Chapter 2 - Stormwater Management

2.1 Hydrology and Drainage Calculations

There are a variety of BMPs that can be designed to capture, store, and treat stormwater runoff from construction sites. Commonly, EPSC measures and BMPs are categorized by their purpose and classified as: stabilization, pollution prevention, erosion prevention, runoff velocity control, sediment control, or stream protection practices, or a combination of the categories. Further, EPSC measures can be structural (i.e., physical structures with engineering design) or nonstructural (i.e., implemented methodologies through planning and policies) practices. Regardless of their classification, many structural EPSC measures are sized by their projected hydrologic or hydraulic capacity. In some scenarios, sizing, or design of EPSC measures may be governed by regulations, hydrologic/hydraulic calculations, or a combination of the two. The following information is presented under the assumption that the designer is proficient with watershed delineations, hydrology, hydraulics, and stormwater runoff. Detailed information may be located in the *Tennessee Department of Transportation Drainage Manual* (TDOT) and the *National Engineering Handbook* [NEH (NRCS, 1967-2019)].

Estimating the peak flow and volume of runoff from a construction site assists in calculating erosion potential, flow routing, and required sediment treatment from EPSC measures. Estimating the maximum flow rate leaving a construction site will guide the sizing of inlets, outlets, and emergency spillways of the EPSC measures. Therefore, accurate, predictive methodologies for both runoff volume and peak flow rates are critically important in the sizing and design of such measures. Hydrologic procedures for the National Resource Conservation Service (NRCS) Technical Release (TR)-55 method are recommended for design and outlined in the following subsections; however, other hydrologic methodologies such as the Rational method (Schueler, 1987), Small Storm Hydrology method (Pitt, 1994), or Green-Ampt method (Green & Ampt, 1911), may be suitable alternatives in particular scenarios for hydrologic computations. For example, the Rational method may be useful for calculating peak flows (more) quickly and relating those flows to peak velocities. This approach may be of interest since peak velocities are directly related to erosive forces and eroded sediments; therefore, the Rational method is also outlined in Section 2.1.3. Common hydrologic software for the NRCS TR-55 methodology include WinTR-55, HEC-HMS, and HydroCAD® which were developed by the United States Department of Agriculture (USDA), the United States Army Corp of Engineers (USACE), and HydroCAD Software Solutions LLC. Computer based software may be a more practical approach than hand calculations due to reduced computation time and the ability to rapidly reanalyze site specific scenarios by changing key inputs.

2.1.1 Runoff Volume

The NRCS runoff curve number (CN) method is the most commonly implemented runoff volume estimation method in the United States. In this method, runoff depth (Q_{CN} [inches]) is a function of precipitation depth (P [inches]), the maximum potential retention in a watershed (S [inches]), and the initial abstractions within the watershed (I_a [inches]), provided that $P > I_a$ (Eqn 1). When $I_a \geq P$, all rainfall is captured within the watershed, and no runoff is produced.

$$Q_{CN} = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \text{(Eqn 1)}$$

Maximum potential retention is an empirically derived variable (Eqn 2). Initial abstraction is also empirically derived and is assumed to have a constant, linear relationship with S (Eqn 3). This linear relationship (λ) is typically set at 0.2, meaning no runoff occurs until 20% of the watershed's ability to retain water has been filled.

$$\mathrm{S} = \frac{1000}{\mathrm{CN_{comp}}} - 10 \quad \text{(Eqn 2)}$$

$$\mathrm{I_a} = \lambda \times \mathrm{S} \quad \text{(Eqn 3)}$$

The CN_{comp} variable accounts for watershed heterogeneity in terms of land use and hydrologic soil group (HSG). More specifically, individual CNs are a function of specific land use and HSG; they can be found in tables provided in the NRCS TR-55 manual (Cronshey, 1986). When a given watershed has more than one land use or more than one HSG, individual CNs can be area weighted to obtain a composite curve number (CN_{comp}) as shown in Eqn 4, where i represents a distinct combination of land use and HSG.

$$\mathrm{CN_{comp}} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{i}} (\mathrm{CN_i} \times \mathrm{A_i})}{\sum_{\mathrm{i=1}}^{\mathrm{i}} \mathrm{A_i}} \quad \text{(Eqn 4)}$$

