3.0 Hydrology

3.1 Symbols and Definitions

To provide consistency within this chapter as well as throughout this Manual, the symbols listed in Table 3-1 will be used. These symbols were selected because of their wide use in technical publications. In some cases, the same symbol is used in existing publications for more than one definition. Where this occurs in this section, the symbol will be defined where it occurs in the text or equation.

Table 3-1 Symbols and Definition

Symbol	Definition	Units
A	Drainage area, cross sectional area	acres, ft^2
B_f	Baseflow	ac-ft
CN	NRCS Curve Number	-
CN_m	Modified NRCS Curve Number	-
CP_v	Channel protection volume	ac-ft
E	Evaporation	ft
E_t	Evapotranspiration	ft
G_h	Hydraulic gradient – pressure head/distance	-
I	Percent of impervious cover	%
I	Inflow	ac-ft
I	Infiltration	ac-ft/day
I_a	Initial abstraction	in
K_h	Saturated hydraulic conductivity	ft/day
P	Rainfall	inches
Q, q	Peak inflow or outflow rate, runoff	cfs, in
Q_f	Overflow	ft
Q_p	Peak rate of discharge	cfs
R_v	Volumetric runoff coefficient	-
R_o	Runoff	ac-ft
S	Potential maximum retention	in
t_c	Time of concentration	hours
V	Pond volume	ac-ft
V_r	Runoff volume	ac-ft
WQ_p	Water quality peak discharge	cfs
WQ_v	Water quality protection volume	ac-ft, in

3.2 Runoff Volume and Peak Flow

3.2.1 Introduction

The following is a discussion of the hydrologic methods needed to calculate the water quality protection volume (WQ_v), channel protection volume (CP_v), and flood event peak flows (Q_2), (Q_{10}), (Q_{25}), (Q_{50}), etc. For more details on hydrologic analysis see Hydrology Chapter, in the Charlotte-Mecklenburg Storm Water Design Manual.

SCMs should be designed to treat and/or control the runoff from the 1-inch storm event (WQ_v) for water quality, and the 1-year, 24-hour (CP_v) for volume control, and 10-year, 6-hour storm event for flood control. More storm events may also be required to be analyzed. Table 3-2 summarizes the design storm events for various types of storm drainage systems.

Table 3-2: Summary of Design Standards

Design feature	Design storm
SCMs for water quality	1-inch, 6-hour
SCMs for channel protection	1-year, 24-hour
SCMs for flood protection for low density development (with over 20,000 SF BUA proposed)	2- and 10- year, 6 hour
SCMs for flood protection	10- and 25-year, 6-hour
Closed pipe and channels	10-year, 6-hour
Culverts (subdivision streets)	25-year, 6-hour
Culverts (thoroughfare roads)	50-year, 6-hour
Building footprints	100-year, 6-hour or 100-year, 24-hour on FEMA regulated streams

Conventional NRCS methods have been found to underestimate the volume and rate of runoff for rainfall events less than 2 inches. This discrepancy in estimating runoff and discharge rates can lead to several potential design challenges including undersizing of SCMs, inadequately sized diversion structures, and undersized outlet pipes, channels, etc. Therefore, a modified NRCSNRCS procedure is required for development for the 1-inch, 6-hour storm event hydrograph.

For accurate runoff volume computational results, the 1-inch storm event runoff volume should be computed using methods developed by Schueler, and the 1-year and larger storm event runoff volumes should be computed using methods developed by NRCSNRCS. The Schueler methods that are published can be used only to compute total runoff volume and cannot be used to develop a hydrograph including a peak flow. In order to overcome the differences of runoff volume results provided by the two methods, a method is presented to adjust the site curve number so that 1-inch storm event runoff volumes computed by NRCS methods match the runoff volumes that are computed by methods developed by Schueler.

3.2.2 Water Quality Protection Volume and Peak Flow Calculation

Water Quality Protection Volume Calculation

The Water Quality Protection Volume (WQ_v) is the runoff volume required to be treated when designing a SCM to meet specific pollutant removal targets. This is achieved by intercepting and treating the runoff from a 1-inch rainfall event. The Water Quality Protection Volume (WQ_v) is calculated by method developed by Schueler by multiplying 1.0 inches of rainfall by the volumetric runoff coefficient (R_v) and the drainage area. R_v is defined as:

$$\mathbf{R_v = 0.05 + 0.009(I)} \qquad (3.1)$$

Where: I = percent of impervious (BUA) cover of the drainage basin (%)

Using the 1.0 inches of rainfall, the WQ_v is calculated using the following formula:

$$\mathbf{WQ_v = 1.0R_vA/12} \qquad (3.2)$$

Where: WQ_v = water quality protection volume (acre-feet)
R_v = volumetric runoff coefficient
A = total drainage area (acres)

WQ_v can be expressed in inches (if the designer wants to compare the result to runoff hydrograph volumes): using the following formula.

$$WQ_v = 1.0(R_v) \qquad (3.3)$$

Where: WQ_v = water quality protection volume (inches)

Peak Flow and Runoff Hydrograph Calculation

The peak rate of discharge (Q_p) and/or runoff hydrograph shape for the Water Quality Protection Volume storm is needed for the sizing of most SCMs such as sand filters, bioretention, infiltration trenches, etc. In addition, the peak rate of discharge (Q_p) and/or runoff hydrograph shape is needed if the designer elects to treat only the Water Quality Runoff Volume (WQ_v) with one SCM such as bioretention and treat the larger storm events with another SCM such as an extended detention basin.

A balanced 6-hour storm event is chosen for use in Mecklenburg County. The method relies on the water quality protection volume and calculation of a modified Curve Number for use in the standard NRCSNRCS method. A description of the calculation procedure is presented below.

Step 1 Using the WQ_v, a modified Curve Number (CN) is computed utilizing the following equation:

$$CN_m = 1000/[10 + 5P + 10WQ_v - 10(WQ_v^2 + 1.25WQ_vP)^{0.5}] \qquad (3.4)$$

Where: P = rainfall, in inches (use 1.0 inches)
WQ_v = Water Quality Volume, in inches ($1.0R_v$)

Step 2 Once a value for CN_m is computed, the time of concentration (t_c) is computed using the standard procedures contained in Hydrology Chapter, in the Charlotte-Mecklenburg Storm Water Design Manual.

