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Irrigation impact on annual water balance of the oases in Tarim Basin, Northwest China

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Abstract:

By taking the sum of annual precipitation and lateral water input (in which irrigation water withdrawal is the main component) for water availability, the Budyko hypothesis and Fu's formula derived from it was extended to the study of oases in the Tarim Basin, Northwest China. For both long-term (multi-year) and annual values on water balances in the 26 oases subregions, the extended Fu's formula was confirmed. Regional patterns on water balance on the 26 oases subregions were related to change in land-use types due to increased area for irrigation. Moreover, an empirical formula for the parameter was established to reflect the influences of change in land use on water balance. The extended Budyko framework was employed to evaluate the impact of irrigation variability on annual water balance. According to the multi-year mean timescale, variabilities in actual evapotranspiration in the oases were mainly controlled by variability in irrigation water withdrawal rather than potential evapotranspiration. The influences of variability on potential evapotranspiration became increasingly apparent together with increases in irrigation water withdrawal. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS oasis; irrigation; actual evapotranspiration; Budyko hypothesis

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INTRODUCTION

The dynamic water balance for a region (or catchment) can be written as Brutsaert (1982)

$$P + I = E + R + \Delta S_w \quad (1)$$

where P is precipitation, I is inflow from outside the region (including surface and groundwater inflow), R is outflow (including surface and groundwater outflow), E is evapotranspiration and ΔS_w is change in water storage in the region. In natural catchments located along extensive land surfaces, the groundwater flows are usually negligible compared with other variables. Inflows from the outside are also usually negligible. Steady-state conditions with ΔS_w at near-zero values were typically established, as evidenced by annual or multi-year analyses (Budyko, 1974; Brutsaert, 1982). Studies on water balances were often conducted by evaluating the variability of evapotranspiration, an important component of both water and energy balance (Entekhabi *et al.*, 1999). The primary controls on evapotranspiration (E) are water and energy availability. In regions or catchments where I and the ΔS_w can be neglected relative to other variables, water availability can be approximated by precipitation. Energy supply, or the atmospheric demand representing maximum possible evapotranspiration, is often denoted by potential evapotranspiration. Budyko (1958, 1974) proposed two boundary conditions under extremely arid and absolutely wet conditions. Next, a general function based on the two boundary conditions was established to partition evapotranspiration from precipitation as a function of the relative magnitude of precipitation and potential evapotranspiration:

$$\frac{E}{P} = F\left(\frac{E_0}{P}\right) \quad (2)$$

where F denotes the function describing the relationship, herein defined as the Budyko hypothesis. Using the Budyko hypothesis, some simple models were obtained to relate annual E with key driving variables, such as annual precipitation, potential evapotranspiration, land topography and vegetation. The impact of change of these variables on regional evapotranspiration and water balance in annual or multi-year timescales have been studied (Fu, 1981; Zhang *et al.*, 2001, 2004; Yang *et al.*, 2007, 2008a,b). The Budyko hypothesis gives reasonable estimates on annual evapotranspiration across large climatic regions with little human interference (Zhang *et al.*, 2001; Yang *et al.*, 2007). A sophisticated assumption wherein available water is supplied entirely by precipitation has been widely applied by previous studies. Several factors affecting water availability at different temporal and spatial scales (e.g. soil water) (Zhang *et al.*, 2008; Zhou *et al.*, 2008) and lateral inflow (e.g. irrigation water withdrawal) were not considered.

In 'sink areas' of a catchment, especially in dry land environments, the lateral water inflows from the outside parts of the region cannot be neglected, as water

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inputs by runoff redistribution, subsurface flow or irrigation water withdrawal can contribute extensively to available water (Bromley *et al.*, 1997; Domingo *et al.*, 2001; Weiskel *et al.*, 2007). In agricultural areas, irrigation water withdrawal takes a large proportion of lateral water inputs and plays an important role in water balance. The effect of irrigation on surface water balance is both locally and regionally important. About half of the water diverted for irrigation is consumed through evapotranspiration (Jackson *et al.*, 2001). Studies on the impacts of irrigation on surface water balance are often conducted by evaluating the influences of irrigation on evapotranspiration. In the agricultural oases in the Tarim Basin, Northwest China, average annual precipitation is no more than 100 mm, while annual evapotranspiration may be larger than 400 mm (Lei *et al.*, 2006). Irrigation water withdrawal plays a significant role in available water. Clearly, water balance is influenced directly by irrigation.

Although the Budyko hypothesis supplies an appropriate methodology to evaluate water balance in annual timescales, it does not accurately represent the true case of the oases in the Tarim Basin. Irrigation water withdrawal should be included in the Budyko framework. The Budyko hypothesis was extended to incorporate irrigation water withdrawal in water availability, and was used to predict annual evapotranspiration in the oases in Tarim Basin (Han *et al.*, 2008). In this study, the extended Budyko hypothesis was analysed further, and the model based on Fu's formula was used to characterize water balance in the oases. In the extended Budyko framework, the influences of land use and the effects of irrigation water withdrawal variability on water balance for the oases were evaluated.

