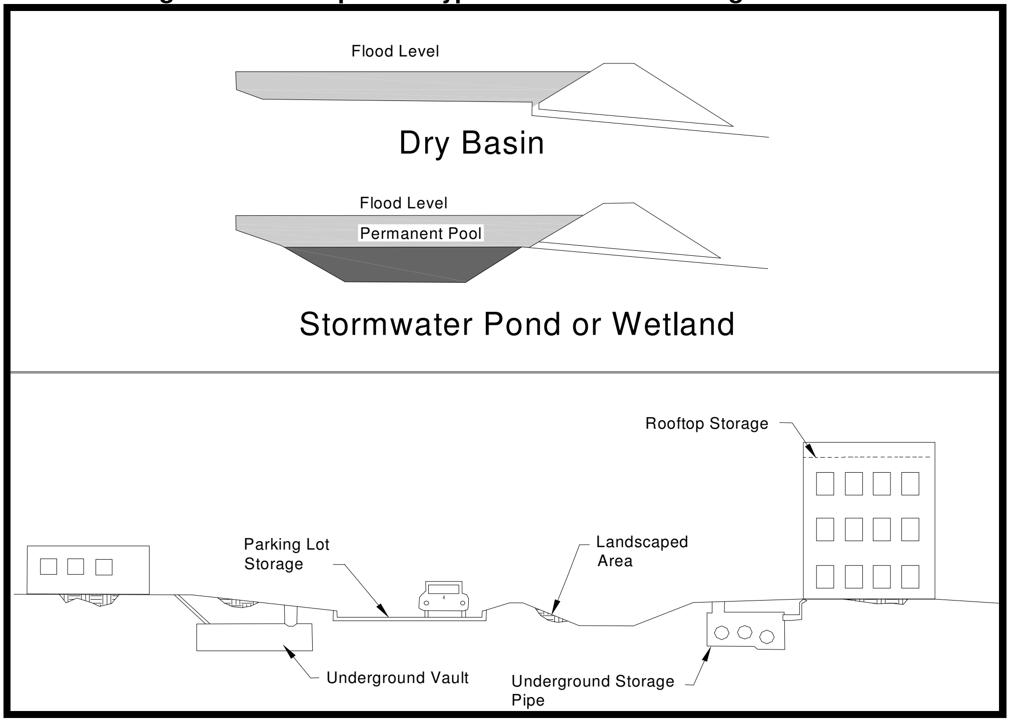
3.2 Storage Design

3.2.1 General Storage Concepts

This section provides general guidance on stormwater runoff storage for meeting control of the WQv, CPv, Qp_2, Qp_{10}, Qp_{25} and the Qp_{100}. Storage of stormwater runoff within a stormwater management system is critical to providing the extended detention of flows for water quality treatment and downstream channel protection, as well as for peak flow attenuation of the larger overbank and extreme flood protection flows. Runoff storage can be provided within an on-site system through the use of structural stormwater BMPs and/or non-structural features and landscaped areas. Figure 3-9 illustrates various storage facilities that can be considered for a development site.