Step 3 Using the computed CN_m, t_c and drainage area (A), in acres, the peak discharge (Q_p) can be calculated using the methods outlined in Hydrology Chapter, in the Charlotte-Mecklenburg Storm Water Design Manual.

Table 3-3 1-inch, 6-hour, Balanced Storm Rainfall Distribution

PH records						
Interval	5 min	15 min	60 min	2 hour	3 hour	6 hour
Rainfall	0.188	0.371	0.640	0.769	0.855	1.0 inch

Table 3-4 1-inch, 6-hour, 5-Minutes Time Increment Precipitation Data

Time	Rain	**Time**	Rain	**Time**	Rain	**Time**	Rain	**Time**	Rain	**Time**	Rain
Min	Inch	**Min**	Inch	**Min**	Inch	**Min**	Inch	**Min**	Inch	**Min**	Inch
0	.000	**65**	.004	**130**	.009	**195**	.043	**260**	.007	**325**	.004
5	.003	**70**	.004	**135**	.010	**200**	.028	**265**	.007	**330**	.004
10	.003	**75**	.005	**140**	.011	**205**	.023	**270**	.006	**335**	.004
15	.003	**80**	.005	**145**	.012	**210**	.020	**275**	.005	**340**	.003
20	.003	**85**	.005	**150**	.013	**215**	.014	**280**	.005	**345**	.003
25	.003	**90**	.005	**155**	.019	**220**	.012	**285**	.005	**350**	.003
30	.003	**95**	.006	**160**	.022	**225**	.011	**290**	.005	**355**	.003
35	.004	**100**	.007	**165**	.025	**230**	.010	**295**	.005	**360**	.003
40	.004	**105**	.007	**170**	.039	**235**	.009	**300**	.004	**365**	.000
45	.004	**110**	.007	**175**	.050	**240**	.009	**305**	.004		
50	.004	**115**	.008	**180**	.108	**245**	.008	**310**	.004		
55	.004	**120**	.008	**185**	.188	**250**	.008	**315**	.004		

60	.004	**125**	.009	**190**	.075	**255**	.007	**320**	.004		

3.2.3 Channel Protection Volume and Peak Flow Calculation

The purpose of controlling the Channel Protection Volume (CP_v) is to protect the downstream channel system from the impacts of increased runoff volumes and peak rates due to development. The entire runoff volume from the 1-year, 24-hour storm event must be controlled (captured and released over a specified time duration through a primary outlet structure) to meet the requirements of controlling the Channel Protection Volume. In Cornelius, Davidson, Matthews, Mint Hill, Pineville and in areas of Mecklenburg County outside of any planning ETJ's, the detailed outlet hydrograph analysis must show that a minimum of 5 percent of the runoff volume is held within the storage volume at the design duration time (36 hours). In Charlotte and Huntersville, the detailed outlet hydrograph analysis must show that a minimum of 50 percent of the runoff volume is held within the storage volume at 24 hours after the center of the rainfall – 12 hours (total 36 hours) and must show that a portion of the runoff volume is held within the storage volume at the design duration time for those jurisdictions (60 hours).

For example, for the CP_v design, the 1-year, 24-hour storm event must be held for 24 hours (or 48 hours in Charlotte). Therefore, the design should compute the amount of runoff volume that is left within the storage volume at 24 hours after the center of the rainfall (total 36 hours) for all jurisdictions and at 48 hours after the center of the rainfall (total 60 hours) for Huntersville and Charlotte. The remaining volume at 36 hours must be at least 50% of the total runoff volume for Huntersville and Charlotte and at least 5% of the total runoff volume in other jurisdictions. The remaining volume at 60 hours must be at least a portion of the total runoff volume for Huntersville and Charlotte.

An NRCSNRCS Type II storm event distribution is required. The NRCS Type II storm event distribution is slightly different than the balanced storm event. Therefore, balanced storm event data cannot be used to generate the hydrograph for the 1-year, 24-hour storm event. Table 3-5 presents the 24-hour NRCS Type II distribution using a 6-minute time interval. Table 3-5 present only the storm event distribution and accumulate to a total rainfall of 1-inch. The user must include the basin-average total precipitation using the total 1-year, 24-hour rainfall, 2.58 inches. This approach results in the distribution of the total 2.58 inches of rainfall over a 24-hour period using the NRCS Type II shape.

The Channel Protection Volume (CP_v) can be computed using the standard NRCS methods described in the Hydrology Chapter of the Charlotte-Mecklenburg Storm Water Design Manual. The equation to compute runoff volume is:

$$\mathbf{Q = (P - 0.2S)^2 / (P + 0.8S)} \qquad \textbf{(3.5)}$$

Where:

Q = accumulated runoff volume, inches
P = accumulated rainfall (potential maximum runoff), inches
S = potential maximum soil retention, inches = 1000/CN – 10
CN = NRCS curve number

Note that the NRCS curve number that is used to generate runoff volumes for all storm events other than the 1-inch, 6-hour storm event is the standard curve number and not the modified curve number discussed in Section 3.2.2. The same method as described in Section 3.2.2. to compute the entire runoff hydrograph including the peak discharge should be applied.

