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Stormwater Quality Management - Design Criteria and Sustainability

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Abstract

The purpose of this paper is to evaluate the design criteria for the minimum water quality volume of detention and retention stormwater ponds for a 25-year return period design. Stormwater ponds are one of the most widely used Best Management Practices (BMPs) for stormwater management in most counties and municipalities. Water quality is achieved by the settling out and removal of suspended sediments, particulate contaminants, and dissolved pollutants that are commonly found in urban stormwater runoff. A very closely associated aspect of this water quality volume is its removal rate or discharge from the ponds. The water quality of the effluent from a pond increases the longer the stormwater resides in it. However, literature review has shown that the detention time ranges widely from 24 to 72 hours.

Keywords:

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Introduction

Stormwater ponds are mainly designed to control runoff from urban, industrial, and construction areas. They serve three main purposes: to capture stormwater runoff to prevent downstream flooding, to temporarily hold and reduce the runoff rate from a site to reduce erosion and protect downstream channels, and to improve water quality by capturing and retaining sediments and other pollutants that are present in the stormwater runoff.

Under the United States Environmental Protection Agency's (EPA) National Pollutant Discharge Elimination System (NPDES) program, developers are required to come up with stormwater management programs or stormwater pollution prevention plans that identify the management practices that they elect to use to manage stormwater. EPA's stormwater permitting regulations do not specify the use of stormwater ponds even though they represent one class of controls that are used to regulate stormwater runoff even though most developers commonly use them. This is because the stormwater management programs in the local ordinances of most counties and municipalities require stormwater treatment ponds for certain types of developments within their jurisdiction.

There are two categories of stormwater ponds: wet ponds (retention ponds) and dry ponds (detention ponds). Wet ponds are commonly known as stormwater ponds, retention ponds, or wet extended detention ponds (California Stormwater Quality Association, 2003). A wet pond has a permanent pool of water to treat incoming stormwater runoff. The permanent pool of water remains in the pond throughout the year or at least throughout the rainy season and provides a dormant and still volume. The pond detains and treats the runoff from each storm event, until it is displaced by runoff from the next storm. As the stormwater resides in the permanent pool of water, sediments and particulate contaminants are settled out and some dissolved pollutants are removed. Biological processes in the pond also remove pollutants, particularly nutrients, by algal uptake. Thus a wet pond provides retention and treatment of contaminated stormwater runoff. By capturing and retaining runoff during storm events, a wet detention pond controls both stormwater quantity and quality.

A variation of the wet pond is the extended detention pond or extended storage pond. It is designed to provide temporary storage for stormwater runoff from multiple design return periods (Metropolitan Council Environmental Services/Barr Engineering, 2001). An extended detention pond typically has three distinct stage volumes. The top stage volume provides the capacity to regulate peak flow rates from extreme infrequent storm events of the 10-, 25-, or 100-yr events. This volume is called the "flood storage volume." It normally drains down after a storm and remains empty in between storms. The middle stage volume provides the room for detention storage for smaller but frequent storms. This volume is called the "water quality volume." The third and lowest stage volume can be designed to have a permanent pool of water below the weir crest, culvert, or outlet elevation. In this case the pond is designed where the water quality volume is split between the permanent pool and the middle stage volume above the permanent pool. During storm events, water is detained above the permanent pool and released over a period which ranges from 12 to 60 hours. The detention storage provides flood control, erosion control, and a degree of water quality enhancement by capturing settleable solids.

A dry detention pond is designed to capture and slowly release stormwater runoff for a period of 24 to 72 hours in between precipitation events. Dry ponds can be used to treat stormwater and are typically constructed in areas where flood control is the greatest concern. They are normally dry during non-storm conditions. Drawdown may be accomplished by an outlet control structure which can be an orifice at the pond bottom or a weir at an outlet control structure. Dry ponds are commonly used in high groundwater table areas. Particulates and associated pollutants are primary removed by sedimentation in a dry pond.

In South Carolina the permanent water quality requirements under the NPDES General Permit for Storm Water Discharges from Large and Small Construction Activities are published in the "Plan Review Checklist for Design Professionals" (South Carolina Department of Health and Environmental Control, Ocean & Coastal Resource Management, 2006). The following are listed in the document.

