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Using Temperature-Based Estimations of Radiation to Approximate Potential Evapotranspiration

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Introduction

Potential Evapotranspiration (PET), essentially the amount of evaporation that would occur if there was an abundant supply of water in the landscape, is a useful concept that allows practitioners to estimate the upper limit of evapotranspiration (ET) using metrological data (Thornthwaite, 1948). The Priestley-Taylor (1972) equation is a commonly-used estimate for PET that depends on knowledge of net radiation (Rn) and temperature at a particular site. While this technique is widely accepted to be one of the more accurate equations for PET (e.g. Sumner & Jacobs 2005, Lu et al. 2005), modelers frequently turn to empirical temperature-based ET models such as Hamon (1963) or Oudin (2005) due to limited data availability. This has particular concern for planners using hydrologic models for future climate conditions, since these empirical models can be over-sensitive to increasing temperatures (Shaw and Riha 2011).

Here we model net radiation using only daily max and min temperature data and basic knowledge of a site's geographic characteristics, allowing the Priestely-Taylor (PT) method to be used with easily accessible data.

Data Sources:

All data used in this analysis were taken with permission from four sites at the AmeriFlux network (ORNL DAAC, 2012). The sites were chosen because of the availability of radiation and water vapor flux records, in addition to being relatively humid sites (Table 1).

Table 1: AmeriFlux sites used in this study

Site	Location	Description	citation
Morgan Monroe State Forest	Indiana, USA Latitude: 38.32	Broadleaf Forest	Schmid et al 2000
Mead – irrigated continuous maize	Nebraska, USA Latitude: 41.17	irrigated agriculture, conservation plow system	Suyker & Verma 2008
Bartlett Experimental Forest	New Hampshire, USA. Lat: 44.06	Mixed Forest	Jenkins et al 2007
UCI 1964wet	Manitoba, Canada. Lat: 55.92	Boreal Forest, poorly drained	Goulden et al 2011

Equations

Priestley-Taylor (1972) equation :

$$PET = \left(\frac{\alpha}{\rho\lambda}\right)\frac{\Delta}{\Delta+\gamma}\,(S + L_A - L_T) \quad (1)$$

Where: α = Priestley-Taylor constant (~1.26),
ρ = density of water (1000 kg/m^3),
λ = latent heat of vaporization (2500 kJ/kg),
Δ = slope of the saturation vapor pressure-temperature curve (kPa/°C),
γ = psychrometric constant (0.066 kPa/°C), and
$S+L_A-L_T$ = net radiation, R_n (kJ/m3/d);
S = net incoming solar radiation (kJ m^{-3} d^{-1}) and
L_A, L_T = Atm and Terrestrial Longwave radiation, respectively.

Slope of the saturation vapor press-temp curve (Tetens, 1930) :

$$\Delta = \frac{2508.3}{(T+237.3)^2}\exp\left(\frac{17.3\,T}{T+237.3}\right) \quad (2)$$

Atmospheric emissivity (modified from Campbell, 1977 and Monteith and Unsworth, 1990) :

$$\varepsilon = (0.72 + 0.005\,T)(1 - 0.84\,C) + 0.84\,C \quad (3)$$

Solar Radiation :

$$S = (1-a)Tr\,S_P \quad (4)$$

where a = albedo (-) ;
Tr = transmissivity, calculated below (-) ;
S_P = Potential Solar radiation at the edge of the atmosphere (kJ/m^3/d) ;

Atmospheric Transmissivity (Bristow & Campbell, 1984):

$$Tr = .75\,\{1 - \exp\{-[0.036\ \exp(-0.154\,\overline{\Delta T})]\,\Delta T^{2.4}\}\} \quad (5)$$

Where
$\overline{\Delta T}$ = Average temperature range in the 15 days before and after the current day (°C);
ΔT = Daily temperature range ($T_{max} - T_{min}$) (°C)

