JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
Vol. 44, No. 1 AMERICAN WATER RESOURCES ASSOCIATION February 2008

MECHANISTIC SIMULATION OF TREE EFFECTS IN AN URBAN WATER BALANCE MODEL[1]

Jun Wang, Theodore A. Endreny, and David J. Nowak[2]

ABSTRACT: A semidistributed, physical-based Urban Forest Effects – Hydrology (UFORE-Hydro) model was created to simulate and study tree effects on urban hydrology and guide management of urban runoff at the catchment scale. The model simulates hydrological processes of precipitation, interception, evaporation, infiltration, and runoff using data inputs of weather, elevation, and land cover along with nine channel, soil, and vegetation parameters. Weather data are pre-processed by UFORE using Penman-Monteith equations to provide potential evaporation terms for open water and vegetation. Canopy interception algorithms modified established routines to better account for variable density urban trees, short vegetation, and seasonal growth phenology. Actual evaporation algorithms allocate potential energy between leaf surface storage and transpiration from soil storage. Infiltration algorithms use a variable rain rate Green-Ampt formulation and handle both infiltration excess and saturation excess ponding and runoff. Stream discharge is the sum of surface runoff and TOPMODEL-based subsurface flow equations. Automated calibration routines that use observed discharge has been coupled to the model. Once calibrated, the model can examine how alternative tree management schemes impact urban runoff. UFORE-Hydro model testing in the urban Dead Run catchment of Baltimore, Maryland, illustrated how trees significantly reduce runoff for low intensity and short duration precipitation events.

(KEY TERMS: UFORE-Hydro; TOPMODEL; canopy interception; runoff reduction; urban forest management; Baltimore, Maryland.)

Wang, Jun, Theodore A. Endreny, and David J. Nowak, 2008. Mechanistic Simulation of Tree Effects in an Urban Water Balance Model. *Journal of the American Water Resources Association* (JAWRA) 44(1):75-85. DOI: 10.1111/j.1752-1688.2007.00139.x

INTRODUCTION

Natural resources in urban areas are under increasing pressure with the growth in urban living. In the last half of the 20th Century, the percentage of the total population living in urban areas grew from 51 to 73% in Europe, 64 to 80% in North America, and 29 to 48% on average across the World. By 2030 urban population is projected to account for 80% of Europeans, 87% of North Americans and 61% of global residents (United Nations, 2004). Given the U.S. growth pattern in urban land between 1990 and 2000, urban land in the lower 48 United States is

[1]Paper No. J06150 of the *Journal of the American Water Resources Association* (JAWRA). Received November 2, 2006; accepted May 24, 2007. © 2008 American Water Resources Association. No claim to original U.S. government works. **Discussions are open until August 1, 2008**.

[2]Respectively, Adjunct Assistant Professor, Faculty of Environmental Resources and Forest Engineering, College of Environmental Science and Forestry, State University of New York, Syracuse, New York 13210; Associate Professor, Faculty of Environmental Resources and Forest Engineering, College of Environmental Science and Forestry, State University of New York, Syracuse, New York 13210; and Project Leader and Research Forester, Northern Research Station, USDA Forest Service, Syracuse, New York 13210 (E-Mail/Endreny: te@esf.edu).

projected to increase from 3.1 to 8.1% between 2000 and 2050, an area larger than the state of Montana (Nowak and Walton 2005). In the United States, land converted into urban development has predominantly come from rural land classes of forest, pasture, and range (USGAO, 2001). Many hydrologic studies have been conducted to examine how land use change from rural to urban cover affects the hydrologic processes. These studies, summarized by Endreny (2005), generally conclude conversion to urban cover reduces *interception* by removing trees and vegetative cover, decreases *infiltration* by compacting soils and expanding impervious cover (IC), and decreases *evaporation* by lowering soil water volumes. The result has been an increase in peak *runoff* magnitude from precipitation events, which has then scoured and destabilized many urban channels (Riley, 1998). Increased surface runoff collects urban pollutants, and has a detrimental impact on runoff water quality because of significant nonpoint source (i.e., nonindustrial and nonwastewater sources) pollutants of solids, metals, and nutrients (WEF/ASCE, 1998; Butler and Davies, 2000). Urban managers have been examining ways to reduce these receiving water scour and pollution impacts, including measures that increase forest cover to promote forest-stormwater interaction.

Management tools that analyze how increasing forest and associated pervious cover (PC) in urban areas results in a naturalized hydrologic cycle are needed. Conceptually, the forest cover increases interception, the pervious soils with tree root activity increases infiltration, and combined the forest and soils affect boundary layer and soil regimes to increase evapotranspiration. These hydrological changes will trigger additional changes by increasing soil moisture volumes, increasing base flow (i.e., nonstorm flow) to channels, reducing the magnitude of peak runoff, and improving water quality discharges. Such hydrological linkages of urban runoff management are also described in detail by Horner *et al.* (1994), the Water Environment Federation (WEF/ASCE, 1998), and the U.S. Environmental Protection Agency (USEPA, 1999, 2000). Modeling methods used to examine management of urban stormwater have been used since the 1960s (James, 1965), and in this paper, we provide an integration of 40 years of modeling work.

Many models have evolved in the past 40 years to examine urban hydrology, yet none were built to explicitly examine tree effects on stormwater and development of urban forest management plans. A review of U.S. government supported urban management models found the simulation of forest controls on hydrology as too highly parameterized for management application or overly simplistic and lacking in physical management implications. The SWAT (Soil and Water Assessment Tool) model (Arnold *et al.*, 1998) and TR-55 (SCS, 1975) model, for example, were limited by using a curve number-based infiltration routine, and therefore, had no explicit consideration of vegetation's interception and evaporation contribution, while the Hydrological Simulation Program FORTRAN (Bicknell *et al.*, 1993) and Storm Water Management Model (SWMM) (Huber and Dickinson, 1992), require numerous input parameters yet do not provide adequate simulation of vegetation interception process. Our research is based on creation of a relatively simple, process-based, forest management and research model that would explicitly represent the effects of vegetation and soils on the urban hydrological cycle.

This paper presents a semidistributed, topographical-based Urban Forest Effects Hydrological (UFORE-Hydro) model that uniquely combines a well established, yet slightly modified, set of interception, storage, infiltration, evaporation, and runoff algorithms. The organization of this paper begins with an explanation of the overall model structure with theory, required inputs, model calibration options, and model outputs. The next section presents the subroutines, their basic algorithms, and the modifications made in this work. The next section illustrates the model application in Dead Run in Baltimore, Maryland. The conclusion section summarizes the work in this paper. This model is available from the USDA Forest Service Northern Research Station in Syracuse, New York.

