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HYDROLOGY-BASED APPROACH TO STORM WATER DETENTION PLIMINARY DESIGN

James C.Y. Guo, PhD., P.E.
Professor, Department of Civil Engineering, University of Colorado at Denver,
Campus Box 113, 1200 Larimer Street, Denver, Denver, CO 80217-23364.James.Guo@cudenver.edu

Abstract Design of storm water detention basins requires both hydrologic and hydraulic information. The basic hydrologic data include the inflow hydrograph and the allowable release. The hydraulic information of a basin requires the prior knowledge of the basin geometry and outlet structures. With a known storage-outflow curve, the performance of the basin can be examined using a reservoir routing procedure. During the planning stage, a series of feasible basin sites is typically studied for comparison and selection. Often little hydraulic information is known about the basin geometry and outlet structures during a feasibility study. This paper presents a hydrology-based approach by which the storage-outflow curve can be solely approximated from the runoff inflow to the basin and the maximum allowable release from the basin. This method applies to both on-line and off-line basins. This hydrologic procedure significantly simplifies the storm water detention modeling technique and is a useful tool for regional drainage planning and alternative studies. In addition, this paper presents two new reservoir routing schemes that provide direct solutions without a numerical iterative process.

Key words: Hydrograph, Routing, Detention, Hydrology, Stormwater, Flood

INTRODUCTION

During the development of a metropolitan area, storm water drainage planning is one of the major tasks for the preservation of urban environment (ASCE, 1994). A storm water drainage system consists of conveyance and storage facilities. Detention and retention basins are the major storage facilities designed for storm water quantity and quality controls. Between storage basins are conveyance facilities such as pipes and channels. Storage facilities in a drainage network should be placed in strategic locations in order to effectively attenuate peak flood flows. In order to achieve an overall optimization of costs and benefits, it is necessary to evaluate all feasible combinations of basin locations, storage volumes, and allowable release rates (McCuen in 1998, Guo and Urbonas in 1996). Decision making relies on the impact assessments by numerical simulations for the entire watershed with and without the proposed drainage facilities. To numerically model a detention basin using a watershed model such as HEC-1 (HEC 1980), the performance of a detention basin has to be depicted by its stage-storage curve as the hydrologic input and its stage-outflow curve as the hydraulic characteristics (Akan 1990). During a feasibility study, the hydrologic information at a basin location is readily available, but not the hydraulic information because the detailed detention basin geometry and outlet works have not yet been developed. Therefore, it is imperative that a hydrology-based approach be developed to approximate the proposed detention basin characteristic curves for the purpose of initial assessments.

This paper presents such a hydrology-based approach that requires only the inflow hydrograph and the maximum allowable release rate to assess the required detention storage volume and to perform reservoir routing through the proposed detention. The algorithm provides a simple and quantifiable basis to conduct comparisons among storm water detention alternatives without any knowledge of basin shape and outlet structures. After having finalized the alternative selection, the detention basin under design can further be refined when more detailed information becomes available.

RUNOFF HYDROGRAPH METHOD

When the design inflow hydrograph is known, the detention basin is designed to reduce the peak inflow rate by temporarily storing the excess storm water and then releasing it at allowable rates over an extended period. As illustrated in Figure 1, whenever the inflow exceeds the channel capacity, Q_b, the excess water is diverted into an off-line basin for temporary storage. Many diversion devices have been developed for on- and off-line detention basins. The maximum allowable release rate, Q_a, from a detention system is dictated by the downstream critical conveyance capacity or the local design criteria applied to the tributary watershed. For instance, the maximum allowable release recommended for the Denver metropolitan area is one cfs per acre for the 100-year event (USWDCM, 2001). The required storage capacity is the volume difference between the inflow and outflow hydrographs prior to the occurrence of the allowable flow rate.

As illustrated in Figure 1, without any knowledge of the outlet structures, the required detention storage volume can be approximated by a linear outflow hydrograph that has a rising limb from the channel capacity, Q_b , to the maximum allowable release rate, Q_a, on the recession of the inflow hydrograph (Malcom 1982). As a result, the outflow rates, O(T), at time T on the rising limb can be expressed as:

$$O(T) = [O_b + \frac{(O_a - O_b)}{T_p} T] \quad for \quad 0 \le T \le T_p \qquad (1)$$

in which T_p = time to peak on outflow hydrograph and T = time. For an on-line basin, the value of Q_b= 0.0.

