ESTIMATION OF DAILY EVAPOTRANSPIRATION BY THREE-TEMPERATURES MODEL AT LARGE CATCHMENT SCALE

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ABSTRACT:

Three-temperatures model (3T model) was a recently proposed algorithm, which could be used to estimate actual evapotranspiration (ET) and evaluate environmental quality. The key parameters included are air temperature, land surface temperature and reference land temperature. Compared with other conventional ET estimation algorithms, site-specific parameters, such as surface resistance and aerodynamic resistance are not required. Although previous ground based experiments showed that the 3T model had reasonable precision for ET estimation, its application for satellite based remote sensing was not yet carried out. This study aims to evaluate its applicability at large catchment scale based on satellite remote sensing. First, the derivative processes to extend the 3T model for remote sensing were developed and by using TM image, a case study was presented. Thereafter, Penman-Monteith equation was chosen to validate the accuracy of the 3T model. Results showed that the absolute error of daily ET estimated by the two algorithms varied from 0.09 to 0.53 mm d^{-1}, with an average of 0.05 mm d^{-1}. Further analysis indicated that the 3T model had a reasonable accuracy. Meanwhile, the simplicity of the 3T model shows a good potential for remotely sensed actual evapotranspiration at large catchment scale.

1. INTRODUCTION

Evapotranspiration (ET) is a key component for terrestrial ecosystems not only for its energy balance, but also for its mass balance. Since surface energy and water exchange are two key processes that can determine the characters of environment to a large extent, researches on ET are focused by scientists around the world, especially on water balance and regional sustainable water management practices.

Ever since Halley (1687) began the study of vapor, many algorithms have been proposed to estimate ET. Generally speaking, there are three groups of methods to measure or estimate ET: water balance method, micrometeorological method and plant physiology method. Weighing lysimeter is a commonly used water balance method. Micrometeorological method is applied widely, such as Penman-Monteith equation, Bowen ratio method and eddy covariance method. Chamber method, tracer technique and cut-tree method belong to plant physiology method. However, due to practical difficulty, most of these methods are classified as traditional and only appropriate for homogenous surfaces at micro scale.

In the late 1970s, with the development of remote sensing technology and its potential capability to provide synoptic surface information, estimating surface ET at large scale has become possible and new algorithms based on thermal remote sensing have been developed, such as simple empirically based (Jackson et al., 1977; Seguin and Itier, 1983; Lagouarde, 1991; Carlson et al., 1995) and theoretically based, e.g., single-layer model (Jackson, 1982; Kustas et al., 1989; Moran et al., 1989; Kustas et al., 1990; Hall et al., 1992), SEBAL (Surface Energy Balance Algorithm for Land) (Bastiaanssen et al., 1998a, 1998b) and two-source model (Norman et al., 1995; Anderson et al., 1997; Kustas and Morman, 1999). Although these algorithms have successful applications in certain places, most algorithms are unsatisfactory to practical applications because of the availability or representability of some necessary data and the rationality of assumptions.

To overcome some of the shortcomings in these algorithms, a simple algorithm called three-temperatures model (3T model) was proposed by Qiu et al. (1996a, 1996b, 1998) to estimate actual ET and evaluate environmental quality. It needs only air temperature, land surface temperature and reference temperature. Previous experiments in situ showed that the 3T model had good precision (Qiu et al., 1999a, 1999b, 2000, 2002, 2003), but has not been applied to mesoscale so for. The aim of this study is that, by combining with remotely sensed data, the 3T model is applied to estimate ET for Jing River basin, a catchment with an area more than 45 000 km^2, to evaluate its applicability at mesoscale.

2. THEORY OF 3T MODEL

The 3T model is based on surface energe balance. By assuming that the land is composed of bare soil, fully vegetated area and a mixture of both, Qiu et al. (1996a, 1996b, 1998) established algorithms for bare soil and fully vegetated area respectively,

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thereafter fractional vegetation cover was introduced to calculate ET for the mixture of both by weighing the soil evaporation and vegetation transpiration.

According to the general energy balance equation, energy exchange just above the bare soil can be express as

$$LE=R_n-G-H \quad (1)$$

where LE is the latent heat flux, of which L is the latent heat of vaporization with a value of 2.49×10^6 W/(m^2 mm) and E is the soil evaporation; R_n is the net radiation at the soil surface in W/m^2; G is soil heat flux in W/m^2; H is the sensible heat flux between soil and atmosphere in W/m^2, which can be derived from the following equation as

$$H=\frac{\rho C_p(T_s-T_a)}{r_a} \quad (2)$$

where ρ is the air density in kg/m^3, C_p is the specific heat at constant pressure in MJ/(kg ℃); T_s is the soil surface temperature and T_a is the air temperature in degree; r_a is the aerodynamic resistance in s/m, the diffusion resistance of the air layer.

