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Hydrologic prediction for urban watersheds with the Distributed Hydrology–Soil–Vegetation Model

Lan Cuo,[1] Dennis P. Lettenmaier,[1]* Bernt V. Mattheussen,[2] Pascal Storck,[3] and Matthew Wiley[3]

[1] *Department of Civil and Environmental Engineering Box 352700, University of Washington, Seattle, WA 98195, USA*
[2] *Norwegian University of Science and Technology, Trondheim, Norway*
[3] *3TIER Environmental Forecast Group, 2001 6th Ave., Suite 2100, Seattle, WA 98121, USA*

Abstract:

Some relatively straightforward modifications to the Distributed Hydrology–Soil–Vegetation Model (DHSVM) are described that allow it to represent urban hydrological processes. In the modified model, precipitation that falls on impervious surfaces becomes surface runoff, and a spatially varying (depending on land cover) fraction of surface runoff is connected directly to the stream channel, with the remainder stored and slowly released to represent the effects of stormwater detention. The model was evaluated through application to Springbrook Creek watershed in a partially urbanized area of King County, Washington. With calibration, the modified DHSVM simulates hourly streamflow from these urbanized catchments quite well. It is also shown how the revised model can be used to study the effects of continuing urbanization in the much larger Puget Sound basin. Model simulations confirm many previous studies in showing that urbanization increases peak flows and their frequency, and decreases peak flow lag times. The results show that the urbanization parameterizations for DHSVM facilitate use of the model for prediction and/or reconstruction of a range of historic and future changes in land cover that will accompany urbanization as well as other forms of vegetation change.

KEY WORDS urban hydrology; spatially distributed hydrology model; impervious area; land cover change

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INTRODUCTION

Urbanization modifies hydrological processes by replacing vegetated land cover with impervious surfaces and by extending the natural drainage network to include artificial ponds, ditches and conduits laid on the ground and underground (Leopold, 1968; Hall, 1984; Konrad and Booth, 2002; Mansell 2003; Berthier *et al*., 2006; Xiao *et al*. 2007; Dow, 2007). Impervious surfaces reduce infiltration, generally resulting in increased surface runoff and reduced base flow. Artificial ditches and conduits alter runoff pathways and change stormwater drainage. In urbanizing catchments, surface flow may be diverted to artificial ponds or flood detention ponds built to reduce flood risks or in some cases for irrigation purposes.

Urban storm water drainage systems usually consist of two elements, termed dual drainage in the urban hydrology nomenclature: (1) surface components such as streets, rooftops, ditches; and (2) subsurface components such as pipes and other manmade stormwater drainage conduits (Schmitt *et al*., 2004; Smith 2006a). These two elements are linked through street curb inlets and manholes. On the other hand, in partially urbanized catchments, these urban drainage components are often mixed with the natural channel drainage in portions of the basin that are unurbanized or partially urbanized. Surface storage is often a component of urban drainage systems, and is typically sized so as to maintain a consistency between post-urbanized catchments under extreme conditions with pre-urbanization extremes (Smith, 2006a).

Urbanization effects on hydrological processes can be studied through modelling and field observations. Field studies of urbanization effects on runoff have used paired catchment and longitudinal (long time series) methods where one member of the pair or a basin in the latter part of a long time series record has undergone urbanization. Examples of such studies include Changnon and Demissie (1996), Moscrip and Montgomery (1997), Leith and Whitfield (2000), Beighley and Moglen (2002), Jennings and Jarnagin (2002), Konrad and Booth (2002), Burns *et al*. (2005), Dow (2007), and Chang (2007). Essentially, all of these studies show that urbanization increases peak flows. On the other hand, inferred effects of urbanization on mean annual flow are mixed (Changnon and Demissie, 1996; Konrad and Booth, 2002; Burns *et al*. 2005, Chang, 2007)—in some cases, annual flows have increased as the result of increased storm runoff, but in others, this effect is more than cancelled by reduction of infiltration during storms and resultant reduction in dry period flows. Interpretation of field studies of urbanization effects on streamflow is often complicated by regional climate variability, variable physical characteristics of the study basin, unaccounted-for human interventions, and observation deficiencies (Chang, 2007). A major advantage of model studies is

* Correspondence to: Dennis P. Lettenmaier, Department of Civil and Environmental Engineering Box 352700, University of Washington, Seattle, WA 98195, USA. E-mail: dennisl@u.washington.edu

that most of the above confounding factors can be controlled, notwithstanding that field data are critical for evaluating model performance.

There are three main types of urban hydrological models. The first focuses on engineering and municipal management objectives and is often used to predict urban flooding and the placement of structures and other measures to control flooding. Such models simulate the hydrodynamics of overland flow, often in the form of a diffusive wave. They typically use GIS and digital elevation models to determine surface runoff direction, location of street, storm sewer pipes, street inlets and manholes. Such models are often composed of separate surface runoff and pipe flow modules. The connections between the two modules are manholes and street inlets. Examples of this type of model are given by Hsu *et al.* (2000), Schmitt *et al.* (2004), Smith (2006b), and Xiao *et al.* (2007). In most applications of this class of model, validation data are limited, and so the simulation quality is difficult to assess other than through highly aggregate performance measures (Mignot *et al.*, 2006). The domain of these urban hydrology models, which are primarily used for engineering design purposes, is mostly densely populated cities and towns, but they are less appropriate to 'mixed' (partially natural, partially urbanized) watersheds.

The second type of urban hydrology model is empirical or semi-empirical. In these models, empirical functions such as the artificial neural network (ANN) method are used to relate input (rainfall) to output (streamflow). Such models can be useful in urban streamflow simulation and forecasting (Filho and Santos, 2006) so long as data exist to 'train' the algorithms.

