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ORIGINAL ARTICLE

Evaluating the best evaporation estimate model for free water surface evaporation in hyper-arid regions: a case study in the Ejina basin, northwest China

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Abstract Free water surface evaporation is an important process in the hydrologic and energy cycle. Accurate calculation of free water evaporation helps in evaluating the reliability of data on the distribution and quantity of water resources. However, the applicability of evaporation models to the calculation of free water surface evaporation in hyper-arid regions is still uncertain. Moreover, the accuracy of previously used evaporation models should be evaluated for hyper-arid regions. In this study, the Ejina basin in the hyper-arid region of northwest China was selected to address this issue. Measured meteorological data (1993–2008) were used to calculate free water surface evaporation using the Dalton model, Penman formula, and energy balance equations. Results from two different Dalton models were higher and lower than the results from E_{601} pan evaporation, respectively. Results from the Penman formula were lower than results from E_{601} pan, whereas results from the energy balance equations are higher than the results from E_{601} pan. The results indicate that previous evaporation models are not suited for calculating free water surface evaporation in hyper-arid regions if not modified. Using meteorological data and radiation data (1993–2000), the Dalton model, energy balance equations, and Penman formula were modified to calculate free water surface evaporation for 2001–2008. The average annual evaporation from the three modified models was slightly lower than the evaporation from E_{601} pan during 2001–2008. However, the errors in the values were only 11–14 mm, which were much lower than in previous models. The modified Dalton model and Penman formula yielded a higher accuracy of the calculation, whereas the modified energy balance equations had the lowest accuracy.

Keywords Evaporation · Hydrologic cycle · Hyper-arid region · Northwest China

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Introduction

Free water surface evaporation is a process that is important to the hydrologic and energy cycle (Fu et al. 2004; Guzha et al. 2015), which is one of the most important factors for the formation of climate and environmental change (Monteith 1965; Brutsaert and Parlange 1998), and also plays a key role in hemispheric energy and the hydrologic cycle at various temporal and spatial scales through the release of latent heat (Zhang and Liu 2013; Ma et al. 2015). Moreover, it affects not only the distribution and quantity of water resources (Morton 1983; Li et al. 2012), but is also crucial for sustainable water resource management in hyper-arid regions (Li et al. 2013b). Therefore, accurate calculation of the free water evaporation is important for the evaluation of the reliability of data of the distribution and quantity of water resources.

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Many evaporation models have been used for calculating evaporation such as the Penman formula (Yang et al. 2010; Shen et al. 2013; Sharifi and Dinpashoh 2014; Zhang et al. 2014), Dalton model (Armstrong et al. 2008) and energy balance equations (Li et al. 2013b). Previous studies focused on changes in evaporation at different spatial and temporal scales in arid regions, using evaporation models (Li et al. 2013a, b; Zhang et al. 2014; Zhao and Zhao 2014a, b). However, parameters in evaporation models were not applicable in every region. In hyper-arid regions, the climate conditions are different from those in arid, semi-arid, and humid regions such as surface reflectance, wind speed, pressure of water vapor and cloud cover (Sellers 1965; Budyko and Miller 1974). Due to the differences between regions, the parameters must be corrected, but different parameter values can cause a large variability of the calculated results (Li et al. 2013b). It is still uncertain whether evaporation models can be used for calculating free water surface evaporation in hyper-arid regions. Moreover, the accuracy of the calculated results using previous evaporation models needs to be evaluated for hyper-arid regions.

For this study, the hyper-arid region in the Ejina basin was selected as the study area, and measured meteorological data were used to calculate free water surface evaporation using different evaporation models including the Penman–Monteith formula, Dalton model and energy balance equations. This paper aims to evaluate the accuracy of the calculated results and to present evaporation models suitable for hyper-arid regions.

Study area

Ejina Basin, located in the lower reaches of the Heihe River, is one of the largest inland basins in arid NW China, and covers an area of approximately 28,000 km^2 with an elevation of 900–1300 m (Fig. 1). Geologically, it belongs to a part of the Alashan Plateau and is located in western Inner Mongolia (40°30′N–43°30′N; 99°45′E–101°45′E). The southwestern and northern parts of the basin are mainly formed by an alluvial plain and aggraded flood area, while the central basin consists of an alluvial plain and a lake plain, and the northeastern part, which borders the Badain Jaran Desert, is formed by an ancient alluvial plain.