STUDY AREA AND DATA

Tarim River, the largest inland river in western China, is located in the east longitude, (71°39′–93°45′), and north latitude, (34°20′–43°39′). In the past, the Tarim Basin consisted of nine drainage systems; at present, only the Akesu, Hotan and Yarkant Rivers can flow into the main channel of the Tarim River (Lei *et al.*, 2001). In this study, the oases in the alluvial plains of six tributaries (namely, Kaidu--Kongque, Weigan, Akesu, Kashgar, Yarkant and Hotan Rivers) were selected as study areas (Figure 1). Four land-use types (namely, irrigation land, natural vegetation, wasteland and water body) were included in each oasis, and the landscapes are Gobi Desert–like out of the reach of riverway and channel. Irrigated land and natural vegetation are distributed mainly along the main river system and irrigation ditches. Several subregions were identified in each oasis, and the boundary subregions were drawn on the basis of satellite images and administrative divisions related to water use (Table I). All the oases subregions are extremely arid, with annual precipitation of less than 100 mm per year and pan evaporation of more than 2000 mm per year.

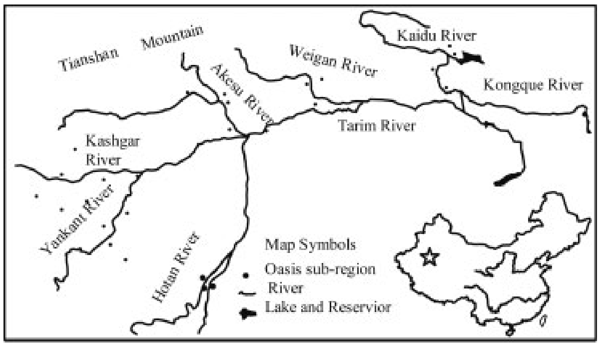

Figure 1. Locations of the study oases in the Tarim Basin, China (☆ shows the location of the study area in China)

Table I. Study periods for the selected oases subregions

No.	Oasis	Number of subregions	Study period
1	Kashgar River	4	2000–2004
		2	1999–2003
2	Yarkant River	5	1998–2002
3	Akesu River	5	1999–2002
4	Weigan River	3	1992–1996
5	Kaidu–Kongque River	4	1999–2003
6	Hotan River	3	1999–2003

These oases have a long history of agricultural development. River water withdrawal has been the main source for irrigation, while groundwater sources were used minimally. Along with the reclamation of wasteland, much more water is diverted into the irrigation land. Water diversion for irrigation now consumes much of the water resource. Irrigation land area increased sharply from the 1980s. By the end of the 1990s, farmland areas were kept relatively steady because of actions to stop wasteland reclamation. The monthly hydrological data of discharge, springs, wells, water withdrawal and drainage for each subregion oasis during the study period were collected. With the assistance of meteorological stations in each subregion, monthly meteorological data were obtained, consisting of precipitation, mean, maximum and minimum air temperatures, sunshine duration, wind speed and relative humidity. The water- and salt-monitoring project of each oasis was conducted for 4 or 5 years, as shown in Table I (Lei *et al.*, 2006; Dong *et al.*, 2007). We surveyed and summarized available meteorological, hydrological, land use and agricultural diversion data, all of which were deemed reliable. To eliminate influences of change in land use, the study periods were set at specific time frames, as shown in Table I.

WATER BALANCE CHARACTERISTICS AND METHODOLOGY

Water balance characteristics of the oases in Tarim Basin

The water balance of the agricultural oases in the Tarim Basin is more sophisticated. The inflow from outside the region I is the sum of irrigation water withdrawal, lateral groundwater inflow from outside and river seepage, outcrop of springs and wells, etc. Irrigation water withdrawal is the most important component of I. The proportions of irrigation water withdrawal in I are larger than 74% for all six oases (Table II). Irrigation also plays an important role in other variables on the right side of Equation (1).

Discharge to surface drainage is the most important component of R (i.e. sum of discharge to surface drainage and discharge outside and groundwater outflow) (Tang *et al*., 2006, 2007). The groundwater system is dominated by the irrigation system. Losses from the canal system and farmland infiltration are the most important sources of groundwater recharge into irrigated land; meanwhile, discharge from irrigated land, showing groundwater flows from irrigated to non-irrigated land (subsurface drainage) provides recharge for non-irrigated areas (Tang *et al*., 2007). Water infiltration for irrigation and the shallow water table provide moisture for evapotranspiration in irrigated lands. Although no water is diverted into non-irrigated lands for purpose of irrigation, almost all moisture in the vadose zone comes from upward capillary moisture that is recharged by groundwater.

