Urban Runoff (URO) process for MODFLOW 2005: Simulation of Sub-grid Scale Urban Hydrologic Processes in Broward County, Florida

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ABSTRACT

Climate change and sea-level rise could cause substantial changes in urban runoff and flooding in low-lying coastal landscapes. A major challenge for local government officials and decision makers is to translate the potential global effects of climate change into actionable and cost-effective adaptation and mitigation strategies at county and municipal scales. A MODFLOW process is used to represent sub-grid scale hydrology in urban settings to help address these issues. Coupled interception, surface water, depression, and unsaturated zone storage are represented. A two-dimensional diffusive wave approximation is used to represent overland flow. Three different options for representing infiltration and recharge are presented. Additional features include structure, barrier, and culvert flow between adjacent cells, specified stage boundaries, critical flow boundaries, source/sink surface-water terms, and the bi-directional runoff to MODFLOW Surface-Water Routing process. Some abilities of the Urban RunOff (URO) process are demonstrated with a synthetic problem using four land uses and varying cell coverages. Precipitation from a hypothetical storm was applied and cell by cell surface-water depth, groundwater level, infiltration rate, and groundwater recharge rate are shown. Results indicate the URO process has the ability to produce time-varying, water-content dependent infiltration and leakage, and successfully interacts with MODFLOW.

INTRODUCTION

Flood management and mitigation strategies are a critical aspect of water resource planning in the coastal communities of Broward County, Florida. Broward County has a total area of more than 3,170 km^2 and is mostly flat with low-lying elevations ranging between 0.5 and 3 meters above sea level. The eastern portion of the county is highly urbanized, while the western portion of the county remains mostly undeveloped. These undeveloped areas represent approximately 65% of the total county area and encompass Water Conservation Areas that recharge the aquifer to supply groundwater to coastal well fields and provide surface-water sheetflow to Everglades National Park. The urban portion of Broward County has an extensive network of canals and a combination of gravity and pumped control structures used to maintain surface-water levels. These canals control inundation and flooding during extreme weather events, and maintain groundwater levels during dry periods to prevent excessive saltwater intrusion.

The proximity to the coast, relatively low elevations of much of urban Broward County, and high aquifer permeability make the county susceptible to the potentially adverse effects of climate change and sea-level rise and reduces efficacy of traditional engineered solutions. The county has already experienced effects of rising sea level in low-lying areas of the City of Fort Lauderdale lacking adequate sea wall protection that have been inundated during spring tides. Additionally, sea-level rise has compounded astronomical tide events leading to increased flooding. As a result, it is becoming increasingly important for Broward County to plan for climate and sea-level changes that will affect flood control.

To address these challenges, the U.S. Geological Survey (USGS) and the Natural Resources Planning and Management Division of Broward County, Florida, are developing tools to test mitigation and adaptation strategies to the adverse effects of sea-level and climate change. The Urban Runoff (URO) process for MODFLOW 2005 simulates local-scale hydrologic processes in urban areas, accounting for the typically high water-table conditions resulting from poor drainage and relatively high soil permeabilities where heavy rains and short-duration inundation events are of particular concern. The URO process

implements a conceptual, water-budget approach that has been successfully applied to this area in the past [Flaig et al, 2005].

NUMERICAL MODEL

The URO process simulates coupled flow through three representative, control volumes: interception storage (IS), surface-water storage (SW), and unsaturated zone storage (UZS) (Figure 1). Conservation of water volume in each of these control volumes can be described using the continuity equation as follows:

Interception Storage control volume:

$$Q_r - Q_{et_{IS}} - Q_{throughfall} - \Delta Q_{IS} = 0 \quad (1)$$

Surface-water control volume:

$$\sum_{i=1}^{nc} Q_{M_i} + Q_{throughfall} - Q_{et_{SW}} - Q_{\inf} - Q_{rec_{SW}} - \Delta Q_{SW} + Q_s = 0 \quad (2)$$

