HYDROLOGIC MODELING OF DETENTION POND

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Abstract

Urban watersheds produce an instantaneous response to rainfall. That results in stormwater runoff in excess of the capacity of drainage systems. The excess stormwater must be managed to prevent flooding and erosion of streams. Management can be achieved with the help of structural stormwater Best Management Practices (BMPs). Detention ponds is one such BMP commonly found in the Austin, TX, USA. The City of Austin developed a plan to mitigate future events of flooding and erosion, resulting in the development and integration of stormwater BMP algorithms into the sub-hourly version of SWAT model. This paper deals with the development of a physically based algorithm for detention pond. The algorithm was tested using a previously flow-calibrated watershed in the Austin area. From the test results obtained it appears that the detention pond algorithm is functioning satisfactorily. The algorithm developed could be used a) to evaluate the functionality of individual detention pond b) to analyze the benefits of such structures at watershed or higher scales and c) as design tool.

Keywords: *flooding, detention, urban, watershed, BMP, algorithm, stormwater, modeling*

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1. INTRODUCTION

A detention pond is a stormwater Best Management Practice (BMP) aimed to protect against flooding. It uses a controlled outflow structure to limit the outflow for large volumes of inflow [1,2]. The outflow structure can be a weir or orifice depending on the need (Figure 1). Detention ponds are typically built across creeks or rivers (on-stream structure) near new land development projects to mitigate flooding and subsequent erosion as a result of increased flow velocity. The outflow from detention ponds is generally passed to the same river or creek from where it received the inflow. Sometimes they are built primarily to control extreme events such as a 100 year storm event. They are typically designed to empty within 6 to 12 hours after the storm [2]. Detention ponds are widely used in many parts of the United States (especially Texas and California) to mitigate flood peaks and magnitude [3].

Scientists [4,5] made an attempt to simulate detention reservoirs using numerical modeling approach with an implicit finite difference scheme. They used the 1D Saint Venant equations to model the unsteady water flow in detention reservoirs. They also developed criteria to estimate the appropriate time step for modeling. They evaluated their approach with observations from Caloosahatchee River Basin in Florida. A watershed-scale evaluation of detention pond was carried out [6]. A model was developed [7] to optimize the size of detention ponds for Austin area. Monitoring of flow and water quality at detention basins is rare given the quick and infrequent nature of rainfall events and other constraints such as cost.

For this study modeling tools were developed to simulate detention pond and integrated with the sub-daily version of SWAT model [8]. To our knowledge this is the first model development study for a detention pond using analytical modeling approach from a hydrologic perspective (rather than a design perspective) intended for applications to watershed and higher scales.

Figure 1a Detention Pond-Type 1 with stepped rectangular weir for flow control (Courtesy: City of Austin, TX)

Figure 1b Detention Pond-Type 2 with multi-stage circular weir for flow control (Courtesy: City of Austin, TX)

Fig -1: Typical detention ponds of Austin, TX, USA

2. MODEL THEORY AND CONFIGURATION

2.1 Detention Pond-Water Balance

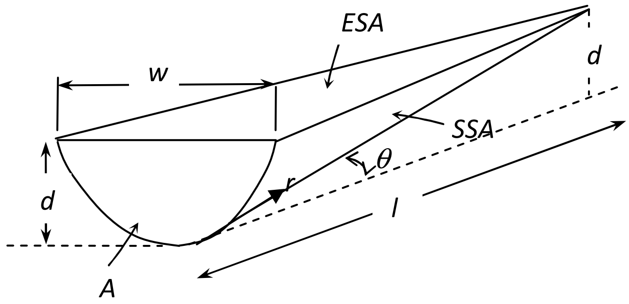
The water balance for a detention pond is:

$$V = V_{backup} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \quad (1)$$

Where V is the volume of water in the detention pond at the end of the time step (m^3 of water), V_{backup} is the volume of water stored in the pond at the beginning of the time step (m^3 of water), V_{flowin} is the volume of water entering detention pond during the time step (m^3 of water), $V_{flowout}$ is the volume of water flowing out of pond during the time step (m^3 of water), V_{pcp} is the volume of precipitation falling on the detention pod during the time step (m^3 of water), V_{evap} is the volume of water removed from the pond by evaporation during the time step (m^3 of water), and V_{seep} is the volume of water lost from the pond by seepage (m^3 of water).

2.2 Water Backup Volume

A detention pond is a controlled release structure. Therefore, for a large volume of water inflow there will be detained water on the upstream side. If the shape and size of water backup is computed, the water balance at any time can be computed. The inflow will be computed by the model depending on the contributing drainage area. Although detention ponds can take many shapes, large detention basins are frequently designed by detaining water within the drainage way and the water backed-up can be assumed to be a semi parabolic wedge behind a dam structure (Figure 2).