Table 3-5 NRCS Type II Storm Event Distribution

Time	Rainfall	Time	Rainfall	Time	Rainfall	Time	Rainfall	Time	Rainfall	Time	Rainfall
Mins	%	**Mins**	%	**Mins**	%	**Mins**	%	**Mins**	%	**Mins**	%
0	0	**240**	0.0014	**480**	0.0022	**720**	0.0951	**960**	0.0023	**1200**	0.0013
6	0.001	**246**	0.0014	**486**	0.0022	**726**	0.019	**966**	0.0023	**1206**	0.0013
12	0.001	**252**	0.0014	**492**	0.0024	**732**	0.0166	**972**	0.0022	**1212**	0.0013
18	0.001	**258**	0.0015	**498**	0.0024	**738**	0.0144	**978**	0.0023	**1218**	0.0013
24	0.0011	**264**	0.0015	**504**	0.0026	**744**	0.0122	**984**	0.0022	**1224**	0.0013
30	0.001	**270**	0.0015	**510**	0.0026	**750**	0.0098	**990**	0.0022	**1230**	0.0012
36	0.0011	**276**	0.0015	**516**	0.0028	**756**	0.0084	**996**	0.0022	**1236**	0.0013
42	0.001	**282**	0.0015	**522**	0.0029	**762**	0.008	**1002**	0.0021	**1242**	0.0013
48	0.0011	**288**	0.0015	**528**	0.0029	**768**	0.0074	**1008**	0.0021	**1248**	0.0012
54	0.0011	**294**	0.0016	**534**	0.003	**774**	0.0068	**1014**	0.0021	**1254**	0.0013
60	0.0011	**300**	0.0016	**540**	0.0032	**780**	0.0064	**1020**	0.0021	**1260**	0.0012
66	0.0011	**306**	0.0016	**546**	0.0032	**786**	0.006	**1026**	0.002	**1266**	0.0013
72	0.0011	**312**	0.0016	**552**	0.0032	**792**	0.0056	**1032**	0.002	**1272**	0.0012
78	0.0011	**318**	0.0017	**558**	0.0032	**798**	0.0054	**1038**	0.002	**1278**	0.0013
84	0.0012	**324**	0.0017	**564**	0.0032	**804**	0.0052	**1044**	0.0019	**1284**	0.0012
90	0.0011	**330**	0.0016	**570**	0.0032	**810**	0.0048	**1050**	0.002	**1290**	0.0012
96	0.0012	**336**	0.0018	**576**	0.0033	**816**	0.0046	**1056**	0.0019	**1296**	0.0013
102	0.0011	**342**	0.0017	**582**	0.0034	**822**	0.0044	**1062**	0.0019	**1302**	0.0012
108	0.0012	**348**	0.0017	**588**	0.0036	**828**	0.0042	**1068**	0.0018	**1308**	0.0012
114	0.0012	**354**	0.0018	**594**	0.0038	**834**	0.004	**1074**	0.0018	**1314**	0.0012
120	0.0012	**360**	0.0018	**600**	0.0039	**840**	0.0038	**1080**	0.0018	**1320**	0.0012
126	0.0012	**366**	0.0018	**606**	0.0041	**846**	0.0037	**1086**	0.0018	**1326**	0.0012
132	0.0012	**372**	0.0018	**612**	0.0044	**852**	0.0036	**1092**	0.0017	**1332**	0.0012
138	0.0013	**378**	0.0019	**618**	0.0046	**858**	0.0035	**1098**	0.0018	**1338**	0.0012
144	0.0012	**384**	0.0019	**624**	0.0048	**864**	0.0034	**1104**	0.0017	**1344**	0.0012
150	0.0012	**390**	0.0018	**630**	0.0051	**870**	0.0034	**1110**	0.0017	**1350**	0.0011
156	0.0013	**396**	0.002	**636**	0.0054	**876**	0.0033	**1116**	0.0016	**1356**	0.0012
162	0.0012	**402**	0.0019	**642**	0.0058	**882**	0.0033	**1122**	0.0017	**1362**	0.0012
168	0.0013	**408**	0.0019	**648**	0.0062	**888**	0.0032	**1128**	0.0016	**1368**	0.0011
174	0.0013	**414**	0.002	**654**	0.0066	**894**	0.0031	**1134**	0.0016	**1374**	0.0012
180	0.0013	**420**	0.002	**660**	0.007	**900**	0.003	**1140**	0.0015	**1380**	0.0011
186	0.0013	**426**	0.002	**666**	0.0077	**906**	0.003	**1146**	0.0016	**1386**	0.0012
192	0.0013	**432**	0.002	**672**	0.0086	**912**	0.0029	**1152**	0.0015	**1392**	0.0011
198	0.0013	**438**	0.0021	**678**	0.0096	**918**	0.0028	**1158**	0.0015	**1398**	0.0012
204	0.0014	**444**	0.0021	**684**	0.0106	**924**	0.0027	**1164**	0.0015	**1404**	0.0011
210	0.0013	**450**	0.0021	**690**	0.0115	**930**	0.0027	**1170**	0.0014	**1410**	0.0011
216	0.0014	**456**	0.0021	**696**	0.0238	**936**	0.0026	**1176**	0.0014	**1416**	0.0012
222	0.0014	**462**	0.0021	**702**	0.0476	**942**	0.0026	**1182**	0.0014	**1422**	0.0011
228	0.0013	**468**	0.0021	**708**	0.0764	**948**	0.0025	**1188**	0.0013	**1428**	0.0011
234	0.0014	**474**	0.0022	**714**	0.1371	**954**	0.0024	**1194**	0.0014	**1434**	0.0011
										1440	0.0011

3.3 Storage Volume Computations

Design of SCMs to treat and control the Water Quality Volume (WQ_v) and the Channel Protection Volume (CP_v) require level pool routing methods as described in the Charlotte-Mecklenburg Storm Water Design Manual and this Manual. The design process is iterative where a preliminary storage volume and outlet system is assumed, the appropriate design hydrographs are routed through the system, output results are assessed, and refinements to the storage volume and outlet systems are made. This process is continued until all design storm events are properly treated or controlled within the SCM storage volume. The Static Method, described in the following section, can be used to estimate initial conditions so that the number of iterations is reduced.

Static Method

The Static Method assumes that all of the runoff volume enters the storage volume instantaneously and therefore, the storage volume is set equal to the runoff volume. The runoff volume exits the storage volume based solely on the outflow system hydraulics and the holding time duration for the selected design condition.

Example

Using the following information, calculate an initial estimate of the SCM storage volume and outlet system to hold the Channel Protection Volume for 24 hours beyond the center of rainfall (12 hours).

Area = 50 acres
CN = 72
t_c = 0.34 hours
t_{lag} = 0.20 hours
Total impervious area = 18 acres

The previous example computed the runoff volume to be 2.38 acre-feet. The storage volume is set equal to the runoff volume and units converted to determine the appropriate outlet flow rate.

$$Q_{outlet} = (2.38 \text{ acre-feet})(43{,}560 \text{ ft}^2/\text{acre})/(36 \text{ hours})(3{,}600 \text{ sec/hour})$$
$$= 0.80 \text{ cfs}$$

It is important to note that within Charlotte and its ETJ, the Channel Protection Volume must be held for 48 hours beyond the center of rainfall. In this example the value of 36 hours would be replaced with 60 hours for sites in the Charlotte area.