The CN_{comp} can be further adjusted to account for variability arising from soil moisture conditions, canopy cover density, stages of growth for vegetation, temperature, rainfall intensity, and rainfall duration. Collectively, these sources of variability are termed antecedent runoff conditions (ARC) and applying the ARC factor to the CN_{comp} is an optional process that is dependent on professional judgment. ARC is divided into three classes: class

I for dry conditions, class II for average conditions, and class III for wet conditions. Some works advise converting the CN_{comp} from case II to case I or III based on previous rainfall (Ward & Trimble, 2003). Rough guidelines are that conditions may be considered dry (ARC I) if the precipitation during the previous five days was less than 0.5 inches during the dormant season or 1.4 inches during the growing season; conditions may be considered wet (ARC III) if the precipitation during the previous five days was more than 1.1 inches during the dormant season or 2.1 inches during the growing season. Tables to convert the ARC II CN_{comp} to ARC I or ARC III are provided in NEH-10 (NRCS & USDA, 2004). However, there is relatively little evidence to suggest applying ARC corrective factors is appropriate. Simpson et al. (2023) discovered ARC corrective factors adjusted the CN_{comp} too severely therefore, professional judgement is advised when implementing ARC factors in development projects. Case III is the most conservative estimate, followed, by case II. More conservative estimates are recommended in the design process to ensure adequate storage volumes.

The overarching process for the NRCS TR-55 composite CN method for calculating runoff volume is outlined:

- Determine the area which drains to an outlet of interest (i.e., determine the watershed of interest).
- Identify and classify the specific soils, soil types, and land uses within the watershed boundary.
- Obtain CNs for each distinct combination of land use and HSG; calculate CN_{comp} (Eqn 4).
- Determine if an ARC factor should be applied.
- Calculate S and I_a (Eqns 2 & 3).
- Determine the design P value which is site specific precipitation depth acquired from National Oceanic and Atmospheric Administration (NOAA) Atlas 14 that correlates with the design storm that can be found in the construction general permit [CGP, (TDEC)].
- Calculate Q_{CN} (Eqn 1).
- Determine the runoff volume by multiplying Q_{CN} with the watershed area and a unit conversion factor.

Further, other CN methodologies exist beyond the composite approach. These include the distributed CN and discrete CN approach (Simpson et al., 2023) as well as modifying λ (Hawkins et al., 2009). These methodologies have proven to be more accurate than the composite method under specific watershed and rainfall conditions. While the composite CN approach is the most commonly implemented CN methodology, these other approaches may be viable alternatives, given professional judgement.

2.1.2 Time of Concentration

Estimating peak flow rates relies on a timing component. This timing component is known as the time of concentration (T_c) which can be defined as the time it takes for water to travel from the hydrologically most distant point in a watershed to the watershed outlet. Therefore, the peak flow rate will occur during a storm's maximum intensity over a duration that matches the watershed's T_c. Estimating T_c can be influenced by a number of variables including watershed surface roughness, shape, size, and slope as well as rainfall characteristics.

The NRCS TR-55 methodology for estimating T_c consists of summing the travel time (TT) of all flow types that may occur within a watershed: sheet flow (SF), shallow concentrated flow (SCF), and open channel flow (OCF). SF occurs over plane surfaces (e.g. a parking lot, grass field), typically has a maximum flow depth of 0.1 feet, travels in a wavelike manner, and has a maximum flow length of 100 feet. The travel time of SF is calculated utilizing the empirical relationship shown in Eqn 5.

$$\mathrm{TT_{SF}} = \frac{0.007 \times (\mathrm{nl})^{0.8}}{(\mathrm{P_2})^{0.5} \times \mathrm{S}^{0.4}} \qquad \text{(Eqn 5)}$$

In Eqn 5, TT_{SF} is the travel time of sheet flow (hours), n is the Manning's roughness coefficient (unitless), l is the length of the longest sheet flow path (feet, maximum of 100 ft), P_2 is the 2-year, 24-hour rainfall depth (inches), and S is the average slope of the longest sheet flow path (ft/ft). P_2 can be acquired from NOAA Atlas 14 for a specific location. The n variable can be looked up in tables in the NRCS TR-55 manual or NEH-15 (Cronshey, 1986; NRCS & USDA, 2008).

