Evaluation and modification of potential evapotranspiration methods in Beijing, China

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Abstract: In this study, seven widely used potential evapotranspiration (ETo) methods were evaluated by comparing with the FAO-56 Penman-Monteith method (PM method) to provide useful information for selecting appropriate ETo equations under data-limited condition in Beijing, China. Statistical methods and parameters, namely linear regression, root mean squared error (RMSE) and mean bias error (MBE), were used to evaluate the seven ETo methods. Results showed that ETo estimated using Kimberly–Penman method have fairly close agreement with the PM method (referring to standard ETo), considering the coefficient of determination (R^2) of 0.96, RMSE of 0.42 mm/day, and a coefficient of efficiency (E) of 0.96. Locally calibrated Penman and Doorenbos–Pruitt methods also have better agreement with the PM method, correspondingly with R^2 of 0.99 and 0.95, RMSEs of 0.24 mm/day and 0.21 mm/day, and coefficients of efficiency of 1.02 and 0.99, respectively. The ETo is the most sensitive to vapor pressure deficit (VPD) and net radiation in the Beijing area. Hence, the VPD-based and VPD-radiation combined ETo methods were developed and calibrated. Results showed that the two developed methods performed well in ETo estimation. By fully considering the data-limit situation, the calibrated Turc method, VPD-based method and VPD-radiation-combined method may be attractive alternatives to the more complex Penman−Monteith method in Beijing.

Keywords: potential evapotranspiration, Penman-Monteith method, determination coefficient, coefficient of efficiency, Beijing
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1 Introduction

Potential evapotranspiration (ETo) is a basic factor for studying water cycle in ecology system, calculating water balance and making irrigation schedule[1-7]. Accurately measuring and calculating ETo is important for efficiently allocating water resources, saving water and improving water use efficiency in a river basin or irrigation districts. Therefore many methods for calculating ETo have been developed mainly during the last century, such as FAO-56 Penman-Monteith method (PM method)[8], Penman method[9], Hargreaves method (Har method)[10], Turc method[11], Priestley-Taylor method (PT method)[12], Makkink method (Mak method)[13] and Doorenbos–Pruitt method (DP method)[14]. Some methods derived from Penman method also have been developed, such as Kimberly–Penman method (KP method), ASCE–PM method, CIMIS–Penman method and a modified Penman suitable for China[15-18]. Among these methods, PM

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method was proved as an accurate method for estimating ETo in different areas with various climate conditions[19-25]. Therefore, PM method has been widely used as a standard method to estimate evapotranspiration and make irrigation schedules[1,26-29].

Previous studies showed that, many ETo methods have been evaluated in different regions for selecting appropriate ETo methods. Kashyap and Panda[30] showed that KP and Turc methods can be used when meteorological data is limited in Kharagpur area in India, but Har and Penman methods are not suitable in these areas. For Indian mustard and maize, PM, corrected Penman, Blaney-Griddle and Pan evaporation methods have close agreement with observed values, while ETo estimated from PT and Har methods has significant deviation as compared with the observed values for both crops[31]. Fan et al.[18] reported that PT method can be used to calculate ETo when meteorological data are limited in the Loess Plateau of China. Mao et al.[32] suggested using PM method to calculate monthly or annual ETo in plain and low-elevation areas, and PM and a modified Penman method in high-elevation areas. Peng and Xu[33] found that ETos calculated by PT and PM methods were close, while Har method underestimated ETo by 23% in Jiangxi Province in middle China. Li and Li[34] showed that Har method is suitable in semi humid zone in the northeast China but not in semiarid area. In the semiarid region in Iran, the Har method agreed fairly well with FAO 56 PM method; conversely, the PT and Mak methods underestimate the ET by about 20% and 18%[35]. With incomplete meteorological data, locally calibrated Blaney–Criddle equation and Hargreaves equation have been proposed by Fooladmand and Haghighat[23] and Fooladmand and Ahmad[24] in Fars province in Iran. In Gansu Province of the northwest China, Zhai et al.[36] pointed out that directly estimating evapotranspiration using equations developed by Hargreaves, Makkink, Turc, Priestley–Taylor, Jensen–Haise, Doorenbos and Pruitt, Abtew, McGuinness and Bordne, Rohwer and Blaney–Criddle caused large errors, but after local calibration, these equations performed well. Therefore, it is evident from the case studies discussed above that appropriate ETo methods vary with places and climates, and there is no agreement among researchers about the most suitable method or approach for the estimation of ETo worldwide.