The third type of urban hydrology model uses conceptual or semi-distributed modeling concepts, examples of which are SWMM5 (Rossman, 2007), MIKE URBAN (Mikkelsen *et al.* 2005), and Aronica and Cannarozzo (2000). Fully distributed hydrology models can be considered to be a generalization of these conceptual semi-distributed models. Within this class are the TIN-based Real-Time Basin Simulator (tRIBS) of Garrote and Bras (1995), the Distributed-Hydrology-Soil-Vegetation Model (DHSVM; Wigmosta *et al*, 1994, 2002), and the TOPMODEL-Based Land Surface-Atmosphere Transfer Scheme (TOPLATS) (Famiglietti and Wood, 1994). Fully distributed models have been used to evaluate vegetation controls on land-atmosphere transfers (Famiglietti and Wood, 1994), for evaluation of land cover change effects on surface runoff (Bowling and Lettenmaier, 2001), and for prediction of slope failures following vegetation disturbance (Tucker and Bras, 1998). Models within this class generally have not, however, been used for prediction in urban or urbanizing basins.

DHSVM is a fully distributed, physically based model that simulates full energy and water balance cycles. It is intended for use primarily in regions of complex terrain. In DHSVM, watersheds are represented by grid cells. The cell size determines the model spatial resolution. Stream channels are linked through grid cells. Examples of DHSVM applications in mountainous watersheds can be found in Storck *et al.* (1998), Bowling *et al.* (2000) and La Marche and Lettenmaier (2001).

Although the standard formulation of DHSVM does not represent urban land use, the structure of the model makes the representation of hydrological processes in partially urbanized basins feasible, and we discuss here parameterizations to do so. It is stressed that the motivation here is not to reinvent a model with characteristics like SWMM5, for instance, but rather to implement a plausible scheme for incorporating urban effects in a more physically based, water and energy balance model. In so doing, we have two objectives: (1) to document adaptations to DHSVM that allow the model to be applied to partially urban or urbanizing conditions; and (2) to evaluate performance of the model under urban or partially urban land cover conditions. The study lays a foundation for land cover change studies in the broader Puget Sound basin, Washington where urbanization is largely mixed with other land cover (e.g. forest).

METHODOLOGY

The intent of the modifications to DHSVM described here is not to produce a model that is applicable to fully urban conditions, such as core metropolitan areas where essentially the entire drainage system is engineered. For such conditions, there exist suitable models already, several of which are mentioned above. Instead, the purpose is to provide sufficient flexibility in DHSVM so that it can be used in regional studies, where part of the domain is urban or urbanizing. The extent of such areas, on a regional basis, generally greatly exceeds that of core urban areas, and is characterized by a mix of natural and engineered drainage facilities. DHSVM, as described by Wigmosta *et al.* (1994) was originally designed for mountainous forested watersheds, and many of its uses have been to evaluate effects of changes in forest cover and/or forest practices (Storck *et al.*, 1998; Bowling *et al.*, 2000; La Marche and Lettenmaier, 2001; Cuo *et al.*, 2006). The original construct of the model is retained, but modifications that allow for urban land cover as one of the optional land cover classifications are described and evaluated. Performance of the new model parameterizations is evaluated for a partially urbanized basin in the Puget Sound region of western Washington. Mean discharge, correlation coefficient and model efficiency (Nash and Sutcliffe, 1970) are used to determine model performance. After calibration and validation, the model is used to evaluate urbanization effects on streamflow using pre-settlement and 2002 land cover.

MODEL DESCRIPTION

DHSVM represents both the land surface energy and water balances at spatial scales at which topographic

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effects dominate the movement of water over the surface and downslope redistribution of moisture in the subsurface. Generally, it is intended for application at relatively high spatial resolution, typically 30–150 m, although both higher and lower resolution implementations have been made. DHSVM is primarily a saturation excess model, although it includes a relatively crude infiltration excess parameterization. In contrast, it has a relatively sophisticated snow accumulation and ablation model, and intermediate complexity representations of vegetation canopy controls on evapotranspiration, canopy interception of liquid and solid precipitation, and vegetation effects on the surface energy balance. Using a digital elevation model (DEM) as a base map, DHSVM explicitly accounts for soil and vegetation variations at the DEM pixel scale, as well as stream channel morphology and location. It uses a linear storage routing scheme. A detailed description of DHSVM can be found in Wigmosta *et al*. (1994, 2002).

To account for urban hydrological processes, DHSVM was modified as follows. A land cover category 'urban' was added, and for pixels with this land cover type, a fraction of impervious surface area is also specified. The fraction of impervious area determines the amount of surface runoff generated on impervious surfaces, whereas for the fraction that is not impervious, DHSVM handles infiltration using the same parameterizations as for non-urban pixels. A second parameter called the fraction of water stored in flood detention was also added. The corresponding fraction of runoff generated from impervious surfaces is assumed to be diverted to detention storage. These two parameters allow the model to mimic, in a qualitative way, the dominant processes in urban runoff, specifically surface runoff generation and detention storage (which, as a practical matter, can either be in constructed detention ponds or tanks, or in the engineered channel system).

The runoff diverted to detention storage is allowed to drain as a linear reservoir, and re-enters the channel system in the pixel from which it is diverted. Surface runoff that is not diverted is assumed to enter the channel system directly, i.e. all urban channels are connected directly to the channel system (this is not generally the case for non-urban pixels). It is assumed that the natural channel system remains intact, and the support area concept that defines the connectivity of pixels to first order channels (Bowling and Lettenmaier, 2001) is retained. However, impervious surface runoff (and drainage from detention reservoirs) is assumed to be connected to the nearest stream channel directly so that overland flow reaches a stream channel at the same time step. Once impervious surface runoff has entered a stream channel, it follows the channel flow routing processes. The nearest stream channel to a pixel with impervious is searched through eight directions based on the flow direction generated in Arcinfo. This information is preprocessed, and is included in the model input.

