Evaluating actual evapotranspiration and impacts of groundwater storage change in the North China Plain

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Abstract:

As a critical water discharge term in basin-scale water balance, accurate estimation of evapotranspiration (ET) is therefore important for sustainable water resources management. The understanding of the relationship between ET and groundwater storage change can improve our knowledge on the hydrological cycle in such regions with intensive agricultural land usage. Since the 1960s, the North China Plain (NCP) has experienced groundwater depletion because of overexploitation of groundwater for agriculture and urban development. Using meteorological data from 23 stations, the complementary relationship areal evapotranspiration model is evaluated against estimates of ET derived from regional water balance in the NCP during the period 1993–2008. The discrepancies between calculated ET and that derived by basin water balance indicate seasonal and interannual variations in model parameters. The monthly actual ET variations during the period from 1960 to 2008 are investigated by the calibrated model and then are used to derive groundwater storage change. The estimated actual ET is positively correlated with precipitation, and the general higher ET than precipitation indicates the contributions of groundwater irrigation to the total water supply. The long term decreasing trend in the actual ET can be explained by declining in precipitation, sunshine duration and wind speed. Over the past ~50 years, the calculated average annual water storage change, represented by the difference between actual ET and precipitation, was approximately 56 mm, or 4.8 km²; and the cumulative groundwater storage depletion was approximately 1700 mm, or 220 km² in the NCP. The significantly groundwater storage depletion conversely affects the seasonal and interannual variations of ET. Irrigation especially during spring cause a marked increase in seasonal ET, whereas the rapid increasing of agricultural coverage over the NCP reduces the annual ET and is the primary control factor of the strong linear relationship between actual and potential ET. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS actual evapotranspiration; complementary relationship; groundwater storage change; North China Plain

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INTRODUCTION

In assessing freshwater availability in catchment scale, the commonly used measurement is to use mean annual river runoff to represent the difference between precipitation and evapotranspiration (ET) (Falkenmark et al., 1989). The equivalence of this difference to the net annual contribution of water from atmosphere to land is based on the assumption that water storage change be negligible. However, this assumption is questionable particularly because climate changes have affected the hydrological system significantly (Taylor, 2009). Remarkable falling in groundwater levels in the North China Plain (NCP) clearly denotes the imbalance between water demand and availability. The precise characterization of actual evapotranspiration (ETₐ) at especially large spatial scales is needed for understanding of hydrological cycle and water resources management, such as water balance calculation, efficient irrigation scheduling and water resources planning (Song et al., 2010). In the NCP, where irrigation agriculture almost consumes 70% of total water supply, 70–80% of which comes from groundwater pumpage (Zheng et al., 2010), accurate estimation of regional ET and agricultural water use are critical for sustainable water resources development. ET is the only term that appears both in a land surface energy balance equation and a water balance equation (Xu and Singh, 2005). Irrigation can influence water and energy budget by transforming ET boundary conditions from water (moisture)-limited to energy-limited (Taylor et al., 2012). The estimations of groundwater storage and its feedback to ET therefore are important in assessing the groundwater budget to develop more sustainable groundwater management plans.

Direct measurement of ETₐ at regional scale is difficult because it is time-consuming and expensive (Allen et al., 1998). Because of complexity of the land–plant–atmosphere system, estimating ETₐ at basin scales is fundamentally difficult. Several methods have been proposed for quantifying ETₐ in the NCP using meteorological, energy balance and remote sensing techniques (e.g. Mo et al., 2005; Lin et al., 2008; Wang et al., 2008; Wu et al., 2008; Tian et al., 2009; Zhao et al., 2009; Zhang et al., 2010a; Moiwo et al., 2011b). More studies employed the Food and Agriculture Organization Penman–Monteith method (Allen et al., 1998) to estimate the crop reference
ET (ET\(_0\)) (Yang et al., 2009a; Song et al., 2010; Zhang et al., 2010b; Wang et al., 2011a). Actual ET is then estimated by multiplying ET\(_0\) by a crop coefficient (\(K_c\)) (Liu et al., 2002; Han et al., 2005). However, there are rare studies to estimate regional ET\(_a\) in a long-term scale, which are particularly important for assessing the primary factors affecting the ET and the relationship between ET and groundwater storage.