Figure 3-9. Examples of Typical Stormwater Storage Facilities

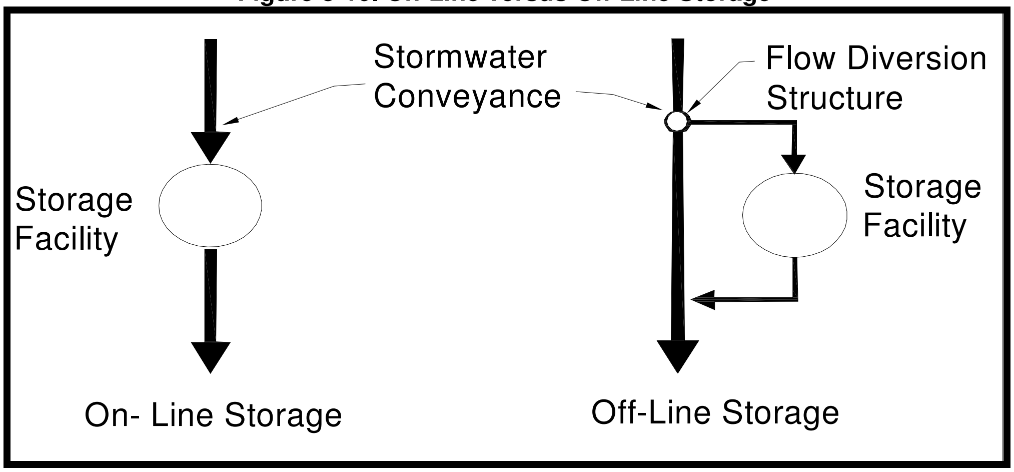


There are three main types of stormwater runoff storage: *detention, extended detention, and retention*. Stormwater *detention* is used to reduce the peak discharge and detain runoff for a specified short period of time. Detention basins are designed to completely drain after the design storm has passed. Detention is used to meet overbank flood protection criteria, and extreme flood criteria where required. *Extended 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 BMP designs (wet ED pond, micropool ED pond, dry extended pond and shallow ED marsh) also include extended detention storage of a portion of the water quality volume. *Retention* facilities, such as stormwater ponds and wetlands, are designed to contain a permanent pool of water that is used for water quality treatment. Some facilities include one or more types of storage. An example of a combined storage facility is one that is sized to provide extended detention of the WQv as well as detention of the Qp_{100}.

Storage facilities are often classified on the basis of their location and size. *On-site* storage is constructed on individual development sites and most often only provides control of the runoff that discharges that individual site. *Regional* storage facilities are designed to manage stormwater runoff from multiple projects and/or properties, or are constructed at the lower end of a sub-basin within which multiple properties are located. Knox County Engineering will determine if the use of a regional storage facility is applicable on a case-by-case basis.

Storage can also be categorized as *on-line* or *off-line*. On-line storage uses a structural BMP 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 3-10 illustrates on-line versus off-line storage.

Figure 3-10. On-Line versus Off-Line Storage



3.2.1.1 Stage-Storage Relationship

A stage-storage curve defines the relationship between the depth of water (stage) and storage volume in a storage facility. An example of a stage-storage curve is presented in Figure 3-11. This curve relationship allows the volume of storage to be calculated by using simple geometric formulas expressed as a function of depth. The storage volume for natural basins may be developed using a topographic map and the double-end area, frustum of a pyramid, prismoidal or circular conic section formulas.

Double-end area method: The double-end area method uses the areas of the planes at two given elevations to calculate the volume between the two area planes. This concept is presented in Figure 3-12. The double-end area equation is presented in Equation 3-28.

Equation 3-28

$$V_{1-2} = \left[\frac{(A_1 + A_2)}{2} \right] d$$

where:

V_{1-2} = storage volume (ft^3) between elevations 1 and 2
A_1 A_2 = surface area at elevation 1 and 2, respectively (ft^2)
d = change in elevation between points 1 and 2 (ft)