ESA-Evaporative surface area SSA-Seepage surface area

Fig -2: Shape of water backup behind a detention pond

Volume of parabolic wedge (V) is a function of area of cross section and length.

$$V = \frac{A \times l}{2} \quad (2)$$

Where, V is volume of parabolic wedge (volume of water back up) (m^3) and l is length of water backed-up (m) and the areas is

$$A = \frac{2 \times d \times w}{3} \quad (3)$$

Where d is the depth (m) and w is width (m).

Substituting equation 3 in 2,

$$V = \frac{d \times w \times l}{3} \quad (4)$$

And evaluating the slope of the creek, S,

$$S = \frac{d}{l} \quad (5)$$

From (5) we have

$$d = S \times l \quad (6)$$

$$R = \frac{l}{w} \quad (7)$$

Where, R is the ratio of length to width of water back up (needed data from user/design monograph/thumb rules)

Rearranging equation 7

$$w = \frac{l}{R} \tag{8}$$

and substituting equations (6) and (8) in equation (4), give

$$V = \frac{S \times l^3}{3 \times R} \tag{9}$$

Or

$$l = \sqrt[3]{\frac{3 \times R \times V}{S}} \tag{10}$$

Once l is known, w and other required parameters can be computed from the above set of equations

2.3 Water Backup Surface Area

Seepage surface area (see Figure 2) is a function of wetted perimeter and channel length

$$SSA = \frac{P \times l}{2} \tag{11}$$

Where, SSA is seepage surface area, P is wetted perimeter (m) and l is length of water backup (m)

$$P = (w + \frac{8 \times d^2}{3 \times w}) \tag{12}$$

Where w is width (m) and d is depth (m) of water backup

Substituting P from 12 into equation 11,

$$SSA = (w + \frac{8 \times d^2}{3 \times w}) \times \frac{l}{2} \tag{13}$$

Evaporative surface area (ESA) is a function of channel length (m) and width (m)

$$ESA = \frac{2 \times w \times l}{3} \tag{14}$$

2.4 Precipitation

The volume of precipitation falling on the detention pond during a given time step is calculated as:

$$V_{pcp} = 10. R_{step}. ESA \tag{15}$$

Where V_{pcp} is the volume of water added to the detention pond by precipitation during the time step (m^3 of water), R_{step} is the amount of precipitation falling on a given time step (mm of water), and ESA is the evaporative surface area of the detention pond (ha).

2.5 Evaporation

The volume of water lost to evaporation on a given time step is calculated as:

$$V_{evap} = 10. \varepsilon. E_0. ESA \tag{16}$$

Where V_{evap} is the volume of water removed from the detention pond by evaporation during the time step (m^3 of water), ε is an evaporation coefficient, E_0 is potential evapotranspiration for a given time step (mm of water), and ESA is the evaporative surface area of detention pond (ha).

2.6 Seepage

The volume of water lost by seepage (assuming uniform pressure gradient along the seepage surface area and gravity drainage) through the bottom of the reservoir on a given time step is calculated as:

$$V_{seep} = 240. K_{sat}. SSA \tag{17}$$

Where V_{seep} is the volume of water lost from the water body by seepage (m^3 of water), K_{sat} is the effective saturated hydraulic conductivity of the creek/river bottom (mm/hr), and SSA is the seepage surface area of detention pond (ha).

2.7 Outflow

The volume of outflow may be calculated using one of three different methods: measured outflow, controlled release rate from weir (circular and rectangular weirs only), stage-discharge relationship.

2.7.1 Measured Outflow

When measured outflow is chosen as the method to calculate detention pond outflow, a file with the outflow rate from the detention pond for every time step should be provided. The volume of outflow from the detention pond is then calculated as:

$$V_{flowout} = q_{out} \times \Delta t \tag{18}$$

Where $V_{flowout}$ is the volume of water flowing out of the detention pond during the time step (m^3), Δt is time step and q_{out} is the outflow rate (m^3/s).

2.7.2 Controlled Release Outflow

When the outflow method is chosen as the controlled release outflow, the water release rate is computed using one of the two weir options (rectangular weir or circular weir (orifice)).

