

Hydrologic Modeling of a Retention-Irrigation System

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Abstract

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Introduction

Urbanization is the conversion of pervious natural ground cover to impervious cover, including roads, parking lots, sidewalks, and buildings. Urbanization dramatically alters the local water balance and affects the water courses. There are two primary types of impervious cover: (1) rooftops over where we live, work, and shop, with associated features such as sidewalks and driveways, and (2) transport systems, including roads, highways, and parking lots (Schueler and Holland 2000). The transport component of impervious cover often exceeds the rooftop component. The extent of imperviousness is an indicator of stress to aquatic systems. For example, the total runoff volume from a 0.405 ha (1-acre) parking lot

is approximately 16 times of what is produced by an undeveloped meadow (Schueler and Holland 2000). An urbanized area such as a parking lot cannot naturally pass water downward. Having lost its natural infiltration and storage capacity, an urbanized area rapidly generates surface runoff or storm water, which can be too much for the existing drainage infrastructure to handle. The excess storm water needs to be managed better to prevent flooding and bank erosion of streams and rivers in urban areas. Excess storm water can be better managed with the help of structural storm-water best management practices (BMPs) such as detention ponds and retention irrigation (RI) systems. A modeling tool was developed to simulate storm-water BMPs and was integrated with the subdaily version of the soil and water assessment tool (SWAT) model (Jeong et al. 2010). Hydrologic modeling of the RI system is discussed in this paper.

Retention irrigation systems are unique to the Austin, Texas, area and are not common in other parts of the United States (California Storm Water Quality Association 2003). Retention irrigation systems are one of the innovative urban BMPs actively implemented by the city of Austin, Texas. The RI system consists of a retention pond (Fig. 1) and an irrigation system. The irrigation system consists of a wet well, pump(s), an intake riser, distribution pipes, and sprinklers. The retention pond retains storm-water runoff generated from urban areas for not more than 72 h after the cessation of rainfall (Environmental Criteria Manual 2011). Typically, the retention pond of RI has no outlet because the water collected in the basin is used for irrigating vegetated areas in the vicinity (Environmental Criteria Manual 2011). However, when the incoming flow exceeds the capacity of the structure, the excess flow is bypassed via diversion structures. Depending on the design, diversion structures can handle up to a 100-year storm. Apart from irrigation, the retention basin loses water by evaporation and seepage loss through the bed. In the case of the city of Austin, Texas, irrigation starts 12 h after the end of a rainfall and must be emptied within 72 h since the last rainfall (Environmental Criteria Manual 2011). To the authors' knowledge, this study is the first attempt to develop an algorithm for the hydrologic modeling of an RI system.

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Water Balance

The major factors that influence the water balance in a retention basin are (1) the inflow of urban runoff, and (2) the consumption of retained water for irrigation. The change of volume in the basin is updated every time step based on the following water balance equation [Eq. (1)]:

$$V_{w;i} = V_{w;i-1} + \Delta t [Q_{in,i} - Q_{bypass,i} - R_i - E_i - T_i + A_p - V_{p,i}]$$

where $V_{w,i}$ = the volume of water (m^3) in the pond at time i ; Q_{in} = the inflow rate (m^3 =time step); Q_{bypass} = bypass flow rate (m^3 =timestep) through the diversion structure; R = rainfall (mm); E = actual evaporation from the pond surface (mm); T = seepage loss through the bed (mm); A_p = the surface area of the basin (ha); and V_p = the volume of water pumped for irrigation (m^3).

Potential evapotranspiration is estimated using the Hargreaves method (Hargreaves and Samani 1985) available in the SWAT. Actual evaporation is then calculated based on the potential evaporation and a user-entered input parameter, as shown in Eq. (2)

$$E_i = \phi \cdot PET_i \cdot A_p$$

where ϕ = an evaporation coefficient (a calibration parameter) varying from 0 to 1; and PET is the potential evaporation (mm) during time step i . The SWAT estimates PET on a daily basis. Therefore, the daily amount is evenly divided for each time interval to compute the actual evaporation.