The reason for appropriate ETo methods varying with climate conditions and research regions may be mainly due to different key meteorological factors that greatly affect ETo. Bois et al.[37] showed that the dominated factor for ETo is air temperature in summer in the southwest French, while it is wind in winter; in the southeast French, the first two key factors are radiation and wind in summer. Liang et al.[38] found in Songnen Plain in the northeast China that relative humidity is the first key factor for ETo, followed by air temperature, wind and sunshine length. Bakhtiari and Liaghat[39] found in the arid and semi-arid regions in Iran that, ETo was sensitive to vapor pressure deficit in all months, to wind speed during March to November, and to radiation during the summer months. Liu and Pereira[40] concluded that air temperature and radiation greatly affect ETo in Xiongxian and Wangdu in Hebei Province in the north China. However, Gao et al.[41] reported that relative humidity and wind speed affect ETo greatly in most low-elevation areas in north China. They further pointed out that the main factors affecting ETo are sunshine length and humidity in summer, while they are relative humidity and wind speed in winter. In the arid region of northwest China, ETo variation is most sensitive to wind speed, followed by relative humidity, temperature and radiation[42].

Above studies showed that dominated factors for ETo differs with areas and seasons, which in turn affect the appropriate ETo methods. Only few studies were conducted to analyze the dominated meteorological factors for ETo and to evaluate different ETo methods in Beijing, China,. In order to find appropriate ETo methods in Beijing, seven widely used ETo methods were collected and compared with the PM method. Statistical method of linear regression and parameters of RMSE and MBE were chose to evaluate the relationships between ETo values calculated using PM method and the seven methods. Relationships between ETo and each climatic variable were analyzed to find dominated factors of ETo in Beijing. Based on the dominated factors, empirical methods were developed to estimate ETo when data are limited.

2 Materials and methods

2.1 Methods for calculating potential ETo

In this study, PM method recommended by FAO 56[8] was used as the standard method, and the estimating daily ETo refers to standard ETo. ETos calculated using other seven methods were compared with the standard ETos.

1) FAO-56 PM method

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{(T+273)} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

2) Penman method[9]

$$ETo = \frac{\frac{\Delta}{\Delta+\gamma}(R_n - G) + 6.43\frac{\gamma}{\Delta+\gamma}(1 + 0.537U_2)(e_s - e_a)}{\lambda} \tag{2}$$

3) KP method[15]

$$ETo = \frac{\frac{\Delta}{\Delta+\gamma}(R_n - G) + 6.43\frac{\gamma}{\Delta+\gamma}(a_w + b_w U_2)(e_s - e_a)}{\lambda} \tag{3}$$

$$a_w = 0.3 + 0.58\exp[-(\frac{J-170}{45})^2]$$

$$b_w = 0.32 + 0.54\exp[-(\frac{J-228}{67})^2]$$

4) Har method[10]