MODEL STRUCTURE

Model Theory

UFORE-Hydro is developed within the OBJTOP (OBJect-oriented, TOPographic) model framework (Wang *et al.*, 2005ab; 2006), which has facilitated design and integration of urban objects representing forest effects. UFORE-Hydro is designed for municipal land cover managers and researchers, with algorithms selected, modified, or developed for minimal data input requirements such that most urban areas would be able to readily apply the model.

UFORE-Hydro, Version 1, is a semidistributed urban soil-vegetation-atmosphere transfer scheme with explicit vertical layers representing the soil, vegetation and atmosphere (see Figure 1). The model represents the watershed surface as impervious or pervious surfaces, with a percent of tree and shrub canopy (SC) cover over either surface. At each time-step, which can be set by the user to any reasonable

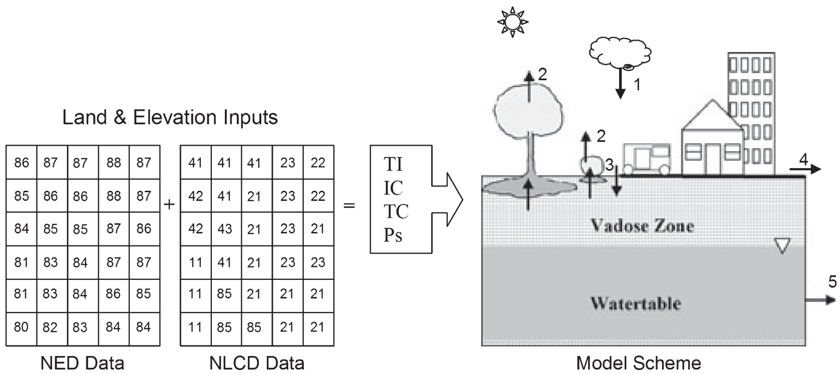

FIGURE 1. Illustration of UFORE-Hydro Spatially Distributed Inputs of Land and Elevation Are Used to Derive Statistical Values of Topographic Index (TI), Fractional Impervious Cover (IC), Fractional Tree Cover (TC), and Other Parameters (Ps). The model fluxes are defined: 1 is precipitation, 2 is evaporation, 3 is infiltration, 4 is surface runoff, and 5 is base flow.

value, the model takes forcing data from the atmosphere and updates the water storage in the soil and vegetation, which then influences watertable depth. UFORE-Hydro then uses a topographically-derived statistical distribution to represent lateral transfers within the watertable throughout the watershed, common to many TOPMODEL schemes (Beven *et al.*, 1995). Snow interception, accumulation, ablation, and melt processes are under design and will be incorporated into UFORE-Hydro Version 2.

Model Inputs, Calibration, and Outputs

Land cover inputs into the model can take any spatial dimensions, but in our applications have been raster images with a pixel for each 30 m × 30 m of area, of national elevation data to derive a topographic index (TI), and enhanced national land cover data (NLCD) that provides subgrid heterogeneity estimates of IC, and tree canopy (TC). The model computes the TI as the quotient of contributing area per contour length and the tangent of local pixel slope. The IC and TC are extracted from the NLCD using the method of Yang *et al.* (2003). Each watershed pixel has a TI value, and these are grouped into blocks of hydrologically representative units (e.g., 10% of watershed is TI < 5). For each TI block, the watershed distribution of IC and TC are represented. Meteorological data for the model are precipitation, potential evaporation, and potential evapotranspiration. These data can be entered at any regular timestep, but increments of 1 h or finer are recommended. UFORE-Hydro requires assignment of initial average watertable depths and soil moistures, and soil physical parameters, such as hydraulic conductivity.

UFORE-Hydro provides an option for automated calibration to observed discharge using the Parmeter ESTimation (PEST) routines of Doherty (2001a,b). These PEST routines were coupled to the UFORE-Hydro code by Doherty in 2005, and based on user preferences will call either a gradient-based or genetic algorithm-based calibration procedure. Outputs at each timestep include canopy interception, impervious depression storage, infiltration, evapotranspiration, surface (pervious and impervious) and subsurface runoff, and channel discharge.

MODEL SUBROUTINES

Description of the model subroutines places emphasis on modifications to established routines, particularly those dealing with vegetation and trees. Trees canopy is simulated over pervious and/or impervious areas, as selected by the user. Otherwise, subroutines that represent well established approaches are briefly described.

Interception Routine

Precipitation is distributed onto the surface of the watershed with a percentage intercepted by either TC or SC if present, and then the remainder reaching the lower IC or PC. The UFORE-Hydro interception algorithm is deterministic and provides a unique adjustment and combination of existing physically based subroutines by Rutter *et al.* (1971, 1975) rather than the empirical methods based on gross precipitation (Jackson, 1975). Our interception routine is based on the Rutter model but considers sparse vegetation (Valente *et al.*, 1997), keeps a running water balance of the canopy and vegetative stem (i.e., branch and trunk), and simulates influence of precipitation intensity, duration and a changing TC. Testing of the Rutter model has occurred in numerous forest types around the world (Gash and Morton, 1978; Calder, 1986; Hutjes *et al.*, 1990; Eltahir and Bras, 1993; Jetten, 1996). Rutter interception theory has been advanced to consider throughfall in sparse vegetation by Gash *et al.* (1995) and Valente *et al.* (1997), providing insights useful for the tree structure common in urban forest environments.

UFORE-Hydro modified the Rutter model by incorporating a seasonally varying leaf area index (LAI) interception storage term, included simulation of sparse vegetation, and reduced model parameters by constraining canopy drip until storage is filled. Interception of precipitation by the canopy is controlled both by weather dynamics of precipitation intensity and duration, and tree characteristic of leaf area, storage capacity, and initial storage. The interception equation in UFORE-Hydro is

$$\frac{\Delta C}{\Delta t} = P - R - E \tag{1}$$

where C (m) is the depth of water on the unit canopy at time t, P (m/s) is above canopy precipitation, R (m/s) is the below canopy throughflow precipitation reaching the ground, diminished from P by interception, E (m/s) is the evaporation rate from the wet canopy, and Δt is the simulation time interval (s in this example). As explained below, UFORE-Hydro simplifies the explicit simulation of canopy drainage performed in the Rutter model to reduce model parameter requirements. Similar to the sparse vegetation simulation of Valente *et al.* (1997), UFORE-Hydro assigns P as the open-sky precipitation for the entire fractional area not covered directly by canopy. UFORE-Hydro uses P_w as the weighted sum of open sky precipitation, P, and below canopy throughflow, R, to represent the watershed average depth of precipitation.