Unsaturated zone control volume:

$$Q_{\inf} - Q_{et_{UZS}} - Q_{rec_{UZS}} - \Delta Q_{UZS} = 0 \quad (3)$$

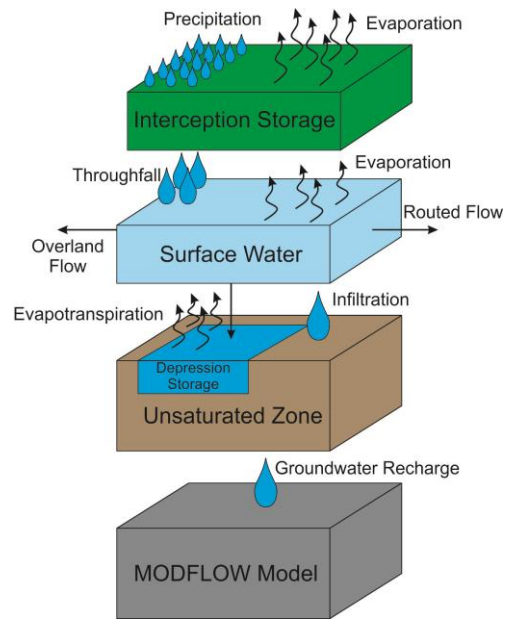

Figure 1. URO Process Control Volumes and Represented Hydrologic Processes.

where Q_r is the precipitation/rainfall rate (L^3/T, where L is length unit and T is time unit), Q_{et} is the evaporation/ evapotranspiration (et) rate from the control volume (L^3/T), $Q_{throughfall}$ is the rate that excess water is shed from the IS into the SW, known as throughfall (L^3/T), ΔQ is the rate of change in volume (L^3/T), Q_M is the rate of volumetric exchange between adjacent, connected SW cells using a diffusive wave approximation (L^3/T), fixed weir, or culvert equations, *nc* is the number of adjacent, connected SW cells, Q_{inf} is the rate of infiltration from SW to UZ (L^3/T), Q_{rec} is the rate of direct recharge to underlying MODFLOW model cell (L^3/T), Q_s represents additional sinks/sources including boundary flows and head-dependent flow exchanges with SWR1 process reaches (L^3/T), such as canals [Hughes et al, 2012], and the subscripts *IS*, *SW*, and *UZS* are for interception storage, surface-water storage, and unsaturated zone storage volumes, respectively. Additionally, each URO cell can consist of multiple UZS land types with different infiltration and recharge properties/methods. Once maximum storage of the IS has been exceeded, any additional precipitation is added directly to the SW as throughfall, $Q_{throughfall}$. Similarly, evaporation demands are first met within the IS using the potential evaporation depth (h_{e1}, in units of L) until IS is fully depleted. The remaining evaporation demands are then met within the SW until surface-water depth is zero. Any remaining evaporation demands are then taken from the UZS at a reduced depth that is dependent upon the UZS storage [Flaig et al, 2005]:

$$h_{UZSet} = h_{ep}(\theta); \quad \theta = \frac{L_{UZS}}{L_{UZSmx}}; \quad h_{ep} = PET(\Delta t) - h_{ISet} - h_{SWet} \quad (4)$$

$$L_{UZSmx} = \max\left(\varphi\left(Z_{elev} - Z_{gw}\right), 0.0\right) \quad (5)$$

where h_{ISet}, h_{SWet}, and h_{UZSet} are the et depth (L) removed from the IS, SW, and UZS, θ is the water content (unitless), L_{UZS} is the UZS depth (L), L_{UZSmx} is the maximum UZS depth (L), *PET* is the potential evaporation rate (L/T), φ is the UZS porosity (unitless), Z_{elev} is the land-surface elevation (L), Z_{gw} is the groundwater elevation (L), and Δt is the URO time step (T).

Overland Flow

The one-dimensional Saint-Venant equations include the continuity and conservation of momentum equations and are a simplification of the Navier-Stokes equations. If the acceleration terms are considered negligible, a Manning's-based flow equation for SI units can be formed [Chin 2000]:

$$Q_{x_i} = \frac{1}{n} A R^{2/3} \left(\frac{\partial Z}{\partial x_i} \right)^{1/2} \tag{6}$$

where Q_{xi} is flow in the x_i direction (L^3/T), n is the Manning's roughness coefficient (unitless), A is the cross-sectional flow area (L^2), Z is stage (L), and R is the hydraulic radius and is approximated as surface-water depth (L). Equation 6 can be combined with the continuity equation to form the diffusive-wave approximation, used to describe overland flow within the URO process (Q_M, in L^3/T). Extension of the one-dimensional formulation of the Saint-Venant equations to two dimensions can result in coordinate system dependent errors. A coordinate-invariant form of the Saint-Venant equations, similar to the form used in the SWR1 process [Hughes et al, 2012], could be evaluated in future versions of the URO process.

