Chapter 15
STORAGE FACILITIES

MONTANA
Department of Transportation

HYDRAULICS MANUAL

January 2022

TABLE OF CONTENTS

LIST OF FIGURES

Chapter 15
STORAGE FACILITIES

15.1 INTRODUCTION

15.1.1 Overview

This chapter provides criteria, design guidelines, sizing, and routing for permanent detention/retention storage basins that are associated with highway drainage. For more detailed information, see HEC 22 (1) and HDS 2 (2).

Use the procedures in Section 9.3 to determine the appropriate design frequencies. Reference the preliminary roadway geometrics before using the design procedures in this chapter. The chapter provides the following:

- General considerations (Section 15.2),
- Design criteria (Section 15.3),
- Design guidelines for sizing detention storage (Section 15.4), and
- Documentation (Section 15.5).

15.1.2 Municipal Separate Storm Sewer System (MS4) Permit

A MS4 permit is required for storm sewer systems associated with MDT highways in urban areas that serve a population of at least 10,000 people. See Section 7.3.3 for a discussion on the MS4 permit.

In addition to the design criteria presented in this chapter, projects in MS4 regulated areas require additional treatment of postconstruction stormwater runoff. The online document *Montana Post-Construction Storm Water BMP Design Guidance Manual* provides guidance for selecting and designing post-construction stormwater controls.

Coordinate with the MDT Environmental Services Bureau to determine when MS4 requirements apply to a project.

15.1.3 Off-Site Development/System Impacts

Off-site development/system impacts are discussed in Sections 15.3.3 and 14.3.6.

15.1.4 Symbols and Definitions

To provide consistency within this chapter and throughout this *Manual*, the symbols in Figure 15.1-1 will be used. These symbols have been 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, the symbol will be defined in the text or equations.

Figure 15.1-1 — SYMBOLS AND DEFINITIONS

Symbol	Definition	Units
A	Cross sectional or surface area	ft^2
C	Weir coefficient	—
d	Change in elevation	ft
D	Depth of basin or diameter of pipe	ft
f	Infiltration rate	in/h
g	Acceleration due to gravity	ft/s^2
H	Head on structure	ft
H_c	Height of weir crest above channel bottom	ft
I	Inflow rate	ft^3/s
L	Length	ft
O	Outflow rate	ft^3/s
r	Ratio of width to length of basin at base	—
Q_i	Peak inflow rate	ft^3/s
Q_o	Peak outflow rate	ft^3/s
S_a	Surface area	acre(s)
t	Routing time period	s, m, h
t_i	Time base on hydrograph	s
T_i	Duration of basin inflow	h
t_p	Time to peak	h
V	Storage volume	ft^3, acre-ft
W	Width of basin	ft
Z	Side slope factor	ft

15.1.5 National Dam Safety Program

The National Dam Safety Program (NDSP), which was formally established by the *Water Resources and Development Act* of 1996, includes grant assistance to states, dam safety research, and dam safety training. Under the federal regulations, a dam is an artificial barrier that does or may impound water that is 25 ft or greater in height or has a maximum storage volume of 50 acre-ft or more (3). National responsibility for the promotion and coordination of dam safety resides with FEMA. Responsibility for administration of the provisions of the NDSP has been given to the states. The Montana DNRC Dam Safety Program oversees dam safety in Montana.

15.2 GENERAL CONSIDERATIONS

15.2.1 Location

The location of a storage facility is important because it relates to the effectiveness of the facility to control downstream flooding. A small facility will only have minimal flood control benefits, and the benefits will quickly diminish as the flood wave travels downstream. 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. Thus, it is important for the hydraulic engineer to design a storage facility as a drainage structure that both controls runoff from a defined area and interacts with other drainage structures within the drainage basin.

15.2.2 Maintenance

Proper design should focus on the elimination or reduction of maintenance requirements by addressing the potential for future problems:

- Control sedimentation by constructing traps to contain sediment for easy removal or low-flow channels to reduce erosion and sediment transport.
- Control bank deterioration with protective lining or preferably by limiting bank slopes.
- Eliminate standing water or soggy surfaces by sloping basin bottoms toward the outlet, constructing low-flow pilot channels across basin bottoms from the inlet to the outlet, or constructing underdrain facilities to lower water tables.
- Select outlet structures to minimize the possibility of blockage (e.g., very small pipes tend to block quite easily and should be avoided). Ice accumulation should also be considered.
- Provide access so that maintenance can be conducted on a regular basis to address litter and sediment removal without causing damage to fences and perimeter vegetation.