Based on the site conditions, the next step is for the designer to fit the 2.38 acre-feet of storage into the site topography. From the site topography, the total and average headwater depth on the outlet structure can be determined. For this example, we assume that the total storage volume depth is 5 feet. The average headwater depth is assumed to be ½ of the maximum depth, or 2.5 feet.

Size the outlet orifice by using the orifice equation to compute cross-sectional area and diameter of outlet.

$Q = CA(2gh)^{0.5}$, for Q = 0.80 cfs, h = 2.50 ft, and C = discharge coefficient = 0.6
Solve for A: $A = 0.80 \text{ cfs} / [0.6((2)(32.2 \text{ ft/s}^2)(2.50))^{0.5}] = 0.105 \text{ ft}^2$
With $A = \pi d^2/4$, d = 0.37 ft = 4.4 inches
Use 4.4 inch orifice plate.

Note that the static method provides an over-estimation of the storage volume needed to hold the runoff volume for the design duration. Detailed routing computations are required to complete the design during which the storage volumes, outlet sizes, etc. are altered during the routing computations. The detailed outlet hydrograph analysis must show that a minimum percentage of the runoff volume is held within the storage volume at the design duration time.

Outlet Works

Outlet works selected for storage facilities typically include a control structure and an emergency outlet and must be able to accomplish the design functions of the facility. Outlet works can take the form of any combination of drop inlets, pipes, weirs, and orifices. The control structure is intended to convey the design storm without allowing flow to enter an emergency outlet. Selecting a magnitude for sizing the emergency outlet should be consistent with the potential threat to downstream life and property if the basin embankment were to fail. The minimum storm to be used to size the emergency outlet is the 50-year storm. The sizing of a particular outlet works shall be based on results of hydrologic routing calculations. A freeboard of 12 inches above the 100-year peak stage to the top of embankment is required. Minimum barrels through embankments are 15 inch reinforced concrete pipes with corresponding orifice plates. Any orifice smaller than 4 inches in diameter must be protected to prevent blockage. If the spillway is in fill material, then the spillway must be lined to the toe of slope. See A-5 of the NCDEQ Stormwater Design Manual, the Charlotte-Mecklenburg table of exceptions for MDC A, and MDC for additional information.

Routing

Detailed routing computations are required for the design of all SCMs where storage volume and detention time are key design parameters. In many cases, the designer will perform the required routing computations using computer models. Computer based methods, such as HEC-1/HEC-HMS, are widely available to perform these iterations quickly. Other computer programs can provide similar results.

The previously described Static Method provides an estimate of the required storage volume to hold the design storm runoff volume for a specific holding duration. Routing computations will be iterative where a preliminary storage volume and outlet system is assumed, the routing computation is performed, and the output is checked to evaluate the success of the SCM meeting the holding duration.

3.4 Water Balance Calculations

3.4.1 Introduction

Water balance calculations are used to determine if a drainage area is large enough, or has the right characteristics, to support a SCM with a permanent pool of water during average conditions. Water balance calculations should be performed if there is concern that the drainage area and/or SCM location will not be able to maintain a permanent pool. The details of a rigorous water balance are beyond the scope of this manual; however, a simplified procedure is described in this section that will provide an estimate of pool viability and point to the need for more rigorous analysis.

The entire water year should be checked with water balance computations, but the summer season is typically the most critical because high outflows are experienced and are combined with the lowest inflows. Each month must be assessed during the analysis. Two starting conditions should be checked, the water year starting in July and the calendar year starting in January.

3.4.1 Basic Equations

Water balance is defined as the change in volume of the permanent pool resulting from the total inflow minus the total outflow (actual or potential).

$$\Delta V = \Sigma I - \Sigma O \quad (3.6)$$

Where: Δ = "change in"
V = pond volume (acre-feet)
Σ = "sum of"
I = inflows (acre-feet)
O = outflows (acre-feet)

The inflows consist of rainfall, runoff and baseflow into the pond or holding area. The outflows consist of infiltration, evaporation, evapotranspiration, and surface overflow out of the pond or wetland. Equation 3.6 can be changed to reflect these factors.

$$\Delta V = P + R_o + B_f - I - E - E_t - O_f \quad (3.7)$$

Where: P = precipitation (ac-ft)
R_o = runoff (ac-ft)
B_f = baseflow (ac-ft)
I = infiltration (ac-ft)
E = evaporation (ac-ft)
E_t = evapotranspiration (ac-ft)
O_f = overflow (ac-ft)

Rainfall (P)
Monthly values are commonly used for calculations of values over a season. Rainfall is the direct amount that falls on the pond surface for the period in question. When multiplied by the pond surface area (in acres) it becomes acre-feet of volume. Table 3-6 shows monthly rainfall values for the Mecklenburg County area.

Table 3-6 Average Monthly Rainfall Values for Mecklenburg County, North Carolina

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Precipitation (in)	3.72	3.84	4.44	2.64	3.84	3.36	3.96	3.72	3.48	3.36	3.24	3.48	43.08

Runoff (R_0)
Runoff is equivalent to the rainfall for the period multiplied by the "efficiency" of the watershed, which is equal to the ratio of runoff to rainfall. The following method can be used for SCM design in Mecklenburg County. Equation 3.1 gives a ratio of runoff to rainfall volume for a particular storm. If it can be assumed that the average storm that produces runoff has a similar ratio, then the R_v value can serve as the ratio of rainfall to runoff (R_v is defined in section 3.2).

