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Potential evapotranspiration estimation in the upper Huaihe River basin, China

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Abstract

The atmospheric evaporative demand, one of principal components in water cycle, its accurate estimation is essential for hydrological simulation and forecasting. The purpose of this paper was to propose a plant-growth based dual-source potential evapotranspiration distributed model and investigate its feasibility with the upper Huaihe River basin (China) above the Xixian station as a case study site. Based on the topography, land-use, hydrological, and meteorological data in the Xixian basin, daily gridded potential evapotranspiration was calculated by the newly-build dual-source potential evapotranspiration model during 2000-2010. The relationship between potential evapotranspiration and pan evaporation at different time scales was investigated thereafter. The result revealed that the newly-built model could capture the temporal and spatial variation patterns of potential evapotranspiration moderately well in the upper Huaihe River basin. The analysis of this study also showed that the correlation between potential evapotranspiration and pan evaporation observations at daily, monthly and seasonal scales was affected together by underlying conditions that include, elevation, seasonality and precipitation.

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1. Introduction

The atmospheric evaporative demand (AED) is one of the principal components of water cycle (McVicar et al., 2012), affecting water resources (Brutsaert 1986; Song et al. 2000; Oki and Kanae 2006; Schlosser and Gao 2010; Liu and Feng 2012) and determines the severity of extreme events like droughts (Sheffield et al., 2012; Dai, 2013; Vicente-Serrano et al., 2014; Yu et al. 2014). Therefore, reliable estimates of the AED is essential for hydrological simulation and forecasting. Potential evapotranspiration (PET), as a reliable estimation of the atmospheric evaporative demand, is combination of two components: the aerodynamic, which is related to the quantity of water that air can store, and radiative, determined by the necessary energy to transform liquid water to vapor (McVicar et al., 2012). In classic hydrological models, PET is always simulated in an empirical or conceptual way (Zhao 1992) or mostly in a lumped way (Singh 1995). The development of computer science on Geographical Information Systems (GIS) and Remote Sensing Technologies provides an effective way to incorporate the spatial variations in plant and soil resistance in PET calculations. Several progress has been made in the improvement of SW model (Mo et al. 2004; Yuan 2006; Yang et al. 2012). However, the Leaf Area Index (LAI), one of the important necessary inputs in the SW model, is often estimated monthly, and monthly estimations are too coarse to reflect the actual dynamic of plants, particularly in the growing season. For this reason, robust estimates of PET, considering the effects of different vegetation types and plant growing process, are essential for accurate management and prediction of crop and forestry production, particularly in the upper Huaihe River basin, which is one of the most important agricultural areas in China (Yu, 2013). In this paper, distributed dual-source evapotranspiration model (Yuan, 2006) coupled with simplified plant growth model Neitsch et al. (2005) was adopted to calculate the basin evapotranspiration.

2. Model development

2.1. Simplified plant growth model

Temperature is one of the most important factors governing plant growth (Neitsch et al., 2005). To measure the total heat requirements of a plant, the accumulation of daily mean air temperatures above the plant’s base temperature is recorded over the period of the plant’s growth and expressed in terms of heat units (Neitsch et al., 2005). Each degree of the daily mean temperature above the base temperature corresponds to one heat unit, and crop growth only occurs those days when mean daily temperature exceeds the base temperature. The heat unit accumulation for a given day is calculated according to Neitsch et al. (2005):

$$ HU = \bar{T}_{av} - T_{base}, \quad \text{when } \bar{T}_{av} > T_{base} $$

where $HU$ is the number of heat units accumulated on a given day (heat units), $\bar{T}_{av}$ is the mean daily temperature ($^\circ$C), $T_{base}$ is the plant’s base or minimum temperature for growth ($^\circ$C). The total number units required for a plant to reach maturity is:

$$ PHU = \sum_{d=1}^{m} HU $$

where $PHU$ is the total heat units required for plant maturity, $HU$ is the number of heat units accumulated on day $d$, where $d = 1$ on the day of planting and $m$ is the number of days required for a plant to reach maturity.

