage volumes for small, urbanizing watersheds in the United States. Prior sensitivity analyses conducted on TR-55 have found that peak discharges can be sensitive to Curve Numbers (CN) and Time of Concentration (T_c) (Shi & Wang 2020; Soomro et al. 2019; Yogi et al. 2021). CNs predict runoff volume by calculating potential maximum retention, *S*, in Equation 1. Initial abstraction is also derived using *S*, whereas rainfall is a user-defined parameter in Equation 1. Although this study examined Ia/S ratios ranging from 0.01 – 0.20, peak discharge sensitivity over realistic Ia/S variation (0.15 – 0.20) was moderate at New Kent (~18% increase in peak discharge rates [Q_p]) and larger at Cow Swamp (~140% increase in Q_p), providing a quantitative basis for deemphasizing Ia/S relative to Hydrologic Soil Group (HSG) effects (Figure S1). CNs remain the primary determinant of runoff volume, and inaccuracies can result in unreliable peak discharge predictions (Tan et al. 2018; Ormsbee et al. 2020; Shi & Wang 2020; Munna et al. 2021). T_c (Equation 2), the time it takes for water at the most hydraulically distant point in a watershed to travel to a point of interest in the same watershed, includes 3 different types of flow: (1) sheet flow, for which its common to use a maximum of 300 ft, (2) shallow concentrated flow, and (3) channel flow (Cronshey et al. 1986, Venkata Ramana 2014; Adalikwu and Burckhard 2021). Because T_c directly controls the shape and timing of the hydrograph, assumptions about sheet flow length influence predicted peak discharge. In addition, CNs and T_c are influenced by soil classifications based on infiltration rates, known as HSGs (Cronshey et al. 1986; Mockus et al. 2007). These classifications include “A” (excellent infiltration rates; lowest runoff), “B” (good), “C” (fair), and “D” (poor infiltration rates; highest runoff) (Cronshey et al. 1986; Mockus et al. 2007). Because both CN and T_c depend directly on HSGs, errors in soil classification can propagate through TR-55/HydroCAD and substantially alter peak discharge predictions.

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{1}$$

Where:
Q = runoff (in)
P = rainfall (in)
S = potential maximum retention after runoff begins (in)
I_a = initial abstraction (in)

$$T_c = T_{t1} + T_{t2} + \cdots T_{tm} \tag{2}$$

Although a wealth of scientific literature addresses stormwater and BMP modeling, design, and performance, a clear gap remains regarding the commonly used stormwater modeling software HydroCAD and the potential for user error when sizing retention ponds. To address this gap, the goal of this study was to compare HydroCAD model outputs (e.g., Q_p), to field measurements and evaluate the influence of key parameters, including HSGs, CNs, and T_c, on those outputs. Specifically, this study aimed to: (1) evaluate the sensitivity of Q_p to changes in HSG classifications, and (2) assess whether the TR-55 maximum sheet flow distance of 91.4 m (300 ft) aligns with realistic site behavior. Analyses were conducted using data from 2 study sites located in James City County, Virginia, United States, and New Kent County, Virginia, United States.

2. Materials and Methods

2.1. Study Sites

Success of retention ponds in moderating stormwater flows can be varied. What has been coined by residents of Williamsburg, Virginia, United States, as the “Grand Canyon,” and serves as the project impetus for this study, is a severely incised channel 7.62 m (25 ft) in depth located immediately downstream from a stormwater retention pond in the coastal plain of Virginia, United

Highlight

Inaccuracies in hydrologic soil group classifications can lead to overestimations of pre-development peak discharge within commonly applied stormwater modeling software (HydroCAD), leading to undersized stormwater control practices and subsequent impairment of downstream watersheds.

States. The resulting erosion illustrates an extreme outcome from incorrectly designed stormwater ponds (Daily Press 2024). Estimates of pre- and post-development peak discharges guide the sizing of these BMPs, where under- or over-estimated peak discharges can lead to stormwater pond designs that do not retain or release runoff similar to pre-development rates (Cronshey et al. 1986). In this example from Virginia, erosion of stream and riparian natural habitat has impaired the overall environmental quality of this waterway. As of fall 2025, the Virginia Department of Transportation (VDOT) has spent $2.25M for stream and floodplain restoration to stabilize and regrade the reach to protect roads and other infrastructure due to the extensive headward erosion (Daily Press 2024).

Two study sites were selected in James City County, Virginia, United States, and New Kent County, Virginia, United States (Figure 1). Both sites are predominantly wooded and undeveloped, with minimal impervious surfaces and similar soil and topographic characteristics. These locations were chosen for accessibility and because their undeveloped status provides conditions likely to challenge HydroCAD modeling assumptions, particularly for TR-55 Q_p estimates.

The study was conducted at New Kent (New Kent County, Virginia) and Cow Swamp (James City County, Virginia). The New Kent site (Figure 2) consisted of ~50% mixed agricultural and ~50% wooded land, with a drainage area of 328,754 m², while Cow Swamp was 100% wooded with a drainage area of 320,000 m². Soil types were classified based on USDA soil maps: New Kent was primarily HSG C and HSG D (69.3%), and Cow Swamp was primarily HSG B (53.8%) (Table 1). Flow monitoring equipment installed at both sites recorded water levels during rainfall events used for both modeling and hand-calculated peak discharge comparisons.

