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Regional evapotranspiration estimation based on a two-layer remote-sensing scheme in Shahe River basin

Jian Yin[1, 2], Huixiao Wang[1]
[1] College of Water Sciences, Beijing Normal University, Beijing, China
[2] School of Resources and Environment, Anqing Normal University, Anqing, China

Email: yinjianbnu@163.com

Abstract. Land surface evapotranspiration (ET) derived from remote sensing data has significant meaning for plant growth monitoring, crop yield assessment, disaster monitoring and understanding energy and water cycle in river basin area and surrounding regions. In the study, we developed a land surface ET remote sensing retrieval system to estimate the daily ET in Shahe river basin using the TM\ETM+ images. The system is based on the two-layer ET model and includes three parts: inversion of the evaporation ration using two-layer model, calculation of total daily net radiation, and estimation of daily ET based on evaporation fraction method. The results show that the average daily ET is about 2.28mm of the typical days in spring, and 2.97mm in summer, 1.59mm in autumn, and 0.5mm in winter. The ET in upstream areas covered by forest is higher than that in the downstream covered by settlement and farmland. In summer the difference of ET between the upper reaches and lower reaches is smaller compared to the other three seasons. The measurements by large aperture scintillometer and eddy correlation instrument were used for validation. By comparing the observed data with the estimated data, we found the estimation system had a high precision with the relative error between 0 and 16% (mean error of 11.1%), and the variance 0.77mm.

1. Introduction

Evapotranspiration (ET), including soil evaporation and vegetation transpiration, is the key link between land surface energy and water balance [1]. The effective estimation of time-continuous daily ET processes at river basin scale is especially important for the study of water resource management, climate change, and agriculture planning. Currently, regional ET can be estimated mainly by the following three methods: empirical formulas, hydrologic process models, and remote sensing ET models. The empirical formulas include water balance method, water heat coupling equations, and complementary relationship method. The water balance method ignores the changes of groundwater and soil water storage, and is typically used to calculate regional ET over long time scales in a closed basin, while the precision of the estimations is not high [2].Water heat coupling equations are mainly used for regional ET estimations at a yearly scale. But the equations are difficult to apply to a large area, because the key state regional soil moisture for estimation is hard to obtain [3]. By utilizing the complementary relationship between actual and potential ET, the regional ET at different time scales can be calculated based on routine meteorological data [4]. However, the relationship is related to weather conditions, and foundunstable in a recent study [5]. Therefore, the regional ET estimation based on the complementary relationship also has a degree of uncertainty. The existence, movement and distribution of water in a certain basin can be simulated and analysed using constructed hydrologic models based on hydrologic processes, however, the ET calculated by the hydrologic models has low accuracy because the simulation error is accumulated throughout the simulation processes [6].

Remote sensing ET models can estimate the surface ET without error accumulation combining the remote sensing technology and traditional ET methods, and have become important tools to estimate regional ET [7]. Currently, remote sensing ET models are based on the theory of surface energy balance, these models can be categorized into one-layer scheme and two-layer scheme [8], differing in the treatment of landscape either as a mixture of soil and vegetation or independent sources of energy turbulent fluxes [9]. One-layer models only compute one resistance and assume that all surfaces can be represented by one effective value combining temperature and humidity. This kind of method is simple and convenient to use, but is not appropriate for land surfaces with high spatial heterogeneity. Two-layer models have two sets of resistance across which individual, or local, source parameterization is applied and may also include a within-canopy air layer where such resistances meet; this parameterization allows for interactions between the soil and vegetation components.

In the existing two-layer models, the cores of the algorithm primarily lie in two aspects: 1) accurately decomposing surface temperature of a mixed pixel into soil temperature and vegetation temperature; 2) obtaining accurate surface resistances, such as aerodynamic resistance, canopy resistance, and residual resistance. In recent years, many efforts have been made to investigate the two issues. For instance, Norman and Kustas [8] used remote measurements of surface directional brightness temperature and some ancillary data to obtain soil temperature and vegetation temperature (called multi-angle method), and applied Beer's law to partition net radiation of a mixed pixel and employed Monin-Obukhov similarity theory to compute aerodynamic resistance; Zhang et al.[10] presented a PCACA algorithm (PCACA, Pixel Component Arranging and Comparing Algorithm) and a layered energy-separating algorithm on the basis of triangle method and Bowen-ratio energy balance method to partition surface temperature, surface albedo and net radiation of a mixed pixel, and finally to estimate soil evaporation and vegetation transpiration. PCACA algorithm is very convenient because only a single angle remotely sensed data is required which can be retrieved from most of the satellite data. Additionally, by using the layered energy-separating algorithm with Bowen-ratio energy balance method as the core, the uncertainties in surface energy partitioning based on the Beer's law are reduced.