The fluctuation of groundwater table depth, which affects the groundwater flows and the change in water storage ΔS_w, is obviously influenced by irrigation. A water table rise occurred in response to individual irrigation events, and a decrease in groundwater table occurred during non-irrigation or low irrigation seasons. The amplitude of groundwater table change could be large on an intra-annual timescale, while a relatively stable groundwater table would be anticipated on an inter-annual timescale unless remarkable changes occur in irrigation water withdrawal and land areas under irrigation.

Mostly, during the study period, stable annual mean groundwater table depth exists with stable agricultural water diversion. Taking the Akesu oasis as an example, the 25 groundwater monitoring wells under different land-use types monitored a dynamic change in groundwater table; the distribution of the wells is shown as a water- and salt-monitoring collocation map (Ma *et al*., 2004; Tang *et al*., 2006, 2007). The mean monthly groundwater depth of 25 wells from 2000 to 2003 is shown in Table III. The groundwater depth of each well can be referred from Ma *et al*. (2004). According to monitoring data, the depth is small during spring irrigation (March or April) and summer irrigation (July), with depth of 2·5–3 m. In February or October, before spring irrigation or winter irrigation, the groundwater table is deep, with mean depth of 3·1–3·5 m. According to the annual timescale, groundwater table was kept relative steady from 2000 to 2003. The differences in mean groundwater depth in 25 wells between 2000 and 2003 were not obvious at an average value of 0·17 m and standard deviation of 0·32 m. Similar conditions were found for the other oases. For example, the average annual mean groundwater table depth of 40 wells in the Kaidu–Kongque oasis increased by 0·22 m from 2000 to 2003, and the average annual mean groundwater table depth of the 59 wells in the Kashgar oasis decreased by 0·09 m from 2000 to 2003 (Hu *et al*., 2004b; Dong *et al*., 2007). As the change in regional water storage ΔS_w in Equation (1) is highly related to change in groundwater depth, the steady-state conditions with $\Delta S_w \approx 0$ can be established in the analyses of water balance for the annual timescale during the study period. The assumption was also confirmed by simulated water balances (Hu *et al*., 2004a; Tang *et al*., 2006; Dong *et al*., 2007; Zhao *et al*., 2009).

Actual evapotranspiration in the oases was obviously influenced by irrigation. As no actual observation on evapotranspiration in the area could be obtained, annual actual evapotranspiration, calculated using a conceptual water balance model (Hu *et al*., 2004a; Tang *et al*., 2006; Dong *et al*., 2007; Zhao *et al*., 2009) employed on a monthly timescale, was taken as the 'measured actual evapotranspiration' in each oasis subregion. The model was validated using modelled and observed downstream discharge and simulated and observed groundwater depth values. For details on the model, refer to Tang *et al.* (2006) and Zhao *et al*. (2009). The calculated ΔS_w approximated zero for each oasis subregion, implying that the calculated evapotranspiration using the conceptual water balance model approximates the values calculated by Equation (1) ($\Delta S_w = 0$).

Table II. Proportion of irrigation water withdrawal in I for the six oases

Oasis	Kashgar	Yarkant	Akesu	Weigan	Kaidu–Kongque	Hotan
Proportion (%)	89·6	75·2	74·1	98·9	95·6	91·1

Table III. Mean groundwater depth of 25 wells from 2000 to 2003 in the Akesu oasis (m)

Month	1	2	3	4	5	6	7	8	9	10	11	12	Average
2000	3·01	3·11	2·88	2·89	2·84	2·87	2·67	2·76	2·89	2·90	2·71	2·74	2·86
2001	3·00	3·01	2·78	2·89	3·00	3·10	3·00	3·11	3·27	3·25	3·16	3·28	3·07
2002	3·04	3·06	2·75	2·72	3·00	2·99	2·83	2·91	3·04	3·21	2·96	2·79	2·94
2003	3·05	3·07	2·50	2·85	2·92	3·12	2·98	3·08	3·20	3·25	3·09	2·99	3·01
Average	3·02	3·06	2·73	2·84	2·94	3·02	2·87	2·96	3·10	3·15	2·98	2·95	2·97

To evaluate water balance characteristics, multi-year mean precipitation (P), calculated actual evapotranspiration (E) and potential evapotranspiration (E_0) of the 26 oases subregions in the Tarim Basin during the study periods were plotted against I in Figure 2. The potential evapotranspiration for each region was calculated by the Penman equation, as recommended by Shuttleworth (1993). For most oases subregions, the amounts of mean annual P are between 40 and 100 mm, while the amounts of mean annual I have a wide range from nearly 100 mm to more than 1000 mm. Considering the large proportion of irrigation water withdrawal in I, irrigation plays the dominant role in water availability for the 26 oases subregions. Along with increase in I, actual evapotranspiration increases while the potential evapotranspiration decreases. A complementary relationship exists between actual and potential evapotranspiration for the oases in the multi-year mean timescale. An obvious relationship between actual evapotranspiration and I is shown in Figure 2. The effects of I and its variability on actual evapotranspiration of the oases in Tarim Basin need further studies.

