Online Supplementary Material

Article title: **Potential surface temperature and shallow groundwater temperature response to climate change: An example from a small forested catchment in east-central New Brunswick (Canada)**

Journal name: *Hydrology and Earth System Sciences*

Authors: Barret L. Kurylyk[1], Charles P.-A. Bourque[2], & Kerry T.B. MacQuarrie[1]

[1]*Department of Civil Engineering and Canadian Rivers Institute, University of New Brunswick, Fredericton, NB, E3B 5A3 Canada*, Phone: 506-453-4521, Fax: 506-453-3568, Email: barret.kurylyk@unb.ca

[2]*Faculty of Forestry and Environmental Management, University of New Brunswick, Fredericton, NB, E3B 5A3 Canada*

Abstract

It was deemed necessary to include additional information detailing the ForHyM2 modeling without providing extraneous details in the main paper. The first section in this supplementary material describes the model mechanics for simulating both thermal and hydrologic processes. The second section lists the ForHyM2 input parameters utilised in the present study.

1. Model Mechanics

The following description of the model mechanics is based primarily on the papers by Arp and Yin (1992) and Yin and Arp (1993). It should be noted that the model has been updated from a monthly model to a daily model. The thermal processes simulated in ForHyM2 are indicated in Figure 1 of this online resource. In ForHyM2, the surface boundary temperature is obtained by rearranging a simplified energy balance equation (Yin and Arp 1993):

$$T_s = \frac{AT}{1+\beta_e} + \frac{\beta_e}{1+\beta_e}\left[T_1 + \frac{L+S}{\lambda_1/(z_1/2)}\right] \quad (1)$$

where T_s is the surface boundary temperature (T), β_e is the dimensionless effective ground to air conductance ratio, λ_1 is the thermal conductivity of the top layer (snowpack, forest floor, or soil, $M\cdot L\cdot t^{-3}\cdot T^{-1}$), z_1 is the thickness of the top layer (L), T_1 is the temperature midway through the upper layer (T), S is the net shortwave radiation ($E\cdot t^{-1}\cdot L^{-2}$), L is the net longwave radiation ($E\cdot t^{-1}\cdot L^{-2}$). Net shortwave radiation is found from the site characteristics (e.g. slope and aspect) and the declination angle (Yin and Arp 1993). The net longwave radiation is computed using a modified Stefan-Boltzmann equation (Lee 1980). The β_e parameter is a measure of the relative rate of heat transfer from the soil to the surface and the heat transfer from the air to the surface:

$$\beta_e = \frac{\lambda_1 / (z_1 / 2)}{h_e} \tag{2}$$

The effective surface heat transfer coefficient h_e ($M \cdot t^{-3} \cdot T^{-1}$) is a lumping parameter that includes the effect of the forest canopy (e.g. reduced radiation, altered evapotranspiration, decreased convective exchange) on the air-surface heat transfer rate. Yin and Arp (1993) developed an empirical relationship to estimate β_e for a particular site:

$$\beta_e = 8.1L\left[1 - \exp\{\min(V_c, V_v) - 6.8\}\right] \tag{3}$$

where V_v and V_c are the vegetation surface area index ($m^2 \cdot m^{-2}$) of the forest in question and the effective maximum vegetation surface area index (6.5 $m^2 \cdot m^{-2}$) respectively.

Heat fluxes through each model layer below the forest canopy (i.e., snowpack, forest floor, soil, and subsoil) are assumed to occur via conduction according to a modified version of Fourier's one-dimensional transient heat conduction law that includes the effect of thermal sources and sinks due to phase change (Yin and Arp 1993):

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\frac{\lambda}{C}\frac{\partial T}{\partial z}\right) + \frac{s}{C} \tag{4}$$

where C is the volumetric heat capacity of the medium ($M \cdot L^{-1} \cdot t^{-2} \cdot T^{-1}$), and s is the internal heat contribution due to phase change ($M \cdot L^{-1} \cdot t^{-3}$) An implicit finite difference scheme is employed to obtain an approximate solution to the governing conduction equation. Further descriptions of the thermal model mechanics can be found in Yin and Arp (1993).