15.2.3 Detention and Retention

Stormwater storage facilities are often referred to as either detention or retention facilities. For this chapter, detention facilities are those that are designed to reduce the peak discharge, detain runoff for a short period of time, and then drain after the design storm has passed.

Retention or infiltration basins do not have an outlet structure (except an emergency overflow) and instead are designed to drain into the groundwater table or evaporate.

Detention and retention facilities may have water quality and water quantity benefits as described in the following two sections.

15.2.3.1 Water Quality

The control of stormwater quality using storage facilities offers the following potential benefits:

- Decreased downstream channel erosion through peak flow reduction;
- Controlled sediment deposition; and
- Improved water quality through stormwater filtration and/or capture of the first flush with detention for 24 hours or more.

15.2.3.2 Water Quantity

Controlling the quantity of stormwater using storage facilities can provide the following potential benefits:

- Prevention or reduction of the peak runoff rate increases caused by urban development,
- Mitigation of downstream drainage capacity problems,
- Recharge of groundwater resources,
- Reduction or elimination of the need for downstream outfall improvements, and
- Maintenance of historic low-flow rates by controlled discharge from storage.

15.2.4 Pedestrians

Consider the risk associated with locating storage areas adjacent to schools, recreational areas, or urban areas that are subject to frequent visits by the public. In high-risk locations, design the storage features to minimize risk by flattening slopes, limiting water depths, and providing fencing where necessary.

15.3 DESIGN CRITERIA

15.3.1 General Criteria

When the capacity of existing downstream conveyance facilities is inadequate to accommodate peak-flow rates from additional storm drain facilities, a reduction of peak flows may be necessary. Reducing peak flows can be achieved by the storage of runoff in detention basins, retention basins, storm drain pipes, swales and channels, and other detention storage facilities. Additional benefits of storage may include the reduction of downstream pipe sizes and the improvement of water quality by removing sediment or pollutants or both.

Projects in a MS4 area will also need to follow the local MS4 requirements for detention. In addition, projects in municipalities may have local requirements for detention.

Storage may be concentrated in large, basin-wide or regional facilities or distributed throughout a drainage system. Storage may be developed in depressed areas in parking lots, road embankments and freeway interchanges, parks and other recreational areas, and small lakes, ponds, and depressions within developments. The utility of any storage facility depends on the amount of storage, its location within the system, and its operational characteristics. An analysis of storage facilities should include comparing the design flow at a point or points downstream of the proposed storage site with and without storage. In addition to the design flow, other flows exceeding the design flow that might be expected to pass through the storage facility should be included in the analysis (e.g., 100-year flood).

The design criteria for storage facilities should include:

- Hydrology (Section 15.3.2),
- Release rate (Section 15.3.3),
- Storage volume (Section 15.3.4),
- Grading and depth requirements (Section 15.3.5),
- Outlet works (Section 15.3.6), and
- Retention facilities (Section 15.3.7).

15.3.2 Hydrology

Reference Section 9.4.3 for hydrograph development.

15.3.3 Release Rates

All storage facilities designed for MDT projects and all off-site development that drains towards MDT property (system impacts) must meet the following criteria:

- The 2-year, 24-hour, peak post-development discharge is detained to the predevelopment peak runoff rate.
- Sufficient storage is provided so that the 100-year, 24-hour event outfall discharges will not increase the risk to adjacent or downstream properties.
- The 100-year, 24-hour event will safely pass through an emergency overflow.

Storage facilities designed for MDT projects must meet the additional criteria below:

- Detain the design flood frequency event (see Section 14.3.3) and the 2-year, 24-hour event to the predevelopment runoff rate. Multi-stage outlet structures will be required.
- If the project is in a municipality, meet the MDT criteria above and the municipality's design criteria for storage-facility release rates. Multi-stage outlet structures will be required.
- For outfalls to existing storm drains or drainage ways, provide storage to ensure that the proposed design flood (see Section 14.3.3) discharge rate does not exceed the capacity of the downstream system.

15.3.4 Storage Volume

Use routing calculations to demonstrate that the storage volume is adequate to meet the criteria in Section 15.3.3. Design detention basins to drain the active storage volume within 72 hours to prevent excessive saturation of embankment material and to allow the pond to drain before a subsequent storm.

