Supplement material content

1 NIHM_Modular LandScape Model model description

The main mathematical formulations applied in NIHM-MLSM are described here. Symbols are detailed in a specific list for simplicity.

1.1 Energy balance model

Assuming steady state, energy balance at the soil surface can be formulated as:

$$R_n - \rho_w \lambda (E + Tr) - G - H = 0, \tag{1}$$

Here, R_n [W.m^{-2}] is the net radiation reaching the surface; $\rho_w \lambda E$ [W.m^{-2}] is the surface latent heat flux related to evaporation; $\rho_w \lambda Tr$ [W.m^{-2}] is the surface latent heat flux related to transpiration; H [W.m^{-2}] represents the sensible heat flux (also termed conductive heat flux) between the surface and the atmosphere; and G [W.m^{-2}] is the conductive heat flux between the surface and the soil.

1.1.1 Estimation of the net radiation

Soil net radiation R_n is rendered by (Haghighi et al., 2017):

$$R_n = R_{S\downarrow}(1-\alpha) + \zeta\varepsilon\left(\varepsilon_a T_a^4 - T^4\right), \tag{2}$$

where $R_{S\downarrow}$ [W.m^{-2}] is the solar incoming radiation (short wave radiation), α [-] is the albedo, ζ [kg.s^{-3}.K^{-4}] is the Stefan-Boltzmann constant, ε [-] is the surface emissivity, ε_a [-] is the air emissivity; and T_a [K] and T [K] are the air and surface temperature, respectively.

If the incoming long wave radiation $R_{L\downarrow}$ is known, the net radiation reads:

$$R_n = R_{S\downarrow}(1-\alpha) + \varepsilon R_{L\downarrow} - \varepsilon\zeta T^4, \tag{3}$$

Energy balance in NIHM-MLSM is formulated for the canopy, which is turn represented by a foliage layer and a soil layer with negligible heat capacity. The canopy layer is assumed to be semi-transparent with a reflectivity associated with the Beer-Lambert type transmission (Deardorff, 1978). Using the resistance analogy based on Ohm's law, conductive heat fluxes G and H are expressed in terms of the near-surface gradient of temperature.

1.1.2 Energy balance in the canopy

For the surface near the canopy layer, the components of the energy balance are:

$$\begin{cases} R_n = R_{S\downarrow}(1-\alpha_c)\left(1-e^{-K_{ext}LAI}\right)+\varepsilon_c R_{L\downarrow}-\varepsilon_c\zeta T_c^4 \\ H = \dfrac{\rho_a c_a}{r_{ac}}\left(T_c - T_a\right) \\ \rho_w \lambda Tr = \dfrac{\rho_a c_a}{\gamma(r_{ac}+r_c)}\left[e_s^{sat}\left(T_c\right)-e_s\right] \end{cases} . \tag{4}$$

Evaporation is included in the interception of precipitation by the vegetation (Kergoat, 1998); we refer to Section 2.1 for additional details. Knowledge of the aerodynamic canopy resistance r_{ac} and the stomatal canopy resistance r_c is required to solve system of Eqs. (4).

1.1.2.1 Aerodynamic canopy resistance

The aerodynamic canopy resistance (r_{ac}) is computed as:

$$r_{ac} = \frac{log\left(\left(z_u - d_u\right)/z_{ou}\right)\cdot log\left(\left(z_h - d_h\right)/z_{oh}\right)}{k^2 \cdot u_c} . \tag{5}$$

Aerodynamic roughness parameters for vegetated areas are related to the vegetation height, h_c, by the empirical formulations of Brutsaert (1982):

$$\begin{cases} z_u = h_c + W_T \\ z_h = z_u \\ d_u = 2/3\, h_c \\ d_h = d_u \\ z_{ou} = 0.123\, h_c \\ z_{oh} = 0.1\, z_{ou} \end{cases} . \tag{6}$$

Wind speed, u_c, is computed by:

$$u_c = \begin{cases} u\, log\left(z_u / z_{um}\right)^{\kappa_u} & z_u > z_{um} \\ u & z_u \le z_{um} \end{cases} , \tag{7}$$

with $\kappa_u = 0.413$ (Brutsaert, 2005).

