CHAPTER 6

STORAGE AND DETENTION

6.1 OVERVIEW

6.1.1 Introduction

The traditional design of storm systems has been to collect and convey storm runoff as rapidly as possible to a suitable location where it can be discharged. As areas urbanize, this type of design can cause major drainage and flooding problems downstream. Under favorable conditions, the temporary storage of some of the storm runoff can decrease downstream flows and often the cost of the downstream conveyance system. Detention storage facilities can range from small facilities contained in parking lots or other on-site facilities to large lakes and reservoirs either on-site or in some suitable off-site location. This chapter provides general design criteria for detention/retention storage basins as well as procedures for performing preliminary sizing and final reservoir routing calculations.

6.1.2 Detention Facilities Used for Credits

If interested in obtaining a storm water fee credit, please refer to the Storm Water Fee Credit manual for application and requirements.

6.1.3 Location Considerations

It should be noted that the location of storage facilities is very important as it relates to the effectiveness of these facilities to control downstream flooding. Small facilities will only have minimal flood control benefits and these 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 engineer to design storage facilities both as drainage structures controlling runoff from a defined area and as facilities that will interact with other drainage structures within the drainage basin.

6.1.4 Detention and Retention

Urban storm water storage facilities are often referred to as either detention or retention facilities. For the purposes of this chapter, detention facilities are those that are designed to reduce the peak discharge and only detain runoff for some short period of time. These facilities are designed to completely drain after the design storm has passed. Retention facilities are designed to contain a permanent pool of water. Since most of the design procedures are the same for detention and retention facilities, the term storage facilities will be used in this chapter to include detention and retention facilities. If special procedures are needed for detention or retention facilities these will be specified.

6.1.5 Computer Programs

Routing calculations needed to design storage facilities, although not extremely complex, are time consuming and very repetitive. To assist with these calculations there are many reservoir routing computer programs which can be used. There are also several simplified techniques that have been developed to design storage facilities which do not involve routing flows through the detention facility and rely on a water balance equation, equating storage to inflow minus outflow. Since these methods do not give accurate and reliable results, they should not be used and will not be presented in this chapter.

6.2 DESIGN CRITERIA

6.2.1 Introduction

If you do not comply with the Post Construction Control Ordinance then you must follow requirements in the zoning ordinance and the control requirements of 6.2.3 and 6.2.4 apply.

6.2.2 General Criteria

Storage may be concentrated in large basin-wide or regional facilities or distributed throughout an urban drainage system. Possible dispersed or on-site storage may be developed in depressed areas in parking lots, road embankments and freeway interchanges, parks and other recreation areas, and small lakes, ponds and depressions within urban 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 such storage facilities should consist of 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 that might be expected to pass through the storage facility should be included in the analysis (i.e., 100-year flood).

The design criteria for storage facilities should include:

- Release rate
- Storage volume
- Grading and depth requirements
- Outlet works
- Location

Note: The same hydrologic procedure shall be used to determine pre- and post- development hydrology.

6.2.3 Release Rate

Control structure release rates shall approximate pre-developed peak runoff rates for the 2-year and 10-year storms, with emergency overflow capable of handling to 50-year discharge. Design calculations are required to demonstrate that the facility will limit the 2- and 10-year developed discharge rates to pre-developed peak discharge rates. If so, intermediate storm return periods can be assumed to be adequately controlled. Multi-stage control structures may be required to control both the 2- and 10-year storms.

6.2.4 Storage

Storage volume shall be adequate to attenuate the post-development peak discharge rates to pre-developed discharge rates for the 2-year and 10-year storms. Routing calculations must be used to demonstrate that the storage volume is adequate. For detention basins, all detention basins, all detention volume shall be drained within 72 hours.

6.2.5 Storage within Parking Areas

Storage within code-required parking areas are allowed a maximum depth of 6 inches; additional parking areas 10 inches; and 15 inches is allowed in truck storage and loading areas.