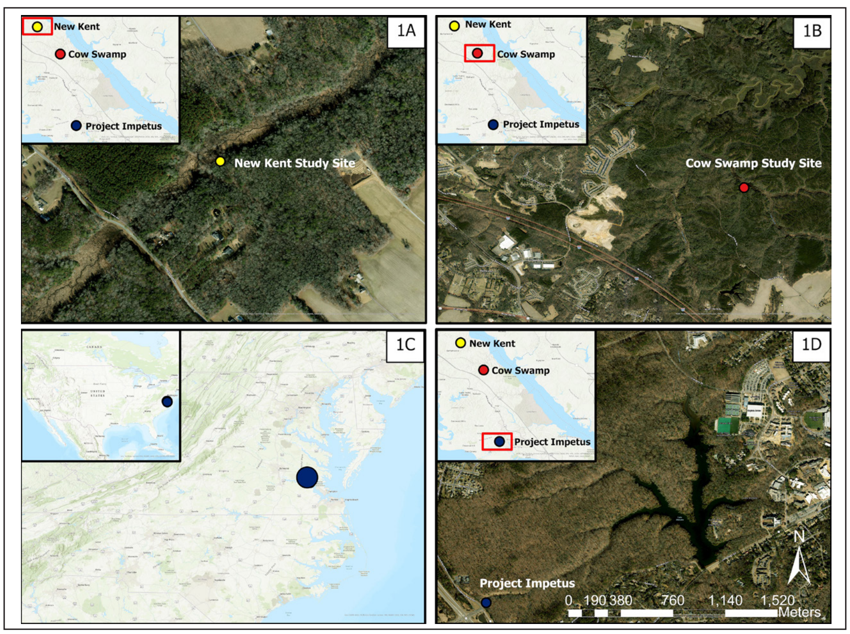

Fig 1. Aerial imagery of the 2 study sites with respect to the Chesapeake Bay, Virginia, United States, and the greater United States. (A) New Kent site in New Kent County, Virginia; (B) Cow Swamp site in James City County, Virginia; (C) Continental United States showing study region; (D) Regional context showing site location within the Chesapeake Bay watershed. Maps data: Esri 2025, Maxar, Earthstar Geographics, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, CGIAR, and the GIS User Community (Esri 2025a, 2025b).

2.2. Field Measurements and Data Collection

Rainfall data were collected at each site using a standard manual rain gauge installed in an open area near each study site. Rainfall depth was recorded following each precipitation event and used to inform model inputs and contextualize hydrologic conditions during field measurement. Field measurements were used for 2 purposes: (1) to inform pre-development HydroCAD model inputs, improving accuracy beyond map-based data, and (2) to calculate pre-development peak discharge (Q_p) manually using Manning's equation.

2.2.1. Topographic Surveys

Topographic surveys were conducted using Leica Total Stations (868812 TS10 1" R1000) with a reflectorless R1000 Electronic Distance Measuring device and a standard surveyor's prism pole. Accuracy of survey points was within ±0.0305 m. Horizontal and vertical control points were established in the field. After the installation of monitoring equipment,

Table 1 Distribution of hydrologic soil groups (HSGs) at the New Kent and Cow Swamp study sites. Areas and percentages are reported for each HSG class, illustrating the spatial composition of soil types used in HydroCAD modeling and sensitivity analyses.

HSGs	New Kent Area (m^2)	New Kent Percentage (%)	Cow Swamp Area (m^2)	Cow Swamp Percentage (%)
A	254	0.077	23,500	7.33
B	100,400	30.6	172,300	53.8
C	116,500	35.4	35,100	11.0
D	111,600	33.9	89,100	27.8

survey points were taken perpendicular to the streams, as well as upstream and downstream of sensor locations for generation of site cross-sections and profiles. Survey data were uploaded and post-processed in Carlson surveying software with AutoCAD using basic coordinate geometry: northings, eastings, elevations, (x, y, z). Profiles informed HydroCAD reach geometry and were also used to calculate cross-sectional area (A) and wetted perimeter (P), which were needed to compute hydraulic radius (R = A / P) for peak discharge calculations.

2.2.2. Soil Sampling

Soil borings were randomly collected only in areas mapped as HSG C and HSC D at each site (Figure 3). These groups were prioritized because misclassification would have a greater impact on runoff estimates: if "C" or "D" are mistakenly identified, pre-development Q_p values may be overestimated, leading to less accurate and potentially more harmful design outcomes. In contrast, errors in "A" or "B" soils are less critical, as they naturally generate lower runoff rates and thus provide more realistic estimates in undeveloped, wooded environments. Collection of samples was done using an 8.255-cm (3.25-in) auger. Two samples per borehole were taken: 0 cm – 66 cm (0 in – 26 in) and 66 cm – 116 cm (26 in – 46 in) following National Engineering Handbook guidelines (Mockus et al. 2007). Samples were analyzed at Landtech Resources Inc. following ASTM D2488. An Authorized Onsite Soil Evaluator and Licensed Professional Soil Scientist (VA #0345) verified classifications. Soil data were used to refine HydroCAD CNs. Initial model runs used map-based HSG data, and subsequent runs incorporated measured soils, with outputs compared for accuracy.

