

ITREE-HYDRO: SNOW HYDROLOGY UPDATE FOR THE URBAN FOREST HYDROLOGY MODEL¹

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ABSTRACT: This article presents snow hydrology updates made to iTree-Hydro, previously called the Urban Forest Effects—Hydrology model. iTree-Hydro Version 1 was a warm climate model developed by the USDA Forest Service to provide a process-based planning tool with robust water quantity and quality predictions given data limitations common to most urban areas. Cold climate hydrology routines presented in this update to iTree-Hydro include: (1) snow interception to simulate the capture of snow by the vegetation canopy, (2) snow unloading to simulate the release of snow triggered by wind, (3) snowmelt to simulate the solid to liquid phase change using a heat budget, and (4) snow sublimation to simulate the solid to gas phase via evaporation. Cold climate hydrology routines were tested with research-grade snow accumulation and weather data for the winter of 1996–1997 at Umpqua National Forest, Oregon. The Nash-Sutcliffe efficiency for open area snow accumulation was 0.77 and the Nash-Sutcliffe efficiency for under canopy was 0.91. The USDA Forest Service offers iTree-Hydro for urban forest hydrology simulation through iTreertools.org.

(KEY TERMS: iTree-Hydro; UFORE-Hydro; cold climate hydrology; snow interception; snow accumulation; snow ablation; snow sublimation.)

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INTRODUCTION

Management tools are needed to reduce the environmental impacts of the global urbanization trend. In the United States (U.S.) urbanization, urban sprawl, and urban infilling are predominantly supplied by forest, agricultural, and grass lands (US GAO, 2001). U.S. urban land cover is projected to increase from 3.1 to 8.1% of total land area between the years 2000 and 2050 (Nowak and Walton, 2005), bringing increased impervious cover, decreased vege-

tation cover, and higher population densities. These land cover changes disrupt the hydrological cycle and create increased runoff volumes (i.e., less surface storage and infiltration), increased velocities (i.e., less flow resistance and steeper, shorter flow paths), and elevated concentration of metals, sediment, and nutrients (Horner *et al.*, 1994; Schueler, 1994; WEF/ASCE, 1998; Endreny, 2005). Several studies have shown a tree-based green infrastructure or low impact development (LID) approach to urbanization will retain or return a predevelopment hydrological cycle and reduce urban runoff flashiness

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and pollutants (Dietz, 2007; She and Clar, 2009; Matel, 2010).

Green infrastructure and LID use vegetation cover to increase interception, pervious soils with tree root activity to increase infiltration, and the combined vegetation and soils to modify atmospheric boundary layer and soil regimes to increase evapotranspiration (Potter, 2006). These hydrological changes extend to increased soil moisture volumes, increased base flow (i.e., nonstorm flow), reduced peak flow, and improved water quality discharges (Horner, 1995; Gobel *et al.*, 2004; She and Clar, 2009). Computational models that simulate these LID impacts include direct use of facility models, such as a bioretention basin model (Dussailant *et al.*, 2004) that mechanistically represents infiltration through a single LID unit, and innovative use of non-LID watershed models. Examples of innovatively adapting non-LID models include coupling a Green-Ampt infiltration routine with the USGS MODFLOW groundwater model (Harbaugh *et al.*, 2000) to simulate groundwater mounding from spatially distributed bioretention basins (Endreny and Collins, 2009) and use of the EPA Storm Water Management Model (Huber and Dickinson, 1992) to simulate hydrograph response to green roofs (Khader and Montalto, 2009) and bioretention basins (Lucas, 2010). We identify a limitation to the facility models in their neglect of watershed effects and a limitation in the non-LID watershed models in their inability to directly represent LID; there is a need for a watershed model that explicitly simulates green infrastructure and LID impacts on stormwater for development of urban forest management plans. The iTree-Hydro model represents an effort to provide this model. iTree-Hydro was developed through USDA Forest Service support and was previously called UFORE-Hydro (Wang *et al.*, 2008). iTree-Hydro was created to simulate how forest and vegetation management impacts urban stormwater volumes and flow rates and can be expanded to include additional LID impacts.