The following equations parameterize the impervious and detention processes. If impervious fraction $f_i > 0$, and detention fraction $f_d > 0$ for a grid cell which has runoff of rf_s:

$$rf_{ch} = (1 - f_d) \times f_i \times rf_s \quad (1)$$

$$D_i = f_d \times f_i \times rf_s \quad (2)$$

$$D_s = D_i - D_o \quad (3)$$

$$D_o = D_s \times C_{dd} \quad (4)$$

$$rf_{ch} = D_o \quad (5)$$

$$rf_p = (1 - f_i) \times rf_s \quad (6)$$

where f_i is the fraction of area that is impervious, or impervious fraction, f_d is detention fraction, i.e. the fraction of water on impervious area that goes to detention, rf_s is the total runoff available on the grid cell (units: m (time step)$^{-1}$), D_i is the runoff from the impervious area that goes to detention (units: m (time step)$^{-1}$), D_s is the detention storage (units: m (time step)$^{-1}$), D_o is the outflow from detention (units: m (time step)$^{-1}$), C_{dd} is the coefficient of detention decay that controls the runoff out of detention storage(unit: (time step)$^{-1}$), rf_{ch} is the runoff that goes to the nearest channel (units: m (time step)$^{-1}$), rf_p is the runoff generated on the pervious area (units: m (time step)$^{-1}$). Runoff units of depth time^{-1} are based on the use in DHSVM of pixels of fixed (equal) area.

Study area

USGS gauge 12113346 (Springbrook Creek near Orillia, WA; Table I) was chosen for the study because it is a partially urbanized basin, is relatively small, and hourly precipitation data from a nearby climate station are readily available. The basin is located in south-west King County (Figure 1). The USGS classifies the Springbrook record as poor, however, the USGS comments for this gauge cite only urbanization upstream, and regulation, presumably by urban detention, which are conditions that are of interest in this study. Consultation with USGS personnel suggested that while the records must be interpreted judiciously, they should be appropriate for the purposes. The records for the sequences of hourly data for the Springbrook Creek station were examined and no behaviour was found that led to questioning the applicability of the data for the time period used in the study.

Annual precipitation in the catchment is about 1000 mm, of which about 70% occurs from October

Table I. Details of stream gauge and climate station

Stream gauge	Climate station
USGS ID: 12113346	COOP ID: 457473
Hydrological unit code: 17110013	WMO ID 72793
Springbrook Creek near Orillia	Seattle Tacoma International Airport station
Latitude: 47°25′53″N	Latitude: 47°27′N
Longitude 122°13′35″W	Longitude:122°19′W
Elevation: 8 m	Elevation: 112·8m
Contribution Area: 21·9 km^2	

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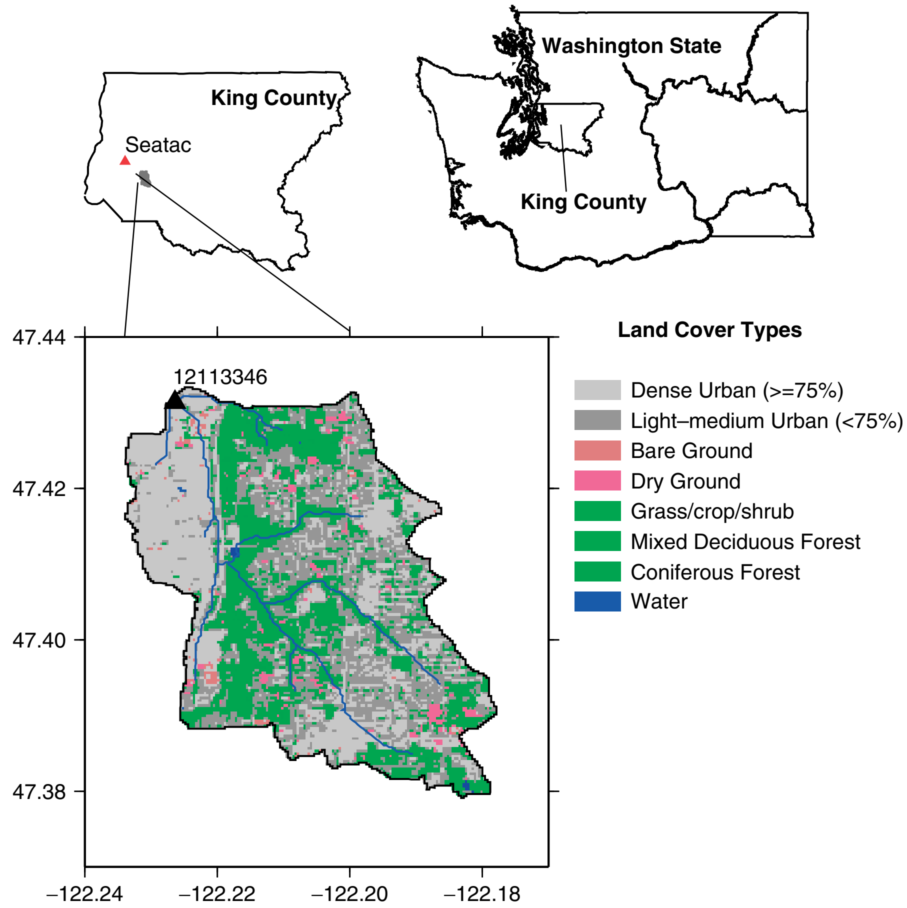

Figure 1. Geographic location and 2002 land cover types of Springbrook Creek basin

through March. Annual mean air temperature is about 10 °C. Springbrook Creek has modest relief, with elevation ranging from 8–160 m. The west side of the basin is essentially flat while the east side has some relief. The soil type is mainly sandy loam. Land cover in the area in recent decades has undergone dramatic changes, and now is dominated by roads, industrial warehouses, commercial and residential houses which are mainly located in the flat, western side of the basin. The total fraction of urban (dense or light-medium) land cover is about 64% in the Springbrook Creek catchment. The stream channel network for the basin, along with current land cover, climate station and the stream gauge locations are shown in Figure 1. Table II shows the proportions of land cover types in 2002 in the study area (Alberti *et al.* 2004).