- Permanent water quality requirement for all projects or larger common plan of development or sale (LCP) that disturb 5 or more acres
    - Wet ponds should be designed to catch the first ½" of runoff from the entire area draining to the pond and release it over at least a 24-hour period
    - Dry ponds should be designed to catch the first 1" of runoff from the entire area draining to the pond and release it over at least a 24-hour period
- Projects that will disturb less than five (5) acres but within one-half (1/2) mile of a receiving water body in the Coastal Zone must meet Section III.C.3.XIII.A of the Coastal Zone Management Program Refinements. Designs must show that the first ½ inch of runoff from the entire site or the first one (1) inch of runoff from the built upon area, whichever is greater, can be stored onsite. Calculating and demonstrating that the stored water is released over a 24 hour period is not a requirement
- Waters of the United States or the State cannot used for permanent water quality control (Alternative means of treatment must be used if an existing pond is to be used water quantity control).

Stormwater Routing through a Stormwater Pond

The typical layout of a stormwater pond (whether it is for detention or retention) consists of an excavated area in the ground with a multi-stage structure to control the outflow from the pond and an emergency spillway. The outflow structure is normally a riser with an inlet orifice, weirs at the top, and an outlet culvert. The emergency spillway is to release stormwater generated from storm events that are greater than the maximum design event for the pond.

Orifice

The equation for an orifice (Intelisolve, 2007) is:

$$Q = C_o A\sqrt{2gh} \qquad (1)$$

where

Q is the discharge (ft^3/s),
A is the orifice area (ft^2),
h is the vertical distance between the water surface and the centroid of the orifice (ft),
C_o is the orifice coefficient,
g is the gravitational acceleration (32.2 ft/s^2).

Culvert

The equation for a culvert is:

$$Q = NAC_o\sqrt{\frac{2gh}{k}}\,. \qquad (2)$$

The amount of outflow from the culvert depends on either inlet or outlet control.

<u>Inlet Control Condition</u>

Under inlet control; the barrel shape, cross-sectional area, and inlet edge control the amount of flow into the culvert and is similar to flow through an orifice. In this situation the terms are as follows:

Q is the discharge (ft^3/s),
A is the culvert area (ft^2),
h is the vertical distance between the water surface and the centroid of the culvert barrel (ft),
C_o is the orifice or culvert entrance coefficient,
g is the gravitational acceleration (32.2 ft/s^2),
N is the number of barrels,
k is 1.

Outlet Control Condition

Under outlet control; the slope, length, and roughness of the barrel control the amount of flow from the culvert. In this situation the flow enters the culvert at a faster rate that can be discharged from it:

Q is the discharge (ft^3/s),
A is the culvert area (ft^2),
h is the vertical distance between the upstream and downstream water surface (ft),
C_o is the orifice or culvert entrance coefficient,
g is the gravitational acceleration (32.2 ft/s^2),
N is the number of barrels,
k is equal to $1.5 + (29n^2 L / R_h{}^{1.33})$,
n is Manning's coefficient,
L is the culvert length (ft),
R_h is the hydraulic radius (ft).

Rectangular and Riser Weirs

The equation for these types of weirs is

$$Q = C_w L H^{1.5} \qquad (3)$$

where

Q is the discharge over the weir (ft^3/s),
L is the length of the weir crest (ft),
H is the head or the distance between the weir crest and the water surface (ft),
C_w is the weir coefficient which is usually 3.33.

Stormwater Pond Routing Analysis Methods

There are numerous procedures used to route stormwater runoff through a stormwater pond. In this paper, the Euler Method and the Modified Puls Method (Stage Indication Method) are evaluated.

Euler Method

In this method, the routing through a pond is generally based on a lumped form of the continuity equation (Bedient and Huber, 2002):

$$Q_{in} - Q_{out} = \frac{dV}{dt} \qquad (4)$$

where

Q_{in} = inflow (ft^3/s),
Q_{out} = outflow (ft^3/s),
V = storage volume (ft^3),
t = time (s),
$\frac{dV}{dt}$ = rate of change of storage volume (ft^3/s).

The right-side of Equation (4) can be written as

$$\frac{dV}{dt} = A(h)\frac{dh}{dt}$$

where

$A(h)$ = pond water surface area which is a function of the depth h.