Additional detention volume may be needed to meet water-quality requirements in MS4 areas; see Section 7.3.3.

15.3.5 Grading and Depth Requirements

Grading is important to ensure that adequate storage volume and an aesthetic appearance are provided for the storage facility. However, it is critical to the safety of individuals who live near the facility or use the facility for recreational purposes. As a general rule, slopes should be as flat and depths as shallow as site conditions and safety considerations allow. If someone falls into the facility, slopes should be flat enough to allow the individual to easily climb out. Slope terracing is sometimes effective. Slope stabilization should be accomplished with vegetation or other materials that are traversable when wet.

The following presents the general grading and depth criteria for storage facilities:

- Vegetated embankments must have side slopes no steeper than 3H:1V and follow federal/state dam safety regulations. Slopes 4H:1V or flatter are preferred.
- Riprap-protected embankments must be no steeper than 2H:1V.
- Where possible, limit the 2-year water storage depth to 3 ft or less.
- Grade the pond to provide a minimum freeboard of 1 ft above the 100-year, 24-hour water surface elevation.
- For detention facilities, a minimum 2% bottom slope is recommended. A low-flow or pilot channel constructed across the facility bottom from the inlet to the outlet is recommended to convey low flows and prevent standing water conditions.
- Geotechnical slope-stability analysis is recommended for embankments constructed from fill material.
- Although rare, impoundment volumes greater than 50 acre-ft may be subject to the requirements of the National Dam Safety Program; see Section 15.1.5.

Other considerations when setting depths include flood elevation requirements, municipality requirements, public safety, land availability, land value, present and future land use, water table fluctuations, soil characteristics, maintenance requirements, and required freeboard. Aesthetically pleasing features including pond shape are also important; avoid square or rectangular ponds. Pedestrian consideration is addressed in Section 15.2.4.

15.3.6 Outlet Works

Outlet works selected for storage facilities should have the capacity to accomplish the design functions of the facility. Typically, outlet works include a principal spillway and an emergency spillway. Outlet works can consist of combinations of drop inlets, pipes, weirs, and orifices. Slotted riser pipes are discouraged because of clogging problems. The principal outlet is intended to convey the design storm without allowing flow to enter an emergency outlet/spillway. For large storage facilities, selecting a flood magnitude for sizing the emergency outlet should be consistent with the potential threat to downstream life and property if the basin embankment fails. Design the emergency overflow for the minimum of a 100-year storm. The size of a specific outlet works is determined using hydrologic routing calculations. See Section 15.4.4.

15.3.7 Retention Facilities

Where an adequate outfall is not available, a retention facility may be considered provided that:

- The entire 2-year, 24-hour storm volume is retained (not the difference between the existing and the proposed volumes);
- When sizing the facility, assume no infiltration while the pond is filling;
- Native soils have an infiltration rate such that the facility will drain in a maximum of 72 hours;
- There is a distance of at least 2 ft to 5 ft between the bottom of the facility to the seasonable high-water table and 5 ft to the underlying bedrock;
- A detailed onsite geotechnical assessment is completed to determine the infiltration rate and the depth to groundwater;
- Sufficient storage is provided so that the 100-year, 24-hour event outfall discharge will not increase the risk to adjacent or downstream properties;
- The 100-year, 24-hour event will safely pass through an emergency overflow; and
- Sufficient distance is provided from the retention facility to avoid flooding or contaminating nearby foundations, septic systems, and water wells.