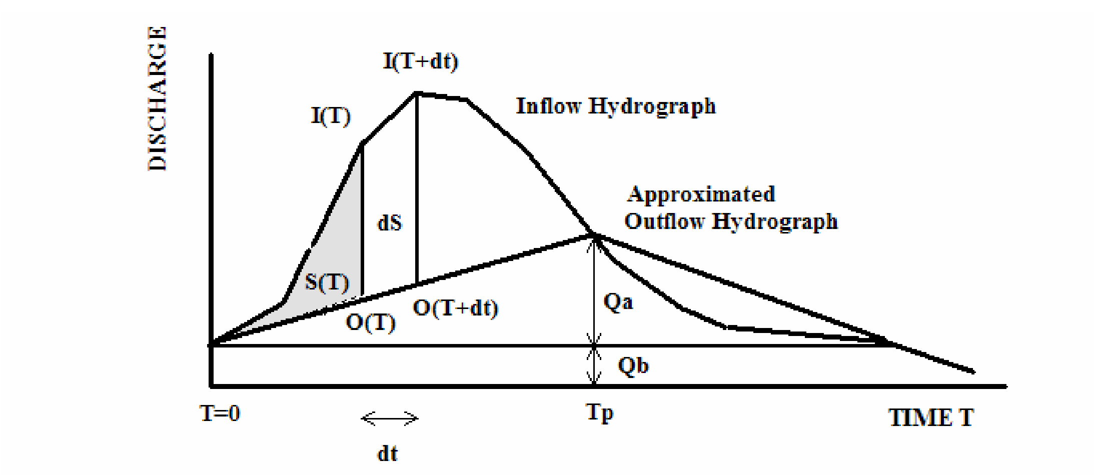

Figure 1   Storage-Outflow Curve by Runoff Hydrograph Method

The accumulated storage volume, S(T), at time T is the difference between the inflow hydrograph and the linear outflow rising hydrograph as:

$$S(T) = \sum_{t=0}^{t=T} [I(t) - O(t)]\Delta t \quad for \quad 0 \le t \le T \;\; and \;\; 0 \le T \le T_p \tag{2}$$

in which S(T) = cumulative storage volume at time, T, I(t) = inflow rate at time t, and Δt= time increment. As illustrated in Figure 1, the basin storage volume, S_s, is equal to the total cumulative storage volume at $T=T_p$ as:

$$S_s = S(T_p) \tag{3}$$

The pairs of storage volume and outflow, (S,O), described by Eq's 2 and 1 is, in fact, the ideal target for the outlet design. In this paper, Eq's 1 and 2 are recommended as the preliminary storage-outflow curve for the basin under design. In fact, these pairs are sufficiently accurate for feasibility studies.

RESERVOIR ROUTING FUNCTIONS

Reservoir routing applies the finite difference scheme to solve the continuity principle among inflow rate, outflow rate, and storage volume. At each time step, the inflow hydrograph prescribes the inflow rate to the detention basin. The variation of storage volume in the basin is described as:

$$\frac{I(t)+I(t+\Delta t)}{2} - \frac{O(t)+O(t+\Delta t)}{2} = \frac{S(t+\Delta t)-S(t)}{\Delta t} \tag{4}$$

Re-arranging Eq 4 yields

$$O(t+\Delta t)\Delta t + 2S(t+\Delta t) = [I(t) + I(t+\Delta t) - O(t)]\Delta t + 2S(t) \tag{5}$$

In this study, two new reservoir routing functions are developed to solve Eq 5. They are: (1) *Storage Routing Function* and (2) *Outflow Routing Function*.

Both routing functions require the prior knowledge of the storage-outflow curve. During the preliminary stage, Eq's 1 and 2 provide the approximate storage-outflow relationship. Of course, the final pairs (S,O) can be refined after the basin shape, outlet work and tailwater effects become known. Although these two routing functions are formulated in different ways, both produce the same outflow hydrograph. The selection of a routing method is a matter of convenience. Details are discussed below.

