A. Introduction

This section provides general guidance on stormwater runoff storage for meeting stormwater management control requirements (i.e., water quality treatment, downstream channel protection, overbank flood protection, and extreme flood protection). Storage of stormwater runoff within a stormwater management system is essential to providing the extended detention of flows for water quality treatment and downstream channel protection, as well as for peak flow attenuation of larger flows for overbank and extreme flood protection. Runoff storage can be provided within an onsite system through the use of structural stormwater controls and/or nonstructural features and landscaped areas. Specific design criteria for detention practices are included in Chapter 7. The design steps for determining the final design storage volume are covered in the following discussion.

1. **Dry detention.** Conventional dry detention practices are used to reduce the peak discharge and detain runoff for a specified short period of time. Detention volumes are designed to completely drain after the design storm has passed. Detention is used to meet overbank flood protection criteria, and extreme flood criteria where required.
2. **Extended dry detention.** Extended dry detention (ED) is used to drain a runoff volume over a specified period of time, typically 24 hours, and is used to meet channel protection criteria. Some structural control designs (wet ED pond, micropool ED pond, and shallow ED marsh) also include extended detention storage of a portion of the water quality volume.
3. **Wet detention.** Wet detention facilities are designed to contain a permanent pool of water, such as stormwater ponds and wetlands, and are often used for water quality treatment in addition to providing storage for peak flow control. A schematic of a wet detention structure is illustrated in Figure C3-S9-1.

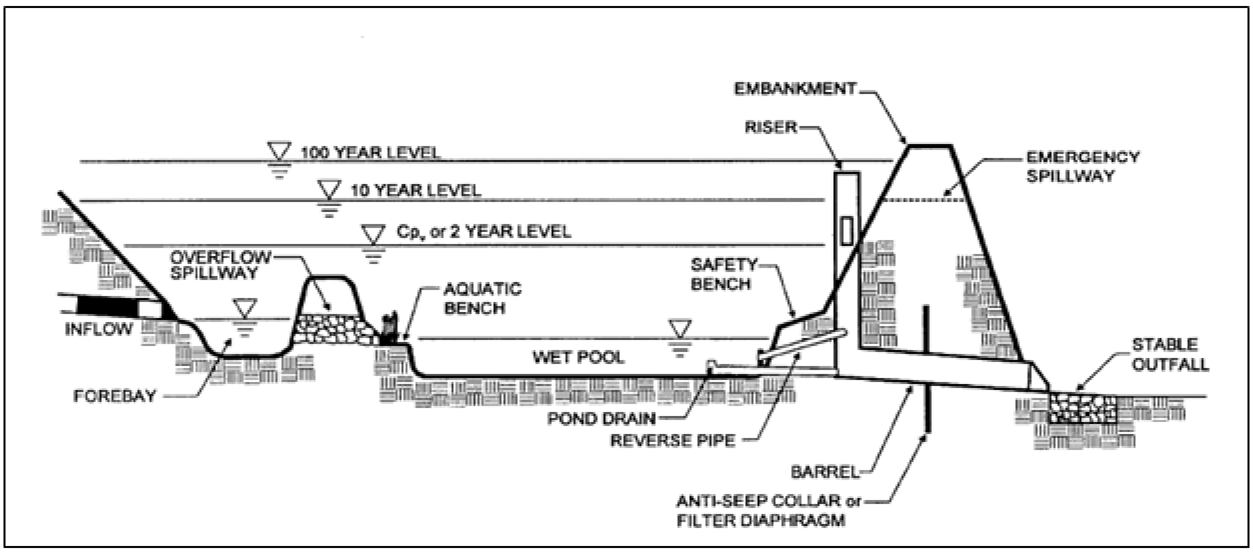

Figure C3-S9-1: Schematic of wet detention structure

Source: Maryland Stormwater Manual, 2000

Detention storage facilities can also be classified on the basis of their location and size. Onsite storage is constructed on individual development sites. Regional detention practices are constructed at the lower end of a sub-watershed and are designed to manage stormwater runoff from multiple projects and/or properties. A discussion of regional stormwater controls is found in Chapter 4.

Storage can also be categorized as online or off-line. Online storage uses a structural control facility that intercepts flows directly within a conveyance system or stream. Off-line storage is a separate storage facility to which flow is diverted from the conveyance system. Figure C3-S9-2 provides a schematic of on-line versus off-line storage configurations.

