2C-10 Channel and Storage (Reservoir) Routing

A. Introduction

Flood routing is the process of calculating the passage of the runoff hydrograph through a conveyance system. If the system is a channel, the flood routing is called a channel (stream flow) routing. If the system is a reservoir, the terms storage routing or reservoir routing are applied.

B. Channel routing

Channel flow elements in urban watersheds include gutters, ditches, swales, and sewers. During a rainfall event, unsteady flow will occur in these conveyance elements. Channel routing is the term applied to methods of accounting for the effects of channel storage on the runoff hydrograph as the hydrograph moves through the channel reach. The input and output functions for the channel routing procedure consists of the runoff hydrographs for upstream and downstream sections of a channel. These two functions are related by a channel routing procedure used to translate and attenuate the upstream runoff hydrograph into a downstream hydrograph. The routing procedure has two components – the routing method and the physical channel characteristics of the stream reach. The channel characteristics (slope, roughness, cross section, vegetation, etc.) can generally be quantified from visual and engineering surveys so the routing method becomes the primary design tool. Where existing measured hydrograph data exists for a channel reach, the coefficients for the routing function can be determined. However, for most design situations, the measured hydrograph data is not available. In this case, the upstream hydrograph is synthesized using methods discussed in Section 2C-7, and the resulting downstream runoff hydrograph is computed. Two general approaches are use for solving the unsteady flow problem in channels – hydrologic and hydraulic. The hydrologic approach is based on the storage concept while the hydraulic approach uses principles of mass and momentum conservation. The Muskingum method is used for the hydrologic approach, while the kinematic wave method is used for the hydraulic transformation. The Muskingum method and the related Muskingum-Cunge modification are presented in this manual as the preferred methods for channel routing.

1. **Muskingum method.** For the Muskingum routing, the hydrologic storage equation for a channel reach is:

   $I - O = dS/dt \sim \Delta S/\Delta t$ **Equation 1**

   where:
   I and O are the inflow and outflow rates respectively during the incremental time, Δt,
   S is volume of water in storage in the channel reach

   For the hydrographs shown in Figure 1, the continuity equation can be expressed in terms of the inflow (upstream) and outflow (downstream) at two times, t_1 and t_2, separated by the time increment $\Delta t = t_2 - t_1$.

   The numerical form of the routing equation is expressed in Equation 2:

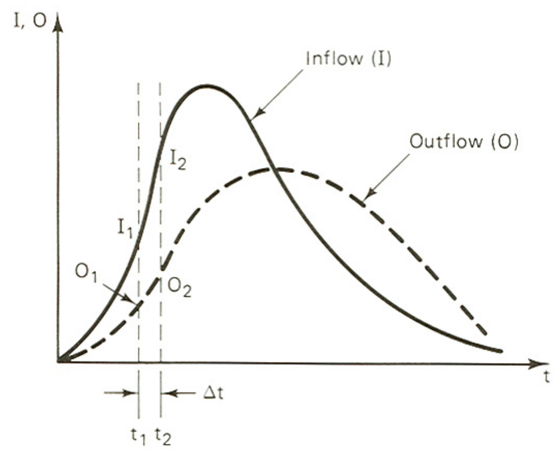
   $(S_2 - S_1)/\Delta t = \frac{1}{2}(I_1 + I_2) - \frac{1}{2}(O_1 + O_2)$ **Equation 2**

Assuming the inflow hydrograph is known for all t, and the initial outflow and storage, O_1 and S_1 are known at time t, then Equation 2 has two unknowns. To use the routing equation, a second relationship is needed. The inflow storage is related to the inflow rate and the outflow storage to the outflow rate, as follows:

$S_I = KI^n$ **Equation 2a**
$S_O = KO^n$ **Equation 2b**

where:
I and O subscripts refer to inflow and outflow
n is an exponent

Figure 1: Schematic of upstream and downstream flood hydrographs



A weighting factor is assigned to account for the relative effect of the inflow and outflow on storage, and then:

$S = xS_I + (1\text{-}x)S_O$ **Equation 2c**

Combining equations 2a, 2b, and 2c gives the relationship between S, I and O (*n* is commonly determined to be 1) as:

$S = K[xI + (1\text{-}x)O]$ **Equation 3**

where:
K = travel time constant
x = weighting factor between 0 and 1.0

When Equation 3 is substituted into Equation 2 and rearranged to solve for O_2, the following expression results:

$O_2 = C_0I_2 + C_1I_1 + C_2O_1$ **Equation 4**

and:

$C_0 = (0.5\Delta t - Kx)/K(1\text{-}x) + 0.5\Delta t$ **Equation 5a**

$C_1 = (0.5\Delta t + Kx)/ K(1\text{-}x) + 0.5\Delta t$ **Equation 5b**

$C_2 = [K(1\text{-}x) - 0.5\Delta t]/ K(1\text{-}x) + 0.5\Delta t$ **Equation 5c**

Equation 4 is the Muskingum routing equation and C_0, C_1 and C_2 are the routing weighting factors.

$C_0 + C_1 + C_2 = 1.0$

Given an inflow hydrograph, an initial flow condition, a chosen time interval ($t_p/\Delta t \geq 5$), and routing parameters K and x, the routing coefficients can be calculated in equations 5a through 5c and the outflow hydrograph from Equation 4. The routing parameters K and x are related to flow and channel characteristics, K being interpreted as the travel time of the flood wave from upstream to downstream end of the channel reach; K is therefore a function of channel length and flood wave speed. The parameter x accounts for the storage portion of the routing – for a given flood event, there is a value of x for which the storage in the calculated outflow hydrograph matches the measured outflow hydrograph. In the Muskingum method, x is used as a weighting factor and restricted to a range of values of 0.0 to 0.5. At $x > 0.5$, the outflow hydrograph becomes greater than the inflow hydrograph (hydrograph amplification). At $K = \Delta t$ and $x = 0.5$, the outflow hydrograph retains the same shape as the inflow and is just translated downstream a time equal to K. For $x = 0$, the Muskingum routing reduced to a linear reservoir routing.

The K and x parameters in the Muskingum method are determined by calibration using streamflow records. The detailed procedure for the calibration is discussed in McCuen (1989).

2. **Muskingum-Cunge method.** An alternative, but related method to the Muskingum procedure, is the Muskingum-Cunge method, which uses a kinematic wave (conservation of mass/momentum) approach. The main advantage of the Muskingum-Cunge method is that the routing coefficients are evaluated from physical channel characteristics and can be determined without existing flood hydrograph data. In the method, for a channel section, it is assumed that:

$Q = eA^m$ **Equation 6**

where:
Q = discharge, cfs
A = flow area, ft^2
e, m = constant parameters

The relationship in Equation 6 can be obtained from a stream channel rating curve. A rating curve can be prepared using the Manning formula. For certain shapes of channels (i.e. triangular, trapezoidal, parabolic), the Manning formula will yield constant values for *e* and *m*. For other x-sectional shapes, *e* and *m* will change with discharge, and average values will need to be used. To apply the Muskingum-Cunge model, first choose a reference flow condition represented by:

Q_0 = reference discharge, cfs
T_0 = top width of the flow at Q_0, ft
V_0 = cross-sectional average velocity at Q_0, fps
A_0 = flow area at Q_0, ft^2

The reference discharge can be chosen as the base flow rate, the peak flow of the inflow hydrograph, or the average inflow rate. Form these reference conditions and the channel characteristics, the Muskingum constants K and x are determined from:

$K = L/mV_0$ **Equation 7**

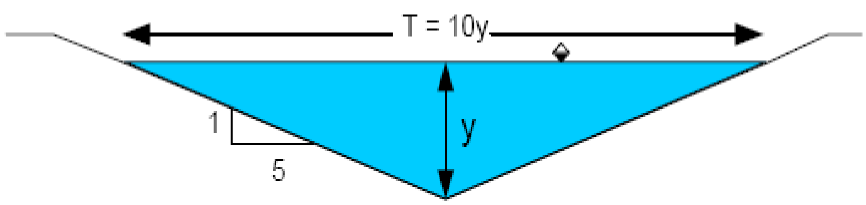
$X = 0.5\,[1-(Q_0/T_o)/(S_0 m V_0 L)]$ **Equation 8**

where:
S_0 = longitudinal slope of the channel, ft/ft
L = length of the channel reach, ft

Using these values of K and x, the coefficients C_0, C_1, and C_2 can be calculated, and the Muskingum Equation 4 is used to route the hydrograph. If the reference discharge is updated every time step, the accuracy of the method is improved by using variable routing coefficients.