SCF is flow that occurs in a defined channel with a flow depth between 0.1 and 0.5 feet and is estimated by calculating the average velocity through the specific channel. Velocity equations for specified channels are provided in NEH-15 (NRCS & USDA, 2008), and the travel time of shallow concentrated flow (TT_{SCF}) can be calculated by dividing the length of the channel by the average velocity and converting units as required.

OCF occurs in defined channels where surveyed cross-sectional data has been obtained, channels are visible on aerial imagery, or flow/stream- lines appear on hydrologic websites such as the United States Geological Survey (USGS), National Hydrography Database (NHD), or StreamStats. Manning's Equation (Eqn 6) is used to estimate the average velocity throughout the length of OCF, and similarly to SCF, that velocity is used to estimate the travel time of OCF (TT_{OCF}) by dividing the length of OCF by velocity and converting units.

$$V = \frac{1.49}{n} \times r^{2/3} \times S^{1/2}$$

(Eqn 6)

In Manning’s Equation (Eqn 6), r is the hydraulic radius (feet), which is found by dividing the cross-sectional area of flow by the wetted perimeter. The hydraulic radius can be a complex variable to calculate; therefore, the designer is referred to “The open channel flow calculator©” developed at the University of Auburn for computations in triangular, rectangular, trapezoidal, or circular culverts (Fang, 2007). For computations in arched or elliptical pipes, the designer is referred to Perez et al. (2015).

2.1.3 Peak Flow Rate

For its simplicity, the rational method is the most commonly used methodology to predict peak flow rates in the United States. It is an empirical relationship between peak discharge (q_p), rainfall intensity (i), a runoff coefficient (C), and drainage area (A) (Eqn 7).

$$q_p = C_{comp} \times i \times A \qquad \text{(Eqn 7)}$$

The rainfall intensity can be calculated for a given recurrence interval (e.g., 2 years or 5 years) for a duration equal to the watershed time of concentration, T_c. Lookup tables in Chapter 4 of TDOT’s Drainage Manual can be used to determine C values based on surface types and conditions within the drainage area (TDOT). When multiple surface types or conditions are present within the drainage boundary area-weighting the C values is appropriate to obtain C_{comp}, a similar process as depicted in Eqn 4. In Eqn 7, the variables q_p, i, and A have units of cfs, in/hr, and acres, respectively, while C is unitless. The Rational method was developed for use when drainage areas are less than 600 acres (Kuichling, 1889); however, caution and engineering judgement are advised once watersheds exceed 10 acres.

The NRCS-TR 55 Graphical Peak Discharge method relates a unit peak discharge (q_p) multiplied with watershed area (A_m), runoff depth (Q_{CN}) and a ponding factor (F_p) to peak discharge (q_p) (Eqn 8).

$$q_p = q_u \times A_m \times Q_{CN} \times F_p \qquad \text{(Eqn 8)}$$

In this equation, q_p is expressed in cubic feet per second (cfs), while q_u, A_m, and Q_{CN} (Eqn 1) are expressed in cubic feet per second per square mile per inch (csm/in), square miles (mi^2), and inches, respectively. F_p is governed by the percent area within the watershed that is ponds or swamps and can be looked up in tables in the NRCS TR-55 manual (Cronshey, 1986). The q_u variable is dependent upon T_c, appropriate rainfall distribution, P (ref. NOAA atlas 14), and I_a (Eqn 3). Utilizing the original NRCS TR-55 methodology, the rainfall distribution is Type II for the entire state of Tennessee and q_u can be determined from graphics (NRCS, 1986) or hydrologic software. More recently, NOAA has created more refined and updated rainfall distributions, in lieu of the NRCS Type II distribution. Within the Ohio Valley geographic region, NOAA has defined four rainfall distributions: Type A, B, C, and D, all of which are represented in the state of Tennessee. These rainfall distributions are pre-loaded in certain hydrologic models (e.g., HydroCAD®) making the calculation of the q_u variable simple. Other software (e.g., WinTR-55) do not have the updated NOAA rainfall distributions incorporated into the models at this time. However, in WinTR-55, users can input custom rainfall distributions. Appendix A of the Georgia Soil and Water Conservation Commission Manual for Erosion and Sediment Control provides resources to implement NOAA rainfall distributions in the NRCS models (GSWCC, 2016).

