APPENDIX A: STORMWATER HYDROLOGY

In low impact development (LID), the objective of stormwater control measures (SCMs) is to mimic or replicate the hydrologic function of a natural system. This approach includes the integration of local site conditions, climate, and community with stormwater management to improve resources and quality of life.

By designing SCMs that closely resemble the runoff characteristics of the "undeveloped" site, the storage, infiltration, and pollutant treatment of a drainage area can be maximized. This is accomplished through the following means, where practical:

- minimizing peak flow runoff and volumes,
- removing pollutants,
- promoting infiltration in proper soil conditions,
- disconnecting otherwise connected impervious surfaces that drain directly to infrastructure.

"Where practical" is very important because as discussed in Chapter 2 on Site Selection, the goals and site constraints of a particular location may prevent or be impractical for the construction of some SCMs.

In addition to examining site goals and constraints, stormwater calculations are required in the design of SCMs. These calculations assist a designer in analyzing the effects of proposed stormwater management on hydrology, particularly peak flows and volumes prior to construction. Traditional stormwater management has always considered water quantity and the solution has been to pipe stormwater directly to the stream. LID and current stormwater management strategies have evolved to include not only water quantity treatment and retention to prevent flooding, but also pollutant treatment and water quality improvements. This chapter focuses on the fundamentals of computing stormwater runoff rates and volumes from rainfall using a variety of mathematical methods and models.

This guidance document includes provisions to control and treat a certain volume of stormwater runoff. Some practices/measures also target the control of peak stormwater discharge rates. Additional calculations are necessary to determine proper treatment capacity. It is up to the designer to determine if the calculations support design requirements.

The methodology for stormwater calculations found in this guidance document and allowable methods are found in Table A.1

Designers may adopt different calculation methods, however, the calculation method must meet or exceed the methodology outlined in this guidance document. The act of converting rainfall to runoff is complex and variable; however, by using the equations in this chapter, along with their assumptions and empirical data, an estimated or predicted runoff can be determined. Various methods are used because some of the equations are suitable for large volumes, while others work better for smaller storm events. Furthermore, some methods can be used to determine peak runoff rates, whereas others can determine both volume and peak runoff.

The equations used to calculate these values are presented in the Design section for each SCM presented in this handbook (Chapters 4.1 - 4.8); however, in some cases a model or automated program could also be used. Design guidance and examples are provided in thishandbook and due to rounding, your answers may vary.

Table A.1
Methodology for Stormwater Calculations

Calculation	Method
Peak Flow	Rational Method
Runoff Volume	Simple Method Discrete Curve Number Method
Channel Geometry	Manning's Equation
Hydraulic Performance of Standard Outlet Devices	Weir Equation
Storage Volume	Orifice Equation Stage-Storage Tables
Pollutant Removal	Pollutant Removal Efficiencies

The equations and methodologies presented in this chapter are unique because they require limited rainfall and drainage area data. More sophisticated methods and models have broader data requirements that may not be as available for widespread use. Often, a more data-intense model will produce a more comprehensive and accurate estimation.

Stormwater hydrology, or the science of stormwater and its interaction with the earth, is often depicted through the image of the hydrologic cycle. Stormwater, or runoff, is the by-product of the interaction of precipitation with the land cover or surface in which it comes into contact. Stormwater runoff is one of many pathways that water may take during the hydrologic cycle. Other pathways include precipitation, evaporation, transpiration from plants, and infiltration into the soil. However, due to the relationship between all of these processes, when stormwater runoff increases, other processes tend to decrease causing the cycle to be imbalanced. Rain or precipitation is considered the input of the hydrologic cycle and runoff or other processes are viewed as outputs. The equations used to calculate runoff are considered in a similar manner. The methods used to calculate runoff presented in this guidance document attempt to mathematically simulate processes observed in the hydrologic cycle. These methods treat rainfall as an input and calculate or convert rainfall into runoff volume and/or rate of runoff.

The magnitude, intensity, and frequency of rainfall are all important factors when characterizing the input or design of SCMs. When observing stormwater hydrology or predicting rainfall characteristics for design, the total rainfall that occurs over a particular duration and the likelihood of the reoccurrence of the same storm events is very important. The likelihood of its reoccurrence is called the Recurrence Interval. For instance, a rainfall event that occurs, on average, once every ten years would have an average Recurrence Interval of 10-years and is considered a 10-year storm. A storm's Recurrence Interval can be used to determine the annual probability or the probability of having a given storm event on any given year.