Storage Routing Function

Let the storage routing function, SO-function, be defined as:

$$SO = 2S + O\Delta t \tag{6}$$

in which SO = storage volume, and Δt = time increment. The storage routing function is formed by pairs (S, O) to provide solutions in terms of storage volume. As shown in Figure 2, both routing function and storage-outflow curve can be plotted versus outflow. In order to apply Eq 6 to determine the outflow, Eq 5 is re-arranged as:

$$[2S(t+\Delta t) + O(t+\Delta t)\Delta t] = [I(t) + I(t+\Delta t) - 2O(t)]\Delta t + [2S(t) + O(t)\Delta t] \tag{7}$$

Eq 7 implies that the flow volumes at time t and t+Δt can be related to the SO function. Substituting Eq 6 into Eq 7 yields:

$$SO(t+\Delta t) = [I(t) + I(t+\Delta t) - 2O(t)]\Delta t + SO(t) \tag{8}$$

The value of SO(t+Δt) in Eq 8 is prescribed by the known variables of I(t), I(t+Δt), O(t) and *S(t)*, at time t. The solution for the two unknowns, O(t+Δt) and S(t+Δt) is the pair (S, O) that has a SO-function value to satisfy:

$$SO(t+\Delta t) = 2S(t+\Delta t) + O(t+\Delta t)\Delta t \tag{9}$$

Figure 2 illustrates how (S,O) pairs can be graphically determined. The approach using the SO function provides direct solutions without any numerical iteration. To begin with, Eq 8 requires the initial condition at the basin. For a dry pond, both O(t=0) =0 and SO(t=0) =0. Otherwise, the permanent pool volume and trickle flow shall be used to initiate the numerical calculations. Repeating Eq's 8 and 9 for the following time step, the complete outflow hydrograph can be generated.

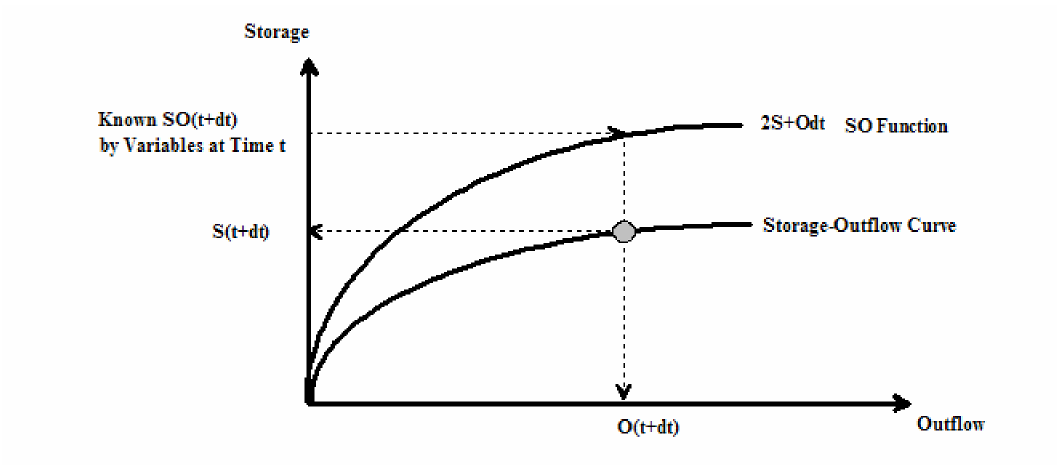

Figure 2 Illustration of (S,O) Function

<u>Outflow Routing Function</u>

Let the outflow routing function, OS-function, be defined as:

$$OS = O + \frac{2S}{\Delta t} \tag{10}$$

in which OS = outflow amount. The outflow routing function, OS-function, is formed by pairs (S,O) to provide the solutions in terms of outflow rates. Similarly, Eq 5 can be re-arranged in terms of OS function as:

$$OS(t+\Delta t) = [I(t) + I(t+\Delta t) - 2O(t)] \ + OS(t) \tag{11}$$

For each time step, the value of OS function at (t+Δt) can be determined by Eq 11, and the solution is the pair that satisfies:

$$OS(t+\Delta t) = \frac{2S(t+\Delta t)}{\Delta t} + O(t+\Delta t) \tag{12}$$

The graphic solution using the OS function is illustrated in Figure 3. These two new routing functions are superior to the Puls method or storage indication method (Puls in 1928, Huber and Bedient in 1992) because both functions provide the solutions without a time-lag, Δt, between storage and outflow variables. Numerically, both SO and OS routing functions are equivalent to an implicit scheme, but without any iterative procedure.