Potential Solar Radiation :

$$S_P = 117500\arccos(-\tan(dec)\tan(lat))\sin(lat)\sin(dec) + \cos(lat)\cos(dec)\sin(\arccos(\tan(dec)\tan(lat)))/\pi \quad (6)$$

where dec = Solar Declination (rad) = $0.4102\,sin\left(\pi\,\frac{Jday-80}{180}\right)$
$Jday$ = day of the year (1-366)
lat = latitude in radians

Longwave Radiation – Stephan-Boltzman Equation :

$$L = \varepsilon\sigma(T + 273.3)^4 \quad (7)$$

where ε = Emissivity : terrestrial = 0.97, atmospheric is calculated above ;
T = temperature (°C) ;
σ = 4.89 x 10^{-6} kJ/m^2/K^4/d (Stefan-Boltzman constant)

Cloudiness :

$$C = \begin{cases} 0, & Tr > 0.75 \\ 1, & Tr < 0.15 \\ 1 - \frac{Tr-0.15}{0.6}, & Tr \geq 0.15, Tr \leq 0.75 \end{cases} \quad (8)$$

Hamon PET equation (mm/day)

$$PET = 29.8\,D_L\,\frac{e_{sat}(T)}{(T+273.2)}$$

Where D_L = Day length (hours) ;
e_{sat}(T) = saturation vapor pressure at temperature T (kPa)

Oudin PET equation (mm/day)

$$PET = \begin{cases} \frac{S_P}{\rho\lambda}\left(\frac{T+5}{100}\right) & ,T \geq -5 \\ 0 & ,T < -5 \end{cases}$$

where
S_P = Potential Solar Radiation, equation above (kJ/m^3/d) ;
ρ = density of water = 1000 kg/m^3 ;
λ = latent heat of vaporization = 2500 kJ/kg ;
T = temperature (°C)