Not all storms produce runoff in an urban setting. Typically initial losses (often called "initial abstractions") are normally estimated to be between 0.1 and 0.2 inches. When compared to the rainfall records in Mecklenburg County, this is equivalent to about a 10% runoff volume loss. Thus a factor of 0.9 should be applied to the calculated R_v value to account for storms that produce no runoff. Equation 3.8 reflects this approach. Total runoff volume (acre-feet) is the product of runoff depth ($0.9PR_v$) times the drainage area.

$$R_o = 0.9PR_vA/12 \quad (3.8)$$

Where: R_o = runoff volume (acre-feet)
P = precipitation (in)
R_v = volumetric runoff coefficient
A = total drainage area – pond area (acres)

Baseflow (B_f)
Most storm water ponds and wetlands have little, if any, baseflow, as they are rarely placed across perennial streams. If so placed, baseflow must be estimated from observation or through theoretical estimates. Review of the USGS Annual Data Report for North Carolina indicates that the watersheds in Mecklenburg County experience a baseflow in the range of 0.2 cfsm (cubic feet per second per square mile of contributing drainage area) for urbanized watersheds and 0.4 cfsm for rural watersheds. The urbanized value 0.2 cfsm should be used for water balance computations when baseflow is present.

Infiltration (I)
Infiltration is a very complex subject and cannot be covered in detail here. The amount of infiltration depends on soils, water table depth, rock layers, surface disturbance, the presence or absence of a liner in the pond, and other factors. The infiltration rate is governed by the Darcy equation as:

$$I = Ak_hG_h \quad (3.9)$$

Where: I = infiltration (ac-ft/day)
A = cross sectional area through which the water infiltrates (acres)
For the purposes of this analysis, use ponding area at the permanent pool
k_h = saturated hydraulic conductivity or infiltration rate (ft/day)
G_h = hydraulic gradient = pressure head/distance

G_h can be set equal to 1.0 for the typical SCM application in the Mecklenburg County area. Infiltration rates can be established through testing, though not always accurately.

The value of k_h should be based on site specific soil condition testing if available. If site specific soil condition testing is not available, the values shown in Table 3-7 can be used based on the NRCS soil type that is present on site. If the proposed site grading is such that significant cut and fill will occur and therefore displace the NRCS soil type, then the site soil type with the highest k_h value shall be selected for use in the water balance computation.

Table 3-7 Saturated Hydraulic Conductivity

NRCS Soil Type	Hydraulic Conductivity In/hr	Hydraulic Conductivity ft/day
Appling	1.3	2.6
Cecil	1.3	2.6
Davidson	1.3	2.6
Enon	0.1	0.2
Georgeville	1.3	2.6
Goldston	4.0	8.0
Helena	0.4	0.8
Iredell	0.1	0.2
Lignum	0.3	0.6
Mecklenburg	0.1	0.2
Monacan	1.3	2.6
Pacolet	1.3	2.6
Pits	0.1	0.2
Vance	0.1	0.2
Wilkes	0.4	0.8

Evaporation (E)
Evaporation is from an open lake water surface. Evaporation rates are dependent on differences in vapor pressure, which, in turn, depend on temperature, wind, atmospheric pressure, water purity, and shape and depth of the pond. It is estimated or measured in a number of ways, which can be found in most hydrology textbooks. Table 3-8 gives evaporation rates for a typical 12-month period based on information from a station in Union, SC. The values in Table 3-8 are converted to volume of evaporation by multiplying by the pond surface area and converting to acre-feet.

Table 3-8 Monthly Evaporation Rates (inches)

Mon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Lake	1.2	1.5	2.5	3.7	4.4	4.6	4.8	4.5	3.3	2.4	1.5	1.1	35.5

Evapotranspiration (E_t)
Evapotranspiration consists of the combination of evaporation and transpiration by plants. The estimate of E_t for crops is well documented and has become standard practice. However, for wetlands the estimating methods are not well documented, nor are there consistent studies to assist the designer in estimating the demand wetland plants would put on water volumes. Literature values for various places in the United States vary around the free water surface lake evaporation values. Estimating E_t only becomes important when wetlands are being designed and emergent vegetation covers a significant portion of the pond surface. In these cases conservative estimates of lake evaporation should be compared to crop-based E_t estimates. Crop-based E_t can be obtained from typical hydrology textbooks and from related web sites.

Overflow (O_f)
Overflow is considered as excess runoff and is defined by the volume of water temporarily held in the pond above the "permanent" pool elevation. In the simplified water balance calculations presented in this Manual, all water volume above the permanent pool volume is considered lost at the end of each month

(no more than the maximum permanent pool volume is carried forward to the next month).

Example
A 23 acre site in Mecklenburg County is being developed along with an estimated 0.5 acre surface wet pond. There is no baseflow. The desired pond volume to the overflow point is 2.0 acre-feet at a pond stage of 705.0 feet. The designer must show that the site be able to support the pond volume. From the basic site data it is determined that the site is 40% impervious and has Enon NRCS soil type throughout the entire site.

- From Equation 3.1, $R_v = 0.05 + 0.009(40) = 0.41$. With the correction factor of 0.9 the watershed efficiency is 0.37.
- The annual lake evaporation is 35.5 inches. (Table 3-8)
- For a Enon soil the infiltration rate is I = 0.20 ft/day (Table 3-7)

Table 3-9 shows summary calculations for this site for each month of the year based on a calendar year computation and water year computation.