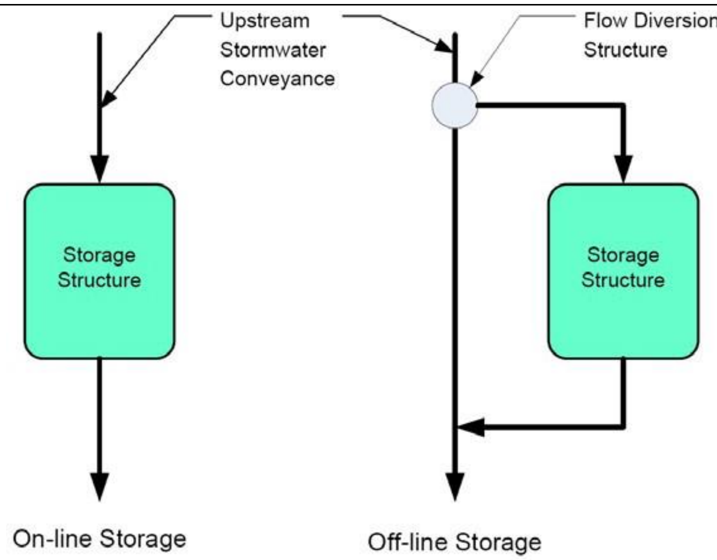

Figure C3-S9-2: Online versus off-line storage

B. Alternatives for estimating detention volume

The general procedures for designing storage to provide standard detention of stormwater runoff for overbank and extreme flood protection (i.e., Q_p and Q_f) are discussed below. The design method for determining the water quality volume (WQv) and channel protection volume (Cpv) were presented in Chapter 3 - Section 6 Small Storm Hydrology. Guidance on required storage volume for dry ED and wet ponds is also provided in Chapter 7. The general procedures for all detention basin facilities are the same whether or not they include a permanent pool of water. In the latter case, the permanent pool elevation is taken as the bottom of storage, and is treated as if it were a solid basin bottom for routing purposes. It should be noted that the location of structural stormwater controls is very important as it relates to the effectiveness of these facilities to control downstream impacts. In addition, multiple storage facilities located in the same drainage basin will affect the timing of the runoff through the conveyance system, which could decrease or increase flood peaks in different downstream locations. Therefore, a downstream peak flow analysis should be performed as part of the storage facility design process (Chapter 3 - Section 14 Downstream Hydrologic Assessment).

For the wet detention basin shown in Figure C3-S9-1 with a two-stage riser design, the basic operation of the storage facility begins with the formation of the pool behind the retaining structure. The hydrograph for the storm event enters from the upper end of the detention basin. For this basin, water will be discharged through either the lower pipe outlet (orifice control) for the smaller storms, or the upper weir structure for larger storm events (>2 year). The size of the pipe or weir is used to control the outflow rate. The volume of the permanent pool is a function of the basin geometry and the elevation of the lower outlet control elevation with respect to the bottom elevation of the basin. For a dry basin or extended detention basin, the control elevation of the single outlet, or lower outlet, is set at the bottom elevation of the structure. The size of the pipe/weir serves to control the outflow rate as a function of the pool elevation (head) above the pipe inlet/weir. For peak discharge control, the design is based on selecting the appropriate size and configuration of the outlet so the maximum rate of discharge does not exceed the limit set forth in local policy. The levels of control for water quality, channel protection, and control of overbank flooding are discussed in Chapter 1, section 4 and Chapter 2. For instance, the standard approach for overbank flooding in most jurisdictions has been control of the post-developed discharge for the Q_5 through Q_{50} to be equal to the pre-developed runoff rate for the 5-year frequency event. For basins with a permanent pool, the WQv will first mix with the permanent pool volume before release through the lower outlet. In this case, the lower outlet is sized to achieve a set detention time rather than a set discharge rate. A common detention time is 24 hours for sediment removal. Treatment for nutrient reduction may require longer detention times (>48 hours; see Chapter 7, section 3). Therefore, for WQv and Cpv, the required detention volume and associated outlet sizing are based on holding the detained volume for a specified time. The rate of discharge is based on the stored volume divided by the desired time of detention. An example volume and outlet sizing for Cpv are provided in Chapter 3 - Section 6 Small Storm Hydrology. For storm events greater than 2-year storm event, the final sizing of the outlet structure is based on peak rate rather than a defined detention time.

The use of a permanent pool has the advantage of providing improved performance for water quality, aesthetics, and the provision of wildlife habitat. The disadvantage of systems with permanent pool storage is the increase in total required storage volume with an increase amount of land (footprint) and perhaps a larger retaining structure. Additional details for the design of outlet structures are provided in Chapter 3 - Section 13 Water Balance Calculations.