2.2.3. Flow Monitoring

Water level and velocity were recorded May 2023 through October 2023 in a stream at each site using a MantaRay Portable Ultrasonic Flow Monitor (Greyline

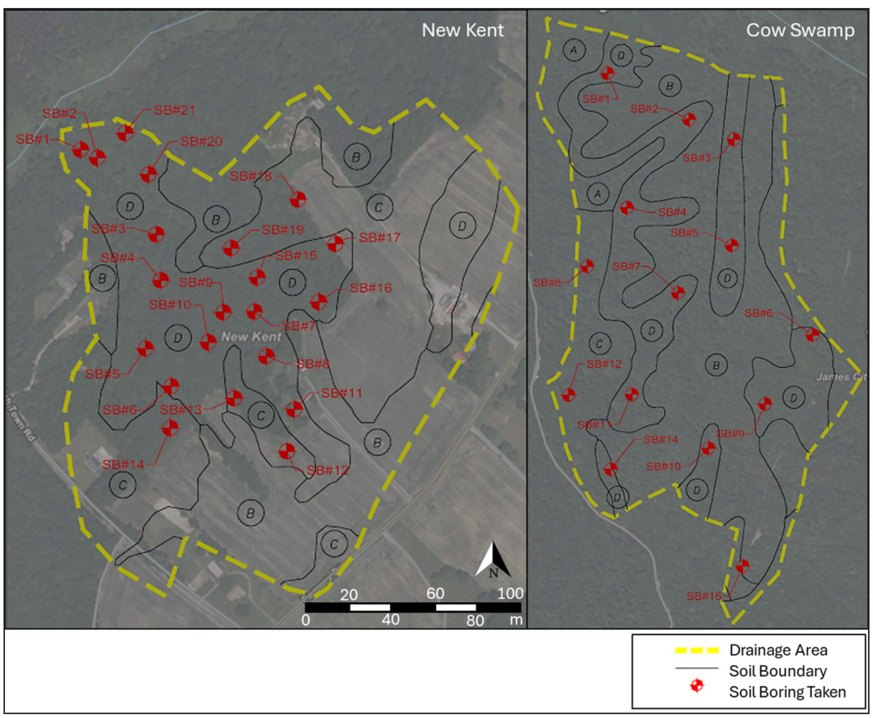

Fig. 2. Maps of the New Kent (A) and Cow Swamp (B) study sites showing delineated drainage areas, soil boring locations, and hydrologic soil group (HSG) distributions based on USDA soil maps. Soil contours highlight spatial variability in mapped HSG classifications, which were later compared with field-verified soil samples. Map data: Google Earth 2025, USDA Web Soil Survey 2019, County of New Kent GIS 2024, James City County GIS 2024 (Google Earth 2025a, 2025b; USDA & NRCS 2019, County of New Kent n.d.; James City County 2024).

Instruments, Massena, New York, United States), which uses a submerged ultrasonic sensor to measure flow in open channels. Water level sensors collected continuous data at 5-minute intervals throughout the monitored storm event, which resulted in one storm event analyzed per site due to study timeframe constraints. These data were used to validate HydroCAD simulations and provide observed water elevations and velocities for the manually calculated peak discharge.

2.3. HydroCAD Modeling

Since only pre-development peak discharges were modeled, one subcatchment per site (i.e., drainage area) was defined in HydroCAD. CNs for each site were based on acreage per HSG, for which all 4 soil classifications were present. Area per HSG was determined through available soil contours and classifications were later corrected based on retrieved soil samples. T_c values were set according to flow characteristics, with undeveloped wooded areas consisting predominately of sheet flow. Reaches were created using field-surveyed cross-section points and elevations. Rainfall was measured directly using site-installed gauges and daily totals (6.4 cm) were distributed in HydroCAD using an NRCS Type II 24-hour curve. HydroCAD generated hydrographs, which were analyzed for Q_p, and compared to independent calculations for validation.

Topographic contours and soil data were obtained from county GIS parcel viewers (James City County 2024; County of New Kent n.d.) and USDA Web Soil Survey (USDA & NRCS 2019), then imported into AutoCAD to verify drainage areas. VADEQ recommendations, based on the Virginia Runoff Reduction Method (VRRM) and Virginia Administrative Code (9VAC25-875-600 E), were applied for cover type conditions, where wooded, undeveloped areas are classified as "good" cover type for all HSGs (Center for Watershed Protection & Chesapeake Stormwater Network 2008; Virginia Administrative Code 2024a).

Sensitivity analyses followed established practices for evaluating parameter uncertainty and model responsiveness in CN-based hydrologic modeling frameworks (Ponce & Hawkins 1996). A series of sensitivity analyses were performed by varying HSGs (5 iterations per site), CNs (5 iterations per site), and sheet flow lengths (30 iterations per site). For soil sensitivity, scenarios included baseline USDA soil map HSGs, field-verified HSGs from soil borings, and uniform HSG assignments (All A, All B, All C, and All D). Hydrographs from multiple runs were exported for analysis in Microsoft Excel and RStudio. For sheet flow sensitivity, flow lengths were varied from 3.048 m to 91.4 m while holding all other inputs constant. Relationships between sheet flow length and Q_p were assessed using second-order polynomial regression to capture nonlinear runoff responses commonly observed in hydrologic systems (Mockus et al. 2007). Percent changes in Q_p relative to baseline conditions were calculated to quantify sensitivity to model parameters.

2.4. Peak Discharge Calculations

Field measurements were used to calculate pre-development Q_p for each site, both for model validation and for direct comparison to hand-calculated values. Two complementary approaches were used: (1) stream discharge using Manning's equation, consistent with procedures outlines in TR-55 for sheet and shallow concentrated flow (Cronshey et al. 1986, Mockus et al. 2007) and (2) drainage area peak flow using the flow rate equation, which relates watershed characteristics, time of concentration, and rainfall depth to peak flow estimates (Cronshey et al. 1986, Mockus et al. 2007).