The land type in the basin is similar to that of the Gobi desert except for adjacent rivers and an oasis. The oasis is distributed along the Heihe river on the alluvial fan, and the predominant natural vegetation includes *Populus euphratica* Olivier, *Tamarix ramosissima* Ledeb. and *Sophora alopecuroides* L. (Zhang et al. 2011). Sparse xerophil vegetation, such as *Nitraria tangutorum* Bobrov and *Haloxylon ammodendron* (C. A. Mey.) Bunge ex Fenzl, also occurs in this region (Zhang et al. 2011).

The basin is outside the direct influence of the Asian summer monsoon, which is controlled by the Indian monsoon and westerly winds, and the present-day climate is extremely dry and continental. According to meteorological data, the average annual precipitation is only ~40 mm/year (Ma et al. 2011), while the average annual evaporation rate from water surfaces is ~2345 mm/year (Li et al. 2013b). Therefore, the ratio between annual precipitation and annual evaporation is less than 0.03, which is defined as the hyper-arid region according to the Food and Agriculture Organization. The annual mean temperature is 8 °C, with a January mean of –12.5 °C and a July mean of 26.2 °C (Zhang et al. 2006).

Data

The data used in this paper mainly consist of meteorological and radiation data. Spatial and temporal resolution of this data is provided in Table 1. In the meteorological data set, evaporation data were obtained from E_{601} pan evaporation with a diameter of 61.8 cm.

Methods

Free water surface evaporation calculation

Free water evaporation can be acquired using the Dalton model, energy balance equations and Penman–Monteith formula, respectively.

The Dalton model is one of the most widely used models for calculating the free water surface evaporation, and can be expressed as:

$$E = \Delta e \times F(W) \quad (1)$$

where E represents evaporation, Δe is the vapor pressure deficit (hPa), W is the wind speed with the height of 1.5 m (m/s) and F(W) is the wind function. Many more evolved models are based on the Dalton model. Here, models suitable for the arid regions of China were selected, which were suggested by Bai (1988) (Eq. 2) and Li (2000) (Eq. 3), respectively:

$$E = 0.492\Delta e \times \sqrt{1 + 0.174W^2} \times (1 - \gamma)^{0.25} \quad (2)$$

$$E = \Delta e \times (0.1 + \sqrt{0.24(1 - \gamma^2)}) \times W^{\frac{0.35W}{W+2}} \quad (3)$$

where E represents evaporation, Δe is the vapor pressure deficit (hPa), W is the wind speed with the height of 1.5 m (m/s) and γ is the relative humidity (%).