In this paper, the daily ET in Shahe river basin is calculated by a two-layer remote sensing model which is based on the Zhang's model [10]. The model is composed of three parts: inversion of the evaporation ration using PCACA algorithm and layered energy-separating algorithm, calculation of total daily net radiation, and estimation of daily ET based on evaporation fraction method. The measurements by large aperture scintillometer and eddy correlation instrument were used for validation.

2. Data and study area

The Shahe River basin is located between 40°00' - 40°30'N and 115°50' - 116°20'E, in Beijing, China and has a drainage area of approximately 1125 km^2. Seventy-five percent of the basin is mountainous terrain. Land use types include woodland, grassland, water areas, developed land and bare land. Woodland takes up the largest proportion of the basin, approximately 47.53% of the total area; most of which is located in the upstream of the basin, farmland is the second largest, accounting for 34.32%, and primarily distributed in the downstream region. . The Shahe River flows from northwest to southeast. The basin is located in a warm climatic zone with a semi-humid and semi-arid climate, which can be characterized as dry cold winter, little-rainfall spring and heavy rainfall summer. The average annual temperature from 1961 to 2007 is 11.5°C, ranging from an average of -4.1°C in January to 25.7°C in July. The average annual precipitation is 548 mm, 80% of which falls from June to September.

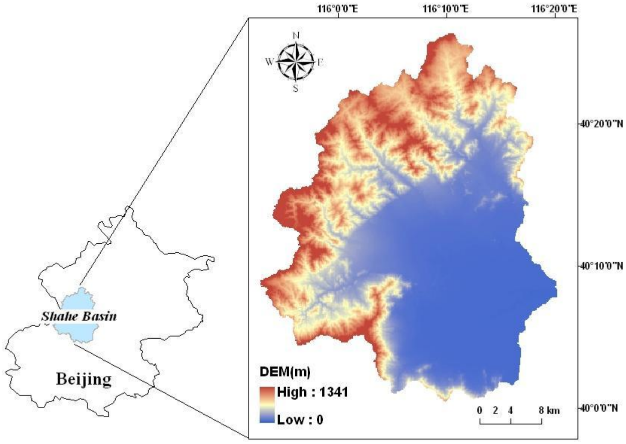


Figure 1. Sketch map of the study area

The data in this study included ground measurements and satellite remote sensing data. The ground measurements included meteorological data and flux data. Remotely sensed data used in the study was TM/ETM+ image (path 123/row 32) on 18 typical clear days in different seasons during 1999-2007. The images were in a descending mode at daytime, having a spatial resolution of about 30 m at the satellite's nadir band. Through image registration, radiometric correction and some necessary pre-treatment for the initial image, vegetation cover, surface albedo, surface temperature and other surface characteristics were inverted. Meteorological data (temperature and global radiation, air temperature, vapor pressure, wind speed and other data) were obtained from one of the nearest Chinese international exchange ground stations - the Beijing Meteorological Station (39° 48'N, 116° 28'E). In addition, DEM (Digital Elevation Model) with spatial resolution 15 m, and some other GIS (Geographic Information System) data of the study area were downloaded from the Science Data Center of Resources and Environment, Chinese Academy of Sciences.

3. Methodology

The two-layer remote sensing ET model includes three parts: the evaporation fraction inversion, the total daily net radiation calculation, and the daily ET estimation. The evaporation fraction inversion contains the pixel component arranging and comparing algorithm (PCACA) and a layered energy-separating algorithm presented by Zhang *et al.* [10], based on the triangle method and the Bowen-ratio energy balance method, to partition surface temperature, surface albedo and net radiation of mixed pixels, and to provide a final estimate of soil evaporation and vegetation transpiration.