If rectangular weir is chosen, discharge through the weir is calculated as [9, 10]

$$V_{flowout} = 1.84 \times dtp_{cdis} \times dtp\_totwrwid \times \sqrt{qdepth} \times 60 \times idt \quad (19)$$

$$qdepth = dtp\_parm \times \sqrt[5]{\frac{3 \times flowin \times ch\_sl}{3.14159}} \quad (20)$$

Where, $V_{flowout}$ is the volume of water flowing out of the detention pond during the time step (m^3), dtp_{cdis} is the discharge coefficient for the rectangular weir, *dtp_totwrwid* is total weir width of detention pond (m) and *qdepth* is depth of flow in the weir (m), *dtp_parm* is detention pond outflow hydrograph shape parameter, flowin is volume of water inflow to the detention pond (m^3), *ch_sl* is the channel slope in fraction and i*dt* is modeling time step.

If circular weir is chosen, discharge through the weir is calculated as

$$V_{flowout} = 0.6 \times dtp_{cdis} \times warea \times \sqrt{19.6 \times watdep} \quad (21)$$

$$warea = \frac{3.14159 \times diaweir^2}{4} \quad (22)$$

$$watdep = qdepth + \frac{dtp\_depweir}{2} \quad (23)$$

Where, $V_{flowout}$ is the volume of water flowing out of the detention pond during the time step (m^3), dtp_{cdis} is the discharge coefficient for the circular weir/orifice, *warea* is the area of cross section of weir (m^2), *diaweir* is the diameter of the orifice (m) and *watdep* is depth of water in the weir (m), *qdepth* is depth of flow in the weir (m), *dtp_depweir* is the depth of circular weir (m). For partially submerged weir, depth, width and flow calculations are computed by making necessary changes in the above equations.

2.7.3 Stage Discharge Relationship

Apart from the physically based algorithm developed for routing flow through detention pond, stage-discharge relationship is provided as one of the options. For using stage-discharge method, the relationship between inflow and outflow of the detention pond in question should be provided. The relationship can be linear (described by a coefficient and an intercept), logarithmic (a coefficient and an intercept), polynomial (one or more depending on the degree of polynomial and an intercept [e.g. two coefficients and an intercept are required for a second degree polynomial]), exponential (a coefficient and an exponent) or a power function (a coefficient and an exponent). The relationship that most closely fits the outflow hydrograph for a given inflow hydrograph for the study area should be accepted. More information on the stage-discharge relationships are provided in Table 1.

Table -1: Stage-discharge relationships for detention pond

Relation-ship	Form	Data needed		
		Coeffi-cient	Inter-cept	Expo-nent
Linear	Y=AX+B	A	B	
Logarithmic	Y=A Ln(X)+B	A	B	
Exponential	$Y=A e^{BX}$	A		B
Polynomial	$Y=AX^2+BX+C$	A,B	C	
Power	$Y=AX^B$	A		B

2.8 Model Configuration for Detention Pond

A detention pond in general is built across a creek/river. It drains water from all upstream areas. Therefore, in terms of configuration it is analogous to a reservoir. The detention pond can be configured to become operational in the middle of a simulation period (e.g. in a simulation of 1981-2000 we can have detention pond from 1995) to reflect construction dates. If available the physical characteristics of the pond need to be entered; if not, the algorithm developed will use model default values based on City of Austin Environmental Criteria manual [2]. The pond can receive direct precipitation, seep water through the bed and evaporate water from its surface. Presently rectangular weir and orifice are included for outlet structures (Figure 1). The outlet can be in multiple stages (vertically) for control of different storm events.

2.9 Data Availability

A Digital Elevation Model (DEM) with 0.3 meter (1 foot) resolution was prepared by City of Austin for watershed delineation. Soil data was obtained from Natural Resources Conservation Service (NRCS) Soil SURvey GeOgraphic (SSURGO) database [11]. A land cover map of the study area for the year 2003 was prepared by City of Austin through aerial survey. The watershed was divided into 4 sub-basins based on the delineated stream network, and 36 HRUs based on land cover, soil and slope combinations (Figure 5). The dominant soils are fine textured (proportion of clay+silt > 65 %) shallow soils underlain by karstic rocks. Most of the soils are classified as hydrologic soil groups C and D. The dominant land cover is undeveloped (70 %), which includes small residential structures and roads. Golf course/pasture (18 %) and residential (12 %) are other dominant land covers in the watershed. The main channel in the LGA watershed is highly ephemeral, having no stream flow for more than 70% - 80% of time during the test period. Rainfall data at 1 minute interval recorded at a weather station near the watershed outlet was collected, and then aggregated to 15 minute interval. Flow calibrated LGA watershed model setup was used for testing detention pond algorithm.

