Modelling seasonal evapotranspiration of arid lands in China
Yuanrun Zheng, Zhixiao Xie, Charles Roberts, Ping An, Xiangjun Li, Guangsheng Zhou, Hideyuki Shimizu and Sam Drake

ABSTRACT
The measurement of actual evapotranspiration, a key term in the water balance equation, has become a very important issue. Many good methods exist for estimating actual evapotranspiration; however, most of these require complicated inputs. Here, a simple but robust model for estimation of actual evapotranspiration in arid areas of western China is proposed. This model is a visual system with a user-friendly interface in the STELLA (a commercial software package for building numerical models) environment combined with two existing water balance equations and local soil and climate data to ensure its easy application in developing areas. Validation with field measurements revealed that the estimated values of actual evapotranspiration obtained using the model are in agreement with the observed values. Both the established Choudhury model and the proposed model produced similar estimates when the actual annual evapotranspiration is below 200 mm, but the model proposed simulates real-world conditions more precisely when the actual annual evapotranspiration is greater than 200 mm. Another advantage of the proposed model is that it uses simple and reliable climate data that are readily available from the network of weather stations in China. The simulation results could serve as a relatively good reference for water resource management in this area.

Key words | actual evapotranspiration, arid regions, Choudhury model, groundwater management, water budget

INTRODUCTION
It is expected that water will become one of the main limiting resources within the next few decades; accordingly, an in-depth knowledge of all the parameters involved in water balance is essential to determining water conservation measures (Droogers 2000). Soil water is an important factor involved in water balance that can influence vegetation patterns (Lauenroth et al. 1994), net primary production (Sala et al. 1988) and so on. Soil water itself is dependent on many factors, the most important of which are evaporation from the soil surface and transpiration from plants (Wythers et al. 1999). As a result, accurate calculation of evapotranspiration, the combination of evaporation and transpiration, is essential for correct analysis of the water balance for both naturally vegetated and agricultural lands (Möller et al. 2004).

Numerous methods have been developed to estimate evapotranspiration during the past few decades. These methods can be classified into two broad categories: direct and indirect methods. Direct methods assess the water balance of a soil column using a lysimeter, or by monitoring changes in the soil water content (Plauborg 1995; Möller et al. 2004). Measurement of evapotranspiration using direct methods is
very accurate, but the process is time-consuming and labour-intensive (Boast & Robertson 1982). Furthermore, direct measurement only represents a local condition for a short time period, and cannot be directly utilized to answer many important questions concerning large catchments over long time periods (Domingo et al. 1999). Therefore, indirect methods have been shown to be a feasible alternative (Shuttleworth 1991; Droogers et al. 2000).

Indirect methods include micrometeorological (Albert et al. 2004), deterministic (Penman 1948) and empirical approaches (Priestly & Taylor 1972). These methods have gained wide acceptance; however, they also have limitations. Micrometeorological methods are based on the assumption of spatially uniform evaporative fluxes over a study area and require precise measurement of parameters such as vapour pressure, air temperature, wind speed and surface roughness (Ben-Asher et al. 1983). Deterministic and empirical methods are generally only suitable for estimating potential (maximum) evaporation, rather than actual evaporation (Ben-Asher et al. 1983). Moreover, the climate data required by these models are not always available (Rivas & Caselles 2004; Villalobos et al. 2004). Recently, methods based on sap-flow, soil water budget, catchment water balance and isotope concentrations have been developed to determine forest evapotranspiration (Wilson et al. 2001; Wever et al. 2002; Yepez et al. 2003). However, it remains a significant challenge to accurately estimate actual evapotranspiration in arid areas, especially on large scales.

In arid lands, vegetation cover exists as significantly separated patches with open soil surface in between. Two characteristics are crucial in defining semiarid grasslands (Wythers et al. 1999). Specifically, the evapotranspiration must exceed the water supply at all temporal scales (Sala et al. 1992), the plant cover must be less than 50% of the land surface and bare soil evaporation is important (Burke et al. 1998). However, these characteristics make it more complicated to estimate evapotranspiration.

This study covers major arid areas in China, including the Xinjiang Uyghur Autonomous Region, western Inner Mongolia Autonomous Region, part of Qinghai Province and the northwest Gansu Province (Figure 1). The annual precipitation over this area ranges from 15.0 mm to 512.1 mm. The mean annual temperature varies from –4.6 °C to 14.3 °C, and the average monthly temperature in January and July ranges from –26.7 °C to –4.7 °C and 7.7 °C to 32.3 °C, respectively.

