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# A hybrid dual-source model for potential evaporation and transpiration partitioning

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SUMMARY

Potential ET (PET) and partitioning of evaporation and transpiration are important information for hydrologic, ecologic, forest, and agricultural studies. Most PET models were developed in flat areas for agricultural purposes, with potential evaporation (PE) and potential transpiration (PT) lumped together. To quantify the evaporative demand for sloped surfaces with a wide range of vegetation coverage, a topography- and vegetation-based surface energy partitioning algorithm for PE and PT estimates (TVET) is developed. In this paper, vegetation-based part of the TVET model is presented. TVET employs a hybrid of layer and patch approaches in partitioning energy and routing vapor and sensible heat. It first uses a layer approach to partition available energy for the canopy and the soil components. The available energy of each component is then partitioned into potential latent heat and sensible heat, using a patch approach. Hybrid of these two approaches results in simple model formulae, while coupling the two components in terms of energy partitioning and aerodynamic resistances for heat and vapor transfer. TVET is different from a layer-approach model in that it distinguishes the difference in evaporation from inter-canopy soil and from under-canopy soil, and limits convective transfer contribution to transpiration only for vegetation-cover fraction. TVET is different from a patch-approach model in that it allows evaporation occurring from under-canopy soil, and that vegetation effect on both evaporation and transpiration is well considered. These features make TVET sensitive to vegetation effect on surface energy partitioning. The model is demonstrated and tested with Penman–Monteith and Shuttleworth–Wallace models, and with observations, at four sites covering mountain, basin floor, and riparian environments. The results indicate that TVET can be used to estimate PE and PT partitioning for a wide range of surfaces with different fractional vegetation cover. Good estimates of riparian surface evapotranspiration at the Rio Grande in the central New Mexico suggest its capacity to estimate ET in similar environments.



## Introduction

Evapotranspiration (ET) is a major water balance component on land surface, quantification of which is important for climatic, hydrologic, ecology, and agricultural studies. ET is a function of atmospheric conditions, surface characteristics, and root-zone soil moisture, among which soil moisture is the most difficult to obtain at a large scale. Thus, potential ET (PET), assuming unlimited soil moisture for evapotranspiration, is often used to quantify the evaporative demand representing the effects of atmospheric and surface conditions, although the latter is not always considered. Actual soil moisture partitioning is often estimated by soil (vadose zone) hydrologic modeling, for which PET becomes a standard atmospheric boundary condition.

Because of different physical mechanisms for evaporation and transpiration, and vegetation's controls on near-surface aerodynamic resistance and bulk canopy resistance, surface vegetation coverage plays an important role in surface energy and water balance. Many studies show that vegetation controls surface ET (Burba and Verma, 2001; Scott et al., 2006; Zhang et al., 2005). PET models distinguishing the difference in heat, mass, and momentum transfer between surface components (e.g., vegetation versus soil surface) represent more physics of ET processes. However, many PET models are empirical, in which evaporation and transpiration are lumped and related to a couple of micrometeorological observations (Xu and Singh, 2002). Some physically-based PET models (e.g., Penman–Monteith (PM) method), treating the surface as a uniform layer, do not have capability to distinguish different contributions from vegetation and soil either. Over the last two decades, some multi-source models have been developed (Choudhury and Monteith, 1988; Dolman, 1993; Kustas and Norman, 1997; Massman, 1992; Sanchez et al., 2008; Shuttleworth and Wallace, 1985). In literature, the term "source" is sometimes interchanged with "component".

Based on how energy is partitioned between sources, and how sensible heat and latent heat are routed, Lhomme and Chehbouni (1999) distinguished two approaches that are used in multi-source

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models. One is the "layer" (coupled) approach in which the energy and vapor flux interact between the components, such as the Shuttleworth–Wallace (SW) model (Shuttleworth and Wallace, 1985). The other is the "patch" (uncoupled) approach in which the energy and vapor flux do not interact between the components, such as the model in (Kustas and Norman, 1997). The layer approach is also termed "series resistance" formulation, and the patch approach termed "parallel resistance" formulation (Li et al., 2005).

The advantage of a multi-source model is that it not only includes more surface characteristic effects on quantifying PET (and ET), but also provides evaporation ($E$) and transpiration ($T$) partitioning. Since $E$ and $T$ consume soil moisture from different depths, and have different plant biophysical significance, partitioning of $E$ and $T$ has attracted fair amount of research effort in hydrologic (Harding et al., 2002), agricultural (Testi et al., 2004), forestry (Yepez et al., 2003) and ecological studies (Zhang et al., 2005). Various approaches, including sap flow (Allen and Grime, 1995; Williams et al., 2004), lysimeter (Zhang et al., 2005), isotope (Williams et al., 2004; Yepez et al., 2003), have been used to measure evaporation and transpiration separately. These point measurements provide support for developing hydrologic models for $E$ and $T$ partitioning at a large scale. A computing code with capacity to simulate $E$ and $T$ separately, such as HYDRUS (Šimůnek et al., 1998), provides a tool to model surface $E$ and $T$ partitioning. For such root-zone hydrological modeling, partitioning of PE and PT are required inputs. The primary objective of this paper is to present a surface characteristics-based PE and PT partitioning algorithm on naturally vegetated surfaces. The rationale of developing such a model is included in the next section. The remaining text is organized in the order of "Model formulation", "Study sites and data", "Model demonstration", "Model testing", and "Concluding remarks".