Table 3-9 Water Balance Result Summary

1		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2	Days/month	31.0	28.0	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0
3	Precipitation (inches)	3.72	3.84	4.44	2.64	3.84	3.36	3.96	3.72	3.48	3.36	3.24	3.48
4	Evaporation (inches)	1.20	1.50	2.50	3.70	4.40	4.60	4.80	4.50	3.30	2.40	1.50	1.10
5	Runoff (acre-feet)	2.57	2.66	3.07	1.83	2.66	2.32	2.74	2.57	2.41	2.32	2.24	2.41
6	Pond Precipitation (acre-feet)	0.16	0.16	0.19	0.11	0.16	0.14	0.17	0.16	0.15	0.14	0.14	0.15
7	Evaporation (acre-feet)	0.05	0.06	0.10	0.15	0.18	0.19	0.20	0.19	0.14	0.10	0.06	0.05
8	Infiltration (acre-feet)	3.10	2.80	3.10	3.00	3.10	3.00	3.10	3.10	3.00	3.10	3.00	3.10
9	Monthly Balance (acre-feet)	-0.42	-0.05	0.05	-1.22	-0.47	-0.73	-0.40	-0.56	-0.58	-0.74	-0.69	-0.59
10	Running Balance of Retained Pond Volume (acre-feet)	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	Pond water surface elevation (feet)	699.8	699.8	700.0	699.8	699.8	699.8	699.8	699.8	699.8	699.8	699.8	699.8
12	Water surface with respect to permanent pool elevation (feet)	-5.2	-5.2	-5.0	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2
1		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
2	Days/month	31.0	31.0	30.0	31.0	30.0	31.0	31.0	28.0	31.0	30.0	31.0	30.0
3	Precipitation (inches)	3.96	3.72	3.48	3.36	3.24	3.48	3.72	3.84	4.44	2.64	3.84	3.36
4	Evaporation (inches)	4.80	4.50	3.30	2.40	1.50	1.10	1.20	1.50	2.50	3.70	4.40	4.60
5	Runoff (acre-feet)	2.74	2.57	2.41	2.32	2.24	2.41	2.57	2.66	3.07	1.83	2.66	2.32
6	Pond Precipitation (acre-feet)	0.17	0.16	0.15	0.14	0.14	0.15	0.16	0.16	0.19	0.11	0.16	0.14
7	Evaporation (acre-feet)	0.20	0.19	0.14	0.10	0.06	0.05	0.05	0.06	0.10	0.15	0.18	0.19
8	Infiltration (acre-feet)	3.10	3.10	3.00	3.10	3.00	3.10	3.10	2.80	3.10	3.00	3.10	3.00
9	Monthly Balance (acre-feet)	-0.40	-0.56	-0.58	-0.74	-0.69	-0.59	-0.42	-0.05	0.05	-1.22	-0.47	-0.73
10	Running Balance of Retained Pond Volume (acre-feet)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00
11	Pond water surface elevation (feet)	699.8	699.8	699.8	699.8	699.8	699.8	699.8	699.8	700.0	699.8	699.8	699.8
12	Water surface with respect to permanent pool elevation (feet)	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.0	-5.2	-5.2	-5.2

Explanation of Table:

1. Months of the year.
2. Days per month.
3. Monthly precipitation from Table 3-6.
4. Evaporation by month from Table 3-8.
5. Watershed efficiency of 0.37 times the rainfall and converted to acre-feet.
6. Precipitation volume directly into pond equals precipitation depth times pond surface area divided by 12 to convert to acre-feet.
7. Evaporation from line 4 converted to acre-feet.
8. Infiltration converted to acre-feet.
9. Lines 5 and 6 minus lines 7 and 8.
10. Accumulated total from line 9 keeping in mind that all volume above 2 acre-feet overflows and is lost in the trial design.
11. Pond water surface elevation based on stage-storage data for pond.
12. Pond water surface elevation with respect to permanent pool elevation.

For this example the wet pond has the potential to go dry throughout the year. This could be remedied in a number of ways including compacting the pond bottom in areas that are not planned to be planted, placing a liner of clay or geosynthetics, and changing the pond geometry to decrease surface area. Table 3-10 shows revised water balance computations for the same site using an infiltration rate of 0.1 ft/day based on a clay liner.

Table 3-10 Revised Water Balance Result Summary (Clay Liner)

1		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2	Days/month	31.0	28.0	31.0	30.0	31.0	30.0	31.0	31.0	30.0	31.0	30.0	31.0
3	Precipitation (inches)	3.72	3.84	4.44	2.64	3.84	3.36	3.96	3.72	3.48	3.36	3.24	3.48
4	Evaporation (inches)	1.20	1.50	2.50	3.70	4.40	4.60	4.80	4.50	3.30	2.40	1.50	1.10
5	Runoff (acre-feet)	2.57	2.66	3.07	1.83	2.66	2.32	2.74	2.57	2.41	2.32	2.24	2.41
6	Pond Precipitation (acre-feet)	0.16	0.16	0.19	0.11	0.16	0.14	0.17	0.16	0.15	0.14	0.14	0.15
7	Evaporation (acre-feet)	0.05	0.06	0.10	0.15	0.18	0.19	0.20	0.19	0.14	0.10	0.06	0.05
8	Infiltration (acre-feet)	1.55	1.40	1.55	1.50	1.55	1.50	1.55	1.55	1.50	1.55	1.50	1.55
9	Monthly Balance (acre-feet)	1.13	1.35	1.60	0.28	1.08	0.77	1.15	0.99	0.92	0.81	0.81	0.96
10	Running Balance of Retained Pond Volume (acre-feet)	1.13	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
11	Pond water surface elevation (feet)	703.0	705.0	705.0	705.0	705.0	705.0	705.0	705.0	705.0	705.0	705.0	705.0
12	Water surface with respect to permanent pool elevation (feet)	-2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
2	Days/month	31.0	31.0	30.0	31.0	30.0	31.0	31.0	28.0	31.0	30.0	31.0	30.0
3	Precipitation (inches)	3.96	3.72	3.48	3.36	3.24	3.48	3.72	3.84	4.44	2.64	3.84	3.36
4	Evaporation (inches)	4.80	4.50	3.30	2.40	1.50	1.10	1.20	1.50	2.50	3.70	4.40	4.60
5	Runoff (acre-feet)	2.74	2.57	2.41	2.32	2.24	2.41	2.57	2.66	3.07	1.83	2.66	2.32
6	Pond Precipitation (acre-feet)	0.17	0.16	0.15	0.14	0.14	0.15	0.16	0.16	0.19	0.11	0.16	0.14
7	Evaporation (acre-feet)	0.20	0.19	0.14	0.10	0.06	0.05	0.05	0.06	0.10	0.15	0.18	0.19
8	Infiltration (acre-feet)	1.55	1.55	1.50	1.55	1.50	1.55	1.55	1.40	1.55	1.50	1.55	1.50
9	Monthly Balance (acre-feet)	1.15	0.99	0.92	0.81	0.81	0.96	1.13	1.35	1.60	0.28	1.08	0.77
10	Running Balance of Retained Pond Volume (acre-feet)	1.15	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
11	Pond water surface elevation (feet)	703.0	705.0	705.0	705.0	705.0	705.0	705.0	705.0	705.0	705.0	705.0	705.0
12	Water surface with respect to permanent pool elevation (feet)	-2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

3.5 Downstream Flood Analysis

3.5.1 Introduction

The purpose of the flood control detention requirements (10- and 25-year, 6-hour storm event control) is to protect downstream properties from increased flooding due to upstream development. Current standard policies require that 10- and 25-year storms are controlled at the outlet of a site such that post-development peak discharge equals pre-development peak discharge. Refer to the Administrative Manual and local regulations for the applicable jurisdiction for volume and peak control requirements. The flood control detention waiver if a project discharges directly to a FEMA floodplain no longer applies. Even though the waiver no longer applies, most developments along the FEMA regulated floodplain will pass the 10 times the site area test described in Section 3.5.3. For example, any project with an area less than 64 acres that discharges directly to the floodway will discharge to a stream system with a drainage area larger than 640 acres and therefore would comply with the 10% rule requirement for downstream analysis at the system outfall.

