Adaptivity of Budyko Hypothesis in Evaluating Interannual Variability of Watershed Water Balance in Northern China

Zhongbo Yu[1]; Huiyi Cai, Ph.D.[2]; Chuanguo Yang[3]; Qin Ju[4]; Di Liu, Ph.D.[5]; and Aili Sun, Ph.D.[6]

Abstract: This study evaluates the performance of three Budyko-type equations (Fu's equation, Turc-Pike's equation, and Milly's equation) in modeling annual evapotranspiration in 32 watersheds covering both humid and arid regions in Northern China. Daily meteorological data and monthly runoff data are used to calculate potential and actual evapotranspirations in the 32 watersheds. The results show that the Budyko-type equations are adaptive in predicting annual evapotranspiration over most of the watersheds, and Fu's and Turc-Pike's equations perform better than Milly's. In addition, the validity of the framework by Koster and Suarez in predicting the evapotranspiration deviation ratio (EDR) (i.e., the ratio of the standard deviation of evapotranspiration to the standard deviation of rainfall) based on Fu's and Ture-Pike's equations is also examined. Given the unexpected Nash–Sutcliffe efficiency values (−0.915 and −1.026 in Fu's and Ture-Pike's, respectively), a linear one-variable model is employed to improve the accuracy of the EDR estimation. Two revised EDR estimation equations are developed in two cases: one includes and the other excludes the three humid watersheds on the basis of the original framework. The results show that the first revised equation may be applied to both humid and arid watersheds, whereas the second revised equation is more appropriate in calculating the EDR for arid watersheds. **DOI:** 10.1061/(ASCE)HE.1943-5584.0000862. *© 2014 American Society of Civil Engineers.*

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Introduction

Evapotranspiration (ET), a key component of the watershed water balance, is one of the most vital parts in the assessment of regional water resources (Liu and Yang 2010). Because evapotranspiration plays an important role in the interactions among climate, soil, and vegetation, it was widely used in studies related to the analysis of the hydrologic response to atmospheric/climate and vegetation changes (Zhang et al. 2001; Yang et al. 2009) and drought analysis and eco-environment research (e.g., salinity) (Narasimhan and Srinivasan 2005).

Annual water balance including evapotranspiration is very important in reality because it allows a direct examination of water availability. The Budyko hypothesis on the control of rainfall and available energy in determining ET and runoff has been widely used to estimate mean annual water balance in recent decades (Budyko 1948, 1974; Zhang et al. 2004; Potter et al. 2005; Xiong and Guo 2012). However, the attention was primarily focused on the year-to-year variations in water balance until recently (Yang et al. 2007; Zhang et al. 2008; Potter and Zhang 2009). Given the development of the Budyko hypothesis, many studies were carried out to extend the application of Budyko's equation and/or Budyko-type equations to model water balance on an annual (as this study considers) or shorter timescale. For example, Zhang et al. (2008) used Fu's equation to simulate water balance for annual, monthly, and daily timescales in Australia. They concluded that the selected model worked well in most of the watersheds for the annual timescale, whereas a more complex model was needed if the timescale changed from an annual to a shorter one. Tekleab et al. (2011) reported that Fu's equation could not adequately predict the annual evaporation given the assumption that the aridity index was a first-order control in all watersheds and that it was needed to increase model complexity to simulate a monthly water balance. Potter and Zhang (2009) compared different curves, including Turc-Pike's, Fu's curve, Milly's alpha and beta curve, and the abcd model (2002), with all of the selected curves that have an adjustable parameter in Australia and found that differences existed among different curves related to simulating annual evapotranspiration. According to previous studies that focused on the applicability of the Budyko hypothesis at a finer temporal scale, not all Budyko-type equations are appropriate for a given watershed.

The evapotranspiration deviation ratio (EDR) provides another way to detect the interannual variability of the water balance. Based on Budyko's hypothesis, Koster and Suarez developed one framework for estimating the EDR (Koster and Suarez 1999). Several studies tested this framework (e.g., Arora 2002; Potter and Zhang 2009; Dooge et al. 1999; Liu and Yang 2010; Sankarasubramanian and Vogel 2002, 2003; Roderick and Farquhar 2011). Arora (2002) and Potter and Zhang (2009) tested the validity of this framework on the basis of several of Budyko's type of equations and found that curve selection was an important step in assessing interannual variability of the water balance and that not every equation was suitable

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for a given watershed. In addition, Dooge et al. (1999) and Liu and Yang (2010) proved that the EDR was a useful way to determine the effects of climate change (such as precipitation) on actual evapotranspiration and/or runoff based on the assumption that the Koster and Suarez framework was valid and practical. By incorporating future climate change scenarios into the Koster and Suarez framework, Roderick and Farquhar (2011) stated that a future evaluation of the evapotranspiration variation would provide a significant contribution to water resource management.

Throughout northern China, climate variability and human activities have caused a series of water resource and ecological problems (Bao et al. 2011; Gong et al. 2004). For example, significant decreasing trends in precipitation and streamflow were found in the Yellow River basin (Fu et al. 2004). Moreover, a large number of zero-flow days existed at the mouth of the Yellow River (Liu and Cheng 2000). Water shortage and eco-environmental degradation issues in the Haihe River basin became serious (Liu and Xia 2004). During the past decades, a significant number of studies explored the effects of climate change and human activities on the hydrologic cycle over northern China. However, the existing works primarily focused on runoff and precipitation attributable to different reasons.