Seepage loss is a function of the saturated hydraulic conductivity (K_{sat}) (mm=h) of the basin's bed material and is provided in Eq. (3)

$$T_i = K_{sat} \cdot A_p$$

Other constraints include (1) no irrigation until 12 h since the last rainfall, as specified by city of Austin criteria (Environmental Criteria Manual 2011), (2) inflow bypasses if the retention pond is full, and (3) no evaporation or seepage loss occurs if the basin is empty.

Irrigation

In practice, water pumped from the retention pond is irrigated through sprinklers that usually have full-circle or partial-circle rotor pop-up heads. Irrigation is stipulated by the permeability, soil depth, and slope constraints. Therefore, theoretically, there should not be any runoff caused by irrigation. To ensure this in the model, some constraints were imposed on each irrigable hydrologic response unit (HRU) (discussed in the model configuration section). The amount of irrigation water for an HRU is calculated by Eq. (4)

$$V_{irr,i,j} = V_{p,i,k} \cdot \frac{A_j}{A_j}$$

where V_{irr} = the volume of water irrigated on the j -th HRU at the i -th time step; and A_j = the pervious area of the j -th HRU. The bracketed term represents the fractional area of the j -th HRU in the subbasin.

Discretization of Watershed in SWAT Model

The RI system is a distributed BMP that can occur anywhere in a study area except on the stream. Existing RI systems (either single or multiple units) in a study area can be represented in the SWAT at a subwatershed level. These systems take the storm water drained from a portion of urban lands within a subbasin, as specified, and the simulation does not use the geographic location of individual systems within the subbasin. The only source of water to a retention pond other than the direct rainfall on the pond is the runoff generated from its urban drainage area. The integrated SWAT-RI model (Fig. 2) allows the simulation of multiple RI systems in one subbasin, and detailed physical characteristics for each RI system can be entered if desired. In the case where the pond dimensions are not known, the SWAT-RI model can automatically estimate the basin's size based on the water quality volume [first 0.5 in. (12.4 mm) of runoff times impervious land area], as specified in the city of Austin's (Environmental Criteria Manual 2011). The option for automatic calculation is especially useful if the model is used for the purpose of designing RI systems or implementing numerous hypothetical systems for a future scenario.

Specific land cover types that do not drain storm water to the retention pond may be excluded from the drainage area. Similarly, any land cover type can be excluded from irrigation. The model allows for flexibility in selecting options for characterizing the areas where the distributed BMPs may be located. Nevertheless, individual RI systems as distributed BMPs may not be regarded as fully physically based systems. Each RI system is simulated individually; however, the inflow to the retention basins is proportioned (on the subbasin area) based on the drainage area of each RI system. For example, the first RI system listed in the RI input file in Subbasin 1 takes 50% of urban runoff generated in the subbasin, whereas the second system takes 20% if the user specifies 0.5 and 0.2 as the fraction of runoff going to each system, respectively. Then, the total amount of water available for irrigation is calculated for the entire subbasin by aggregating the pumping rates from individual basins [Eq. (4)]. The actual irrigation amount for each HRU is allocated in accordance with the areal proportion of the HRU over the entire irrigable area in the subbasin.

The SWAT-RI module adopted the following technical constraints regarding the operation of RI systems (Fig. 2) from the city of Austin's (Environmental Criteria Manual 2011):

1. The minimum soil permeability for irrigation is 0.76 mm=h.
2. Irrigation must not occur on land with slopes greater than 10%.
3. The retention pond must be emptied by pumping within 72 h after a rain event ends.
4. Irrigation must begin no sooner than 12 h after the end of a rainfall event.
5. Retention basins are designed to capture and hold the water quality volume routed to them via diversion structures.
6. The water quality volume is calculated based on the city of Austin's Design Guidelines for Water Quality Controls in the Environmental Criteria Manual (2011).