6.2.6 Grading and Depth of Earthen Storage Facility

The construction of storage facilities usually requires excavation or placement of earthen embankments to obtain sufficient storage volume. Vegetated and riprap protected embankments shall have side slopes no steeper than 2:1 (H:V) and shall meet requirements of the Dam Safety Law when necessary.

Areas above the normal high water elevations of storage facilities should be sloped at a minimum of 5 percent toward the facilities to allow drainage and to prevent standing water. Careful finish grading is required to avoid creation of upland surface depressions that may retain runoff. The bottom area of storage facilities should be graded toward the outlet to prevent standing water conditions. A minimum 2 percent bottom slope is required. A concrete paved low flow or pilot channel (minimum slope of ½ %) constructed across the facility bottom from the inlet to the outlet shall be considered for conveyance of low flows to prevent standing water conditions.

A minimum freeboard of 6 inches above the 50-year design storm high water elevation shall be provided all impoundments. Storage facilities under the jurisdiction of the North Carolina Department of Environment and Natural Resources (NCDENR), Dam Safety Program of Land Quality are in addition subject to the requirements of the Dam Safety Law (see Section 6.2.9).

6.2.7 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. Curb openings may be used for parking lot storage. 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. Minimum barrels through embankments are 12 inch pipes with corresponding orifice plates. Any orifice smaller than 4 inches in diameter must be protected to prevent blockage. A 2 foot by 2 foot concrete pad must be placed in front of any orifice plate at the invert of the outlet. If the spillway is in fill material then the spillway must be lined.

6.2.8 Off-site Storm Water Detention Facilities

When considering off-site storm water detention facilities (or for storm water release through recorded easements to regulated floodway in lieu of detention) the following requirements must be met:

- All pipes/channels leading from the subject site to the off-site storm water detention facility (or regulated floodway) must be sized to carry the 10-year storm water runoff.
- A “Permanent Detention Easement” leading from the subject site to the off-site detention facility (or regulated floodway) must be shown on a map which has been recorded with the Mecklenburg County Register of Deeds Office. This easement should be centered on the pipe or channel and must be at least 15 feet wide for pipes and 20 feet wide for channels (refer to City Std. #20.30 for easement widths). A metes and bounds description is not required for this portion of the easement.
- A “Permanent Detention Easement” which encompasses the detention facility must be shown on the recorded map. This easement must be described by metes and bounds.

- The recorded map must have a note which clearly states who is responsible for maintenance of the detention facility, pipes, and/or channels located within the Permanent Detention Easements (these easements will not be maintained by the City).
- For off-site detention facilities the recorded map must have a note stating, "The purpose of the Permanent Detention Easement is to provide storm water detention for Lot(s) _____. The pipes and/or channels located within the Permanent Detention easement and leading to the detention facility carry unrestricted storm water flow from the developed upstream Lot(s) ___.
- For storm water released to regulated floodway through an easement, the recorded map must have a note stating "The purpose of the Permanent Detention Easement is to allow storm water release directly to regulated floodway in lieu of on-site storm water detention. The pipes and/or channels located within the Permanent Detention Easement and leading to the regulated floodway carry unrestricted storm water flow from the developed upstream Lot(s) ___.

6.2.9 Dam Safety Law

Under the Dam Safety Law regulations, a dam is a structure and appurtenant works erected to impound or divert water that is 25 feet or greater in height and has a maximum storage volume of 50 acre-feet or more. A number of exemptions are allowed from the Dam Safety Law and any questions concerning a specific design or application should be addressed to the NCDENR, Dam Safety Program of Land Quality (919-707-9220).

6.3 GENERAL PROCEDURE

6.3.1 Data Needs

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

- Inflow hydrograph for all design storms for fully developed and pre-developed conditions.
- Stage-storage curve for proposed storage facility (see Figure 6-1 for an example).
- Stage-discharge curve for all outlet control structures (see Figure 6-2 for an example).