2.2 Estimating Sediment Yield

Sediment yield is a critical design element for EPSC measures on construction sites in regard to sediment storage capacity and maintenance. Erosion potential is dependent on four primary factors: soil erodibility, vegetative cover, topography, and climate. Understanding the parameters affecting soil loss helps with construction stormwater management by informing planners which project stages have the largest predicted soil losses. One of the most well-known models for estimating long-term soil loss is the Universal Soil Loss Equation (USLE), which was developed in the 1950s by the United States Department of Agriculture's Agricultural Research Service (USDA-ARS), Soil Conservation Service (SCS, now known as NRCS), and Purdue University. The USLE model is on its second revision, the Revised Universal Soil Loss Equation 2 (RUSLE2), which was developed in the 1990s. Though the use of RUSLE2 is recommended for calculating soil loss on any development project, it is especially useful when site specific designs are required. The CGP (TDEC) requires that site specific calculations be completed to design temporary sediment basins with a contributing drainage area of 25 acres or greater.

2.2.1 RUSLE2

2.2.1.1 Model

The RUSLE2 model is freely available at the USDA-ARS website and is recommended for use as opposed to performing hand calculations (https://fargo.nserl.purdue.edu-/rusle2_dataweb/RUSLE2_Index.htm). Foster and Toy (2005) and Toy and Foster (2007) are excellent resources for learning the software. The RUSLE2 model calculates sediment loss on slopes from rill and interrill erosion on an annual basis. The interrill erosion process (also known as sheet erosion), starts with raindrop impact detaching soil particles (i.e., sediment), thereby allowing the particles to move across the soil surface. Interrill erosion forms rills on the hill slope. Sediment is transported through the rills down the slope until the runoff slows enough to allow the deposition on either the land surface or in concentrated flow areas such as channels. Specific variables for RUSLE2 include annual erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management factor (C), and a support practices factor (P) all of which are used to predict the average soil loss (A) from rill and interrill erosion (Eqn 9).

$$A = R \times K \times LS \times C \times P \qquad \text{(Eqn 9)}$$

Each variable in the RUSLE2 equation is determined based on a set of empirical equations and is dependent on a number of factors. Computation of variables requires caution and time; therefore, use of the model is advised. A brief explanation of the variables is provided, but for further specifics, the user is referred to the RUSLE2 user's manual (USDA, 2001).

The R-factor quantifies the amount and rate of runoff likely associated with rain by assessing raindrop impact on soil. This is impacted by weather, climate, and seasonal variations in temperature, rainfall, and wind. The R-factor has units of hundreds of [ft × tonf × in × $(ac \times hr \times yr)^{-1}$] and has typically been expressed as an annual average. However, in RUSLE2 the R-factor can be multiplied by a fractional amount of erosion to obtain daily, weekly, monthly, etc. values.

The K-factor is the rate of soil loss per rainfall erosion index plot, has a unit of [ton × ac × hr × $(\text{hundreds of } ac \times ft \times tonf \times in)^{-1}$], and is influenced by temperature, precipitation, and intrinsic soil properties. In general, soils with high clay or sand content have lower values of K. In high clay soils, this low value is because the attraction forces between clay particles are often stronger than the forces applied to soils by raindrops. In sandy soils, it is due to the high infiltration capacity. Conversely, silty soils typically yield moderate to high values of K because particles can be easily detached by the forces imparted by raindrop impact and the soils are unable to infiltrate rainfall at a high enough rate.

Topography is accounted in RUSLE2 by considering the horizontal distance from the origin of overland flow to the point where either (1) the slope gradient decreases enough for deposition to begin or (2) runoff enters a defined channel and becomes concentrated (slope length). Topography is also accounted for by the gradient of the slope length (slope steepness). Slope length is typically limited to 400 feet, although longer sections may be applicable in certain scenarios. Together, slope length (feet) and steepness (%) are used to obtain a unitless LS factor from tables in Renard (1997) or within the RUSLE2 model.