The unique geographic location and environmental conditions make this area an important ecological barrier for inland China and East Asia, as well as an important agricultural zone for high-value crops such as cotton and grapes (Zhu et al. 1986). However, limited water is a key factor involved in the serious environmental degradation that is currently occurring in this area. For example, the middle reach of the Tarim River has experienced serious desertification over the past few decades; the desertified area has increased from 59% of the total area (1553 km²) in 1960 to 63% in 1990, within which heavily desertified areas have increased significantly. It is therefore imperative to have a better understanding of the water balance process in this area. A study conducted by Zhang (1990) assessed the actual evapotranspiration at several locations in this area using a water balance method (Table 1). However, studies have been devoted to estimating actual evapotranspiration from natural landscapes over this large area.

The present study was therefore conducted to develop a model for this region. Important features of the model developed here are that it can be used with existing data routinely collected at weather stations and it does not require additional resources for sampling environmental parameters. It is expected that the results generated using the model will facilitate a better understanding of the water balance process and provide critical baseline information for regional water resources management. In addition, a visual modelling
A new model for estimating actual evapotranspiration

Due to the lack of detailed microclimatic data for arid areas of China, a more ecologically sound model that can be based on readily available meteorological data is urgently needed for estimation of actual evapotranspiration. Because most of the study area has very low precipitation, the availability of soil water is the major factor controlling actual evapotranspiration. This principle was used to develop a new model for estimation of the actual evapotranspiration. This model is based on the fundamental axioms of water balance and describes in general terms the functions of an ‘average’ ecosystem (plant community) throughout a year with a monthly time-step.

It is assumed that a plant community will grow as long as the soil moisture conditions are favourable. The soil moisture conditions are dependent on water availability, which is the result of a simple one-layer water balance, with rainfall as input and actual evapotranspiration and drainage as outputs.

In terms of water input, the soil moisture will continuously increase as the rainfall increases. However, this increase will stop once the soil is fully charged with water, i.e. when the soil moisture reaches the soil water-holding capacity with respect to the soil tension water ($S_{\text{max}}$). At that point, additional water input will become runoff or will drain to deep vadose zones or below and will no longer be utilized by the plant community. The $S_{\text{max}}$ is the maximum amount of water that can be held in the soil, and is determined by the soil depth, texture, quantity of rock and the soil water-holding capacity of each horizon in a soil profile.

Regarding water outflow, the available water will be consumed as far as the atmosphere will allow i.e. as far as evapotranspiration can continue. Soil surface evaporation is primarily reliant on the evaporative power of the atmosphere and insolation. The amount of water passing through a plant community is constrained by the leaf area and distribution. Plants can temporarily resist water loss by closing their leaf stomata, but this restricts physiologically necessary gas exchange so the effect is limited (Specht & Specht 1999).

A key assumption in the model developed here is that plant communities tend to maximally utilize the available soil moisture without exhausting the soil moisture to below the permanent wilting point. This assumption is realized during the initial model calibration phase; the slope ($k$) of

### Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Vegetation</th>
<th>$P$ (mm)</th>
<th>$R_{\text{n}}$ (mm)</th>
<th>$E_{\text{D}}$ (mm)</th>
<th>$\text{Evap}$ (mm)</th>
<th>Source</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tucson</td>
<td>32, –111</td>
<td>Desert</td>
<td>275.0</td>
<td>1180.0</td>
<td>2629.2</td>
<td>262.0</td>
<td>Choudhury (1999)</td>
<td>Micrometeorology</td>
</tr>
<tr>
<td>Cabauw</td>
<td>52, 5</td>
<td>Grass</td>
<td>926.0</td>
<td>520.0</td>
<td>750.0</td>
<td>523.0</td>
<td>Choudhury (1999)</td>
<td>Micrometeorology</td>
</tr>
<tr>
<td>Alatai</td>
<td>47.73, 88.08</td>
<td>Grass</td>
<td>180.8</td>
<td>461.5</td>
<td>1812.2</td>
<td>180.1</td>
<td>Zhang (1990)</td>
<td>Water balance</td>
</tr>
<tr>
<td>Wulumuqi</td>
<td>43.78, 87.62</td>
<td>Grass</td>
<td>277.6</td>
<td>481.1</td>
<td>1914.1</td>
<td>200.0</td>
<td>Zhang (1990)</td>
<td>Water balance</td>
</tr>
<tr>
<td>Kuche</td>
<td>41.72, 82.95</td>
<td>Desert</td>
<td>64.8</td>
<td>613.5</td>
<td>2842.5</td>
<td>63.8</td>
<td>Zhang (1990)</td>
<td>Water balance</td>
</tr>
<tr>
<td>Tulufan</td>
<td>42.93, 89.2</td>
<td>Desert</td>
<td>16.4</td>
<td>601.7</td>
<td>2837.8</td>
<td>16.1</td>
<td>Zhang (1990)</td>
<td>Water balance</td>
</tr>
<tr>
<td>Yining</td>
<td>43.95, 81.03</td>
<td>Grass</td>
<td>257.5</td>
<td>623.3</td>
<td>1613.6</td>
<td>256.5</td>
<td>Zhang (1990)</td>
<td>Water balance</td>
</tr>
<tr>
<td>Ruoqi</td>
<td>39.03, 88.02</td>
<td>Desert</td>
<td>17.4</td>
<td>653.2</td>
<td>2902.2</td>
<td>17.2</td>
<td>Zhang (1990)</td>
<td>Water balance</td>
</tr>
<tr>
<td>Hashi</td>
<td>39.47, 75.98</td>
<td>Desert</td>
<td>61.5</td>
<td>673.6</td>
<td>2487.1</td>
<td>61.0</td>
<td>Zhang (1990)</td>
<td>Water balance</td>
</tr>
<tr>
<td>Hami</td>
<td>42.82, 93.52</td>
<td>Desert</td>
<td>34.6</td>
<td>666.7</td>
<td>3064.3</td>
<td>34.2</td>
<td>Zhang (1990)</td>
<td>Water balance</td>
</tr>
<tr>
<td>Hetian</td>
<td>37.13, 79.93</td>
<td>Desert</td>
<td>34.4</td>
<td>699.3</td>
<td>2602.0</td>
<td>33.1</td>
<td>Zhang (1990)</td>
<td>Water balance</td>
</tr>
</tbody>
</table>
the $\text{Evap}/E_0$ versus soil moisture function is optimized to ensure that as much water as possible is used by the plant community without exhausting the soil moisture in any month. A simple iterative optimization algorithm (for detailed information of this technology, refer to Specht & Specht 1999) is used to achieve convergence at an appropriate slope value.

In the developed model, it is assumed that the ratio of actual to potential monthly evapotranspiration ($\text{Evap}/E_0$) is linearly related to the soil moisture level, as described by Specht (1981) and Specht & Specht (1999). The slope of $\text{Evap}/E_0$ versus soil moisture function is termed the evaporation coefficient ($k$), and $k$ actually characterizes the combined horizontal distribution of foliage and its water use in both the overstory and understory strata within a plant community (Specht & Specht 1999). When the plant community and zonal climate reach the equilibrium state, $k$ will remain stable in a specific climate zone.

When soil water storage is limited, the rate of water loss from a plant community through evapotranspiration is closely related to the leaf cover and, in particular, the horizontal surface exposed to the atmosphere. This can be expressed by:

$$\text{Evap}/E_0 = k \times (P - D + S_{\text{ext}}) \quad (1)$$

$$\text{ASW} = P - D - \text{Evap} + S_{\text{ext}} \quad (2)$$

where $\text{Evap}$ is the actual monthly evapotranspiration (mm), $E_0$ is the monthly pan evaporation (mm), $k$ is the evaporation coefficient and $\text{ASW}$ is the available soil water (mm) over a month. $\text{ASW}$ is calculated using Equation (2) where $P$ is the monthly rainfall (mm), $D$ is the monthly drainage loss (mm) and $S_{\text{ext}}$ is the water stored within the root zone of the soil at the beginning of a month, extractable by the plant community (mm). When water is non-limiting, $\text{Evap}$ tends to $E_0$ while $k$ tends to $\sim 1 \times 10^{-2}$.

Equation (1) has been tested in Australia by Specht & Specht (1999) and Equations (1) and (2) are utilized in this study for the arid areas of China. The model is implemented in STELLA (High Performance Systems 2000). The main module is presented in Figure 2 to illustrate its implementation. This module is used to simulate the relationship between water balance and the evaporation coefficient $k$.