Results

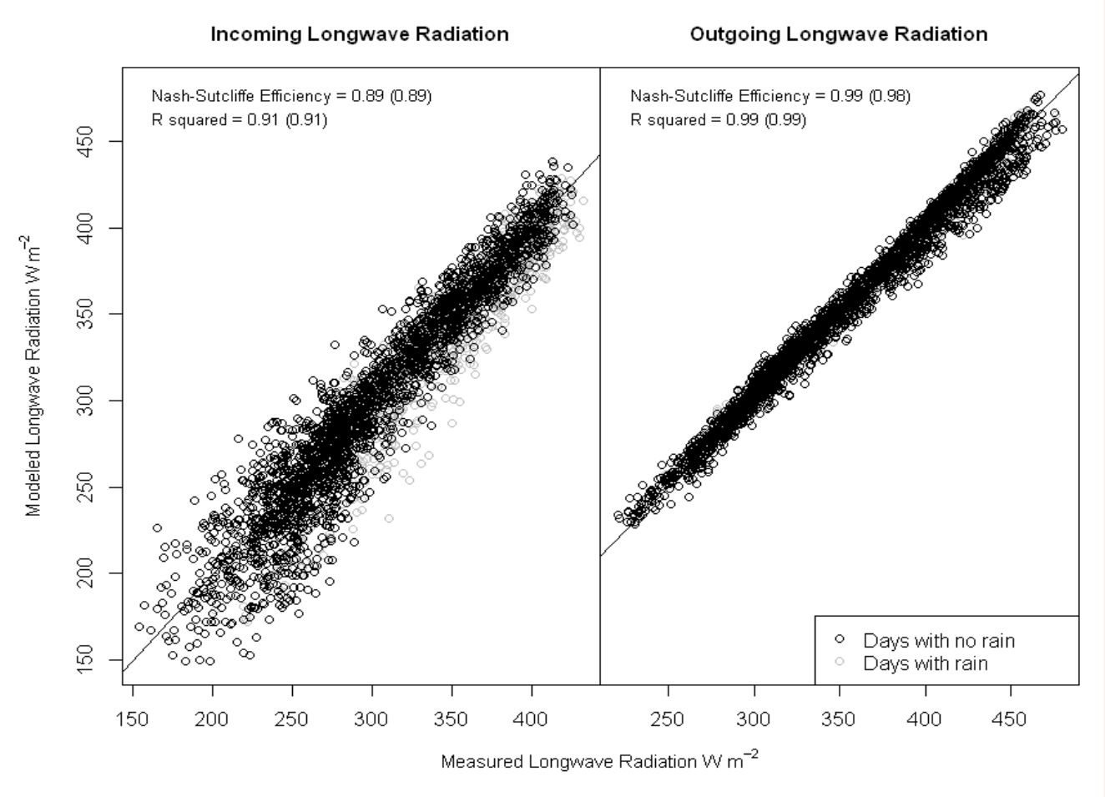

Figure 1: Modeled vs. measured longwave radiation at Mead Irrigated (efficiency values in parentheses represent only days with no rain for all figures)