The PCACA algorithm is based on the fact that the scatter plot of "surface temperature of mixed pixel - the vegetation coverage" (" $T_m - f$ " space) is like a trapezoid; in combination with the observations of the dry point and the wet point, the real temperature of the four corner points is calculated so as to bound the trapezoid. According to the trapezoidal space, the linear interpolation method was used to obtain the relationship between the mixed temperature, T_m, and the soil temperature, T_s. In other words, the surface temperature of mixed pixels, T_m, was separated into soil temperature, T_s, and vegetation temperature, T_v.

$$\frac{dT_m}{df} \approx T_v - T_s \tag{1}$$

The f is the fractional vegetation cover of the mixed pixel. $\mathrm{d}T_m/\mathrm{d}f$ represents the slope of the line of equal soil-water availability within the trapezoid. $\mathrm{d}T_m/\mathrm{d}f$ was calculated by determining the configuration of " $T_m - f$ " space. Similarly, surface albedo, α_m, was separated into soil albedo, α_s, and vegetation albedo, α_v.

The Layered Energy-separating Algorithm aims to calculate the Bowen-ratio (β, the ratio of sensible heat flux to latent heat flux) of soil and vegetation, expressed as β_s and β_v, respectively. By using the relationship between the Water Deficit Index (WDI) and the potential ET [11], we can obtain

β [12]. Then, combine with the '$T_m - f$' space, the soil Bowen ratio, β_s, and vegetation Bowen ratio, β_v, were calculated. Then, the net radiation at the soil surface, R_{sn}, and at the vegetation surface, R_{vn}, can be calculated based on the surface energy balance of longwave radiation and shortwave radiation. Net radiation of a mixed pixel, R_n, and soil heat flux, G, can be estimated using the empirical formulation, which has been confirmed in the study by Zhang *et al.* [10].

Then, soil evaporation (λE_s) and vegetation transpiration (λE_v) are retrieved via Bowen-ratio energy balance method in Eq. (2). If the energy exchange between vegetation and bare soil is negligible, λE of a mixed pixel can be described as a linear combination of λE_s and λE_v, Eq. (3). Evaporative fraction Λ was calculated using Eq. (4).

$$\lambda E_s = \frac{R_{sn} - G}{1 + \beta_s}, \quad \lambda E_v = \frac{R_{vn}}{1 + \beta_v} \tag{2}$$

$$\lambda E = f \lambda E_v + (1 - f) \lambda E_s \tag{3}$$

$$\Lambda = \frac{\lambda E}{R_n - G} \tag{4}$$

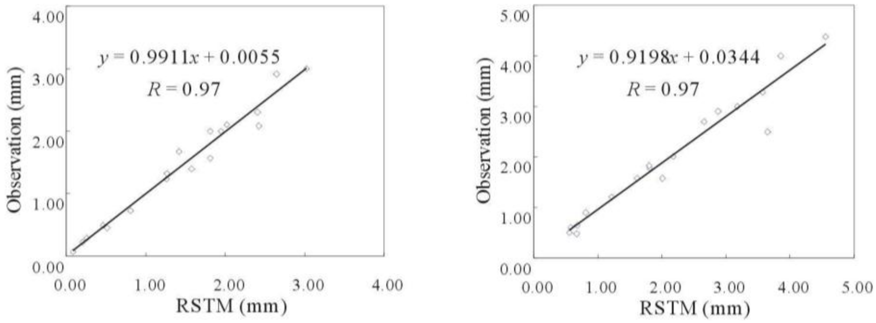
The daily ET was estimated by the evaporative fraction method, which has been relatively commonly used [1]. After evaporative fraction, Λ, daily net radiation, R_{daily}, and other parameters are obtained; the daily ET is calculated using Eq (5):

$$ET_{daily} = \frac{\Lambda R_{daily}}{\lambda} \tag{5}$$

where λ is latent heat for vaporization, $2.501\text{-}0.02361T_0)\times10^3$ MJ·m^{-3} [13]. T_0 is the average daily temperature (^{o}C). R_{daily} is the daily net radiation, equal to the difference between net shortwave radiation and net long wave radiation.