Table II. Proportions of land cover types in 2002 in Springbrook Creek basin (source: Alberti *et al.*, 2004)

Land cover types	Springbrook Creek basin
Dense urban	32·6
Light-medium urban	31·3
Bare ground	0·83
Dry ground	2·2
Grass/crop/shrub	7·8
Mixed/deciduous forest	22·5
Coniferous forest	2·5
Water	0·12

Data

A 30 m resolution USGS DEM was used as a base map for the watershed. Owing to the flat terrain in the western parts of the basin, the DEM had to be manually modified to remove sinks and to produce basin boundaries that resulted in drainage area comparable to those estimated by the USGS. The ratio between the Arcinfo outlined watershed area and USGS defined area was used to adjust model-predicted discharge because of the slight mismatch in area. Hourly stream discharge (measured by USGS) between 1 January 1996 and 31 December 1999 at gauge 12113346 was used for calibration, and from 1 January 2000 to 30 September 2002 was used for validation. After calibration and validation, the model was run from 1 January 1915 to 30 September 2002 at a 3 h time step to study urbanization effects.

The model forcing data, which are standard for DHSVM, include surface air temperature (C°), relative humidity (%), wind speed (m s^{-1}), downward shortwave and longwave radiation (W m^{-2}) and precipitation (m). Hourly precipitation measured at the Seattle-Tacoma International Airport, about 13·6 km northwest of the gauge (see Figure 1, in which the station is denoted by the red triangle labelled SeaTac, and Table I for details) was used to drive the hydrology model. The area has modest relief, and while there are inevitably timing differences between basin precipitation and that recorded

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at the station, major storm peaks mostly result from large frontal activity rather than small- scale convective storms, which reduces the effects of spatial separation between the climate station and the catchment. Hourly temperature, relative humidity, incoming shortwave and longwave radiation are not routinely recorded, instead, they were generated from one-sixteenth degree gridded daily precipitation, minimum and maximum temperature data set for the Puget Sound produced using methods described in Maurer *et al*(2002), Hamlet and Lettenmaier (2005, 2007). All precipitation and temperature data were extracted from archives of the National Climate Data Center (NCDC). Wind speed was obtained from National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis project (Kalnay *et al*., 1996).

In the Hamlet and Lettenmaier (2007) data set, decadal scale variability is controlled to match the US Historical Climatology Network (HCN; Karl *et al*., 1990). Because the interest is in isolating urbanization effects, climate trends need to be removed, and an approach similar to Hamlet and Lettenmaier (2007) was followed. The trend in the annual precipitation, minimum temperature and maximum temperature for the period 1 January 1915 to 30 September 2002 was examined first. Based on application of the Mann–Kendall trend test to annual precipitation and temperature maxima and minima, it was found that only annual minimum temperature had a statistically significant increasing trend over the time period, and therefore this trend was removed using the method described by Hamlet and Lettenmaier (2007). Figure 2 shows the historical and detrended annual minimum temperature for1915–2002 for the one-sixteenth degree data.

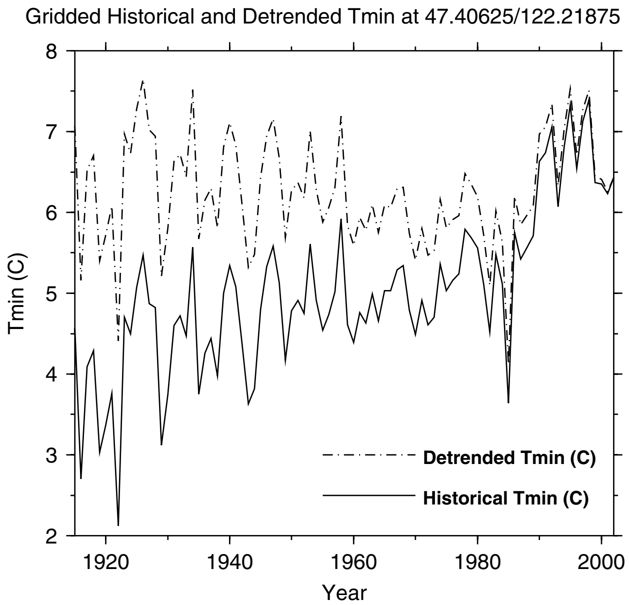

Figure 2. Historical and adjusted annual minimum temperature at grid node 47·40625 N latitude, 122·21875 W longitude

RESULTS

To evaluate performance of the method, the sensitivity of the simulations to the parameterization for impervious fraction was determined first. To do so the model was run with the hourly forcings as described above, and soil parameters were transferred from nearby relatively unurbanized catchments (Westrick *et al*., 2002). Land cover classifications for the basin from Alberti *et al*. (2004) (see Table II for summary) were used for those areas not classified as either 'dense urban' or 'light-medium urban'. For land cover types 'dense urban' and 'light-medium urban', vegetation cover type 'grass/crop/shrub', which approximates the vegetation cover in landscaped urban areas, was used. By replacing the urban with non-urban land cover types, the model defaults back to the 'standard' version of DHSVM. Figure 3, panels a1 and a2 shows results for DHSVM without the urban parameterization—typically storm peaks are underpredicted, and baseflow is overpredicted, relative to observations.