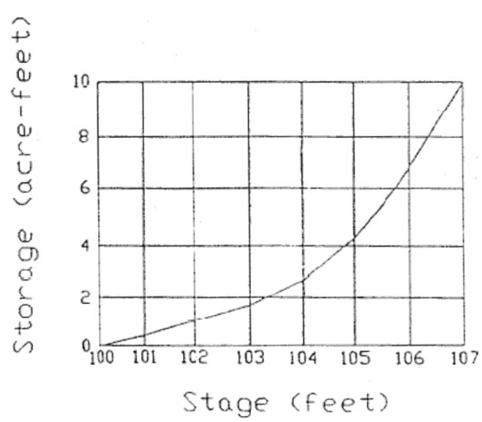

Figure 6-1 Example Stage-Storage Curve

Source: www.lincoln.ne.gov/city/pworks/watrshed/require/drainage/pdf/chapt6.pdf

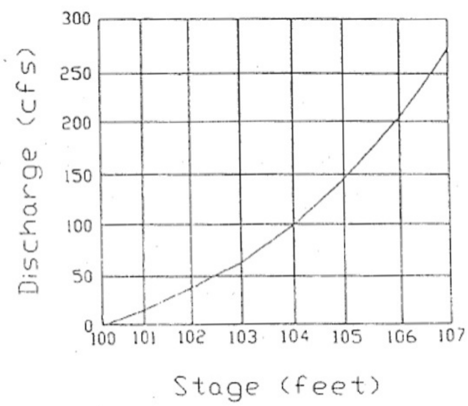

Figure 6-2 Example Stage-Discharge Curve

Source: www.lincoln.ne.gov/city/pworks/watrshed/require/drainage/pdf/chapt6.pdf

Using these data a trial and error design procedure is used to route the inflow hydrograph through the storage facility until the desired outflow hydrograph is achieved.

6.3.2 Procedure

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

1. Compute inflow hydrograph for the 2-, 10-, and 50-year design storms using the procedures outlined in the Hydrology Chapter. Both pre- and post-development hydrographs are required for the 2- and 10-year design storms. Only the post-development hydrograph is required for the 50-year design storm.

2. Perform preliminary calculations to evaluate detention storage requirements for the hydrographs from Step 1 (see Appendix 6A). If storage requirements are satisfied for the 2- and 10-year design storms, intermediate storms are assumed to be controlled.

3. Determine the physical dimensions necessary to hold the estimated volume from Step 2, including freeboard. The maximum storage requirement calculated from Step 2 should be used.

4. Size the outlet structure. Estimate the peak stage for the estimated volume from Step 2. The outlet structure should be sized to convey the allowable discharge at this stage.

5. Perform routing calculations using inflow hydrographs from Step 1 to check preliminary design using the storage routing equations. If the routed post-development peak discharges, 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.

6. Consider emergency overflow from the 50-year (or larger) design storm and establish freeboard requirements, as referenced within this manual and the Dam Safety Law, whichever is more restrictive.

   This procedure can involve a significant number of reservoir routing calculations to obtain the desired results. Computer based methods, such as HEC-1/HEC-HMS, are widely available to perform these iterations quickly. Other computer programs can provide similar results. For guidelines for using other party software, please refer to Section 2.1.2 – Hydrologic Method.

6.4 OUTLET HYDRAULICS

6.4.1 Outlets

Sharp-crested weir flow equation for no end contractions, two end contractions, and submerged discharge conditions are presented below, followed by equations for broad-crested weirs, v-notch weirs, proportional weirs, and orifices, or combinations of these facilities. If culverts are used as outlets works, procedures presented in the Culvert Chapter should be used to develop stage-discharge data.