The hydrologic processes simulated by ForHyM2 are also indicated in Figure 1 of this online resource. Precipitation input data are first partitioned into rain and snow at a predermined temperature threshold; for the present study, this was assumed to be 0°C. Precipitation entering the forest canopy is separated into throughfall (rain or snow), stemflow, and interception. Snow and rain interception are functions of the leaf area index which is taken as the weighted average of the coniferous (8 $m^2 \cdot m^{-2}$) and deciduous (5.5 $m^2 \cdot m^{-2}$ at full-leaf season) fractions. Under a partial or full deciduous canopy, the LAI varies seasonally; leaf shedding is a function of cumulative-degree days. During the winter, the snowpack accumulates through snow throughfall until it is abated via melting or evaporation. Snow throughfall (TF, $M \cdot L^{-2} \cdot t^{-1}$) and snow stemflow ($SF$, $M \cdot L^{-2} \cdot t^{-1}$) are related to the canopy water (W_c) by proportionality constants A_{TF} and A_{SF} (Arp and Yin 1992):

$$TF = A_{TF} \times W_c \tag{5}$$

$$SF = A_{SF} \times W_c \tag{6}$$

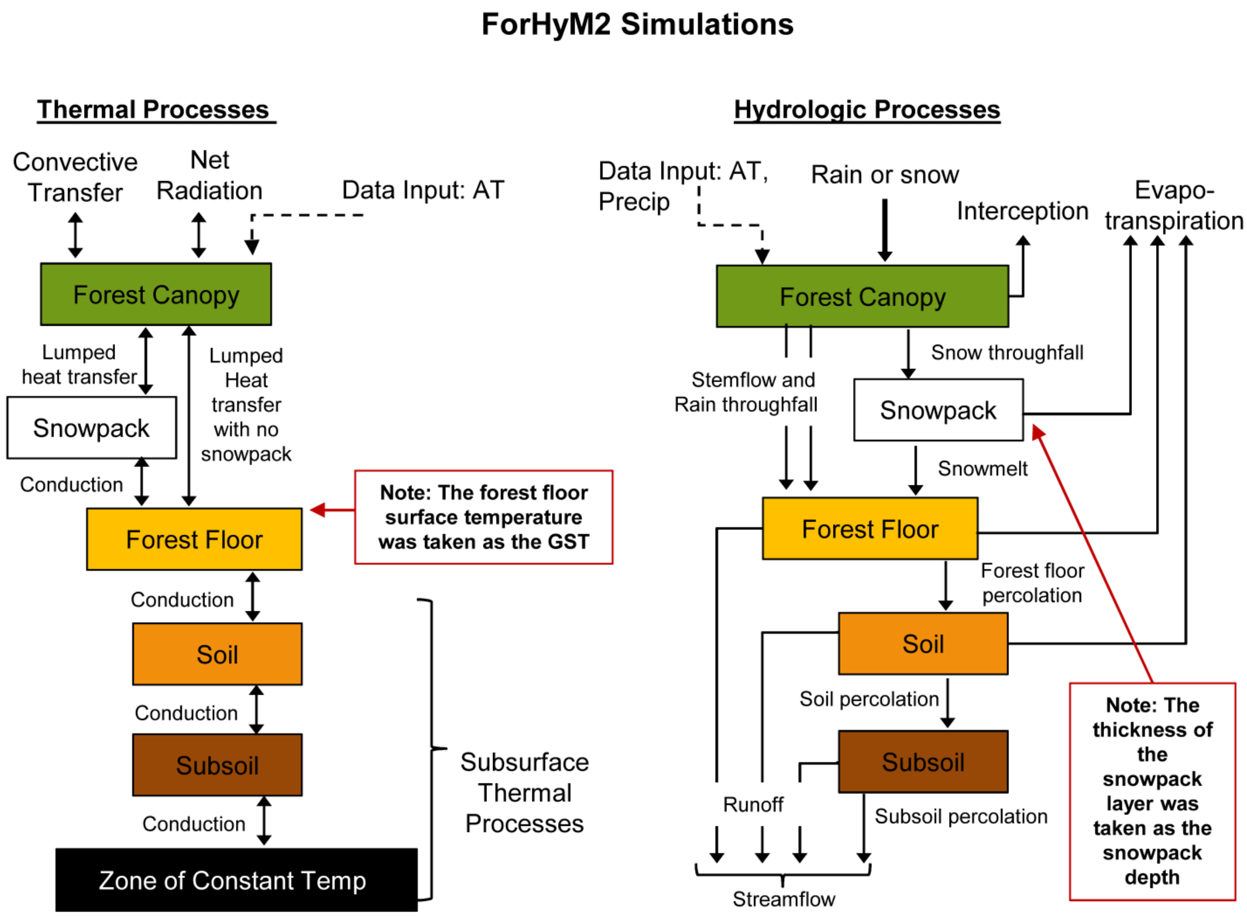

Figure 1: Flowchart of the modeling algorithm for ForHyM2 (adapted from, Arp and Yin 1992, Meng et al. 1995, Yin and Arp 1993).

The snowmelt process in ForHyM2 is described by Meng et al. (1995). Snowmelt SM ($M{\cdot}L^{-2}{\cdot}t^{-1}$) is computed by first summing the shortwave radiation at the snow surface S_s, longwave radiation at the snow surface L_s, convective sensible heat exchange between the snow and the atmosphere H_c ($M{\cdot}t^{-3}$), rain-induced energy input to the snowpack H_r ($M{\cdot}t^{-3}$), and the negative of the heat transfer from the snow surface to the snowpack H_s ($M{\cdot}t^{-3}$) and then dividing through by the heat of fusion h_f ($L^2{\cdot}t^{-2}$):

$$SM = (S_s + L_s + H_c + H_r - H_s)/h_f \tag{7}$$

Formulae are given by Meng et al. (1993) for computing the net shortwave and longwave radiation at the snow surface. The convective heat exchange is calculated as follows:

$$H_c = h[1 - \exp\{\min(V_c, V_v) - 6.8\}] \times [AT - ST] \tag{8}$$