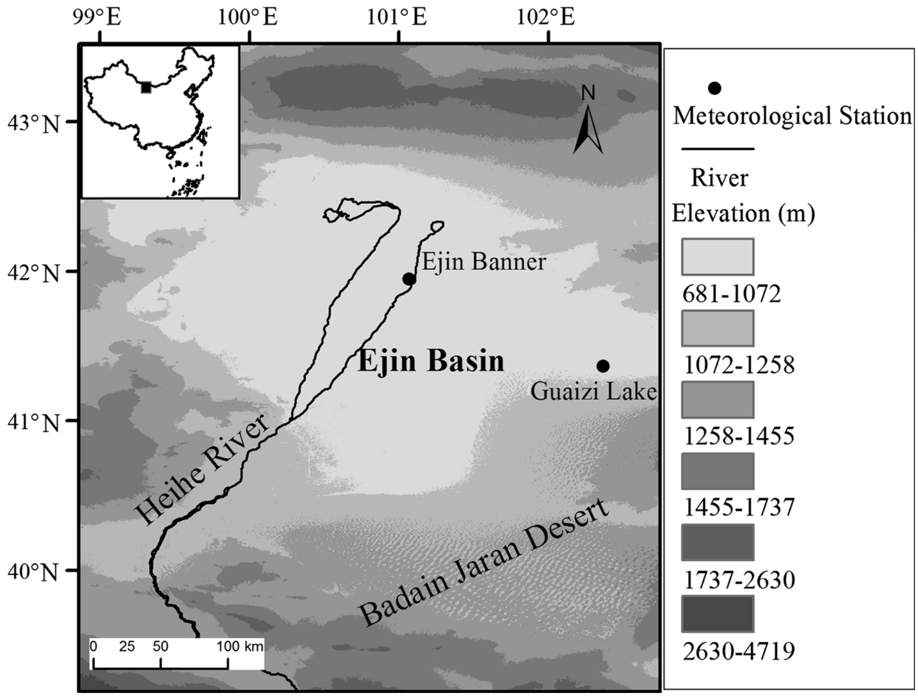

Fig. 1 Map of the research area showing the elevations (*m*) and the distribution of the meteorological stations

Table 1 Data used in this study

Data type	Data content	Sequence length/year	Temporal resolution	Situation
Meteorological data	Temperature, water vapor pressure, cloud fraction, evaporation and precipitation	1993–2008	Month	Ejin meteorological station and guaizi lake meteorological station
Radiation data	Monthly total amount of radiation, net radiation, scatter radiation and reflective radiation	1993–2008	Month	Ejin meteorological station

Energy balance equations are used to calculate the energy that is consumed by evaporation. Thus, the evaporation can be calculated as the following (Kutzbach 1980):

$$E = \frac{R'}{(1+B)L} \tag{4}$$

where R' is the net radiation (W/m^2), B is the Bowen ratio, and L is the latent evaporation, which varies with temperature. However, L is considered to equal 0.0769 W/m^2 in the temperature range of 0–30 °C (Dong et al. 2009). Net radiation can be calculated using the following formula:

$$R' = G_0(1-\alpha)(1-C) - A\varepsilon\delta T^4 \tag{5}$$

where G_0 is the clear-sky solar total radiation (W/m^2), α is the surface reflectivity, C is the cloud fraction, A is the Angstrom coefficient, ε is the surface emissivity, δ is the Stefan–Boltzman constant (5.67×10^{-8} W m^{-2} K^{-4}), and T is the air temperature (K). The formula for calculating the Angstrom coefficient is

$$A = (a_1 - b_1\sqrt{e})(1 - c'C^2) \tag{6}$$

where c' is the Berliand latitude coefficient, e is the water vapor pressure (hPa), and C is the cloud-sky cover ratio. a_1 and b_1 are coefficients determined from a global database (Berliand 1952). Therefore, evaporation can be calculated by Eqs. (4), (5) and (6). Here, the models suitable for the arid regions of China were selected and defined a_1, b_1 and c' as 0.535, 0.07 and 0.68, respectively, as has been suggested by Li et al. (2013b).

The Penman formula can be used also to calculate free water surface evaporation using the air dynamics equation and the energy balance equations:

$$E = \frac{\Delta R + r \times 0.35(1 + 0.526W_2) \times (e_0 - e_d)}{\Delta + r} \tag{7}$$

where Δ is the slope of the saturation vapor pressure curve at a certain air temperature (hPa/°C), R is the net radiation, r is a psychrometric constant (hPa/°C), W_2 is the wind speed with the height of 2 m (m/s), and e_0 and e_d are the water surface equilibrium vapor pressure (hPa) and the actual land vapor pressure (hPa). Δ can be calculated using the following formula:

$$\Delta = \frac{dE}{dT} = \frac{Le_0}{R_W T^2} \quad (8)$$

where e_0 is the water surface equilibrium vapor pressure (hPa), L is the latent heat of condensation (W/m^2), $R_w = 461$ J/kg K and T is air temperature (K). Therefore, evaporation can be calculated using Eqs. (7) and (8).

Modification of the parameters in the evaporation models

To present suitable evaporation models for hyper-arid regions, the parameters in the models were modified. Here, annual free water surface evaporation data from E_{601} pan evaporation measurements during the years of 1993–2000 were selected for the modeling. The results of the modeling were compared to annual evaporation data from E_{601} pan evaporation measurements during the years of 2001–2008. The optimization scheme of evaporation models is described in the following.