Once the interannual variability of the water balance is simulated, the trends in evapotranspiration and/or runoff and the effect of climate change on water resources may be evaluated, which will be of great significance on water resource decision making. Therefore, having the application of ET to related studies is of great importance. Although the role of interannual variability of ET over watersheds was investigated worldwide (Zhang et al. 2008; Potter and Zhang 2009), studies on China are still rare, particularly based on the different Budyko-type equations related to humid and arid watersheds.

This paper investigates the adaptivity of the Budyko hypothesis in evaluating the interannual variability of watershed water balance in northern China on the basis of a dataset from 32 watersheds over northern China. The objectives of this study are to (1) examine the applicability of Budyko-type equations in predicting annual evapotranspiration in both humid and arid watersheds by employing three Budyko-type equations, namely, Fu's, Turc-Pike's, and Milly's equations; (2) evaluate the validity of the Koster and Suarez framework to estimate the EDR; and (3) improve the accuracy of estimating the EDR by employing a linear regression model to develop a revised model.

Data Description

This study selected 32 watersheds in the Huaihe River basin, the Haihe River basin, and the Yellow River basin of northern China as the study areas (Fig. 1). Among the 32 watersheds, three watersheds in the Huaihe River basin with a relatively small aridity index ($\phi < 1$, where ϕ is the mean annual aridity index represented as the ratio of mean annual potential evapotranspiration to mean annual precipitation) are considered humid regions, whereas the remaining watersheds, including three in the Huaihe River basin, eight in the Haihe River basin, and 18 in the Yellow River basin, all have an aridity index greater than 1 ($1.33 < \phi < 3.31$), are classified as arid regions.

Monthly runoff data for the 32 watersheds are collected. The longest record length is 30 years and the shortest is 12 years. Potential evapotranspiration for each watershed is derived from the averaged station values. The potential evapotranspiration of each station is calculated from the Penman-Monteith equation using a dataset (including daily observations of maximum, minimum, and mean air temperature, wind speed (2-m height), relative humidity, sunshine hours, and precipitation) from 100 National Meteorological Observatory stations (Fig. 1). The rainfall data for each watershed are also obtained from the mean station values of precipitation. Mean annual actual evapotranspiration, calculated using the water balance method (i.e., precipitation minus runoff) by assuming that the interannual change of groundwater and soil-moisture storage are negligible, is regarded as the observed actual evapotranspiration.

Methodologies

Budyko's Framework

Using the assumption of the dominant role of precipitation and available energy in the regional water balance for the long-term

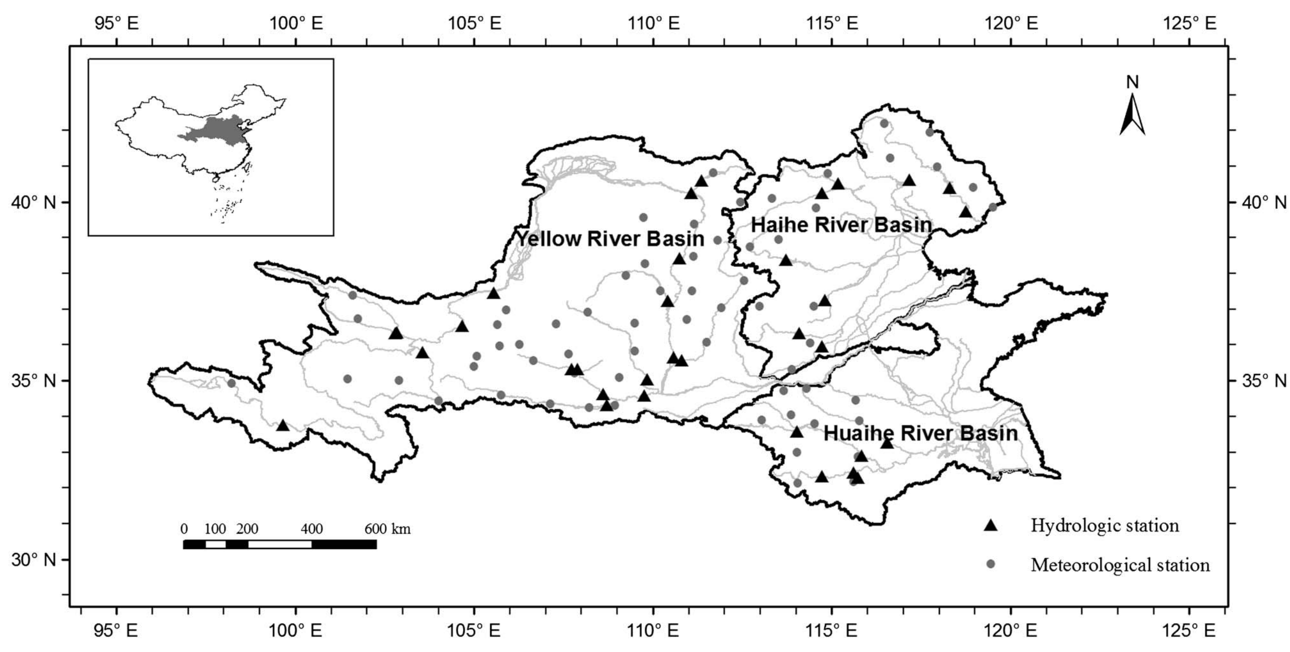

Fig. 1. Study area and hydrologic (triangles) and meteorological (circles) stations used in the study