Example channel routing (Muskingum-Cunge)
A channel reach has a length , L = 2420 ft, slope, S_o = 0,001 ft/ft, and a Manning roughness coefficient of *n* = 0.05. The channel is rectangular in shape with a side slope of 5:1 (H:V). The channel geometry is shown in Figure 2.

Figure 2: Schematic for Muskingum-Cunge routing example



a. Using Figure 2, the flow area, A, wetted perimeter, P, and the hydraulic radius, R are expressed as:

$A = (y)\,(10y) / 2 = 5y^2$

$P = 2y\,(1 + 25)^{0.5} = 10.2y$

$R = A/P = 0.49y$

b. Substituting these into the Manning formula:

$Q = 1.49/n\,[AR^{2/3}S_o^{0.5}]$

$Q = (1.49/0.05)\,(5y^2)(0.49y)^{2/3}(0.001)^{1/2}$

$Q = 2.928y^{8/3}$

and since $A = 5y^2$:

$Q = 0.343A^{4/3}$

Therefore, using Equation 6, *e* = 0.343 $ft^{1/3}$/sec, and *m* = 4/3.

c. An inflow hydrograph for a small watershed is tabulated in Table 1. Complete the routing through the channel described above. A time increment of Δt = 0.5 hours and a reference discharge of 10 cfs (base flow) will be used.

d. To begin the solution, first determine T_0 and V_0. Using the reference discharge of Q = 10 cfs:

$A_0 = (10/0.343)^{3/4} = 12.55\ ft^2$

$y_0 = (12.55\ ft^2)/5)^{0.5} = 1.58\ ft$

$T_0 = (10)(1.58) = 15.8\ ft$

$V_0 = (10\ cfs)/(12.55\text{-}ft^2) = 0.797\ fps$

From Equations 7 and 8:

$K = (2420\ ft)/[(4/3)(0.797\ fps)] = 2277\ sec = 0.632\ hr$

$X = 0.5\ \{1 – [(10\ cfs)/(15.8\ ft)/(0.001)(4/3)(0.797\ fps)(2420\ ft)]\} = 0.377$

e. Next compute C_0, C_1, and C_3 from Equations 5a through 5c:

$C_o = 0.0182$ $C_1 = 0.7585$ $C_2 = 0.2233$

The routing is completed using the routing Equation 4, and the results are listed in Table 1.

Table 1: Results for Muskingum-Cunge routing example

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Time Step	t_1 (hr)	t_2 (hr)	I_1 (cfs)	I_2 (cfs)	O_1 (cfs)	O_2 (cfs)
1	0	0.5	10	15	10.0	10.09
2	0.5	1.0	15	20	10.09	13.99
3	1.0	1.5	20	25	13.99	18.75
4	1.5	2.0	25	30	18.75	23.70
5	2.0	2.5	30	25	23.70	28.50
6	2.5	3.0	25	20	28.50	25.69
7	3.0	3.5	20	15	25.69	21.18
8	3.5	4.0	15	10	21.18	16.29
9	4.0	4.5	10	10	16.29	11.40
10	4.5	5.0	10	10	11.40	10.31
11	5.0	5.5	10	10	10.31	10.07
12	5.5	6.0	10	10	10.07	10.02

In the WINTR-55 and WINTR-20 computer models, the Muskingum-Cunge method is used to perform the routing of the channel reaches in the watershed. A full inflow hydrograph is computed for each watershed, and the hydrograph is routed along the reach, then added to subsequent reaches as the combined hydrographs are conveyed downstream to the watershed outlet or designated point of design. If the reach contains a storage structure (pond), storage routing is performed using the procedures discussed below (storage-indication routing).

C. Storage (reservoir) routing

Storage routing is similar in concept to channel routing. The inflow hydrograph to the detention basin corresponds to the hydrograph at the upstream location, and the hydrograph for the outflow from the basin corresponds to the downstream hydrograph. The variables involve with storage routing are:

- Input (upstream hydrograph
- Outflow (downstream) hydrograph
- Stage-storage volume relationship
- Physical characteristics of the outlet facility (i.e., weir length, riser pipe diameter, orifice diameter, number of outlet stages, length of the discharge pipe, etc.)
- Energy loss (weir and orifice) coefficients
- Storage volume versus time relationship
- Depth (stage) – discharge relationship
- Target peak discharge allowed from the reservoir (see Section 2C-9)
- Volume and time for extended detention