In the canopy fraction of the watershed and at the first stage of interception, which is from the start of precipitation until the canopy storage capacity (S) is filled and equal to C_{max}, the forest canopy intercepts most of the precipitation. Simulation allows a small amount of precipitation to fall through the canopy as free throughfall (P_f) without contact, and while interception is active (i.e., prior to S reaching C_{max}) R is equal to P_f. S is defined as the water retained on the canopy that would not drain to the ground under normal conditions. The UFORE-Hydro model allows no drips from the canopy before S is filled in the first stage. The second stage starts when stored rain equals S with no further interception and all subsequent precipitation reaches the ground, either as P_f or canopy drip. The third, drying stage starts when precipitation has stopped. Evaporation is permitted to occur in each of the three stages to recover the interception storage, creating a dynamic process. Eq (1) regulates canopy storage using throughflow rates, precipitation rates, and evaporation rates, the last two representing meteorological controls.

Derivation of Canopy Parameters. Based on the work of van Dijk and Bruijnzeel (2001), the value of P_f has been set as complementary to canopy cover fraction, c, which is related to the canopy LAI and is relative to the fraction of watershed with vegetation cover

$$P_f = P(1 - c) \tag{2a}$$

$$c = 1 - e^{-\kappa LAI}, \tag{2b}$$

where κ is an extinction coefficient, which has ranged between 0.6 and 0.8 in forests (Ross, 1975). For a number of agriculture crops κ has values with 0.2 to 0.8 (van Heemst, 1988), and based on these studies, the UFORE-Hydro default values of κ is 0.7 for forest and 0.3 for other short vegetation. The LAI exponent term in the above equation is defined as the cumulative one-sided area of leaves (healthy) per unit area (Watson, 1947), with a phenology further elaborated below.

UFORE-Hydro treats the storage capacity, S, of the forest canopy as linearly related to LAI (Aston, 1979; Pitman, 1989; Liu, 1998), expressed as

$$S = S_L \text{LAI}, \tag{3}$$

where S_L (m) denotes specific leaf storage, which is the maximum depth of water retained by leaves of a particular species per unit leaf area (Lousteau *et al.*, 1992; Tobón Marin, 1999). Aston (1979) and Liu (1998) described laboratory methods for experimentally deriving a value of S_L, however, for model simplification and based on reported averages (Dickinson, 1984), UFORE-Hydro sets a default value of S_L to 0.0002 m.

Seasonal Variation of Leaf Area Index. For deciduous trees, LAI experiences leaf-on, growth, and leaf-off processes within a year, and is set to include a stem area index that intercepts precipitation even during leaf-off. LAI is a minimum in winter (full leaf-off), dominated by stem area, and reaches its maximum with full grown leaf area in summer (full leaf-on). There are transition days between full leaf-off and leaf-on. For simplicity in UFORE-Hydro, we assume Equation (3) still applies with a combined effect of *LAI* and stem bark, denoted as bark area index (BAI), represented as total tree area index (TAI). BAI is used to represent average interception storage capacity of tree stem bark (branch and trunk) and is assumed constant for all seasons for one growing year; it is based on canopy area and is updated with tree growth. The following formulas are used to describe the variations of average daily TAI in the catchment:

$$\mathrm{TAI} = \mathrm{LAI} \cdot F_{\mathrm{leaf}} + \mathrm{BAI} \quad (4)$$

where F_{leaf} is the fraction of TC in-leaf (i.e., not counting bare trees) in the catchment. This value is a maximum of 100% after full leaf-on in summer, and is a minimum after deciduous leaf drop, representing only the percent of evergreen canopy. The maximum TAI, $\mathrm{TAI}_{\mathrm{max}}$, is in summer and minimum TAI, $\mathrm{TAI}_{\mathrm{min}}$, is in winter, adjusted base on F_{leaf} in Equation (4) decreasing in winter.

For daily TAI values in spring and autumnal transition days, when leaf cover is changing, a modified sigmoid function is used, as adapted from the work of Koller and Upadhyay (2005).

$$\mathrm{TAI}_{\mathrm{daily}} = \frac{(\mathrm{TAI}_{\mathrm{max}} - \mathrm{TAI}_{\mathrm{min}})}{1 + e^{-0.37(\mathrm{day}_{\mathrm{a}} - \mathrm{day}_{\mathrm{b}})}} + \mathrm{TAI}_{\mathrm{min}} \quad (5)$$

For TAI in spring, $\mathrm{day}_{\mathrm{a}}$ is the Julian day (day of year) of simulation and $\mathrm{day}_{\mathrm{b}}$ is the half-way point between leaf-off and leaf-on. For autumnal transition days transitioning to leaf-off, $\mathrm{day}_{\mathrm{a}}$ is the half-way point between leaf-on and leaf-off and $\mathrm{day}_{\mathrm{b}}$ is the day of simulation, and 0.37 is growth rate parameter. Tree cover values for UFORE-Hydro are derived from USFS field plots and enhanced NLCD that have been processed to extract percent canopy cover in each 30-m pixel (Huang *et al.*, 2001). The TAI derivation is based on multiple urban tree studies (Nowak *et al.*, 2002, 2006), and values are adjustable in UFORE-Hydro. The model assumes the user-input transition period is the same for spring and fall, and Equations (4) and (5) are suitable for other short vegetation types besides trees.

Impervious Depression Storage

Precipitation that falls on the IC fraction of watershed is allocated initially to depression storage, such as road potholes, if that storage is not filled. The depression storage theory is based on the non-slope related SWMM algorithm, and users can input SWMM recommended depth of storage values or other field-derived values. Depression storage of the impervious surface, S_{Ur}, in the urban catchment has a maximum capacity of $S_{\mathrm{Ur\text{-}max}}$, beyond which runoff occurs. A default value of 1.5 mm is set in the model parameter file. Evaporation is used to remove water from depression storage and update the available storage fraction.

Evaporation and Transpiration From Vegetation, Soil and Water Surfaces

Atmospheric demand for water is satisfied based on available water in the canopy, depression storage at the surface, and soil. Canopy interception is removed as an evaporation flux, E (m/s), and adjustment of E updates canopy storage. The evaporation flux is based on work of Deardorff (1978) and Noilhan and Planton (1989), and given as

$$E = \left(\frac{C}{S}\right)^{2/3} E_{\mathrm{p}}, \quad (6)$$

where E_{p} is potential evaporation (m/s). Potential evaporation values are computed in the UFORE model, which serves as a pre-processor for the UFORE-Hydro application. Three distinct atmospheric loss terms input into, and processed by, UFORE-Hydro are E_{p} from the free water in the TC, E_{p} from the free water in the short crop (grass or shrub) canopy and also for depression storage, and potential evapotranspiration, ET_{p}, of soil water volumes through direct evaporation and vegetation transpiration. This distinction is used to allow for higher potential values above the turbulent TC, lower values above the low-lying shrub and depression stores, and yet more constrained values in soils because of resistances. An energy balance is maintained to ensure total available energy is reduced by the energy used to evaporate intercepted water from the canopy, and leaves a smaller total available energy for soil and transpiration.