Methodology

For the oases subregions in the study area, although the steady-state conditions can be presumed, the Budyko hypothesis cannot be used directly as I cannot be neglected (Peugeot *et al.*, 2003; Tang *et al.*, 2006; Weiskel *et al.*, 2007). Using the sum of inflow from outside and precipitation ($P+I$) as water availability, the two boundary conditions postulated by Budyko remain valid. Following a similar argument, it can be postulated that under very dry conditions wherein water is limited ($(P+I) \ll E_0$) (e.g. an oasis at the end of an inland river), all precipitation and inflow evaporate into the atmosphere:

$$\frac{E}{P+I} \longrightarrow 1 \text{ when } \frac{E_0}{P+I} \longrightarrow \infty \tag{3}$$

Under absolutely wet conditions wherein energy is limited ($(P+I) \gg E_0$) (e.g. endorheic lake in arid areas), evapotranspiration demand is far less than water availability, and thus, all of the energy used in evapotranspiration is changed into latent heat:

$$\frac{E}{E_0} \longrightarrow 1 \text{ when } \frac{E_0}{P+I} \longrightarrow 0 \tag{4}$$

The postulation of the Budyko hypothesis and the derivation (Fu, 1981; Arora, 2002) are still valid for oases in arid regions for the two boundaries mentioned earlier. Water balance components can be partitioned from the sum of inflow from outside and precipitation ($P+I$), and the water–energy balance can be extended as

$$\frac{E}{P+I} = F\left(\frac{E_0}{P+I}\right) \tag{5}$$

As the derivations of the functions partitioning annual water balance as a function of the relative magnitude of water and energy supply retain their validity, the relationship for water–energy balance can be written using Fu's equation (Fu, 1981; Zhang *et al.*, 2004):

$$\frac{E}{P+I} = 1 + \frac{E_0}{P+I} - \left[1 + \left(\frac{E_0}{P+I}\right)^{\omega}\right]^{1/\omega} \quad \text{or}$$
$$\frac{E}{E_0} = 1 + \frac{P+I}{E_0} - \left[1 + \left(\frac{P+I}{E_0}\right)^{\omega}\right]^{1/\omega} \tag{6}$$

where ω is a constant of integration with values range (1, ∞).

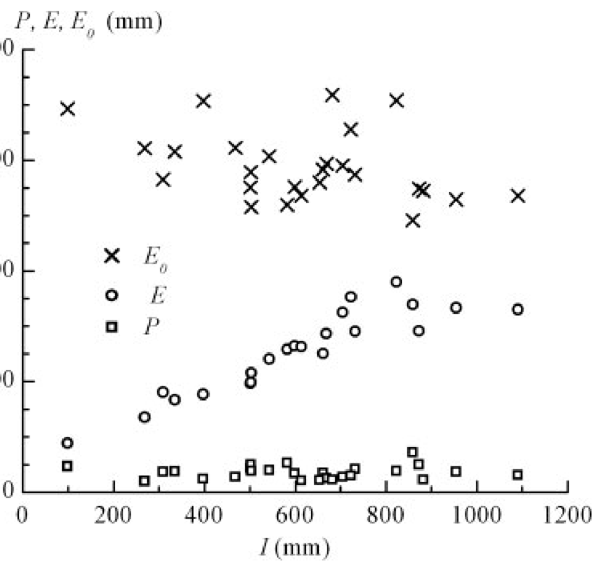

Figure 2. Plots of precipitation (P), calculated actual evapotranspiration (E) and potential evapotranspiration (E_0) with inflow from outside I for the 26 oases subregions in the Tarim Basin

RESULTS AND DISCUSSIONS

Extended Fu's curves for water balance

In this study, the extended Fu's formula was calibrated on two timescales. For the multi-year mean timescale, the parameter ω was calibrated using 4 or 5 years of mean water balance and climate data of all or part of the 26 oases subregions. For the annual timescale of each oases subregion, the parameter ω was calibrated using annual data series of water balance during the study periods shown in Table I.