Substituting for $\frac{dV}{dt}$ in Equation (4), it becomes

$$Q_{in} - Q_{out} = A(h)\frac{dh}{dt}. \quad (5)$$

Re-arranging Equation (5) it becomes

$$\frac{dh}{dt} = \frac{Q_{in} - Q_{out}}{A(h)}. \quad (6)$$

Replacing the right-hand side of Equation (6) with $f(h,t)$, it is written as

$$\frac{dh}{dt} = f(h,t). \quad (7)$$

The Euler Method (Chapra and Canale, 2002) is used as a numerical solution to Equation (6). For a time step of Δt, the approximation to the derivative $\frac{dh}{dt}$ is

$$\frac{dh}{dt} \approx \frac{h(t+\Delta t) - h(t)}{\Delta t}. \tag{8}$$

Substituting Equation (8) into Equation (7) and re-arranging, it becomes

$$h(t+\Delta t) = h(t) + \Delta t \; f(h,t), \tag{9}$$

with

$$f(h,t) = \frac{Q_{in} - Q_{out}}{A(h)}. \tag{10}$$

The following table shows the tabular setup to solve the above equations. The routing procedure is as follows:

Table 1. *Euler Method Solution*

Time	Q_{in}	h_t	Q_{out}	$A(h)$	$f(h,t)$	$h(t+\Delta t)$
(hr)	(ft^3/s)	(ft)	(ft^3/s)	(ft^2)	(ft/s)	(ft)
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
i = 0						
j =						
k =						

1. Columns 1 and 2 are the inflow hydrograph values into the pond,
2. Column 3 is the initial depth or head on the culvert,
3. Column 4 is the computed outflow from the pond based on h_t,
4. Column 5 is the water surface area which is a function of h_t,
5. Column 6 is [(Column 2 – Column 4)/Column 5],
6. Column 7 is Column 3 + Δt (Column 6) where Δt is the time step from i to j,
7. The value at h_t at time j is the value of $h(t+\Delta t)$ at time i and is repeated for all subsequent rows.

Modified Puls Method (Stage Indication Method) (Gribbin, 2002)

In this method, the continuity equation is written as

$$\bar{I} - \bar{O} = \frac{\Delta S}{\Delta t} \tag{11}$$

where

$\bar{I}$ = mean inflow into pond during time Δt (ft^3/s),
$\bar{O}$ = mean outflow from pond during time Δt (ft^3/s),
$\bar{S}$ = change in pond storage during time Δt (ft^3),
Δt = incremental time step (s).

Equation (11) is rewritten as

$$\frac{I_i + I_j}{2} - \frac{O_i + O_j}{2} = \frac{S_j - S_i}{\Delta t} \tag{12}$$

where the subscripts i and j denote the respective beginning and end of the chosen time step Δt.

Further re-arranging Equation (12), it becomes

$$(I_i + I_j) + \left[\frac{2S_i}{\Delta t} - O_i\right] = \frac{2S_j}{\Delta t} + O_j. \tag{13}$$

The left-hand side terms of Equation (13) are calculated or known from the preceding routing computations. The terms on the right-hand side are unknown and are determined by storage routing by an iterative process.

In order to implement the iterative solution of Equation (13) the following must be known or calculated:

1. Inflow hydrograph into the pond,
2. The storage volume-surface water elevation relationship of the proposed pond,
3. The outflow-surface water elevation relationship of the proposed pond (outflow rating curve),
4. Based on a chosen time step Δt, the plots of O versus $2S/\Delta t + O$ and O versus $2S/\Delta t - O$ are generated.

The assumptions of this routing method are:

1. The outflow and storage volume have a unique relationship,
2. The outflow rate varies linearly with time during each time step Δt,
3. The water surface in the pond is horizontal.

Table 2. *Modified Puls Method (Stage Indication Method) Solution*

Time	I_i	I_j	$2S/\Delta t - O$	$2S/\Delta t + O$	O
(hr)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
i = 0	$I_i = 0$	I_j	0	-	0
J	I_j		Value from step 5	Value from step 3	Value from step 4

1. Columns 1 and 2 are the inflow hydrograph values into the pond,
2. Column 3 is the inflow at time j,
3. Column 5 for time j is the sum of [column 2 + column 3 + column 4] at time i,
4. In column 6 at time j, the value of O_j is obtained from the plot of O versus $2S/\Delta t + O$ using the value calculated in step 3,
5. In column 4 at time j, the value of $(2S/\Delta t - O)_j$ is obtained from the plot of O versus $2S/\Delta t - O$ with the value calculated in step 4,
6. Steps are 3, 4, and 5 are repeated for the subsequent rows.