Potential evaporation for the tree and SC is computed using the modified Penman-Monteith equation (Shuttleworth, 1993) with distinct values for canopy resistance, r_{s}. Evapotranspiration of soil water through the vegetation is also based on Penman-Monteith formulations, where potential values are modified downward based on soil and leaf canopy moisture resistances. Direct evaporation from soil surfaces is based on the same soil moisture resistances. The resistances are simulated in the root zone at rate ET_a (m/s) based on the method of Beven *et al.* (1995),

$$ET_a = ET_p\left(1 - \frac{S_r}{S_{max}}\right) \quad (7)$$

in which S_r is root zone storage deficit (m), S_{max} is maximum allowable storage deficit (m), ET_p is potential evapotranspiration (m/s), where the resistance is inversely related to LAI. In this case, more trees will lead to higher catchment LAI, lower resistances, and higher evapotranspiration.

Infiltration Into Soils

UFORE-Hydro in the pervious area watershed fraction takes precipitation not allocated to interception and partitions it between ponding, infiltration, or runoff. In considering partition between ponding, infiltration, and runoff UFORE-Hydro uses the modified Green-Ampt infiltration theory together with TOPMODEL concepts of infiltration and saturation excess processes (Beven, 1984; Beven *et al.*, 1995). In this formulation of the infiltration routine, the infiltration rate, i, is given as

$$i = \frac{dI}{dt} = \frac{\Delta\psi + Z}{\int_{z=0}^{z=z} \frac{d_z}{K_z}} \quad (8)$$

in which I is the cumulative infiltration, K_z is the hydraulic conductivity (m/s) at soil depth Z (m), and $\Delta\psi$ is effective wetting front suction (m). In the numerical solution to this equation, hydraulic conductivity was set to decay exponentially with soil depth (Beven, 1984), and model output provides instantaneous and cumulative infiltration at any time. UFORE-Hydro also provides an infiltration formulation where hydraulic conductivity decays as a power function with soil depth (Wang *et al.*, 2006),

$$K_z = K_0(1 - fz)^n \quad (9)$$

Two power function options are linear, where $n = 1$, and parabolic, where $n = 2$, to match infiltration rates and processes observed in the field. The user selects the fraction of the pervious watershed controlled by infiltration excess runoff, with the remaining fraction using a direct incorporation of precipitation into soils until the watertable reaches the surface.

In all cases of infiltration, the model accounts for watertable depth, and rain falling directly on saturated soils will be converted to surface runoff known as saturation excess overland flow. In urban areas, hydraulic conductivity values may be set to represent the impedance of compacted soils (Hamilton and Waddington, 1999; Pitt *et al.*, 2003), and the case of precipitation rates exceeding infiltration will result in ponding and possible runoff known as infiltration excess overland flow. The model can dynamically move between these scenarios across time and across the topographic index (TI) distribution in space. Based on standard TOPMODEL theory, the watertable rise will be allocated across all TI distributions. To capture tree effects on infiltration, the user might increase surface hydraulic conductivity values to represent the benefit tree growth has on reducing soil compaction.

Overland, Impervious, and Subsurface Runoff

Surface water beyond the depression storage depth, in impervious and pervious areas, is directly converted to overland flow, which is in keeping with standard urban runoff models such SWMM. UFORE-Hydro uses TOPMODEL-based runoff routines, where streamflow (q_{total}) per unit watershed area (m/s) is the sum of unit area subsurface flow ($q_{subsurface}$), overland flow ($q_{overland}$) and impervious area runoff ($q_{impervious}$):

$$q_{total} = q_{subsurface} + q_{overland} + q_{impervious} \quad (10)$$

The total overland flow in Equation (11) ($q_{overland}$) is the sum of the saturation excess and infiltration excess overland flow from pervious areas. The term $q_{overland}$ is calculated based on TOPMODEL theory using

$$q_{overland} = \frac{A_{sat}}{A} P_w \quad (11)$$

where A_{sat}/A is the quotient of saturated to total hillslope area, and P_w is spatially weighted open-sky and below-canopy precipitation (m/s) for the appropriate watershed area. Impervious surfaces have no infiltration capacity and no watertable exposure; hence, overland flow follows the TOPUrban application of Valeo and Moin (2000) when surface storages are maximized. UFORE-Hydro estimates total impervious runoff to the channel based on the effective or connected impervious area, and assumes runoff from disconnected impervious area will run-on to pervious areas and infiltrate.

Subsurface flow in UFORE-Hydro is water reaching the stream channel from the saturated subsurface zone. Subsurface flow is simulated in UFORE-Hydro using TOPMODEL concepts (Beven *et al.*, 1995; Wang *et al.*, 2005a). The TI is used to map hydrologically similar areas, and soil depth-transmissivity relationships are simulated either as exponential (Beven and Kirkby, 1979) or generalized power function (Ambroise *et al.*, 1996; Iorgulescu and Musy, 1998). UFORE-Hydro assigns each form of the soil depth-transmissivity relationship a unique form of the TI and a unique form of the subsurface and overland flow equations. For more detail, the reader is directed to Wang *et al.* (2006). These equations require common TOPMODEL parameters of T_0, the surface soil transmissivity at saturation, λ the mean TI, m a scaling parameter, and $\bar{s}$, the average soil moisture deficit under λ. The terms λ and $\bar{s}$ terms are computed differently for the exponential or power function formulations.

The hydrograph time series discharge, q_{total}, at the watershed outlet is either generated as a step-function or an optional channel routing function. Channel routing is modeled using a time-area convolution technique, where further upstream sections of the watershed are assigned longer flow routing times. There are model default time-area values that are adjusted in the model calibration step to fit the shape of observed hydrographs.

MODEL APPLICATION IN DEAD RUN, MARYLAND

Study Site

Dead Run is an urban catchment with a drainage area of 14.3 km^2 in Baltimore, and is gauged by the U.S. Geological Survey at Franklintown (Figure 2); further downstream it becomes tributary to the Gwynns Falls drainage. Bedrock underlying Dead Run is primarily composed of crystalline igneous and metamorphic rocks. Soils are predominantly classified as poorly drained with hydraulic conductivities lower than 1 cm/h. Annual precipitation is predominantly liquid, and averages 1100 mm. Precipitation data for the model simulation came from the Baltimore Ecosystem Study gauge at McDonough School, 10 km north of the watershed, and all other weather data came from Baltimore Washington International (BWI) Airport, 14 km south of the watershed.