Traditionally, the total amount of rainfall, or runoff volume, for a given storm event has been the primary value of concern. However, a storm event's distribution or intensity variation over a span of time is also of interest, including the peak rate or peak runoff. A storm event's duration can vary dramatically and the peak runoff is dependent on both storm intensity and the surface that runoff encounters.

The equations presented in this chapter compute runoff and address this variability. Methods such as the Rational Method and Natural Resources Conservation Service (NRCS) Soil Conservation Service (SCS) Discrete Curve Number Method depend on a hypothetical rain event, or the design storm for the rainfall input. The design storm event is based on a compilation of local, regional, and statewide data recorded over an extended period of time. Using the design storm, a designer assumes existing waterway conditions and average antecedent moisture conditions. Depending on the existing conditions, these average conditions may case computations to differ from observed current wetter or drier conditions. Hydrologic conditions of the soils in the drainage area as well as the land cover over those soils can also significantly affect both runoff volume and peak runoff. Runoff calculations are impacted by pervious and impervious surfaces, whether those surfaces are connected or disconnected, and the time of concentration or the measure of how quickly or slowly a drainage area responds to rainfall.

The stormwater water quality design storm for Alabama is the rainfall event used to design structural and non-structural SCMs. The water quality design storm has a rainfall depth ranging from 1" - 1.5" depending on geographic location (e.g., coastal locations are 1.5"). See Runoff Volume below for more information. The design storm can be used to design SCMs based on the Rational, Simple, and Discrete Curve Number Methods. The appropriate SCM selection will depend on SCM type and required design data.

Modeling Various Site Conditions

Any given drainage area can have a variety of site conditions that affect the analysis and design of SCMs. This guidance, where applicable, is intended for all of the methodologies discussed above for the computation of runoff volumes and peak runoff. For all sites, a pre-developed land cover at a development site must be assumed to be forested and in good hydrologic condition, unless it can be verified that a different land cover has existed for a minimum of five years prior to the analysis.

Sites will typically have a mixture of pervious and impervious surfaces. Impervious surfaces are defined as any surface that will not allow water to penetrate the surface or infiltrate. Examples of these surfaces include but are not limited to roads, roofs, driveways, and parking lots. Impervious surfaces can be considered connected or disconnected. A connected impervious surface is a surface whose runoff drains directly to a pipe, stormwater conveyance network, or other impervious surface. These types of surfaces do not allow for infiltration or treatment of stormwater. Impervious surfaces, particularly directly connected surfaces, should be modeled and runoff calculated using linear methods such as the Rational Method or the Simple Method. When using the Discrete Curve Number Method to calculate runoff, the impervious and pervious surfaces should be treated separately, calculating runoff from each surface using a weighted average curve number (CN). This is particularly important when calculating runoff for a small rainfall event, with rainfall less than 2”, as with using the design storm. It is recommended that runoff volumes be computed using a combined weighted average as a result of separately calculating runoff from the pervious and directly connected impervious portions of the drainage area. For larger storm events and larger rainfall depths, the designer can use his or her discretion in which technique to use.

Peak Flow

When designing practices such as swales, grassed filter strips, and riparian buffers, the calculated flow rate is needed to complete the design. In some states, peak runoff attenuation is required.

The Rational Method is the primary equation used to calculate peak flow.

This method uses an empirical linear equation to compute the peak runoff rate using a period of uniform rainfall intensity. The Rational Method uses a composite runoff coefficient, C, which is correlated with runoff potential and is unitless. A value of 0 is assigned to a surface with no runoff and a value of 0.95 - 1.0 is assigned to completely impervious surfaces. Typically a range of runoff coefficients is provided for a given land use. The designers must use his or her judgment to select an appropriate runoff coefficient value. Generally, larger areas with flat slopes, permeable soils, and dense vegetation are assigned a runoff coefficient from the low end of the range and the opposite is true for small, steep, and impervious areas. On the following page, Table A.2 shows examples if Rational Method runoff coefficients.