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mean annual timescale, combined with water balance data from a number of watersheds, Budyko (1974) developed an equation, called Budyko's equation, the geometric mean of Schreiber's formula (Schreiber 1904), and Ol'dekop's formula (Ol'dekop 1911) to express the evapotranspiration ratio ($\bar{E}/\bar{P}$) as a function of the aridity index (ϕ):

$$\frac{\bar{E}}{\bar{P}} = f(\phi) = \left[\phi \tanh\left(\frac{1}{\phi}\right)(1 - e^{-\phi})\right]^{1/2} \tag{1}$$

where $\bar{E}$, $\bar{P}$, and $\overline{ET}_0$ = mean annual actual evapotranspiration, precipitation, and potential evapotranspiration, respectively. Fig. 2 illustrates the curve of equation (1), which shows that the evapotranspiration relationship pattern approaches the water limit (i.e., segment A in Fig. 2 where $\bar{E} = \bar{P}$) when the aridity index becomes large, and approaches the energy limit (i.e., segment B in Fig. 2 where $\bar{E} = \overline{ET}_0$) when the aridity index becomes small.

Several other Budyko-type equations were proposed on the basis of Budyko's framework. For example, Pike (1964) derived a relationship between $\bar{E}/\bar{P}$ and ϕ, called Turc-Pike's equation, by modifying Turc (1954)'s equation

$$\frac{\bar{E}}{\bar{P}} = (1 + \phi^{-v})^{-1/v} \tag{2}$$

The original value of parameter v is 2. Many studies considered parameter v as a calibration parameter (Potter and Zhang 2009).

Zhang et al. (2001) described a one-parameter model that related average annual evapotranspiration to precipitation, available energy, and plant-available water capacity. Then, Zhang et al. (2004) developed a rational function, called Fu's equation, with parameter w from Fu's analysis on phenomenological considerations (Fu 1981), which was expressed as

$$\frac{\bar{E}}{\bar{P}} = 1 + \phi - (1 + \phi^w)^{1/w} \tag{3}$$

where parameter w = an adjustable parameter representing the plant-available water coefficient.

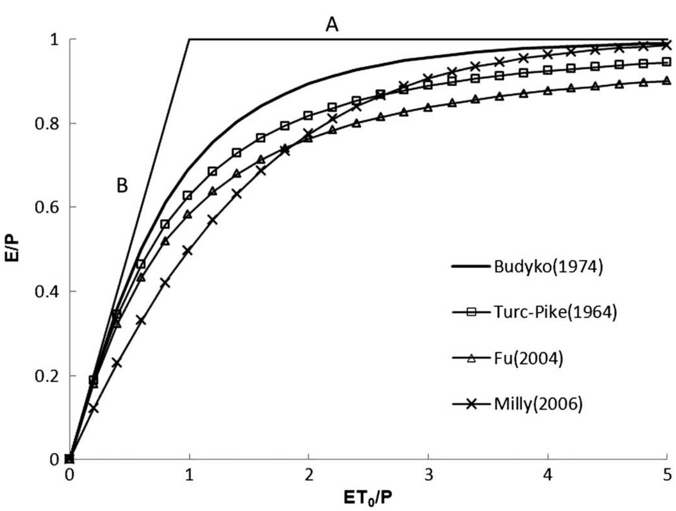

Fig. 2. Comparison of different Budyko-type curves: original Budyko curve; Turc-Pike curve ($v = 1.5$); Fu's curve ($w = 2$); and Milly's curve ($\beta = 1$)

Potter (2006) developed a similar formula to that of Milly's (1993) using an adjustable parameter β, the reciprocal of the standardized interstorm potential evapotranspiration

$$\frac{\bar{E}}{\bar{P}} = \{\exp[\beta(\phi - 1)] - 1\}/\{\exp[\beta(\phi - 1)] - 1/\phi\} \tag{4}$$

This study considers Eq. (4) as Milly's equation.

In comparison, Fig. 2 shows Turc-Pike's, Fu's, and Milly's equations. The equations discussed are only some of the Budyko-type equations. Other studies provide additional information on Budyko-type formulas (e.g., Arora 2002; Sun 2007; Yang 2007; Roderick and Farquhar 2011).

Koster and Suarez Framework for Interannual Water Balance Variability

Koster and Suarez described the ratio of the standard deviation of annual evapotranspiration to the standard deviation of precipitation as a function of the aridity index ϕ using the assumption that interannual changes in surface storage may be ignored and interannual variations in potential evapotranspiration may be considered negligible. The function equation is given as follows:

$$\frac{\sigma_{ET}}{\sigma_P} = f(\phi) - \phi f'(\phi) \tag{5}$$

where σ_{ET}/σ_P = EDR. The larger the ratio, the more rainfall variation is translated to evapotranspiration variation, indicating that evapotranspiration is more sensitive to rainfall. The EDR, which describes the sensitivity of actual evapotranspiration to rainfall and potential evapotranspiration, implies a method for assessing the hydrologic response to future climate change. Additionally, the EDR is calculated by connecting with rainfall and potential evapotranspiration, which may help when exploring the evaporation paradox (Yang et al. 2006).