When long-term period of standard meteorological data is available while variations in crop coefficient cannot be obtained, methods employing the complementary relationship (hereinafter CR) of ET (Boucet, 1963) seem the most suitable methods for estimating regional ET\(_a\) (McMahon et al., 2012). These methods bypass the complex plant–soil system and only require routine meteorological data. Despite some debates with respect to the symmetric relationship used in these models (Huntington et al., 2011), the CR has been widely used to estimate regional ET in terms of different climate conditions (Hobbins et al., 2001; Xu and Singh, 2005) and has been evaluated through comparison with other ET estimation methods (Doyle, 1990; Lemeur and Zhang, 1990; Chiew and McMahon, 1991; Yang et al., 2006). The results of all these studies provided support evidence of the physical basis of the CR. Moreover, modified ET models requiring less meteorological data (e.g. Crago et al., 2010) can be used to estimate historic and predict future ET variation, which are great challenges for remote sensing methods.

The direct way to estimate groundwater storage change is to use groundwater level changes monitoring data multiplying by the specific yield (McGuire, 2009; Wang, 2012). The reliability of this estimation depends on the accuracy of the specific yield, the coverage and representativeness of the monitoring network and wells. Groundwater levels in the monitoring wells in the NCP are severely affected by the nearby groundwater pumping; therefore, groundwater storage depletion may be overestimated using this method. The reliable estimations of ET could assess to estimation of groundwater storage change (Moiwo et al., 2011a). The primary objective of this work is to evaluate the ET variations and the feedback of groundwater storage during the past ~50 years in the NCP. For this purpose, the ET\(_a\) calculated using the model based on CR is firstly validated by ET derived by basin water balance during a sub-period when monthly time series of groundwater level are available. And then, the ET\(_a\) is calculated during the period of 1960 to 2008 and is used to derive the groundwater storage change in this period. Seasonal and long-term variations of ET\(_a\) and the primary weather variables are analysed to evaluate the primary controlling factors of ET\(_a\). The results of this study can be used to evaluate the changes in components of hydrological cycle and the sustainability of water resources development in the NCP and provide an alternative to estimate regional ET\(_a\) in semiarid agricultural regions relying on groundwater irrigation such as the NCP.

**STUDY AREA**

The NCP refers to the plain bounded on the north by the Yanshan Mountains, on the east by the Bohai Sea, on the south by the Yellow River and on the west by the Taihang Mountains, covering ~140,000 km\(^2\) in northeast China (Figure 1). The NCP is primarily located in Hebei Province and also covers main plain parts of Beijing and Tianjian, and parts of plains of Shandong and Henan Provinces. The NCP accounts for only ~1.5% of China’s total land area but supports ~10% of China’s total population, making it one of the regions with most population density in the world. The NCP contributes ~12% of China’s gross domestic product and ~10% of total grain production as one of its most important economic regions (Zheng et al., 2010). With rapid population growth, industrialization and urbanization, water shortage and groundwater overexploitation has been the critical constrain to sustainable development in this region (Liu and Xia, 2004; Liu et al., 2008).

The climate in the NCP is continental semi-arid, with annual temperature of 12–13 °C and annual precipitation of 400–700 mm (Chen et al., 2003). The precipitation influenced by the East Asia monsoon decreases from southeast to northwest, and approximately 70–80% of precipitation occurs during the monsoon season from June to September (Chen, 1999). Snow contributes the majority of the precipitation in winter, but generally melts in 2–3 weeks (Wang et al., 2011b). The mean annual pan evaporation ranges from 1100 to 2000 mm (Chen et al., 2005), which is measured by the diameter 20 cm of the evaporation pan.

**DATA AND METHODOLOGY**

Assuming that interbasin groundwater flow is limited, a basin-scale water balance can be written as follows (Zhang et al., 2001; Moiwo et al., 2011a):

\[
P = ET + R + \Delta S
\]

where \(P\) is the precipitation, \(ET\) is the evapotranspiration, \(R\) is the net runoff and \(\Delta S\) is the total water storage, including soil water storage change and groundwater storage change. In the NCP, irrigation from groundwater abstraction is mainly lost through ET, and the groundwater recharge from precipitation and irrigation return flow is considered as internalized water redistribution, which is implicitly accounted for in Equation (1).