## A hybrid-approach dual-source PE and PT partitioning model: TVET

Both layer and patch approaches provide approximation of PE and PT. Conceptually, the layer approach is more appropriate for a surface with higher fractional and more uniform vegetation cover, while the patch approach works better for a surface with lower fractional and clumped vegetation cover. For a surface with uniform vegetation coverage, an appropriate approach can be selected based on surface characteristics. For some situations, such as mountain hillslopes, vegetation types and coverage may change significantly, a dual-source model which applies for a wide range of vegetation coverage is needed. Another difficulty in quantifying PET on mountain hillslopes is that a sloped surface receives different solar radiation per unit surface area (or solar irradiance) from a flat surface. To address the complexity of topography and vegetation in mountains, a topography- and vegetation-based dual-source PE and PT model (or TVET) is developed. Because the topography and vegetation parts of the model are independent to each other, we present the vegetation-based part in this paper.

Different from either a layer or a patch approach, the TVET model is a hybrid of the two, which compromises the disadvantage of both approaches. In a layer approach, soil under the canopy is not distinguished from that in the inter-canopy space. The canopy is treated as a semi-transparent layer for radiation input to the soil surface. The aerodynamic resistances, for transferring momentum, heat, and vapor from the soil surface, are dependent of the vegetation characteristics. Because transpiration from the canopy surface and evaporation from the soil surface are highly coupled, a layer-approach model has complex formulae. Moreover, the layer approach assumes a uniform vegetation layer, it does not represent actual situations on sparse and clumped vegetated surfaces. In a patch approach, evaporation of the under-canopy soil is not considered. It treats transpiration from the canopy patch and evaporation from the inter-canopy soil patch independently in terms of available energy (although aerodynamic resistances could be coupled). It usually employs the Penman equation for the soil patch, and the Penman–Monteith equation for the vegetation patch. Thus, a patch approach usually has simple formula, but may oversimplify the physical processes. In TVET, a layer approach is used to partition available energy and calculate aerodynamic resistances. A patch approach is then used to derive potential evaporation for the soil component, and potential transpiration for the vegetation component. By doing this, the TVET model considers evaporation from both the under-canopy soil and the inter-canopy soil surfaces, and distinguishes them. The vegetation controls for transpiration and evaporation are realized through vegetation-dependent energy partitioning, and vegetation-dependent resistance network parameterization.

## Model formulation

### *Available energy partitioning based on a layer approach*

Energy partitioning for the TVET model is shown in Fig. 1. The energy balance equation for a surface is expressed by

$$A' = R_n - A_{it} \tag{1}$$

where $A'$ is the total net radiation energy subtracted by occasional interception-water evaporation loss (it is daily for the TVET model, which is applied for all other energy terms except for those with specific descriptions); $R_n$ is total net radiation of the surface, which is $R_{ns} - R_{nl}$, with $R_{ns}$ of the incoming net short-wave radiation to the surface, and $R_{nl}$ of the outgoing net long-wave radiation leaving the surface; $A_{it}$ is the energy used to evaporate intercepted rainfall. All are in a unit of $\mathrm{J m^{-2}\,day^{-1}}$. Net radiation estimates are conducted using published empirical method based on various degree of data availability (Allen et al., 1998). Different interaction with vegetation between direct radiation and diffuse radiation is not considered, similar to Shuttleworth and Wallace (1985).

In the model, the surface is classified into two components: vegetation canopy and soil. The radiation energy at the surface thus further partitions into energy for these two components ($A_s$ for the soil, and $A_c$ for the canopy), using a layer approach based on Beer's law (Eqs. (2) and (3)), in which the soil component is considered under a semi-transparent canopy layer. Snow (if there is) is assumed to fall only on the soil surface, and consumes energy $A_{sn}$ for snowmelt.

The available energy for the soil is,

$$A_s = A' e^{-k_c L} - A_{sn} - G \tag{2}$$

where $k_c$ is the extinction coefficient; and $L$ is the bulk surface leaf area index, which is the multiplication of canopy leaf area index $L_c$ and the fractional vegetation cover $Fr$ of the surface ($L = L_c * Fr$). $A_{sn}$ is the energy used for snowmelt. $G$ is the net downward ground heat flux (usually assumed to be zero for daily time step). Following Shuttleworth and Wallace (1985), Eq. (2) is based on a Beer's law relationship. For a layer canopy cover, $k_c$ is a constant, e.g., 0.7 in Shuttleworth and Wallace (1985). In TVET, a range of fraction vegetation cover is attempted, thus, physically $k_c$ should vary with vegetation-cover fraction. Due to the difficulty to quantify $k_c$ as a function of $Fr$, at this stage, we fix $k_c$ of a value of 0.4, considering that clumpy vegetation intercepts less radiation than a layer canopy with the same $L$. Mathematically, the $Fr$ effect on radiation energy partitioning is included surface albedo and $L$ term, which may compromise the $k_c$ parameterization problem to some extent. Nevertheless, $k_c$ parameterization is an issue that needs to be further