The portion of the 10- and/or 25-year storm event control requirement that can be waived is based on how well the receiving system meets design standards. The 10- and/or 25-year storm event control cannot be waived, if through the waiver portions of the downstream system do not meet design standards.

Design standards are defined as all storm drainage system requirements described in the Charlotte-Mecklenburg Storm Water Design Manual. These include providing pipe capacity for the 10- and 25-year storm events using Mannings formula and hydraulic gradeline computations, culvert capacity for design storms based on roadway type, and providing protection for first floor flooding for the 100-year storm event. The storms that will need to be analyzed will be based on what features are located within the limits of this study area. Design storms for various features are listed in Table 3-11.

Table 3-11: Summary of Design Standards for Downstream Analysis

Design feature	Design storm for analysis (all 6-hr)
Closed pipe/Channel systems/Driveway culverts	10-year
Culverts (subdivision streets)	25-year
Culverts (thoroughfare roads)	50-year
Building footprints	100-year

The design storms to be analyzed will depend upon what is downstream from the project site. For example, if there is only a local street crossing within the study area, only the 25-yr 6-hr storm would need to be modeled. The other storms would have to be analyzed as needed.

3.5.2. Reasons for Downstream Problems

Many of the sites that are being developed are upstream from existing urbanized areas where the storm drainage infrastructure has been in place for some time. In some cases, this storm drainage infrastructure does not meet current design standards or is showing some signs of failure due to deterioration, poor installation, etc. Design standards for these systems vary based on the potential for flood damage from the 10-year flood event for the pipe and channel systems up to the 100-year flood event for the protection of living space. Current detention requirements require the attenuation of some of these flood events, but not all of the flood events. Therefore, there may be some downstream systems that experience increased discharges due to upstream development for flood events that are not addressed by the current detention requirements. Therefore, the flood damages on these properties may be exacerbated by the upstream development.

3.5.3 The Ten-Percent Rule

The “ten-percent” rule is a practical, flexible and effective approach for ensuring all potential impacts of flooding or increased volume from development are assessed. The ten-percent rule recognizes the fact that development and/or a structural SCM control providing detention has a “zone of influence” downstream where its effectiveness can be felt. Beyond this zone of influence the development and/or structural control becomes relatively small and insignificant compared to the runoff from the total drainage area to that point. Based on studies and master planning results, that zone of influence is considered to be the point where the drainage area controlled by the detention facility comprises 10% of the total drainage area (Debo & Reese, 1990). Although the detention exemption along floodplains will no longer be in the ordinance, most developments along the FEMA regulated floodplain will pass the 10 times the site area test. For example, any project with an area less than 64 acres that discharges directly to the floodway will discharge to a stream system with a drainage area larger than 640 acres and therefore would be immediately complying with the 10% rule requirement for downstream analysis.

For example, if the structural SCM control drains 10 acres, the zone of influence ends at the point where the total drainage area is 100 acres or greater.

Typical steps in the application of the ten-percent rule are:

1. Using a topographic map determine the lower limit of the zone of influence (10% point).
2. Using a hydrologic model determine the pre-development peak flows and timing of those peaks at each tributary junction beginning at the pond outlet and ending at the next tributary junction beyond the 10% point. Two watershed land use conditions should be considered when developing the hydrologic model and assessing the potential for downstream impacts, existing and future land use. In addition, the designer should assess other watershed conditions such as sub-basins size, upstream attenuation, etc. so that the results are conservative.
3. Change the land use on the site to post-development and rerun the model.
4. Perform appropriate hydraulic computations for the downstream system to determine if the drainage systems meet or do not meet design standards. Hydraulic computations that may need to be considered include pipe capacity computations, culvert capacity analysis, floodplain backwater computations, channel stability assessment, etc. Storm and flood events that should be assessed include the 10-, 25, 50-, and 100-year events based on the downstream system design standards. For both models, the base survey will need to identify all features that could be affected by flooding to adequately assess impacts. The accuracy of the analysis shall meet current site plan design standards and be sealed by a North Carolina Professional Engineer or Landscape Architect. The field survey shall meet current site plan design standards and be sealed by a North Carolina registered land surveyor.
5. Design the structural SCM control facility such that the pre-developed conditions and post-developed conditions are the same at the downstream site property line and downstream receiving system meets all design standards.

Example
Figure 3.5.1 illustrates the concept of the ten-percent rule for two sites in a watershed.