Hargreaves method is based on air temperature and is given by:

$$ETo = 0.0023R_a(T_{mean} + 17.8)\sqrt{T_{\max} - T_{\min}} / \lambda \tag{4}$$

5) PT method[12]

$$ETo = 1.26\frac{\Delta}{\Delta+\gamma}\frac{R_n - G}{\lambda} \tag{5}$$

6) Mak method[13]

$$ETo = 0.61\frac{\Delta}{\Delta+\gamma}\frac{R_s}{\lambda} - 0.12 \tag{6}$$

7) Turc method[11]

$$ETo = a_T 0.013\frac{T_{mean}}{T_{mean} + 15}\frac{23.8856R_s + 50}{\lambda} \tag{7}$$

$$HR \geq 50,\ a_T = 1;\ HR < 50,\ a_T = 1 + \frac{50 - HR}{70}$$

8) DP method[14]

$$ETo = b[\frac{\Delta}{\Delta+\gamma}\frac{R_s}{\lambda}] - 0.3 \tag{8}$$

$$b = 1.066 - 1.3\times10^{-3}RH_{mean} + 0.045u_d - 2\times10^{-4}RH_{mean}u_d - 3.15\times10^{-5}RH_{mean}{}^2 - 0.0011u_d{}^2 \tag{9}$$

where, ETo is potential evapotranspiration, mm/day; R_n is net radiation, MJ/(m^2 day); G is soil heat flux density, MJ/(m^2 day), G was set zero at a daily intervals suggested by Allen et al.[8]; γ is psychrometric constant, kPa/℃; U_2 is mean daily wind speed at 2 m height, m/s; e_s and e_a are saturation vapor pressure and actual vapor pressure, respectively, kPa; Δ is slope of saturation vapor pressure versus air temperature curve, kPa/℃; J is the number of the day in the year (the first day in the year is 1, the last day in the year is 365 or 366); T_{mean}, T_{max}, T_{min} are daily mean, maximum and minimum air temperatures, respectively, ℃; λ is latent heat of vaporization, λ = 2.501-0.002361T_{mean}, MJ/kg; R_a is extraterrestrial radiation, MJ/(m^2 day); R_s is incoming solar radiation, MJ/(m^2 day); u_d is wind speed at day time, m/s; RH_{mean} is daily mean relative humidity, %.

Net radiation was not directly measured in the research region. In this study, the net radiation was calculated using the data of daily sunshine hours, maximum and minimum air temperatures. The incoming solar radiation, R_s, was determined with actual daily sunshine duration and the maximum possible duration of sunshine at study region. Both calculation processes of net radiation and incoming solar radiation were following methods suggested by Allen et al[8].

2.2 Climatic station and data sources

Beijing region is located in the north China, with a semi-arid climate. All meteorological data were recorded at a national climatic station, located in south of Beijing city (39°48′N in latitude, 116°28′E in longitude, 31.3 m above sea levels). The meteorological data include atmosphere pressure at station, daily mean, maximum and minimum temperatures, daily mean relative humidity, daily mean wind speed and daily sunshine hours from 1951 to 2007.

2.3 Statistical analysis

The PM method was set as the standard method for estimating ETo. ETos calculated using PM method and the seven methods were evaluated through linear regression analyses, root mean squared error and mean bias error approaches. Root mean squared error (RMSE) and mean bias error (MBE) were expressed as follows:

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}(E_i-M_i)^2}{n}}\quad \text{(mm/day)} \tag{10}$$

$$MBE=\frac{\sum_{i=1}^{n}(E_i-M_i)}{n}\quad \text{(mm/day)} \tag{11}$$

where, E_i is ETo calculated with the seven methods; M_i is standard ETo calculated with PM method; n is number of meteorological sets.

3 Results and discussion

3.1 Comparison of ETos estimated by the seven methods and PM method

During linear regression analysis processes, ETo calculated using PM method was taken as independent variable and ETo calculated using the seven methods was set to dependent variable. The intercept for each regressed line between ETos from PM method and the seven methods was not significant (*P*>0.05). Therefore, the intercept was set zero for the each linear regressions. The results of linear regression were shown in Figure 1. Root mean squared error and mean bias error between ETos from PM method and the seven methods are listed in Table 1.