Based on the 4- or 5-year mean water balance and climate data, Figure 3 shows the water–energy balance for the 26 oases subregions in two different but equivalent forms of Fu's curves: $E/(P+I)$ versus $E_0/(P+I)$ and E/E_0 versus $(P+I)/E_0$. The parameter $\omega = 2{\cdot}11$ was optimized by minimizing the square root of the mean square error (RMSE) of the estimated annual evapotranspiration. A high correlation (determination coefficient $R^2 = 0{\cdot}83$) and relative small prediction error (RMSE = 57·8 mm; mean absolute error MAE = 46·1 mm; mean relative error MRE = 9%) imply that Equation (6) can

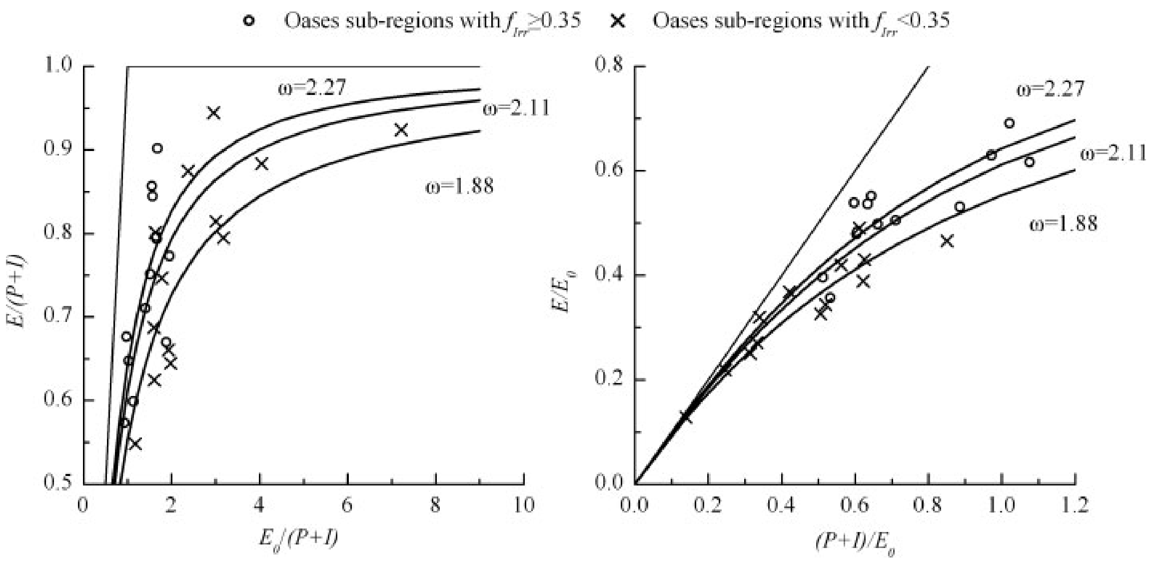

Figure 3. Two different but equivalent forms of the Budyko-type relations for the 26 oases subregions on the multi-year mean timescale (plotted as scatter plots) together with Fu's curves with optimized parameter ω

be used for predicting the actual evapotranspiration for the 26 oases subregions of Tarim Basin on the multi-year mean timescale.

To evaluate and validate the extended Budyko hypothesis for inter-annual variability of water–energy balance in the oases subregions, the predictability of the extended Fu's equation was examined further on an annual timescale. Using annual data series of water balance and average climate in relation to the study periods (Table I), the parameter ω for each oasis subregion was calibrated by minimizing the square-RMSE of the estimated annual evapotranspiration over 4 or 5 years. Figure 4 shows the cumulative distribution functions of MRE, MAE and RMSE for the predicted annual evapotranspiration. The ranges of MRE, MAE and RMSE for the 26 oases subregions were 1·3–12·7%, 4·66–57·33 mm and 4·93–77·37 mm, respectively. In 22 of the 26 oases subregions (81%), the values of MAE and RMSE are less than 45·42 mm and 49·33 mm, respectively. In conclusion, Fu's equation can be used to predict inter-annual change in water–energy balance using the optimized parameters.

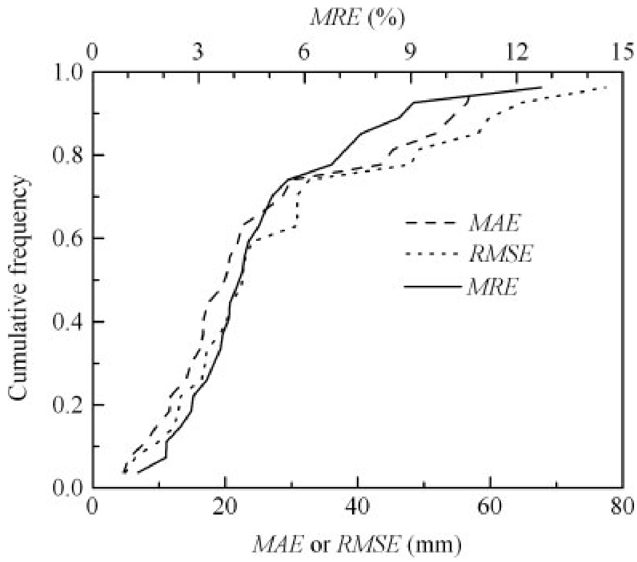

Figure 4. Statistical comparisons of the distributions of the mean relative error (MRE), the mean absolute error (MAE) and the square root of the mean square error (RMSE) for evaluating the estimated annual actual evapotranspiration using extended Fu's equation with calibrated parameters for 26 oases subregions