In most standard detention design scenarios, the inflow hydrograph will usually be derived from a design storm model as discussed in previous sections. The outflow hydrograph will not be known, although a target peak discharge, such as the pre-development peak rate discharge, can be developed from existing watershed conditions for the design storm of interest (usually the Q_5). The stage-storage relationship for the proposed site can be developed, and values for the loss coefficients for the various types of outlets can be determined. The design problem is to determine:

- The type and physical characteristics of the outlet structure
- The storage volume vs, time relationship
- The depth-discharge relationship

The storage routing equation is based on the conservation of mass. The inflow (I), outflow (O), and storage (S) are related by:

Inflow (I) – Outflow (O) = $\Delta S/\Delta t$ **Equation 9**

where:
ΔS is the change in storage during time increment Δt

Both I and O vary with time and are defined by the inflow and outflow hydrographs. Equation 9 can be re-written as :

$$I\,\Delta t - O\,\Delta t = \Delta S$$

Adding the subscripts 1 and 2 for sequential time steps, Equation 9 is re-written as:

$$\tfrac{1}{2}(I_1 + I_2)\,\Delta t - \tfrac{1}{2}(O_1 + O_2)\,\Delta t = S_2 - S_1$$ **Equation 10**

While values for I_1, I_2, O_1, and S_1 are known at any time *t*, values for O_2 and S_2 are unknown. Equation 10 is rearranged to so that the known parameters are placed on the left side of the equation and the unknown parameters on the right side:

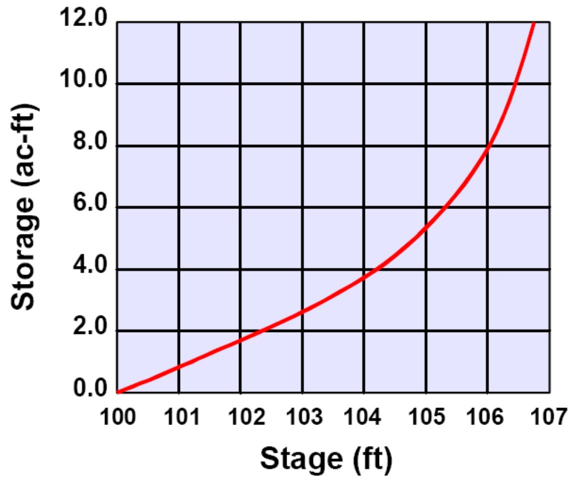
$$\tfrac{1}{2}(I_1 + I_2)\,\Delta t + (S_1 - 1/2 O_1 \Delta t) = (S_2 + 1/2 O_2 \Delta t)$$ **Equation 11**

Equation 11 is one equation with two unknowns (S_2 and O_2), and another equation is needed for a solution. In storage routing, the outflow-storage relationship is used for the other equation. The outflow-storage function is expressed as a stage-storage-discharge relationship.

D. Stage-storage relationship

A stage-storage curve defines the relationship between the depth of water and the associated storage volume in a storage facility. An example is shown in 3. The volume of storage can be calculated by using simple geometric formulas expressed as a function of depth.

Figure 3: Stage-storage curve



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. The double-end area formula is expressed as:

$V_{1,2} = [(A_1 + A_2)/2]d$ **Equation 12**

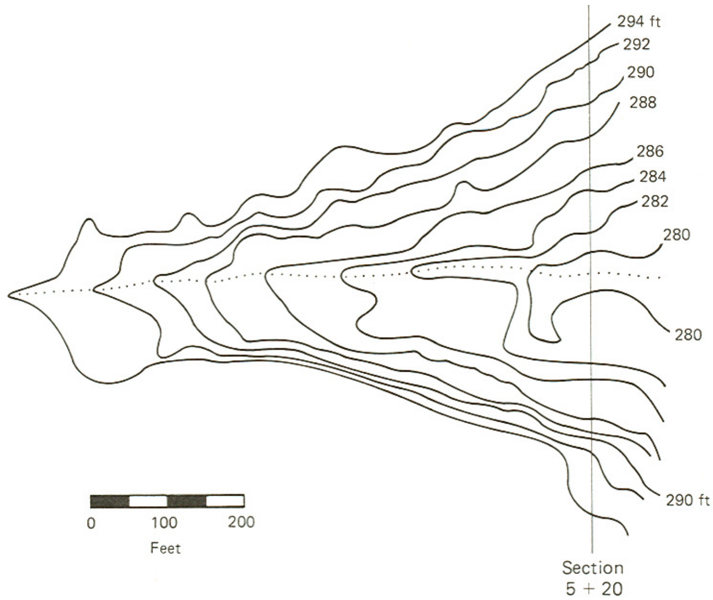
where:
$V_{1,2}$ = storage volume (ac-ft) between elevations 1 and 2
A_1 = surface area at elevation 1 (ac)
A_2 = surface area at elevation 2 (ac)
d = change in elevation between points 1 and 2 (ft)