15.4 DESIGN GUIDELINES FOR SIZING DETENTION STORAGE

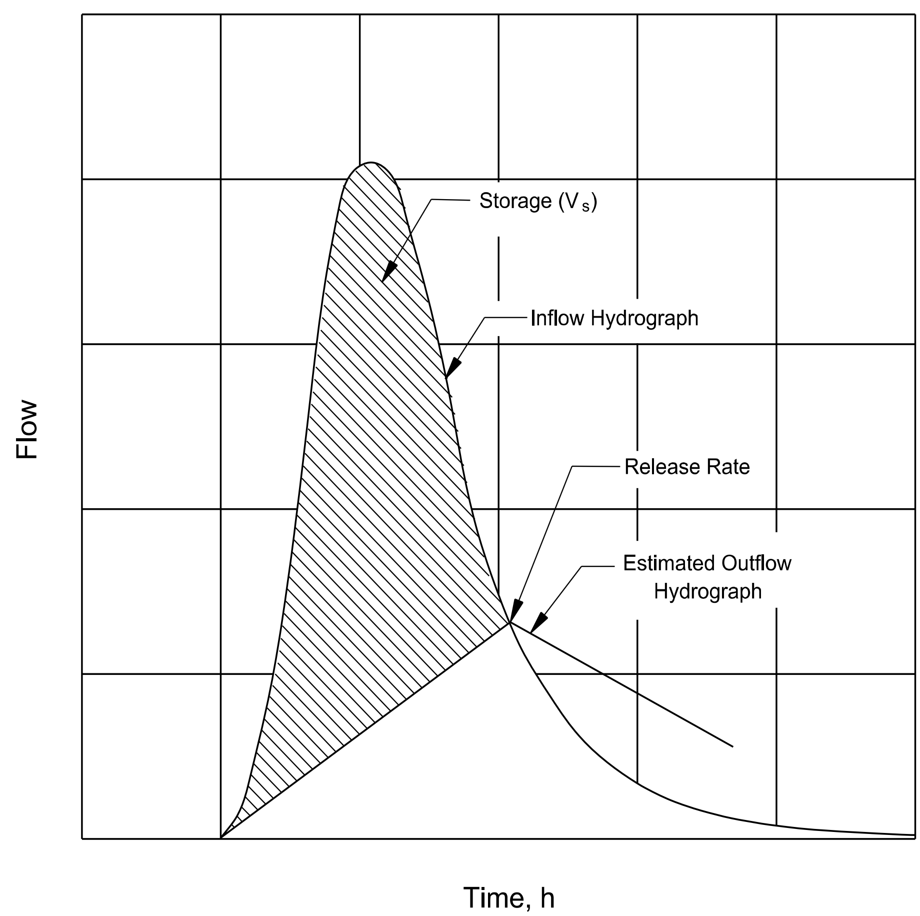
15.4.1 Data Needs

The following data will be needed to complete storage design and routing calculations:

- Inflow hydrograph for all selected design storms; see Figure 15.4-1 for an example.
- Stage-storage curve for proposed storage facility (see Section 15.4.2 and Figure 15.4-2 for an example). For large storage volumes (e.g., for reservoirs), use acre-ft; otherwise, use cubic feet.
- Stage-discharge curve for all outlet control structures (see Section 15.4.3 and Figure 15.4-3 for an example).

Using this data, a design procedure, typically through software, is used to route the inflow hydrograph through the storage facility to establish an outflow hydrograph (see Figure 15.4-1). If the desired outflow results are not achieved, basin and outlet geometry are varied to yield new stage-storage and stage-discharge curves, and the routing procedure is repeated until the desired outflow hydrograph is achieved.

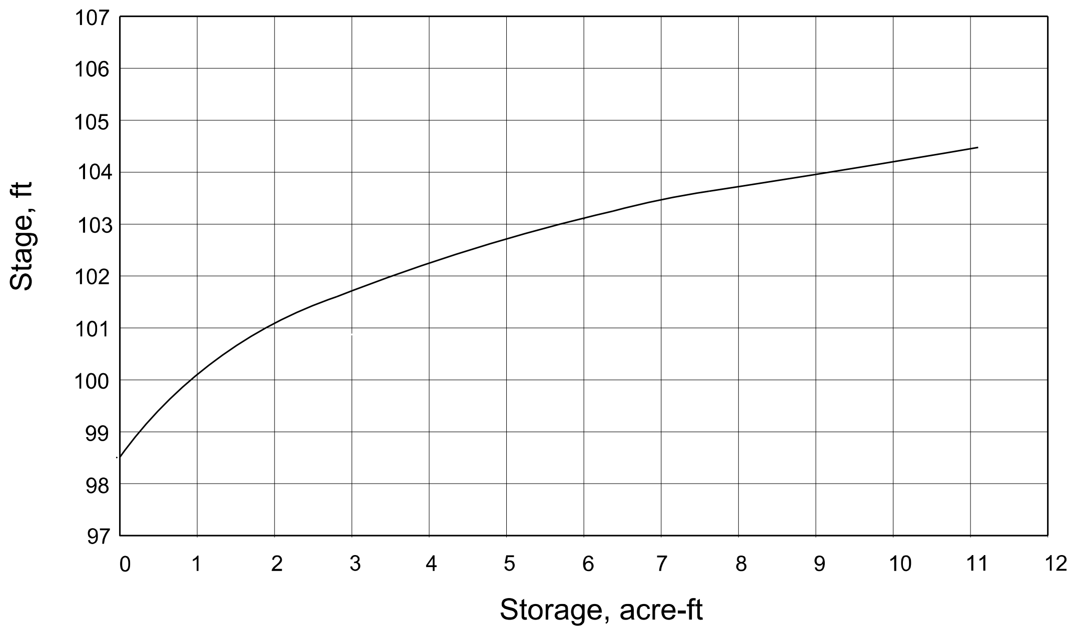
Figure 15.4-1 — INFLOW AND OUTFLOW HYDROGRAPHS FROM A STREAM REACH