Infiltration from SW to UZS

Infiltration within the URO process can be represented using empirical linear or non-linear water-content dependent functions, or the Green-Ampt equation [Chin 2000]:

Linear, water content dependent: $$h_{\inf} = k_{\inf 0} \left(1-\theta\right) \Delta t \,; \tag{7}$$

Non-linear (sigmoid), water content dependent: $$h_{\inf} = k_{\inf 0} \left(1/\left(1+\exp\left(12\theta-6\right)\right)\right) \Delta t \tag{8}$$

Green-Ampt: $$h_{\inf} = K_s \Delta t + \psi \Delta\theta \ln\left[1+\frac{h_{\inf}}{\psi\Delta\theta}\right] \tag{9}$$

where h_{inf} is the infiltration depth (L), k_{inf0} is the maximum infiltration rate (L/T), K_s is the saturated soil conductivity (L/T), ψ is the wetting front soil suction head (L) and $\Delta\theta$ is the change in soil water content (unitless). The linear water-content dependent function is based on the formulation of Flaig et al (2005). The choice of infiltration method is left to the user with the Green-Ampt presenting a physically based empirical method with known parameters for certain soil types and the water-content dependent methods providing a flexible, conceptualized approach. As formulated, the Green-Ampt equation is solved iteratively and may not be well suited for partially saturated soils or substantial surface-water inundation.

Groundwater Recharge from UZS and SW

Similarly, groundwater recharge is independently calculated using empirical linear or non-linear water-content dependent functions from the UZS and/or calculated using a head-dependent recharge equation from the SW.

Linear: $$h_{rec_{UZS}} = fx_1 K_{rec0} \theta \Delta t \tag{10}$$

Non-linear (sigmoid): $$h_{rec_{UZS}} = fx_1 K_{rec0} \left(1/\left(1+\exp\left(12\left(1-\theta\right)-6\right)\right)\right) \Delta t \tag{11}$$

Head dependent: $$h_{rec_{SW}} = \frac{1}{fx_1} K_v \left(\frac{Z_{SW} - Z_{gw}}{0.5 dZ_{Layer1}} \right) \Delta t \tag{12}$$

where subscript *rec* denotes recharge, K_{rec0} is the maximum recharge rate (L/T), K_v is the vertical conductivity of MODFLOW layer 1 (L/T), Z_{SW} is the surface-water stage (L), and dZ_{Layer1} (L) is the thickness of MODFLOW layer 1. As the water table rises and the unsaturated zone shrinks, a linear transition from unsaturated zone groundwater recharge to head-dependent recharge occurs over an unsaturated maximum storage depth range:

For $L_{UZSmx} < DMIN_{rec}$: $$fx_1 = \frac{L_{UZSmx}}{DMIN_{rec}} \tag{13}$$

where $DMIN_{rec}$ is a user-specified transition parameter (L) with typical values from 0.02 to 0.05 m. For all other values of L_{UZSmx}, fx_1 is equal to unity. To avoid instabilities, the maximum groundwater recharge calculated during a MODFLOW time step is limited to the total storage of the unsaturated zone and also to the volume that would prevent a GW/SW head reversal (Equation 14) [Lohmann et al 2012]:

$$h_{rec_{SW\max}} = S_O\left(Z_{SW} - Z_{gw}\right) \tag{14}$$

where S_O is the confined storage coefficient (unitless).

URO Process Solution and Coupling to MODFLOW

The resulting system of simultaneous equations for overland flow (Equation 6) is solved using a bi-conjugate gradient stabilized method and the other fluxes are explicitly calculated at each URO time step. Iterations continue until user-specified SW stage-change (Δh) criteria are satisfied. The URO process system of equations is solved for one or more URO time steps within a MODFLOW time step. The URO process is integrated into MODFLOW through the addition of the calculated groundwater recharge/discharge to the right-hand side (***RHS***) of the groundwater flow equation. Groundwater levels from the previous MODFLOW time step (***HOLD***) or latest MODFLOW iteration (***HNEW***) are used to calculate URO processes for each URO time step where appropriate. MODFLOW outer iterations continue until standard head and flow convergence criteria are met.

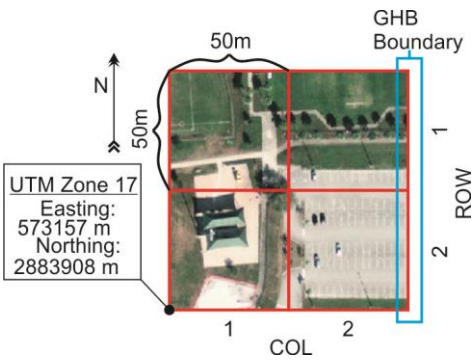

Figure 2. Extents of Test Problem.