6.4.2 Sharp-Crested Weirs

A sharp-crested weir with no end contractions is illustrated below. The discharge equation for this configuration is (Chow, 1959):

$$\mathbf{Q = CLH^{1.5}} \qquad \mathbf{(6.1)}$$

Where: Q = discharge (cfs)

H = head above weir crest excluding velocity head (ft)

L= horizontal weir length (ft)

C= sharp crested weir coefficient, use 3.3

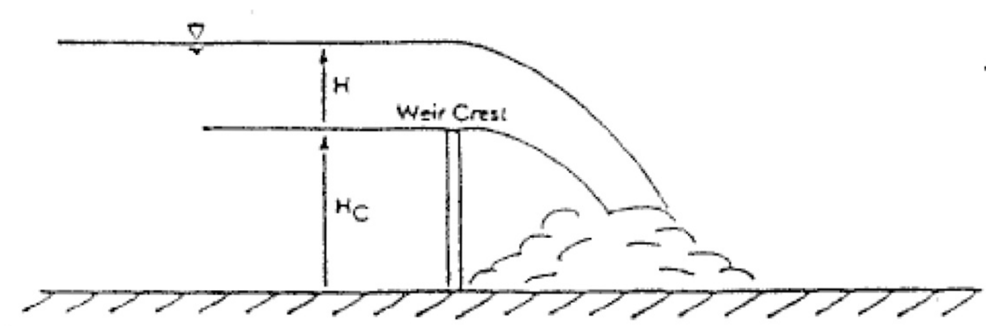

Figure 6-3 Sharp-Crested Weir

Source: www.georgiastormwater.com/vol2/2-3.pdf

6.4.3 Broad-Crested Weirs

The equation generally used for the broad-crested weir (see sketch below) is (Brater and King, 1976):

$$\mathbf{Q = CLH^{1.5}} \qquad \mathbf{(6.2)}$$

Where: Q = discharge (cfs)

C = broad-crested weir coefficient, use 3

L = horizontal weir length (ft)

H = head above weir crest (ft)

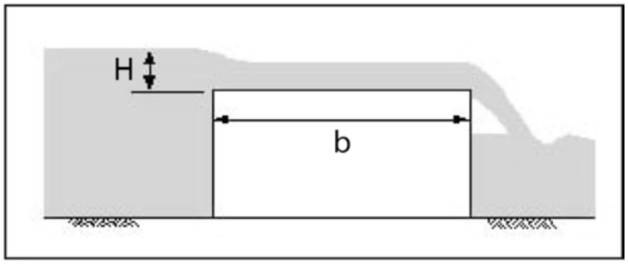

Figure 6-4 Broad-Crested Weir
Source: www.georgiastormwater.com/vol2/2-3.pdf

6.4.4 V-Notch Weirs

The discharge through a v-notch weir can be calculated from the Weirs following equation (Brater and King, 1976).

$$\mathbf{Q = 2.5\tan(\theta/2)H_v^{2.5}} \qquad \textbf{(6.3)}$$

Where: Q = discharge (cfs)

θ = angle of v-notch (degrees)

H_v = head on vortex of notch (ft)

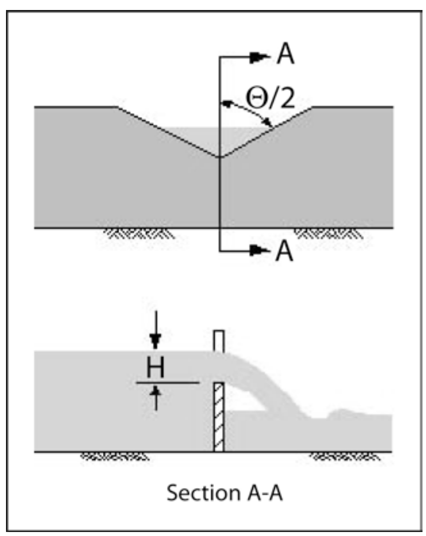

Figure 6-5 V-Notch Weir
Source: www.georgiastormwater.com/vol2/2-3.pdf

6.4.5 Orifices

The general equation for discharge through a submerged orifice is:

$$\mathbf{Q = CA(2gH)^{0.5}} \qquad \textbf{(6.4)}$$

Where: Q = discharge (cfs)