iTree-Hydro can assist urban forest managers and planners quantify how changes in tree, vegetation, and impervious cover impact local hydrology (iTree-Tools, 2011). This model is a balance between representing governing hydrological processes and not requiring extensive input data so it serves as a planning tool with robust water quantity and quality predictions given data limitations common to most urban areas. A performance review of iTree-Hydro Version 1 revealed opportunities for model improvements, and this paper presents iTree-Hydro Version 2 as providing needed updates. A major concern was iTree-Hydro Version 1 had no cold climate hydrology routines and was unable to simulate the annual water balance for many northern and high altitude

cities where snow is also an important storage component of the hydrological cycle (Liu and Moore, 2004; Roesch and Roekner, 2006; Seitz *et al.*, 2008). Water released from snow cover can significantly contribute to urban runoff, and trees have been shown to intercept up to 60% of annual snowfall and facilitate by sublimation its direct return to the atmosphere (Storck *et al.*, 2002). The iTree-Hydro Version 2 adds proven algorithms for cold climate hydrology. This article is organized into the following sections. Below the iTree-Hydro Model Review section summarizes Version 1 model features and algorithms, the iTree-Hydro Model Version 2 section documents cold climate hydrology routines added to the model, the Model Evaluation section tests the model with snow hydrology data, and the Summary section explores model updates.

ITREE-HYDRO MODEL REVIEW

iTree-Hydro simulates the hydrological processes of precipitation, interception, evaporation, infiltration, and runoff using the data inputs of near surface weather (~ 2 m above the ground surface), land surface elevation, and land cover along with parameters of channel, soil, and vegetation. iTree-Hydro is a physically based (i.e., not empirical) semi-distributed rainfall-runoff model that combines urban and forest hydrology concepts. The vertical water balance is simulated with mechanistic equations, and the topographic index (Beven and Kirkby, 1979) is used to set spatial variation in saturation likelihood. The land surface elevation data are used to compute the topographic index (TI) for each watershed cell based on watershed contributing area and cell slope, $TI_i = \ln(a_i/\tan\beta_i)$, where a_i is the local pixel i upslope watershed area per pixel width, and β_i is the local pixel slope angle. Soil moisture and watertable dynamics in cells with the same topographic index value are assumed to respond in a hydrologically similar way and are aggregated for water balance computations.

iTree-Hydro Version 1 has six main routines simulating the rainfall-runoff process (Figure 1). The *interception routine* simulates the rain interception by the vegetation canopy with a seasonally varying Leaf Area Index (LAI). The *impervious routine* simulates the filling of land surface depression storage (Huber and Dickinson, 1992) prior to generating runoff. The *soil routine* simulates water storage on, movement through, and discharge from, the soil area. The *evaporation and transpiration routine* updates the water storage on the vegetation canopy, impervious area, and soil area. The *routing routine* takes all the watershed runoff for each time step and uses a

time-area delay function (Wang *et al.*, 2008) or a one-parameter diffusion-based exponential function (Criss and Winston, 2008) to construct a hydrograph for the watershed outlet. The *pollution routine* utilizes the same Event Mean Concentration algorithm applied in the Storm Water Management Model (SWMM) to compute pollution loads. We use the Nash-Sutcliffe efficiency (NSE) criteria (Nash and Sutcliffe, 1970) to evaluate model performance. The readers who want to know more details about iTree-Hydro Version 1 are directed to Wang *et al.* (2005).

iTree-Hydro Version 1 has been used to examine impervious cover (ranging from 0 to 24%) and tree cover (ranging from 7 to 95%) effects on annual hydrographs and water budgets in six Chesapeake Bay watersheds: (1) Accotink, Virginia at 61.9 km²; (2) Basisman Run, Maryland at 3.8 km²; (3) Gwynns Falls, Maryland at 84.7 km²; (4) Mill Creek, Virginia at 140.8 km²; (5) Pond Branch, Maryland at 0.5 km²; and (6) Rock Creek, Maryland/D.C. at 161.7 km². In each of these watershed simulations there was no significant snow, and the annual NSE values for each watershed ranged from 0.43 to 0.70. To create a more robust model, allowing for cold climate simulation, snow-related algorithms have been created in Version 2.