Figure 3-11. Stage-Storage Curve

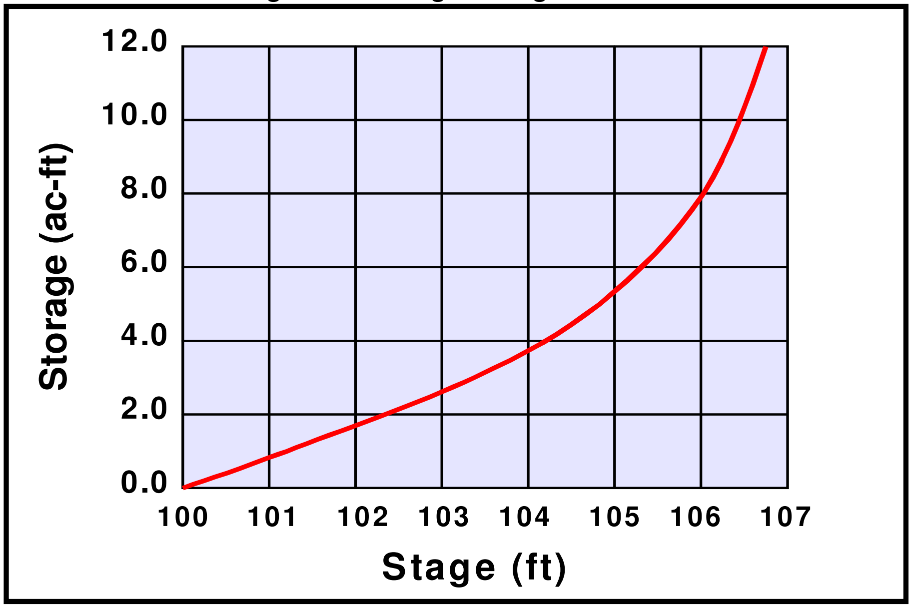
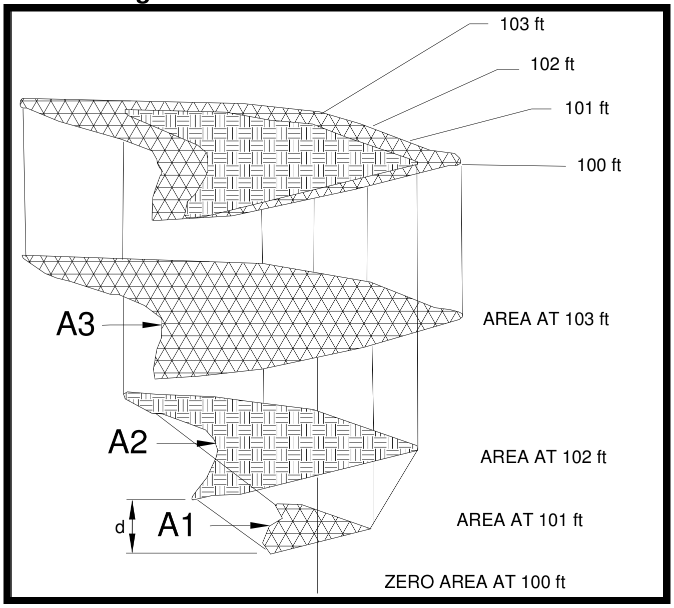


Figure 3-12. Double-End Area Method



Frustrum of a pyramid method: Another calculation involves treating the storage as a pyramid frustum, or a part of a pyramid. The frustum is formed by truncating the pyramid using two planes parallel to the pyramid base. The frustum of a pyramid can be calculated using Equation 3-29.

Equation 3-29

$$V = \frac{d}{3}\left[A_1 + \left(A_1 \times A_2\right)^{0.5} + A_2\right]$$

where:

- V = volume of frustum of a pyramid (ft^3)
- d = change in elevation between points 1 and 2 (ft)
- A_1 = surface area at elevation 1 (ft^2)
- A_2 = surface area at elevation 2 (ft^2)

Frustrum of a prismoid method: A trapezoidal basin can be represented as a prismoid since the volume is formed by the trapezoidal faces. Equation 3-30 presents the prismoidal equation for trapezoidal basins.

Equation 3-30

$$V = LWD + \left(L + W\right)ZD^2 + \frac{4}{3}Z^2 D^3$$

where:

- V = volume of trapezoidal basin (ft^3)
- L = length of basin at base (ft)
- W = width of basin at base (ft)
- D = depth of basin (ft)
- Z = side slope factor, ratio of horizontal to vertical

Frustrum of a cone or conic section method: Equations 3-31 and 3-32 present the calculation approach for the basin storage volume represented is as a circular cone.

Equation 3-31

$$V = 1.047D\left(R_1^{\ 2} + R_2^{\ 2} + R_1 R_2\right)$$

Equation 3-32

$$V = 1.047D\left(3R_1^{\ 2} + 3ZDR_1 + Z_2 D^2\right)$$

where:

- V = volume of circular cone basin (ft^3)
- R_1 , R_2 = bottom and surface radii of the conic section (ft)
- D = depth of basin (ft)
- Z = side slope factor, ratio of horizontal to vertical

3.2.1.2 Stage-Discharge Relationship

A stage-discharge curve defines the relationship between the depth of water and the discharge or outflow from a storage facility. Figure 3-13 presents an example stage-discharge curve. A typical storage facility has multiple outlets or spillways: a principal outlet that handles the range of design storms and design criteria and a secondary (or emergency) outlet. The principal outlet is usually designed with a capacity sufficient to convey the design discharges and volumes without allowing flow to enter the emergency spillway. Pipes, culverts, weirs, perforated risers and other appropriate outlets can be used in the principal spillway or outlet.