By introducing a dry soil without evaporation (reference surface, E=0), Qiu et al. (1998) assumed that the atmosphere condition around the reference surface might not be significantly changed and the aerodynamic resistance of the dry soil and the around drying soil was the same, under this condition r_a of the drying soil could be calculated by combining Eq. (1) and Eq. (2).

$$r_a=\frac{\rho C_p(T_{sd}-T_a)}{R_{nd}-G_d} \quad (3)$$

where T_{sd}, R_{nd} and G_d are, respectively, soil temperature, net radiation and soil heat flux of the dry soil (reference site).

When combining Eqs. (1) to (3), evaporation (E) for bare soil can be derived by

$$LE=R_n-G-(R_{nd}-G_d)\frac{T_s-T_a}{T_{sd}-T_a} \quad (4)$$

With the same method and by introducing an imitation canopy (a canopy without transpiration, T=0), r_a of the vegetation could be estimated using the following formula:

$$r_a=\frac{\rho C_p(T_{cp}-T_a)}{R_{np}} \quad (5)$$

where T_{cp} and R_{np} are, respectively, temperature and net radiation of the imitation canopy (reference site).

Thus, when combining Eq. (1), Eq. (2) and Eq. (5), formula of transpiration (T) for fully vegetated area can be obtained as

$$LT=R_n-R_{np}\frac{T_c-T_a}{T_{cp}-T_a} \quad (6)$$

where T_c is vegetation canopy temperature.
By introducing the fractional vegetation cover, f, ranging from 0 to 1 (0 for non-vegetation cover and 1 for fully vegetation cover), ET for soil and vegetation mixed area can be weighed as

$$ET=(1-f)E+fT \quad (7)$$

where f is defined by Kerr et al. (1992) as

$$f=\frac{NDVI-NDVI_{\min}}{NDVI_{\max}-NDVI_{\min}} \quad (8)$$

where NDVI (normalized difference vegetation index) can be retrieved from reflectance of red and near-infrared band, α_r for the former and α_{nir} for the latter, of remotely sensed data using the following equation:

$$NDVI=\frac{\alpha_{nir}-\alpha_r}{\alpha_{nir}+\alpha_r} \quad (9)$$

where $NDVI_{max}$ and $NDVI_{min}$, correspond to the values of NDVI for bare soil and a surface with a fractional vegetation cover of l00%, respectively.

The other two kind of unknown parameters in the 3T model are net radiation R_n and soil heat flux G. If the model is used on small scale, e.g., on plot, these two parameters can be measured; if the scale becomes larger, especially to meoscale, it is difficult to measure R_n or G. In this case, remote sensing could be an effective alternative method, and R_n and G can be estimated using the flowing algorithms:

$$R_n=R_{swd}-R_{swu}+R_{lwd}-R_{lwu} \quad (10)$$

where R_{swd}, R_{swu}, R_{lwd} and R_{lwu} stand for the incoming shortwave and outgoing shortwave radiation and incoming longwave and outgoing longwave radiation respectively.

$$R_{swd}=\tau\cdot S\cdot E_0\cdot\cos\theta \quad (11)$$

$$\tau=0.75+2\times10^{-5}\times h \quad (12)$$

$$E_0 = 1 + 0.033\cos(2\pi d_n / 365) \tag{13}$$

where τ is the atmospheric transmittance coefficient and can be derived from measurements at the meteorological station, or from elevation (h, in meter) using Eq. (12) proposed by Allen et al. (1994); S is the solar constant (1 367 W/m^2); E_0 is the eccentricity correction factor and can be calculated with d_n (Allen et al., 1998), the number of the day in the year between 1 (1 January) and 365 or 366 (31 December); θ is the solar zenith angle in radian.

$$R_{swu} = \alpha R_{swd} \tag{14}$$

where α is the surface albedo, and can be calculated with remote sensing data as proposed by Liang (2001).

$$R_{lwd} = \sigma \cdot \varepsilon_a \cdot (T_a + 273.15)^4 \tag{15}$$

$$\varepsilon_a = 9.2 \times 10^{-6} \times (T_a + 273.15)^2 \tag{16}$$

where σ is the Stefan-Boiltzmann constant (5.67×10^{-8} W/(m^2 K^4)); ε_a is the atmospheric emissivity and can be calculated from practical approaches such as Eq. (16) proposed by Swinbank (Campbell and Norman,1998); T_a is air temperature in Celsius.

$$R_{lwu} = \sigma \cdot \varepsilon_s \cdot T_s^4 \tag{17}$$

where ε_s is surface emissivity and T_s is land surface temperature in Kelvin, which can be retrieved from remote sensing data.