ITREE-HYDRO VERSION 2: COLD CLIMATE HYDROLOGY ROUTINES

The main cold climate hydrological processes are shown in Figure 2. Four routines were modified or

added to iTree-Hydro Version 1 to simulate the cold climate hydrology (Figure 1). The interception of rain or snow is simulated by the modified interception routine which built on the old rain-only interception routine. The snow unloading routine simulates wind-induced removal of accumulated snow from the canopy. The snowmelt and snow sublimation routines simulate the melt (solid to liquid) and sublimation (solid to vapor) of accumulated snow on the canopy, as well as on bare soil and impervious surfaces. In the following subsections, these new routines are discussed in detail.

Snow Interception Routine

The modified interception routine couples a snow interception routine with the rain interception routine described in the paper of Wang *et al.* (2008). The interception of snow is treated in a similar way as that of rainfall. The maximum canopy storage capacity of snow $S_{\max}$ (m) is calculated by Equation (1):

$$S_{\max} = S * LAI \quad (1)$$

in which the LAI is the Leaf Area Index value and the S (m) is a mean storage value. S is calculated by the function of Schmidt and Gluns (1991), $S = \bar{S}[0.27 + (46/\rho_s)/\rho_s]$, in which ρ_s (kg/m³) is the snow density, and $\bar{S}$ is average mass storage per area. Schmidt and Gluns (1991) used extensive measurements to set the values of $\bar{S}$ equal to 6.6 kg/m² for pine (*Pinus* spp) and to 5.9 kg/m² for spruce (*Picea* spp). For heterogeneous vegetation cover, $\bar{S}$ is an

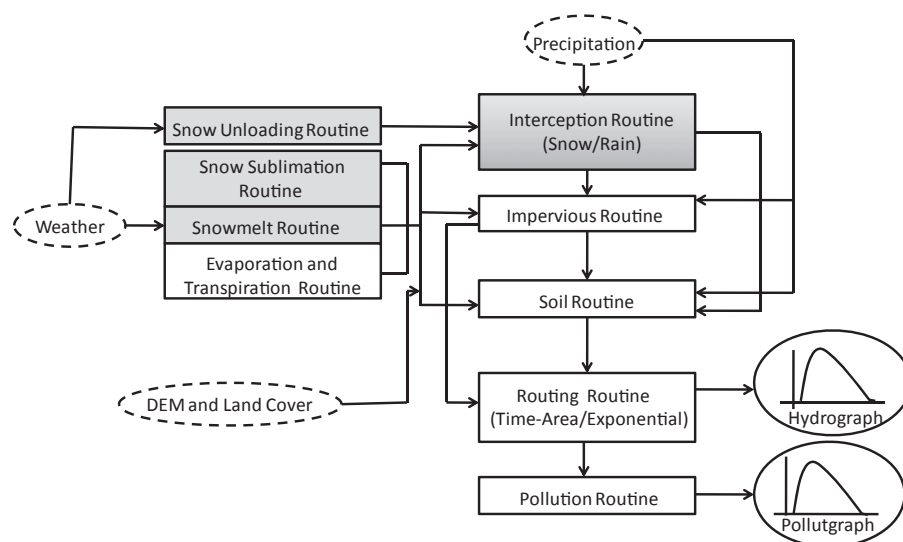


FIGURE 1. iTree-Hydro Routines and Data Flow Directions. The white-filled boxes are the Version 1 routines, the gradient-filled box (Interception Routine) is modified routine, and the gray-filled boxes are new routines. The arrows indicate the data flow directions. Dashed ellipses indicate data inputs and solid ellipses indicate selected model outputs.