Manning's equation was applied to each surveyed stream cross-section to calculate flow in the channel (Equation 3). Manning's roughness coefficient of 0.40 for sheet flow in wooded areas, provided from TR-55 reference table, was used at each site. This coefficient was based on observed site conditions characterized by dense vegetation and surface roughness, consistent with values reported in TR-55 and established guidance for natural surfaces (Cronshey et al. 1986).

$$Q = \left(\frac{1.49}{n}\right) A R^{\frac{2}{3}} \sqrt{S} \tag{3}$$

Where:

Q = Discharge $\left(\frac{\mathrm{m}^3}{s}\right)$

n = Manning's Roughness Coefficient

A = Flow area (m^2)

R = Hydraulic radius (m)

S = Channel slope $\left(\frac{m}{m}\right)$

Topographic survey data provided A and P, while flow monitoring sensors supplied water level measurements to define flow depth during storm events. The discharge calculation yielded peak flow rates in the stream channel that were compared to HydroCAD outputs to assess model performance.

The peak discharge of the entire drainage area was estimated using the flow-rate equation (Equation 4), where A was derived from the topographic surveys and Q was derived from the in-stream flow monitors.

$$Q = vA \tag{4}$$

Where:

Q = Discharge $\left(\frac{\mathrm{m}^3}{s}\right)$

A = Cross-sectional vector area (m^2)

By combining Manning-derived velocities with measured water levels, we calculated the total peak flow exiting the drainage area. These values were compared to HydroCAD

Table 2 Summary of HydroCAD modeling scenarios used in sensitivity analyses. Each scenario group varied specific TR-55 parameters—Hydrologic Soil Groups (HSGs), Curve Numbers (CNs), or sheet flow length—to evaluate their influence on time of concentration (T_c) and peak discharge (Q_p).

Scenario Group	Parameters Varied	Purpose
HSG's influence on modeled Q_p	USDA soil map HSG classification vs. field-verified HSG classification	Compare standard HydroCAD inputs with site-specific soil data and its effect on Q_p
CN sensitivity to HSGs	Hypothetical uniform HSGs (all A, B, C, and D)	Test sensitivity of Q_p to soil group classifications
Sheet Flow Sensitivity	Sheet flow lengths from 3.048 m – 81.4 m (increments of 10)	Evaluate TR-55's 91.4 m sheet flow assumption on T_c and its effect of Q_p

outputs to assess model accuracy and sensitivity to soil, topography, and channel parameters. In total, we evaluated 3 groups of model runs in HydroCAD: baseline comparisons of mapped vs. field-verified soils, soil sensitivity tests with uniform HSG classifications, and sheet flow sensitivity analyses (Table 2).

3. Results

3.1. Soil Samples

At both sites, 0% of the soil samples collected from sections of "D" classified soil were found to be representative of "D" HSG classifications. Similar misrepresentations were identified across both sites for "C" classified soils, where 0% of "C" classified soil for New Kent and Cow Swamp were found to be representative of a "C" HGS classification. Most notably, of the soil borings taken, 60% of "C" designated soil at New Kent was actually "B" soil and 75% of "C" designated soil at Cow Swamp was "B" soil. Overall, "C" and "D" classified samples were more representative of either "B" or "A" HSG classifications (Figure 3; Table S2).

3.2. HydroCAD Modeling Scenarios

For the New Kent site using a Type II 24-hr observed rainfall event of 6.4 cm and USDA soil map HSG classifications, a HydroCAD Q_p of 0.81 m^3/s can be