2.2. Daily leaf area index

Leaf area index is defined as the area of green leaf per unit area of land (Watson 1947). The change in LAI related with the fraction of the PHU through the growing season for most crops is expressed by (Neitsch et al. 2005).

$$ \Delta LAI = (fr_{LAI_{mx},j} - fr_{LAI_{mx},j+1}) \cdot LAI_{mx} \cdot (1 - \exp(\delta(LAI_{i-1} - LAI_{mx}))) $$
where $\Delta LAI_i$ is the leaf area added on day $i$, $LAI_i$ and $LAI_{i-1}$ are the leaf area indices for day $i$ and $i-1$ respectively, $frLAIm_{x,i}$ and $frLAIm_{x,i-1}$ are the fraction of the plant’s maximum leaf area index for day $i$ and $i-1$.

2.3. Dual-source potential evapotranspiration model

Here is a brief introduction of the dual-source PEt model.

$$E_t = E_{ps} + E_{pc} + E_i$$

where $E_t$ is the total PEt, $E_{ps}$ is the soil potential evaporation, $E_{pc}$ is the vegetation potential evaporation, and $E_i$ is the evaporation of intercepted rainfall. Dynamic daily LAI calculated by the simplified EPIC model was adopted during the daily PEt computation.

3. Model application

3.1. Case study site

The Huaihe River, located in north-south climatic transition zone of China, with a length of 1,000 kilometers, is the third largest river in China and located about mid-way between the Yellow River and Yangtze River, with the 382-kilometer long upper reach running across the Tongbai and Funiu mountains. The upper Huaihe River basin above Xixian gauge station was selected as the case study site. The catchment area is 10190 km2, and it is located between North latitude 31.52°~32.72° and East longitude 113.15°~114.77° with an annual average pan evaporation value range from 800 to 1000mm and an annual average rainfall of 1145 mm (Cai et al., 2012), both of which were unevenly spatially and temporally distributed. There are three pan evaporation gauge stations in the Xixian basin, i.e. Nanwan and Shishankou stations, situated in the middle part of the basin and Xixian station being in the outlet of the basin.

3.2. Data

The topography of the Xixian basin is described by a Digital Elevation Model (DEM), which was downloaded from the Global Land One kilometer Base Elevation database with a spatial resolution of 1 km × 1 km (http://www.ngdc.noaa.gov/mgg/topo/globe.html). The river network and basin boundary was automatically extracted from the DEM using the ARCSWAT© software.

The land-use map of the Xixian basin was obtained from the China national land use map of 2000s, with the spatial resolution of 1km. This map has been created by the Chinese Academy of Science (Figure 1).

Vegetation parameters including minimum stomata resistance $r_{min}$, albedo at canopy source height $\alpha_c$, vegetation height $h_c$, maximum vegetation leaf width $\omega_{max}$, roughness length $Z_0$ and zero-plane displacement $d_0$ in the dual-source model were determined according to Zhou et al. (2006) (Table 1). Plant growth parameters for different vegetation, including $LAI_{mx}$, PHU, $T_{base}$, $fr_{PHU,i}$, $fr_{LAI,i}$ i = 1,2 were presented in Tables 2-4 according to the Plant Growth Database of the SWAT model and Li et al.(2013).
The meteorological data, including daily maximum and minimum temperature, solar net radiation, relative humidity, wind speed at five weather stations in or neighboring the study area during 2000-2010 were collected from the China Meteorological Administration (CMA). The homogeneity and reliability of the meteorological data have been checked and firmly controlled by CMA before their release.

Fig. 1. Land use pattern in 2000s of Xixian catchment

Table 1 Parameter values of different vegetation types

<table>
<thead>
<tr>
<th>Land use type</th>
<th>$r_{\text{min}}$</th>
<th>$\alpha_c$</th>
<th>$h_c$</th>
<th>$\omega_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest land</td>
<td>150</td>
<td>0.17</td>
<td>18.5</td>
<td>0.04</td>
</tr>
<tr>
<td>Cultivated land</td>
<td>109</td>
<td>0.20</td>
<td>0.75</td>
<td>0.01</td>
</tr>
<tr>
<td>Sparse wood</td>
<td>138</td>
<td>0.23</td>
<td>6.89</td>
<td>0.0187</td>
</tr>
<tr>
<td>Grassland</td>
<td>130</td>
<td>0.23</td>
<td>0.60</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 2 Monthly roughness length of different vegetation types