The Dalton model (Eq. 1) reveals that evaporation is affected by Δe and F(*W*). Δ*e* can be calculated from the temperature and relative humidity data, while F(*W*) contains the meteorological factor for the wind speed (Bai 1988; Singh and Xu 1997):

$$F(W) = \sqrt{A + BW^2} \quad (9)$$

where *A* and *B* are coefficients. Therefore, F(*W*) is a key factor for calculating the free water surface evaporation, using the Dalton model. In this study, the modification of the Dalton model focuses on the parameter optimization of the wind function. Here, the least-square regression method was used to determine the parameters.

According to Eqs. (4), (5) and (6), the accuracy of the energy balance equations depends on the net radiation that is determined by the Angstrom coefficient (Li et al. 2013b). Thus, the accurate calculation of the Angstrom coefficient using meteorological factors is crucial to parameter optimization. In this study, the principle of the energy balance equation modification is shown on the basis of the Angstrom coefficient using common meteorological factors in the equation such as water vapor pressure (*e*) and cloud-sky cover ratio (*C*). Then, the coefficients of a_1 and b_1 in Eq (6) can be calculated using the least-square regression method.

The merit of the Penman formula for calculating free water evaporation lies in the combination of two classical approaches: the energy budget and the aerodynamic. For Eq (7), the correction of the energy term *R* has been described above in the modification part of the energy balance equation, while Δ can be calculated using Eq. (8), and *r* is the psychrometric constant. In addition, the aerodynamic factor, which is usually calculated using wind speed and the water vapor deficit, is modified in this study using linear regression.

Results

Calculating free water surface evaporation

Free water evaporation was calculated using the Dalton model, energy balance equations and Penman formula. Figure 2 shows that results for the evaporation obtained from Eq. 2 (Bai 1988) are slightly higher than the results from E_{601} pan evaporation, while results obtained from the other Dalton model that was suggested by Li (2000) are significantly lower than the results from E_{601} pan evaporation. Moreover, results from the energy balance equations that were suggested by Li et al. (2013b) are higher than other model results, and the results obtained from the Penman formula are significantly lower than the observations. Therefore, the Dalton model, energy balance equations and Penman formula are not suited for calculating free water surface evaporation in hyper-arid regions without modification of the models.

Modification of the evaporation models

Using meteorological data and radiation data (1993–2000), the Dalton model, energy balance equations, and Penman formula were modified. The results are presented in Table 2. For each model, the annual free water surface

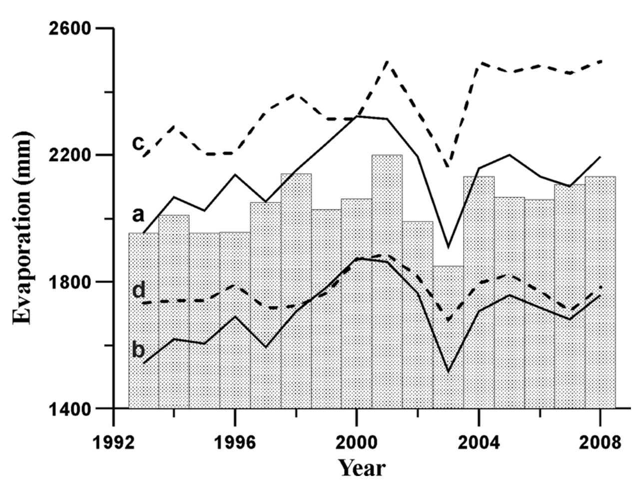

Fig. 2 The variability of the results for the free water evaporation acquired using different equations in the period 1993–2008. The histogram shows the evaporation from E_{601} pan evaporation, **a** and **b** are the calculation results from Eqs. 2 and 3, respectively (Dalton models); **c** is the result from the energy balance equations (Eqs. 4–6) and **d** is the result from the Penman formula (Eqs. 7–8)

Table 2 Modified free water surface evaporation models in hyper-arid regions

Evaporation models	Modified models	Equations
Dalton model	$E = \Delta e \times \sqrt{0.021W^2 + 0.2664}$	(10)
Energy balance equations	$E = \frac{G_0(1-\alpha)(1-C)-(0.42-0.0086e)(1-0.68C^2)\times\varepsilon\delta T^4}{(1+B)L}$	(11)
Penman formula	$E = \frac{\Delta\times[(1-\alpha)Q-(0.42-0.0086e)(1-c'C^2)\varepsilon\delta T^4]+[\Delta e(0.818+0.10W)]\times r}{\Delta+r}$	(12)

evaporation for the years 2001–2008 was calculated using Eqs. (10)–(12). Afterwards, the modeling results were compared to the annual evaporation data obtained from E_{601} pan evaporation (Fig. 3). It appears that the modeling results are similar to the E_{601} pan evaporation during 2001–2008 (Fig. 3).