Extensive land exploitation and surface water development has caused rapid runoff decreasing since the 1960s (Shao et al., 2010; Wu et al., 2011). By the 1980s, runoff in the basin has been reduced to insignificant level with no surface flow in most river channels for most time of the year (Wu et al., 2011). Under these hydrologic conditions and the flat topography in the NCP, runoff in Equation (1) can therefore be ignored, and the balance equation can be modified and re-arranged as

\[
\Delta S = P - ET
\]

The challenge in the water balance is the estimation of ET over a long period, the reason why in this work the
CR (Bouchet, 1963; Granger and Gray, 1989) was adopted. The CR between $ET_a$ and potential evapotranspiration ($ET_p$) (Bouchet, 1963) is described as follows:

$$ET_a + ET_p = 2ET_w$$  \hspace{1cm} (3)

where $ET_a$ is the actual evapotranspiration, $ET_p$ is the potential evapotranspiration and $ET_w$ is the wet environmental evapotranspiration. The $ET_w$ is defined as the evapotranspiration from the saturated soil–plant surface under limited energy but abundant water supply and normal atmospheric conditions (e.g. Priestley and Taylor, 1972; Ramírez et al., 2005).

The most widely know models derived using the CR are the advection-aridity model (Brutsaert and Stricker, 1979), the complementary relationship areal evapotranspiration (CRAE) model (Morton, 1983) and the CR model proposed by Granger and Gray (1989) (named as GG) using a parameter defined as the relative ET (the ratio of actual to potential ET). The original form of the CRAE model presented by Morton (1983) was used in this study. Morton (1983) decomposed the Penman equation (Penman, 1948) into two separate parts describing the energy balance and vapour transfer process. The ‘equilibrium temperature’, $T_p$,

which was obtained by iteration, was introduced to calculate the potential evapotranspiration $ET_p^{CRAE}$:

$$\lambda ET_p^{CRAE} = Q_n - \left[ \gamma f_T + 4\varepsilon\sigma T_p^3 \right] (T_p - T)$$  \hspace{1cm} (4)

in which, $T_p$ and $T$ are the equilibrium and air temperature, respectively, $\varepsilon$ is the surface emissivity, $Q_n$ is the net radiation at air temperature, $\sigma$ is the Stefan–Boltzmann constant and $f_T$ is the vapour transfer coefficient.

Morton (1983) modified the Priestley–Taylor partial equilibrium ET equation (Priestley and Taylor, 1972) to account for the temperature dependence of both the net radiation term and the slope of the saturated vapour pressure curve. The Priestley–Taylor equation was transformed by a constant multiplier $b_2$ and an additive constant $b_1$:

$$\lambda ET_w^{CRAE} = b_1 + b_2 \frac{\Delta_p}{\Delta_p + \gamma} Q_{TP}$$

$$= b_1 + b_2 \frac{\Delta_p}{\Delta_p + \gamma} \left[ Q_n - 4\varepsilon\sigma T_p^3 (T_p - T_a) \right]$$  \hspace{1cm} (5)

where $\Delta_p$ and $Q_{TP}$ are the slope of the saturated vapour pressure curve and the net available energy adjusted to the equilibrium temperature.
In implementing the CRAE model on a monthly basis, the ground heat flux is neglected, and ET$_a$ is calculated as a residual of Equation (3) after that ET$_p$ and ET$_w$ are determined by Equations (4) and (5), respectively.