An example is illustrated using Figure 3. The area within the contour lines in Figure 3 is planimetered (or determined using a CADD program) with the storage at any depth increment Δh (Δd) equal to the product of the average area and the depth increment.

$\Delta S = [(A_1 + A_2)/2]\Delta d$

The results for Figure 3 are summarized in Table 2. The stage-storage relationship was computed and is shown in tabular form in Table 2 and in Figure 4.

Figure 4: Example for deriving stage-storage relationship from topographic map



Source: McCuen, 1989

Table 3: Stage-storage data for Figure 3

Contour elevation	Area within contour elevation (acres)	Average area (acres)	Contour Interval (ft)	Depth (ft)	Change in Storage (acre-ft)	Storage (acre-ft)
279	0.00			0		0
		0.10	1		0.10	
280	0.20			1		0.10
		0.46	2		0.92	
282	0.72			3		1.02
		1.25	2		2.50	
284	1.78			5		3.52
		2.32	2		4.64	
286	2.86			7		8.16
		3.58	2		7.15	
288	4.29			9		15.31
		4.81	2		9.62	
290	5.33			11		24.93
		5.89	2		11.77	
292	6.44			13		36.70
		7.35	2		14.70	
294	8.26			15		51.40

Calculation formulas for other excavated geometric volumes area are listed below:

1. **Frustrum of a pyramid formula.** The frustum of a pyramid formula is expressed as:

   $V = d/3\ [A_1 + (A_1 \times A_2)^{0.5} + A_2]/3$ **Equation 13**

   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)

2. **Prismoidal formula.** The prismoidal formula for trapezoidal basins is expressed as:

   $V = LWD + (L + W)\ ZD^2 + 4/3\ Z^2\ D^3$ **Equation 14**

   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

3. **Circular conic section formula.** The circular conic section formula is:

   $V = 1.047\ D\ (R_1^2 + R_2^2 + R_1R_2)$ **Equation 15**

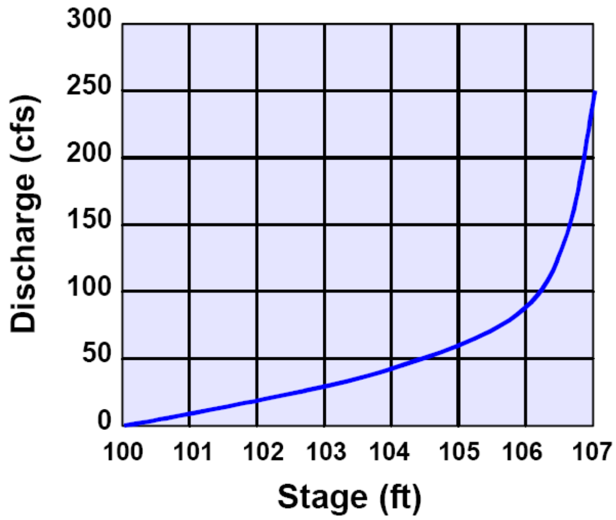
   $V = 1.047\ D\ (3\ R_1^2 + 3ZDR_1 + Z_2D^2)$

   where:
   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

E. Stage-discharge relationship

A stage-discharge curve defines the relationship between the depth of water and the discharge or outflow from a storage facility. An example stage-discharge curve is shown in Figure 5. A typical storage facility has two outlets or spillways: a principal outlet and a secondary (or emergency) outlet. The principal outlet is designed with a capacity sufficient to convey the design flows without allowing flow to enter the emergency spillway. A pipe culvert, weir, or other appropriate outlet can be used for the principal spillway or outlet.