The fraction of impervious area was estimated from Alberti *et al*. (2004), the same period was simulated, without the detention parameterization described above (i.e. all runoff from impervious surfaces was assumed to reach the channel system directly). In Alberti *et al*. (2004), the dense urban classification was assigned to areas where the fraction of impervious surface is greater than or equal to 0·75 while the light-medium urban classification was defined as having impervious surface fraction less than 0·75. In the model simulation, for the dense urban, the fraction of impervious surface area was set to 0·75; while for the light-medium urban, the impervious surface fraction was set to 0·35, roughly in the middle of the range 0–0·75. The results shown in Figure 3 (panels b1 and b2) indicate that peak flows are largely overpredicted, presumably because detention storage is not accounted for. Finally, the fraction of runoff generated from impervious areas that goes to detention storage was estimated, together with a detention recession coefficient to provide a plausible match with observations. By trial and error, detention fractions of 0·3 for dense urban and 0·2 for light-medium urban were found to produce reasonable results, and seem physically plausible. The detention recession coefficient was estimated to be 0·1 (units: h^{-1}, i.e. model time step) for both urban types. In Figure 3, panels c1 and c2 show that these detention parameters produce plausible reproductions of observed flows.

Following testing of the urban parameterization as described above, some additional calibration was performed by adjusting the model's soil parameters (soil depth, lateral hydraulic conductivity, maximum infiltration capacity, field capacity, wilting point and vertical saturated hydraulic conductivity). This calibration resulted in modest adjustments of soil parameters.

Figures 4 and 5 show the simulated and observed hourly streamflow in Springbrook Creek basin during calibration and validation periods, respectively. Table III

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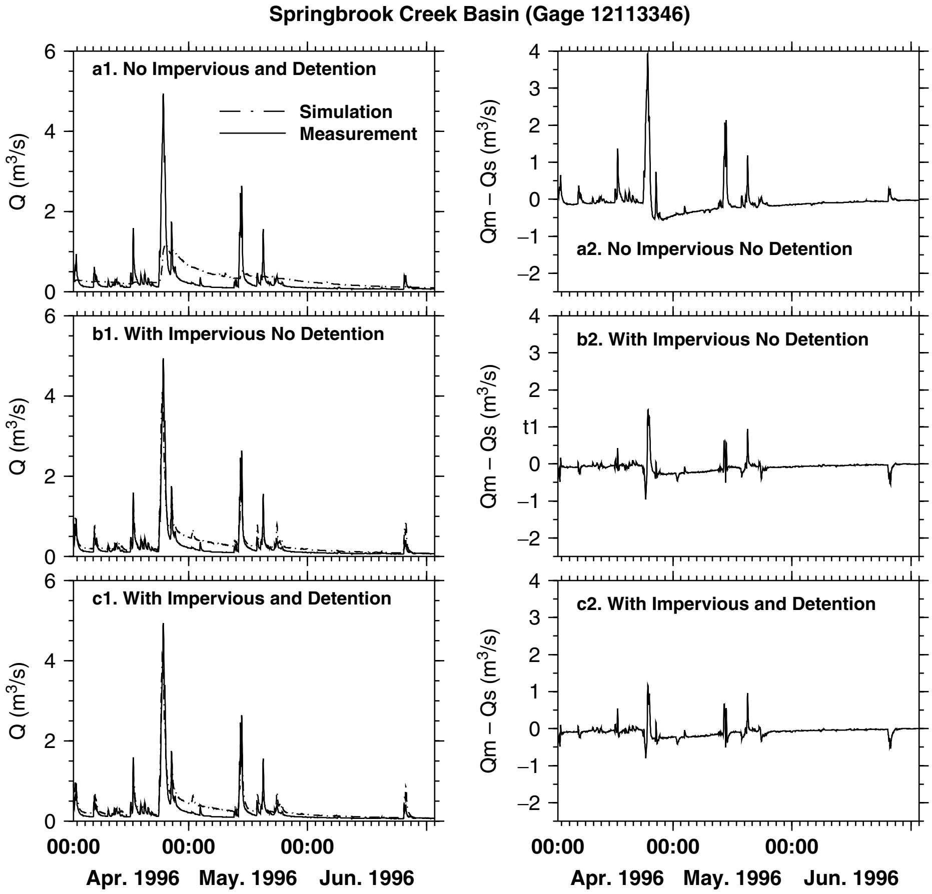

Figure 3. Model sensitivity evaluation of urban parameterization at hourly time step. Figures a1, b1, and c1 show the hourly simulation and measurement during 1 April, 1996 and 30 June 1996. Figures a2, b2 and c2 show the difference between measurement and simulation during the same period

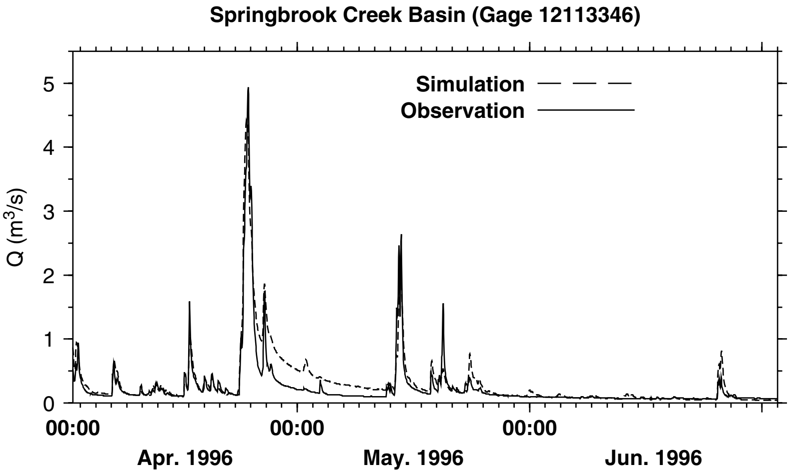

Figure 4. Simulated and measured hourly streamflow at gauge 12113346 (Springbrook Creek basin at Orillia, WA)

shows the observed and simulated hourly streamflow statistics for calibration and validation periods. The figures and table demonstrate that modified DHSVM is able to capture the major characteristics of the hourly hydrographs well in the urban watershed.