Because actual evapotranspiration cannot be directly calculated using Equations (1) and (2), an iterative mathematic algorithm was used to estimate its value at the equilibrium state. The iterative method was implemented in the STELLA environment (Figure 2). The required model inputs include monthly precipitation (mm), monthly pan evaporation (mm) and $S_{\text{max}}$. For other variables, only the initial values need to be set which are then updated during the iteration.

In the module (Figure 2), the two variables minASW tolerance and convergence rate were both initialized to 0.01. During the optimization process, the available soil water
(ASW) and k were changed gradually in every iteration. After 100 iterations, k reached the stable point at which it became constant. At that point, the resultant ASW should be the minimum value for the maximum k, under the constraint that the ASW was not at the level at which vegetation collapse could occur due to drought. In this way, the model could calculate all parameter values involved in Equations (1) and (2) including Evap.

The iteration process was also described by Specht (1981). The twelve mean monthly values (subscripted 1 to 12) of Evap may be estimated as follows. The computations involve the following four steps repeated in sequence for the 12 months of the year: (1) $Evap_1/E_{01} = k(P_1 - D_1 + S_{ext1})$; (2) if $Evap_1/E_{01} > 1.0$, then assume $Evap_1 = E_{01}$; (3) $S_{ext2} = P_1 - D_1 + S_{ext1} - Evap_1$; and (4) if $S_{ext2} > S_{max}$ then assume $D_1 = S_{max} - S_{ext2}$. Because no mean value of $S_{ext1}$ is known, the computations can be initiated by using an arbitrary value of $S_{ext1}$. The values of $Evap_1$ and $D_1$ will be corrected by repeating the series of twelve monthly computations, now using the December calculation of total soil water ($S_{ext\ 13}$) to initiate the new series of calculations ($S_{ext\ 1\ 1}$ now equals $S_{ext\ 13}$). This process was repeated 100 times to make $k$ stable.

To illustrate the basic terms and typical implementation of STELLA, see Figure 2. In this figure, an accumulation (e.g. water) is represented with a rectangular stock or state variable symbol. The value of an accumulation is calculated as the sum of its initial value and the balance of inward and outward flow over a specified period. A flow is represented using a pipe with a spigot (valve), while the flow direction is shown with an arrow. Sometimes, a flow can be bidirectional. Other variables and constants are represented with circular ‘convertor’ symbols. A simple directional line (with arrow) is used to represent relationships between other variables (symbols).

### Available climate and soils data

Climate data covering the period from 1965 to 1999 (34-year average) were collected from the Chinese Central Meteorological Office. The data include latitude, longitude and altitude, monthly sunshine fraction, monthly air temperature, monthly relative humidity, monthly wind speed, monthly precipitation and monthly pan evaporation. The $S_{max}$ for the soil type at each meteorological station in the study area was derived from Xiong & Li (1987).

### Model validation and evaluation

The model was validated against field-observed actual evapotranspiration at 11 sites (Table 1), including nine located in Xinjiang Uyghur Autonomous Region, which is part of this study area. At these sites, actual evapotranspiration was measured using water balance methods by Zhang (1990). Data cited from Zhang (1990) were the mean observed regional data over 51 years (1950–1980) based on the water balance principle. This can be expressed:

$$Evap = P - R - \Delta W$$

(3)

where $Evap$ is the annual actual evapotranspiration (mm), $P$ is the annual precipitation (mm), $R$ is the annual run-on and runoff (mm) and $\Delta W$ is the annual change in soil water. $P$, $R$ and $\Delta W$ are measured directly by equipment, which enables $Evap$ to be obtained by Equation (3).

At two additional sites, Tucson and Cabauw, the actual evapotranspiration cited by Choudhury (1999) was determined using the micrometeorology method. In addition, a measure used by Qiu et al. (1998) was adopted to examine the correlation between the modelled and observed annual actual evapotranspiration. In this method, the observed and estimated data were used to derive a linear regression equation ($y = a + bx$) which was then compared with the 1:1 observed data line ($y = x$). Testing showed that the intercept and slope of the regression equation were not significantly different from 0 and 1, respectively, at the 0.05 probability level. It is clear from Figure 3 that the data points lie on or close to the 1:1 line, showing very good agreement between the simulated and observed actual evapotranspiration.