The C-factor is a unitless variable reflecting the effect of cover crops and management practices (e.g., vegetation type, growth, application of biomass, crop rotation, conservation tillage, and surface roughness) on erosion rates. The C-factor is split into subfactors including canopy, ground cover, surface roughness, ridges, below ground biomass, soil consolidation, and antecedent soil moisture in which a set of predetermined equations are used to calculate their interactions related to soil loss.

The P-factor describes the ratio of soil loss with a specific support practice to the corresponding loss with upslope and downslope tillage. It is a unitless variable calculated from a product of P subfactors for individual support practices that can be standalone practices or used in series.

The product of all RUSLE2 variables is average soil loss expressed in tons per acre per year. However, decomposition of the R and K variables allows the user to better refine soil loss estimates for a user-specified timeframe. The average loss can also be viewed as the net sum of soil losses related to the following four processes:

- soil loss on the eroding portion the slope;
- soil detachment on the entire slope;
- conservation planning soil loss; and
- sediment delivery for the slope length.

2.2.1.2 Model Output and Summary

RUSLE2 provides multiple model outputs that can be used for gauging performance and for planning different management scenarios. One output value is the average soil loss for the user-specified timeframe. Soil loss values can be compared for different management scenarios and different timeframes to determine if the construction project's EPSC measures or construction timing can help reduce estimated soil losses. RUSLE2 also outputs a critical slope length that indicates the maximum slope length before a contouring management practice (such as silt fence) begins to fail. If the actual slope length is greater than the critical slope length, the slope may be more vulnerable to failures of EPSC measures. Cover management systems that increase slope roughness or ground cover can increase the critical slope length. Other measures, such as grass strips or terraces, may also increase the critical slope length. It is desirable for the actual slope length to be less than the critical slope length for erosion control applications. Model users should carefully review RUSLE2 model input and output information to check that the results are reasonable and consistent with accepted values from the user's manual.

2.2.1.3 Applicability

The RUSLE2 model can be used for planning, implementing, and designing EPSC measures as well as for construction planning and sequencing. Scenarios where RUSLE2 are particularly useful are listed below:

- Calculating a baseline estimated soil loss for comparison with other scenarios;
- Comparing slope erosion rates at various stages of construction;
- Ranking EPSC measures erosion control performance;
- Calculating estimated sediment yields for phased and timed projects to minimize soil exposure during rainfall events;
- Diverting runoff away from potential high erosion areas;

- Reducing overland flow path length where EPSC measures do not provide desired functionality;
- Displaying positive effects of stabilizing disturbed areas with vegetation, ground cover, biomass, etc.;
- Selecting local vegetation types for long term erosion control;
- Adding flat segments at the end of overland flow paths to promote sediment deposition; and
- Implementing sediment trapping devices.

RUSLE2 output may be used to evaluate the relative effectiveness of different EPSC measures; however, RUSLE2 does NOT apply in the following scenarios:

- Concentrated flow areas (e.g., gullies, ditches, streams);
- Undisturbed forestland;
- Erosion by piping;
- Erosion caused by snowmelt;
- Erosion by mechanical processes (mass movement such as landslides, movement by tillage operations);
- Organic soils;
- Slope lengths longer than 1000 feet;
- Slopes steepness greater than 100%;
- Sediment basins beyond small, simple designs; or
- Diversion engineering designs.

2.2.2 Other Models

As previously mentioned, RUSLE2 is suggested when determining annual site-specific sediment storage volume. Site specific sediment loadings are required when the contributing drainage area to an outfall is greater than 25 acres. While various methodologies may be applicable, only one alternative (the sediment yield ratio) is outlined below. However, another model, the Modified Universal Soil Loss Equation (MUSLE), is mentioned and supplemented with a reference (Williams, 1975). MUSLE is an adjustment from USLE by incorporating runoff factors, making it applicable to individual rainfall events, rather than giving annual or long-term averages.