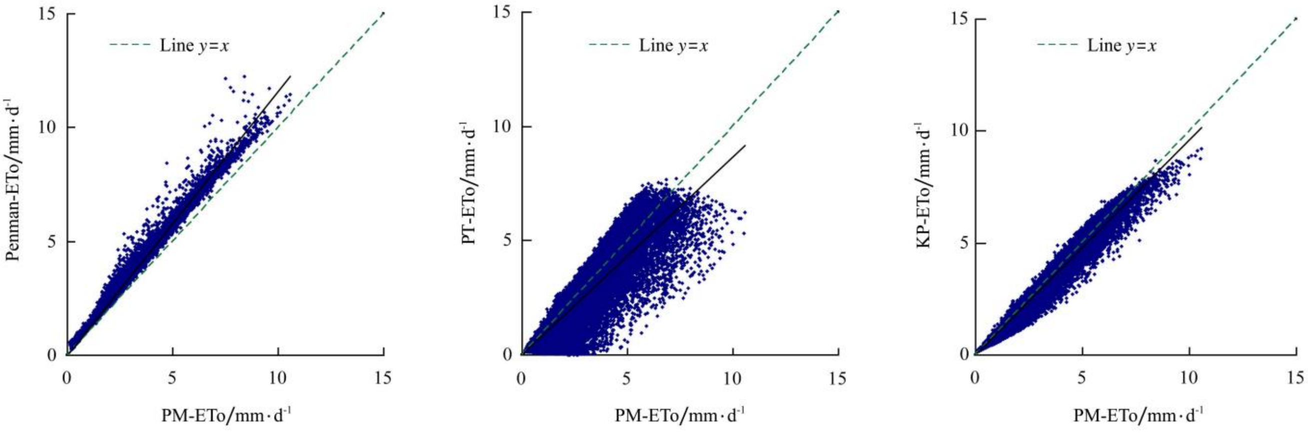
Table 1 Statistical results of relationships between ETos calculated by using PM method and the other seven methods

ETo methods	Determination coefficient of regression line (R^2)	Coefficient of efficiency of linear regression (E)	MBE (mm d^{-1})	RMSE (mm d^{-1})
KP method	0.959	0.958	-0.172	0.420
Penman method	0.991	1.160	0.528	0.608
DP method	0.927	1.146	0.380	0.826
Turc method	0.862	0.376	-2.195	2.214
Mak method	0.853	0.740	-0.758	1.089
PT method	0.770	0.869	-0.464	1.071
Har method	0.764	0.939	0.123	0.965

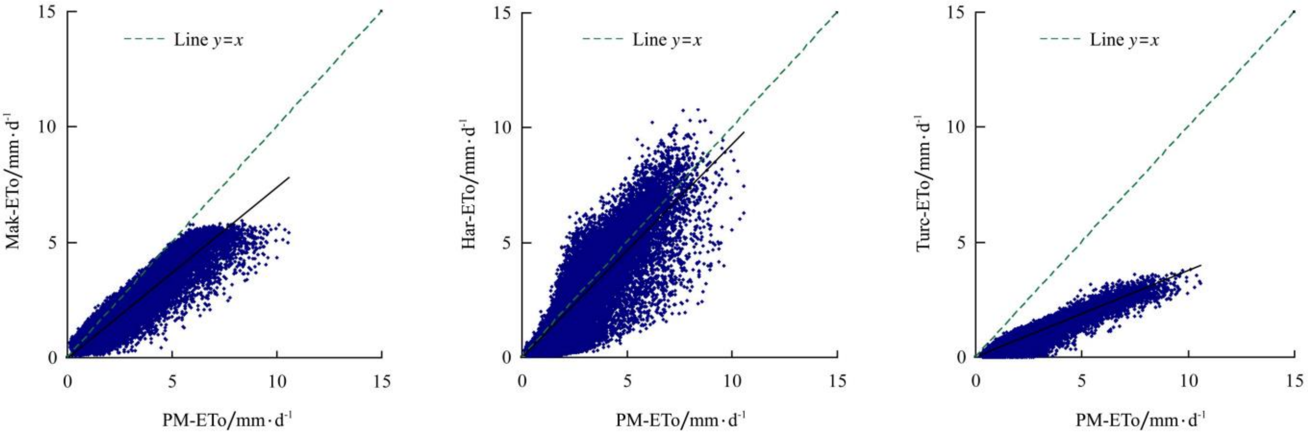
Figure 1 and Table 1 showed that ETos calculated with KP method were the closest to standard ETos, with a determination coefficient (R^2) of 0.96 and a coefficient of efficiency of 0.96. The root mean squared error and mean bias error were -0.17 mm/day and 0.42 mm/day, respectively, which is the smallest among the seven methods. Kashyap and Panda[30] found that ETo calculated with KP was close to ETo of PM method in India, which is similar to this result.