1.1.2.2 Stomatal canopy resistance

In the literature, stomatal conductance is typically preferred to its inverse, i.e., the stomatal resistance. Stomatal conductance is calculated using a Jarvis-type multiplicative model (Cox et al. 1998; Jarvis 1976) and it is affected by environmental factors embedded in efficiency functions (solar radiation, air temperature, vapor pressure deficit, and CO_2 concentration). The *LAI* is used to scale stomatal conductance to canopy conductance, i.e.,

$$g_C = g_s^{\max} LAI_{act}\left(F_{PAR}F_{VPD}F_T F_{CO2}\right), \tag{8}$$

Here, $g_s^{\max}$ is the maximum value of the stomatal conductance, LAI_{act} is the active part of the LAI. Considering the whole canopy as a 'big leaf', the active part of the canopy is equal toLAI or $LAI/2$ if only one half of the big leaf is considered (Allen et al., 2004).

The efficiency functions F are defined by:

$$F_{PAR} = \ln\left(\frac{R_S^* + K_{ext} R_{S\downarrow}}{R_S^* + K_{ext} R_{S\downarrow} \exp(-K_{ext} LAI)}\right), \tag{9}$$

R_S^* corresponding a parameter that varies between 30 and 300 W/m^2 depending on species (Saugier and Katerji, 1991).

The function F_{VPD} takes water pressure deficit into account as (Avissar et al., 1985):

$$F_{VPD} = \left[1 + \exp(-2.86\Delta e - 3.110^{-6}\right]^{-1}, \tag{10}$$

where Δe is vapor pressure difference between the canopy layer surface and the ambient air.

The function F_T describes the temperature dependence of the stomatal resistance and is expressed as:

$$F_T = \left(\frac{T_a - T_{\min}}{T_{opt} - T_{\min}}\right)\left(\frac{T_{\max} - T_a}{T_{\max} - T_{opt}}\right)^{(T_{\max} - T_{opt})/(T_{opt} - T_{\min})}. \tag{11}$$

The optimal temperature T_{opt} is around 20 to 30°C (Baldocchi et al., 1991), T_{min} and T_{max} being about 5°C and 45°C, respectively (Jarvis, 1976).

F_{CO2} depends on the CO_2 concentration in the atmosphere according to:

$$F_{CO2} = \frac{1}{1.4 - 0.4 CO_2 / CO_2^*} \tag{12}$$

where CO_2 [ppm] is carbon dioxide concentration in and CO_2^* [ppm] is the reference carbon dioxide concentration (which is usually set at 330 ppm) (Stockle et al., 1992).

1.1.3 Energy balance at the soil surface

For the soil surface, the components of the energy balance equation are:

$$\begin{cases} R_{n,s} = R_{S\downarrow}(1-\alpha_s)e^{-K_{ext}LAI} + \varepsilon_s R_{L\downarrow} - \varepsilon_s \zeta T_s^4 \\ G = \dfrac{\rho_a c_a}{r_g}\left(T_s - T_g\right) \\ H = \dfrac{\rho_a c_a}{r_{as}}\left(T_s - T_a\right) \\ \rho_w \lambda E = \dfrac{\rho_a c_a}{\gamma r_{as}}\left(e_s^{sat}(T_s) - e_s\right) \end{cases}. \tag{13}$$

The aerodynamic soil resistance, r_{as}, is computed using the formulation of Choudhury and Monteith (1988) and Shuttleworth and Gurney (1990), i.e.,

$$\begin{cases} r_{as}^{0} = \dfrac{\ln\left(z_u / z_{sr}\right)^2}{k^2 u_z} \\ r_{as} = \begin{cases} r_{as}^{0} / (1+Ri)^2 & Ri < 0 \\ r_{as}^{0} / (1+Ri)^{0.75} & Ri > 0 \end{cases} \\ Ri = 5g\left(z_u - d_u\right)\dfrac{T_s - T_a}{T_a u^2} \end{cases} . \qquad (14)$$

The quantity r_{as}^{0} is considered as the resistance under neutral conditions (i.e., corresponding to no temperature or vapor pressure differences at a horizontal surface of roughness z_{sr}). Under non-neutral conditions, r_{as} is modified using the Richardson number Ri.

Ground conduction is considered as a fraction of soil net radiation (Choudhury et al., 1987; Kustas and Daughtry, 1990):

$$G = \alpha Rn , \qquad (15)$$

Here, α = 0.50 or 0.70 for bare soil or open water, respectively.