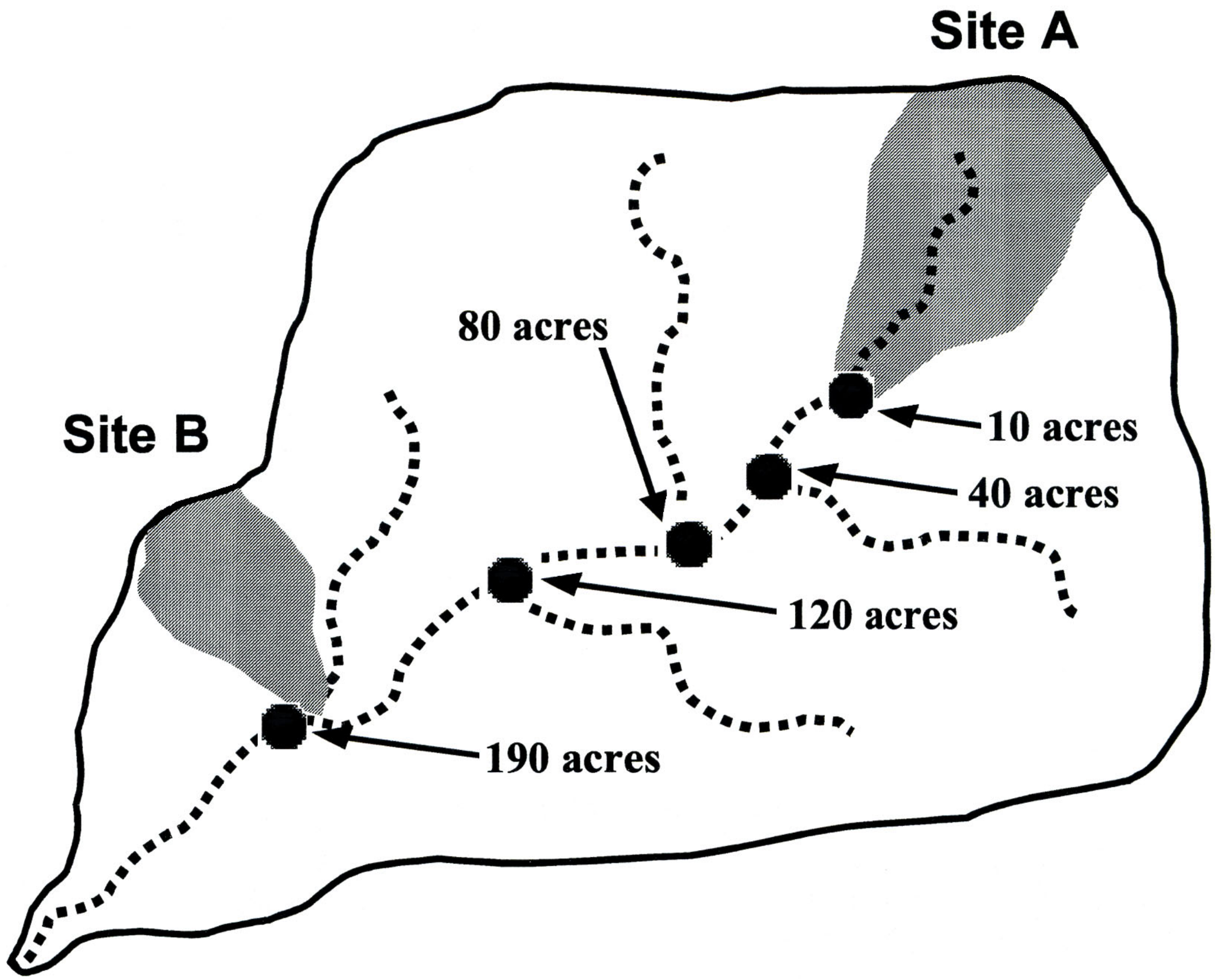

Figure 3.5.1 Example of the Ten-Percent Rule

Site A is a commercial development of 10 acres, all draining to a wet pond SCM. The design standards require the post-developed discharges for the 10- and 25-year storm events are controlled to pre-developed conditions at the property line unless a downstream analysis is performed that shows the receiving system can accept additional discharge. The receiving drainage system requires the assessment of the 10-, 25-, 50-, and 100-year storm events down to the ten-percent rule location (see Table 3-11 for appropriate design storms). Looking downstream at each tributary in turn, it is determined that the analysis should end at the tributary marked "120 acres". The 100-acre (10%) point is in between the 80-acre and 120-acre tributary junction points. For simplicity, the analysis can be run down to the 120-acre point, or if the designer wishes, drainage areas can be iteratively drawn to find the exact 100-ac point.

The designer constructs a HEC-1 model, or equivalent, of the 80-acre areas using existing and future land use conditions for each sub-watershed in each tributary. Major attenuation throughout the watershed that could impact the accuracy of the analysis should be included in the model in order to produce conservative results. Hydraulic computations are performed to assess the capacity of the receiving system. The downstream analysis indicates that the entire drainage system meets design standards for all appropriate storm event; 10-, 25-, 50-, and 100-year. Therefore, control of only the 10-year storm event at the outfall of the development site is required. If the downstream analysis showed that downstream system did not meet design standards, then controlling both the appropriate design storms would be required.

Site B is located downstream at the point where the total drainage area is 190 acres. The site itself is only 6 acres. The first tributary junction downstream from the 10-percent point is the junction of the site outlet with the stream. Therefore, the limits of the downstream analysis are the downstream site boundary.

3.6 Combined Water Quality (WQ_v) and Channel Protection (CP_v) Design

3.6.1 Introduction

The post-construction ordinance requires treatment of the 1-inch, 6-hour storm event to meet water quality (WQ_v) goals and control of the 1-year, 24-hour storm event to meet channel protection (CP_v) goals. For some sites (relatively small and high impervious sites) the SCM storage volume needed to meet both of these goals may be similar in size. To facilitate a simpler and more straight-forward design process, a design target has been developed that meets both the water quality treatment (WQ_v) and channel protection control (CP_v) goals of the post-construction ordinance.

The simpler and most straight-forward design process is called the *Combined Water Quality and Channel Protection Design* and was developed by assessing numerous sites with various watershed sizes and imperviousness intensity. The results of the numerous site assessment indicates that holding the 1-year, 24-hour storm event for 24 hours longer than the detention time for the 1-inch, 6-hour storm event will provide the appropriate water quality treatment. Therefore, a site designer can elect to perform a *Combined Water Quality and Channel Protection Design* for the optimal efficiency wet pond by holding the 1-year, 24-hour storm event for 120 hours (4 days detention time for the optimal efficiency design plus 24 hours) after the center of rainfall (12 hours). Design computations showing that the 1-inch, 6-hour storm event will not need to be performed.

The *Combined Water Quality and Channel Protection Design* applies to SCMs in this Manual that are designed by routing the design storms through the SCM storage volume which include wet ponds, wetlands, and bioretention. The design is met by controlling the channel protection volume (CP_v) for a duration that is 24 hours longer than the design duration for the water quality (WQ_v) design. For example, the optimal efficiency for a wet pond is met by controlling the 1-year, 24-hour storm event for 120 hours (4 days plus 24 hours). The standard efficiency for a wet pond is met by controlling the 1-year, 24-hour storm event for 72 hours (2 days plus 24 hours). These design durations are always measured after the center of rainfall.

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