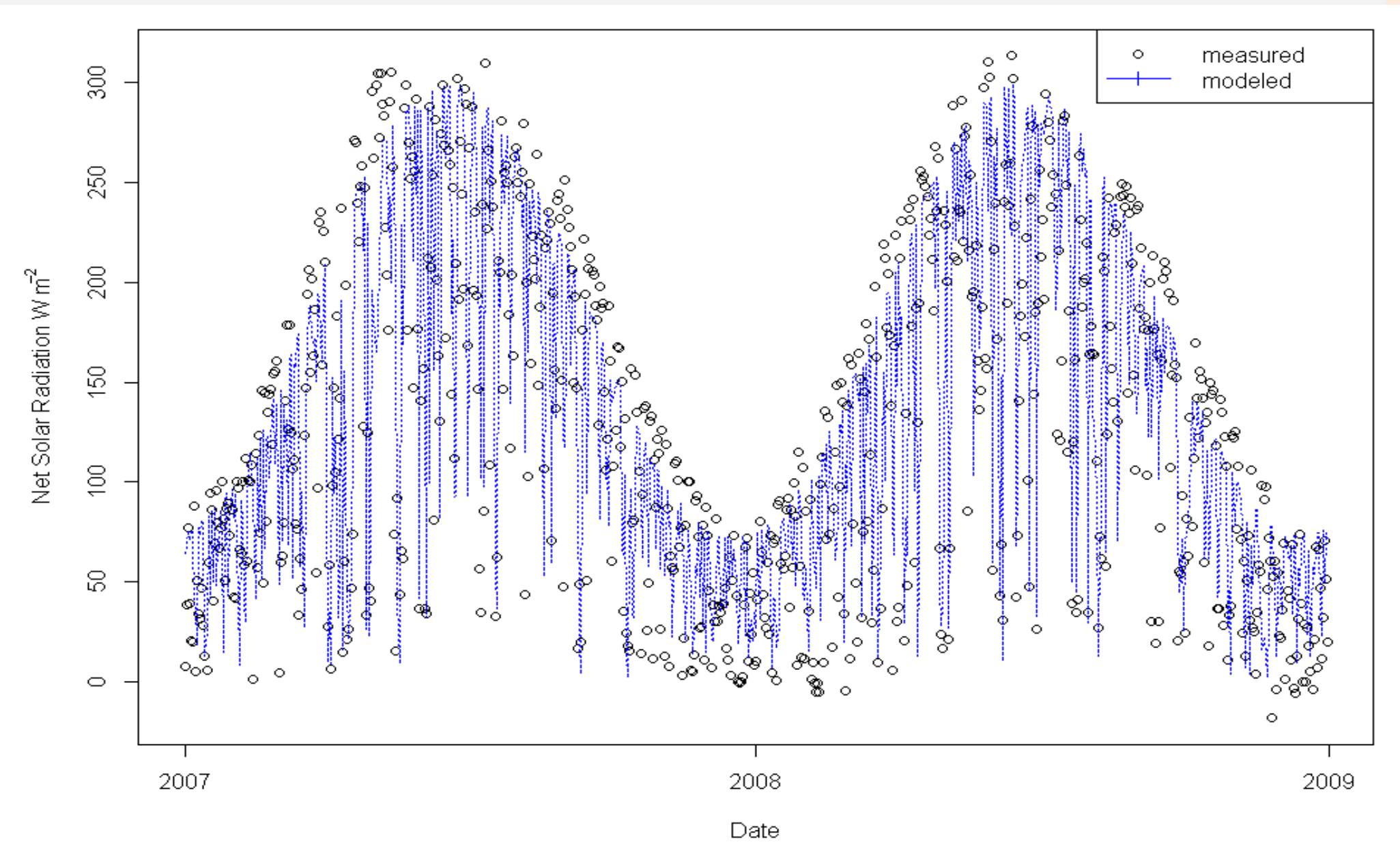

Figure 2: Modeled and measured Solar radiation, 2007-2008, at Bartlett Forest

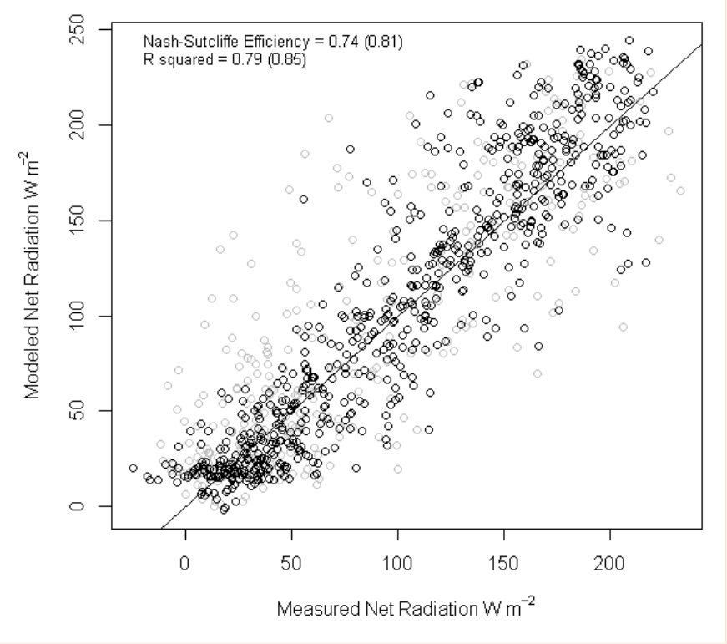

Figure 3: Rn at Morgan Monroe

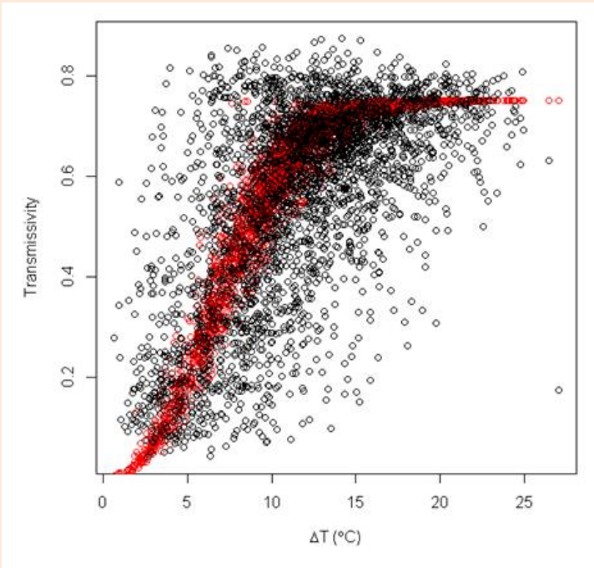

Figure 4: Measured transmissivity (black) and modeled transmissivity (red) vs. daily temperature change at Mead Irrigated