where h is the heat transfer coefficient ($M{\cdot}t^{-3}{\cdot}T^{-1}$), ST is the snow surface temperature, and all other terms have been previously defined. Thus, SM is calculated based on the daily AT input to

ForHyM2. The heat conduction to the snowpack, H_s was computed as the thermal conductivity of the snowpack times the difference between ST and the temperature of the snow/forest floor interface. The rain-induced energy input is assumed to be proportional to the difference between the mean monthly AT and mean monthly snowpack temperature. Further details for the snowmelt equations and related applications are given by Meng et al. (1993), Balland (2002), Balland et al. (2006), and Jutras et al. (2011).

Snowmelt, stemflow, and rain throughfall enter the forest floor layer until the saturation reaches field capacity, at which point percolation occurs to the soil layer. The flow of water between layers is always taken as proportional to the available moisture in that layer. This process continues to the subsoil. Water is also lost from the snowpack, forest floor, and soil layers through evapotranspiration (Arp and Yin 1992). Potential evapotranspiration (PET) is calculated according to the modified Hamon equation (Federer and Nash 1978). Actual evapotranspiration is equal to the lesser of PET or the soil water available (soil water content minus the permanent wilting point times a proportionality constant). Further descriptions, equations and applications of the hydrological component of ForHyM2 can be found in Arp and Yin (1992),

2. Model Inputs

ForHyM2 requires the input of several parameters to describe the climate and site conditions. Table 1 details the values and justification for each parameter. ForHyM2 also has default values for soil and subsoil mineral composition and thermal properties. These subsurface values were not altered as the intent of the present study was to utilise ForHyM2 to simulate the impact of atmospheric processes on surface processes. Although surface and subsurface processes are interrelated, surface conditions (e.g. GST) are relatively robust in ForHyM2 compared to subsurface conditions (soil temperature and moisture content). Because of the relative robustness of GST, no calibrations of input parameters were required.