Moreover, the errors between the results from E_{601} pan and the modified models were calculated, which are shown in Table 3. Table 3 reveals that the average annual evaporation calculated with the three modified models is slightly lower than the evaporation obtained from E_{601} pan during 2001–2008. However, the error values are only in the range of 11–14 mm, which is much lower than those in previous models. Variance analysis results suggest that calculating free water surface evaporation in hyper-arid regions using previous models (Dalton model, energy balance equations and Penman formula) can lead to great deviation (Table 3). In addition, the deviation of test results was reduced remarkably using modified models, indicating that the model computational accuracy improved significantly.

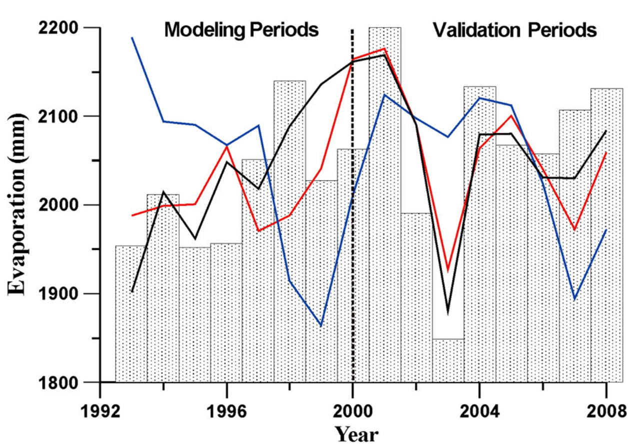

Fig. 3 Results of free water surface evaporation from the modeling and E_{601} pan evaporation. The histogram shows the evaporation from E_{601} pan evaporation. The *black line* represents the results from the modified Dalton model (Eq. 10), the *blue line* represents the results of the modified energy balance equations (Eq. 11) and the *red line* represents the results from the modified Penman formula (Eq. 12)

Discussion

Uncertainty of the evaporation data measured by E_{601} Pan

The evaporation data were measured in this study using a E_{601} Pan. However, it is not completely the same as free water surface evaporation (Stanhill 2002), because the evaporation amount from evaporators is affected by the installation modes, structures, and composition of the evaporators (Fu et al. 2004). E_{601} Pan has four arc water troughs of 20 cm in width, which comprise a circle to reduce the effects of turbulence generated by the pan itself and in particular by the rim of the pan (Jacobs et al. 1998; Fu et al. 2004). Therefore, the evaporation data measured by E_{601} Pan may be less influenced by wind speed due to the shelter of the evaporation barrel, leading to a slightly lower amount of evaporation than that of free water surface evaporation (Fu et al. 2004, 2009). Fu et al. (2004) suggested that the ratio between free water surface evaporation and evaporation from E_{601} pan is 1.07 in eastern China. Unfortunately, the ratio between free water surface evaporation and evaporation from E_{601} pan remains unclear in this area. Free water surface evaporation was presumed to have been slightly higher than evaporation from E_{601} in this area. Table 3 indicates that calculation errors in our modified models are much lower than calculation errors in unmodified models. The results of calculation errors in the modified models may increase in the previous presumed case; nevertheless, the results of calculation errors will be higher in unmodified models. It can be inferred that although evaporation data from E_{601} Pan are not completely the same as free water surface evaporation, the computational accuracy of modified models still has significantly improved.