National Land Cover Data with subgrid impervious and canopy cover statistics was used to characterize the Dead Run watershed. The area was 70% pervious and 30% impervious, and in the impervious area 5%

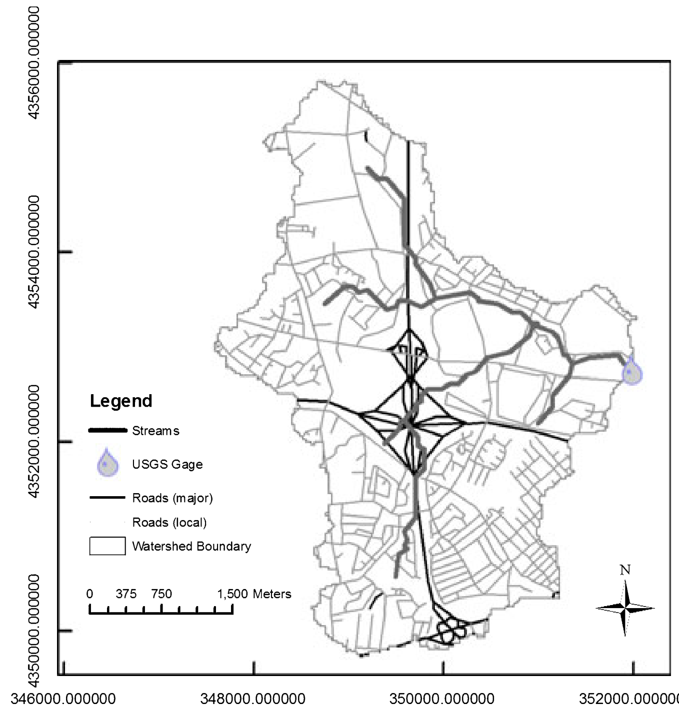

FIGURE 2. Dead Run Catchment in Baltimore, Maryland, With Overlay of Watershed Boundary, the USGS Gauge at the Outlet, Elevation Contours (m), Local Arterial Roads, and Major Interstate Roads.

was covered by trees, and in the pervious area, 17% was covered by trees, 69% covered by short vegetation, and 14% bare soil. Connected impervious area was estimated at 19.5%, which was the transportation network of driveway, road, sidewalk, and was based on using a typical value of 65% total IC in U.S. urban areas (WEF/ASCE, 1998). Two hundred 0.04 hectare U.S. Forest Service sample plots in Baltimore were used to characterize the 2001 year vegetation classes and LAI. Evergreen trees were 12% of total tree cover, and evergreen shrubs were 14% of total shrub cover. BAI for trees was set to 1.7 (Whittaker and Woodwell, 1967), and BAI for short vegetation was set to 0.5. Maximum LAI was set at 4.3, while shrubs and grass had a maximum combined LAI set to 2 based on LAI from field data and a grass LAI of 1.2 (Brede and Duich, 1984). Leaf-on and leaf-off were set to begin using the mean frost end and frost start dates for the area, which was Julian Day 97 for leaf-on, and Julian Day 311 for leaf-off, and the transition lasted 4 weeks. Depression storage was set to 1.5 mm based on SWMM values and studies in Baltimore (Viessman *et al.*, 1977).

Model Simulation Evaluations

UFORE-Hydro was run at a 1-h timestep, and 15-min discharge from the USGS gage at

Franklintown (#01589330) were coarsened to 1 h and used for model calibration and validation. Calibration to observed discharge was performed using the coupled PEST routines for from June 8 to December 31, 2000. Based on our knowledge of watershed behavior along calibration results, UFORE-Hydro was set to use a power function decay of surface hydraulic conductivity, combined infiltration and saturation excess runoff, and channel routing. Further, based on our assessment of soil compaction, we set 20% of the pervious area to generate infiltration excess overland flow. Calibrated model parameters and their values are given in Table 1, with the calibrated observed and predicted runoff for the biggest liquid precipitation event shown in Figure 3. Calibration achieved a goodness of fit of 0.86 using the peak weighted Nash-Sutcliffe criteria (Nash and Sutcliffe, 1970), 0.63 using a base flow weighted criteria (Ye *et al.*, 1997), and 0.78 using the balanced peak and base flow criteria (Chiew and McMahon, 1994).

Model validation tested these parameters for the earlier simulation period of January 1 to May 28, 2000. Goodness of fit results of validation was 0.85

TABLE 1. UFORE-Hydro Simulation Parameters and Values for Dead Run Catchment, Baltimore, Maryland.

Parameter Name	Parameter Value	Descriptions and Comments
N	2.0	Exponent of power function decay
M	0.026	A scaling parameter for T_0
T_0 (m^2/h)	0.185	Saturated surface soil transmissivity
T_d (h)	10.0	Unsaturated zone time delay
MRZD (m)	0.032	Maximum root zone storage deficit
CRV (m/h)	950.0	Channel routing velocity
K_0 (m/h)	0.002	Saturated hydraulic conductivity
ψ (m)	0.1	Wetting front suction factor
θ (%)	0.48	Wetted soil moisture content

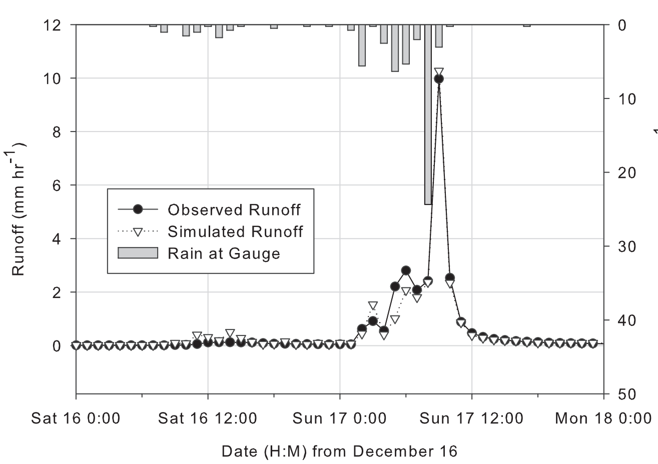

FIGURE 3. Liquid Precipitation (mm/h) and the Resulting Observed and Model Predicted Areal Runoff Hydrograph (mm/h) for the Largest Precipitation, a Warm Weather December Event.

for peak weighted, 0.60 for base flow weighted, and 0.72 for balanced flow criteria. The validation values were within a respectable 8% of calibration values; however, additional validation data would provide more robust assessment of model adequacy. From January to February, only two snow events were recorded for a period of 9 h with liquid depths of 6 and 10 mm, and in December only 10 h had precipitation events with temperatures below 0°C. Runoff simulated during these events is thought to partially explain the lower objective function values for validation compared to calibration. Nearly 11 days, from May 28 to June 8, 2000 (262 h), had missing observed discharge data.