The meteorological monitoring network in this study included 23 stations across the NCP (Figure 1 and Table I), maintained by China Meteorological Administration. Most stations have continuous data records since 1957, and the data records are updated continuously. Monthly data, including precipitation ($P$), maximum, minimum and average air temperature ($T_{\text{max}}$, $T_{\text{min}}$ and $T$), wind speed measured at 10 m height, relative humidity ($RH$) at 2 m height and sunshine duration were obtained from China’s Monthly Surface Climate Data Set (http://cdc.cma.gov.cn/, accessed in January, 2012). Wind speed was adjusted to 2 m height ($U_2$) using the wind profile relationship given by Allen et al. (1998). The meteorological data set is in discrete format, i.e. point values for station locations. To estimate areal ET, point values of these variables were interpolated to a grid of 320 rows and 300 columns with a uniform 2-km cell size. Because the station networks in this study cannot support the semivariogram estimation, an inverse distance scheme was used in the interpolation procedure. Monthly ET was calculated at each resulting grid cell, and the annual ET was obtained by summing up the monthly values. Monthly average data value was estimated as the mean of the average monthly maximum and average monthly minimum data values. Dew point temperature ($T_{\text{dew}}$) required by the CRAE model was calculated using temperature and $RH$ as (Allen et al., 1998)

\[
T_{\text{dew}} = \frac{237.7 \gamma(T, RH)}{17.27 - \gamma(T, RH)}
\]

\[
\gamma(T, RH) = \frac{17.27T}{237.7 + T} + \ln(RH/100)
\]

where $T$ is air temperature in degrees Celsius and $RH$ is the relative humidity.

RESULTS AND DISCUSSION

Model calibration and validation

The advantage of the complementary models is that they do not require any parameter calibration and is only true in local scale (Hobbins et al., 2001). Some studies have shown that the model parameters vary both spatially and temporally (Yang et al., 2008, 2009b). The ET$_a$ calculated by the CRAE model is compared with the ET$_a$ derived using Equation (2) when available data of groundwater level change and specific yield to estimate the storage change ($\Delta S$) during the period of 1993–2008. Calculated annual rates of ET$_a$ with original $b_1$ and $b_2$ values are shown in Table II and plotted in Figure 2a. The ET$_a$ rates calculated by the CRAE model illustrate a smoother fluctuation than that calculated by water balance (Figure 2a). The relative discrepancy between mean annual ET$_a$ calculated by model and water balance is ~16%. The discrepancies are larger than the mean annual value in 1997, 1999 and 2002 with annual precipitation less than 400 mm, and in 2006 with precipitation of

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<th>Longitude</th>
<th>Altitude (m)</th>
<th>$P$ (mm)</th>
<th>$T_{\text{max}}$</th>
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Table II. Annual ETa calculated by basin water balance and the CRAE model with original and calibrated model parameters (b1 and b2)

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CRAE, complementary relationship areal evapotranspiration.

424 mm. The maximum discrepancy occurs in 1999, with relative discrepancy of 60%. The aforementioned results indicate that the ETa calculated by the CRAE model respond slower than that calculated by water balance to the climate change, which is also shown in its application in the Yellow River basin (Liu et al., 2004).

To verify the results obtained from different model parameters, two parameters calibrations were performed. First, model parameters (b1 and b2) were calibrated using ETa calculated by annul water balance. Second, one set of parameters for each year were calibrated using the ETa obtained by the water balance with other parameters unchanged. The calibrated parameters of the second procedure can then give the temporal variations of model parameters. The parameters calibration procedure was conducted using the automated Parameter ESTimation (PEST) code (Doherty, 2003) to minimize the sum of square of residuals (water balance derived ETa minus that calculated by the model) through automatically adjusting of b1 and b2. Calculated ETa with calibrated model parameters are presented in Table II and Figure 2a. The relative discrepancy between mean annual ETa calculated and water balance is reduced to ~1%. The parameters of b1 = 14.00 and b2 = 1.20 in Equation (7) are changed to 13.15 and 1.15.

With calibrated parameters, the discrepancies are still larger than the mean annual value in 1997, 1999 and 2002 with annual precipitation less than 400 mm.

The temporal variations of model parameters were obtained by minimizing the discrepancy between ETa calculated by the model and water balance in each year. To calibrate parameters automatically using PEST, the number of parameters is required less than observations (ET calculated by water balance). Therefore, only the b2 in the CRAE were calibrated with b1 unchangeable through calibration. When the discrepancy between the ETa calculated by model and annual water balance (closely to zero achieved in this study) achieves its minimum, the corresponding parameters are treated optimal for application of the model in that year. Interannual variations of b2 show a positive correlation with precipitation (Figure 2b). The obtained optimal b2 value of the CRAE model ranges from 1.11 to 1.21, except 1.06 and 1.02 in 1997 and 1999, respectively.