Calibration of Three Budyko-Type Equations Parameters

This paper adopts one optimization method to calibrate the parameters in the three Budyko-type equations (Turc-Pike's, Fu's, and Milly's equations) shown in Fig. 2, except for the original Budyko equation because it does not have an adjustable parameter. Similar to Yang et al. (2007), the estimated mean annual evapotranspiration obtained from each Budyko-type equation is set equal to the observed mean annual evapotranspiration, allowing for the calculation of each parameter for each watershed.

To compare the simulated results with the observed data, the Nash-Sutcliffe efficiency (NSE) index (Nash and Sutcliffe 1970), the determination coefficient (R^2), the root-mean square error (RMSE), and the mean absolute error (MAE) (Legates and McCabe 1999) are used for the performance evaluation.

Linear Regression

Donohue and Roderick (2010) modeled both the long-term and mean annual Budyko scatter using the linear regression method, and argued that the linear regression equation acted well when including only one variable as the independent variable. Later, Xiong and Guo (2012) established a linear model to evaluate the relative errors of the Budyko modeling based on Donohue's work.

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Table 1. Parameter Values for Each Budyko-Type Equation

Evaluation indicators	w (Fu)	v (Turc-Pike)	β (Milly)
Mean	3.19	2.46	2.47
Maximum	8.3	7.5	8.9
Minimum	1.65	0.92	0.51

This study uses the method proposed by Donohue and later developed by Xiong to model the relative errors of the evapotranspiration deviation ratio. The relative error of the EDR, denoted by δ_E, is calculated as

$$\delta_E = (\mathrm{EDR_{OBS}} - \mathrm{EDR_{SIM}})/\mathrm{EDR_{OBS}} \tag{6}$$

where $\mathrm{EDR_{OBS}}$ = the EDR obtained from observed evapotranspiration and rainfall data; $\mathrm{EDR_{SIM}}$ = the EDR calculated from the Koster and Suarez framework on the basis of the Budyko-type equation with an optimized parameter; and δ_E = the relative error of the EDR estimate. Then, the relationship of relative error to relevant variables is established using the one-variable linear regression method, which is modeled as

$$\delta_E = ax + b \tag{7}$$

where x is the independent variable; and a and b are the regression coefficient and intercept, respectively. Then, the revised EDR estimation model is calculated as follows:

$$\mathrm{EDR_{SIM}^{(r)}} = \mathrm{EDR_{SIM}}/(1-\delta_E) = \mathrm{EDR_{SIM}}/[1-(ax+b)] \tag{8}$$

where $\mathrm{EDR_{SIM}^{(r)}}$ = revised EDR estimation.

Results

Parameter Calibration

Table 1 shows the parameters of the three Budyko-type equations calibrated using the method described in the section on "Calibration of Three Budyko-type Equations." According to Yang et al. (2008), parameter w in Fu's equation and v in Turc-Pike's equation are more or less linearly related as follows:

$$w \approx v + 0.72 \tag{9}$$

where the relationship between the values of w and v [Eq. (10)] is

$$w = v + 0.7385 \tag{10}$$

The determination coefficient (R^2) of Eq. (10) is 0.9996. Eq. (10) is well consistent with Eq. (9), indicating a reasonable result for the parameter calibration. For the 32 watersheds, the maximum value of w is 8.3, which is significantly larger than the mean value of 3.19 (Table 1). One reason for the abnormal phenomena is probably the special geographical condition.

Long-Term Evapotranspiration Simulation

The three Budyko-type equations with the optimized parameters in each watershed are applied in the 32 watersheds to evaluate their general applicability to the annual water balance (referred to in this paper as annual evapotranspiration) modeling. Fig. 3 shows the