Table 1: Input parameters for the ForHyM2 simulations

Input Parameters	Value	Justification and/or Reference
Latitude	46.8670°	-
Altitude	50 m	New Brunswick DEM (NBADW 2011)
Aspect	0	The watershed is quite flat (NBADW 2011)
Slope	1°	See above
Coniferous fraction	0.65	(Alexander 2006)
Deciduous fraction	0.35	(Alexander 2006)
Root depth index	2	This is the model value for medium shallow species.
Mean snow depth	13 cm	(EC 2010)
Climate factor	0.5	1 = continental, 0 = maritime (Alexander 2006)
Distance to coast	200 km	Number of kilometres to the reference coast (Bay of Fundy)

References

Alexander, M. D.: The thermal regime of shallow groundwater in a clearcut and forested streamside buffer, Doctorate of Philosophy Dissertation, University of New Brunswick. Department of Civil Engineering, Fredericton, NB, 436 pp., 2006.

Arp, P. A. and Yin, X.: Predicting water fluxes through forests from monthly precipitation and mean monthly air temperature records, Can. J. For. Res., 22, 864-877, 10.1139/x92-116, 1992.

Balland, V.: Hydrogeologic modeling of the flow of cations and anions in select watersheds of eastern Canada with special focus on snowpack effects, MScF thesis, University of New Brunswick, Fredericton, New Brunswick, 175 pp., 2002.

Balland, V., Bhatti, J., Errington, R., Castonguay, M. and Arp, P. A.: Modeling snowpack and soil temperature and moisture conditions in a jack pine, black spruce and aspen forest stand in central Saskatchewan (BOREAS SSA), Can. J. Soil Sci., 86, 203-217, 2006.

EC, Environment Canada Historical Weather Database: http://www.climate.weatheroffice.gc.ca/climateData/dailydata_e.html?Prov=XX&timeframe=2&StationID=10808&Day=1&Month=1&Year=2010&cmdB1=Go, last accessed: December, 2012.

Federer, C. A. and Nash, D.: Brook: A hydrologic simulation model for eastern forests, Water Resources Research Centre Rep. 19, University of New Hampshire, Durham, 1978.

Jutras, M., Nasr, M., Castonguay, M., Pit, C., Pomeroy, J. H., Smith, T. P., Zhang, C., Ritchie, C. D., Meng, F., Clair, T. A. and Arp, P. A.: Dissolved organic carbon concentrations and fluxes in forest catchments and streams: DOC-3 model, Ecol. Model., 222, 2291-2313, 10.1016/j.ecolmodel.2011.03.035, 2011.

Lee, R.,: Forest hydrology, Columbia University Press, New York, 1980.

Meng, F. -., Bourque, C. P. -., Jewett, K., Daugharty, D. and Arp, P. A.: The Nashwaak Experimental Watershed Project: Analysing effects of clearcutting on soil temperature, soil moisture, snowpack, snowmelt and stream flow, Water, Air, & Soil Pollution, 82, 363-374, 10.1007/BF01182847, 1995.

NBADW, New Brunswick Aquatic Data Warehouse: http://www.unb.ca/research/institutes/cri/nbaquatic/index.html, last accessed: December, 2012.

Yin, X. and Arp, P. A.: Predicting forest soil temperature from monthly air temperature and precipitation records, Can. J. For. Res., 23, 2521-2536, 10.1139/x93-313, 1993.