PROBLEM DESCRIPTION

A synthetic test problem was simulated to demonstrate the URO process. An area within Broward County was selected and a 2 column by 2 row model was created with a 50-m grid (Figure 2). This is a synthetic, representative sub-section of an 18 km x 7 km proposed model application. The test problem included 2 pervious and 2 impervious land-use types, each with assigned values for Manning's n (n), porosity (φ), maximum infiltration rate (K_{inf0}), and maximum recharge rate (K_{rec0}) (Table 1). Each cell was assigned land-use coverages (Table 2) and a uniform surface elevation of 1.00 m and a boundary (GHB) was applied to the eastern side of the model with a controlling head of 0.00 m and a conductance of 9.0 x 10^{-5} m^2/s (Figure 2). Three uniform groundwater model grid layers were used with a 3-m thickness for each and hydraulic conductivity of 0.03 m/s. No-flow boundaries were specified for the remaining surface-water and groundwater boundaries to produce primarily horizontal flow to the east. A uniform initial groundwater head of 0.00 m was specified, resulting in an initial 1-m depth to the water table. Time-varying rainfall with a total depth accumulation of 0.25 m over the first 24 hours was applied to all cells (Figure 3A). A 7-day period was simulated using daily MODFLOW stress periods and hourly MODFLOW time steps. The URO process used 1-minute time steps. Infiltration and recharge were calculated using the linear water-content dependent function.

Type	Name	n	φ	K_{inf0} (mm/Hr)	K_{rec0} (mm/Hr)	Desc.
1	Pervious 1	0.24	0.3	75	75	Dense Grass
2	Pervious 2	0.40	0.3	50	50	Landscape areas
3	Impervious 1	0.02	0.3	0	0	Parking lot/Path
4	Impervious 2	0.60	0.3	2	2	Building/Structure

Table 1. URO Land-Use Types for Test Problem

Col.	Row	1	2	3	4
1	1	74.25%	0.00%	25.75%	0.00%
2	1	69.75%	5.00%	25.25%	0.00%
1	2	39.50%	2.75%	48.25%	9.50%
2	2	8.75%	3.50%	87.75%	0.00%

Table 2. Test Problem Land-Use Distribution

RESULTS AND DISCUSSION

The total volume of rainfall was 2,500 m^3. The total infiltrated water volume was 2,490 m^3 and the cumulative volume of recharge to underlying MODFLOW cells was 2,484 m^3. The differences in rainfall and cumulative infiltration and recharge are attributable to the specification of residual storage depths in the SW and UZS for model stability. Final volumes within the SW and UZS storage are 10 m^3 (0.4% of total volume) and 6 m^3 (0.24% of total volume), respectively.