Influences of irrigation land use on annual water balance

The value of the parameter ω has been proven to be closely related to land-use types for catchments in humid areas (Zhang *et al*., 2001; Donohue *et al*., 2007; Zhang *et al*., 2007). In the oases, both irrigated and non-irrigated lands are supported by irrigation water withdrawal (Tang *et al*., 2006). If the proportion of irrigated land increases with other conditions kept constant, the groundwater recharge from irrigated land to non-irrigated land would increase and the discharge to surface drainage would decrease. As a result, the actual evapotranspiration over an oasis subregion increases. Therefore, water balance in the oases is influenced by land used for irrigation. In this study, the proportion of irrigated land area (f_{Irr}) is used as the index to reflect the conditions of land used for irrigation. The proportion of the sum of irrigated land and wetland area is employed for an oasis with wetlands, as much surface- or groundwater flow into the wetland, and the actual evapotranspiration over an oasis would increase if the proportion of wetland increases.

To evaluate the influences of land use on the parameter ω, the 26 oases subregions were divided into two groups according to the proportions of irrigation area (f_{Irr}). For each group, the parameter ω was optimized by minimizing the RMSE using the 4- or 5-year mean water balance and climate data. For the 13 oases with $f_{\mathrm{Irr}} < 0{\cdot}35$, the optimized parameter ω was 1·88; for the remaining 13 oases with $f_{\mathrm{Irr}} \geq 0{\cdot}35$ (Figure 3), $\omega = 2{\cdot}27$. The optimized parameter ω is large if the proportion of irrigated land area is high. In the left panel of Figure 3, the different regional features of Fu's curves can be seen more clearly, whereas in the right panel, these regional differences tend to be obscured, suggesting that actual evapotranspiration in the oases is governed more by water availability rather than potential evapotranspiration (Yang *et al*., 2007).

The 26 parameters for the oases subregions calibrated at annual timescales ranged from 1·68 to 3·15. A more detailed research is needed to examine the regional change for the parameters. The non-irrigated lands of an oasis can be divided into native vegetation area and wasteland. The proportion of wasteland area (f_{Waste}) is used to denote the influence of non-irrigated areas, while the proportion of the native vegetation can be determined from the residual term. This study selected the proportion of irrigated land and wasteland (f_{Waste}) to determine ω.

$$\omega = a + b f_{\text{Irr}} - c f_{\text{Waste}} \quad (7)$$

where the values of coefficients a, b and c should be greater than zero. By taking the logarithm of Equation (7), the values of the coefficients can be estimated by regression analysis. The final form of Equation (7) for the 26 oases subregions for the annual timescale becomes $\omega = 2{\cdot}40 + 0{\cdot}27 f_{\text{Irr}} - 0{\cdot}93 f_{\text{Waste}}$. This study applies the extended Fu's equation together with the parameter ω estimated by Equation (7) to predict the mean annual values of actual evapotranspiration for the 26 oases subregions. As indicated by the results in Figure 5, the predicted mean annual evapotranspiration in the 26 oases subregions can explain 97·4% of the variance of the observed values.

The extended Fu's equation together with the parameter ω estimated by Equation (7) can also be used to predict annual values of actual evapotranspiration using the annual data series of water balance and average climate. Figure 6 shows the cumulative distribution functions of MRE, MAE and RMSE for the predicted annual evapotranspiration. The ranges of MRE, MAE and RMSE for the 26 oases subregions were 1·9–17·9%, 7·20–90·18 mm and 9·16–107·46 mm, respectively. Although the results are not better than the calibrated parameter ω (Figure 4), it shows that the parameter ω can be estimated from regional characteristics by an empirical formula, i.e. Equation (7), without calibration, and that the extended Fu's equation is reliable and robust for predicting annual evapotranspiration in the Tarim Basin.