ETos calculated from Penman and DP methods also were significantly linear related to standard ETos with corresponding R^2 of 0.99 and 0.93, respectively. However, the values of MBE and RMSE for Penman and DP methods were higher than those for KP method, indicating greater bias. ETos were overestimated by 16% and 14.6% using Penman and DP methods, respectively, as compared to standard ETos. Penman[9] pointed out that evaporations from soil surface and crop canopy are generally lower as compared to those from water surface due to lower resistance to evaporation flux from water surface, for example, the evaporation from continuously wet bare soil is 0.9 times than that from an open water surface exposed to the same water conditions, and the evapotranspiration from turf with a plentiful water supply is 0.75 times of free water evaporation averaged over a season. Doorenbos and Pruitt[14] presented that DP method may overestimate ETo by 10% to 15% at some mid-latitude, semi-arid locations, which is in agreement with our result. Based on the results showed in Figure 1 and Table 1, it could be concluded that Penman method and DP method may not be suitable for directly estimating ETo in Beijing.

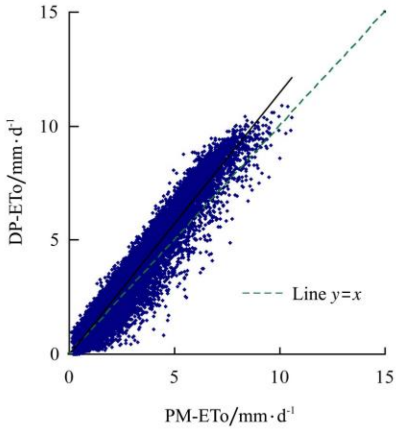
Though ETos calculated using Turc, Mak, PT and Har methods were significantly (F<0.001) linear related to the standard ETos, with R^2 from 0.76 to 0.86, but ETos have been underestimated by 6%-62% as compared to PM method, resulting in higher RMSE and MBE values. Allen et al.[8] pointed out that radiation methods (like Turc, Mak and PT methods) showed good results in humid climates where the aerodynamic term is relatively small, but performance in arid conditions is erratic and tends to underestimate evapotranspiration. Cheng et al.[43] found that aerodynamic term accounts for 12.2% of heat consumption of evaporation in a paddy field in a semi-arid region (similar to Beijing), and 7%-10% in the period from florescence stage to harvest day in a well-irrigated winter wheat field. Similar results have been found in north Spanish by Landeras et al.[44], in south China by Peng and Xu[33], and in an arid region of Inner Mongolia by Li et al[45]. Therefore, it may be concluded that Turc, Mak, PT and Har methods cannot be used in the semi-arid region of Beijing.



a. Penman method b. PT method c. KP method



d. Mak method e. Har method f. Turc method



g. DP method

Figure 1 Regression analysis on potential evapotranspiration calculated by FAO-56 Penman-Monteith (PM-ETo) and by Penman method, PT method, KP method, Mak method, Har method, Turc method and DP method (total data sets of 21032 in each figure)

Figure 1 and Table 1 showed that KP method can be used to directly calculate ETo in Beijing, while DP method, Penman method, Mak method, PT method, Har method and Turc method may cause great errors in directly calculating ETos. For evaluating the possibility of using these six methods to calculating ETos in Beijing region, they were calibrated using local meteorological data from 1951-1959, 1970-1979 and 1990-1999, and validated using data from 1960-1969, 1980-1989 and 2000-2007. The six calibrated methods were expressed as Equations (12) to (17), and related statistical results of method calibration and validation were listed in Table 2.