15.4.2 Stage-Storage Curve

A stage-storage curve defines the relationship between the depth of water and storage volume in a reservoir. The data for this type of curve is usually developed in CADD from survey data or proposed surfaces. See Figure 15.4-2.

Figure 15.4-2 — EXAMPLE STAGE-STORAGE CURVE



15.4.3 Stage-Discharge Curve

A stage-discharge curve defines the relationship between the depth of water and the discharge or outflow from a storage facility. A typical storage facility has two outlets — principal and emergency. The principal outlet is a multiple stage outlet designed to convey the 2-year and the design flood (and potentially other events if required by local regulations) without allowing flow to enter the emergency outlet or spillway.

A typical outlet structure may include culverts, weirs, orifices, or a combination of all three. Because culverts are typically used as the principal outlet, culvert sizing software such as HY-8 can be used to develop the stage-discharge curve. Avoid slotted riser pipe outlet facilities due to the debris-plugging potential. For design information on weirs and orifices, see HEC 22 (1).

The emergency outlet or spillway should be sized to provide a bypass for the 100-year, 24-hour event. When designing the outlet and spillway, consider the potential threat to downstream life and property.

The stage-discharge curve should reflect the discharge characteristics of both the principal and emergency outlets. Develop a composite stage-discharge curve, which combines the discharge rating curve for all components of the outlet control structure. Figure 15.4-3 illustrates a simple stage-discharge curve, and Figure 15.5-4 illustrates an example composite or combined stage-discharge curve.