Different impacts of irrigation and E_0 variabilities on water balance

Irrigation water withdrawal, and potential evapotranspiration are the dominant controls of water balance for the oases in Tarim Basin. Actual evapotranspiration is affected by both natural and anthropogenic factors, as indicated by potential evapotranspiration and irrigation water withdrawal, respectively. The influence of irrigation water withdrawal variability on actual evapotranspiration can be analysed in a manner similar to the analysis of the impact of climate variability on water balance (Yang *et al*., 2006; Ma *et al*., 2008). For the oases, by neglecting the variability in precipitation, and with the steady state assumed as having a constant parameter ω, the variabilites in irrigation water withdrawal and potential evapotranspiration can lead to variabilities in actual evapotranspiration. The relationship can be approximated as

$$\delta E = \frac{\partial E}{\partial I}\delta I + \frac{\partial E}{\partial E_0}\delta E_0 \quad (8)$$

where δE is variability in actual evapotranspiration; δI is variability in lateral water inflow mainly dominated by irrigation water withdrawal, representing anthropogenic

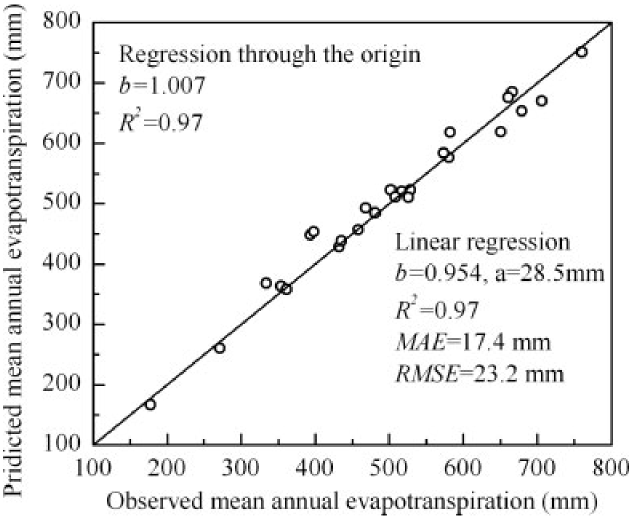

Figure 5. Predicted values of mean annual evapotranspiration using Fu's equation with the estimated parameter ω from the empirical formula plotted versus observed values. (The 1 : 1 line is plotted for comparison; and b denotes the slope of linear regression and a denotes the intercept)

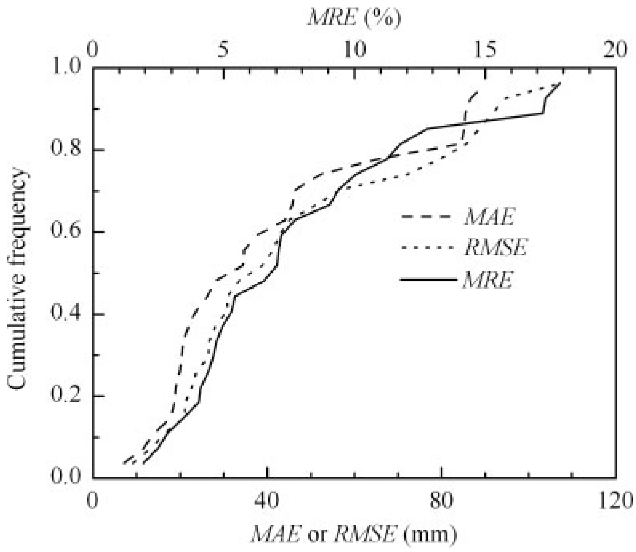

Figure 6. Statistical comparisons of the distributions of the mean relative error (MRE), the mean absolute error (MAE) and the square root of the mean square error (RMSE) for evaluating the estimated annual actual evapotranspiration using extended Fu's equation with parameters ω estimated by Equation (7) for 26 oases subregions

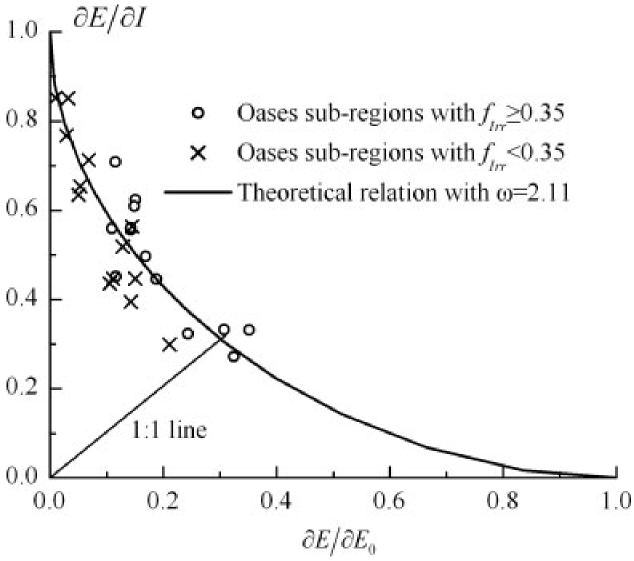

Figure 7. Comparison between $\partial E/\partial I$ and $\partial E/\partial E_0$ for the 26 oases subregions in the Tarim Basin