In addition to validation against field data, it is also beneficial to assess the performance of a model relative to other models. Many models are available for estimating evapotranspiration and these are based on water budget methods, temperature methods, humidity methods, radiation methods, mass transfer (aerodynamic) methods or combined (energy budget and aerodynamic) methods (Xu & Singh 1998). Choudhury (1999) developed a model that has been used to estimate actual evapotranspiration worldwide; we therefore used this model to evaluate the proposed model.
in this paper. The Choudhury model can be described as:

\[
\text{Evap} = \frac{P}{1 + \left(\frac{P}{R_n}\right)^{a}}
\]

where \( \text{Evap} \) is the actual evapotranspiration (mm), \( P \) is the annual precipitation (mm), \( R_n \) is the water equivalent of the annual net radiation (mm) and \( a \) is an adjustable parameter. Choudhury (1999) reported that an \( a \) value in the range of 2.5–2.7 (2.6 in his study) resulted in a modelled \( \text{Evap} \) very close to the field-observed \( \text{Evap} \). The same \( a \) value (2.6) is also used in this study.

Although \( R_n \) can be monitored, it is not measured at most weather stations in the study area. Another model must be used to calculate \( R_n \) (Zhang 1993):

\[
R_n = \frac{\text{RDI} \times P}{1 + \left(\frac{P}{R_n}\right)}
\]

(5)

where \( P \) is the annual precipitation (mm) and \( \text{RDI} \) is the radiance dryness index, calculated as (Zhang 1993):

\[
\text{RDI} = 0.629 + 0.237\text{PER} - 0.00313\text{PER}^2
\]

(6)

where \( \text{PER} \) is the evapotranspiration rate, defined (Zhang 1993) as:

\[
\text{PER} = \frac{\text{PET}}{P}
\]

(7)

where \( \text{PET} \) (mm) is calculated by Penman’s equation using the method proposed by Rosenberg et al. (1983).
productive grassland. Based on these arguments, the proposed model in this paper is likely more appropriate than Equation (4) for estimating actual evapotranspiration in the study area. More importantly, the climate data required by the proposed model are readily available from most weather stations, making the model more applicable.

RESULTS

The results obtained using the proposed model indicated that the estimated annual actual evapotranspiration was below 50 mm in 34% of the study sites, below 100 mm in 55% of the sites and less than 200 mm in 85% of the sites. This is in agreement with the fact that the study area is overall a very arid area (Figure 4, 5).

The seasonal changes in actual evapotranspiration were dramatic (Figure 6). In January and February, the monthly Evap was below 10 mm in most desert sites, and slightly over 20 mm in several grassland or mountain forest sites. From March to August, Evap increased significantly, exceeding 80 mm each month for mountain forest sites and 20 mm each month for steppe sites. However, Evap in desert sites remained lower, at around 5–10 mm. Evap peaked from May to August. From September, Evap decreased dramatically for sites of all types, with most showing less than 10 mm each month. Monthly Evap was lowest between November and December, during which time it was less than 5 mm. It is clear that the periods of very low Evap persisted for six months from September to the following March. This was due to the high potential evaporation and low precipitation in desert areas, as well as the low temperature in mountain forest and grassland areas. Relatively higher values of Evap only lasted for a period of 4-6 months in summer. Taken together, these findings indicate that efficient land and water resource management policies are essential for natural vegetation and crop development in this region.

DISCUSSION AND CONCLUSIONS

A simple but robust model was established to estimate actual evapotranspiration based on water balance principles. The developed model was found to be appropriate for use in estimating actual evapotranspiration in arid areas of China. The model was validated against field observations. In addition, the simulation results of this model were compared to those of a well-established model developed by Choudhury (1999). The two models gave quite similar results, and both should be reliable in arid areas. However, slight differences in the estimation results were found especially for areas with higher relative humidity. In these areas the model proposed in this paper resulted in higher actual evapotranspiration estimates, in agreement with the fact that these locations are highly productive grasslands and should produce higher actual evapotranspiration than more xeric sites. The use of empirical equations (including Penman’s) to derive $R_n$ due to the lack of observed $R_n$ data was possibly a source of bias in

Figure 5 | Spatial distribution of estimated Evap using the proposed model. Data from 65 sites in arid areas of China shown in Figure 1.

Figure 6 | Estimated monthly average Evap for five groups of sites shown in Figure 1 by the proposed method.
the Choudhury model results. Conversely, the proposed model requires simpler and more easily accessible input data, and can be easily applied to extensive arid areas in western China. This is one of the key reasons a novel model such as that proposed here is necessary. As argued by Beven (1979), for a model to have widespread application it must make maximum use of the data available for a given site. While there are some lysimeters in China, data are rarely available from them and they are often used to monitor croplands for crop production (Liu et al. 2002). Conversely, there are over 2000 weather stations distributed across China with long-term (over 50 years of record) and detailed weather data. Simplicity is important for a model to be easily understood and widely accepted by policy makers in developing regions such as the study area. The model proposed in this study could serve as a good starting point in this regard, providing a simple method to derive actual evapotranspiration and to evaluate the water balance.