Figure 5: Example stage-discharge curve



The stage-discharge relationship can be computed for various values of *h* once the physical characteristics of the weir or orifice are defined. For multiple stage outlets, both sets of dimensions and loss coefficients for the weir and orifice will be required.

Equation 16 can be used to calculate the stage-discharge (H vs Q) relationship for a sharp-crested weir of length L.

$$Q = 3.3\ LH^{1.5}$$ **Equation 16**

where:
Q has units of cfs
L and H are in units of feet

For the example shown in Table 3 and using a weir length of 1.5 ft, the stage-discharge data is computed. Table 4 contains the computed data for both the stage-storage and stage-discharge relationships. For this example, the invert (crest) elevation of the weir is set 4 feet up from the bottom elevation (i.e. there will be a permanent pool in this structure). Discharge through the outlet begins at depth just over 4 feet, and reaches a maximum rate of 180 cfs at a depth (stage) of 15 feet.

Table 4: Stage-storage and stage-discharge results for example site

Contour elevation	Area within contour elevation (acres)	Average area (acres)	Contour Interval (ft)	Depth (ft)	Change in Storage (acre-ft)	Storage (acre-ft)	Discharge (ft^3/sec)
							0.00
279	0.00			0		0	0.00
		0.10	1		0.10		0.00
280	0.20			1		0.10	0.00
		0.46	2		0.92		0.00
282	0.72			3		1.02	0.00
		1.25	2	4	2.50		0.00
284	1.78			5		3.52	4.95
		2.32	2	6	4.64		14.00
286	2.86			7		8.16	25.72
		3.58	2	8	7.15		39.60
288	4.29			9		15.31	55.34
		4.81	2	10	9.62		72.75
290	5.33			11		24.93	91.68
		5.89	2	12	11.77		112.01
292	6.44			13		36.70	133.65
		7.35	2	14	14.70		156.53
294	8.26			15		51.40	180.59

F. Storage-indication routing

The routing equation below is used to derive the downstream hydrograph O_2 when the stage-storage-discharge relationship is known. The stage-storage-discharge relationship is used to derive the storage-indication curve, which is the relationship between O and $(S + O\Delta t/2)$.

$$\tfrac{1}{2}(I_1 + I_2)\,\Delta t + (S_1 - 1/2O_1\Delta t) = (S_2 + 1/2O_2\Delta t) \qquad \textbf{Equation 17}$$

Given the storage-discharge curve, O vs S, the following four-step procedure is used to develop the storage-indication curve.

- Select a value of O.
- Determine the corresponding value of S from the storage-discharge curve.
- Use the values of S and O to compute $(S + O\Delta t/2)$.
- Plot a point on the storage-indication curve) versus $(S + O\Delta t/2)$.

The steps are repeated for a sufficient number of values for O to define the storage-indication curve.

The objective of the storage-indication method is to derive the outflow hydrograph. Five data sources are required as follows:

- Storage-discharge relationship (based on site geometry)
- Storage-indication curve
- Inflow hydrograph (from hydrograph synthesis or computer output)
- Initial values of the storage and outflow rate.
- Routing increment ($\Delta t \geq t_p/5$); $t_p = 2/3t_c$

The outflow hydrograph is the main output of interest for most design cases. However, the storage function, S vs. t, can also be determined from the storage-indication method. As a check on the final design, one may want to know the storage (and hence water surface elevation) as a function of time. The following five steps can be sued to derive the outflow hydrograph with the storage-time function as a by-product.

- Determine the average inflow: $0.5\Delta t(I_1 + I_2)$
- Compute $S_1 - 1/2O_1\Delta t$
- Using Equation 17 and the values from Steps 1 and 2, compute $S_2 + 1/2O_2\Delta t$
- Using the value computed in Step 3, determine O_2 from the storage-indication curve
- Use O_2 with the storage-discharge relationship to obtain S_2

The five steps are repeated for the next time-increment using I_2, O_2, and S_2 as the new values of I_1, O_1, and S_1, respectively. The process is solved iteratively until the entire outflow hydrograph is compiled. Once the stage-storage-discharge relationships and the storage-indication curve data are determined and plotted, a mathematical expression can be developed for each and used in a spreadsheet computation to speed the process.

The procedure is an iterative solution and does involve a number of calculation steps. The procedure may also need to be repeated over several trial calculations should the outlet configuration need to be modified to meet a peak discharge limitation. WINTR-55 and WINTR-20 contain the storage-indication routing procedure to assist with the design of detention structures. The advantage of the computer models is the speed at which the designed can check several trial sizes of outlet structures to achieve the correct level of control.