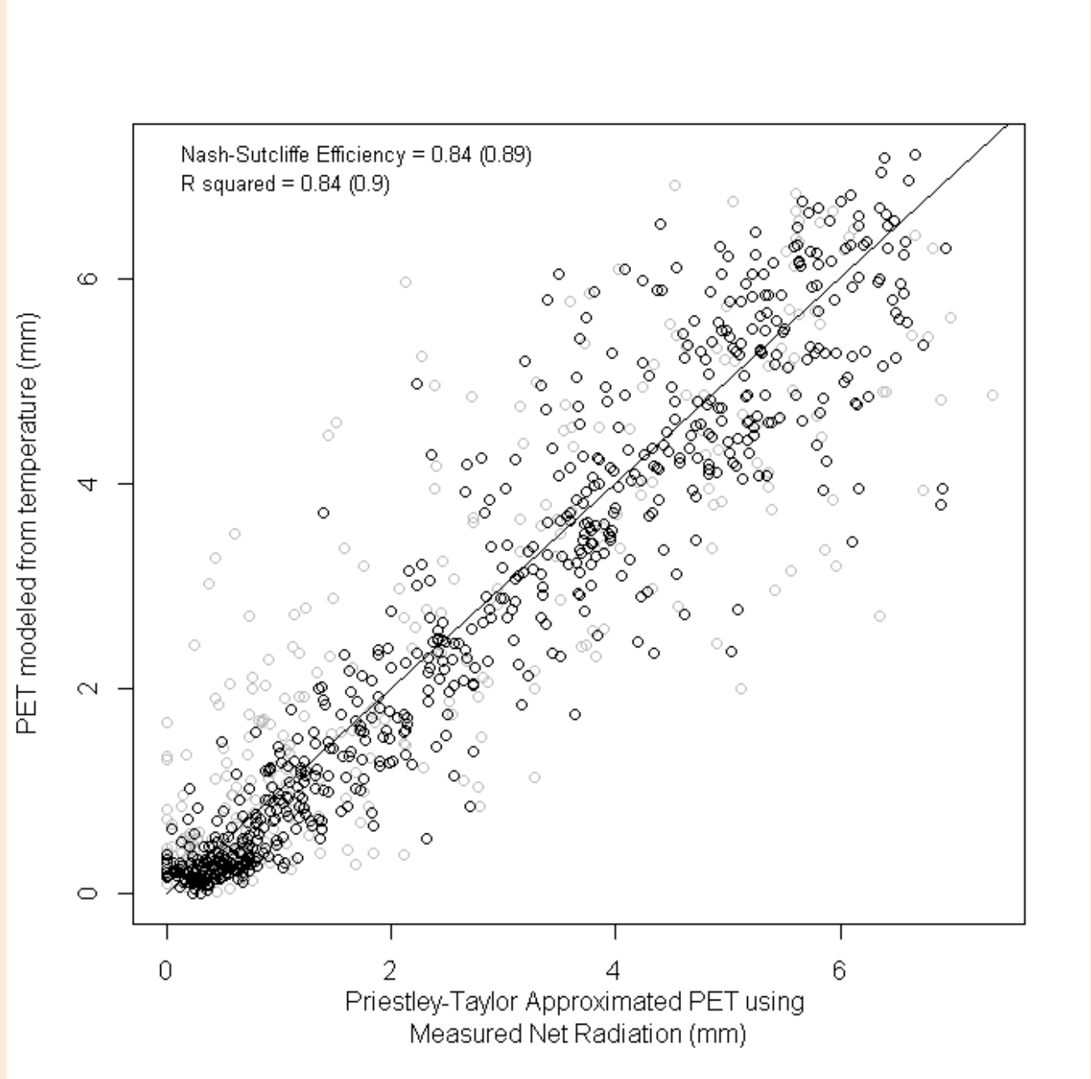

Figure 6: PT PET calculated using modeled vs measured Rn

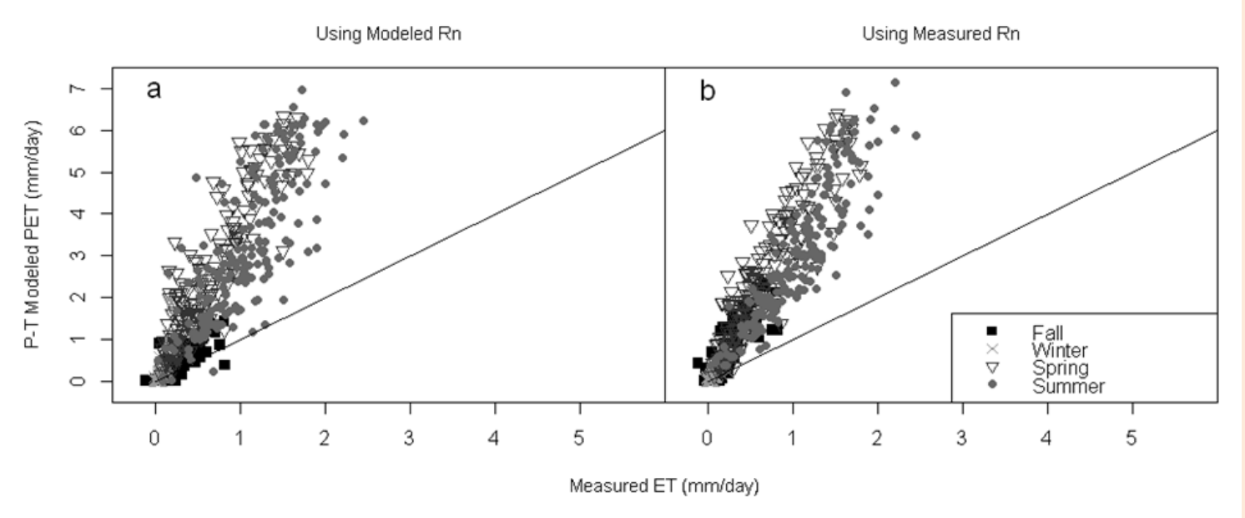

Figure 5: Modeled PET vs measured ET at UCI

Table 2: Efficiency (Nash Sutcliffe / R^2) of modeled verses measured radiation and ET. ND = No data.

	Morgan Monroe	Mead Irrigated	Bartlett	UCI
Net Solar	0.65 / 0.69	0.76 / 0.80	0.64 / 0.69	0.44 / 0.58
Transmissivity	0.24 / 0.36	0.33 / 0.45	0.04 / 0.14	-0.13 / 0.42
Incoming Longwave	0.84 / 0.86	0.89 / 0.91	ND	ND
Outgoing Longwave	0.91 / 0.96	0.99 / 0.99	ND	ND
Net Longwave	0.31 / 0.36	0.22 / 0.34	-0.033 / 0.18	-0.29 / 0.09
Net Radiation (Rn)	0.72 / 0.77	0.76 / 0.84	0.66 / 0.78	0.7 / 0.79
PET (PT) using measured vs modeled Rn	0.83 / 0.84	0.87 / 0.89	0.8 / 0.84	0.83 / 0.84
PET (PT) using modeled Rn vs measured ET	-0.21 / 0.66	0.18 / 0.60	-0.88 / 0.65	-14 / 0.80
PET (Hamon) vs measured ET	0.36 / 0.63	0.65 / 0.66	0.32 / 0.59	-3.1 / 0.71
PET (Oudin) vs measured ET	0.27 / 0.66	0.58 / 0.63	0.13 / 0.58	-3.5 / 0.71

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Discussions and Conclusions

- Transmissivity was the most inaccurately-modeled component of net Solar radiation.
- Although both incoming and outgoing longwave radiation were well-modeled, the difference between these -net longwave radiation – did not agree particularly well with measurements.
- Surprisingly, modeled net radiation had consistently better agreement with measured Rn than either net longwave or net solar had with measured values.
- PET calculated using PT based on modeled Rn was considerably higher than both measured ET and PET calculated from the two temperature-based methods. However, temperature-based PT PET had a stronger linear correlation to actual ET in three out of the four sites.
- Net radiation and PET were modeled more accurately on days without precipitation.
- Overall, combining temperature-based radiation estimates with the PT equation is a useful and fairly accurate method for modeling PET in the absence of radiation measurements.

Note : All equations used in this poster can be found in the EcoHydRology package in R (R Development Core Team 2012)