A sensitivity run was made to determine differences between the current, urbanized condition of the Springbrook Creek catchment, and pre-settlement land cover conditions. In pre-settlement land cover conditions, all vegetation was set to mature coniferous forest, and the model was forced with gridded observations for the period 1915 to 2002. The statistics of daily peak flows were evaluated using an algorithm that peaks as being larger than both the day before and the day after. The average of the 2218 daily peaks so defined (roughly two per month) for the mature forest scenario was $0{\cdot}12$ m^3 s^{-1}. This value was used as a threshold, and the total number of peak flows exceeding this value was

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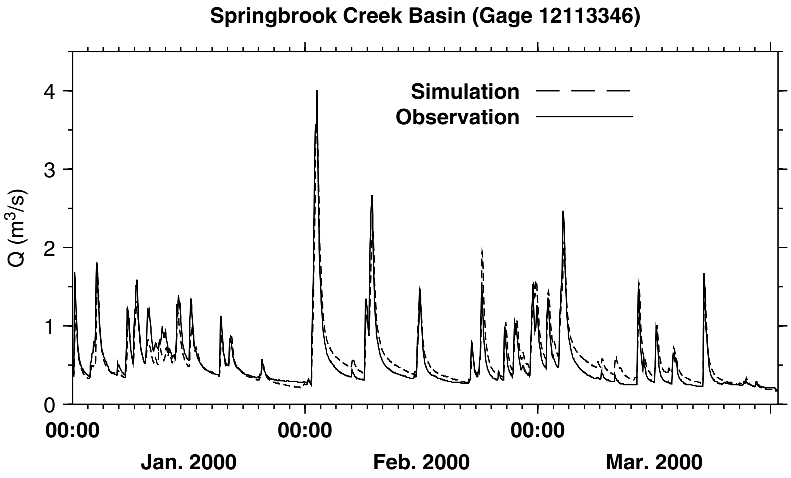

Figure 5. Simulated and measured hourly streamflow at gauge 12113346 (Springbrook Creek basin at Orillia, WA) during validation period

Table III. Hourly simulation and measurement statistics

	Springbrook Creek basin (gauge 12113346)	
	Calibration period	Validation period
Observed mean (m^3 s^{-1})	0·35	0·29
Simulated mean (m^3 s^{-1})	0·45	0·30
Correlation coefficient	0·83	0·85
Nash–Sutcliffe efficiency	0·56	0·68

counted, giving 614 in the mature forest scenario and 3550 for 2002 conditions. The annual maximum series (maximum daily flow each year) for the mature forest (0·73 m^3 s^{-1}) and for 2002 conditions (2·24 m^3 s^{-1}) were also computed. The ratio of about 3·1 shows the very strong effect that urbanization has on peak flows. Figure 6 shows that in the Springbrook Creek basin, the probability distribution of (simulated) annual (daily) maximum flows was higher in the 2002 scenario than for mature forest across the entire range of probabilities. For example, a daily flow of 2·0 m^3 s^{-1} has a 35 year return period in the mature forest scenario, but the same flow has return period of about 2 years under 2002 conditions. The timing of the annual maxima shifted substantially as well. 38 of the 87 peak flows occurred 1 or 2 days earlier in the 2002 scenario than in the mature forest scenario.

Figure 7 shows that urbanization increased both seasonal and annual streamflows substantially. The largest increases occurred in the winter and the smallest increases were in the summer (most of the annual precipitation in the region occurs in winter). The seasonal peak in the 2002 scenario (December) is one month earlier than that in the mature forest scenario. The mean annual streamflow increased by a factor of over 4 for 2002 compared with fully forested conditions, with the annual runoff ratio increasing from 0·13 to 0·58. Evapotranspiration was reduced by essentially the same amount.

Annual minimum daily flows, and accumulated annual minimum 3 day and 7 day flows were examined for the mature forest and 2002 scenarios (Figure 8). The figure shows that all low flows are higher for 2002 land cover. This result is somewhat contrary to expectation, as increased urbanization is often thought to be associated

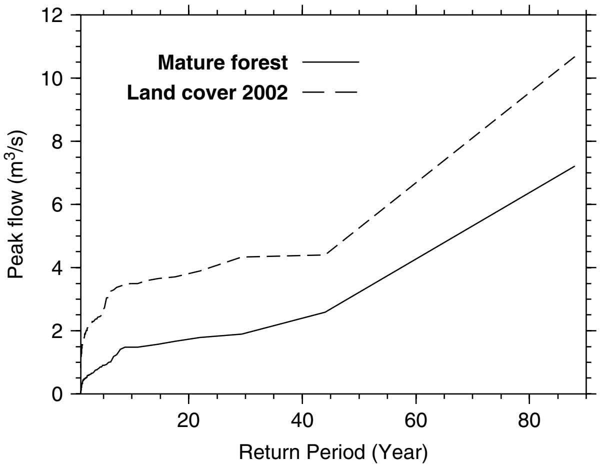

Figure 6. Annual maximum daily peak flow frequency for mature forest and 2002 scenarios

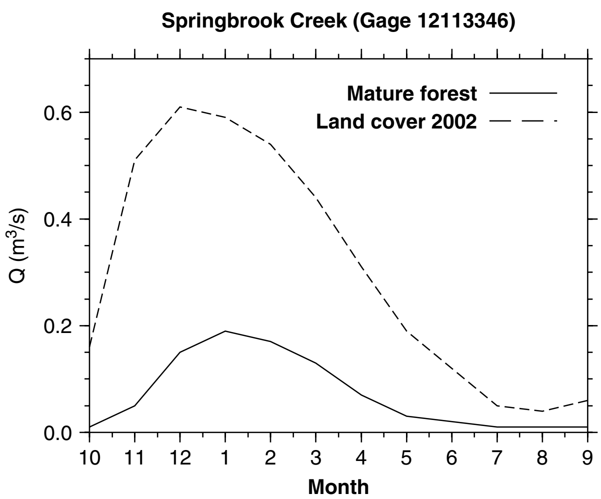

Figure 7. Seasonal streamflow for mature forest and 2002 land cover scenarios in Springbrook Creek at Orillia (gauge 12113346)