UFORE-Hydro was run for the combined validation and calibration period, which totaled 1029 mm of precipitation. Total predicted TC interception was 18.4% of precipitation (189 mm). Unit area runoff for Dead Run was predicted at 342 mm, where 50% was from connected impervious areas, 23% from pervious areas, 27% was from ground-water discharge.

Examining Tree Effects on Interception

Trees can provide significant interception of precipitation under certain vegetative and meteorological conditions, summarized by: (1) tree interception storage capacity *S* (mm), which is related to LAI, (2) evaporation capacity, and (3) precipitation duration and intensity. Tree interception under different vegetative and meteorological conditions was studied and presented below by using UFORE-Hydro based on the year 2000 data of Dead Run, Maryland, catchment.

Vegetation (LAI) Location Effects on Tree Interception. As summer tree LAI increased from 3 to 6, the tree interception rate increased by 2.7% (17.1-19.8%) and annual runoff from the tree-covered pervious unit area decreased by 4.3 mm and from the connected impervious unit area decreased by 20.1 mm. A significant impact of location tree was observed when the canopy extended over IC, and in their absence rain in excess of depression storage was directly converted to runoff.

Effects of Evaporation Rate on Tree Interception. Precipitation intercepted by vegetation, when storage is not filled, is typically evaporated. Tree storage capacity is regulated in part by the potential evaporation rate, which is determined by meteorological conditions. Changes in meteorological conditions arise due to urban heat island effects, climate change, and because of factors, such as radiation varying with tree exposure and wind speed varying with tree height. The annual percentage of precipitation

TABLE 2. Model Predicted Interception, and Its Percentage of Precipitation, for Three Separate Storms Observed in Dead Run.

Storm Period (2000)	Total Precipitation (mm)	Total Interception (mm)	Interception (%)
July 14, 18:00-July 15, 17:00	18.0 (three storms)	3.4	18.9
July 31, 22:00-August 1, 21:00	7.1 (three storms)	2.9	40.8
August 27, 06:00-August 28, 05:00	50.3 (one storm)	1.8	3.6

intercepted by the TC increased from current 18.4-24.6% by doubling the potential evaporation rate for free water in TCs. Doubling the potential evaporation rate may not double the actual evaporation rate if the amount of precipitation intercepted on the TC is less than the potential evaporation capacity.

Effects of Precipitation Type on Tree Interception. Canopy cover had different interception effects with different storm types. UFORE-Hydro was used to examine how three different intensities and durations of precipitation affected interception, each with the same potential evaporation (see Table 2). The potential evaporation for each storm period was 10 mm, and LAI values were all the same maximum value such that the only factor affects interception was precipitation type (intensity and duration). While tree interception across the three periods varied between 1.8 and 3.4 mm, the percentage of total precipitation intercepted was 3.6, 18.9 and 40.8%, where the lowest percent occurred during the highest intensity single storm event. The period with the greatest relative interception was during the lowest intensity with three scattered storm events. Hydrological models using daily timestep cannot distinguish among such interception differences which may impact runoff predication and water quality evaluation under certain conditions.

Tree Effects on Runoff Generation

Increasing tree cover over the pervious area from the current 12% to a possible 40%, by replacing bare soil and short vegetation, reduced total unit area runoff by 2.6%. A greater impact on runoff reduction was achieved working with the IC, which was 30% of catchment area. Total runoff decreased by 3.4% when trees over IC were increased from the current 5% to a possible 40%, or 12% of catchment area. These reductions are relatively slight, however, compared with pre-development runoff volumes. UFORE-Hydro will be further refined to simulate tree-based best management practices, such as bioretention basins (USEPA, 1999), that intercept and recharge larger runoff volumes. Trees over impervious areas reduce the frequency and magnitude of pollutant wash-off phenomenon many cities are trying to control (WEF/ASCE, 1998). UFORE-Hydro has a water quality event mean concentration algorithm that simulates these runoff-pollutant loading relationships.

Effects of Tree and Impervious Cover on Runoff Generation

UFORE-Hydro also simulated increases in impervious area to examine impacts on runoff, and general trends are shown in Figure 4. Doubling IC from 30 to 60%, by replacing bare soil and short vegetation classes with IC in the model, doubled the impervious runoff, increased total runoff by 33%, reduced pervious runoff by 53%, and reduced base flow by 17%. Such land cover change analysis is typical for urban planners, and is typically conducted with Curve Number-based models (Chin, 2000).

As urban growth often alters both tree and IC simultaneously, three scenarios with different land cover conditions were simulated. The base case was the existing conditions. The first change scenario reduced pervious tree cover from 12.0 to 6.0% and replaced it with connected impervious area with no trees. The second change scenario doubled pervious tree cover from 12.0 to 24.0% in bare soil and short

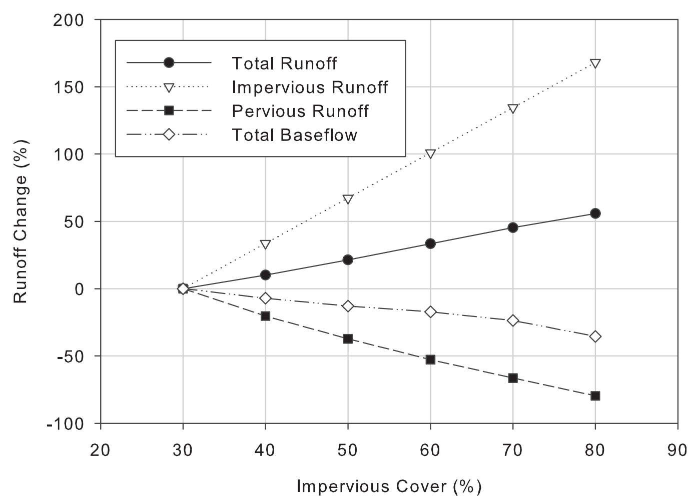

FIGURE 4. Model Predicted Impact of Increasing Watershed Impervious Area (%) on Changes in Runoff From the Whole Watershed, Runoff From Impervious Areas, Runoff From Pervious Areas, and Watershed Base Flow. Impervious area was simulated as 65% directly connected.

vegetation areas, and increased impervious area covered by trees from 5 to 20%. In Scenario 1, with increased IC, total annual runoff increased by 10% (~500,000 m^3 yr^{-1}), while in Scenario 2, with increased tree cover, annual runoff decreased by 3% (~140,000 m^3 yr^{-1}). In addition to volumetric changes, UFORE-Hydro simulated a 12% lower peak discharge for Scenario 2 as compared with Scenario 1.