The precipitation intensity, i, can be determined using the National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum NWS HYDRO -35 “Five – to 60 – minute precipitation frequency for the eastern and central United States”, published in 1977. The maps found in this document can be used to determine precipitation intensity.

NOAA is in the process of using data stations across the state of Alabama to update precipitation intensity data. Rainfall frequency and intensity data from NOAA is currently found at http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=al. Precipitation intensity can be determined for a given annual return interval or specific storm duration. The technical memorandum has a series of graphs that can be used to determine rainfall intensity and equations for the partial duration series for selected return periods. Additionally, Technical Paper #40, “Rainfall

EQN A.1

$$Q = CiA$$

C = Composite runoff coefficient (unitless)
i = Rainfall intensity (in/hr)
A = Area (ac)
Q = Estimated Disign discharge or flow (cfs)

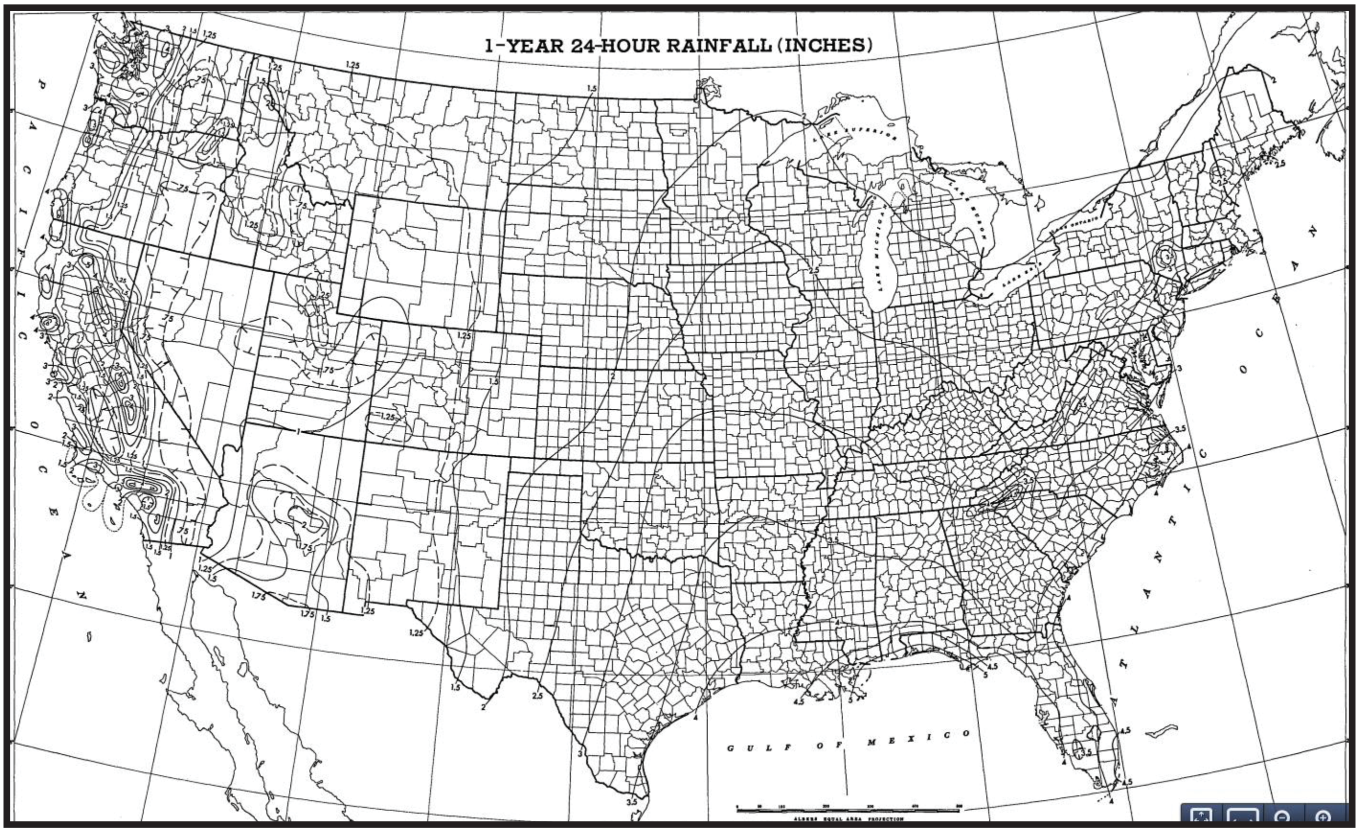

Figure 1. The 1-year 24-hour rainfall frequency graph, an example of graphs found in Technical Paper #40, “Rainfall Frequency Atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years”