Runoff was not included in Equation (2) for water balance simulation since, at most of the research sites, the annual precipitation is very low (often below 15 mm in the central Taklimakan desert). In addition, the sky quickly becomes clear after rains, and the high solar radiation and temperature lead to rapid evaporation of the precipitation. Other studies (Sala et al. 1992) have also indicated that deep drainage, runoff and run-on are infrequent and can be safely ignored in semiarid short grass steppes. The validity of the proposed model should not be affected by this simplified assumption.

It should be noted that $R$ and $\Delta W$ in Equation (3) might be quite low in most sites in arid areas, and that $Evap$ is expected to be similar to $P$ on an annual basis (Table 1). The estimated $Evap$ should therefore approximate the annual precipitation in such areas. However, in the present study, it was found that a higher annual precipitation was associated with a greater difference between precipitation and $Evap$. For example, $Evap$ is very different from precipitation in Wulumuqi (Table 1) where $Evap$ is larger than 200 mm. Of the 65 studied sites, the calculated annual $Evap$ was larger than 200 mm in ten sites and between 100 mm and 200 mm in 20 sites. In most of these 30 sites in which $Evap$ was greater than 100 mm, $Evap$ was different from precipitation. It should therefore be better to use the proposed model to estimate $Evap$ for these sites than the annual precipitation.

There are other possible ways to validate models such as the methods described here. For example, NCAR/NCEP (National Center for Atmospheric Research, USA / National Centers for Environmental Prediction, USA) re-analysis data provided by the NOAA-CIRES (National Oceanic and Atmospheric Administration - Cooperative Institute for Research in Environmental Science, USA) Climate Diagnostics Center, Boulder, Colorado, US (http://www.cdc.noaa.gov/) could provide another alternative to test the performance of model prediction. However, there is little suitable $Evap$ data available for validation of this model. Although there has been some progress in estimating evapotranspiration (Soares et al. 1988; Choudhury et al. 1994), there is still no remotely sensed evapotranspiration image product that can be used to validate the proposed model results. Such a product based on the MODIS (Moderate Resolution Imaging Spectroradiometer) data is in development, but it is not clear when that will become available (especially for China). A future comparative study of the model results with the MODIS evapotranspiration product (MOD16) will certainly be warranted.

Finally, the implications of evapotranspiration and water balance assessment are of particular significance for this study area. Because of low precipitation and high evaporation, desert landscapes occupy a large proportion of western China. Oases are seen only along rivers and in basin areas where water is supplied by underground sources. Due to increasing human pressure in this area, environmental degradation has been serious and vegetation rehabilitation projects have been undertaken. Future projects should be carefully planned based on water balance principles, particularly large-scale efforts such as the Great Exploitation in Western China; the latter represents a current policy shift aimed at alleviating the social, ecological and developmental gaps between western and eastern parts of China. Resource utilization-oriented projects may incorporate conservation measures, but potential mismanagement on a large scale is a danger.

Lessons could be learned from past ecological engineering projects in China such as the Three-North Shelterbelt Development Program, initiated in 1978 by the central government to form a Green Great Wall 700 km wide across northern China (Mitchell et al. 1998). Because this forestry program is still in its early stages, it is hard to assess the future sustainability of the shelterbelt. However, problems may arise from falling and deteriorating water tables (Mitchell et al. 1998).
The results obtained using the model developed here show that low actual evapotranspiration occurs over large parts of western China, indicating that natural desert, Gobi or very sparse vegetation is ecologically more suitable than afforestation for this land. For effective agricultural practices in this area, it is necessary to utilize water-saving drip irrigation technologies to avoid water loss by bare soil evaporation, which is useless for crop production. Pipelines should replace open ditch-irrigated systems where possible. In fact, underground irrigation canals (conceptually similar to pipelines) have played a major role in the history of central Asia for thousands of years (Longworth & Williamson 1993). It is expected that other technologies can be developed to achieve more efficient water use. From this perspective, the results obtained using the proposed model to estimate the actual evapotranspiration could serve as a good reference for developing strategies for water resource utilization and vegetation rehabilitation.

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