i-Tree Eco United States County-Based Hydrologic Estimates

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Satoshi Hirabayashi[1]

[1] The Davey Institute, 5 Moon Library, State University of New York, Syracuse, New York 13210, United States

1. Introduction

This document briefly explains the method to estimate the six hydrologic variables, Potential Evaporation, Potential Evapotranspiration, Evaporation, Transpiration, Precipitation Interception, and Avoided Runoff, for each county in the conterminous United States in 2010 using i-Tree Eco. As Potential Evaporation and Potential Evapotranspiration are calculated using i-Tree Eco's Weather Preprocessor, ones can refer to Hirabayashi and Endreny (2015) for more detail. Precipitation interception model of i-Tree Eco is fully described in Hirabayashi (2015).

2. Hourly Estimates

2.1. Potential Evaporation (PE)

Potential evaporation (PE) is defined as the amount of water released from tree surface that would occur if a sufficient water source were available. Hourly potential evaporation, E [m hr^{-1}] is calculated by the modified Penman-Monteith equation (Shuttleworth 1992):

$$PE = \frac{1}{\lambda \rho_w} \left[\frac{\Delta R_n + \frac{\rho_a c_p D}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \right] \times 10^{-3} \tag{1}$$

where

λ	=	latent heat of vaporization ($= 2.501 - 0.002361T$) [Mj kg^{-1}]
T	=	temperature [°C]
ρ_w	=	density of water ($= -0.0051T^2 + 0.018T + 999.88$) [kg m^{-3}]
Δ	=	slope of vapor pressure temperature curve ($= \frac{4098e_s}{(237.3+T)^2}$) [kPa °C^{-1}]
R_n	=	available energy (net radiation) [W m^{-2}]
ρ_a	=	density of air ($= 3.486 \cdot \frac{P}{275+T}$) [kg m^{-3}]
P	=	measured surface pressure [kPa]
c_p	=	specific heat of moist air (=1.013 [kJ kg^{-1} °C^{-1}])
D	=	vapor pressure deficit ($= e_s - e$) [kPa]
e_s	=	saturated vapor pressure ($= 0.6108exp\left(\frac{17.27T}{237.3+T}\right)$) [kPa]
e	=	vapor pressure ($= 0.6108exp\left(\frac{17.27DT}{237.3+DT}\right)$) [kPa]
γ	=	psychrometric constant ($= \frac{c_p p}{\lambda}$) [kPa °C^{-1}]
p	=	measured surface pressure [mBar]
r_s	=	stomatal resistance ($= \frac{200}{L}$) [s m^{-1}]
L	=	leaf area index
r_a	=	aerodynamic resistance ($= \frac{4.72 \cdot ln\left(\frac{z_t}{z_{ov}d_t}\right)}{1+0.536U_t}$) [m s^{-1}]
Z_t	=	wind estimate height for trees (=7 [m])
Z_{ov}	=	mass transfer coefficient (=0.0123 [m])
d_t	=	roughness height for tree (=0.95 [m])
U_t	=	wind speed at the tree top ($= U \frac{ln\left(\frac{Z_t}{d_w}\right)}{ln\left(\frac{Z_u}{d_w}\right)}$) [m s^{-1}]
U	=	measured wind speed [m s^{-1}]
Z_u	=	wind measurement height (=2 [m])
d_w	=	roughness height for water (=0.00137 [m])

2.2. Potential Evapotranspiration (PET)

Potential evapotranspiration (PET) is defined as sum of water released from inside the soil (evaporation) and trees (transpiration) that would occur if a sufficient water source were available. To estimate the hourly potential evapotranspiration, the aerodynamic resistance r_a [s m^{-1}] shown below is used in Eqn. 1.

$$r_a = \frac{208}{U_t} \tag{2}$$

2.3. Precipitation Interception and Evaporation by Trees

Precipitation interception is defined as water caught by tree leaves. Evaporation is part of intercepted precipitation escaped to the atmosphere from the leaf surface. It is assumed the area of interest is partially covered by vegetation (trees or shrubs) and the other is impervious or pervious ground cover. The model assumes that precipitation is uniformly distributed over the area, some portion of which falls on the area covered by vegetation and the others fall on the ground cover. The precipitation fell on the vegetation is partially intercepted by leaves, and the remainder reaches the ground under the canopy. Some portion of the precipitation intercepted by leaves is evaporated to the atmosphere, and the remainder drops to the ground when it exceeds the maximum capacity of water storage of leaves. Precipitation reached on the ground (directly and/or through canopy) is intercepted by depressions on the ground, or infiltrates to the ground of pervious cover, or run offs over the impervious cover.