CONCLUSIONS

UFORE-Hydro was developed to incorporate process-based water balance equations into an urban forest effects model developed by the USDA Forest Service. The model provides a research and management tool for urban foresters considering water balance impacts across a growing season or a single precipitation event. It is an object-oriented, physical-based model with topographically delineated similar units that simulates interception, depression storage, evapotranspiration, infiltration, and runoff processes. Model inputs are land cover data, elevation data, meteorological data, and nine soil and runoff parameter values, many satisfied using optional default values or constrained-calibration values.

UFORE-Hydro presents a unique simulation scheme linking together trusted algorithms and some modified and tested algorithms, with TCs simulated over pervious and impervious surfaces. Vegetation interception is simulated using a modified Rutter algorithm to incorporate sparse vegetation, seasonal adjustments to leaf area, and simplify parameter inputs. Depression storage is provided in impervious areas, and surface runoff either flows along connected impervious areas or by infiltration excess or saturation excess runoff in pervious areas. Potential evaporation is set by the Penman Monteith method with actual evaporation constrained by available water resistances, and allocated between tree and SC intercepted water, and soil evaporation and transpiration. Subsurface flow uses the TOPMODEL theory, and channel routing is performed with an optional area-time algorithm. An automated Parameter ESTimation (PEST) has been coupled with UFORE-Hydro to facilitate calibration to observed discharge values. UFORE-Hydro functionality in predicting the urban water balance, and its ability to examine tree management scenarios, was demonstrated for Dead Run in Baltimore. Testing UFORE-Hydro for longer simulation periods and additional watersheds, mostly draining to the Chesapeake Bay, is underway.

ACKNOWLEDGMENTS

The authors thank USDA Forest Service personnel Bob Hoehn, Gordon Heisler, Jeff Walton and Daniel Crane for their assistance with data processing for the UFORE-Hydro model development.

LITERATURE CITED

Ambroise, B., K. Beven, and J. Freer, 1996. Towards a Generalization of the TOPMODEL Concepts: Topographic Indices of Hydrological Similarity. Water Resources Research 32(7):2135-2145.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams, 1998. Large Area Hydrologic Modelling and Assessment, Part I: Model Development. Journal of the American Water Resources Association 34:73.

Aston, A.R., 1979. Rainfall Interception by Eight Small Trees. Journal of Hydrology 42:383.

Beven, K., 1984. Infiltration Into a Class of Vertically Non-Uniform Soils. Hydrological Sciences Journal 29:425.

Beven, K., and J. Kirkby, 1979. A Physically Based, Variable Contributing Area Model of Basin Hydrology. Hydrological Sciences Bulletin 24(1):43.

Beven, K., R. Lamb, P. Quinn, R. Romanowics, and J. Freer, 1995. TOPMODEL. *In:* Computer Models of Watershed Hydrology, V.P. Singh (Editor). Water Resources Publications, Colorado, pp. 627-688.

Bicknell, B.R., J.C. Imhoff, J.L. Little, A.S. Donigian, and R.C. Johanson, 1993. Hydrological Simulation Program – Fortran (HSPF): User's Manual. Release 10. USEPA. EPA-600/R-93/174, Athens, Georgia.

Brede, A.D. and J.M. Duich, 1984. Initial Mowing of Kentucky Bluegrass-Perennial Ryegrass Seeding Turf Mixtures. Agronomy Journal 76(5):711.

Butler, D. and J.W. Davies, 2000. Urban Drainage. E & FN Spon, New York, p. 489

Calder, I.R., 1986. A Stochastic Model of Rainfall Interception. Journal of Hydrology 89:65.

Chiew, F.H.S. and T. McMahon, 1994. Application of the Daily Rainfall-Runoff Model MODHYDROLOG to 28 Australian Catchments. Journal of Hydrology 153:383.

Chin, D.A., 2000. Water Resources Engineering. Prentice-Hall, Upper Saddle River, New Jersey.

Deardorff, J.W., 1978. Efficient Prediction of Ground Surface Temperature and Moisture With Inclusion of a Layer of Vegetation. Journal of Geophysical Research 83:889.

Dickinson, R.E., 1984. Modeling Evatranspiration for Three-Dimensional Global Climate Models. Climate Processes and Climate Sensitivity, Geophysical Monograph Series 29:58.

van Dijk, A.I.J.M. and L.A. Bruijnzeel, 2001. Modeling Rainfall Interception by Vegetation of Variable Density Using an Adapted Analytical Model. Part 1. Journal of Hydrology 247:230.

Doherty, J., 2001a. PEST-ASP User's Manual. Watermark Numerical Computing, Brisbane, Australia.

Doherty, J., 2001b. PEST Surface Water Utilities User's Manual. Watermark Numerical Computing, Brisbane, Australia.

Eltahir, E.A. and R.L. Bras, 1993. A Description of Rainfall Interception Over Large Areas. Journal of Climate 6:1002.

Endreny, T.A., 2005. Land Use and Land Cover Effects on Runoff Processes: Urban and Suburban Development. *In*: Encyclopedia of Hydrological Sciences, M.G. Anderson (Editor). Wiley, Chichester, United Kingdom, pp. 1775-1804.

Gash, J.H.C., C.R. Lloyd and G. Lachaud, 1995. Estimating Sparse Rainfall Interception With an Analytical Mode. Journal of Hydrology 170:79.

Gash, J.H.C. and A.J. Morton, 1978. An Application of the Rutter Model to the Estimation of the Interception Loss From Thetford Forest. Journal of Hydrology 38:49.

Hamilton, G.W. and D.V. Waddington, 1999. Infiltration Rates on Residential Lawns in Central Pennsylvania. Journal of Soil and Water Conservation 54:3rd Quarter:564.

Horner, R.R., J.J. Kupien, E.H. Livingston, and H.E. Shaver, 1994. Fundamentals of Urban Runoff Management: Technical and Institutional Issues. Terrene Institute, Washington, D.C.

Huang, C., L. Yang, B.K. Wylie, and C.G. Homer, 2001. A Strategy for Estimating Tree Canopy Density Using Landsat 7 ETM+ and High Resolution Images Over Large Areas. Third International Conference on Geospatial Information in Agriculture and Forestry, 10 pp.

Huber, W.C. and W.T. Dickinson, 1992. Storm Water Management Model, Version 4, User's Manual, USEPA. EPA-600-3-88-001a, Athens, Georgia.

Hutjes, R.W.A., A. Wierda, and A.W.L. Veen, 1990. Rainfall Interception in the Taý Forest, Ivory Coast: Application of Two Simulation Models to a Humid Tropical System. Journal of Hydrology 114:259.

Iorgulescu, I. and A. Musy, 1998. Generalization of TOPMODEL for a Power law Transmissivity Profile. Hydrological Processes 11:1353.

Jackson, I.J., 1975. Relationships Between Rainfall Parameters and Interception by Tropical Forest. Journal of Hydrology 24:215.