The emergency spillway is sized to provide a bypass for floodwater during a flood that exceeds the design capacity of the principal outlet. This spillway should be designed taking into account the potential threat to downstream areas if the storage facility were to fail. The stage-discharge curve should take into account the discharge characteristics of both the principal spillway and the emergency spillway. For more details, see Section 3.3 of this chapter.

3.2.2 Symbols and Definitions

To provide consistency within this section, the symbols listed in Table 3-20 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 equations.

Figure 3-13. Example Stage-Discharge Curve

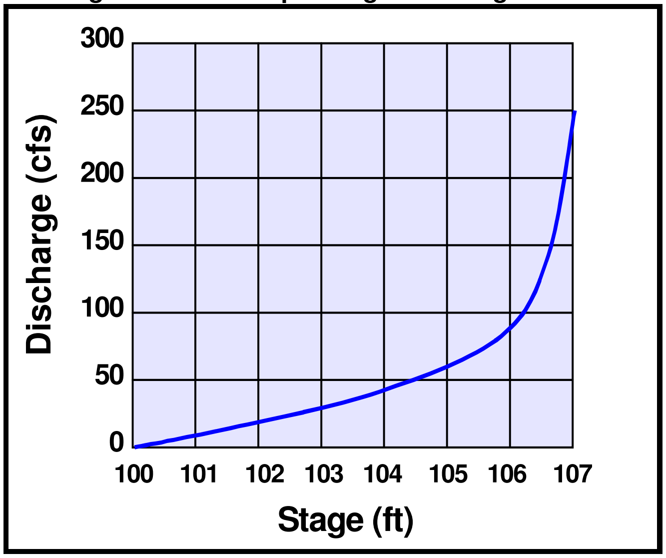


Table 3-20. Symbols and Definitions for Storage Design

Symbol	Definition	Units
a,b	Rainfall factors for Modified Rational Method	-
A	Cross sectional or surface area	ft^2
A	Drainage area	acres (or mi^2)
C_w	Weir coefficient	-
C	Rational Method Runoff Coefficient	-
CN	Curve number	-
CPv	Channel protection volume	acre-ft
d	Change in elevation	ft
D	Depth of basin or diameter of pipe	ft
g	Acceleration due to gravity	ft/s^2
H	Head on structure	ft
H_C	Height of weir crest above channel bottom	ft
i	Rainfall intensity	in/hr
L	Length	ft
P_x	Storm depth for x duration storm	in
q_i,q_o	Peak inflow or outflow rate	cfs, in
R	Surface Radii	ft
Rv	Runoff coefficient	-
t	Routing time period	sec
t_b	Time base of hydrograph	sec, hr
t_c	Time of concentration	min
T_d	Critical storm duration	min
T_i	Duration of basin inflow	hr, min, sec
t_P	Time to peak of hydrograph	hr
T_t	Travel time	min
V, V_s	Storage volume	ft^3, acre-ft
V_r	Runoff volume	ft^3, acre-ft
W	Width of basin	ft
WQv	Water quality volume	acre-ft

Symbol	Definition	Units
Z	Side slope factor	-

3.2.3 General Storage Design Procedures

This section discusses the general design procedures for designing storage to provide standard detention of stormwater runoff for the Qp_2, Qp_{10}, Qp_{25} and Qp_{100}. The design procedures for all storage 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.

The location of a storage facility can have a sizeable impact on the effectiveness of such 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 downstream conveyance system, which could decrease or increase flood peaks in different downstream locations. Therefore, a downstream peak flow analysis (i.e., the 10% rule) should be performed as part of the storage facility design process. In multi-purpose multi-stage facilities such as stormwater ponds, the storage design must be integrated with the overall design for water quality treatment objectives. See Volume 2, Chapter 4 for further guidance and criteria for the design of structural best management practices (BMPs) for water quality control.

3.2.3.1 Design Procedure

The following data are needed for storage design and routing calculations:

- inflow hydrograph for all selected design storms;
- stage-storage curve for proposed storage facility; and
- stage-discharge curve(s) for all outlet control structures.

A general procedure for using the above data in the design of storage facilities is presented below.