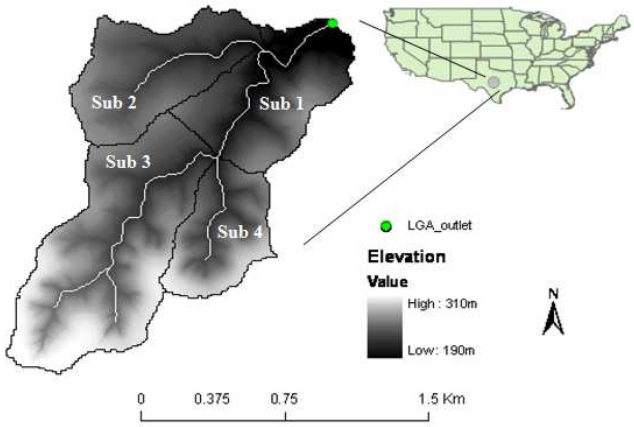


Fig-3: Study area-LGA watershed

3. RESULTS AND DISCUSSION

Monitored outflow data from a detention pond is not available to validate the developed algorithm. Instead the flow calibrated LGA watershed (from a previous study) was used as a hypothetical case study to simulate the detention pond performance. Flow results from the outlet of LGA watershed for year 2004 (annual precipitation about 1318 mm) were assumed to flow through a detention pond with two different outlet structures namely a stepped rectangular weir and circular weir (or orifice) (Figure 1). Year 2004 was one of the wettest years for Austin and therefore the runoff from that year offered a good data set to test the detention pond algorithm. The outflow from each case corresponding to inflow was plotted to analyze the behavior of the detention pond algorithm and to check whether the algorithm is performing as is expected. From the analysis, we see that the detention pond algorithm is mitigating the hydrograph peaks and delay the recession which is expected from the functionality of the BMP in reality. In addition, it makes sense from the results that the detention pond algorithm describing multiple outlets (weirs with 2 or more stages) pass more water through the structure at a given time than single stage weir outlet (Figure 4 and Figure 5). In addition, the pattern of detention pond outflow results looks similar to some of the published results from previous studies [12-16]. Therefore, it appears that the developed algorithm for the detention pond is working well.

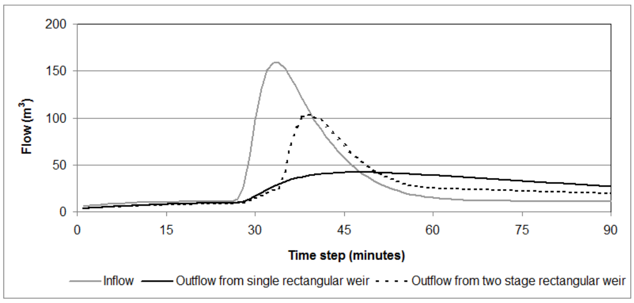


Fig-4: Flow through a detention pond with rectangular weir

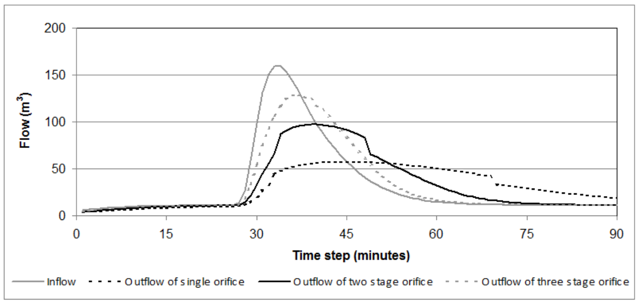


Fig -5: Flow through a detention pond with circular weir

4. CONCLUSIONS

Texas AgriLIfe Research in collaboration with City of Austin is developing modeling tools in SWAT to simulate urban and urbanizing watersheds at sub-hourly scale. As a part of this project, modeling tools are developed to simulate structural stormwater Best Management Practices (BMPs). One such BMP is detention pond. This paper describes the development of a detention pond modeling tool, testing and integration of the tool in Soil and Water Assessment Tool (SWAT) model. The integrated algorithm was tested with a previously modeled and flow calibrated LGA watershed in Austin, Texas, USA.

Hypothetical detention pond systems were modeled in LGA and the results were analyzed to check whether the algorithm developed is functioning well without programming and logical errors. From the results obtained it appears that the detention pond algorithm is functioning well. Detention pond captures water and performs a controlled release and therefore helps to mitigate the flood peaks and flow velocity in urban streams. The results of hypothetical case study of LGA watershed mimicked the expected functionality of detention ponds. The detention pond modeling tool developed could be used a) to evaluate the functionality of individual detention ponds b) to analyze the benefits of such structures at watershed or higher scales and c) use them as design tools.

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BIOGRAPHIES

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