4. Results

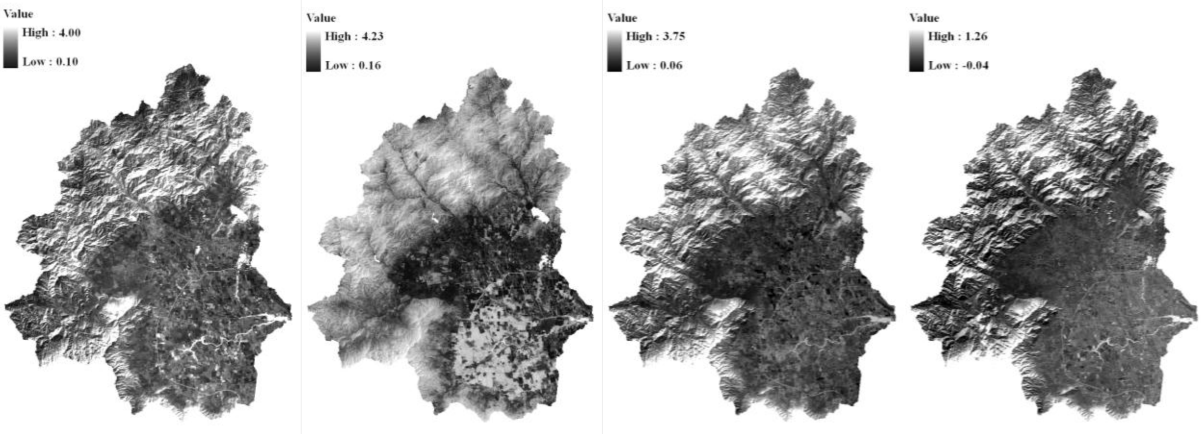
The measured data in Xiaotangshan flux observation stations and Miyun stations were selected to validate the results of remote sensing algorithm. By applying the eddy correlation system and large aperture scintillometer (LAS), Xiaotangshan station and Miyun Station can provide real-time observations of surface fluxes. Previous research demonstrates that the eddy correlation system and LAS, which is 2 m above the ground, have an optical path of approximately 200 m to 900 m. In this study, the remotely estimated daily ETs were based on TM/ETM+ with 30 m spatial resolution, while the impact of spatial scale was reduced and could be ignored. The Xiaotangshan flux observation station is located in sub-basin No.1 (Figure 2-b) of the Shahe River basin. In order to match the time and space scale for verification, the instantaneous observed flux was converted into daily data, and the remotely sensed daily ET of pixels which the Xiaotangshan flux station located in was averaged. The results show that the absolute percentage errors of remotely sensed daily ETs in 18 days are between 1.5% and 11.1%, the MAPE(mean absolute percentage error) is approximately 7.1%, the root mean square error is approximately 0.77 mm and the correlation coefficient is 0.97. We also compare the remotely RSTM-based daily ETs in some pixels with the observed data from the Miyun station for additional verification. The RSTM-based daily ETs for comparison located in the research area with similar ET conditions indicate that the MAPE of the two sets is 13%, the root mean square error is 1.45 mm and the correlation coefficient is 0.95. Therefore, the accuracy of the remote sensing inversion is high. Figure 2 gives the relationship between the RSTM-based daily ETs and the observations at the Xiaotangshan and Miyun stations.



(a) (b)

Figure 2. Comparison of the inversion and observation (a - Xiaotangshan，b - Miyun). “RSTM” represents the inversion results of the two-layer remote sensing model and “Obs.” represents the measurement values in the flux station.

The 18 typical daily ETs with clear sky condition by remote sensing are distributed in each season. The average daily ET is approximately 2.28mm in spring; 2.97mm in summer; 1.59mm and 0.5mm in the fall and winter. The following chart reflects the daily ETs of different typical date in each season in the Shahe river basin. The woodlands in upstream mountainous terrain inthe northwest is the main water consumption area of the basin, where the daily ET is higher than in other regions throughout the year; the plain area in downstream is mainly covered by the urban land and agricultural dry lands, where the average ET is smaller than other area.



(a) 2003-3-19 (b) 2002-7-9 (c) 2007-10-3 (d) 2002-12-16

Figure 3. The daily ET distribution maps of the typical day in Spring (a), Summer (b), Autumn (c),Winter (d) of Shahe river basin (mm)

5. Discussion and conclusion

In this paper, a two-layer model and the total amount of net radiation estimates are combined to estimate the daily evapotranspiration, and the results are in good agreement with the measurements, which implies that the algorithm is application for daily scale ET. However, the spatial coverage of the non-remote sensing parameters of the model inputs needs to be further extended, e.g. the area extension of stations of the air temperature and wind velocity. At the same time, we also plan to simulate the ET in different climatic regions, so as to further estimate the capability of the model for ET estimation under various climate conditions, and to better understand the interactions between ET and its influencing factors, the characteristics of water cycle in a changing climate, and the sustainability and utilisation of water resources.

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