A = cross-section area of smallest section (ft^2)

g = acceleration due to gravity, 32.2 ft/s^2

H = head on pipe, or the vertical distance from the center of the orifice to the upstream free-water surface

C = discharge coefficient, use .60

6.5 CONSTRUCTION AND MAINTENANCE CONSIDERATIONS

An important step in the design process is identifying whether special provisions are warranted to properly construct or maintain proposed storage facilities. To assure acceptable performance and function, storage facilities that require extensive maintenance are discouraged. The following maintenance problems are typical of urban detention facilities and facilities shall be designed to minimize such problems.

- weed growth
- grass and vegetation maintenance
- sedimentation control
- bank deterioration
- standing water or soggy surfaces
- mosquito control
- blockage of outlet structures
- litter accumulation
- maintenance of fences and perimeter plantings

Proper design should focus on the elimination or reduction of maintenance requirements by addressing the potential for problems to develop.

- Both weed growth and grass maintenance may be addressed by constructing side slopes that can be maintained using available power-driven equipment, such as tractor mowers.
- Sedimentation may be controlled by constructing traps to contain sediment for easy removal or low-flow channels to reduce erosion and sediment transport.
- Bank deterioration can be controlled with protective lining or by limiting bank slopes.
- Standing water or soggy surfaces must be eliminated by sloping basin bottoms toward the outlet, constructing low-flow pilot channels across basin bottoms from the inlet to the outlet, or by constructing underdrain facilities to lower water tables.
- In general, when these problems are addressed, mosquito control will not be a major problem.
- Outlet structures should be selected to minimize the possibility of blockage (i.e., very small pipes tend to become blocked quite easily and should be avoided). Outlets shall be no less than 4 inches in diameter.

- Finally, one way to deal with the maintenance associated with litter and damage to fences and perimeter plantings is to locate the facility for easy access where this maintenance can be conducted on a regular basis.

6.6 UNDERGROUND STORAGE

If surface ponding is not feasible, underground storage may be necessary. This can be accomplished by installation of a storage facility under a parking or grassed area. This area shall be required to have appropriate access to allow for its maintenance. In structures over 3’-6” in depth, steps shall be provided in accordance with Charlotte Land Development Standards Manual. The storage facility shall also be required to have all joints properly sealed to prevent undermining of the structures.

When storage is used within a pipe system all pipes shall have sealed joints. The use of o-rings on reinforced concrete or neoprene gaskets for coupling on corrugated metal pipe is necessary. Metal pipe will not be required to have paved inverts. However, they should be designed to prevent corrosion with the use of aluminum pipe and corrosion resistant coatings. The minimum slope on any underground storage structure is 0.5%.

Appendix 6A
CALCULATIONS

6A.1 Routing Calculations

The following procedure is used to perform routing through a reservoir or storage facility (Puls Method or storage indication method of storage routing).

1. Develop an inflow hydrograph, stage-discharge curve, and stage-storage curve for the proposed storage facility. For example of stage-storage and state-discharge curves see Figures 6-1 and 6-2.

2. Select a routing time period, d_t, to provide at least three points on the rising limb of the inflow hydrograph.

3. Use the storage-discharge data from Step 1 to develop storage characteristics curves that provide values of S ± $(0/2)d_t$ versus stage. An example tabulation of storage characteristics curve data is shown below.

(1) Stage (Hs) (ft)	(2) Storage[1] (S) (ac-ft)	(3) Discharge[2] (O) (cfs)	(4) (ac-ft/hr)	(5) S – (O/2) d_t (ac-ft)	(6) S + (O/2) d_t (ac/ft)
100	0.05	0	0	0.05	0.05
101	0.30	15	1.24	0.20	0.40
102	0.80	35	2.89	0.56	1.04
103	1.60	63	5.21	1.17	2.03
104	2.80	95	7.85	2.15	3.45
105	4.40	143	11.82	3.41	5.39
106	6.60	200	16.53	5.22	7.98
107	10.00	275	22.73	8.11	11.89

[1] Obtained from the Stage-Storage Curve above.
[2] Obtained from the Stage-Discharge Curve above.
Note: d_t = 10 minutes = 0.167 hours and 1 cfs = 0.0826 ac-ft/hr

Note: If detention facility contains a permanent pool of water, this can be accounted for by considering the water surface as the zero stage.