Figure 3 presents time series of seasonal ETa calculated by water balance and by the CRAE model with calibrated parameters along with seasonal precipitation from 1993 to 2008. The water storage change in the NCP is primarily driven by the groundwater storage change (Moiwlo et al., 2009). Because recharge, precipitation and groundwater extraction are the primary input and output terms for the groundwater system, there exists a clear correspondence of storage change with precipitation and groundwater extraction, with highest value in summer (highest precipitation) and lowest value in spring (highest groundwater extraction). A good agreement was obtained between the ETa calculated by the CRAE model and by water balance (Figure 3a). The mean error and root mean square error were 2.7 mm and 21.6 mm, respectively. In the NCP, ~80% of annual precipitation is captured in summer (June–August), during which the temperature is also highest. This explains the high correlation of ETa and precipitation in seasonal scale (R = 0.93) (Figure 3b), which supports the CR in non-humid regions (Yang et al., 2006; Yang et al., 2007). In the NCP, spring is the primary crop growing season when great amount of water is required. Figure 3b indicates that calculated ETa is higher than precipitation in spring, and the additional water consumed by ET comes from soil water. ETa generally is lower than precipitation in summer season.
except the dry year of 1999 and 2002. The ET_a calculated by the CRAE model is generally higher than that estimated by the ETWatch model (Wu et al., 2008; Moiwo et al., 2011b; Wu et al., 2012) using remote sensing data (Figure 4). The failure of capturing the ET peak in May and the higher summer ET_a in dry years are likely caused by the annual averaged \( b_1 \) and \( b_2 \) that are used while their seasonal variations can significantly impact the estimated ET_a (Yang et al., 2009b).

The relationship between pan ET (ET_{pan}) and regional ET_a is apparent in Figure 5, which contains 42 data pairs, each consisting of an annual average of ET_{pan} at 23 meteorological stations and an annual average of ET_a across the NCP estimated by the CRAE model. The highest values of ET_{pan} occur at the left part of the graph (water limited environment). Moving to the right with more water supply, the water limitation on the evaporative process transforms to an energy limitation, and ET_{pan} decreases as ET_a increases. In general, ET_{pan} and ET_a rates converge in the wettest environment, where the purely energy-limited ET_w can be obtained. Irrigation as additional source of total water supply except precipitation can transform areas from water-limited to energy-limited ET, thereby influencing water and energy budget. Because the cultivation in the NCP is dominated by groundwater fed, the feedback of groundwater storage change on the ET should be evaluated both in seasonal and long-term scale.

Seasonal variations of evapotranspiration and driving variables

The variation trends in ET_p and ET_{pan} were not in accordance with that of ET_a, showing the largest ET_a in July and the largest ET_{pan} in June (Figure 6). Large ET_p or ET_{pan} does not necessarily correspond to large terrestrial ET_a; conversely, they are often indicators of large drying power of the air and thus small ET_a. ET_{pan} and ET_a are slightly positively correlated to changes in measured soil moisture in winter months (December–February) because of energy-limited conditions (Figure 7). As the ET_a and ET_{pan} increase during spring months (March–May) because of increased \( Q_s \) and drying power, ET_a increases significantly (that simulated by ETWatch reached a peak in May); the rapid increase of ET_a during this period was likely due to the utilization of groundwater for winter wheat irrigation. During early summer (June), the soil moisture is slightly increased (continuing to decrease with smaller slope in dry years) because of the increase in precipitation (Figure 7);
ET_p and ET_pan reach their annual maximums because of increase in \( Q_n \) and drying power, but the ET_a increase slightly (decrease in the ETWatch simulation) because of significant decrease in irrigation. During middle and late summer (July and August), soil moisture significantly increases because of summer monsoon precipitation; ET_a reaches the annual maximum and drying power, and hence, ET_p and ET_pan are significantly reduced because of the increase in ET_a. Fall months (September–November) experience a general decrease in ET_a following the general decrease in ET_p and ET_pan. During this period, there is a marked increase in soil moisture. These rapid land surface and lower boundary layer feedbacks are remarkably captured by the CRAE model in the prediction of ET as illustrated in Figures 6 and 7. Average annual precipitation during this period is 520 mm, whereas the ET_a is 540 mm, indicating consumption groundwater for irrigation. The CRAE model is able to predict the variations in ET_a and ET_p in the NCP where they are correlated not only with precipitation but also irrigation by groundwater.