1. Compute inflow hydrographs for the 2, 10, 25 and 100-year, 24-hour design storms using the hydrologic methods outlined in Section 3.1. Both existing conditions and post-development hydrographs are required.
2. Perform preliminary calculations to evaluate detention storage requirements for the hydrographs from Step 1.
3. Determine the physical basin dimensions necessary to hold the volumes determined in Step 2, including freeboard, which is defined as 1.0 foot above the Qp_{100} water surface elevation to the lowest point in the detention embankment, excluding the emergency spillway. The maximum storage requirement calculated from Step 2 should be used. From the selected basin shape, determine the maximum depth in the pond.
4. Select the type of outlet(s) and size each outlet structure. The outlet type and size will depend on the type of basin (detention, extended detention or retention) as well as the allowable discharge. The estimated peak stage will occur for the estimated volume from Step 2. The outlet structure(s) should be sized to convey the allowable discharge at this stage.
5. Perform routing calculations using inflow hydrographs from Step 1 to check the preliminary design using a storage routing computer model. If the routed post-development peak discharges (Qp_2, Qp_{10}, Qp_{25} and the Qp_{100}) exceed the existing conditions peak discharges, then revise the available storage volume, outlet device(s), etc., and return to Step 3 until the basin size, basin depth, outlet type and outlet size meet the allowable discharge requirements.
6. Apply the 10% rule (i.e., downstream effects of detention outflows) for the 2-year, 10-year, 25-year and 100-year storms to ensure that the routed hydrograph does not cause downstream flooding problems.
7. Evaluate the control structure outlet velocity and provide channel and bank stabilization if the velocity

will cause erosion problems downstream.

Routing hydrographs through storage facilities is critical to the proper facility design and is required in Knox County. Although storage design procedures have been developed that use inflow/outflow analysis without routing, these design procedures have not produced acceptable results in designing detention facilities for many areas of the country, including Knox County.

Although hand calculation procedures are available for routing hydrographs through storage facilities, these procedures are very time consuming, especially when several different designs are evaluated. Many standard hydrology and hydraulics textbooks give examples of hand-routing techniques. For this manual, it is assumed that designers will be using one of the many computer programs available for storage routing and thus other procedures and example applications will not be given here.

3.2.4 Preliminary Detention Calculations

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 routing should be used for actual (final) storage facility calculations and design.

3.2.4.1 Storage Volume Estimation

For small drainage areas, a preliminary estimate of the storage volume required for peak flow attenuation may be obtained from a simplified design procedure that replaces the actual inflow and outflow hydrographs with the standard triangular hydrograph shapes shown in Figure 3-14. The required storage volume may be estimated from the hatched area between the inflow and outflow hydrographs. This preliminary storage volume estimate can be calculated using Equation 3-33.

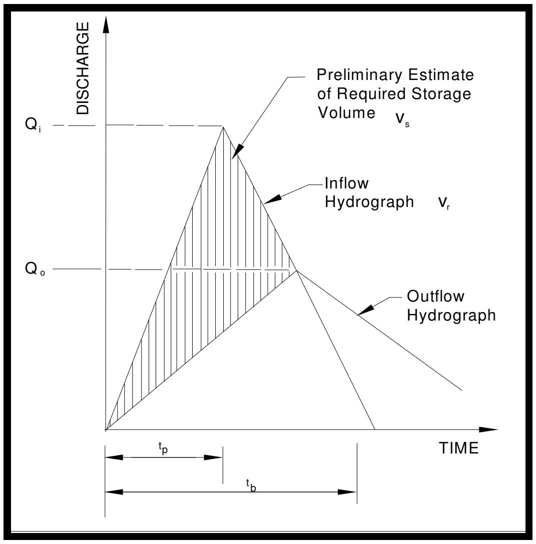
Equation 3-33

$$V_s = 0.5 t_b \left(Q_i - Q_o \right)$$

where:

V_s = storage volume estimate (ft^3)
t_b = time base of hydrograph (s)
Q_i = peak inflow rate (cfs)
Q_o = peak outflow rate (cfs)

Figure 3-14. Triangular-Shaped Hydrographs
(For Preliminary Estimate of Required Storage Volume)


DISCHARGE
Preliminary Estimate
of Required Storage
Volume V_s
Q_i
Inflow
Hydrograph V_r
Q_o
Outflow
Hydrograph
TIME
t_p
t_b

3.2.4.2 Alternative Storage Volume Estimation Method

An alternative preliminary estimate of the storage volume required for a specified peak flow reduction can be obtained using the following regression equation procedure (Wycoff and Singh, 1976).