James, L.D., 1965. Using a Digital Computer to Estimate the Effects of Urban Development on Flood Peaks. Water Resources Research 1(2):223.

Jetten, V.G., 1996. Interception of Tropical Rain Forest – Performance of a Canopy Water Balance Model. Hydrological Processes 10:671.

Koller, M. and S.K. Upadhyay, 2005. Prediction of Processing Tomato Yield Using a Crop Growth Model and Remotely Sensed Aerial Image. Transactions of ASAE 48(6):2335.

Liu, S., 1998. Estimation of Rainfall Storage Capacity in the Canopies of Cypress Wetlands and Slash Pine Uplands in North-Central Florida. Journal of Hydrology 207:32.

Lousteau, D., P. Berbigier, and A. Granier, 1992. Interception Loss, Throughfall and Stemflow in a Maritime Pine Stand. II. An Application of Gash's Analytical Model of Interception. Journal of Hydrology 138:469.

Nash, J.E. and J.V. Sutcliffe, 1970. River Flow Forecasting Through Conceptual Models. Part I – A Discussion of Principles. Journal of Hydrology 27(3):282.

Noilhan, J. and S. Planton, 1989. A Simple Parameterization of Land Surface Processes for Meteorological Models. Monthly Weather Review 117:536.

Nowak, D.J. and J.T. Walton, 2005. Projected Urban Growth (2000-2050) and Its Estimated Impact on the U.S. Forest Resource. Journal of Forestry 103(8):383.

Nowak, D.J., D.E. Crane, J.C. Stevens, and M. Ibarra, 2002. Brooklyn's Urban Forest. Newtown Square, Pennsylvania, p. 107.

Nowak, D.J., R. Hoehn, D.E. Crane, J.B. Stewart, and J.T. Walton, 2006. Assessing Urban Forest Effects and Values: Minneapolis' Urban Forest. USDA Forest. USDA Forest Service, Newtown Square, Pennsylvania, p. 20.

Pitman, J.I., 1989. Rainfall Interception by Bracken in Open Habitats – Relations Between Leaf Area, Canopy Storage and Drainage Rate. Journal of Hydrology 105:317.

Pitt, R., S.E. Chen, S. Clark, J. Lantrip, C.K. Ong, and J. Voorhees, 2003. Infiltration Through Compacted Urban Soils and Effects on Biofiltration Design. Practical Modeling of Urban Water Systems 11:217.

Riley, A.L., 1998. Restoring Streams in Cities: A Guide for Planners Policymakers and Citizens. Island Press, Washington, D.C.

Ross, J., 1975. Radiative Transfer in Plant Communities. Vegetation and the Atmosphere 1:13.

Rutter, A.J., A.J. Morton, and P.C. Robins, 1975. A Predictive Model of Rainfall Interception in Forests. II. Generalization of the Model and Comparison With Observations in Some Coniferous and Hard-Wood Stands. Journal of Applied Ecology 12:367.

Rutter, A.J., A.J. Morton, and P.C. Robins, 1971. A Predictive Model of Rainfall Interception in Forests. I. A Derivative of the Model From Observations in a Plantation of Corsican Pine. Agricultural Meteorology 9:367.

SCS (Soil Conservation Service), 1975. Urban Hydrology for Small Watersheds. SCS, Washington, D.C.

Shuttleworth, J.W., 1993. Evaporation. *In*: Handbook of Hydrology, D.R. Maidment (Editor). McGraw-Hill, New York, New York, pp. 5.1-5.51.

Tobón Marin, C., 1999. Monitoring and Modelling Hydrological Fluxes in Support of Nutrient Cycling Studies in Amazonian Rain Forest Ecosystems. *Tropenbos Series No. 17*.

United Nations, 2004. World Urbanization Prospects: The 2003 Revision. Population Division, Department for Economic and Social Affairs, New York, New York, p. 323.

USEPA (U.S. Environmental Protection Agency), 1999. Storm Water Technology Fact Sheet: Bioretention. EPA-832-F-99-012, USEPA, Washington, D.C.

USEPA (U.S. Environmental Protection Agency), 2000. Storm Water Phase II Final Rule. EPA 833-F-00-002, USEPA, Washington, D.C.

USGAO (U.S. General Accounting Office), 2001. Water Quality: Better Data and Evaluation of Urban Runoff Programs Needed to Assess Effectiveness. USGAO, Washington, D.C.

Valente, F., J.S. David, and J.H.C. Gash, 1997. Modeling Interception Loss for Two Sparse Eucalypt and Pine Forests in Central Portugal Using Reformulated Rutter and Gash Analytical Models. Journal of Hydrology 190:141.

Valeo, C. and S.M.A. Moin, 2000. Variable Source Area Modelling in Urbanizing Watersheds. Journal of Hydrology 228(1-2):68.

van Heemst, H.D.J., 1988. Plant Data Values Required for Simple Crop Growth Simulation Models, Review and Bibliography. Wageningen, The Netherlands.

Viessman, J.W., J.W. Knapp, G.L. Lewis, and T.E. Harbaugh, 1977. Introduction to Hydrology. Harper and Row, New York, New York.

Wang, J., T.A. Endreny, and J.M. Hassett, 2005a. Flexible Modeling Package for Topographically Based Watershed Hydrology. Journal of Hydrology 314(1-4):78-91.

Wang, J., T.A. Endreny, and J.M. Hassett, 2006. Power Function Decay of Hydraulic Conductivity for a TOPMODEL-Based Infiltration Routine. Hydrological Processes, DOI: 10.1002/hyp.6159.

Wang, J., J.M. Hassett, and T.A. Endreny, 2005b. An Object Oriented Approach to the Description and Simulation of Watershed Scale Hydrologic Processes. Computers and Geosciences 31(4):425-435.

Watson, D.J., 1947. Comparative Physiological Studies on the Growth of Field Crops. Annals of Botany 11:41.

WEF/ASCE, 1998. Urban Runoff Quality Management. Water Environment Federation and American Society of Civil Engineers, Alexandria, Virginia.

Whittaker, R.H. and G.M. Woodwell, 1967. Surface Area Relations of Woody Plants and Forest Communities. American Journal of Botany 54(8):931.

Yang, L., C. Huang, C.G. Homer, B.K. Wylie, and M.J. Coan, 2003. An Approach for Mapping Large-Area Impervious Surfaces: Synergistic Use of Landsat 7 ETM+ and High Resolution Imagery. Canadian Journal of Remote Sensing 29(2):230.

Ye, W., B.C. Bates, N.R. Viney, M. Silvapan, and A.J. Jakeman, 1997. Performance of Conceptual Rainfall-Runoff Models in Low-Yielding Ephemeral Catchments. Water Resources Research 33(1):153.

All in-text references underlined in blue are linked to publications on ResearchGate, letting you access and read them immediately.