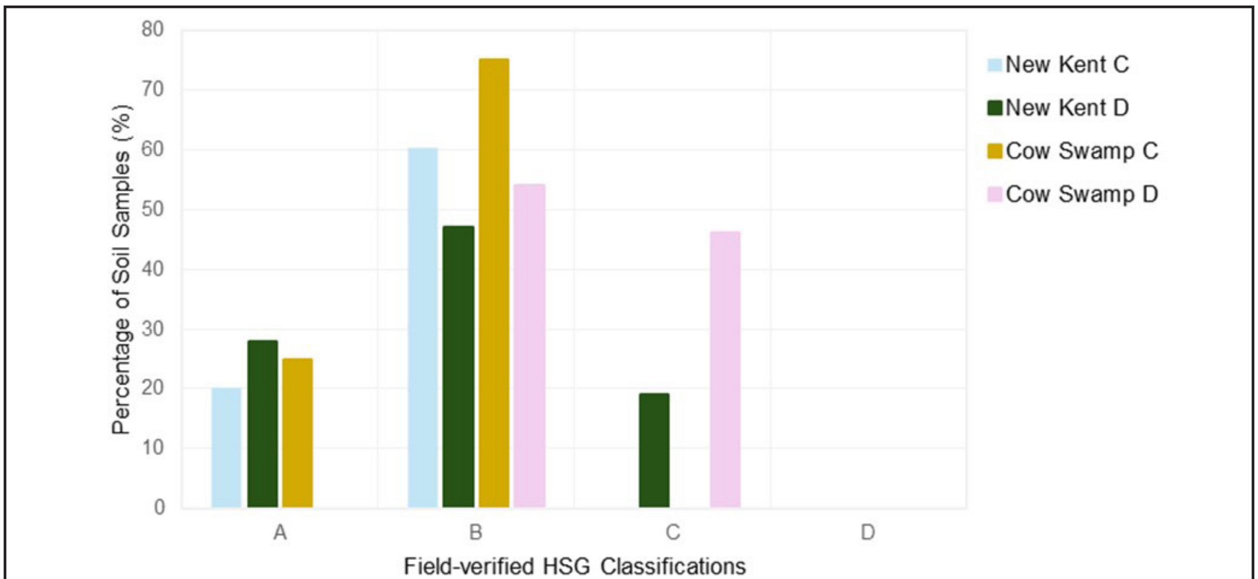

Fig. 3. Comparison of USDA soil map classifications ("C" and "D") and field-verified HSGs at the New Kent and Cow Swamp sites. Grouped bars show the proportion of C- and D-classified soils that were found to be A, B, C, or D, based on soil borings, highlighting the extent of misclassification in the baseline soil maps.

observed (Figure 4). Alteration of HSG classifications within the model, from majority "C" and "D" classifications to majority "B" and "A" classifications based on site soil samples, decreased Q_p to 0.10 m^3/s, approximately 8.1 times smaller than what was initially modeled. The Q_p calculated using direct measurements was 0.11 m^3/s with a stream discharge of 0.217 m^3/s. The direct measurements and the HSG-adjusted model both show Q_p is overestimated using USDA soil map data by approximately 640% and 710%, respectively. Additionally, the estimated total volume using the model outputs associated with USDA soil maps was approximately 7,600 m^3/s, whereas the estimated total volume using site collected data was 800 m^3/s, an overestimation by a factor of 9.5.

At the Cow Swamp site, a Type II 24-hour rainfall event of 6.4 cm and USDA soil map HSG classifications yielded a HydroCAD Q_p of 0.31 m^3/s (Figure 4). Adjusting HSG classifications based on soil samples reduced Q_p to 0.09 m^3/s, 3.4 times smaller than the original model output. Using the direct measurements, Q_p was calculated at 0.14 m^3/s, with a stream discharge of 0.223 m^3/s. The direct measurements and the HSG-adjusted model indicate the USDA soil maps overestimated Q_p by approximately 120% and 240%, respectively. Similar to the New Kent site, the estimated total event discharge volume for Cow Swamp using the model outputs associated with USDA soil maps was approximately 2,200 m^3, whereas the estimated total volume using site collected data was about 600 m^3, an overestimation by a factor of 3.7.

Table 3 summarizes the modeled pre-development Q_p for New Kent and Cow Swamp under baseline USDA soil maps HSGs, field-verified soils HSGs, uniform HSG sensitivity scenarios, and variations in minimum and maximum sheet flow length. This summary highlights the influence of soil classification and flow path length on modeled runoff and provides context for subsequent sensitivity analyses.

3.3. Sensitivity Analysis of HSG Influence on Q_p

The biggest changes in Q_p outputs were seen at both sites when comparing the Q_p modeled with USDA soil maps to that modeled with corrected HSG conditions, and