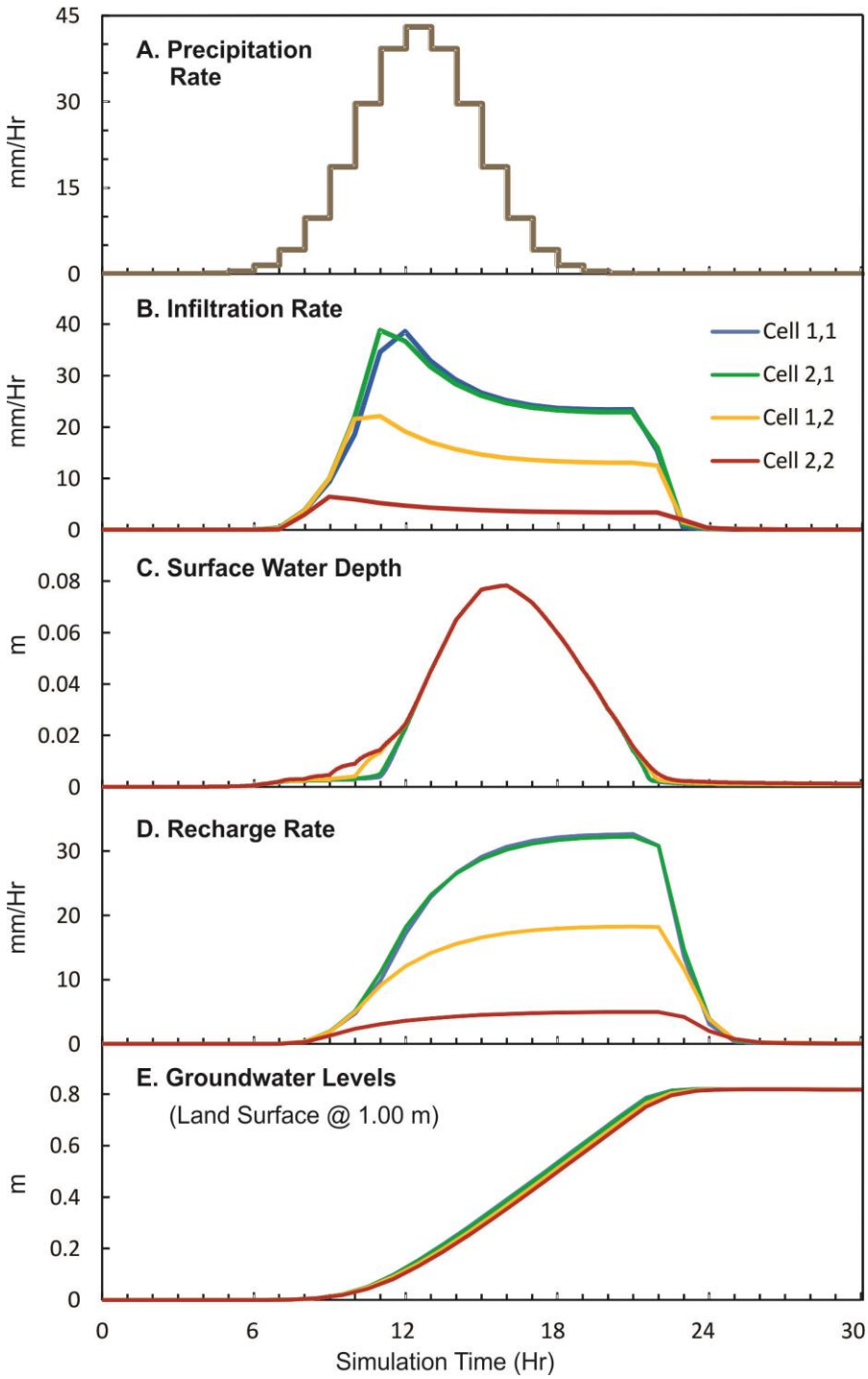

Figure 3. Test Problem Precipitation and Results.

The higher infiltration and recharge values by cell (Figure 3B & D) occur within the more pervious cells; cell (1,1) and cell (2,1). Cell (2,2) has the lowest value of pervious land use and therefore has the lowest infiltration and recharge rates. Infiltration rate reached a peak of 38.84 mm/h in cell (2,1) during the 10th hour of the simulation and a maximum recharge of 32.62 mm/h occurred in cell (1,1) during the 21st hour of the simulation. Movement of surface water by overland flow allowed the surface water in all four cells to reach a maximum elevation of 0.078 m simultaneously in the 16th hour (Figure 3C). Lateral movement within the groundwater model allowed the groundwater levels in all four cells to reach their peak within similar time frames (Figure 3E). Comparison of URO process groundwater recharge results with other software packages that use the Richards Equation to solve for groundwater movement in the unsaturated zone would provide validation and be beneficial to further model development.

SUMMARY

A new MODFLOW process has been developed (URO) to simulate time varying infiltration, groundwater recharge, and overland flow for multiple land-use types. The URO process uses a conceptual water-budget approach that applies the continuity equation to calculate flow between three coupled control volumes. Overland flow is represented using a two-dimensional diffusive wave approximation. Infiltration can be represented using empirical water-content dependent linear or sigmoid function relations or the Green-Ampt formula. Recharge can be represented using linear or non-linear empirical water-content dependent functions. The URO process is coupled with MODFLOW through the addition of calculated recharge to the right-hand side of the groundwater equation.

A test problem demonstrating the URO process consisted of four cells with varying land-use distributions. Two pervious and two impervious land-use types were used with differing values of maximum infiltration and recharge rates. A hypothetical rainfall event was applied to the model area and the URO process calculated time-varying surface-water storage, infiltration, groundwater recharge, unsaturated-zone storage, and runoff that reflect sub-grid scale land-use variations and hydrologic processes. These capabilities allow the application of the URO process in areas where heavy rains and short-duration inundation events are of particular concern.

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