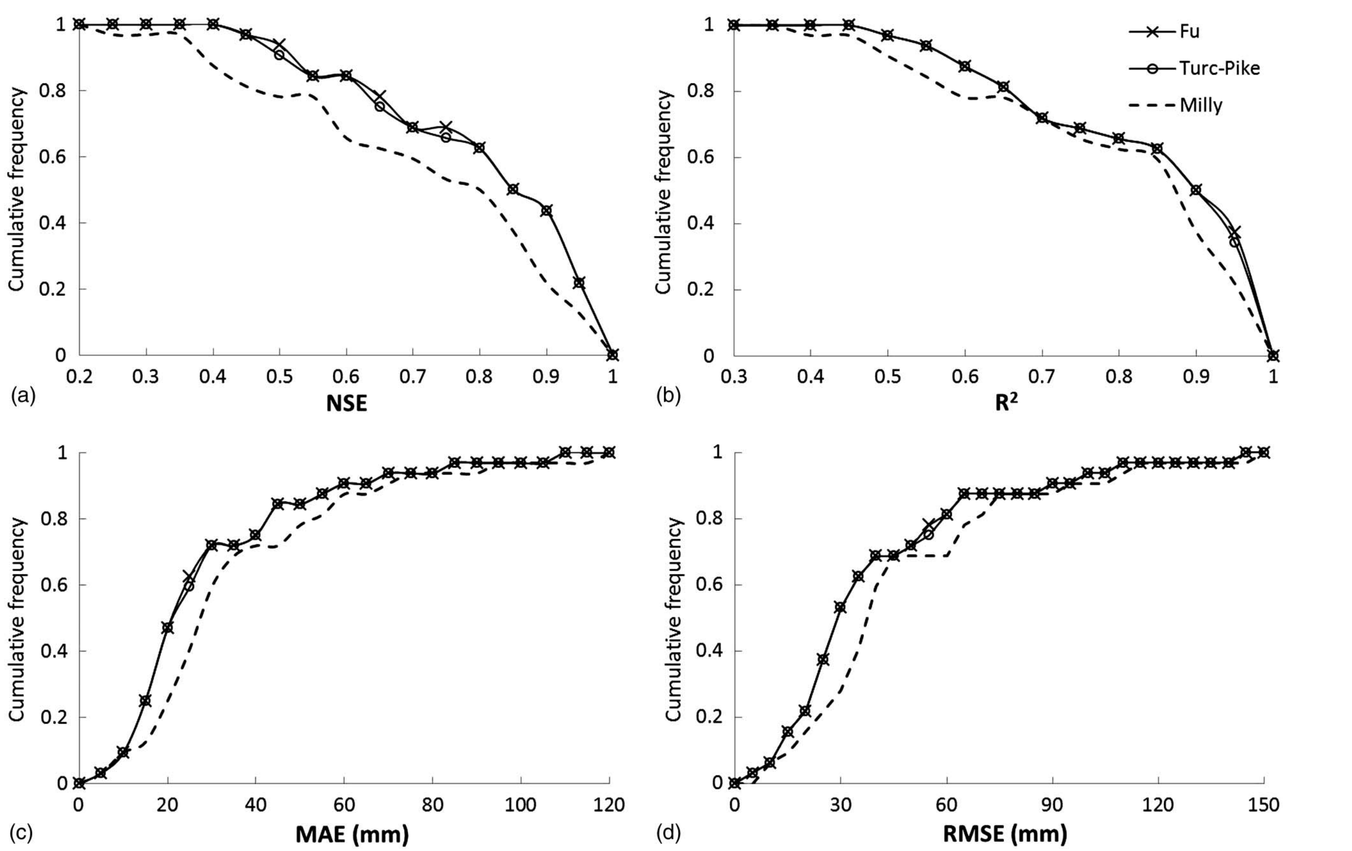

Fig. 3. Statistical comparisons of criteria distributions to evaluate predicted annual evapotranspiration using Fu's, Turc-Pike's, and Milly's equation; criteria include Nash-Sutcliffe efficiency (NSE) index, determination coefficient (R^2), mean absolute error (MAE), and root-mean square error (RMSE)

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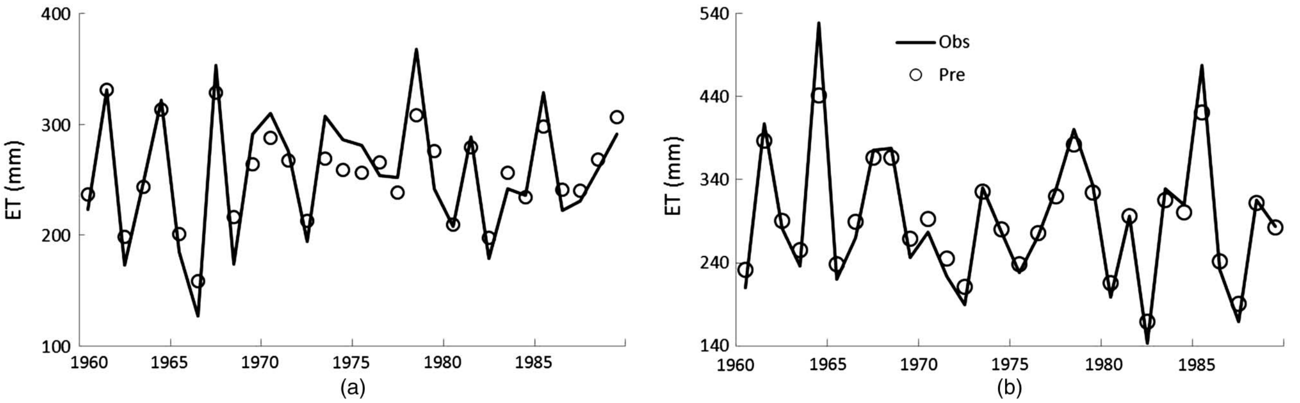