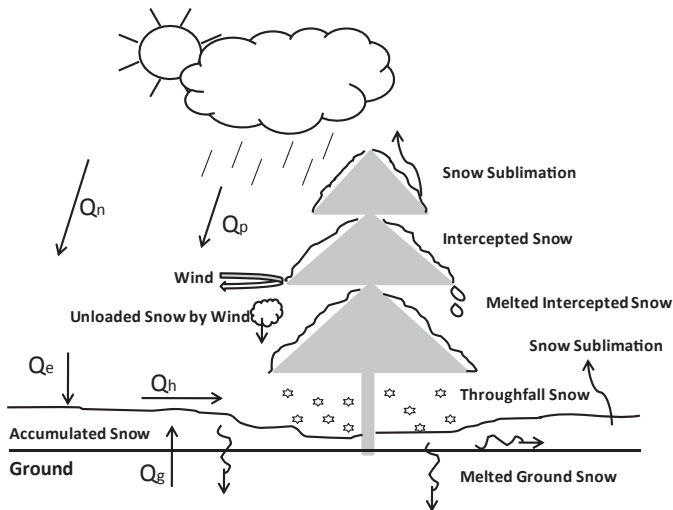


FIGURE 2. Illustration of iTree-Hydro Simulated Cold Climate Hydrology. Q -values (W/m^2) are the energy sources for snow ablation. Q_n is the energy from net radiation, Q_p is the energy from liquid precipitation, Q_e is the energy from latent heat, Q_h is the energy from sensible heat, and Q_g is the energy from ground heat. The melted snow contributes to base flow or surface flow. This illustration complements the iTree-Hydro schematic in figure 1 of Wang *et al.* (2008).

effective average value and can be set by the user based on expert knowledge, literature values, or selection from the values listed above. The snow interception storage approaches its maximum S_{max} , at a rate controlled in part by the interception efficiency. The snow not intercepted by the canopy passes to the area underneath the canopy. The percentage of the snow which is intercepted by the canopy is calculated by the same formula for rain interception:

$$c = 1 - e^{-\kappa \cdot LAI}, \quad (2)$$

in which κ is the extinction coefficient, which ranges from 0.2 to 0.8. The free throughfall of snow is $(1 - c) \cdot P_s$, in which P_s is the snow precipitation ($m/\Delta t$). When snow interception storage is equal to the maximum canopy storage S_{max} , all subsequent snow is treated as free throughfall.

Intercepted snow may sublimate (Lundberg *et al.*, 1998) or drop as clumps and drip as melted water onto the snowpack or ground. iTree-Hydro tracks the time rate of change in intercepted snow water equivalent (SWE) depth, I (m), with all terms as liquid equivalent in Equation (3):

$$\frac{I}{\Delta t} = P_{SWE} - R - U - E - M, \quad (3)$$

in which P_{SWE} ($m/\Delta t$) is the instantaneous above canopy SWE precipitation, R ($m/\Delta t$) is the snow through-

fall reaching the ground, U ($m/\Delta t$) is the unloading rate of snow due to branches movement, E ($m/\Delta t$) is the sublimation rate, and M ($m/\Delta t$) is the snowmelt rate. The unloaded snow will contribute to the snow throughfall, and the melted snow contributes to the canopy liquid storage. When the canopy liquid storage reaches its maximum value, which is based on a function defined by Wang *et al.* (2008), the remaining intercepted snow will drop to the ground. The calculations of the right hand side terms in Equation (3) are presented in the following snow unloading routine, snow sublimation routine, and snowmelt routine.

Snow Unloading Routine

The wind-induced movement of the tree branches and subsequent removal of canopy snow is simulated in iTree-Hydro with the Roesch *et al.* (2001) equation. This equation represents wind-induced unloading of intercepted SWE, U (m/hour):

$$U = 0.0231 v_m I, \quad (4)$$

in which v_m (m/s) is the mean wind speed at the mean canopy height, and I (m) is the intercepted depth of SWE. As an example, 50% of the intercepted snow can be unloaded within 6 hours for $v_m = 5$ m/s.