All detention basins are configured with a secondary (emergency) spillway to pass runoff from the 100-year event (Q_f), and to prevent overtopping and subsequent failure of the retaining structure. The elevation of the secondary spillway is above the elevation of the upper opening on the primary outlet structure, but below the top of the retaining structure. The sizing of the secondary spillway weir length is established to maintain a minimum freeboard of 1 foot between the basin water surface elevation at the 100-year event and the top of the retaining structure.

C. Planning and design alternatives

Based on the above discussion, the design of detention structures requires the simultaneous sizing of both the detention volume characteristics and the outlet riser configuration and size. Planning level (preliminary design) methods will generally provide an estimate of the required volume of storage to meet a specific stormwater management objective (Cpv, Q_p). Other methods are used to determine the characteristics (dry vs. wet, onsite vs. offsite, etc.). The final design is determined using a method that simultaneously determines the volume of storage and the sizing of the outlet structure. The simultaneous solution of the volume of storage and outlet sizing is completed using a storage routing procedure.

D. Preliminary detention storage design

A number of methods are available for estimating detention volumes. The ratio of the storage volume to the runoff volume and the ratio of the predevelopment and post-development are the basis for most of these methods. For peak discharge control objectives, the before-to-after development ratio is called the ratio of outflow/inflow (the peak outflow is the predevelopment peak discharge, and the inflow to the basin equals the post-development peak discharge). Procedures for preliminary detention calculations are included here to provide a simple method that can be used to estimate storage needs and also provide a quick check on the results of using different computer programs. Standard storage routing is then used for actual (final) storage facility calculations and design. Three methods are presented below for determination of preliminary storage volumes for peak flow reduction:

1. **Rational hydrograph method.** Based on the difference between the pre- and post-development peak discharges (ft^3/sec) and the predevelopment time of concentration, T_c (hr).
2. **Wycoff and Singh method.** Method for making preliminary hydrologic designs of small flood detention reservoirs. Developed from a regression of data generated from a more detailed hydrologic model. The time base, Tb, is measured from the start of runoff to the time when the discharge on the recession limb equals 5% of the peak discharge rate.
3. **The NRCS Urban Hydrology for Small Watersheds (WinTR-55) method.** This method has been discussed earlier (Chapter 3 - Section 3 Time of Concentration, Chapter 3 - Section 5 NRCS TR-55 Methodology, and Chapter 3 - Section 6 Small Storm Hydrology), and is well-documented. The use of WinTR-55 procedures for determining the runoff volume (Q_a), peak discharge (q_p), and time of concentration have been discussed previously. The use of TR-55 for the determination of channel protection volume (Cpv) for extended detention practices is described in Chapter 3 - Section 6 Small Storm Hydrology. The preliminary sizing equation in the worksheet below can be used for preliminary sizing. The WinTR-55 computer model uses the full TR-20 method of hydrograph generation, and includes an option for the sizing of detention structures.
4. **The low-impact hydrology (LID) method.** This method is based on determining the volume of storage required to reduce the post-development runoff volume to predevelopment levels. The LID methodology is summarized in Chapter 3 - Section 8 Low-Impact Development (LID) Hydrology. Note that the LID hydrologic method in practice uses complementary practices to increase the volume of water infiltrated, and reduces the time of concentration by reducing impervious area, lengthening flow paths across pervious areas, and by using other practices to reduce the volume of direct runoff.

   For planning purposes, the assumptions for the Rational method are used to determine an initial estimate for storage volume. Specifically, a triangular hydrograph with a time to peak equal to T_c and a time base of $2T_c$ is assumed. The peak discharges for the pre- and post-development conditions are denoted as q_{pb} and q_{pa}. A schematic of the before and after runoff hydrographs and associated terms are provided in Figure C3-S9-3.