Soil heat flux can be estimated from net radiation as suggested by Su et al. (2001)

$$G = R_n \cdot [\Gamma_c + (1-f) \cdot (\Gamma_s - \Gamma_c)] \tag{18}$$

where Γ_c and Γ_s are empirical coefficient: Γ_s = 0.315 (Kustas and Daughtry, 1990) and Γ_c = 0.05 (Monteith, 1973).

When applying the 3T model at large catchment scale, it is important to find out the reference site of bare soil or fully vegetated area. Usually the temperature of the reference site has the maximum value, according to this, the reference site can be determined. Thus reference temperature of bare soil or canopy, T_{sd} or T_{cp}, is respectively obtained as the maximum temperature of bare soil or canopy, T_s or T_c, in a given image or in a given area, with which reference value of R_n or G can be calculated.

With all the needed inputs of 3T model (Table 1) are available, instantaneous ET can be estimated; thereafter daily ET can be derived by (Xie et al., 1991)

$$ET_d = \frac{ET_i \cdot 2N_E}{\pi \cdot \sin(\pi \cdot t / N_E)} \tag{19}$$

where ET_d is daily ET and ET_i is instantaneous one at any time-of-day; N_E is the daily ET hours and equals to the time interval between sunrise and sunset minus two; t is the time interval between sunrise and the data-collecting time of the satellite sensor passing by.

input parameter	source	advantages
air temperature	meteorological station	easy to obtain
surface temperature	retrieve from remote sensing data	there are land surface temperature products, or the algorithms to retrieve land surface temperature are mature
net radiation	retrieve from remote sensing data	the algorithms to retrieve net radiation are mature
soil heat flux	calculate from net radiation	easy to calculate
parameters of reference site	the parameters of reference site can be obtained from the above results correspondingly	reference site is determined by the maximum surface temperature, thus it is easy to obtain

Table 1 Parameters needed in the 3T model

3. MODEL APPLICATION

In this study, one TM data inside Jing River basin, China (Figure 1), scanned in August 28th, 1987 from path 128 and row 35, was adopted as the original data to retrieve land surface temperature (LST), using the mono-window algorithm proposed by Qin et al. (2001). However, it was difficult to separate soil temperature from vegetation canopy temperature with the adopted algorithm, hence the retrieved LST was assumed to be the temperature of bare soil (T_s) where NDVI less than 0.05, or of canopy (T_c) where NDVI larger than 0.70, and when DNVI ranging between 0.05 and 0.70, the retrieved LST was assumed to be the mixture of soil and canopy, which could be departed through Eq. (20) (Lhomme et al., 1994).

$$\begin{aligned} f \cdot T_{cm} + (1-f) \cdot T_{sm} &= T_{mix} \\ T_{sm} - T_{cm} &= a \cdot (T_{mix} - T_a)^m \end{aligned} \tag{20}$$

where T_{cm} and T_{sm} are, respectively, the temperature of the foliage and the soil surface; T_{mix} is the radiometric surface temperature, which was assumed to be the retrieved LST; a and m are empirical coefficients, because approaches to adjust these parameters are not currently available so that the values of a = 0.1 and m = 2 given by Lhomme et al. (1994) were used.

The air temperature was interpolated with daily values from several national meteorological stations (Figure 1). Based on the results of LST, interpolated air temperature and some auxiliary data such as DEM, net radiation and soil heat flux were calculated with algorithms in section 2.

By using the 3T model, the instantaneous ET was estimated: the maximum value was 1.5 mm/h; the minimum value was 0 mm/h; and the average was 0.46 mm/h, as shown in Figures 2 and 3, based on which daily ET could be calculated (Figure 4).