Application to Stormwater Runoff from a Project

Study Site

The above two routing methods are used to evaluate the stormwater routing through the stormwater pond for the 25-year event for the post development condition of a project. It consists of the construction of a commercial building, a paved parking lot for 125 vehicles, and a stormwater pond. There is a 0.42-acre wetlands area on the site. Stormwater from the site will drain into the stormwater pond by surface runoff and proposed drainage structures. Upon completion of the project the site will have the following types of coverage:

Built-upon area (impervious surface area) = 1.60 acres,
Stormwater pond (pervious surface area) = 0.23 acres (10,126 ft^2),
Pervious surface area (excluding stormwater pond) = 0.93 acres,
Wetlands area (pervious surface area) = 0.42 acres,
Total area = 3.18 acres.

Stormwater Pond Configuration

The outflow is control by a multi-stage structure (Figure 1) which consists of 18-in culvert (culvert A), a 12-in orifice (culvert B), a 2.2-ft riser weir (weir A), and a 3-ft rectangular secondary weir (weir B). The entries for the various components of the structure are shown in Table 3. The stage/storage/discharge relationship of the pond is shown in Table 4.

Figure 1. *Multi-Stage Outflow Structure*

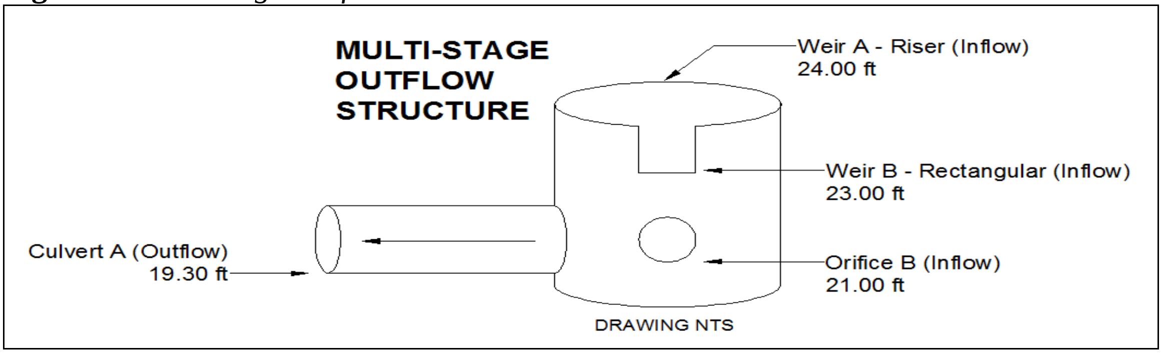


Table 3. *Multi-Stage Outflow Structure Invert Elevations*

Culvert/Orifice	A	B	Weir	A	B
Rise (in)	18	12	Weir Type	Riser	Rectangular
Span (in)	18	12	Crest Elev (ft)	24.00	23.00
No. of Barrels	1	1	Crest length (ft)	8.5	3.00
Invert Elev (ft)	19.30	21.00	Weir Coeff.	3.33	3.33
Length (ft)	38	0			
Slope (%)	2.11	0			
Manning's n	0.013	0.013			
Orifice Coeff.	0.6	0.6			