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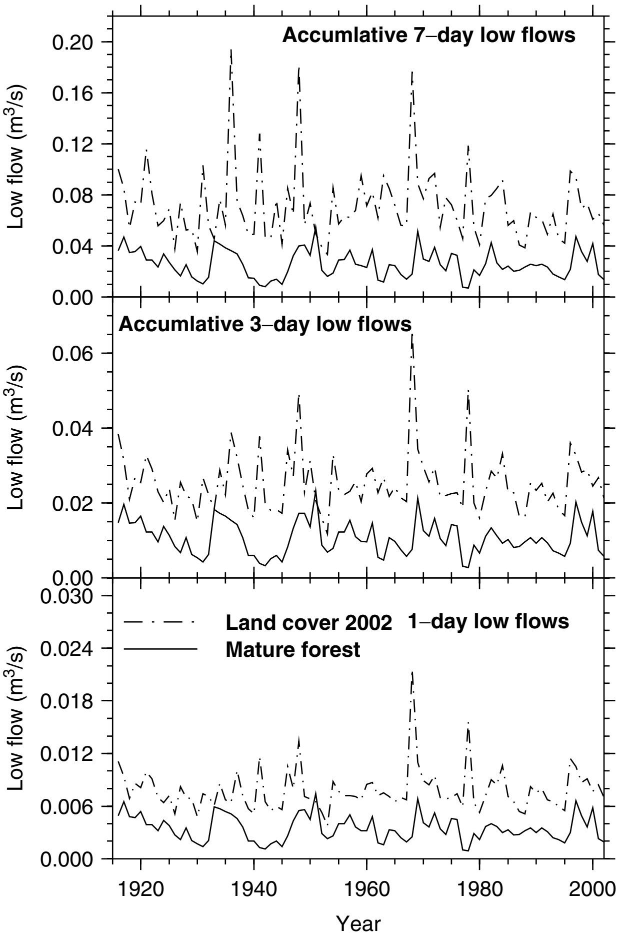

Figure 8. Annual minimum 1 day low flows, 3 day accumulative low flows and 7 day accumulative low flows for mature forest and 2002 land cover

with decreased low flows, owing to reduced infiltration associated with increased impervious area (Rose and Peters, 2001). However, such changes are not universal, and in fact, Konrad and Booth (2002) found, of three urbanized streams with long-term records in the Puget Sound basin, one had statistically significant upward trends in 7-day low flows, and the other two did not have statistically significant trends. The change in low flows is associated with both evapotranspiration and infiltration capacity. In the model, the mature forest scenario has lower water table than the 2002 land cover scenario which is a result of reduced evapotranspiration more than compensating for decreased infiltration.

DISCUSSION AND CONCLUSION

A modified version of DHSVM is described that is appropriate for application to partially urbanized basins. The main changes to the standard version of DHSVM, which has been widely used to predict runoff in mountainous, forested catchments, is the specification of a fractional impervious area (which can be extracted from land cover maps) for urbanized or partially urbanized areas, the specification of a fraction of runoff from impervious areas that is controlled by stormwater detention, and a linear reservoir coefficient to described drainage from detention storage. Application of the model to a partially urbanized catchment in the Puget Sound drainage showed that using physically realistic values of impervious fraction, fraction of impervious runoff routed to detention, and detention drainage parameters resulted in good matches with observed flows. Simulations without the effects of detention storage greatly overestimated observed peak flows.

Simulation results for the Springbrook Creek catchment were consistent with results of many other studies (Leopold, 1968; Hall, 1984; Changnon and Demissie, 1996; Moscrip and Montgomery, 1997; Leith and Whitfield, 2000; Beighley and Moglen, 2002; Konrad and Booth, 2002; Burns *et al*., 2005; Dow, 2007) in showing that urbanization increases peak flow magnitudes, and decreases peak flow lag time. On the other hand, conclusions as to the effects of urbanization on low flows and mean annual flow are less consistent (Changnon and Demissie, 1996; Konrad and Booth, 2002; Jennings and Jarnagin, 2002; Chang, 2007). In this study, substantial increases in mean annual streamflow, annual minimum low flows, and increases in all seasons, including the dry summer season, were found when reduced evaporative demand owing to vegetation removal more than compensated for reduced infiltration.

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REFERENCES

Aronica G, Cannarozzo M. 2000. Studying the hydrological response of urban catchments using a semi-distributed linear non-linear model. *Journal of Hydrology* **238**: 35–43.

Alberti M, Weeks R, Coe S. 2004. Urban land-cover change analysis in central Puget Sound. *Photogrammetric Engineering and Remote Sensing* **70**: 1043–1052.

Beighley RE, Moglen GE. 2002. Trend assessment in rainfall-runoff behavior in urbanizing watersheds. *Journal of Hydrological Engineering* **7**(1): 27–34.

Berthier E, Dupont S, Mestayer PG, Andrieu H. 2006. Comparison of two evapotranspiration schemes on a sub-urban site. *Journal of Hydrology* **328**: 635–646.

Bowling LC, Lettenmaier DP. 2001. The effects of forest roads and harvest on catchment hydrology in a mountainous maritime environment. In *The Influence of Land Use on the Hydrologic-Geomorphic Responses of Watersheds*, Wigmosta MS, Burges SJ (eds). AGU Monograph; 145–164.

Bowling LC, Storck P, Lettenmaier DP. 2000. Hydrologic effects of logging in western Washington, United States. *Water Resources Research* **36**(11): 3223–3240.

Burns D, Vitvar T, McDonnell J, Hassett J, Duncan J, Kendall C. 2005. Effects of suburban development on runoff generation in the Croton River basin, New York, USA. *Journal of Hydrology* **311**: 266–281.

Chang H. 2007. Comparative streamflow characteristics in urbanizing basins in the Portland Metropolitan Area, Oregon, USA. *Hydrological Processes* **21**(2): 211–222 DOI: 10·1002/hyp 6233.