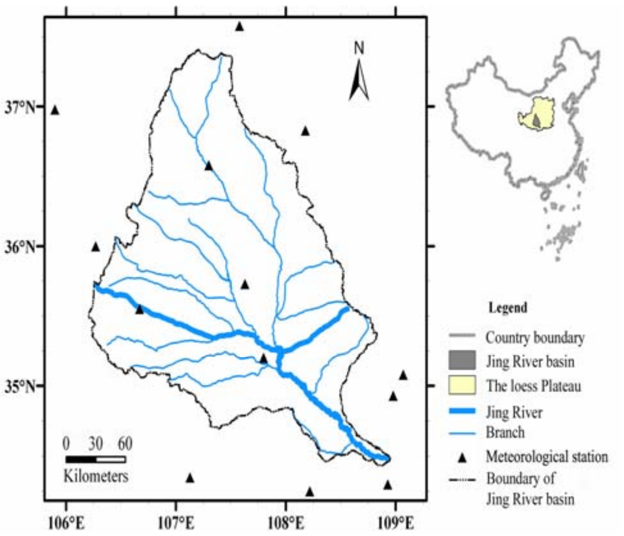

Figure 1 Location of the study area

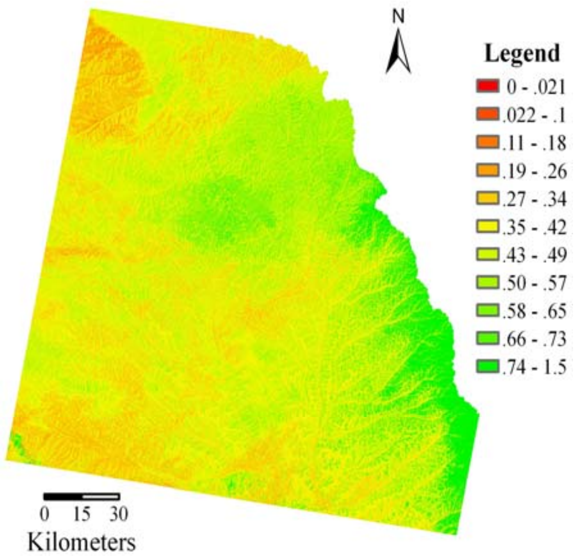

Figure 2 Instantaneous ET (mm/h) estimated by the 3T model based on TM image on August 28th, 1987

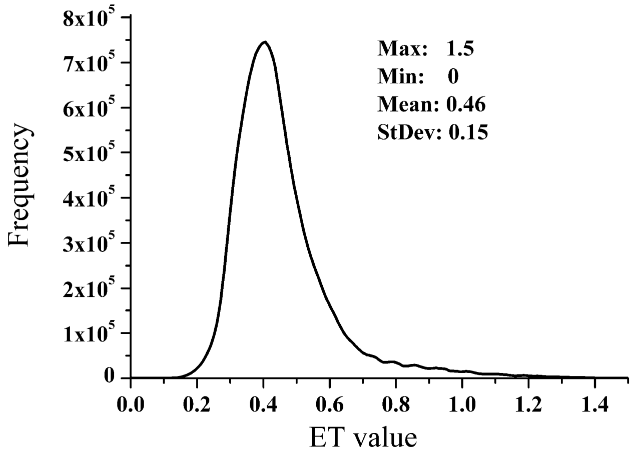

Figure 3 Histogram of the estimated instantaneous ET (mm/h)

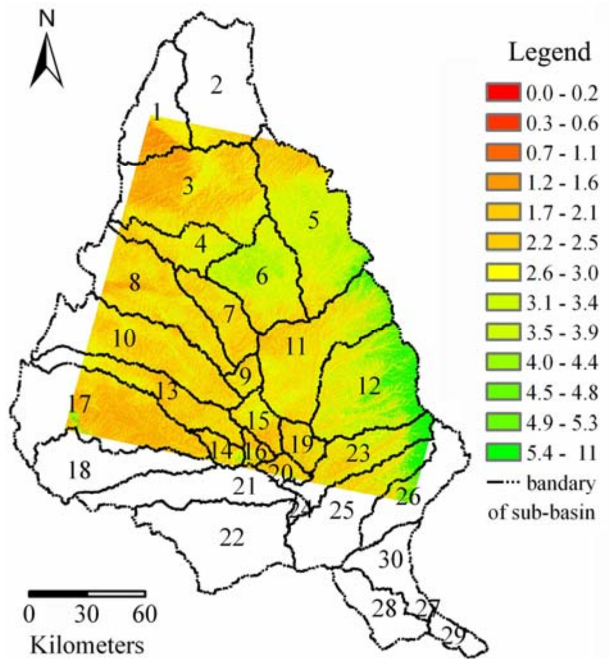

Figure 4 Daily ET (mm/d) based on TM image on August 28th, 1987 in Jing River basin

4. MODEL VALIDATION AND DISCUSSION

In order to validate the accuracy of the 3T model, its results were compared with the results of another study in Jing River basin, in which the ET was estimated using Penman-Monteith (P-M) equation by SWAT model (Kannan et al., 2007). One defect was that the ET resulted from SWAT model was not pixel based, instead it divided the whole river basin into a couple of sub-basins and each sub-basin gave one ET value. Therefore, the validation was based on sub-basin, and daily ET of each sub-basin estimated from the 3T model was averaged for the comparison.