Figure 15.4-3 — EXAMPLE STAGE-DISCHARGE CURVE

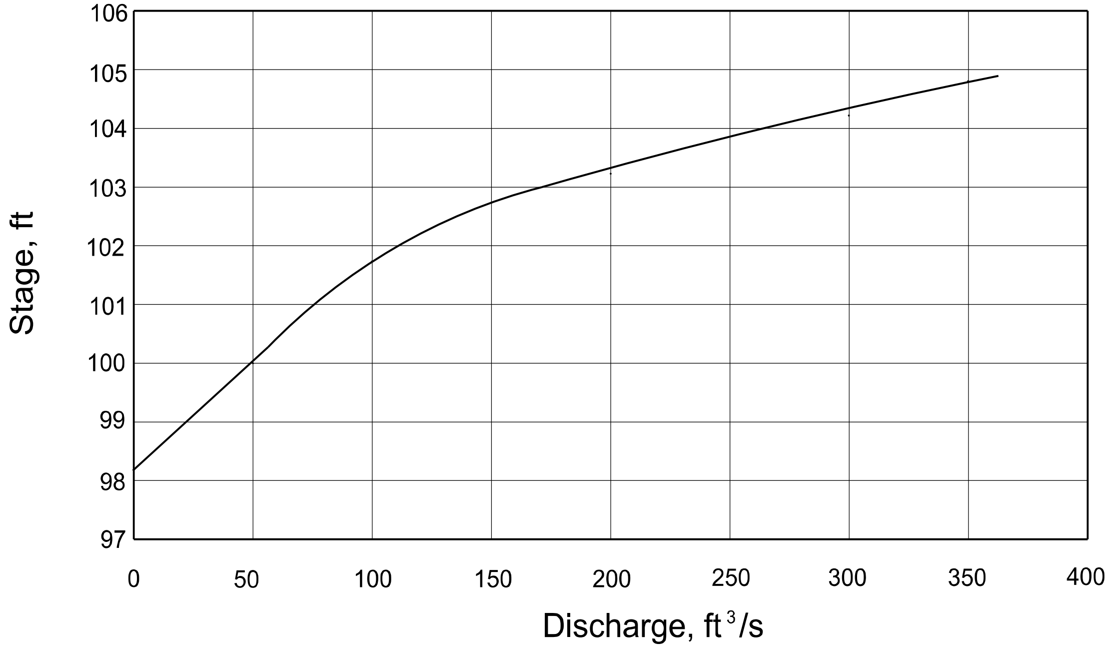
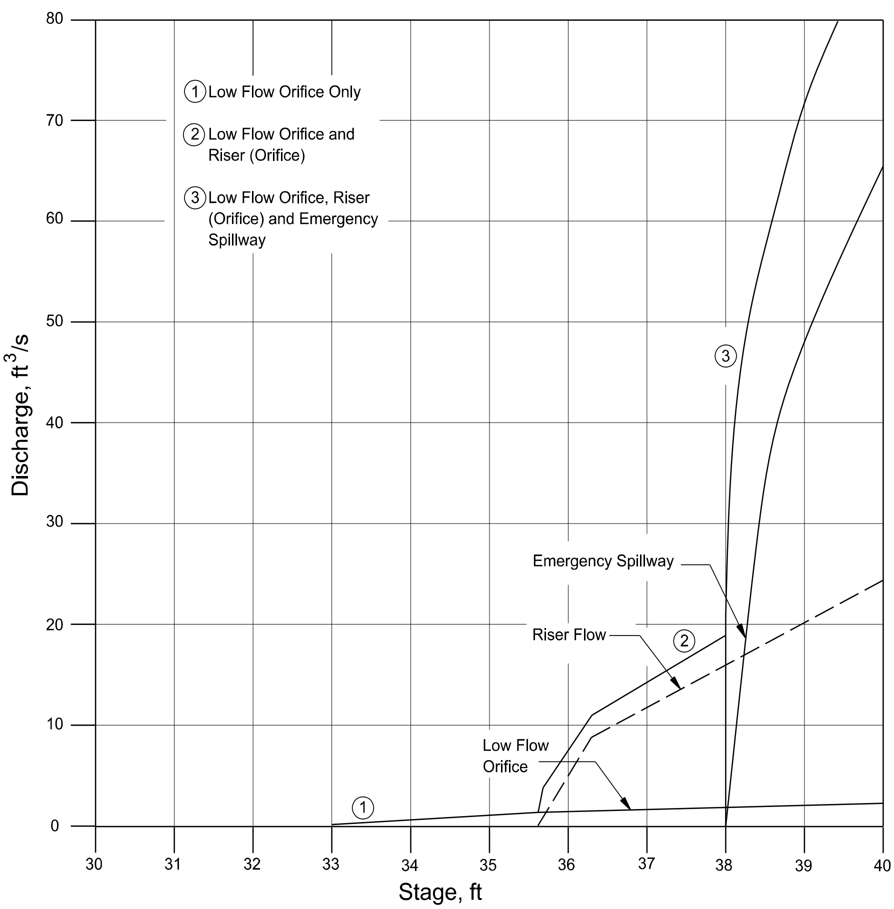


Figure 15.4-4 — COMBINED STAGE-DISCHARGE RELATIONSHIP



15.4.4 Routing Procedure

A commonly used method for routing an inflow hydrograph through a detention pond is the Storage Indication or Modified Puls Method. This method begins with the continuity equation that states that the inflow minus the outflow equals the change in storage (I – O = S). By taking the average of two closely spaced inflows and two closely spaced outflows, the method is expressed by Equation 15.4-1:

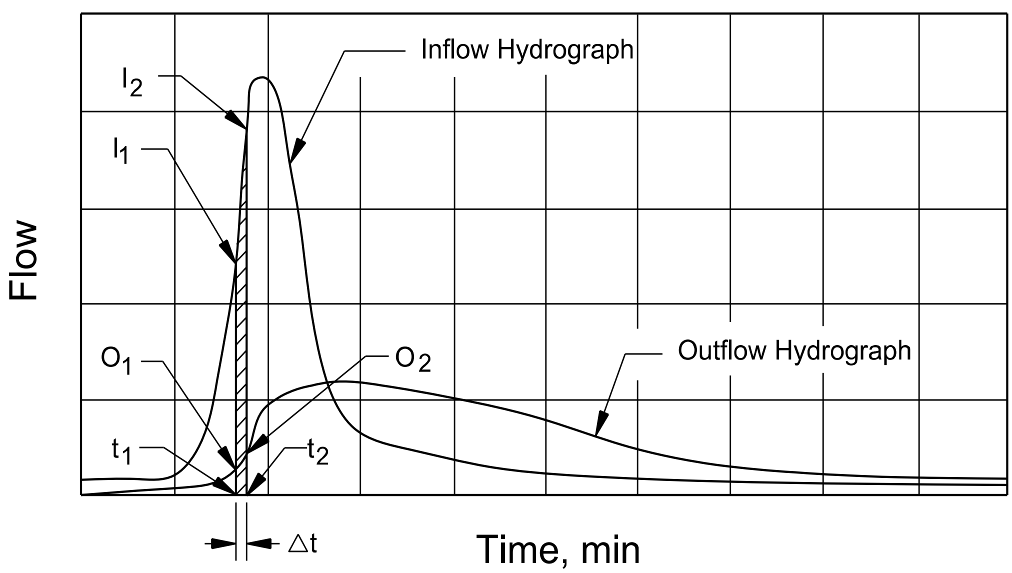
$$\frac{\Delta S}{\Delta t} = \frac{I_1 + I_2}{2} - \frac{O_1 + O_2}{2}$$ Equation 15.4-1

Where:

ΔS = change in storage, ft^3
Δt = time interval, min
I = inflow, ft^3
O = outflow, ft^3

In Equation 15.4-1, subscript 1 refers to the beginning, and subscript 2 refers to the end of the time interval. This relationship is illustrated graphically in Figure 15.4-5.

Figure 15.4-5 — ROUTING HYDROGRAPH SCHEMATIC



Equation 15.4-1 can be rearranged so that all known values are on the left side of the equation and all unknown values are located on the right-hand side of the equation, as shown in Equation 15.4-2. Now, the equation with two unknowns, S_2 and O_2, can be solved with one equation:

$$\frac{I_1 + I_2}{2} + \left(\frac{S_1}{\Delta t} + \frac{O_1}{2}\right) - O_1 = \left(\frac{S_2}{\Delta t} + \frac{O_2}{2}\right)$$ Equation 15.4-2

15.4.5 Preliminary Detention Calculations

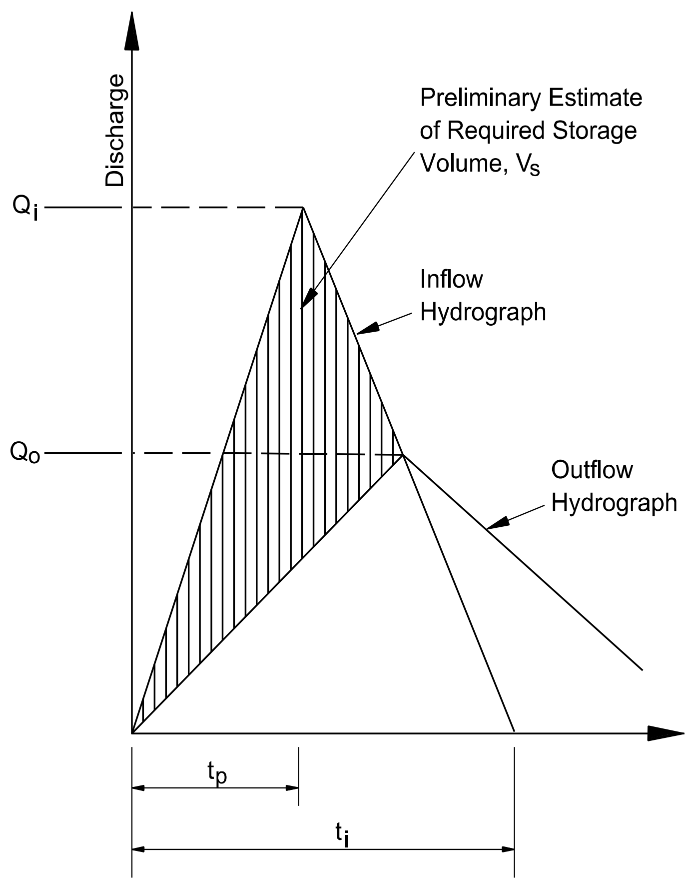
15.4.5.1 Storage Volume

Before designing a detention basin, the required storage volume may be estimated using the methods in HEC-22, Section 8.4. One of the methods, the triangular hydrograph, is described below.