8. Determine input data, including the allowable peak outflow rate, Q_O; the peak flow rate of the inflow hydrograph, Q_i; the time base of the inflow hydrograph, t_b; and the time to peak of the inflow hydrograph, t_p.

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9. Calculate a preliminary estimate of the ratio V_S/V_r using the input data from Step 1 and Equation 3-34.

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Equation 3-34

$$\frac{V_s}{V_r} = \frac{1.291\left(1 - \frac{Q_o}{Q_i}\right)^{0.753}}{\left(\frac{t_p}{t_b}\right)^{0.411}}$$

where:

V_s = volume of storage (in)
V_r = volume of runoff (in)
Q_o = outflow peak flow (cfs)
Q_i = inflow peak flow (cfs)
t_b = time base of the inflow hydrograph (hr) [Determined as the time from the beginning of rise to a point on the recession limb where the flow is 5% of the peak]
t_p = time to peak of the inflow hydrograph (hr)

3. Multiply the volume of runoff, V_r, times the ratio V_s/V_r, calculated in Step 2 to obtain the estimated storage volume V_s.

3.2.4.3 Peak Flow Reduction Estimate

A preliminary estimate of the potential peak flow reduction for a selected storage volume can be obtained by the following procedure.

4. Determine volume of runoff, V_r; peak flow rate of the inflow hydrograph, Q_i; time base of the inflow hydrograph, t_b; time to peak of the inflow hydrograph, t_p; and storage volume V_s.

5. Calculate a preliminary estimate of the potential peak flow reduction for the selected storage volume using Equation 3-35 (Wycoff and Singh, 1976):

Equation 3-35

$$\frac{Q_o}{Q_i} = 1 - 0.712\left(\frac{V_s}{V_r}\right)^{1.328}\left(\frac{t_b}{t_p}\right)^{0.546}$$

where:

Q_o = outflow peak flow (cfs)
Q_i = inflow peak flow (cfs)
V_s = volume of storage (in)
V_r = volume of runoff (in)
t_b = time base of the inflow hydrograph (hr) [Determined as the time from the beginning of rise to a point on the recession limb where the flow is 5 percent of the peak]
t_p = time to peak of the inflow hydrograph (hr)

3. Multiply the peak flow rate of the inflow hydrograph, Q_i, by the potential peak flow reduction calculated from Step 2 to obtain the estimated peak outflow rate, Q_o, for the selected storage volume.

3.2.5 Calculation of the Channel Protection Volume

The Simplified SCS Peak Runoff Rate Calculation approach (see Section 3.1.5.4) can be used for determination of the channel protection volume (CPv) for storage facility design. The calculation procedure is as follows.

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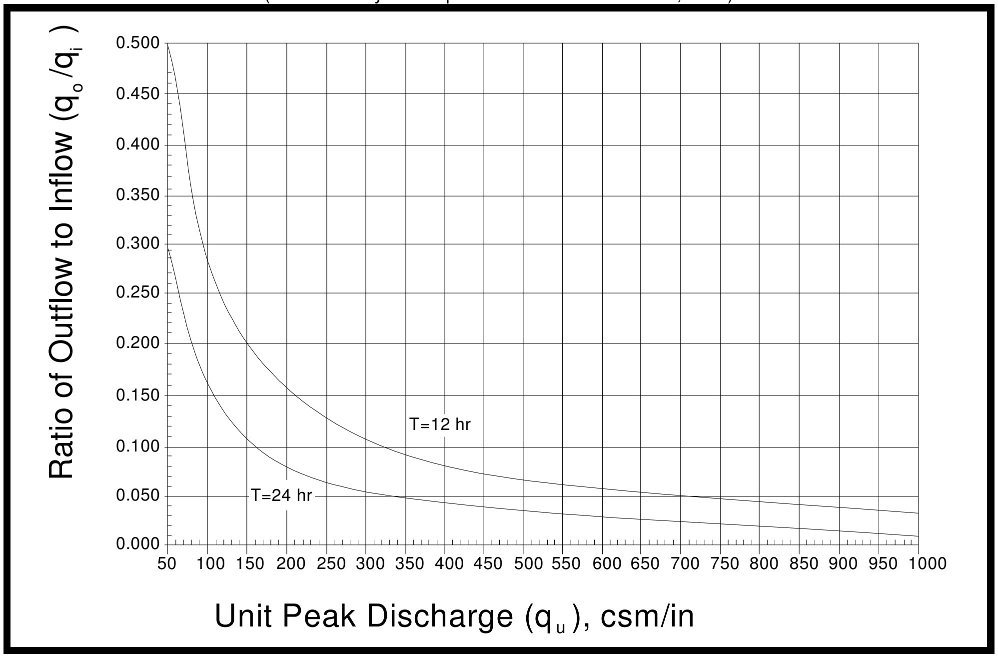
4. Use Figure 3-6 to determine the unit peak discharge (q_U) based on I_a/P and time of concentration (t_c).
5. Knowing q_U and T (extended detention time, minimum of 24 hours and maximum of 72 hours), the q_o/q_i ratio (peak outflow discharge/peak inflow discharge) can be estimated from Figure 3-15.