Table A.2
Values of Runoff Coefficient (C) for Rational Formula*

Land Use	C	Land Use	C
Business:		***Lawns:***	
Downtown areas	0.70 - 0.95	Sandy soil, flat, 2%	0.05 - 0.10
Neighborhood areas	0.50 - 0.70	Sandy soil, avg., 2-7%	0.10 - 0.15
		Sandy soil, steep, 7%	0.15 - 0.20
		Heavy soil, flat, 2%	0.13 - 0.17
		Heavy soil, avg., 2-7%	0.18 - 0.22
		Heavy soil, steep, 7%	0.25 - 0.35
Residential:		***Agricultural land:***	
Single-family areas	0.30 - 0.50	*Bare packed soil*	
Multi units, detached	0.40 - 0.60	-Smooth	0.30 - 0.60
Munti units, attached	0.60 - 0.75	-Rough	0.20 - 0.50
Suburban	0.25 - 0.40	*Cultivated rows*	
		-Heavy soil, no crop	0.30 - 0.60
		-Heavy soil, with crop	0.20 - 0.50
		-Sandy soil, no crop	0.20 - 0.40
		-Sandy soil, with crop	0.10 - 0.25
		Pasture	
		-Heavy soil	0.15 - 0.45
		-Sandy soil	0.05 - 0.25
		Woodlands	0.05 - 0.25
Industrial:		*Streets:*	
Light areas	0.50 - 0.80	Asphaltic	0.70 - 0.95
Heavy areas	0.60 - 0.90	Concrete	0.80 - 0.95
		Brick	0.70 - 0.85
Parks, cemeteries	0.10 - 0.25	Unimproved areas	0.10 - 0.30
Playgrounds	0.20 - 0.35	Drives and walks	0.75 - 0.85
Railroad yard areas	0.20 - 0.40	Roofs	0.75 - 0.95

Frequency Atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years" published for the Engineering division of the Soil Conservation Service of the U.S. Department of Agriculture and the Department of Commerce can be used to determine precipitation intensity for smaller duration storm events (see Figure 1).

The Rational Method is most effective for drainage areas less than 20 acres in size and should be limited to drainage areas that are fairly uniform in land cover/land use and topography.

Runoff Volume

The majority of SCMs described in this guidance document are designed as volume control structures. The National Pollutant Discharge Elimination System (NPDES) Permit, General Permit (ALR100000) for Alabama states that "The permittee is encouraged to design the site, the erosion prevention measures, sediment controls measures, and other site management practices with consideration of minimizing stormwater runoff, both during and following construction, including facilitating the use of low-impact development (LID) and green technologies," and in order to comply, some volume control is necessary.

In Alabama, the current recommendation is to capture, retain, and infiltrate the "first flush" (first 1 - 1.5" of stormwater) volume within 2 - 4 days. The "first flush" is the initial surface runoff of a rainstorm. This volume of runoff has higher concentrations of pollutants in comparison with runoff later in the storm. By capturing this volume and treating it - we can account for 80% of the pollution. There is variation in the volume of water and rainfall depth that represents the first flush. This capture depth ranges from 1-1.5" across the state of Alabama, with the Coastal Plain experiencing a high first flush runoff depth (1.5"). When designing for the first flush, the SCM will be sized to appropriately capture, store, treat, or infiltrate this volume of stormwater. Due to the range of first flush depths across Alabama this guidebook uses varying first flush amounts corresponding with site location in the design examples presented. A 1.5” depth is most conservative and will size SCMs to ensure pollutant capture. Designers should check with the municipality they are working in to confirm an appropriate first flush depth. To achieve proper design for the capture, retention, and infiltration of this volume, two methods, the Simple Method and the Discrete Curve Number Method, are used to determine the runoff volume for a specific design storm. Runoff volume calculations are intended for site application and the scale of a single site.