The triangular hydrograph may be used as a preliminary estimate of the required storage volume of a detention facility, but do not use the triangular hydrograph for the final design of the detention facility.

The triangular hydrograph method provides a preliminary estimate of the storage volume required for peak-flow attenuation using the simplified design procedure below that replaces the actual inflow and outflow hydrographs with the standard triangular shapes shown in Figure 15.4-6.

Figure 15.4-6 — TRIANGULAR SHAPED HYDROGRAPHS (Preliminary Storage Volume Estimate)



The required storage volume may be estimated from the area above the outflow hydrograph and inside the inflow hydrograph, expressed as:

$$V_S = 0.5t_i\,(Q_i - Q_o) \qquad \text{Equation 15.4-3}$$

Where:

V_S	=	storage volume estimate, ft^3
Q_i	=	peak inflow rate, ft^3/s
Q_o	=	peak outflow rate, ft^3/s
t_i	=	duration of basin inflow, s (typically 2 × time of concentration)
t_p	=	time to peak, s (time of concentration)

Any consistent units may be used for Equation 15.4-3.

15.4.5.2 Preliminary Basin Dimensions

Use the following procedure to develop the preliminary basin dimensions:

1. Plot the control structure location on a contour map.
2. Select a desired depth of ponding for the design storm.
3. Divide the estimated storage volume needed by the desired depth to obtain the surface area required of the reservoir.

Based on site conditions and contours, estimate the geometric shape(s) required to provide the estimated reservoir surface area.

15.4.6 Detention Storage Design Procedure

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

Step 1: Compute the inflow hydrograph for the runoff from the 2-year, 24-hour, and 100-year, 24-hour storms using the procedures outlined in Chapter 9, "Hydrology," Section 9.4.3. Both pre- and post-development hydrographs are required for the design storms.

Step 2: Perform preliminary calculations to evaluate detention storage requirements for the hydrographs from Step 1 (see Section 15.4.5).

Step 3: Determine the physical dimensions necessary to contain the estimated volume from Step 2, including freeboard. Compare the required volume against available volume at the site. If the site has sufficient available storage, continue to Step 4.

Step 4: Size the outlet structure. The estimated peak stage will occur for the estimated volume from Step 2. Size the outlet structure to convey the peak outflow rate from the desired outflow hydrograph.

Step 5: Perform routing calculations using inflow hydrographs from Step 1 and Equation 15.4-2 or hydraulic routing software to check the preliminary design. If the routed post-development peak discharges from the design storm exceed the predevelopment peak discharge or if the peak stage varies significantly from the estimated peak stage from Step 4, then revise the estimated volume and return to Step 3.

Step 6: Design the emergency overflow for the minimum of a 100-year storm, and design pond grading to have a minimum freeboard of 1 ft above the 100-year water surface elevation.

Step 7: Assess the downstream effects of detention outflow to ensure that the routed hydrograph does not cause downstream flooding problems. If a sensitive area exists downstream, route the exit hydrograph from the storage facility through the downstream channel system to evaluate the area of interest.

Step 8: Evaluate the control structure outlet velocity, and provide channel and bank stabilization if the velocity will cause erosion problems downstream.

This procedure is typically completed using hydraulic routing software (see Section 8.2.5) and requires multiple iterations to reach a final design.

15.5 DOCUMENTATION

Document the storage design and include the calculations in the Storm Drainage Report. See the Storm Drainage Memo and Report Template in Appendix 14A.

15.6 REFERENCES

1. **FHWA.** *Urban Drainage Design Manual, Hydraulic Engineering Circular No. 22, Third Edition.* Washington, DC : Federal Highway Administration, 2009 (revised 2013). FHWA-NHI-10-009.

2. —. *Highway Hydrology, Hydraulic Design Series No. 2, 2nd Edition.* Washington, DC : Federal Highway Administration, 2002. FHWA-NHI-02-001.

3. **FEMA.** *Federal Guidelines for Dam Safety.* Washington, D.C. : Federal Emergency Management Agency, 2004. FEMA-P-93.