Table 4. *Stage-Storage-Discharge of Stormwater Pond*

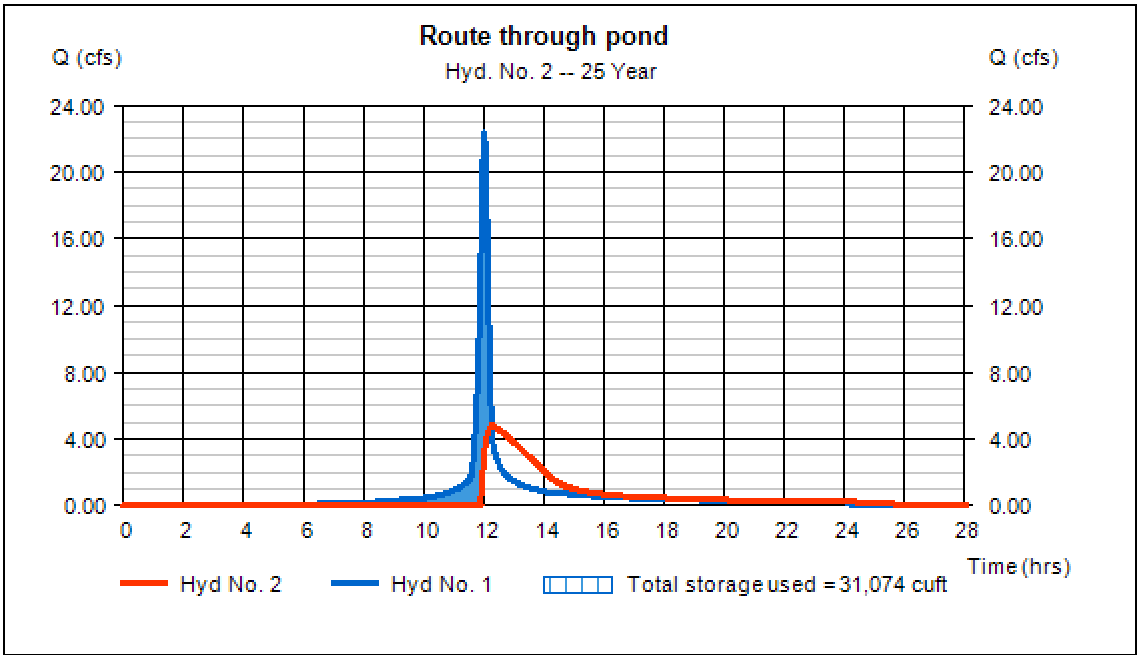
Stage (ft)	Elevation (ft)	Storage (ft^3)	Culvert A (ft^3/s)	Orifice B (ft^3/s)	Weir A (ft^3/s)	Weir B (ft^3/s)	Total Outflow (ft^3/s)
0	19.3	0	0	0	0	0	0
0.2	19.5	1,366	0	0	0	0	0
0.4	19.7	2,763	0	0	0	0	0
0.6	19.9	4,191	0	0	0	0	0
0.8	20.1	5,652	0	0	0	0	0
1	20.3	7,145	0	0	0	0	0
1.2	20.5	8,670	0	0	0	0	0
1.4	20.7	10,228	0	0	0	0	0
1.6	20.9	11,819	0	0	0	0	0
1.8	21.1	13,443	0.046	0.044	0	0	0.044
2	21.3	15,101	0.382	0.372	0	0	0.372
2.2	21.5	16,793	0.97	0.964	0	0	0.964
2.4	21.7	18,518	1.713	1.688	0	0	1.688
2.6	21.9	20,278	2.442	2.413	0	0	2.413
2.8	22.1	22,072	2.954	2.929	0	0	2.929
3	22.3	23,901	3.412	3.382	0	0	3.382
3.2	22.5	25,766	3.8	3.781	0	0	3.781
3.4	22.7	27,665	4.188	4.142	0	0	4.142
3.6	22.9	29,600	4.495	4.474	0	0	4.474
3.8	23.1	31,571	5.099	4.783	0	0.316	5.099
4	23.3	33,578	6.731	5.073	0	1.642	6.715

Results of Stormwater Pond Analysis by the Modified Puls Method (Stage Indication Method)

The Hydraflow Hydrographs Extension for AutoCAD Civil 3D 2013 computer software was used to analyze the stormwater routing for the 25-year event through the stormwater pond. This program uses the Storage Indication Method for the routing procedure. It starts with a stage/storage/discharge relationship and internally plots a graph of $2S/\Delta t + O$ versus O. An inflow hydrograph is entered into the program which will evaluate the steps listed in Section 3.2 to compute outflow hydrograph from a straight line interpolation of the plot of $2S/\Delta t + O$ versus O.

The first flush volume from the first 0.5 inches of runoff from the built upon area is 2904 ft^3. The first flush volume from the first 1 inch of runoff from the entire site is 9183 ft^3. In order to address the permanent water quality requirements, the stormwater pond is configured as a retention pond or dry extended detention pond and the permanent pool volume must be at least 9183 ft^3 (the larger of the two volumes). The invert of orifice B is set at 21.00 ft to insure that first flush volume of 9183 ft^3 inflow into the pond is retained in it. Figure 2 shows the results of the stormwater routing through the pond.

Figure 2. *Hydraflow Hydrographs Extension for AutoCAD Civil 3D 2013 Results*



The peak of the inflow hydrograph is 22.37 ft^3/s and the outflow hydrograph peak is 4.82 ft^3/s. Stormwater first begins discharging from the pond at 11.83 hour at the rate of 0.007 ft^3/s. At the 28 hour mark stormwater is still discharging from the pond at the rate of 0.03 ft^3/s. The significance of this pond design is that it retains all first flush volume and the balance of the inflow hydrograph volume is released over at least a 24-hour period. The first flush volume either leaves the pond by infiltration or displaced by inflow from the next storm.