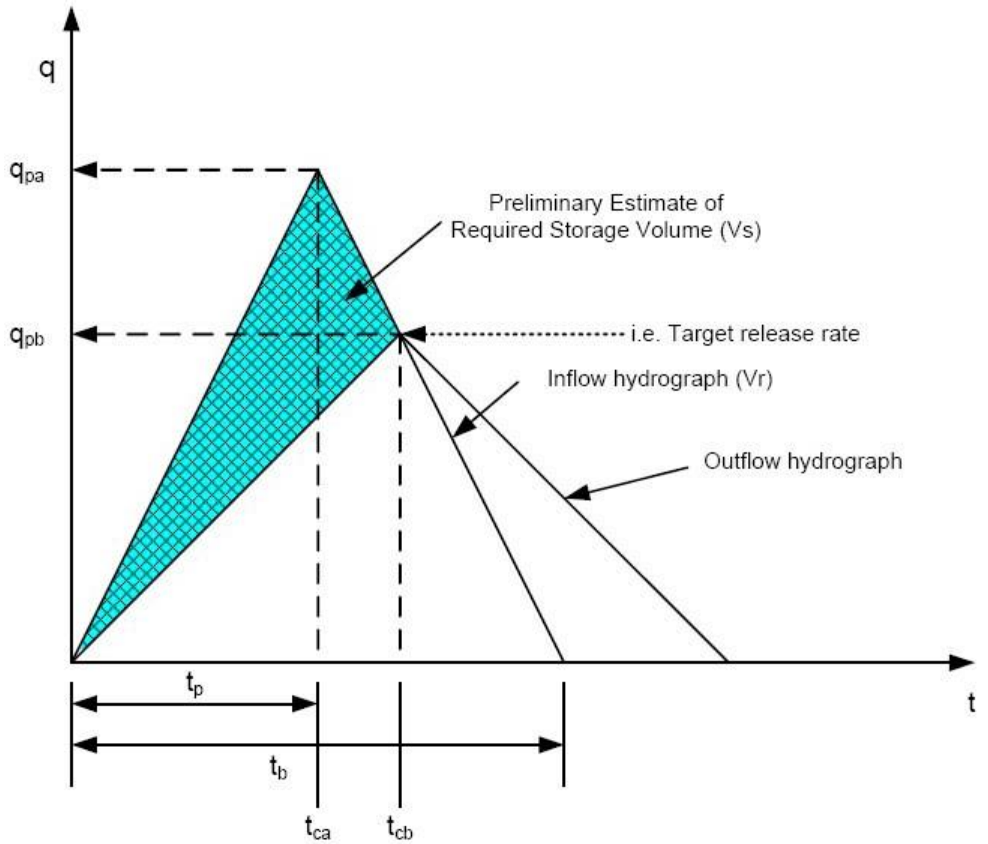

Figure C3-S9-3: General schematic for estimating the volume of required storage (cross-hatched area)

A summary of the required data and the associated formulas for the methods are summarized in Table C3-S9-1.

Table C3-S9-1: Worksheet for planning estimates of required storage volume

Parameter	Symbol	Units	Value	Required for Method			
				1	2	3	4
Drainage Area	A_m	Acres		✓	✓	✓	✓
Runoff depth - before	Q_b	Inches					✓
Runoff depth - after	Q_a	Inches		✓	✓	✓	✓
Peak discharge - before	q_{pb}	ft3/sec		✓	✓	✓	
Peak discharge - after	q_{pa}	ft3/sec		✓	✓	✓	
Discharge ratio[1]	α			✓	✓	✓	
Time of concentration - before	T_{cb}	hours		✓			
Time of Concentration - after	T_{ca}	hours					
Time to peak - before	t_{pb}	hours					
Time to peak - after	t_{pa}	hours					
Storage volume/runoff volume	R_v						
Hydrograph time base - after	T_b	hours					
Time ratio[2]	γ						

[1]α = qpb/qpa
[2]γ = tpb/tpa or tcb/tca (where tp = tc)
[3]Vs = volume of storage in inches
[4]Rv = Vs/Qa (Note: Q = Vr in inches)
[5]Vst = VsAm/12 [=] acre-ft

Method		Computational Form	R_v	V_s (inch)	V_{st} (ac-ft)
1	Rational hydrograph	V_{st} = .08264 T_c b(q_{pa}-q_{pb})			
2	Wycoff and Singh	V_s = 1.29Q_a(1- α)0.753(T_b/t_{pa})-0.411			
3	NRCS TR-55 (Type II)	R_v = 0.682 -1.43 α + 1.64 α2 - 0.805 α3			
4	LID Hydrologic method	V_s = Q_a - Q_b			

Source: Adapted from McCuen, 1989

E. Modified Rational method

The Rational method was originally intended for the peak discharge design only. The runoff coefficients represent the ratio of the peak discharge per unit area to average intensity of a storm that has the same return period. The runoff volume was not considered in developing the Rational formula, and the Rational method was not meant for detention basin design. However, a modified Rational method, actually an extension of the conventional Rational method, has been used in the past for preliminary sizing of detention basins. The method is included in this manual with a restriction to drainage areas of less than 20 acres. The Modified Rational method uses the peak flow calculating capability of the Rational method, paired with assumptions about the inflow and outflow hydrographs to compute an approximation of storage volumes for simple detention calculations. There are many variations on the approach.