The Simple Method was developed in the late 1980’s and as the name implies, uses minimal site information. Schueler, et. al. developed the equation by collecting/measuring runoff data and plotting the relationship between percent imperviousness and runoff.

The Simple Method uses two equations to calculate runoff volume:

EQN A.2

$$R_V = 0.05 + 0.9 * I_A$$

R_V = Runoff coefficient, unitless
I_A = Impervious fraction, unitless

Upon determination of the runoff coefficient, the runoff volume can be calculated.

EQN A.3

$$V = 3630 * R_D * R_V * A$$

V = Volume of runoff that must be controlled for the design storm (ft^3)
R_D = Design storm rainfall depth (in) Typically 1 - 1.5”
A = Area (ac)

EQN A.3

$$S = \left(\frac{1000}{CN}\right) - 10$$

EQN A.4

$$Q = \frac{\left[P - (0.2S)\right]^2}{P + 0.8S}$$

The Discrete Curve Number Method, developed by NRCS, is an excellent fit for designing LID practices. The Discrete Curve Number Method, like the Simple Method, uses two equations to calculate runoff. The curve number, CN, is descriptive of the drainage area land use and the characteristics effecting stormwater runoff. The CN Discrete Curve Number Method uses a hypothetical design storm and an empirical nonlinear runoff equation to compute runoff volumes into runoff hydrographs and is the most widely used method for computing runoff.

Hydrologic soil group (HSG) classifications are crucial in the determination of curve number values. The four hydrologic soil groups are summarized in the Table A.3. Descriptions of saturated hydraulic conductivity for HSGs can be found

Table A.3
Four Hydrologic Soil Groups

	Properties
HSG A	Low runoff potential when thoroughly wet, less than 10 percent clay and more than 90 percent sand or gravel, and have sandy texture
HSG B	Moderately low runoff potential when thoroughly wet, between 10 percent and 20 percent clay and 50 percent to 90 percent sand, and have loamy sand or sandy loam texture
HSG C	Moderately high runoff potential when thoroughly wet, between 20 percent and 40 percent clay and less than 50 percent sand; and have loam, silt loam, sandy clay loam, clay loam, and silty clay loam textures.
HSG D	High runoff potential when thoroughly wet, greater than 40 percent clay and less than 50 percent sand, and have clayey textures.