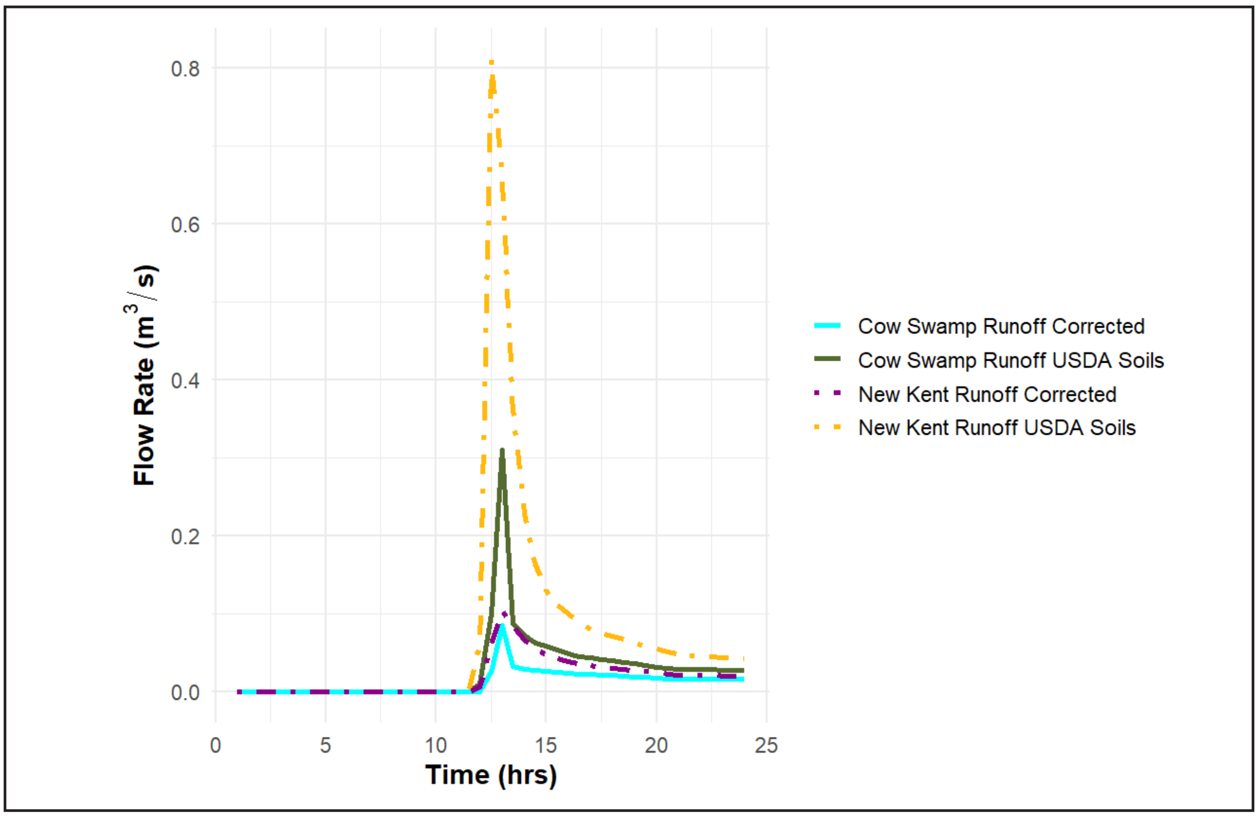

Fig. 4. Comparison of HydroCAD model Q_p outputs for the New Kent study and Cow Swamp study sites. HydroCAD model using New Kent Runoff USDA Soils (yellow) had a Q_p of 0.81 m^3/s. New Kent Runoff Corrected (purple) using HSG classifications from site samples had a Q_p of 0.10 m^3/s. HydroCAD model using Cow Swamp Runoff USDA Soils (green) had a Q_p of 0.31 m^3/s. Cow Swamp Runoff Corrected (blue) using HSG classifications from site samples had a Q_p of 0.09 m^3/s.

Table 3 Modeled HydroCAD peak discharge (Q_p) for the New Kent and Cow Swamp study sites under different scenarios. Scenarios include baseline conditions using USDA soil map hydrologic soil groups (HSGs), field-verified soil HSGs, uniform HSG sensitivity analyses (All A and All D), and sheet flow length sensitivity analyses. Values illustrate the influence of soil classification and flow path length on Q_p, highlighting the potential for over- or under-estimation of runoff depending on input assumptions.

Scenario	Parameter Varied	New Kent Q_p (m^3/s)	Cow Swamp Q_p (m^3/s)	Notes
Baseline (USDA soils)	HSG classification (map)	0.81	0.31	Default inputs
Field-verified soils	HSG classification (samples)	0.10	0.09	CN adjusted for soil borings
Soil sensitivity – All A	Uniform HSG	0.01	0.00	Lowest runoff potential
Soil sensitivity – All D	Uniform HSG	1.25	2.22	Highest runoff potential
Sheet flow sensitivity	Sheet flow (3.048 m)	33.82	24.55	T_c minimized with default inputs
Sheet flow sensitivity	Sheet flow (91.4 m)	22.83	9.55	T_c maximized with default inputs

thereby varying CNs, based on site samples. Additionally, noticeable changes were observed when comparing the Q_p modeled with USDA soil maps to the All A HSG and All D HSG conditions (Figure 5; Table 3). Sensitivity analyses for the New Kent and Cow Swamp sites indicate that baseline Q_p outputs are highly sensitive to the extremes (“A” and “D”) of the HSG spectrum. Notably, the All C HSG condition produced very little change in Q_p for New Kent, whereas Cow Swamp showed more pronounced changes. This difference is attributable to the baseline (USDA Soil Map) HSG distribution at each site. New Kent’s soils were classified predominately as “C” and “D” soil, therefore assigning all “C” results in minimal deviation from the baseline. Cow Swamp, on the other hand, was predominantly “B” soil, making the All “C” assumption more notable. A similar trend between the 2 sites can be observed in the All D HSG condition as well.