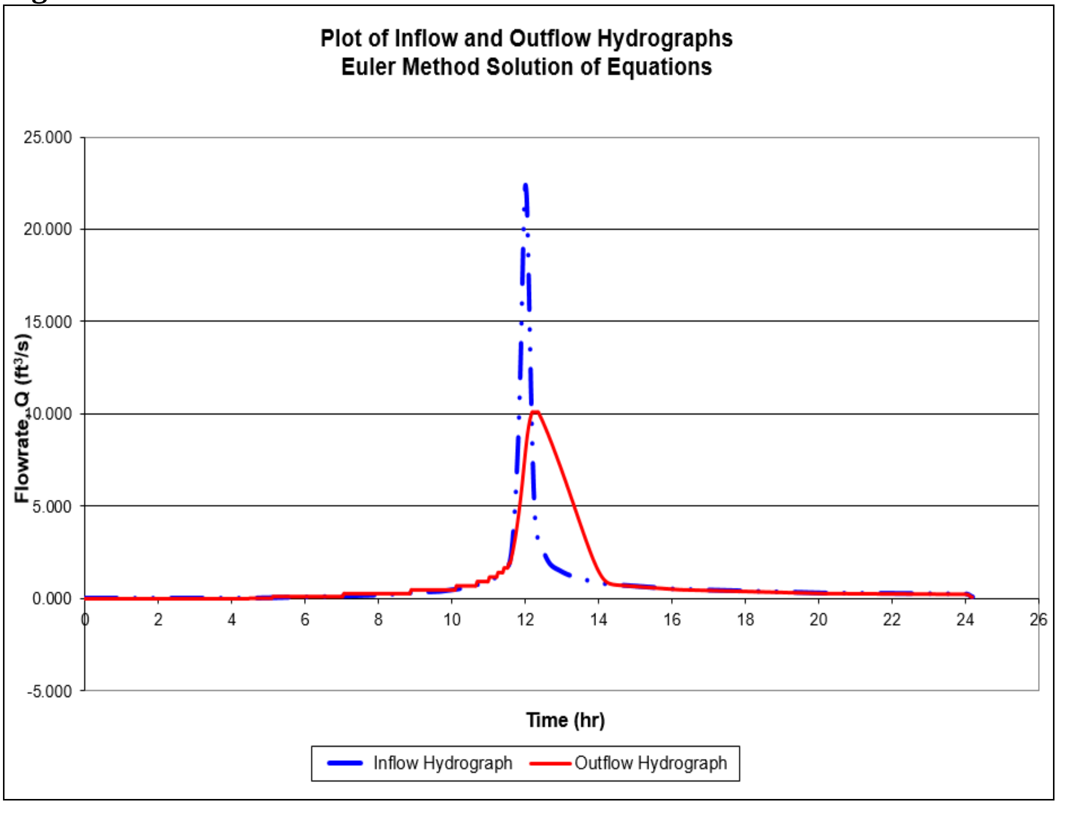
Results of Stormwater Pond Analysis by the Euler Method

The Euler Method discussed in Section 3.1 was also used to route the stormwater through the pond. Due to the constraints of the limited space available for this paper, the tabulation of the detail results from the Euler Method is not included. The key results as shown in Figure 3 are listed below:

1. The peak flowrate of the inflow hydrograph is 22.37 ft^3/s and time to peak is 12.00 hour,
2. The peak flowrate of the outflow hydrograph is 10.105 ft^3/s and time to peak is 12.20 hour,
3. At the 24.2 hour mark the discharge is 0.083 ft^3/s.

Again the results show that entire first flush volume is retained in the pond and the remainder of the inflow volume is released over at least a 24-hour period.

Figure 3. *Euler Method Results*



Conclusions

In order to meet water quality requirements it is essential that a wet retention pond or a dry extended detention pond is used for stormwater routing. The minimum water quality volume is the larger of first flush volume either first 0.5 inches of runoff from the built upon area or first 1 inch of runoff from the entire project site. The peak outflow result from the Euler Method is twice the Modified Puls Method (Stage Indication Method). The peak flowrates for the inflow and outflow hydrographs, by the Euler Method, are 22.37 ft^3/s and 4.82 ft^3/s respectively. The peak flowrates for the inflow and outflow hydrographs, by the Modified Puls Method (Stage Indication Method), are 22.37 ft^3/s and 10.105 ft^3/s respectively. The drawdown time of the stormwater pond is at least a minimum of 24 hours from both methods. If this requirement is not met it is relatively simple to adjust or use different design parameters to achieve this goal. Studies have shown that stormwater detained in the pond for at least 24 hours significantly improved the water quality of the effluent.

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