4. For a given time interval, I_1 and I_2 from the post development hydrograph are known. Given the depth of storage or stage H_{s1}, at the beginning of that time interval, S_1 – $(O_1/2)$ d_t can be determined from the appropriate storage characteristics curve (example given below).

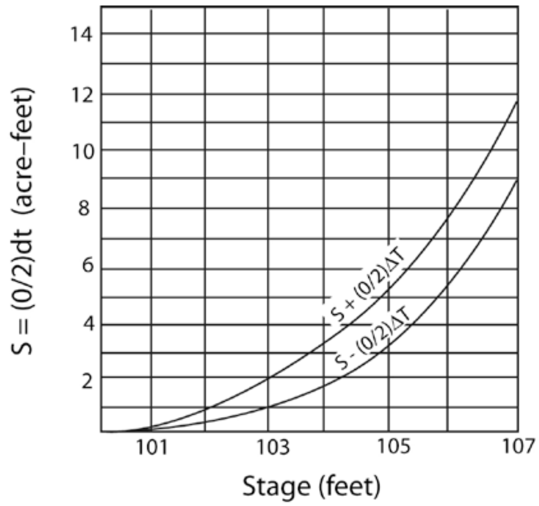

Figure 6A-1 Storage Characteristics Curve

Source: www.lincoln.ne.gov/city/pworks/watrshed/require/drainage/pdf/chapt6.pdf

5. Determine the value of S2 + (O2/2) d_t from the following equation:

$$\mathbf{S_2 + (O_2/2)\, d_t = [S_1 - (O_1/2)\, d_t] + [\{I_1 + I_2\}\, d_t]} \qquad \textbf{(6.7)}$$

Where : S_2 = storage volume at time 2 (ft^3)

O_2 = outflow rate at time 2 (cfs)

d_t = routing time period (sec)

S_1 = storage volume at time 1 (ft^3)

O_1 = outflow rate at time 1 (cfs)

I_1 = inflow rate at time 1 (cfs)

I_2 = inflow rate at time 2 (cfs)

Other consistent units are equally appropriate.

6. Enter the storage characteristics curve at the calculated value of $S_2 + (O_2/2)\, d_t$ determined in Step 5 and read off a new depth of water, H_{s2}.

7. Determine the value of O_2, which corresponds to a storage of H_{s2} determined in Step 6, using the stage-discharge curve.

8. Repeat Steps 1 through 7 by setting new values of I_1, O_1, S_1, and H_{s1} equal to the previous I_2, O_2, S_2, and H_{s2} and using a new I_2 value. This process is continued until the entire inflow hydrograph has been routed through the storage basin.

   When the proposed outlet is large and proposed storage is small, this routing technique may initially be numerically unstable. The actual effect is that the outflow hydrograph and inflow hydrograph virtually match each other during the earliest portion of the design storm. Mathematically, negative storage results on the routing calculation table, and in most spreadsheet applications this will effectively stop the calculation process. The routing may be re-initialized as follows:

1. Set outflow equal to inflow.

2. Set stage based on outflow by referring to the already developed stage-discharge function.

3. Set storage based on stage by referring to the already developed stage-storage function.

4. Restart the routing and repeat steps 1-3 until the system behaves.

(Adapted from H. R. Malcom, P.E., *Elements of Urban Stormwater Design*, NCSU Press, 1989)

APPENDIX 6B
EXAMPLE PROBLEM

6B.1 Example

This example demonstrates the application of the methodology presented in this chapter in routing an inflow hydrograph through a storage facility.