Fig. 4. Prediction of annual evapotranspiration for (a) Minhe watershed; (b) Baijiachuan watershed

cumulative distribution functions of the Nash-Sutcliffe efficiency (NSE) index, the determination coefficient (R^2), the root-mean square error (RMSE), and the mean absolute error (MAE) for the predicted annual evapotranspiration. Fu's equation works best with the ranges of NSE, R^2, RMSE, and MAE for the 32 watersheds (NSE: 0.44–1.00, R^2: 0.49–1.00, RMSE: 4.11–142.61 mm, and MAE:3.17–108.89 mm). The mean values of these four evaluation indices are 0.80, 0.84, 39.61, and 29.10 mm respectively. Most of the watersheds (30 out of the 32 watersheds) have NSE values greater than 0.5, whereas the MAE values were less than 50 mm in 27 out of the 32 watersheds. The results from using Turc-Pike's equation approximate that from Fu's equation with mean values of these evaluation indices of 0.80, 0.84, 39.95 mm, and 29.38 mm, respectively. However, the performance of Milly's equation is less satisfactory compared with the other two equations. The average values of NSE, R^2, RMSE, and MAE using Milly's equation are 0.72, 0.80, 47.15 mm, and 35.06 mm, respectively. As analyzed, Fu's and Turc-Pike's equations provide good estimates of annual evapotranspiration in the study areas, whereas Milly's equation performs relatively poor. However, Potter and Zhang (2009) found that Milly's equation has better performance in Australia's summer-dominant rainfall watersheds than Fu's and Turc-Pike's, which was opposite to the finding in northern China. Possible reasons for this phenomenon are as follows: (1) although both study areas in this study and in Potter and Zhang (2009) are summer-dominant watersheds, some differences still exist in watershed properties; as a result, the performance of a given formula varies among watersheds; and (2) the sample size in the Potter and Zhang (2009) study is larger than that in this study, which probably has a certain influence on the results.

Fig. 4 provides a comparison of the annual evapotranspiration series between the estimated actual evapotranspiration using Fu's equation and the observed values in two watersheds. A general phenomenon is found from these two watersheds—an overestimation for lower evapotranspiration and an underestimation for higher evapotranspiration. In addition, the same phenomenon is presented in most of the other watersheds. Moreover, similar results appeared in Yang et al. (2007) and Potter (2009).

Precipitation significantly affects actual evapotranspiration. Accordingly, further analysis is conducted for Fu's equation to explore the reasons for the unreliable NSE distribution pattern (Fig. 5). The ratio of actual evapotranspiration to precipitation, $f(\phi)$, and the EDR represent the control of precipitation over actual evapotranspiration. The following two points are found. First, a relationship exists between NSE and $f(\phi)$, and NSE and EDR (Fig. 5). Humid watersheds often have low NSE values but only three out of the 32 watersheds studied are humid, indicating that additional studies should be conducted in the future. Second, the NSE has correlativity with the observed $f(\phi)$ and the EDR (Fig. 5), indicating that, for a given watershed, greater sensitivity of actual evapotranspiration to precipitation results in a higher NSE value. Additionally, the greater the degree of precipitation

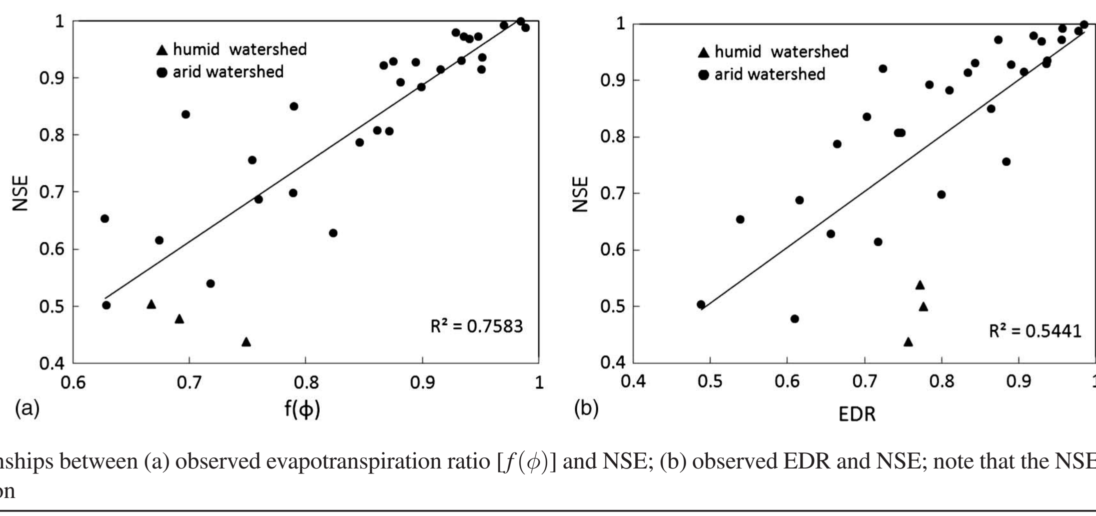

Fig. 5. Relationships between (a) observed evapotranspiration ratio [$f(\phi)$] and NSE; (b) observed EDR and NSE; note that the NSE results are based on Fu's equation

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controlling actual evapotranspiration, the better the simulation validity using Fu's equation.

Evapotranspiration Deviation Ratios

On the basis of the framework of Koster and Suarez, only Fu's equation and Turc-Pike's equation are selected to assess their ability to simulate EDRs because Milly's equation works relatively poorly in simulating annual water balance in the study watersheds. Figs. 6(a and b) compared the observed and simulated EDRs for all watersheds with optimized parameters. Table 2 shows the four evaluation indices. The estimations from Fu's equation show a very similar pattern to that of Turc-Pike's equation: the observed EDR is underestimated in most watersheds, which may result from the overestimation for lower evapotranspiration and the underestimation for higher evapotranspiration using the selected equations (Fig. 4). However, the EDR results for the equations are unsatisfactory given the negative NSE values, despite the fact that the R^2 values are significant. Therefore, improvement is made based on the linear regression method introduced in the section on "Linear Regression," and the result is documented in the following section.