Changnon SA, Demissie M. 1996. Detection of changes in streamflow and floods resulting from climate fluctuations and land use-drainage changes. *Climatic Change* **32**: 411–421.

Cuo L, Giambelluca TW, Ziegler AD, Nullet MA. 2006. Use of the distributed hydrology soil vegetation model to study road effects on hydrological processes in Pang Khum Experimental Watershed, northern Thailand. *Forest Ecology and Management* **224**: 81–94.

Dow CL. 2007. Assessing regional land-use/cover influences on New Jersey Pinelands streamflow through hydrograph analysis. *Hydrological Processes* **21**(2): 185–197 DOI: 10·1002/hyp 6232.

Famiglietti JS, Wood EF. 1994. Application of multiscale water and energy balance models on a tallgrass prairie. *Water Resources Research* **30**(11): 3061–3078.

Filho AJP, Santos CCD. 2006. Modeling a densely urbanized watershed with an artificial neural network, weather radar and telemetric data. *Journal of Hydrology* **317**: 31–48.

Garrote L, Bras RL. 1995. A distributed model for real-time flood forecasting using digital elevation models. *Journal of Hydrology* **167**: 279–306.

Hall MJ. 1984. *Urban Hydrology*. Elsevier Applied Science Publishers: New York.

Hamlet AF, Lettenmaier DP. 2005. Production of temporally consistent gridded precipitation and temperature fields for the continental United States. *Journal of Hydrometeorology* **6**: 330–336.

Hamlet AF, Lettenmaier DP. 2007. Effects of 20th century warming and climate variability on flood risk in the western US. *Water Resources Research* **43**: W06427, DOI:10·1029/2006WR005099.

Hsu MH, Chen SH, Chang TJ. 2000. Inundation simulation for urban drainage basin with storm sewer system. *Journal of Hydrology* **234**: 21–37.

Jennings DB, Jarnagin ST. 2002. Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-Atlantic subwatershed. *Landscape Ecology* **17**: 471–489.

Kalnay E, *et al*. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of American Meteorological Society.* **77**: 437–471.

Karl TR, Williams Jr CN, Quinlan FT, Boden TA. 1990. United States Historical Climatology Network (HCN) serial temperature and precipitation data. Environmental Science Division, Publication 3404, Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, 389.

Konrad CP, Booth DB. 2002. Hydrologic trends associated with urban development for selected streams in the Puget Sound Basin, Western Washington. US Geological Survey, water-resources investigations report 02–4040.

La Marche J, Lettenmaier DP. 2001. Effects of forest roads on flood flows in the Deschutes river, Washington. *Earth Surface Processes and Landforms* **26**: 115–134.

Leith RM, Whitfield PH. 2000. Some effects of urbanization on streamflow records in a small watershed in the lower Fraser Valley, BC. *Northwest Science* **74**(1): 69–75.

Leopold LB. 1968. Hydrology for urban land planning—a guidebook on the hydrologic effects of urban land use. US Geological Survey, Geological Survey Circular 554, 18.

Mansell MG. 2003. *Rural and Urban Hydrology*. Thomas Telford: London.

Maurer EP, Wood AW, Adam JC, Lettenmaier DP, Nijssen B. 2002. A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States. *Journal of Climate* **15**: 3237–3251.

Mignot E, Pauier A, Haider S. 2006. Modeling floods in a dense urban area using 2D shallow water equations. *Journal of Hydrology* **327**: 186–199.

Mikkelsen PS, Madsen H, Arnbjerg-Nielsen K, Rosbjerg D, Harrmoës P. 2005. Selection of regional historical rainfall time series as input to urban drainage simulation at ungauged locations. *Atmospheric Research* **77**(1–4): 4–17.

Moscrip AL, Montgomery DR. 1997. Urbanization, flood frequency, and salmon abundance in Puget lowland streams. *Journal of the American Water Resources Association* **33**(6): 1289–1297.

Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models part I—A discussion of principles. *Journal of Hydrology* **10**(3): 282–290.

Rose S, Peters NE. 2001. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. *Hydrological Processes* **15**: 1441–1457.

Rossman LA. 2007. Storm water management model user's manual version 5·0, United States Environmental Protection Agency, EPA/600/R-05/040, Cincinnati, OH.

Schmitt TG, Thomas M, Ettrich N. 2004. Analysis and modeling of flooding in urban drainage systems. *Journal of Hydrology* **299**: 300–311.

Smith MB. 2006a. Comment on 'Analysis and modeling of flooding in urban drainage systems'. *Journal of Hydrology* **317**: 355–363.

Smith MB. 2006b. Comment on 'Potential and limitations of 1D modeling of urban flooding' by O. Mark, *et al*. [*J. Hydrol*. 299 (2004) 284–299]. *Journal of Hydrology* **321**: 1–4.

Storck P, Bowling L, Wetherbee P, Lettenmaier DP. 1998. Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak stream flow in the Pacific Northwest. *Hydrological Processes* **12**: 889–904.

Tucker GE, Bras RL. 1998. Hillslope processes, drainage density and landscape morphology. *Water Resources Research* **34**(10): 2751–2764.

Westrick KJ, Storck P, Mass CF. 2002. Description and evaluation of a hydrometeorological forecast system for mountainous watersheds. *Weather and Forecasting* **17**: 250–262.

Wigmosta MS, Vail LW, Lettenmaier DP. 1994. A distributed hydrology soil vegetation model for complex terrain. *Water Resources Research* **30**(6): 665–1679.

Wigmosta MS, Nijssen B, Storck P. 2002. The distributed hydrology soil vegetation model. In *Mathematical Models of Small Watershed Hydrology and Applications*, Singh VP, Frevert DK (eds). Water Resource Publications: Littleton, CO; 7–42.

Xiao Q, McPherson EG, Simpson JR, Ustin SL. 2007. Hydrologic processes at the urban residential scale. *Hydrological Processes* **21**(6): 2174–2188.