6.B.2 Inflow Hydrograph

Following is the inflow hydrograph for this example (methods described in the Hydrology Chapter would be used to develop this hydrograph).

Time (min)	Inflow (cfs)	Time (min)	Inflow (cfs)
0	0	90	91
10	2	100	61
20	27	110	37
30	130	120	20
40	300	130	11
50	360	140	5
60	289	150	1
70	194	160	0
80	133		

6B.3 Stage-Storage Curve

From the physical characteristics of the storage facility to be used, a stage-storage is developed. Use Figure 6-1 for this example.

6B.4 Stage-Discharge Curve

From the characteristics of the outlet device, a stage-discharge curve is developed. Use Figure 6-2 for this example.

6B.5 Storage Characteristics Curve

A routing time period (d_t) of 10 minutes is selected for this example. Using this routing time period, the stage-storage curve and the stage-discharge curve, storage characteristics curves can be developed. Use Figure A-1 for this example.

6B.6 Routing Calculations

Following are routing calculations for this example. Table B-1 on the next pages gives the results of these calculations.

1. Given that $S_1 - (O_1/2)d_t = 0.05$ acre-foot for $H_{s1} = 0$ foot, find $S_2 + (O_2/2)\ d_t$ by adding 0.05 + 0.01 (column 5 value plus column 3 value) and tabulate 0.06 acre-foot in column 6 of Table B-1.

2. Enter the $S + (O/2)\ d_t$ storage characteristics curve and read the stage at the value of 0.06 acre-foot. This value is found to be 100.10 feet and is tabulated as stage H_{s2} in column 7 of Table B-1.

3. Using the stage of 100.10 feet found in step 2, enter the stage-discharge curve and find the discharge corresponding to that stage. In this case, outflow is approximately 1 cfs and is tabulated in column 8 of Table B-1.

4. Assign the value of H_{s2} to H_{s1}, find a new value of $S_1 - (O_1/2)\ d_t$ and repeat the calculations for steps 1, 2, and 3. Continue repeating these calculations until the entire inflow hydrograph has been routed through the storage facility.

5. The routing calculations give a peak outflow of 220 cfs. The inflow hydrograph has a peak rate of 360 cfs, so a reduction of approximately 40 percent is calculated.

6. If the 40 percent reduction is acceptable then the calculations are complete. If more or less reduction is needed, then new values for stage-storage or stage-discharge must be assigned and the calculations repeated. To comply with local regulations by keeping the peak developed outflow the same as the peak undeveloped outflow for the 2- through 10-year floods, many iterations of the routing calculations may be needed.

(1) Time	(2) Inflow	(3) $[(I_1+I_2)/2]dt$	(4) H_1	(5) S_1-(O/2)dt	(6) $S_2+(O_2/2)dt$	(7) H_2	(8) Outflow
0	0						
10	2	0.01	0.00	0.05	0.06	100.10	1
20	27	0.20	100.10	0.06	0.26	101.10	16
30	130	1.08	101.10	0.21	1.29	102.20	41
40	300	2.96	102.20	.061	3.57	104.10	100
50	360	4.55	104.10	2.20	6.75	105.60	175
60	289	4.47	105.60	4.40	8.87	106.25	217
70	194	3.33	106.25	5.80	9.13	106.30	220
80	133	2.25	106.30	5.90	8.15	105.05	205
90	91	1.54	106.05	5.30	6.84	105.65	177
100	61	1.05	105.65	4.50	5.55	105.10	147
110	37	0.67	105.10	3.60	4.27	104.50	116
120	20	0.39	104.50	2.70	3.09	103.80	87
130	11	0.21	103.80	1.90	2.11	103.05	64
140	5	0.11	103.05	1.18	1.29	102.25	43
150	1	0.04	102.25	0.63	0.67	101.40	22
160	0	0.00	101.40	0.35	0.35	100.70	10

Table 6B-1

Storage Facility Routing Calculations