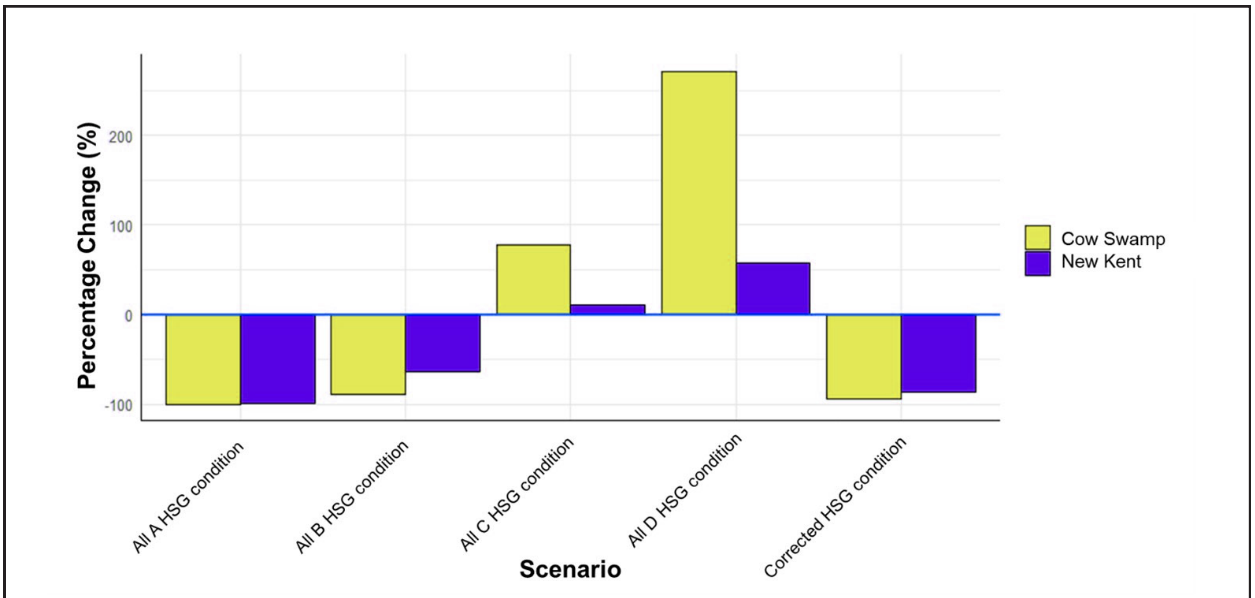

Fig. 5. Sensitivity analysis for the Cow Swamp and New Kent study sites. The X-axis shows different HSG scenarios and the Y-axis represents percentage change (%) of Q_p. The solid blue line represents the baseline scenario (current USDA soil map conditions for both sites).

3.4. Sensitivity Analysis of Sheet Flow Length on Q_p

Across both sites, sheet flow lengths were negatively correlated with respect to HydroCAD Q_p (Figure S1; Table 3), indicating that shorter flow paths produce higher Q_p values, whereas longer flow paths reduce Q_p by increasing travel time and flow attenuation. Under baseline conditions, using USDA HSGs, only sheet flow lengths were varied to isolate their influence on modeled Q_p. Increasing sheet flow length increases time of concentration by prolonging overland flow, thereby delaying watershed response and reducing peak discharge, consistent with NRCS TR-55 hydrologic theory. Alternative functional forms (linear and logarithmic) were explored during preliminary evaluation but did not adequately capture the observed non-linear relationship between sheet flow and Q_p across the tested range. A second order polynomial regression was therefore selected and yielded a statistically significant relationship between sheet flow lengths and Q_p for both sites (New Kent: df = 28, F-stat = 750.1, $R^2 = 0.997$, adjusted $R^2 = 0.9963$, p-value <0.05; Cow Swamp: df = 28, F-stat = 85.12, $R^2 = 0.94$, adjusted $R^2 = 0.936$, p-value <0.05).

4. Discussion

4.1. Parameter Influence on Q_p

The Q_p was demonstrably sensitive to changes in HSG, particularly to inaccuracies in applied soil classification. Soils misclassified as “C” or “D,” but more representative of “A” or “B,” led to overestimations of pre-development Q_p. Thus, a model output that over-estimated pre-development Q_p would cause a retention pond to be undersized, leading to excess stormwater discharge and downstream channel erosion. The HydroCAD model outputs using HSG classifications derived from USDA soil maps over-estimated pre-development Q_p by approximately 710% for New Kent and 240% for Cow Swamp, relative to modeled outputs using HSG classifications from field samples.

The large discrepancies in modeled Q_p, observed when using corrected HSGs, underscore the importance of accurate soil classification. HSGs are used to estimate infiltration rates via CNs, where group “A” soils are highly permeable, producing low runoff, while group “D” soils have poor permeability, producing high runoff. Post-development, additional impervious surfaces increase runoff relative to pre-development conditions. Retention ponds are sized based on the difference between pre- and post-development Q_p. Therefore, if an undeveloped wooded area is classified primarily as “D” (low permeability soil), the difference in pre- and post-development runoff would be small, resulting in a smaller sized pond to catch the runoff. However, if that site was better represented as a “B” soil, the true pre-development Q_p would be high, meaning a larger difference compared to post-development Q_p, and therefore a larger pond would be needed. Misclassifying a site as a more permeable soil type can therefore drastically underestimate peak discharge, particularly for shorter flow paths where water concentrates quickly. These results highlight that even small errors in HSG assignment can propagate through hydrologic models, influencing stormwater management decisions. Due diligence to corroborate soil map accuracy is crucial for accurate HydroCAD results, as this study has highlighted a potential systemic issue in the application, warranting the need for further research.

When HSGs are misclassified, the effect on modeled runoff can be substantial. For example, consider a site that is mistakenly classified as consistently entirely or poorly drained soils (“D”). Under this misclassification, the pre-development Q_p is estimated at 30 m^3/s and the post-development Q_p rises to 40 m^3/s. Because the model difference is only 10 m^3/s, the required retention pond would be relatively small. However, if the soils are correctly identified as well-drained (“B”), the pre-development Q_p is about 5 m^3/s. With post-development Q_p still at 40 m^3/s, the actual increase is 35 m^3/s, meaning the retention pond must be designed much larger to safely manage stormwater. This example illustrates how misclassification can mask the true change in runoff and lead to undersized infrastructure.

4.2. Realistic Use of Sheet Flow Length

HydroCAD does not allow sheet flow lengths to exceed 91.4 m (300 ft), rejecting higher inputs. Considering the various model iterations and analysis of sheet flow lengths on Q_p, a smaller sheet flow length results in a higher Q_p, and potentially unrealistic pre-development representations. For example, using a smaller flow length of 30.5 m resulted in higher Q_p outputs of 0.81 m^3/s and 0.31 m^3/s for New Kent and Cow Swamp, respectively. Using the maximum length of 91.4 m instead of the above example of 30.5 m lowered Q_p outputs by approximately 22% and 48%, respectively. The sensitivity of Q_p to flow length is not as severe in comparison to sensitivity to HSGs in the model but obviates the need for site inspections to discern sheet flow length as accurately as possible. Utilizing the 91.4 m maximum within HydroCAD, in tandem with accurate HSG classifications, will provide a more realistic output for undeveloped wooded areas that avoid the deleterious outcomes of overestimating pre-development Q_p.