Improvement in Estimating Evapotranspiration Deviation Ratio

As previously discussed, the original Koster–Suarez methodology using Fu's equation and Turc-Pike's equation cannot properly predict the EDR. Thus, a method to establish a linear relationship between the relative error of the calculated EDR and the observed EDR and the independent variables is developed to improve the EDR estimation. However, selecting the best variable related to the relative error is difficult. For example, in previous studies, Xiong and Guo (2012) selected five independent variables (such as observed aridity index and the standard deviation of annual precipitation), but none of them focused on improving the accuracy of the EDR prediction. This study used the predicted evapotranspiration ratio $[f(\phi)]$ as the independent variable because it is one of the terms in the original Koster–Suarez framework. Only Fu's equation is used for this improvement study given the very similar prediction results from Fu's equation and Turc-Pike's equation.

Fig. 7(a) shows the linear regression between the relative EDR error and the predicted evapotranspiration ratio for all 32 watersheds. As described in the section on "Linear Regression," a revised Fu's EDR estimation equation called Revised Fu's equation I, is derived as

Table 2. Statistical Comparisons for Evaluating the Predicted Evapotranspiration Deviation Ratio

Equation	NSE	R^2	MAE	RMSE
Original Fu's equation	−0.915	0.662	0.133	0.178
Original Turc-Pike's equation	−1.026	0.659	0.138	0.183
Revised Fu's equation I	0.449	0.560	0.066	0.095
Revised Fu's equation II	0.645	0.681	0.054	0.068

$$\mathrm{EDR}^{(r)}_{\mathrm{SIM}} = EDR_{\mathrm{SIM}}/(1-\delta_E) = EDR_{\mathrm{SIM}}/[1-(-1.2339f(\phi)+1.2299)] \quad (11)$$

Substituting Eq. (5) into Eq. (11) yields

$$\mathrm{EDR}^{(r)}_{\mathrm{SIM}} = [f(\phi)-\phi f'(\phi)]/[1-(-1.2339f(\phi)+1.2299)] \quad (12)$$

The results from Eq. (12) are plotted in Fig. 6(b). The accuracy of predicting the EDR is shown to significantly improve with the coefficient of efficiency (NSE) increasing from −0.915 to 0.449, whereas the MAE and the RMSE decrease from 0.133 to 0.066 mm and from 0.178 to 0.095 mm, respectively. However, the determination coefficient (R^2) decreases from 0.662 to 0.560. One reason for this phenomenon might be the weak application of Fu's equation in humid watersheds ($\phi < 1$), as shown in Fig. 5(a). Recall that Eq. (5) was derived by assuming that interannual variations in potential evapotranspiration may be neglected relative to the interannual variations in rainfall (Koster and Suarez 1999). Hence, as suggested by Milly and Dunne (2002), the second reason for this phenomenon might be that the interannual covariability of potential evapotranspiration with rainfall may play a significant role, particularly in humid watersheds. Thus, the steps for the linear regression and revised Fu's EDR estimation equation are repeated by removing the three humid watersheds, leading to the formation of a new relationship between δ_E and $f(\phi)$ [Fig. 7(c)] and a new revised Fu's equation II as follows:

$$\mathrm{EDR}^{(r)}_{\mathrm{SIM}} = [f(\phi)-\phi f'(\phi)]/[1-(-1.0447f(\phi)+1.0463)] \quad (13)$$

Fig. 7(d) plots the calculation results from Eq. (13), which shows that the results without humid watersheds achieved a better satisfied outcome through increased NSE (from 0.449 to 0.681) and R^2 (from 0.560 to 0.681) values, and decreased MAE (from 0.066 to 0.054) and RMSE (from 0.095 to 0.068) values. This result

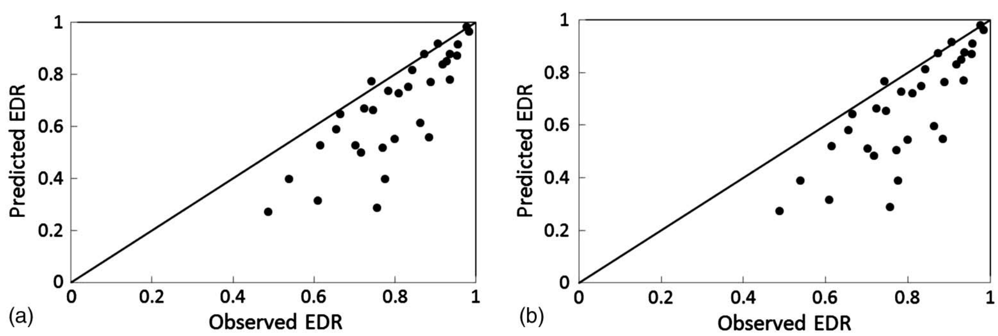

Fig. 6. Comparison of observed and predicted EDR using (a) Fu's equation; (b) Turc-Pike's equation