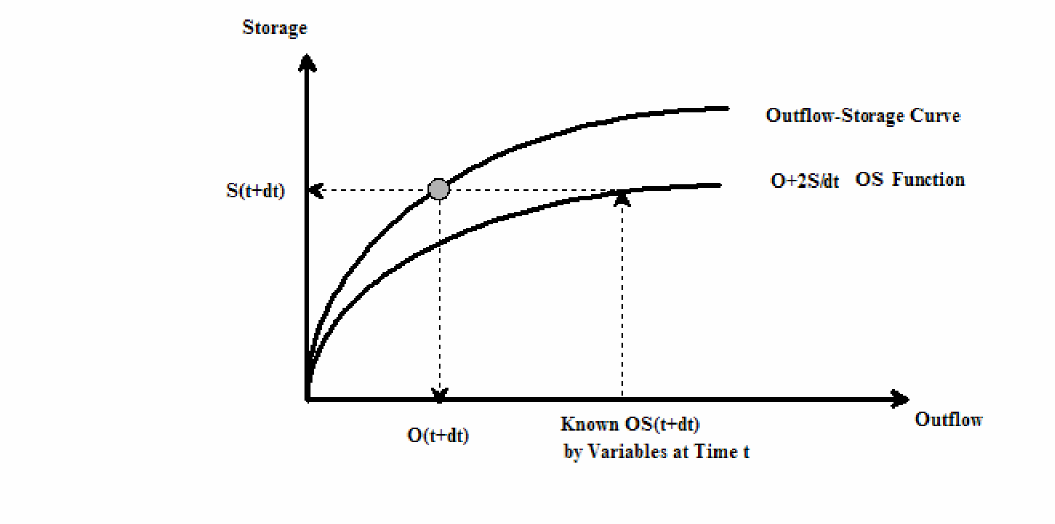

Figure 3 Illustration of OS Function

DESIGN EXAMPLE

For the design example, the Colorado Urban Hydrograph procedure was employed to generate the 100-year inflow hydrograph from the watershed. After subtracting the on-line release of 15 cfs, the diverted hydrograph is presented in Table 1. With an assumed linear rising outflow hydrograph with a peak flow of 47 cfs, the pairs (S, O) are derived by Eq's 1 and 2 and their SO function values in acre-ft are calculated by:

$$SO = 2S + \frac{O * 300}{43560} \tag{13}$$

Table 2 is an example for hydrograph routing procedure using the SO function in Table 1. The initial condition was a dry pond. At each time step, Eq 8 defines the value of the SO function for the next time step, and the solution for the next time step is the pair (S,O) that satisfies the prescribed SO function value by Eq 9. Numerically, the storage volume dictates the value of SO function. As a result, the prescribed value by Eq 8 provides a good guidance to determine the pair (S,O) at $t+\Delta t$. For this case, the required detention volume is 11.0 acre-ft.

Time minutes	Inflow Hydrograph cfs	Outflow Linear Rising Hydrograph cfs	Cumulative Volume acre-ft	SO Function acre-ft
0.00	0.00	0.00	0.00	0.00
5.00	4.00	2.00	0.01	0.03
10.00	10.00	7.23	0.03	0.11
15.00	23.20	10.85	0.12	0.31
20.00	52.00	14.46	0.38	0.86
25.00	110.00	18.08	1.01	2.14
30.00	165.00	21.69	2.00	4.15
35.00	185.00	25.31	3.10	6.37
40.00	150.00	28.92	3.93	8.06
45.00	120.00	32.54	4.53	9.28
50.00	90.00	36.15	4.90	10.05
55.00	75.00	39.77	5.15	10.57
60.00	58.00	43.38	5.25	10.80
65.00	48.00	**47.00**	**5.30**	**10.92**
70.00	35.00	----*	----	----
75.00	28.00	----	----	----