Snowmelt Routine

The quantity of snowmelt is determined by the available heat and the thermal condition of the snowpack. During winter, the temperature of the snowpack may be below $0^\circ C$ in some regions and not ripe, defined as available for melt. In this case additional heat is required to ripen the snowpack to the melting point of $0^\circ C$. The heat to warm 1 g of $-10^\circ C$ snow to $0^\circ C$ and satisfy its free-water-holding capacity is only about 8% of the total heat required to melt it (USACE, 1956). Given the uncertainty in snow pack temperature and the relatively small (<10%) heating difference to ripen snow, iTree-Hydro simplifies the data input needs and assumes the snowpack is ripe. The snowmelt is simulated with a heat budget method introduced and updated in the 1956 and 1998 Snow Hydrology Report (USACE, 1956, 1998). The heat budget method was utilized by research-grade cold climate hydrology models such as DHVSM (Storck *et al.*, 2002). iTree-Hydro evaluates each of the heat budget terms individually. For snowmelt in an open area, the total snowmelt M (m/hour) can be calculated by the USACE (1956) Equation (5):

$$M = M_n + M_h + M_e + M_g + M_p, \quad (5)$$

in which M_n (m/hour) is the snowmelt by net radiation of both shortwave and longwave, M_h (m/hour) is snowmelt by the sensible heat, M_e (m/hour) is the snowmelt by the latent heat, M_g (m/hour) is the snowmelt by the ground heat, and M_p (m/hour) is the snowmelt by rain. At each time step (hourly), these terms are estimated with the following equations:

$$M_n = 0.000011R_s(1 - \alpha) + 0.0000396T_a - 0.00089 \quad (6)$$

$$M_h = 0.00000792k_p(Z_a Z_b)^{-1/6}T_a V \quad (7)$$

$$M_e = 0.0000223k_p(Z_a Z_b)^{-1/6}T_d V \quad (8)$$

$$M_g = 0.0000277 \quad (9)$$

$$M_p = 0.0232P_r T_a \quad (10)$$

In Equation (6) the first term on the right hand side represents snowmelt by shortwave radiation R_s (W/m^2), where α is the albedo of snow surface, and the last two terms represent snowmelt by longwave radiation under a clear sky. These two terms are replaced by $0.000054T_a$ for cloudy sky situations. In Equations (7) and (8) k_p is the ratio of atmospheric pressure at the location to the atmospheric pressure at the sea level, z_a (m) is the height at which the temperature and the air vapor pressure are measured, z_b (m) is the height of wind velocity measurement, T_a ($^{\circ}\text{C}$) is the air temperature, T_d ($^{\circ}\text{C}$) is the dew-point temperature, and v (m/s) is the wind velocity. Only when T_a and T_d are $>0^{\circ}\text{C}$ will longwave radiation, latent heat, and sensible heat cause snowmelt. The constant value in Equation (9) is obtained setting ground heat flux to a constant value of $2.5 \text{ J/m}^2\text{s}$ which is in the range of reported daily values from 0 to $5 \text{ J/m}^2\text{s}$ (USACE, 1998). The constant value can be changed if there is urban infrastructure or other conditions influencing thermal conductivity and ground temperature gradients. In Equation (10) P_r (m/hour) is the hourly rainfall.

For snowmelt under the canopy Equation (5) is used with modified parameter values (USACE, 1956). Shortwave radiation is treated as a constant and longwave radiation is a simple temperature function. The total net radiation snowmelt (m/hour) is estimated by Equation (11):

$$M_n = 0.0000317 + 0.0000553T_a, \quad (11)$$

where the first term on the right hand side is shortwave induced melt and the second term is longwave induced melt. The combined sensible and latent heat snowmelt (m/hour) becomes:

$$M_{he} = r * (M_h + M_e), \quad (12)$$

in which r is wind coefficient and ranges from 0.3 to 1, decreasing as forest density increases (USACE, 1956). The M_h and M_e terms in Equation (12) can be obtained by Equations (7) and (8). Ground heat snowmelt M_g (m/hour) can change with soil temperature gradient and thermal conductivity, and a default value of 0.000021 m/hour was based on a USACE recommendation (USACE, 1998). The snowmelt by rain has the same function as Equation (10) in the open area, but the precipitation is the throughfall of water from vegetation canopy. For the canopy intercepted snow the heat for snowmelt is from net radiation and rain (i.e., no ground heat flux) using Equations (6) and (10).