Plots of basin-wide mean monthly of ET_a versus meteorological data highlight a considerable scatter within the ~50-year datasets (Figure 8). Wind speed (\( U_2 \)) exhibits an anticlockwise loop variation (Figure 8a). Wind speed
shows a general increasing trend from January to April and then decreases to the minimum in August because of crop cultivation and then shows a slight increasing trend from September to December. Mean monthly air temperature ($T$) reaches peak in July with a minimum in January (Figure 8b), and the ET$_a$ shows accordingly a parabolic increase from January to July and then decreases. RH exhibits a clockwise loop variation (Figure 8c): increasing from January to July, and then decreasing from August to December. The relationship between ET$_a$ and sunshine duration is more dispersed (Figure 8d). Seasonal patterns of metrological data in the NCP basically reflect the climate characteristics of north China, indicating the controlling effects of the climate change on ET.

Long-term variations of evapotranspiration and driving variables

Figure 9 presents the temporal trend of the mean calculated ET$_a$ and main meteorological variables in summer season and the relationship with ET$_a$. The variations of relative sunshine duration, wind speed and RH present variations of the available energy, aerodynamic resistance and saturation deficit, respectively. The relative sunshine duration exhibits a similar decreasing trend with the ET$_a$ (Figure 9a), which is believed to be the most parameter contributing to the ET decrease in the NCP (Song et al., 2010; Wang et al., 2011a). The decline in solar radiation possibly can be explained by larger cloudy coverage and increasing aerosol concentration caused by human activities (Cong et al., 2009; Liu et al., 2010). As shown in Figure 9b, the wind speed is the second contribution to the declining trend in ET$_a$. Decreased wind velocity leads to direct reduction in eddy diffusivity, which causes evaporative demand to decline. Decrease in wind velocity is a global issue (McVicar et al., 2008; Bichet et al., 2012; Chen et al., 2012). The reasons for the decrease in wind speed are complicated but mainly lie in the increases in roughness caused by increasing vegetation (Ozdogan and Salvucci, 2004; Bichet et al., 2012) and decreases in the aerodynamic component (Rayner, 2007). Significant decreasing in wind speed associated with increasing local vegetation (Figure 7) suggests the possible potential impact of irrigation on local wind speed and then ET$_a$ in the NCP.

The variation of air temperature shows an interesting relationship with ET$_a$ (Figure 9c). The summer air temperature shows an overall increasing trend after 1970, and most of the increase occurred after 1990. However, the calculated ET$_a$ does not show an increasing trend correspondingly. This contrast between ET and air temperature is consistent with that for ET$_{pan}$ observed over the past 50 years overall the world (e.g. Peterson et al., 1995; Cong et al., 2009), which is called ‘evaporation paradox’ (Brutsaert and Parlange, 1998). This indicates that the impact of air temperature is altered by changes in solar radiation and wind speed and other possible sources for total water supply.

As shown in Figure 9d, the RH would be the most sensitive variable to ET$_a$: large value of RH corresponds to large ET$_a$, whereas small values of RH corresponds to small ET$_a$. This sensitivity of ET$_a$ to humidity can also support the domination of humidity on monthly ET$_a$ distribution (Figure 6). However, its contribution to long-term declining of ET$_a$ should be small because of its relative small variation range.