USDA and NRCS, 2007

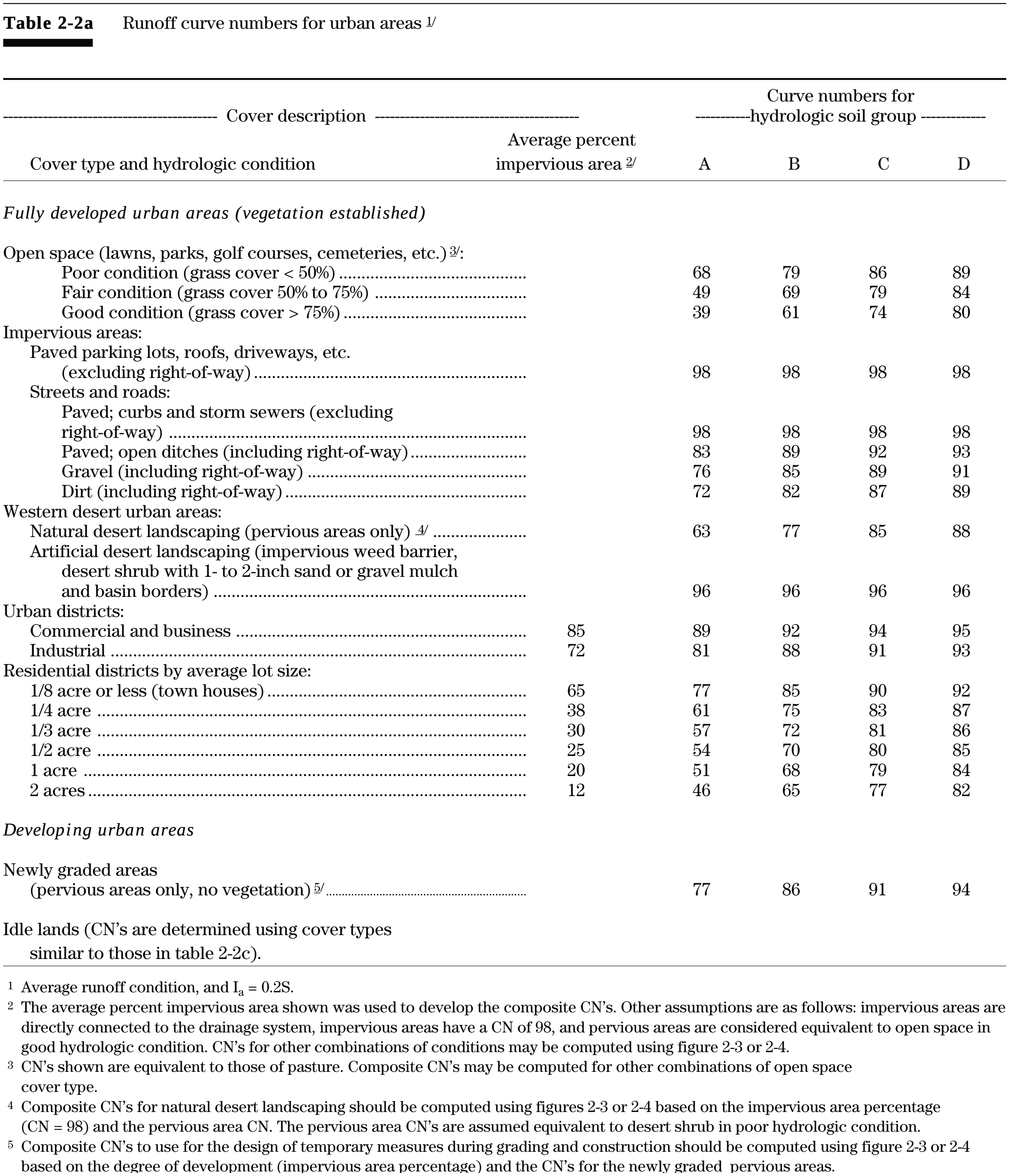

Table 2-2a Runoff curve numbers for urban areas [1]

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) [5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

[1] Average runoff condition, and I_a = 0.2S.

[2] The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.

[3] CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.

[4] Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.

[5] Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

Table A.4 Soil Conservation Service Discrete Curve Numbers, Table 2-2a in Technical Release (TR-55), "Urban Hydrology for Small Watersheds"

in Chapter 7 of the USDA and NRCS National Engineering Handbook.

Another characteristic effecting CN is land use, or more specifically, land cover. Impervious surfaces have high runoff potential because unlike vegetated open space, they have no means of infiltration. Higher runoff potential correlates to a higher CN. Geographic Information Systems (GIS) can aid in determining land cover, as well as site assessments, aerial photography, and land use.

A site will usually have more than one land use. The SCS Curve Number Method is applied to each land use separately and summed to determine total stormwater runoff. In some cases, such as the constructed stormwater wetland design example (see Chapter 4.2 on Constructed Stormwater Wetlands), an area-weighted composite curve number (CCN) can be used. This is called the Composite Curve Number Method and it should only be used for sites that do not have directly connected impervious surfaces and runoff. Runoff that is not directly connected simply means the runoff is “disconnected” by passing over a pervious surface, such as a lawn, and allowed to infiltrate.

Channel Geometry

Manning’s Equation is applicable in determining channel geometry. To justify the use of Manning’s steady-state flow, gravitational influences must be assumed. Channel geometry is important for the stability of design, with particular regard to erosion and sediment control. Manning’s Equation is used to calculate channel geometry in the case of a grassed swale or level spreader channel and is often an iterative process that assumes channel dimensions to calculate the variables of area, wetted perimeter, and hydraulic radius.

Manning’s Equation is:

EQN A.5

$$Q = \frac{1.489}{n} * A * R^{0.667} * S^{0.5}$$

Q = Peak Discharge or flow (cfs)
n = Manning’s roughness coefficient (dimensionless)
A = Cross-sectional area (sq.ft.), typically triangular or trapezoidal
R = Hydaulic radius (ft)
S = Longitudinal slope, (ft/ft)

The hydraulic radius can be determined using:

EQN A.6

$$R = \frac{A}{P}$$

R = Hydaulic radius (ft)
A = Cross-sectional area (sq.ft.)
P = Wetted perimeter (ft)

For detailed equations on the calculation of trapezoidal and triangular channel geometry, please refer to Chapter 4.4 on Grassed Swales, Infiltration Swales, and Wet Swales.