As the area of Jing River basin was larger than one TM image, eight intact sub-basins inside the TM boundary were chosen for a meaningful validation (Figure 4), but TM data was covered by cloud in the number six sub-basin and the comparison of this region was eliminated (Table 2). In the seven regions, the maximum daily ET estimated by Penman-Monteith equation was 2.88 mm/d, whereas 3.74 mm/d for the 3T model, and the minimum value estimated by Penman-Monteith equation was 0.92 mm/d, while 2.35 mm/d for the 3T model. In the whole, the maximum absolute error was 2.81 mm/d whereas the minimum was 0.09 mm/d and 0.63 mm/d in average. The RMSE (Root Mean Square Error) was 2.92 mm/d for these seven basins. The results of the other eight partial sub-basin extended outside the TM boundary were also given in Table 2, and the absolute error varied differently.

However, some ET values estimated by SWAT model might be unreasonable as their showed abnormal value. For instance, the value of sub-basin 12 was only 0.92 mm/d, but in this region, at least one third area was covered by forest, how could the transpiration have such a low value? In addition, if considering the average value of the two methods, it was found that the absolute error was only 0.05 mm/d for the six intact sub-basins whereas 0.02 mm/d for the whole sub-basins list in Table 2.

No. of sub-basin		ET (mm/d)		Absolute error (mm/d)
		SWAT (P-M)	3T	
intact[a]	6	1.88	*	*
	7	2.35	2.44	0.10
	9	2.40	2.49	0.09
	11	2.56	2.88	0.32
	12	0.92	3.74	2.81
	15	2.39	2.51	0.12
	16	2.88	2.35	0.53
	19	2.84	2.44	0.40
	average[b]	2.47	2.52	0.05
Partial[a]	3	2.86	2.34	0.52
	4	3.35	2.73	0.62
	5	0.92	3.04	2.12
	8	3.37	2.42	0.96
	10	3.42	2.41	1.01
	13	3.68	2.39	1.29
	14	2.87	2.50	0.37
	17	3.44	2.11	1.33
	23	2.93	3.27	0.34
	25	2.94	3.63	0.69

Notice:
a: intact means the boundary of each sub-basin was in the adopted TM imagery, whereas partial means a little part of each sub-basin was outside of the imagery; half of No. 6 watershed is covered by cloud in the TM imagery and the estimated value was eliminated.
b: the average value did not include the value of sub-basin 12.

Table 2 Comparing of the estimated daily ET between the 3T model and the P-M equation (SWAT)

Statistical results further showed the reasonability of the 3T model (Figure 5). The minimum ET was from bare soil, with 2.25 mm/d on average, the maximum ET was from fully vegetated areas, with 5.41 mm/d on average, and ET from the mixed land was in the middle, with 2.81 mm/d on average.

5. CONCLUSION

This study provided a process to extent the 3T model for estimating the ET of larger catchment by remote sensing. After comparing with P-M equation, it was concluded that the 3T model had a reasonable accuracy. Meanwhile, the simplicity of the 3T model shows a good potential for remotely sensed actual evapotranspiration at large catchment scale.

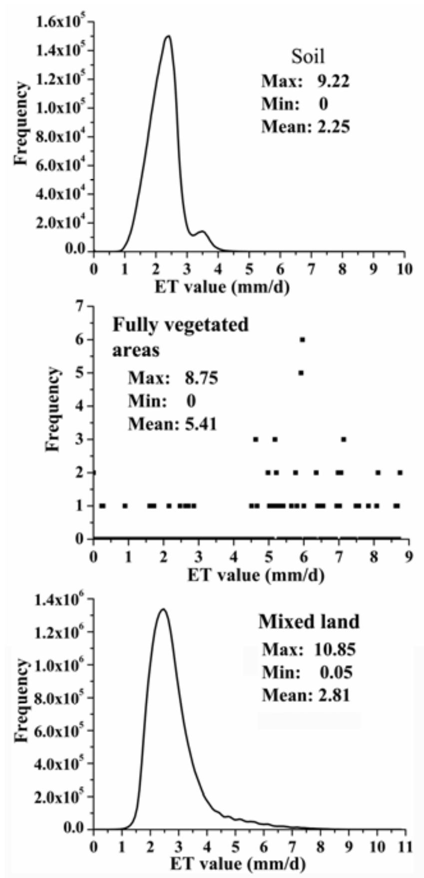

Figure 5 Statistical results of daily ET estimated by the 3T model for different covers on August 28th, 1987

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