Evapotranspiration and water storage change trend over the past 50 years

The potential and actual ET is calculated with the CRAE model using calibrated parameters for the period 1960 to 2008. Figure 10 presents the average of annual
Although variations of calculated ET\textsubscript{a} show an obvious high continuous dry years around 1980. As shown in Figure 11, were the periods with low precipitation, with obvious increasing trend. The 1980s and the past 10 years after 1997 lower than that in the 1960s, there was still a slight occurrence in the 1960s with larger interannual variability. In the 1970s, although the mean annual precipitation was

\begin{table}[h]
\centering
\begin{tabular}{lccccc}
\hline
\hline
\textbf{P (mm)} & 554 & 589 & 557 & 580 & 489 \\
\textbf{ET\textsubscript{a} (mm)} & 590 & 630 & 603 & 578 & 524 \\
\textbf{ET\textsubscript{pan} (mm)} & 1377 & 1461 & 1328 & 1298 & 1802 \\
\textbf{ET\textsubscript{p} (mm)} & 1388 & 1399 & 1378 & 1380 & 1389 \\
\textbf{ET\textsubscript{a} – P (mm)} & 36 & 41 & 47 & –2 & 34 \\
\hline
\end{tabular}
\caption{Table III. Mean annual precipitation (P), measured pan evaporation (ET\textsubscript{pan}), calculated potential evapotranspiration (ET\textsubscript{p}) and actual evapotranspiration (ET\textsubscript{a}) and (ET\textsubscript{a} – P) for different periods}
\end{table}

ET\textsubscript{p} values calculated by the CRAE model and mean ET\textsubscript{pan} in the NCP. Although the ET\textsubscript{pan} shows an overall decreasing trend over the past ~50 years, the variation trend varied in different period (Table III). The ET\textsubscript{pan} was higher in the 1960s with a peak occurring in 1968 and began to decrease since then to its lowest value in 1990, and then increased slightly from 1991 to 2001, even the sunshine duration continued decreasing (Figure 9a). This kind of trend of ET\textsubscript{pan} is similar with the overall trend across China (Liu et al., 2011). In the NCP, decreased in wind speed controlled the decreasing of ET\textsubscript{pan} from 1960 to the early 1990s, whereas increased in air temperature dominates the increases in ET\textsubscript{pan} from the early 1990s to the present (Liu et al., 2011). The calculated ET\textsubscript{p} is close to the ET\textsubscript{pan} with low root mean square error of 80 mm and also shows a slight decreasing trend, reducing from over 1500 mm in 1968 to approximately 1350 mm in 2008. The long-term declining trend in ET\textsubscript{p} and ET\textsubscript{pan} and increasing trend in irrigated area, particularly in the 1960s and 1970s, suggests the influence of irrigation on ET conditions.

Although a long-term decreasing trend in summer precipitation in the NCP has been reported by some literatures (e.g. Piao et al., 2010; Zhang and Feng, 2010; Liu et al., 2012), this trend is not significant for annual precipitation (Figure 11, Table III). Highest precipitation occurred in the 1960s with larger interannual variability. In the 1970s, although the mean annual precipitation was lower than that in the 1960s, there was still a slight increasing trend. The 1980s and the past 10 years after 1997 were the periods with low precipitation, with obvious continuous dry years around 1980. As shown in Figure 11, although variations of calculated ET\textsubscript{a} show an obvious high correlation with precipitation (R = 0.75), the interannual variability in the ET\textsubscript{a} is relatively gentle. Because runoff in the NCP has heavily reduced, precipitation and ET are the principle input and output terms for the entire study area. Calculated ET\textsubscript{a} generally exceeds precipitation when annual precipitation is lower than 500 mm. This can be explained by the great amount of applied irrigation from pumped groundwater, particularly in dry years. Despite irrigation return flow that may contribute part of groundwater recharge, the net effect of irrigation is negative: irrigation water except which percolate to groundwater is lost by ET. Therefore, because groundwater storage change is the primary provider to total water storage and long-term average soil storage change is relatively small in the NCP (Moiwo et al., 2011a), the difference between ET\textsubscript{a} and precipitation (ET\textsubscript{a} – P) can represent groundwater storage change. Average annual ET exceeds the precipitation, i.e. average annual groundwater depletion is approximately 36 mm (Table III), or in volume of 4.8 km\textsuperscript{3}. In the past ~50 years, the total groundwater depletion is ~1700 mm, or in volume of 220 km\textsuperscript{3} in the NCP. Figure 11 also indicates an annual threshold precipitation of approximately 500–600 mm, and approximately 8% of precipitation which is higher than this threshold will become potential recharge. The result is comparable with recharge estimation using environmental traces (Wang et al., 2008a).