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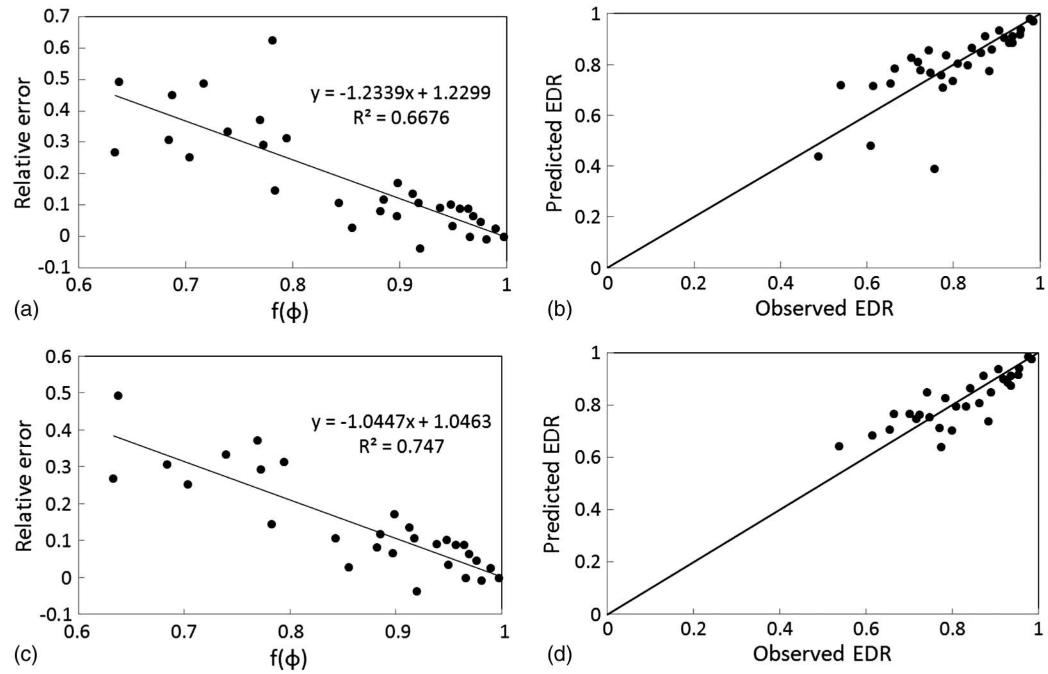

Fig. 7. Results of one-parameter linear regression relationship for relative error of the estimated EDR and the corresponding revised EDR estimation equation; (a) and (b) describe the case of retaining three humid watersheds; (c) and (d) describe the case of removing three humid watersheds

proves that the latter revised EDR estimation equation works well in arid watersheds. Thus, Eq. (13) is a god choice for studying the effects of future climate changes (i.e., precipitation, potential evapotranspiration) on actual evapotranspiration because of its simple form and good performance. Note that this study has only three humid watersheds with aridity index less than 1. Hence, to explore the possibility of Budyko-like equations in humid watersheds, additional studies should be conducted in the future.

Conclusions

This paper investigated the performance of the extension of the Budyko framework in simulating annual water balance using three Budyko-type equations. Several analyses were conducted in this study. First, three Budyko-type equations, namely, Fu's, Turc-Pike's, and Milly's equations, were employed to examine the applicability of Budyko-type equations in predicting annual evapotranspiration in both humid and arid watersheds. Second, the validity of the Koster and Suarez framework in estimating the EDR was tested. Third, a linear regression model was applied to improve the accuracy of the EDR by producing a revised model. The findings are summarized as follows.

First, Fu's and Turc-Pike's equations have better performance than Milly's equation in the study watersheds. These results contradict the findings presented by Potter and Zhang (2009), who demonstrated that Milly's equation worked better than Fu's and Turc-Pike's equations for summer-dominant watersheds in Australia. In addition, the deviation between the estimations of annual evapotranspiration for humid watersheds and the observed data are much more significant than that for arid watersheds.

Second, the results from the validity of the Koster and Suarez framework in modeling the EDR using Fu's and Turc-Pike's equation showed that the EDR was underestimated in almost all watersheds. The linear one-variable regression model based on the analysis of the relationship between relative error and EDR in all watersheds seems to work well to improve this EDR estimation. The new equation provides an improvement over the original framework with the coefficient of efficiency increasing from −0.915 to 0.449 and the value of MAE and RMSE decreasing by nearly half. However, the value of the determination coefficient decreased from 0.662 to 0.560. Arora (2002) and Potter and Zhang (2009) documented that a lower aridity index (e.g., humid) may more easily trigger the underestimation of the EDR. Therefore, the three humid watersheds were removed and the linear regression method was reapplied. The latter revised equation provided significantly improved results on the basis of the work of Koster and Suarez (1999).

As previously noted, this paper studied only three humid watersheds with an aridity index less than 1. The revised method to estimate the EDR on the basis of the original framework for arid watersheds in northern China provides a direct method for studying the effect of climate change on evapotranspiration and, thus, runoff. In the future, greater attention will be paid to this field, and whether Budyko's hypothesis is suitable for the interannual variability of evapotranspiration simulation in the humid watersheds will be investigated.

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