The applicability of modified models

Our results suggest that previous evaporation models, especially the Penman formula, are not suited for calculating free water surface evaporation in hyper-arid regions. Figure 2 implies that free water surface evaporation results calculated with the Penman formula are lower than results

Table 3 Free water surface evaporation from evaporation models and E_{601} pan (2001–2008)

Evaporation models	Average evaporation (mm)	Calculation errors (mm)	Variance
Unmodified Dalton model (Eq. 2)	2150	83	10,796
Unmodified Dalton model (Eq. 3)	1721	−346	123,189
Unmodified energy balance equations (Eqs. 4–6)	2423	366	127,993
Unmodified Penman formula (Eqs. 7–8)	1783	−284	86,549
Modified Dalton model (Eq. 10)	2056	−11	2995
Modified Energy balance equations (Eq. 11)	2053	−14	17,847
Modified Penman formula (Eq. 12)	2054	−13	5805
E_{601} pan	2067	–	–

from E_{601} pan, indicating that calculated results for annual evaporation were underestimated in this area using the Penman formula. Therefore, the parameters of the Penman formula must be corrected for the calculation of the evaporation in hyper-arid regions. The same problem appears in the other two models and, therefore, the parameters need to be corrected for these models, as well.

In the arid region of northwest China, evaporation is sensitive to wind speed and saturation vapor pressure, whereas the relative humidity and the sunshine duration have minor impacts on the evaporation (Zhang et al. 2010; Zheng and Wang 2014). Moreover, Huo et al. (2013) suggested that the contribution of the wind speed to evaporation is higher than the contribution of other meteorological variables. Therefore, the results of models including parameters for wind speed and saturation vapor pressure will have a higher accuracy than the results of models without these parameters. In the three modified models, both the Dalton model and Penman formula contain wind speed and saturation vapor pressure parameters. According to the result of variance analysis (Table 3), the modified Dalton model has a higher calculation accuracy and less parameters compared to the other models. Therefore, it is simple and effective in calculating evaporation in hyper-arid regions with limited observation data. However, because of the few parameters, regional differences can result in large errors without correction of these parameters for each specific region. For instance, Elsawwaf et al. (2010) found that the highest uncertainty in evaporation models applied to Nasser Lake in Egypt appeared in the Dalton model. However, the modified Penman formula has also a high calculation accuracy according to the result of the variance analysis (Table 3). Moreover, it is based on a clear physical foundation and has advantages in calculating long-term evaporation over areas of a regional scale (Armstrong et al. 2008). However, more parameters are used in this formula indicating that it is not suitable for areas with limited observation data.

The modified energy balance equations have the lowest accuracy of the three models (Fig. 3), because they contain no parameters for the wind speed and the saturation vapor pressure. However, the evaporation can be calculated without wind speed data indicating that these equations have an advantage in reconstructing paleo-precipitation and paleo-runoff in drainage basins (Kutzbach 1980; Li et al. 2013b). In closed-basin lake systems, the basic hydrologic mass balance model for a closed-basin lake must balance inputs from precipitation to the catchment with output through evaporation from the catchment to maintain lake level at steady state and thus form a shoreline (Kutzbach 1980; Rhode et al. 2010; Li et al. 2013b; Huth et al. 2015). Therefore, the input by precipitation to the catchment can be acquired by calculating the output through evaporation from the catchment. In this case, the evaporation from the catchment can be acquired using the energy balance equations. Hence, water and energy balance equations can be applied in arid regions for paleo-precipitation and paleo-runoff reconstructions.

Conclusions

In the Ejina basin, a hyper-arid region of China, measured meteorological data were used to calculate free water surface evaporation using the Dalton model, Penman formula and energy balance equations. Results from two different Dalton models are higher and lower than the results from E_{601} pan evaporation. In addition, results from the Penman formula are lower than results from E_{601} pan, whereas results from the energy balance equations are higher than results from E_{601} pan. The results indicate that previous evaporation models are not suitable for calculating free water surface evaporation in hyper-arid regions without modification of the models.

Using meteorological data and radiation data (1993–2000), the Dalton model, energy balance equations and Penman formula were modified, and the free water surface evaporation was calculated for the years 2001–2008. Average annual evaporation, calculated using the three modified models, was slightly lower than evaporation from E_{601} pan during 2001–2008. However, the error values were only in the range of 11–14 mm, which is much lower than in previous models. Furthermore, the modified Dalton model and the modified Penman formula have a higher calculation accuracy, whereas the modified energy balance equations have the lowest accuracy of the three models.

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