1.2 Water balance in the atmosphere-vegetation- soil system

1.2.1 Water balance in the canopy

Interception by the forest canopy plays a critical role by diverting significant quantities of precipitation that would otherwise be directed to soil moisture, transpiration, and surface and groundwater recharge. Key concepts of the water balance model include:

- the intercepted water I_c is evaporated and does not contribute to the throughfall;
- the excess of water is partly stored in the canopy, whose storage capacity S_c is limited to a maximum value $S_c^{\max}$;
- throughfall is the remaining part of exceeding water.

The amount of water intercepted by the canopy is given by (Kergouat, 1998):

$$I_c = P_r \, \kappa_p \, LAI , \qquad (16)$$

where κ_p is the rainfall interception coefficient whose value varies between 0.01 and 0.06 (Kergouat, 1998).

There are two different contributions to throughfall, i.e.,:

- the amount of water above the maximum storage capacity, defined by:

$$T_{P1} = (S_c - S_c^{\max}) / \Delta t \qquad (17)$$

- and the canopy leakage, defined by:

$$T_{P2} = S_c \, (1 - K_c) / \Delta t \ . \qquad (18)$$

Water balance in the canopy is therefore expressed as:

$$\begin{cases} \dfrac{dS_c}{dt} = \mathrm{P_r} - E_c - T_P \\ E_c = I_c \\ T_P = T_{P1} + T_{P2} \end{cases}, \tag{19}$$

$\mathrm{P_r}$, S_c, and T_P orresponding to the rainfall rate, the actual canopy storage, and the throughfall, respectively.

The maximum canopy storage capacity is estimated by (von Hoyningen-Huene, 1983):

$$S_c^{\max} = \left(0.935 + 0.498 \cdot LAI - 0.00575 \cdot LAI^2\right) \cdot 10^{-3}. \tag{20}$$

1.2.2 The snow routine

The model is an adaptation of the snow module of the HBV hydrological model (Seibert and Bergström, 2022; Seibert and Vis, 2012). The first step consists in splitting precipitation (after interception) in either snow, rain, or both. This is achieved through the following formulations:

$$\begin{cases} P_s = T_P & P_{Sn} = 0 & T \geq T_s^{\max} \\ P_s = 0 & P_{Sn} = T_P & T \leq T_s^{\min} \\ P_s = \kappa_{sn}\, T_P & P_{Sn} = \left(1 - \kappa_{Sn}\right) T_P & T_s^{\min} < T < T_s^{\max} \end{cases}, \tag{21}$$

where P_S and P_{Sn} denote the amount of water and snow reaching the soils surface, respectively; $T_s^{\min}$ and $T_s^{\max}$ are the two temperature thresholds, set to -3°C and 1°C, respectively; and κ_p is a proportional factor varying linearly from 0 at $T_s^{\min}$ to 1 at $T_s^{\max}$.

We use a conceptual model based on snowpack temperature to estimate snow volume and snowmelt flux. The average snow pack temperature is estimated through (Neitsch et al., 2002):

$$T_{Sn}^{n+1} = \min\left(0, w_{sn} T_{Sn}^n + \left(1 - w_{sn}\right) \cdot T_A^n\right), \tag{22}$$

where T_{Sn}^n is the snow pack temperature [°C] at time step n, T_A^n is the air temperature [°C], and w_{sn} is a user defined weighting factor, here set to 0.3.

The stored snow volume is updated accordingly. Snow melting takes place only if the temperature is higher than the user defined melting temperature T_m (set to 0 °C in this model) and if the snow pack temperature is 0 °C. When these two conditions are fulfilled, the melted snow flux is given by:

$$Q_{Sm} = \kappa_{Sm} \left(T_a^n - T_{Sm}\right), \tag{23}$$

where Q_{Sm} is the melted snow flux and κ_{Sm} is a proportionality coefficient, also termed degree-day factor, which is set to 10^{-4} m/s/°C.

1.2.3 Flow in the unsaturated zone

Flow in the unsaturated zone is described by a series of reservoirs. The first two represent the litter and the root zone, respectively. Each reservoir is defined by the water content at saturation, θ_s, the water content at wilting point, considered as the residual water content, θ_r, and the water content at field capacity, θ_c.