Hourly vegetation storage at time t, Sv_t [m hr^{-1}] is calculated as:

$$Sv_t = Sv_{t-1} + Pc_t - Ev_{t-1} \tag{3}$$

Sv_t is capped with Sv_{max}, maximum storage of water ($= S_L LAI$)

S_L = specific leaf storage of water (=0.0002 [m])

Pc_t = in canopy precipitation at time t ($= P_t - Pt_t$) [m hr^{-1}]

P_t = precipitation at time t [m hr^{-1}]

Pt_t = through canopy precipitation at time t ($= P_t(1 - c)$) [m hr^{-1}] (van Dijk and Bruijnzeel 2001)

c = canopy cover fraction related to the canopy LAI ($= 1 - e^{-kLAI}$)

k = extinction coefficient (=0.7 for trees and 0.3 for shrubs) (Wang et al. 2008).

Hourly evaporation from vegetation at time t, Ev_t [m hr^{-1}] is calculated as:

$$Ev_t = \left(\frac{Sv_t}{Sv_{max}}\right)^{2/3} PE_t \tag{4}$$

Ev_t is capped with Sv_t so as not to exceed Sv_t.

PE_t = potential evaporation at time t calculated by Eqn. 1. [m hr^{-1}]

Hourly interception at time t, Iv_t [m hr^{-1}] is calculated as difference between hourly precipitation and under canopy throughfall, TF_t [m hr^{-1}]:

$$Iv_t = P_t - TF_t \tag{5}$$

$$TH_t = Pt_t \ \text{ when } \ Ev_t < Sv_{max} \tag{6}$$

$$TH_t = D_t + Pt_t \ \text{ when } \ Ev_t \geq Sv_{max} \tag{7}$$

D_t = hourly canopy drip at time t [m hr-1] and calculated as:

$$D_t = Pc_t - (Sv_{max} - Sv_{t-1}) - Ev_{t-1} \tag{8}$$

2.4. Transpiration

Transpiration is the escape of water vapor from plants as controlled to a considerable degree by leaf resistances. The process is comprised of two stages: evaporation of water from cell walls and diffusion out of the leaf mainly through stomata (Kramer 1983). Hourly transpiration flux, T_f [g m^{-2} hr^{-1}] is estimated as (Kramer 1983):

$$T_f = \frac{C_{leaf} - C_{air}}{\frac{1}{g_s} + R_a} \cdot \frac{3600}{LAI} \tag{9}$$

where

C_{leaf} = Water vapor concentration at the evaporating surfaces within the leaf [g m^{-3}]

C_{air} = Water vapor concentration in the air [g m^{-3}]

g_s = Stomatal conductance [s m^{-1}]

R_a = Aerodynamic resistance [s m^{-1}]

LAI = Leaf area index

C_{leaf} and C_{air} are calculated as (Monteith and Unsworth 1990):

$$C_{leaf} = \frac{M_w e_s}{RT} = \frac{2165 e_s}{T} \quad (10)$$

$$C_{air} = \frac{M_w e}{RT} = \frac{2165 e}{T} \quad (11)$$

M_w = Molecular weight of water (=18 [g mol^{-1}] = 18000 [g $kmol^{-1}$])

R = Universal gas constant (=8.314 [J mol^{-1} K^{-1}] = 8.314 [kPa m^{-3} $kmol^{-1}$ K^{-1}])

e_s = Saturation vapor pressure [kPa]

e = Vapor pressure [kPa]

T = Temperature [K]

The hourly transpiration flux mass per unit canopy cover, T_f [g m^{-2} hr^{-1}] is converted to depth [m hr^{-1}] by multiplying 10^{-6} (1 g of water flux m^{-2} = 10^{-6} ton m^{-2} = 10^{-6} m^3 m^{-2} = 10^{-6} m). It is then adjusted based on hourly potential evapotranspiration (*PET*) [m hr^{-1}] from inside of soil and trees. When *PET* is larger than T_f during the leaf-on season, the ratio between T_f and *PET* is averaged:

$$\bar{R} = \frac{\sum_t \left(T_{f_t} / PET_t\right)}{n} \quad (12)$$

For T_f during the leaf-off season as well as when T_f exceeds *PET* throughout a year, T_f is calculated by:

$$T_f = \bar{R} \cdot PET \quad (13)$$

2.5. Runoff

Hourly surface runoff from impervious cover under canopy at time t, Rv_t [m hr^{-1}] is calculated as:

$$Rv_t = (Pt_t + D_t) - (Si_{max} - Svi_{t-1}) - Evi_t \tag{14}$$

Si_{max} = maximum impervious cover depression storage of water (=0.0015 [m])

Svi_t = under canopy impervious cover depression storage of water at time *t* [m hr^{-1}], and calculated as:

$$Svi_t = Svi_{t-1} + (Pt_t + D_t) - Evi_{t-1} \tag{15}$$

Evi_t = evaporation from under canopy impervious cover at time *t* [m hr^{-1}], and calculated as:

$$Evi_t = \left(\frac{Svi_t}{Si_{max}}\right) PEg_t \tag{16}$$

PEg_t = potential ground evaporation at time *t* [m hr^{-1}]

Evi_t is capped with Svi_t so as not to exceed Svi_t.