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest land</td>
<td>0.82</td>
<td>0.81</td>
<td>0.88</td>
<td>1.00</td>
<td>1.05</td>
<td>1.06</td>
<td>1.06</td>
<td>1.06</td>
<td>1.06</td>
<td>1.00</td>
<td>0.89</td>
<td>0.82</td>
</tr>
<tr>
<td>Cultivated land</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Sparse wood</td>
<td>0.35</td>
<td>0.35</td>
<td>0.37</td>
<td>0.41</td>
<td>0.42</td>
<td>0.42</td>
<td>0.42</td>
<td>0.43</td>
<td>0.43</td>
<td>0.41</td>
<td>0.37</td>
<td>0.35</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Table 3 Monthly zero-plane displacement of different vegetation types

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest land</td>
<td>13.71</td>
<td>13.73</td>
<td>14.24</td>
<td>14.79</td>
<td>15.12</td>
<td>15.28</td>
<td>15.29</td>
<td>15.25</td>
<td>15.15</td>
<td>14.8</td>
<td>14.21</td>
<td>13.71</td>
</tr>
<tr>
<td>Cultivated land</td>
<td>0.22</td>
<td>0.23</td>
<td>0.23</td>
<td>0.24</td>
<td>0.26</td>
<td>0.22</td>
<td>0.24</td>
<td>0.205</td>
<td>0.27</td>
<td>0.28</td>
<td>0.24</td>
<td>0.22</td>
</tr>
<tr>
<td>Sparse wood</td>
<td>5</td>
<td>5.01</td>
<td>5.17</td>
<td>5.35</td>
<td>5.46</td>
<td>5.54</td>
<td>5.56</td>
<td>5.54</td>
<td>5.48</td>
<td>5.36</td>
<td>5.16</td>
<td>5</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.22</td>
<td>0.23</td>
<td>0.23</td>
<td>0.24</td>
<td>0.26</td>
<td>0.3</td>
<td>0.33</td>
<td>0.31</td>
<td>0.27</td>
<td>0.24</td>
<td>0.23</td>
<td>0.23</td>
</tr>
</tbody>
</table>
4. Results and discussions

4.1. Daily potential evapotranspiration

Temporal variations of daily areal PEt and areal pan evaporation in Xixian watershed were presented in Figure 2. Generally, the variation patterns of daily PEt agreed well with the observed pan evaporation with the daily PEt being slightly lower. However, the areal PEt was significantly lower than areal pan evaporation in winter that could be attributed to lower LAI values in plant dormancy period as a result of low air temperature and rare precipitation in the basin.

To further investigate the rationality of the calculated daily PEt, linear regression model and correlation analysis between daily PEt and daily pan evaporation at Nanwan, Shishankou and Xixian stations were performed and F-test was used to verify the significance level of linear regression between daily PEt and daily pan evaporation. Table 5 showed the statistics of linear regression model and correlation analysis at three stations. Figure 3 showed the correlation between daily PEt and daily pan evaporation at Xixian station during 2000-2010. F-test demonstrated that the regression equations between daily PEt and daily pan evaporation at three stations were significant at the significance level of 0.01, and the daily PEt was positively correlated daily pan evaporation due to positive values of slope in the regression equations. Differences of intercept and slope in these three stations also indicated significant effect of vegetation type differences on the correlation between PEt and pan evaporation. The vegetation type at Nanwan, Shishankou and Xixian stations was forestland, grassland and cultivated land, respectively. Table 5 showed that the slope and intercept of regression equation at Nanwan station were highest among the three stations, with the slope and intercept of regression equation at Xixian station being the lowest, which implied that with similar meteorological conditions, daily PEt of forest land was higher than that of grassland, while daily PEt of grassland was higher than that of cultivated land in the upper Huaihe River basin. Additionally, there also exist differences in elevation among the three stations. Our analysis revealed that the underlying conditions and elevation of the station should be considered in the KC value for the Huaihe River basin PEt simulation instead of the traditional way of using the same value of KC being adopted over the whole basin. Generally, it has been found that the dual-source PEt model could perform well and improve the accuracy of basin PEt simulation since it takes factors of underlying conditions and elevation into account in the model.