When intrinsic soil properties of the area to be disturbed are known (from local studies and tests), a simple sediment yield ratio relating the disturbed area with sediment yield can be implemented. In this instance, the bulk density of the sediment must be considered to obtain a sediment yield in tons. When local studies have not been conducted, a general rule is that one inch of disturbed/exposed soil will erode over a given acre per year, yielding 3,618 cubic feet of soil loss per acre of disturbed area per year. Therefore, when using this ratio for temporary sediment basin calculations, the sediment storage should be sized to hold the sediment yield of 3,618 cubic feet per acre of disturbed area. In addition, the basin and outlet structure must be sized to detain the runoff from the entire drainage area and treat the design storm that is required in the CGP (the 2yr, 24hr or 5yr, 24 hr storm event). Use of the sediment yield ratio is limited to when there is sufficient knowledge on the soils, drainage basin, and climate. This generalized rule should not be used for areas that are over 25 acres; instead, a site-specific design must be completed for the sediment storage required for sediment control measures (such as temporary sediment basins).

2.2.3 Design Concepts for Structural Sediment Controls

To limit the discharge of sediment from construction site developments, erosion prevention practices and sediment control practices are implemented. The design of sediment control practices relies on the predicted volume (or weight) of eroded soils (i.e., the resultant calculation from RUSLE2, MUSLE, sediment yield ratio, etc.), among other factors. These practices are designed to trap, and store suspended sediment carried by surface water from a construction site until maintenance operations remove the trapped sediment. A common sediment control practice utilized in Tennessee is a temporary sediment basin. These basins are required when the total drainage area to an outfall is greater than or equal to 10 acres or, if discharging runoff to a surface body of water with unavailable parameters for siltation or is listed as an Exceptional Tennessee Water, when the drainage area is greater than or equal to 5 acres. To view the status of receiving waters for a designation of unavailable parameters for siltation in Tennessee, consult the Construction General Permit Map viewer at https://tdeconline.tn.gov/dwrcgp/. To view the current list of Exceptional Tennessee Waters, consult TDEC's data viewer at https://dataviewers.tdec.tn.gov/dataviewers/f?p=2005:34304:9725246335398:. Other sediment control practices [e.g., sediment trap, silt fence, check dams, etc. (Section 4.4)] can be implemented in series, combination, or alone to provide sediment trapping and stormwater treatment. These alternates may be necessary when site conditions make temporary sediment basins infeasible (Section 5 and 6).

For temporary sediment basins, the efficiency and effectiveness of trapping and storing sediment not only depends on the geometry and size of the practice but also the design components (sediment and water storage, forebay, principal spillway, outlet pipe and protection, emergency spillway, and dam embankment) and soil characteristics. The design procedures and functions of these components are specified in Section 4.4.7.

The geometry can impact the treatment efficiency especially when it comes to stormwater's flow path in a temporary sediment basin. Longer flow paths from the inlet to outlet allow more time for finer sediments to settle out of the stormwater before exiting the sediment basin. Generally, settling velocity estimates are 3.28×10^{-3} to 3.28×10^{-1} feet per second for sands, 3.28×10^{-5} to 3.28×10^{-3} feet per second for silts, and less than 3.28×10^{-5} feet per second for clays. However, these ranges can vary based on factors such as water turbulence, particle size and density, and temperature (Winterwerp & Kranenburg, 2002). Depending on the particle size to be removed in a sediment basin, the required retention time of that particle varies drastically (Table 1), thereby influencing the flow path length.

Table 1: Example settling times for sand, silt, and clay are shown for comparison.

Particle Type	Approximate Particle Size (µm)	Settling Velocity (ft/s)	Depth of Basin (ft)	Settling Time (s)	Settling Time (min)	Settling Time (hr)
Sand	202	3.28E-02	4	122	2	0.03
Silt	20	3.28E-04	4	12192	203	3
Clay	6	3.28E-05	4	121920	2032	34
Clay	2	3.28E-06	4	1219200	20320	339

The table above is only shown as an example to compare the settling time for different soil types. In no way does this table show the required settling time to meet regulatory requirements for a sediment basin design. The comparison shows that the finer particles can take upwards of 10,000 times longer to settle than coarse particles.

Effective EPSC measure design and sizing depend on accurate analyses of runoff volume, peak flow rates, and sediment yield, informed by established hydrologic methodologies and supported by computational tools for efficient and precise scenario evaluation. Ultimately, the responsibility for ensuring a compliant and effective design rests with the design engineer.

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