Hourly surface runoff from impervious cover outside of canopy area at time *t*, Rg_t [m hr^{-1}] is calculated as:

$$Rg_t = P_t - (Si_{max} - Sgi_{t-1}) - Egi_t \tag{17}$$

Sgi_t = outside canopy impervious cover depression storage of water at time *t* [m hr^{-1}], and calculated as:

$$Sgi_t = Sgi_{t-1} + Pt_t - Egi_{t-1} \tag{18}$$

Egi_t = evaporation from outside canopy impervious cover at time *t* [m hr^{-1}], and calculated as:

$$Egi_t = \left(\frac{Sgi_t}{Si_{max}}\right) PEg_t \tag{19}$$

Egi_t is capped with Sgi_t so as not to exceed Sgi_t.

3. Annual Estimates

Hourly hydrologic variables estimated in the Section 1 are summed throughout a year and multiplied by associated area to derive annual total volume of the hydrologic variables.

3.1. Potential Evaporation (PE)

Annual potential evaporation, PE_a [m^3] can be calculated as:

$$PE_a = \sum PE_t \times A \times \frac{TC}{100} \tag{20}$$

A = area of interest [m^2]
TC = tree cover [%]

3.2. Potential Evapotranspiration (PET)

Annual potential evapotranspiration, PET_a [m^3] can be calculated as:

$$PET_a = \sum PET_t \times A \times \frac{TC}{100} \tag{21}$$

3.3. Precipitation Interception

Annual precipitation interception, Iv_a [m^3] can be calculated as:

$$Iv_a = \sum Iv_t \times A \times \frac{TC}{100} \tag{22}$$

3.4. Evaporation

Annual evapotranspiration, Ev_a [m^3] can be calculated as:

$$Ev_a = \sum Ev_t \times A \times \frac{TC}{100} \tag{23}$$

3.5. Avoided Runoff

In calculating annual avoided runoff, hourly runoff model is run for two scenarios: 1) the actual scenario in which the area of interest is partially covered by vegetation and the other is impervious or pervious ground cover, and 2) the hypothetical scenario in which the same area of interest is not covered by vegetation at all and has impervious or pervious cover. The hourly surface runoff in the scenario 1 is a sum of runoff from impervious cover under canopy and outside canopy, while in the scenarios 2 is runoff from impervious cover. The annual surface runoff volume is calculated as a sum of the hourly runoff multiplied with impervious cover areas for both scenarios. In general, the actual scenario produces less annual surface runoff than the hypothetical scenario due to the effect of vegetation that intercepts, stores, and evaporates precipitation water. By taking difference in surface runoff between the two scenarios, the effect of vegetation in reducing the surface runoff can be determined as net avoided runoff. Therefore, annual avoided runoff, AvR_a [m^3] can be calculated as:

$$AvR_a = \sum Ri_t \times IA_2 - \left(\sum Rv_t \times IAv_1 + \sum Rg_t \times IAg_1\right) \tag{24}$$

Ri_t = surface runoff from impervious cover in scenario 2 at time t [m hr^{-1}]
IA_2 = impervious cover in scenario 2 [m^2]
IAv_1 = under canopy impervious cover in scenario 1 [m^2]
IAg_1 = outside canopy impervious cover in scenario 1 [m^2]

For each county, mean impervious cover IC [%] was derived from National Land Cover Database (NLCD) 2011 Percent Developed Imperviousness (MRLC 2015). Impervious areas in Eqn. 24 can be calculated as:

$$IA_2 = A \times \frac{IC}{100} \tag{25}$$

$$IAv_1 = A \times \frac{TC}{100} \times \frac{IC}{100} \tag{26}$$

$$IAg_1 = A \times \left(1 - \frac{TC}{100}\right) \times \frac{IC}{100} \tag{27}$$

IC = mean impervious cover for county [%]

3.6. Transpiration

Annual transpiration, Tf_a [m^3] can be calculated as:

$$Tf_a = \sum Tf_t \times A \times \frac{TC}{100} \tag{28}$$

4. References

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