Table 1 Approximation of Storage-Outflow Relationship by Inflow Hydrograph

		Solution Pair (S,O)		Value of	Prescribed
Time t	Inflow I	Outflow O	Storage S	SO Function	SO Function
minuets	cfs	cfs	acre-ft	acre-ft	acre-ft
0.00	0.00	0.00	0.00	0.00	0.00
5.00	4.00	2.00	0.01	0.03	0.03
10.00	10.00	7.00	0.03	0.11	0.10
15.00	23.20	10.00	0.09	0.25	0.23
20.00	52.00	12.00	0.25	0.58	0.61
25.00	110.00	16.00	0.71	1.53	1.56
30.00	165.00	20.00	1.55	3.24	3.23
35.00	185.00	24.00	2.60	5.37	5.37
40.00	150.00	27.00	3.57	7.33	7.34
45.00	120.00	30.00	4.30	8.81	8.83
50.00	90.00	35.00	4.80	9.84	9.87
55.00	75.00	39.00	5.13	10.53	10.52
60.00	58.00	44.00	5.30	10.90	10.90
65.00	**45.00**	**48.00**	**5.34**	**11.01**	**11.00**
70.00	35.00	44.00	5.30	10.90	10.89
75.00	28.00	42.00	5.20	10.69	10.72
80.00	22.00	38.00	5.10	10.46	10.48
85.00	17.00	37.00	5.00	10.25	10.23
90.00	13.00	36.00	4.86	9.97	9.93
95.00	11.00	34.00	4.70	9.63	9.60

Table 2 Example for Hydrograph Routing through Virtual Pond

CONCLUSION

Using the assumption of linear outflow hydrograph, the storage-outflow characteristic curve can be approximated for the detention basin under design using the inflow hydrograph. This hydrology-based approach can be a very useful planning tool for alternative studies and site comparisons during the feasibility study.

The pairs of storage volume and outflow rate derived from inflow and outflow hydrographs can be converted into storage-outflow (SO) and outflow-storage (OS) routing functions. These two routing functions developed in this study are superior to the Puls reservoir routing method because both provide stable and direct solution that does not need any numerical iterative process. These two new routing functions are applicable to both preliminary and final (S,O) pairs. The selection between these two routing methods is a matter of mathematical convenience. The SO function provides solution in terms of storage volumes, and the OS function provides solution in terms of flow rates.

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APPENDIX -- NOTATIONS

A = tributary area
C = runoff coefficient
C_1, C_2, C_3 = rainfall formula coefficients
I = rainfall intensity
I(t) = inflow rate at time t.
m = coefficient to calculate the average release
O(t) = outflow rate at time t
O_a = maximum allowable release rate
O_b = channel capacity to trigger diversion flow
Q_p = peak inflow
OS = outflow-storage function
S(t)= storage volume at time t
SO = storage-outflow function
S_i = inflow runoff volume
S_o = outflow runoff volume
S_s = design storage volume
T = time
T_b = time to start diversion flow
T_c = time of concentration
T_p = time to peak on the outflow hydrograph
t = time variable
Δt = time increment
α= unit conversion factor

Figure 2 Storage-Outflow Curve by Runoff Volume Method

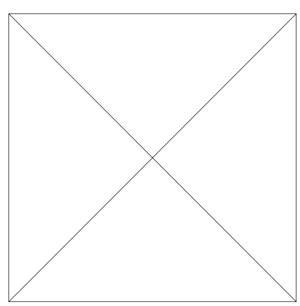

Figure 3 Graphic Solution for Reservoir Routing Using SO Function

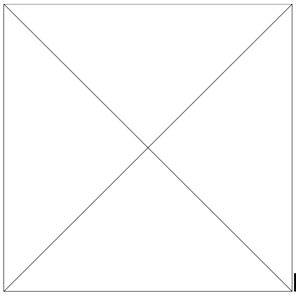

Figure 4 Graphic Solution for Reservoir Routing Using OS Function

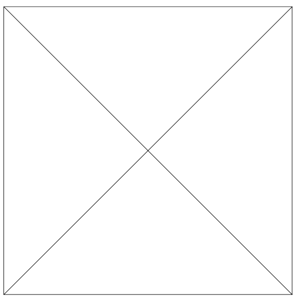

Figure 5 Outfall System for Example Watershed

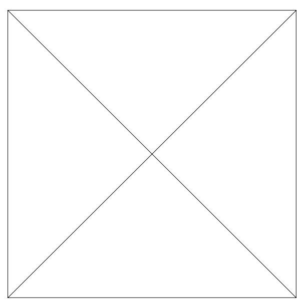

Figure 6 Impact of On-line Release on Off-line Storm Water Detention Volume

Duration minutes	Rainfall Intensity inch/hr	Inflow Volume acre-ft	Peak Runoff cfs	Diversion Time T_b minutes	Coeff m	Outflow Volume acre-ft	Storage Volume acre-ft
	Eq 4	Eq 11	Eq 7	Eq 6	Eq 9	Eq 8	Eq 12