4.2. Monthly potential evapotranspiration

Correlation analysis between monthly PEt and monthly pan evaporation at Nanwan, Shishankou and Xixian stations were also carried out, and T-test was used to testify the significance level of the correlation between monthly PEt and monthly pan evaporation (Table 6; Figure 4). Table 6 showed positive correlation between monthly PEt and monthly pan evaporation with the correlation coefficient being higher than 0.85 at the three stations, and T-test also revealed that their correlation was significant at a significance level of 0.01. The above analysis indicated that the calculated PEt values at daily and monthly time scales were consistently in good agreement with the pan evaporation values. In addition, the correlation between monthly PEt and monthly pan evaporation for different land cover showed highest ranking for forest land, followed by grassland land and cultivated land, respectively.

Table 4 Plant growth parameters

<table>
<thead>
<tr>
<th>Land use type</th>
<th>LAImx</th>
<th>Tbase (°C)</th>
<th>PHU (°C)</th>
<th>frLAI₁</th>
<th>frPHU₁</th>
<th>frLAI₂</th>
<th>frPHU₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest land</td>
<td>5.5</td>
<td>8</td>
<td>1634</td>
<td>0.15</td>
<td>0.05</td>
<td>0.53</td>
<td>0.95</td>
</tr>
<tr>
<td>Cultivated land</td>
<td>6.4</td>
<td>10</td>
<td>2500</td>
<td>0.05</td>
<td>0.05</td>
<td>0.41</td>
<td>0.95</td>
</tr>
<tr>
<td>Sparse wood</td>
<td>4.6</td>
<td>10</td>
<td>2514</td>
<td>0.05</td>
<td>0.05</td>
<td>0.42</td>
<td>0.96</td>
</tr>
<tr>
<td>Grassland</td>
<td>2.6</td>
<td>10</td>
<td>1815</td>
<td>0.04</td>
<td>0.04</td>
<td>0.35</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 5 Statistics of linear regression and correlation analysis at three stations between daily potential evapotranspiration and daily pan evaporation

<table>
<thead>
<tr>
<th>Stations</th>
<th>Samples</th>
<th>Interceptb₀</th>
<th>Slope</th>
<th>Correlated coefficient</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
</table>


<table>
<thead>
<tr>
<th>Stations</th>
<th>Samples</th>
<th>b₁</th>
<th>r</th>
<th>T value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanwan</td>
<td>3652</td>
<td>0.584</td>
<td>0.924</td>
<td>0.863</td>
<td>3987.52</td>
</tr>
<tr>
<td>Shishankou</td>
<td>3652</td>
<td>0.577</td>
<td>0.912</td>
<td>0.827</td>
<td>3845.35</td>
</tr>
<tr>
<td>Xixian</td>
<td>3652</td>
<td>0.560</td>
<td>0.903</td>
<td>0.811</td>
<td>4012.53</td>
</tr>
</tbody>
</table>

Table 6 Statistics of linear regression and correlation analysis at three stations between monthly potential evapotranspiration and monthly pan evaporation.

(a) 2000

(b) 2005
Fig. 2. Temporal variations of daily areal potential evapotranspiration and areal pan evaporation in Xixian catchment.

Fig. 3. Scatterplot and correlation relationship between daily potential evapotranspiration and daily pan evaporation at Xixian station.

Fig. 4. Scatterplot and correlation relationship between monthly potential evapotranspiration and monthly pan evaporation at Xixian station.
5. Conclusion

This study developed a modified dual-source PEt distributed model for estimating the PEt in the upper Huaihe River basin above the Xixian station. Applying this modified model for the Xixian watershed showed that the PEt is not only being affected by climate patterns, but also change in land cover (i.e., different vegetation types and their development). Correlation between PEt and pan evaporation observations at daily, monthly scales was influenced by underlying conditions that include elevation, seasonality and precipitation. The result revealed that the newly-built model estimates are in excellent agreement with available, but limited, observations in the upper Huaihe River basin. This could be because of its comprehensive consideration of meteorological variables, topography and underlying conditions. Based on the correlation between PEt and pan evaporation at daily, monthly scales for different land cover, forest land was ranked first followed by grassland land and cultivated land. The output of this study is expected to provide a new way of calculating basin PEt and references for hydrological simulation and crop water demand management in the upper Huaihe River basin, particularly for regions without observed hydrological data series.

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