Case Study

Study Area

There are no monitored data for RI systems for Austin, Texas, watersheds that can be used for validating the SWAT algorithms discussed in this paper. Therefore, the algorithm was tested by simulating a hypothetical RI system in the Lost Creek Golf Course

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Fig. 1. Retention irrigation system (reprinted with permission from the American Legal Publishing Corporation)

(LGA) watershed (Fig. 3), which was previously used for testing the subhourly rainfall runoff processes developed as part of this study (Jeong et al. 2010). The LGA watershed (located in Austin, Texas) is a small (1.94 km²) and mostly undeveloped watershed that has low-density residential areas in several subbasins.

Data Availability

A digital elevation model (DEM) with 0.3-m (1-ft) resolution was prepared by the city of Austin, Texas, for watershed delineation. Soil data were obtained from the Natural Resources Conservation Service (NRCS) Soil SURvey GeOgraphic (SSURGO) database (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture 2009). A land cover map of the study area for the year 2003 was prepared by the city of Austin through aerial survey. The watershed was divided into four subbasins based on the delineated stream network and 36 HRUs based on land cover, soil, and slope combinations (Fig. 3). 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 the time during the test period. Rainfall data at 1-min intervals recorded at a weather station near the watershed outlet were collected and then aggregated to 15-min intervals.

Model Setup

The flow-calibrated watershed model setup was used for testing the retention pond algorithm. However, a few additional changes were required in the LGA model setup to validate the RI algorithm. They are described in the following sections.

Subbasin 1 of the LGA watershed has 5.9 ha of the urban residential area contributing to runoff, which accounts for 14% of the total subbasin area (43.2 ha). The ideal size of a retention basin was estimated at 655 m³ based on the city of Austin water quality volume guidelines. With this basic information, two scenarios were modeled for a hypothetical RI system in Subbasin 1: (1) a retention basin of 500 m³ of the total volume (RI-500), and (2) an RI system with 1,000 m³ (RI-1000). Pond depth was assumed as 1.0 m for all scenarios. The hydraulic conductivity of the basin bed was assumed as 2.5 mm=h, and the actual evaporation coefficient was 0.6. The drawdown time was 72 h after the last rainfall. The land cover types that do not typically drain to urban BMPs were excluded from the contributing land covers to the retention basin. These land cover