Figure 12 shows annual ET\textsubscript{a}/P versus ET\textsubscript{a}/P in the Budyko (1974) framework for the NCP. The unit slope line from the left represents a theoretical upper limit for the ET\textsubscript{a}/P values in humid regions where ET\textsubscript{a} is energy limited, and the horizontal line is the upper limit in arid regions where ET\textsubscript{a} is water limited (Szilagyi and Joza, 2009). Compared with the case ignoring groundwater storage change (ET\textsubscript{a}/P = 1 derived from Equation (2) by ΔS = 0), the data points tend to move upward for large values of aridity index but move downward for small
values of aridity index because of the effects of groundwater storage change. For northwest China with similar climatic characteristics as the NCP, Han et al. (2010) estimated the total water supply as the sum of annual precipitation and irrigation. During the dry years with annual $P < 550$ mm (the mean annual precipitation over past ~50 years), $ET_a$ exceeded the annual precipitation, indicating that total water supply is affected by irrigation from groundwater withdrawal and assumption of soil water storage (Figure 7). Although the long term decline in $ET_a$ is slightly different with the variations of $ET_p$ and $ET_{pan}$ (Figure 10), a strong linear relationship between $ET_a/P$ and $ET_{pan}/P$ ($R^2 = 0.85$) is presented, which was also observed across the United States (Cheng et al., 2011; Wang, 2012). Soil water storage and agricultural land usage are the primary control factors of the interannual relationship between $ET_a/P$ and $ET_{pan}/P$ (Cheng et al., 2011). Catchments with higher agricultural land coverage generally have stronger linear relationship, especially in semiarid regions with intensive irrigation (Cheng et al., 2011). Therefore, the high crop cultivation coverage in the NCP (Figure 1) can explain explicitly the strong relationship between $ET_a/P$ and $ET_{pan}/P$, which may allow prediction of $ET_a$ using precipitation and $ET_p$ data.

CONCLUSIONS

The regional $ET_a$ in the NCP is estimated using the CRAE model based on the CR. Model calibrations using $ET_a$ estimations from basin water balance from 1993–2008 indicated a clear interannual variation in model parameters highly related to precipitation. Good agreement between $ET_a$ calculated by basin water balance and using remote sensing data and by the CRAE model using calibrated parameters both in annual and seasonal scale verified the model applicability in semiarid region with large agricultural land coverage. Using calibrated parameters, the CRAE model was used to determine the variation of the annual $ET_a$ for the period from 1960 to 2008. The calculated $ET_p$ by the CRAE model was close to pan ET showing an ‘evaporation paradox’ relationship before 1990 and increased slightly after that along with the considerable increase in air temperature. The great amount of applied irrigation from groundwater withdrawal tended to transform water-limited to energy-limited ET and increased significant increase seasonal ET. However, over the entire study period, the $ET_a$ presented a long-term declining trend that was controlled by decline in precipitation (especially in the past ~10 years), sunshine duration and wind speed, indicating that the $ET_a$ in the NCP is still controlled by the combined effects of total water, energy supply and human activities.

Considering water storage change in the NCP is dominated by change of groundwater storage; the amount of $ET_a$ exceeds the precipitation ($ET_a – P$) can be used to represent groundwater depletion. Over the past ~50 years, the total groundwater depletion was ~1700 mm, or 220 km$^3$ in the NCP. The significant contribution of groundwater storage to the total water supply can explain the generally higher ET than precipitation. This appeared to be an annual precipitation threshold of approximately 500–600 mm, and approximately 8% of annual precipitation with higher threshold will potentially become groundwater recharge. Considering the reliability of the CR model, those kind methods can provide a valuable alternative to estimate regional $ET_a$ for water balance analysis and forecast and then sustainable water resources management semiarid agricultural regions relying on groundwater irrigation such as the NCP.

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