Throughfall and melted snow infiltrate in the litter layer. Evaporation computed by energy balance at soil surface occurs in this layer only, and is depending on the water content. The water drained from the litter layer enters the root layer. Transpiration, estimated by energy balance at the canopy, occurs in this layer only, and is depending on the available water. Drainage from these two layers is estimated in two ways: (*i*) the water volume above the layer field capacity is drained immediately, representing water movement through gravity; (*ii*) when the water content lies between the field capacity and the wilting point (residual water content), drainage is computed as an exponential function of the available water.

Water balance for a given layer is formulated as:

$$T_L \frac{d\theta}{dt} = Q_{\text{in}} - Q_s - Q_d \,, \tag{24}$$

where T_L is the layer thickness, θ is the volumetric water content, Q_{in} is water infiltration (throughfall and melted snow for the first layer), Q_s is the sink/source term due to evaporation or transpiration, and Q_d is the drainage flux leaving the layer and supplying the next one.

For the first layer, if the water content is greater than porosity, θ^{n+1} is set to the saturated water content θ_s and the amount of infiltrated water is reduced accordingly, assuming that runoff occurs.

The drainage Q_d is computed through:

$$\begin{cases} Q_d = \left(\theta - \theta_c\right) / \Delta t & if\ \theta \geq \theta_c \\ Q_d = (e^{\kappa_d\left(\theta_L - \theta_p\right)} - 1.00) / \Delta t & if\ \theta_r \leq \theta \leq \theta_c \\ Q_d = 0.0 & if\ \theta \leq \theta_r \end{cases} , \tag{25}$$

where κ_d is the drainage coefficient.

In this version of NIHM-MLSM, the root zone drainage is considered as groundwater recharge.

2 Estimation of canopy albedo

Values of albedo used in NIHM-MLSM are provided by satellite data and correspond to average values at the pixel size. Since information on land use are available (through Corine Land Cover), it is possible to distinguish bare soils from vegetated areas and assess energy balance. Following Taconnet et al. (1986), we consider a soil layer below the canopy that allows accounting for the reflection of the radiation trapped between soil and vegetation. The global albedo, α_g, of this system is given by (Taconnet et al., 1986):

$$\alpha_g \simeq \sigma_c \alpha_c + \frac{\alpha_s (1-\sigma_c)^2}{1-\sigma_c \alpha_c \alpha_s}, \tag{26}$$

with:

$$\sigma_c = 1 - \exp(-K_{ext} LAI). \tag{27}$$

From the global albedo, α_g, and assuming that the soil albedo, α_s, is known, it is possible to estimate the canopy albedo by:

$$\left(\sigma_c^2 \alpha_s\right)\alpha_c^2 - \sigma_c \left(\alpha_g \alpha_s + 1\right)\alpha_c + \left(\alpha_g - \alpha_s (1-\sigma_c)^2\right) = 0 \tag{28}$$

It can be readily shown that Eq. (28) has always two real solutions and only one, i.e.,:

$$\alpha_c = \frac{\left(\alpha_g \alpha_s + 1\right) - \sqrt{\left(\alpha_g \alpha_s - 1\right)^2 + 4\alpha_s^2 (1-\sigma_c)^2}}{2\sigma_c \alpha_s}. \tag{28}$$

is comprised between 0 and 1.

3 NIHM_Modular LandScape Moldel symbol list

Symbol	Description	Unit	Value
c_a	Specific heat of dry air at constant pressure	J/kg/K	$1.013\ 10^3$
CO_2	Carbone dioxide concentration (ppm)	kg/kg	
d_h	Reference elevation for humidity	m	
d_u	Evaporation flux	m/s	
E_c	Evaporation flux from the canopy	m/s	
e_a	Air partial water vapor pressure.	Pa	
e_s	Vapor pressure.	Pa	
e_s^{sat}	Vapor pressure at saturation.	Pa	
F_{CO2}	CO_2 efficiency function.	-	
F_{PAR}	Photosynthetic active radiation efficiency function.	-	
F_T	Temperature efficiency function.	-	
F_{VPD}	Vapor pressure deficit efficiency function.	-	
G	Conductive heat flux between surface and the ground	W/m^2	
g	Gravity	m/s^2	9.81
g_c	Canopy conductance	m/s	
g_s^{max}	Maximum conductance of fully open stomata	m/s	
H	Sensible heat flux (conductive heat flux) between the surface and the atmosphere	W/m^2	
h_c	Canopy height	m	
I_c	Water interception by the canopy	m/s	
K_{ext}	Attenuation coefficient depending on the vegetation	-	
k	Von Karman constant	-	0.40
LAI	Leaf area index	m^2/m^2	
LAI_{act}	Active part of the LAI	m^2/m^2	
P_{atm}	Air pressure	Pa	
PAR	Photosynthetic active radiation (400–700 nm)	W/m^2	
P_r	Precipitation	m/s	
P_s	Precipitation as liquid	m/s	
P_{sn}	Precipitation as snow	m/s	
Q_{Sm}	Melted snow infiltration flux	m/s	