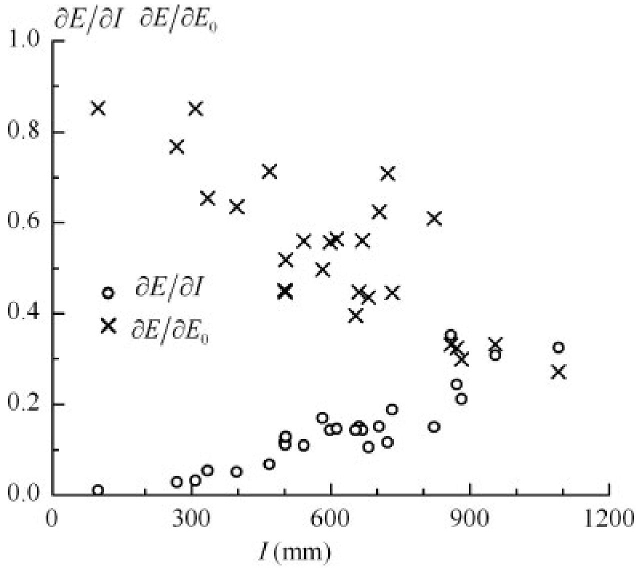

Figure 8. Plots of $\partial E/\partial I$ and $\partial E/\partial E_0$ with I for 26 oases subregions in the Tarim Basin

influences and δE_0 is variability in potential evapotranspiration, representing natural influences. The partial differential form of Equation (8) can be given as

$$\frac{\partial E}{\partial I} = 1 - \left[1 + \left(\frac{P+I}{E_0}\right)^{\omega}\right]^{\frac{1}{\omega}-1} \left(\frac{P+I}{E_0}\right)^{\omega-1} \quad (9)$$

$$\frac{\partial E}{\partial E_0} = 1 - \left[1 + \left(\frac{E_0}{P+I}\right)^{\omega}\right]^{\frac{1}{\omega}-1} \left(\frac{E_0}{P+I}\right)^{\omega-1} \quad (10)$$

The relative magnitude of $\partial E/\partial E_0$ and $\partial E/\partial I$ reflect the relative effect of δI and δE_0 on the variability in E. The magnitude of $\partial E/\partial I$ and $\partial E/\partial E_0$ of the 26 oases subregions were compared for the two groups along with the theoretical relationship in Figure 7. For most oases, the value of the sensitivity coefficient $\partial E/\partial I$ was much larger than the value of $\partial E/\partial E_0$, which means that the variability in actual evapotranspiration was dominated by the irrigation variability, rather than potential evapotranspiration variability. For the oases subregions with $f_{\mathrm{Irr}} < 0{\cdot}35$, $\partial E/\partial I$ was much larger than $\partial E/\partial E_0$. For the oases subregions with $f_{\mathrm{Irr}} \geq 0{\cdot}35$, the differences were not as evident.

Figure 8 shows the plots of $\partial E/\partial I$ and $\partial E/\partial E_0$ with respect to I for the 26 oases subregions. In extremely arid regions with minimal irrigation, the $\partial E/\partial I$ is much larger than $\partial E/\partial E_0$, which means that the variability in actual evapotranspiration are dominated by the variabilities in irrigation water withdrawal, whereas variabilities in E_0 result in little change in actual evapotranspiration. Along with increase in irrigation water withdrawal, there is an increase in $\partial E/\partial E_0$ and decrease in $\partial E/\partial I$, making the difference between the values of $\partial E/\partial I$ and $\partial E/\partial E_0$ decrease. This means that the influence of irrigation water withdrawal on actual evapotranspiration has become weaker, while the influence of potential evapotranspiration has become increasingly more apparent.

CONCLUSIONS

Taking the sum of lateral water inflow and precipitation as water availability, the Budyko hypothesis and Fu's equation derived from it could be extended to the study on the oases in the Tarim Basin, Northwest China. By analysing annual water balance for the 26 oases subregions, the extended Fu's formula was validated for both multi-year water balance and annual water balance per individual oasis. As indicated by the results, the extended Fu's equation could accurately predict multi-year means and inter-annual actual evapotranspiration for the oases.

The Budyko-type curves plotted for the 26 oases subregions showed significant regional patterns. It is apparent that in addition to mean climate conditions, the regional features of water balance were related to land-use types. This was especially evident for the fractional irrigation area and fractional wasteland. Through a regression analysis, an empirical formula on parameter ω was derived and finally proved to be used to accurately predict the annual actual evapotranspiration.

The different influences of variabilities in irrigation and potential evapotranspiration on actual evapotranspiration were analysed and compared. For most oases, the value of the sensitivity coefficient $\partial E/\partial I$ was much larger than the value of $\partial E/\partial E_0$, which means that the variability in actual evapotranspiration was dominated by irrigation variability rather than potential evapotranspiration variability. Nevertheless, the influences of potential evapotranspiration variabilities have become increasingly apparent along with increases in irrigation water withdrawal.

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