Snow Sublimation Routine

iTree-Hydro uses the Fassnacht (2004) equation to calculate the sublimation of the accumulated snow stored on the canopy and ground. This method sets the saturated vapor pressure of the snow surface, e_0 , to 0.611 kPa , sets all other meteorological measurements to the same height, and computes the sublimation rate E (m/hour) using Equation (13):

$$E = \frac{0.1}{P} \cdot \frac{U_a}{\left[\ln\left(\frac{z_a}{z_0}\right)\right]^2} (0.611 - e_a). \quad (13)$$

In Equation (13) P (kPa) is the air pressure, z_0 (m) is the roughness height, U_a (m/s) is the wind velocity at measurement height z_a (m), and e_a (kPa) is the actual vapor pressure at the measurement height z_a (m) calculated as

$$e_a = 0.611 \exp\left(\frac{17.27T_d}{237.3 + T_d}\right),$$

where T_d ($^{\circ}\text{C}$) is the dew-point temperature.

MODEL EVALUATION: COLD CLIMATE HYDROLOGY TEST

The cold climate hydrology routines were tested using snow data from a well-instrumented research site. This site provided weighing lysimeter measured SWE budgets for adjacent open (clearcut) and under-canopy areas in the Umpqua National Forest of southwestern Oregon. The SWE accumulation and weather data were gathered and reported by Storck *et al.* (2002) for the winter of 1996-1997. The snow accumulation began in late November and continued throughout the winter, with partial melts during mid-winter and a final melt of the snowpack occurring in late April. Wind speed, air temperature, relative humidity, and incoming short and longwave radiation were measured at each weighing lysimeter site (clearcut and under canopy) at 2-m above the soil surface. These data were recorded every 30 min and processed to 1 hour for our study. For detailed information of the field setup and snow measurements, please refer Storck *et al.* (2002).

The cold climate hydrology routines were run at a 1-hour time step for the period November 26, 1996-April 21, 1997. Initial conditions were set to zero snow pack, conifer trees had an LAI of 5, shrubs had LAI ranging from 0.8 to 2.7, and $\bar{S}$, the average mass storage per area, was 6 kg/m^2 . The model input and output time series (Figure 3) include liquid equivalent precipitation (m/hour), and simulated and observed SWE (m) accumulation for the clearcut and forest canopy areas. The predicted SWE trends with the observed values during most of the winter for the clearcut and under-canopy areas, but it lags the observed during the final melt. The NSE was com-

puted between observed and predicted SWE values, and for the clearcut area the NSE was 0.77 and for forest canopy area the NSE was 0.91, with a value of 1 suggesting optimal model efficiency. The SWE accumulation is mainly determined by precipitation amount and snowmelt rate. In our simulation, we assigned the reported liquid equivalent precipitation to rain or snow depending on air temperature at 2 m above the ground, with temperatures of 35°F or greater used to indicate rain. Since the upper atmosphere temperatures often determine precipitation type, and these critical temperatures may change during the season and single event, we anticipate some errors in our simulation results due to errors in our estimated precipitation input. Additional errors are introduced by the snowmelt routines.

In the open clearcut area, the snowmelt rate from net radiation is influenced by the snow surface albedo and fraction of clear skies (Equation 6), and we are uncertain in our estimates of both terms. Typically the snow surface albedo decreases with time, from 0.85 to 0.7, at a rate regulated by the location and slope of the area (USACE, 1998). The albedo value is ideally obtained from experiments but it was not available for our site. For our simulation, we maintained a constant albedo of 0.85 based on the high frequency of snow events with the old snow albedo refreshed by new snow every few hours to few days. Users can set the albedo to other values based on their own snow surface condition. The fraction of clear sky conditions was not available in our meteorological data so we used a simple algorithm to determine the clear skies: if precipitation occurred then skies were cloudy, otherwise, a clear sky snowmelt rate was applied. These simulation assumptions may explain some discrepancies between observed and