Figure 3-15. Detention Time vs. Discharge Ratios

(Source: Maryland Department of the Environment, 1998)



6. A <u>preliminary estimate</u> of CPv can then be determined using calculation of V_s/V_r from Figure 3-16 or Equation 3-36, developed from the SCS TR-55 hydrologic model using a Type II rainfall distribution. Equation 3-36 is not appropriate for final calculation of CPv because the accuracy of the equation is suspect when the expression q_o/q_i approaches the limits given of 0.1 and 0.8.

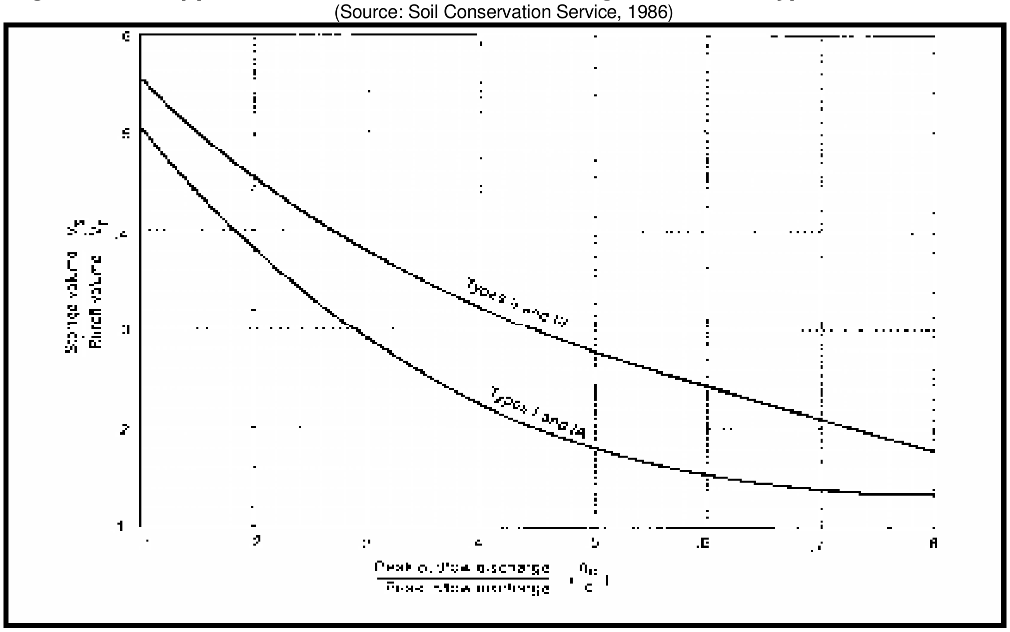
Equation 3-36

$$\frac{V_s}{V_r} = 0.682 - 1.43\left(\frac{q_o}{q_i}\right) + 1.64\left(\frac{q_o}{q_i}\right)^2 - 0.804\left(\frac{q_o}{q_i}\right)^3$$

where:

V_s = required storage volume (acre-feet)
V_r = runoff volume (acre-feet)
q_o = peak outflow discharge (cfs)
q_i = peak inflow discharge (cfs)

Figure 3-16. Approximate Detention Basin Routing for Rainfall Types I, IA, II, and III
(Source: Soil Conservation Service, 1986)



7. The required storage volume (CPv in this case) can then be calculated using Equation 3-37.

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Equation 3-37

$$V_s = \frac{\left(\frac{V_s}{V_r}\right) Q_d A}{12}$$

where:

V_s and V_r are defined above
Q_d = the developed runoff for the design storm (inches)
A = total drainage area (acres)

<u>Example 3-10. Calculation of WQv and CPv</u>

Compute the 100-year peak discharge for a 50-acre wooded watershed located in Knox County, which will be developed as follows:

Forest land - good cover (hydrologic soil group B) = 10 ac
Forest land - good cover (hydrologic soil group C) = 10 ac
Residential with 1/3 acre lots (hydrologic soil group B) = 20 ac
Industrial development (hydrological soil group C) = 10 ac

Other data include the following:
Total impervious area = 18 acres
% of pond and swamp area = 0

<u>Step 1.</u> Calculate the rainfall excess.
The 100-year, 24-hour rainfall is 6.50 inches (0.275 in/hr x 24 hours from Table 3-4).
The 2-year, 24 hour rainfall is 3.30 inches (0.138 in/hr x 24 hours from Table 3-4).
The composite weighted runoff coefficient is calculated in the table below.

Dev. #	Area (ac)	% Total	CN	Composite CN[1]
1	10	20	55	11
2	10	20	70	14
3	20	40	72	28.8
4	10	20	91	18.2
Total	50	100	-	72

1 – Composite CN = $\frac{\%\ Total}{100}$ * CN.

From Equation 3-12, Q_d= 0.53 inches and Q_{100} = 3.4 inches

Step 2 Calculate t_c.
The hydrologic flow path for this watershed = 1,890 ft. It is divided into segments as shown in the table below.

Segment	Type of Flow	Length (ft)	Slope (%)
1	Overland n = 0.24	40	2.00
2	Shallow channel	750	1.70
3	Main channel*	1100	0.50

* For the main channel, n = 0.06 (estimated), width = 10 feet, depth = 2 feet, rectangular channel

Segment 1 – Travel time from Equation 3-4 with P_2 = 3.30 in (0.138 x 24 from Table 3-4)
T_t = $0.007[(0.24)(40)]^{0.8}/(3.30)^{0.5}(0.02)^{0.4}$
= 0.115 hrs = 6.75 minutes

Segment 2 – Travel time from Figure 3-2 or Equation 3-7
V = 2.1 ft/s
T_t = 750/(60)(2.1) = 5.95 min

Segment 3 - Using Equations 3-10 and 3-9
V = $[(1.49)(0.06)(1.43)]^{0.67}/(0.005)^{0.5}$ = 2.23 ft/s
T_t = 1100/60(2.23) = 8.22 min

Therefore, adding the three segments using Equation 3-3:
t_c = 6.75 + 5.95 + 8.22 = 20.92 min = 0.35 hours

Step 3 Calculate I_a/P for CN= 72, I_a = 0.778 (Table 3-14)
I_a/P = (0.778 / 6.50) = 0.12
(Note: Use I_a/P = 0.10 for Figure 3-6. Straight line interpolation can also be used.)

Step 4. Unit discharge q_u (100-year) from Figure 3-6 = 650 csm/in, following process yields q_u (1-year) = 580 csm/in

Step 5. Calculate peak discharge with F_p = 1 using Equation 3-16
Q_{100} = 650(50/640)(3.4)(1) = 170 cfs

Step 6. Calculate water quality volume (WQv)
Compute runoff coefficient, Rv
Rv = 0.015 + 0.0092IA = 0.015 + 0.0092(18) = 0.18
WQv = 1.1(0.18)(50)/12 = 0.83 ac-ft

Step 7. Calculate channel protection volume (CPv = V_S)

Knowing q_u (1-year) = 580 csm/in from Step 4 and T (extended detention time of 24 hours), find q_o/q_i from Figure 3-15.

q_o/q_i = 0.03

For a Type II rainfall distribution,

V_s/V_r = 0.682 - 1.43(q_o/q_i) + 1.64$(q_o/q_i)^2$ – 0.804$(q_o/q_i)^3$

V_s/V_r = 0.682 - 1.43(0.03) + 1.64$(0.03)^2$ – 0.804$(0.03)^3$ = 0.64

Therefore, stream channel protection volume with Q_d (1-year developed) = 0.53 inches, from Step 1, is

CPv = V_x = (0.64)(0.53)(50)/12 = 1.41 ac-ft