4.3. Regional Implications

Regulatory requirements varying by state, county, and municipality commonly demonstrate that post-development Q_p for 2- and 10-year, 24-hour storms does not exceed pre-development Q_p. In some cases, larger, 50- or 100-year, 24-hour storms are also modeled for flood controls. For example, Virginia's state-level stormwater management standards suggest 1-, 2-, and 10-year, 24-hour storms should be used unless otherwise specified (Virginia Administrative Code 2024b).

The results of this study indicate that substantial discrepancies in modeled pre-development Q_p can arise even under relatively typical rainfall events when key input parameters are mischaracterized. Such discrepancies raise concerns regarding the reliability of stormwater modeling conducted under current regulatory frameworks, as underestimated retention pond sizing may lead to increased discharge volumes, elevated erosion potential, and degraded downstream water quality.

Within the context of this study, the project impetus site drains into Lake Matoka, which ultimately contributes to the James River, a major tributary of the Chesapeake Bay. The 2022 Chesapeake Bay and watershed report card highlighted ongoing challenges across the watershed, with many tributaries exhibiting static or declining recovery trends (Vargas-Nguyen et al. 2023). Given that excess sedimentation remains a leading pollutant in U.S. waterways, ensuring that stormwater BMPs are appropriately sized to reflect true runoff conditions is critical for protecting receiving waters (U.S. EPA 2025).

Beyond environmental consequences, the financial implications of inadequate stormwater design can be substantial. For example, the ongoing VDOT restoration project associated with the project impetus site represents a cost of approximately $2.25 million (Kale 2024). Improved stormwater modeling practices may therefore reduce both ecological impacts and the long-term economic burdens associated with corrective restoration efforts.

4.4. National Implications

Proper modeling and management of stormwater runoff is a growing necessity, with the need for proper BMP design becoming more urgent as urbanization increases concomitant with increased rainfall intensities and amounts predicted from climate change models (Roy et al. 2008; Steinman et al. 2015; Sparkman et al. 2017). Since its nationwide adoption in 1986, TR-55 has remained a foundational method for stormwater modeling and is widely applied through software platforms such as HydroCAD.

This study demonstrates that modeled peak discharge using TR-55 based methods is highly sensitive CN, which is itself derived primarily from HSG classification. Although the modeling framework should be robust when properly parameterized, inaccuracies in input data, particularly soil classifications, can propagate through the model and result in substantial errors in predicted runoff.

While this analysis focuses on 2 coastal plain watersheds, the implications extend beyond the study area. USDA soil data sets, including the web soil survey, are routinely relied upon for stormwater modeling across the United States. These datasets explicitly note that mapped soil properties are intended for general planning purposes and should be verified through site-specific investigation. Despite these disclaimers, such data are often used without field validation and engineering practice. Continued reliance on misclassified HSGs has the potential to systematically underestimate or overestimate stormwater impacts, contributing to channel erosion and degradation of receiving waters at broader spatial scales. Taken together, these findings demonstrate the importance of careful evaluation of soil data inputs when implying TR-55-based methods nationwide. Improved attention to parameter accuracy, rather than changes to the modeling framework itself, represents a practical pathway for enhancing stormwater design outcomes across diverse watershed settings.

5. Conclusion

This study identified substantial inaccuracies in TR-55/HydroCAD predictions for undeveloped, wooded areas, primarily related to HSG classification. While these results are limited to one storm at each site, they highlight important limitations of current practice that may systematically affect BMP sizing and watershed outcomes. Broader, multi-event studies will be critical for fully assessing the scope of these limitations across differing land covers and regions. Our recommendations for the general enhancement of accuracy include 1) updating soil maps and 2) requiring soil analyses and site inspections (i.e., to confirm watershed boundaries, groundcover, and topography) prior to development. Specific recommendations for using HydroCAD to model undeveloped, wooded sites in good condition include 1) eliminating the use of HSGs "C" and "D" to reduce the overall risk of overestimating pre-development Q_p and 2) estimating sheet flow lengths obtained via site inspections and applying the 91.4 m (300 ft) maximum length for T_c calculations when applicable. These will produce more representative pre-development runoff rates.

Future work should focus on analyzing model outputs across various rainfall events at multiple undeveloped wooded sites in different regions. Studies comparing USDA soil maps to site soil analyses should also be conducted to identify the degree of potential discrepancies across various states. Lastly, these potential issues should be examined across different types of land cover (i.e., cultivated agricultural, grassland or pasture, fully developed, etc.) to determine if similar large systemic modeling errors may be occurring.

Supplementary Material

The online version of this article includes a link to a supplementary material file that contains the following supporting material: **Table S1,** Ia/S Ratio data for New Kent and Cow Swamp sites and their respective sensitivities; **Table S2,** Soil boring number, depth (cm), USDA HSG classification, and field sample classification of the soils taken from the New Kent and Cow Swamp study sites; **Figure S1,** Polynomial regression between various sheet flow lengths and Q_p.

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Author Contributions Statement

Conceptualization: BOC, MC; methodology: BOC, MC, WS; data analysis: BOC; writing original draft: BOC; review/editing original draft: RC, LK, WS; investigation: BOC; resources: MC; data curation: BOC; supervision: RC, LK, MC, WS. All authors have read and agreed to the published version of the manuscript.

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The authors have no conflict of interest to report.

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