40.00	3.42	8.02	144.32	2.08	1.16	3.00	5.01
50.00	2.97	8.68	125.05	2.40	1.08	3.51	5.18
60.00	**2.63**	**9.23**	**110.78**	**2.71**	**1.03**	**4.01**	**5.22**
70.00	2.37	9.70	99.75	3.01	1.00	4.52	5.18
80.00	2.16	10.10	90.93	3.30	0.97	5.02	5.08

Table 1 Maximization of Detention Volumes for Example Off-line Basin

On-Line Release Q_b cfs	Off-Line Release Q_a cfs	Detention Volume S_s acre-ft	Comparison between the rising limbs between inflow and outflow hydrographs
10.00	52.00	5.42	the same rising limbs up to 10 cfs
20.00	42.00	5.03	
30.00	32.00	4.66	
40.00	22.00	4.31	
50.00	10.00	3.87	the same rising limbs up to 50 cfs

Table 2 Impact of On-line Release on Off-line Storage Volume For Example Basin

Time minutes	Inflow Hydrograph cfs I	Outflow Linear Rising Hydrograph cfs O	Cumulative Volume acre-ft S	SO Function acre-ft SO
		Eq 1	Eq 2	Eq 30
0.00	0.00	0.00	0.00	0.00
5.00	4.00	2.00	0.01	0.03
10.00	10.00	7.23	0.03	0.11
15.00	23.20	10.85	0.12	0.31
20.00	52.00	14.46	0.38	0.86

25.00	110.00	18.08	1.01	2.14
30.00	165.00	21.69	2.00	4.15
35.00	185.00	25.31	3.10	6.37
40.00	150.00	28.92	3.93	8.06
45.00	120.00	32.54	4.53	9.28
50.00	90.00	36.15	4.90	10.05
55.00	75.00	39.77	5.15	10.57
60.00	58.00	43.38	5.25	10.80
65.00	48.00	**47.00**	**5.30**	**10.92**
70.00	35.00	----*	----	----
75.00	28.00	----	----	----

* ---- means not applicable

Table 3 Storage-Outflow Approximation by Inflow Hydrograph and Peak Outflow

		Solution Pair (S,O)		Value of	Prescribed
Time t	Inflow I	Outflow O	Storage S	SO Function	SO Function
minuets	cfs	cfs	acre-ft	acre-ft	acre-ft
				Eq 19	Eq 18
0.00	0.00	0.00	0.00	0.00	0.00
5.00	4.00	2.00	0.01	0.03	0.03
10.00	10.00	7.00	0.03	0.11	0.10
15.00	23.20	10.00	0.09	0.25	0.23
20.00	52.00	12.00	0.25	0.58	0.61
25.00	110.00	16.00	0.71	1.53	1.56
30.00	165.00	20.00	1.55	3.24	3.23
35.00	185.00	24.00	2.60	5.37	5.37
40.00	150.00	27.00	3.57	7.33	7.34
45.00	120.00	30.00	4.30	8.81	8.83
50.00	90.00	35.00	4.80	9.84	9.87

55.00	75.00	39.00	5.13	10.53	10.52
60.00	58.00	44.00	5.30	10.90	10.90
65.00	**45.00**	**48.00**	**5.34**	**11.01**	**11.00**
70.00	35.00	44.00	5.30	10.90	10.89
75.00	28.00	42.00	5.20	10.69	10.72
80.00	22.00	38.00	5.10	10.46	10.48
85.00	17.00	37.00	5.00	10.25	10.23
90.00	13.00	36.00	4.86	9.97	9.93
95.00	11.00	34.00	4.70	9.63	9.60

Table 4 Example Hydrograph Routing using SO Function