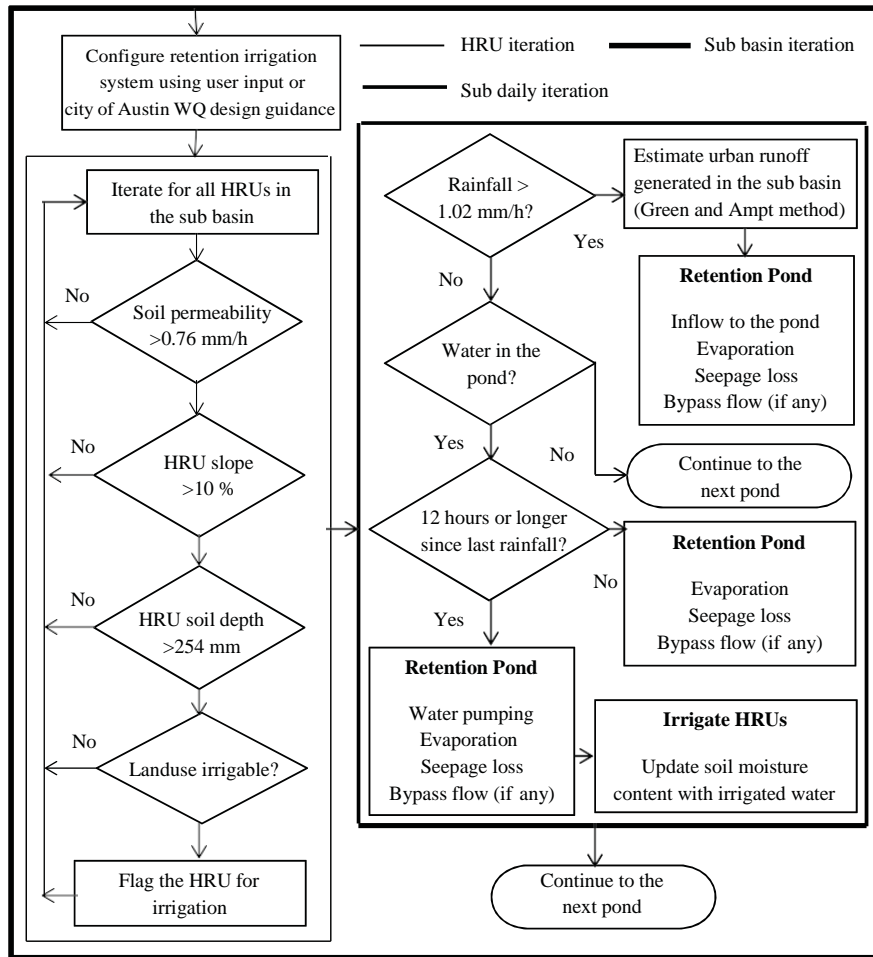


Fig. 2. Modeling retention irrigation system

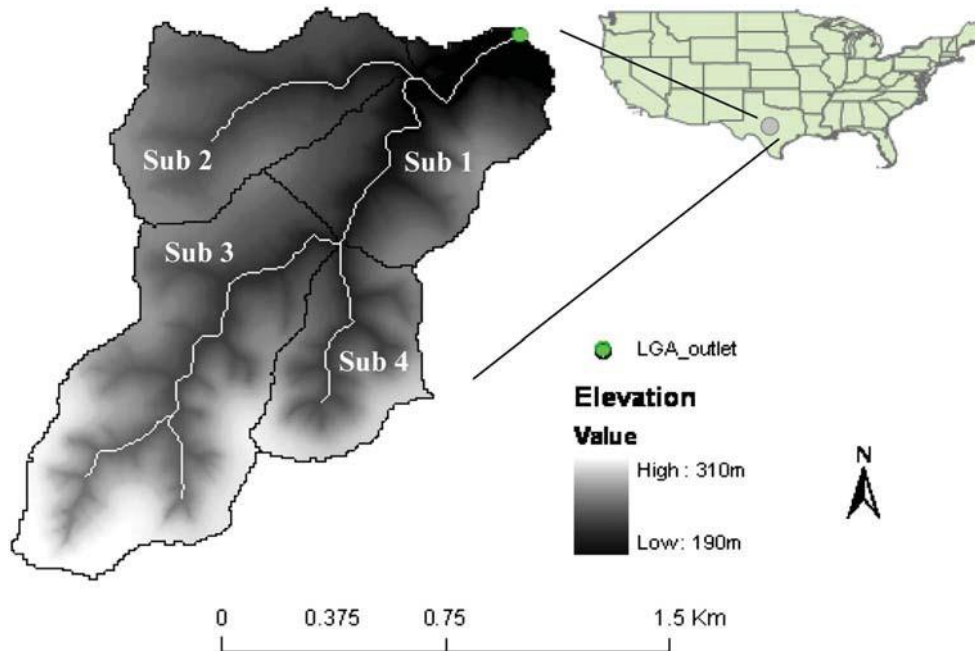


Fig. 3. Study area—LGA watershed

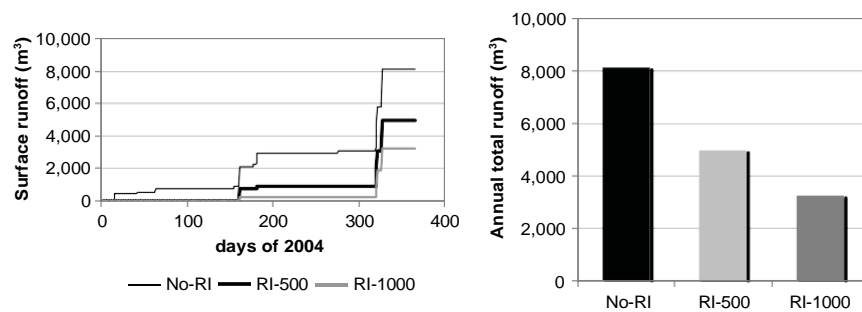


Fig. 4. Simulated surface runoff and total runoff from retention irrigation scenarios

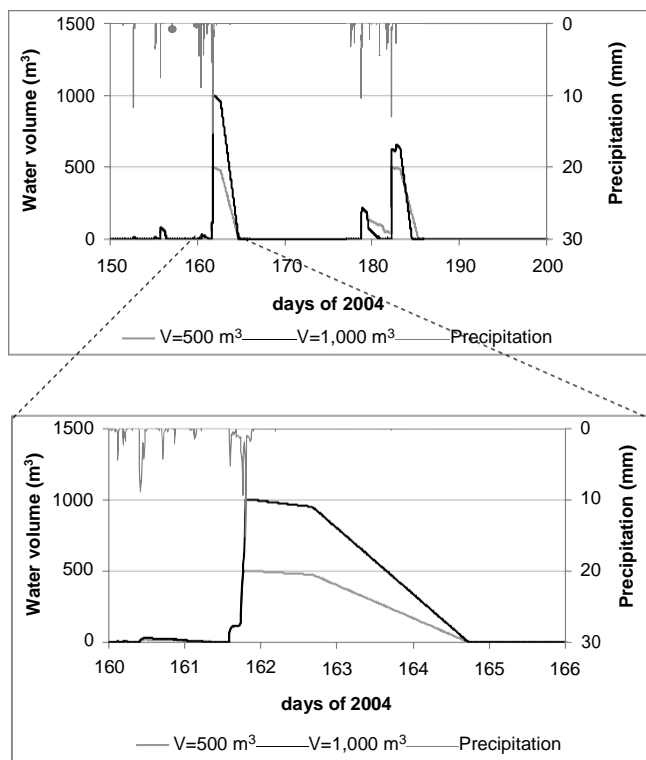


Fig. 5. Water volume in the retention irrigation system

types include Large Lot Single Family (A160), Mining (A560), Landfill/Salvage (A570), Cemetery (A670), Parks and Recreation (A710), Golf Course (A720), Camp Grounds (A730), Protected Open Space (A750), Undeveloped (A900), Agriculture (A910), and Water (A940). Several HRUs in Subbasin 1 were classified as "Undeveloped" and thus excluded from the drainage area of the retention basin. The model allows excluding any urban land use types from the areas that are irrigated by the RI system. However, no land cover types were excluded in this case study. A sub-daily SWAT simulation ($\Delta t = 15$ min) was conducted for 3 years (2002–2004), and a detailed analysis was made for the year 2004.

The subhourly flow calibration parameters for this watershed, which were previously determined, were used in this model (Jeong et al. 2010). In addition to the two aforementioned scenarios, a baseline scenario was also developed without any RI system for analysis of the results.

Results and Discussion

With the RI systems simulated for Subbasin 1, the total annual runoff that reached the subwatershed outlet in 2004 decreased by 40% with RI-500 and decreased by 60% with RI-1000 (Fig. 4). The surface runoffs for the two scenarios represent cumulative bypass flow from the basin, as the retention basins do not have flow outlets. It is likely that only a few floods resulted in flow bypassing the RI system. The urban runoff presented in Fig. 4 accounts for approximately one-third of the total surface runoff (not plotted in the graph) generated from the subbasin.