Manning’s n, is a roughness coefficient assigned to a particular material used to line the design channel, such as grass – n=0.035.

Hydraulic Performance of Standard Outlet Devices

The SCM designs presented in this guidance document are intended to target and treat smaller storm events. These systems require an outlet device or overflow to bypass larger storm events in order to maintain functionality and to meet safety guidelines. These outlet/overflow components must be considered and properly analyzed to determine how overflow from larger events will exit the system. These devices are usually weirs or orifices. Weirs are used to control exit elevations or to divert flow, whereas orifices are typically used to drawdown a SCM detaining stormwater for treatment.

Weir

The broad-crested weir application is most common for practices specified in this handbook. The Weir Equation is:

EQN A.7

$$Q = C_W * L * H^{1.5}$$

Q = Discharge or flow (cfs)
C_w = Coefficient of discharge (dimensionless), 3.0 for broad crested weirs
L= Length of weir (ft)
H = Driving head (ft)

Orifice

For most applications within this guidance document, an orifice is used to control the release of a designed volume of stormwater over an increased time interval. The primary equation is:

EQN A.8

$$Q = C_D * A * \sqrt{2 * g * H_O}$$

Q = Discharge or flow (cfs)
C_D = Coefficient of discharge (dimensionless), default value is 0.60
A = Cross-sectional area of flow at the orifice (sq ft)
g = Acceleration of Gravity (32.2 ft/s^2)
H_O= Driving head (ft) - measured at the centroid of the orifice to the water surface

Storage Volume

Many of the SCMs outlined in this guidance document do not have the capability to provide volume control. SCMs such as bioretention design include a storage volume allowing for some volume control, but the primary function of the SCM is water quality treatment, not water quantity. Each SCM chapter includes the specific calculations for meeting volume control; however, certain SCMs such as constructed stormwater wetlands, involve stormwater detention. These SCMs are designed to provide volume control for the design storm in temporary storage. For SCMs that involve the detention of stormwater, a stage-storage-discharge model is used to determine this relationship for proper design. Examples of models that may be used include but are not limited to HEC-HMS, WinTR-55, SWIMM, and HydroCAD.

Pollutant Removal

Within each SCM chapter there is a discussion of pollutant removal and a table of specified values for each specific SCM according to other jurisdiction. Alabama currently does not assign a specific removal rate of pollutants for each SCM; however, estimated pollutant removal for a designed practice can be assumed using the values found in the Pollutant Removal Table for each practice. In some instances, a municipal entity or a total maximum daily load (TMDL) may require a designer to use a practice that meets a specific pollutant removal standard, such as 85% removal of total suspended solids (TSS). To calculate nutrient removal, an approved removal efficiency can be multiplied by the pollutant loading in the influent to determine the pollutant loading in the effluent (typically in lb/ac/yr).

Pollutant removal can be calculated for each SCM. A given site may include multiple drainage areas and multiple SCMs; however, the overall site must meet the regulatory requirements set forth in the NPDES permit for quantity and quality. If multiple SCMs are used for the same drainage area, they may be weighted to meet the removal requirement of the overall site. For SCMs that do not provide direct input into another SCM, the SCMs can be considered in "parallel" and a flow-weighted removal proportional to the individual removal rate and the fraction of total flow passing through each SCM can be calculated to determine the site's pollutant removal efficiency. Volumes treated for SCMs in parallel are summed for a total volume treated for the site. For SCMs that are placed in a "treatment train" or in series and capture the same drainage area, volume control can be combined, as well as removal efficiency. However, the removal efficiencies are not additive.

The following equation can be used to calculate combined removal efficiency for a given site utilizing a "treatment train":

EQN A.9

$$Q = SCM_1 + SCM_2 - \left[\frac{(SCM_1 * SCM_2)}{100} \right]$$

E = Total pollutant removal efficiency (%)
SCM_1 = Efficiency of first SCM
SCM_2 = Efficiency of second SCM

In cases where the "treatment train" includes more than two SCMs, the equations can be applied iteratively.

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