Table 5: Table of values for storage indication curve*

Contour Interval (ft)	Depth (ft)	Change in Storage (acre-ft)	Storage (acre-ft)	Storage (ft^3)	Outlet Discharge, O (ft^3/sec)	$S + O\Delta t/2$ (ft3)	$2S/\Delta t + O$ (ft3/sec)
					0.0		
	0		0		0.0		
1		0.10			0.0		
	1		0.10	4,356	0.0		
2		0.92			0.0		
	3		1.02	44,431	0.0		
2	4	2.50			0.0		
	5		3.52	153,331	5.0	154,816	516
2	6	4.64			14.0		
	7		8.16	355,450	25.7	363,166	1,211
2	8	7.15			39.6		
	9		15.31	666,904	55.3	683,506	2,278
2	10	9.62			72.7		
	11		24.93	1,085,951	91.7	1,113,453	3,712
2	12	11.77			112.0		
	13		36.70	1,598,652	133.7	1,638,747	5,462
2	14	14.70			156.5		
	15		51.40	2,238,984	180.6	2,293,161	7,644

* Storage indication ($S_2 + 1/2O_2\Delta t$) calculated for a time-increment of 10 minutes

As another alternative, predetermined solutions to the reservoir routing problem are available for quick estimation of the peak outflow rates from single and double outlet detention basins (Akan, 1989, 1990). The procedures are not included in this manual.

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 is 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 2C-12.

G. Detention design procedure with storage routing

Compute inflow hydrograph for the 2-year, 10-year, and 100-year design storms using WINTR-55. Both pre-development and post-development hydrographs are required for the 2-year and 10-year design storms. Only the post-development hydrograph is needed for the 100-year design storm.

1. Perform preliminary calculations to evaluate detention storage requirements for the post-development hydrographs in Step 1. A general assumption is that if the 2-year and 10-year storage requirements are met, runoff from intermediate storms will be controlled as well.

2. Determine the physical dimensions necessary to detain the estimated volume determined in Step 2, including a minimum of 1 foot freeboard for the 100-year design storm. From the selected shape, determine the maximum depth in the pond.

3. Select the type of outlet and size the outlet structure. The estimated peak stage will occur for the estimated peak stage calculated in Step 2. The outlet structure is sized to convey the allowable discharge at this stage.

4. Perform the storage-indication routing calculation using the runoff hydrographs from Step 1 to check the preliminary design using the storage routing procedure. If the routed post-development peak discharges from the 2-year and 10-year design events exceed the pre-development discharges, or if the peak stage varies significantly from the estimated peak stage in Step 4, revise the estimated volume and repeat Step 3.

5. Complete a routing for the 100-year design storm through the basin and determine requirements for a secondary spillway and check for minimum freeboard.

6. Evaluate downstream effects of the detention basin outflow to ensure the routed hydrograph does not increase downstream flooding. The outflow hydrograph from the storage basin is routed through the downstream channel until a confluence point is reached. The recommended criteria for locating the confluence point is where the drainage area being analyzed represents 10% of the total drainage area.

7. Evaluate the outlet structure exit flow velocity, and provide channel and bank stabilization if the velocity will cause channel degradation and erosion.

As noted in the discussion of the storage routing procedures, a significant number of modifications in storage estimates, outlet structure configurations, and routing iterations may be necessary to achieve a suitable design. For outlet structures controlling multiple design storm runoff events, the following general sizing criteria is provided (Debo and Reese, 2002):

- Generally, for the 2-year and 10-year design storms, the 10-year runoff volume will determine the size of the detention basin, while the 2-year storm peak control requirement will determine the size of the minimum outlet configuration.
- Size the detention volume for the basin for the 10-year storm. The 2-year storm is then routed through the basin, and the 2-year outlet structure is sized. If 2-year control is not required, then check the outlet sizing for the 5-year storm.
- In the case where multiple outlets are provided for WQv and CPv, the lower orifice outlet for the CPv will also convey a portion of the outflow.
- The depth of the storage when the 2-year (or 5-year) is routed through the basin, then establishes the invert or weir elevation for the 10-year storm outlet. The 10-year through 50-year events are then routed through both outlets.

H. Design example

Example detention basin design with routing