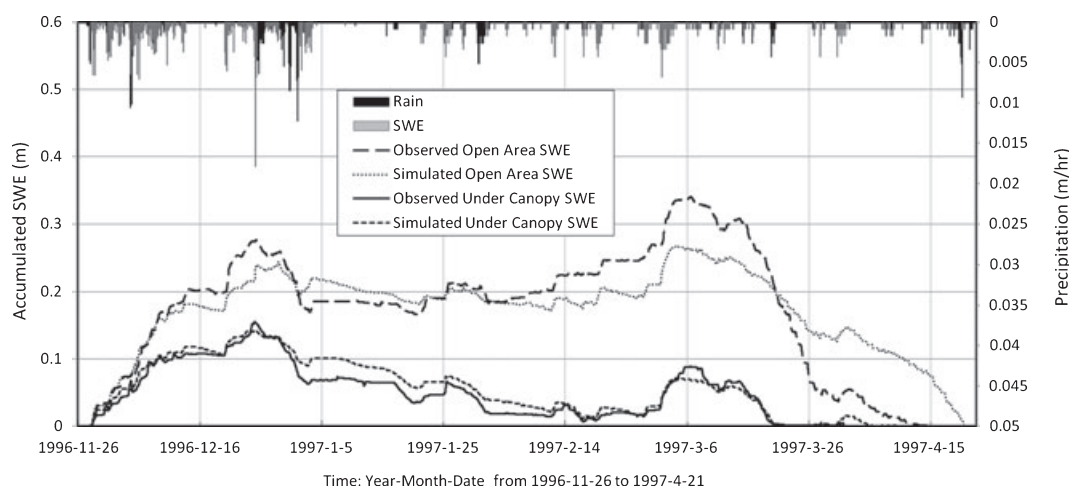


FIGURE 3. Umpqua National Forest, Oregon Precipitation (m/hour) With Observed and Predicted Accumulated Snow Water Equivalent (m) for the Clearcut Open Area and Under-Canopy Area From November 26, 1996 to April 21, 1997.

predicted SWE accumulation, particularly after March 16, 1997 when the observed snowmelt rate was significantly higher than our simulated rate. At this simulation point, the precipitation frequency was relatively low and we presumed clear sky conditions. Using clear sky data caused lower melt rates than cloudy sky conditions since cloudy skies generate greater longwave radiation energy for snowmelt. Our use of a constant albedo and our simple clear sky algorithm may have contributed to our underestimate of the snowmelt rate. In simulations of below canopy area snowpack, the snowmelt rate is independent of snow surface albedo and clear sky conditions, and our simulation better fit observed conditions compared with the open area simulation. Comparison of the SWE accumulation in the open clearcut area and the below canopy area reveals the canopy can intercept more than 50% of the snow, and depending on canopy cover this may significantly decrease the snow-runoff during the accumulation and melt seasons.

SUMMARY

iTree-Hydro Version 2 provides cold climate hydrology routines and builds on the warm climate hydrology in iTree-Hydro Version 1. The model uses robust but simplified equations to provide process-based hydrological simulation for the data limitations faced by urban forest planners and common to noninstrumented watersheds. The cold climate hydrology routines simulate the snow interception, accumulation, unloading, ablation, and sublimation. These routines are mainly based on USACE algorithms with some modification. This paper presents a single test of the cold climate hydrology routines with high-quality snow time-series data. The results show very good model performance for under-canopy areas ($NSE > 0.9$) and reasonable performance for open area snow budgets ($NSE > 0.7$). Limitations to the snow simulation include presuming snowpack is ripe and does not require additional energy for heating to 0°C, albedo is constant, and it neglects longwave radiation from urban structures. We encourage additional testing of iTree-Hydro for other regions and conditions and welcome feedback including suggestions for model enhancement. Planned updates for iTree-Hydro include simulation of snow removal (e.g., plowing) and storage (e.g., municipal snow banks) as well as simulation of spatially distributed best management and LID practices that intercept urban runoff. The iTree-Hydro model is supported by the USDA Forest Service and supplied through <http://www.itreetools.org>.

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