The basic approach assumes the stormwater runoff hydrograph (detention basin inflow hydrograph) for the design storm is trapezoidal in shape. The peak runoff rate is calculated using the rational formula

Equation C3-S9-1

$$q_{pi} = CiA$$

Where:
q_{pi} = peak discharge (peak inflow rate for the detention basin)
C = runoff coefficient
i = rainfall intensity (in/hr)
A = area of the watershed, ac

It is assumed the peak of the outflow hydrograph falls on the recession limb of the inflow hydrograph (see Figure C3-S9-3), and the rising limb of the outflow hydrograph can be approximated by a straight line. With these assumptions (Aron and Kibler, 1990):

Equation C3-S9-2

$$S_d = q_{pi}t_d - \frac{Q_a(t_d + t_c)}{2}$$

Where:
S_d = detention volume required
Q_a = allowable peak outflow rate
t_d = design storm duration
t_c = time of concentration for the watershed

The design storm duration is that duration that maximizes the detention storage volume, S_d, for a given return period. The storm duration can be found by trial and error using local I-D-F data (or extracted from the rainfall data in Chapter 3 - Section 2 Rainfall and Runoff Analysis).

Figure C3-S9-3 provides an illustration. The rising and falling limbs of the inflow hydrograph have a duration equal to the time of concentration (T_c). An allowable target outflow is set based on predevelopment conditions. The storm duration is t_d, and is varied until the storage volume (shaded area) is maximized. It is normally an iterative process done by hand or on a spreadsheet. Downstream analysis is not possible with this method, as only approximate graphical routing takes place.

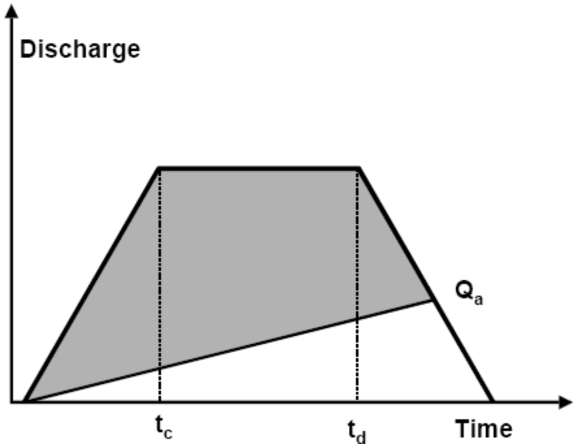

Figure C3-S9-4: Modified Rational hydrograph definitions

F. Design example

The development drainage area, A, is 18 acres (784,080 ft2), the runoff coefficient, C, is 0.72, and the time of concentration is 20 minutes (1200 seconds). The detention basin will be used to reduce the post-development peak discharge to 20 cfs. The rainfall duration and intensity for this return period is provided in tabular format in Table C3-S9-2. Determine the size of the required detention basin. The calculations are summarized in Table C3-S9-2. The given storm durations and rainfall intensities are converted to seconds and feet per hour and tabulated in columns 3 and 4 to provide for consistent units.

Table C3-S9-2: Tabular data for modified rational example

(1) t_d (min)	(2) i (in/hr)	(3) t_d (sec)	(4) i (ft/sec)	(5) q_{pi} (cfs)	(6) S_d (ft^3)
20	4.3	1200	9.95 x 10-5	56.19	31,341
30	3.2	1800	7.41 x 10-5	41.82	33,272
40	2.8	2400	6.48 x 10-5	36.59	39,817
60	2.0	3600	4.63 x 10-5	26.14	34,090
90	1.6	5400	3.70 x 10-5	20.91	34,908

The peak runoff rate is calculated using Equation C3-S9-1 for each storm duration and intensity data pair included in the table and entered in column 5. Finally, the detention volume is calculated using Equation C3-S9-2, and tabulated in column 6.

The maximum value in detention column 6 is 39,817 ft^3, and this value would be chosen as the size of detention basin required (use 40,000 ft^3). As shown in the table, the design storm for this detention basin has a duration of 40-min and an intensity of 2.8 in/hr.

An adjustment factor to the calculated storage volume can be applied to account for undersizing. The factor (P_{180}/P_{td}) is the ratio of the 3-hour storm depth for the return frequency divided by the rainfall depth for the critical duration calculated determined above. For the example above, the 10-year storm depth for the 3-hour and 40-minute durations are 2.73 inches and 1.72 inches, respectively. The adjustment factor would then have a value of 2.73/1.72, or 1.58. The detention volume calculated above when multiplied by the adjustment factor gives a final maximum detention volume of 62,910 ft^3. The Modified Rational method will also often undersize storage facilities in flat and sandy areas where the target discharge may be set too large, resulting in an oversized orifice. In these locations, a C factor of 0.05 to 0.1 should be used. A more detailed discussion of the Modified Rational method results compared to the use of TR-55 and the adjustment of C factors can be found in Debo and Reese (2002).