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

Y. J. Xiong a, G. Y. Qiu a,b, *, J. Yin a, S. H. Zhao a, X. Q. Wu a, P. Wang a, S. Zeng a

a College of Resources Science and Technology, Beijing Normal University,
Xinjiekou Outer St. 19th, Haidian District, Beijing, P. R. China, 100875
b State Key Laboratory of Earth Surface Processes and Resource Ecology (Beijing Normal University)

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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 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 far. 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 km², to evaluate its applicability at mesoscale.

2. THEORY OF 3T MODEL

The 3T model is based on surface energy 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,

First author, Tel.: +86 10 58801294. Email address: xiongyj@ires.cn
* Corresponding author, Tel./Fax: +86 10 58802716. Email address: gqiu@ires.cn

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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

\[ LE = R_n - G - H \]  \hspace{1cm} (1)

where \( LE \) is the latent heat flux, of which \( L \) is the latent heat of vaporization with a value of \( 2.49 \times 10^6 \) 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

\[ H = \rho C_p (T_s - T_a) / r_a \]  \hspace{1cm} (2)

where \( \rho \) is the air density in kg/m\(^3\), \( C_p \) is the specific heat at constant pressure in MJ/(kg \( ^\circ \)C); \( T_s \) 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).

\[ r_a = \frac{\rho C_p (T_{sd} - T_a)}{R_{sd} - G_d} \]  \hspace{1cm} (3)

where \( T_{sd} \), \( R_{sd} \) 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

\[ LE = R_n - G - (R_{sd} - G_d) \frac{T_s - T_a}{T_{sd} - T_a} \]  \hspace{1cm} (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:

\[ r_a = \frac{\rho C_p (T_{cp} - T_a)}{R_{vp}} \]  \hspace{1cm} (5)

where \( T_{cp} \) and \( R_{vp} \) 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

\[ LT = R_n - R_{vp} \frac{T_c - T_a}{T_{cp} - T_a} \]  \hspace{1cm} (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

\[ ET = (1-f)E + fT \]  \hspace{1cm} (7)

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

\[ f = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \]  \hspace{1cm} (8)

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

\[ NDVI = \frac{\alpha_{nir} - \alpha_r}{\alpha_{nir} + \alpha_r} \]  \hspace{1cm} (9)

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:

\[ R_n = R_{swd} - R_{swu} + R_{lwd} - R_{lwu} \]  \hspace{1cm} (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.

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:

\[ r_a = \frac{\rho C_p (T_{cp} - T_a)}{R_{vp}} \]  \hspace{1cm} (5)

where \( T_{cp} \) and \( R_{vp} \) are, respectively, temperature and net radiation of the imitation canopy (reference site).
where $T_s$ is the soil surface temperature, which was assumed to be the retrieved LST; $T_i$ and $T_{cm}$ 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.

\[ E_0 = 1 + 0.033 \cos(2\pi d_\theta / 365) \]  

(13)

$E_0$ 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; $\theta$ is the time interval between sunrise and the data-collecting time of the satellite sensor passing by.

\[ ET_d = \frac{ET_i \cdot 2N_E}{\pi \cdot \sin(\pi \cdot t / N_E)} \]  

(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; $\theta$ is the time interval between sunrise and the data-collecting time of the satellite sensor passing by.

<table>
<thead>
<tr>
<th>input parameter</th>
<th>source</th>
<th>advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>air temperature</td>
<td>meteorological station</td>
<td>easy to obtain</td>
</tr>
<tr>
<td>surface temperature</td>
<td>remote sensing data</td>
<td>retrieve from remote sensing data</td>
</tr>
<tr>
<td>net radiation</td>
<td>remote sensing data</td>
<td>calculate from net radiation</td>
</tr>
<tr>
<td>soil heat flux</td>
<td>surface temperature</td>
<td>easy to calculate</td>
</tr>
</tbody>
</table>

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 mixture of soil and canopy, which could be departed through Eq. (20) (Lhomme et al., 1994).

\[ f \cdot T_{sm} + (1 - f) \cdot T_{cm} = T_{mix} \]  

(20)

where $T_{sm}$ and $T_{cm}$ 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).

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
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.

5. CONCLUSION

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.

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

<table>
<thead>
<tr>
<th>No. of sub-basin</th>
<th>ET (mm/d)</th>
<th>Absolute error (mm/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SWAT (P-M)</td>
<td>3T</td>
</tr>
<tr>
<td>6</td>
<td>1.88</td>
<td>*</td>
</tr>
<tr>
<td>7</td>
<td>2.35</td>
<td>2.44</td>
</tr>
<tr>
<td>9</td>
<td>2.40</td>
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<td>Partial^a</td>
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<tr>
<td>25</td>
<td>2.94</td>
<td>3.63</td>
</tr>
</tbody>
</table>

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.

REFERENCES


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