Q_{in}^{n}	Reservoir inflow water flux	m/s	
Q_{d}^{n}	Reservoir drainage water flux	m/s	
Q_{s}^{n}	Sink/source term in the soil reservoir (evaporation for litter layer, transpiration for the root zone)	m/s	
q_a	Air specific humidity	kg/kg	
$R_{\downarrow S}$	Short wave radiation incoming from the sun (400–2500 nm).	W/m^2	
$R_{\downarrow L}$	Long wave (infra-red) incoming radiation	W/m^2	
Ri	Richardson number	-	
R_n	Net radiation	W/m^2	
r_{ac}	Aerodynamic resistance of the canopy surface	s/m	
r_{as}	Aerodynamic resistance of the soil surface	s/m	
r_{as}^{0}	Soil surface aerodynamic resistance at neutral conditions	s/m	
r_c	Canopy resistance	s/m	
r_g	Soil resistance to heat exchange	s/m	
S_c	Canopy water storage capacity	m	
S_c^{max}	Canopy maximum water storage capacity	m	
T_a	Air temperature	K	
T_c	Near canopy surface temperature	K	
T_s	Near soil surface temperature	K	
Tr	Transpiration flux	m/s	
T_{min}	Minimal temperature threshold for stomatal resistance.	K	
T_{max}	Maximal temperature threshold for stomatal resistance.	K	
T_{opt}	Optimal temperature for stomatal resistance.	K	
T_s^{min}	Minimal temperature threshold for liquid/snow partition.	K	
T_s^{max}	Maximal temperature threshold for liquid/snow partition.	K	
T_{Sm}	Snow melting threshold coefficient	-	
T_L	Layer thickness	m	
T_p	Throughfall	m/s	
T_{p1}	Throughfall from water excess	m/s	
T_{p2}	Throughfall from canopy drainage	m/s	
u	Measured wind speed	m/s	
u_c	Corrected wind speed	m/s	
w_{sn}	Weighting coefficient for snow storage	-	0.30

W_T	Turbulence layer thickness above canopy	m
z_u, z_h	Height above the canopy layer for wind and humidity	m
z_{um}	Elevation at which wind speed has been measured	m
z_{sr}	Soil roughness length	m
z_{ou} , z_{oh}	Roughness length for momentum and humidity	m

Symbol	**Description**	**Unit**	**Value***
α_c , α_s	Canopy and soil albedo.	-	
χ	Psychrometric function.	Pa/K	
Δe	Vapor pressure difference between the canopy layer surface and the ambient air.	Pa	
ε_a, ε_c, ε_s	Air, canopy and soil emissivity and absorptivity.	-	
ζ	Stefan-Boltzmann constant.	$W/m/K^4$	$5.670\ 10^{-8}$
θ	Water content.	m^3/m^3	
θ_c	Water content at field capacity.	m^3/m^3	
θ_r	Water content at the wilting point.	m^3/m^3	
θ_σ	Water content at saturation.	m^3/m^3	
κ_d	Drainage coefficient.	-	
κ_p	Rainfall interception coefficient.	-	
κ_{sn}	Water/snow partition coefficient.	-	
κ_{Sm}	Degree day factor for snow melting.	m/s/°C	10^{-4}
λ	Latent heat of water vaporization.	J/kg	$2.45\ 10^6$
ρ_a	Air density.	kg/m^3	1.204
ρ_w	Water density.	kg/m^3	999.9

4 Parameter identification codes for the sensitivity analysis

Id	Parameter
1-12	LAI
13-24	Albedo
25	Root zone field capacity
26	Root zone porosity
27	Litter drainage rate
28	Root zone drainage rate
29	Litter layer thickness
30	Litter layer porosity
31	Litter zone field capacity
32	Rainfall interception coefficient.
33	Canopy radiation attenuation coefficient
34	Root zone thickness
35	Maximum conductance of fully open stomata
36	Canopy height

The five last lines are repeated for each type of vegetation.

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