The retention basin is filled with storm water during wet weather conditions, and the retained water is pumped for irrigation after 12 h to empty the basin in less than 72 h. Two flooding events are presented in Fig. 5 for a demonstration of the dynamic response of the retention basin. The first storm event that occurred on Day 161 generated a large amount of urban runoff that exceeded the maximum capacity of both the RI-500 and RI-1000 systems, and the water volume retained in the pond hit the maximum capacity in both scenarios. This storm event is highlighted in a box and shown in detail at the bottom of Fig. 5. Once the water level hits the maximum capacity, any additional inflow bypasses through a diversion structure to prevent from flooding over the bank. Therefore, the retained water volume does not exceed the maximum capacity of the basin. The first slow decrease in the hydrograph in Fig. 5 (shown in detail in the second part of the figure) during 12 h since the cessation of rainfall represents losses by evaporation and seepage loss. The recession of the hydrograph gets steeper as irrigation begins after 12 h. The retention basin was emptied within 72 h as scheduled.

The pumping rate of RI-500 was estimated at $2.1 \text{ m}^3 = 15 \text{ min}$. This rate is calculated such that the water in the RI pond is emptied within 72 h of the precipitation event with no pumping within 12 h after the cessation of precipitation ($500 \text{ m}^3 = 60 \text{ h} \times 4 \text{ time}$

Table 1. Annual Water Budget for Retention Ponds

Scenario	Basin volume (m ³)	Inflow ρ directrainfall (m ³)	Bypass flow (m ³)	Irrigated water (m ³)	Transmission losses (m ³) ^a	Pumping rate (m ³ =15 min)
RI-500	500	8,913	4,998	2,509	1,406	2.1
RI-1000	1,000	9,472	3,247	3,846	2,379	4.2

^aTransmission losses include evaporation and seepage loss.

steps = $h \times 15 \text{ min} = \text{time step} \times 2.1 \text{ m}^3 = 15 \text{ min}$). Similarly, the pumping rate was $4.2 \text{ m}^3 = 15 \text{ min}$ for RI-1000—twice that of the RI-500 system, as the basin volume is doubled. Approximately 56% of total inflow bypassed the RI-500 system, whereas 34% bypassed the RI-1000 system. The ratio of irrigated water over the volume of retention basin was 5 for RI-500 and 3.8 for RI-1000, which implies that the RI-500 system was more efficient than the RI-1000 system in terms of using more storm water for irrigation. This is mainly because more transmission losses are associated with a bigger RI system ($2,379 \text{ m}^3$ for RI-1000 versus $1,406 \text{ m}^3$ for RI-500) (Table 1). Therefore, it appears that the size of the retention basin is critical in controlling high floods, but the pond surface area and bed lining that affect transmission losses are more important than the pond size when it comes to using storm water for irrigation. The model could be used to analyze whether many small RI systems work better or some large RI systems work well under a given set of hydrological conditions.

Summary and Conclusions

Modeling tools in SWAT to simulate urban and urbanizing watersheds at a subhourly scale are being developed. As part of the project, modeling tools were developed to simulate structural storm-water BMPs. One such BMP—namely, RI—is described in this paper. A modeling tool was developed to simulate an RI system and was integrated into the SWAT model. The integrated algorithm was tested with a previously modeled and flow-calibrated LGA watershed in Austin, Texas. Hypothetical RI systems were modeled in the LGA watershed, and the results were analyzed to check whether the developed algorithm was

functioning well. The test results suggest that the RI algorithm functions rationally.

Retention irrigation captures water, stores it temporarily, and releases it at a controlled rate. The results of the hypothetical case study outlined in this paper suggest that an RI system could be a very useful structure in mitigating urban flooding. The algorithms developed as part of this study could be used to (1) evaluate the functionality of individual BMP structures, (2) analyze the benefits of such structures at a watershed scale, and (3) use them as design tools.

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