Table 2 Statistical analysis on calibrated Penman, DP, Turc, Har, Mak and PT methods in developing and validating processes

	Calibrated methods	Linear relationships between ETos calculated by PM method and calibrated methods	Determination coefficient of the linear relationships (R^2)	MBE (mm d^{-1})	RSME (mm d^{-1})
Method developing processes	Penman			0.000	0.261
	DP			-0.154	0.212
	Turc			0.035	0.615
	Har			-0.155	0.949
	Mak			0.000	0.719
	PT			-0.333	1.045
Method validating processes	Penman	$Y=1.0194X$	0.986	0.076	0.243
	DP	$Y=0.9915X$	0.945	-0.151	0.208
	Turc	$Y=0.9769X$	0.863	-0.030	0.620
	Mak	$Y=0.9279X$	0.840	-0.097	0.744
	Har	$Y=0.9125X$	0.768	-0.211	0.980
	PT	$Y=0.877X$	0.775	-0.450	1.078

Note: *Y* is daily ETo calculated using the six improved methods, and *X* is ETo calculated by PM method.

Calibrated Penman method:

$$ETo=\frac{\frac{\Delta}{\Delta+\gamma}(R_n-G)+4.3\frac{\gamma}{\Delta+\gamma}(1+0.6U_2)(e_s-e_a)}{\lambda}$$

$$(R^2=0.987) \qquad (12)$$

Calibrated DP method:

$$ETo=(0.816-7.67\times10^{-3}RH_{mean}+0.162u_d-1.34\times10^{-2}RH_{mean}u_d+6.66\times10^{-5}RH_{mean}{}^2-1.73u_d{}^2)(\frac{\Delta}{\Delta+\gamma}\frac{R_s}{\lambda})-0.3$$

$$(R^2=0.926) \qquad (13)$$

Calibrated Turc method

$$ETo=a_T\,0.0327\frac{T_{mean}}{T_{mean}+15}\frac{23.8856R_s+50}{\lambda}$$

(14)

Calibrated Har method:

$$ETo=0.00225R_a(T_{mean}+17.8)\sqrt{T_{\max}-T_{\min}}\,/\,\lambda \qquad (15)$$

Calibrated Mak method:

$$ETo=0.713\frac{\Delta}{\Delta+\gamma}\frac{R_s}{\lambda}-0.187 \qquad (16)$$

Calibrated PT method:

$$ETo=1.296\frac{\Delta}{\Delta+\gamma}\frac{R_n-G}{\lambda} \qquad (17)$$

Parameters in Equations (12)-(17) are the same to those defined in Equations (1)-(9).

Table 2 shows that the calibrated Penman method and DP method performed well for estimating ETo. The determination coefficients (R^2) of estimated and standard ETos were 0.99 and 0.95 for the calibrated Penman and DP methods, respectively, and corresponding coefficients of efficiency (E) were 1.02 and 0.99, respectively. MBE values in validating processes were 0.08 and -0.15 mm/day, respectively, for Penman and DP methods, and the corresponding RMSE values were 0.24 and 0.21 mm/day. Statistical parameters (R^2, E, MBE and RMSE) for calibrated Penman and DP methods listed in Table 2 indicated that the two calibrated methods can be used to calculate ETo in Beijing region. ETos was underestimated by 2% for calibrated Turc method, close to those for calibrated Penman and DP methods, but has greater RMSE as compared to the two methods. Compared to Penman and DP methods, Turc method needs less meteorological variables. Hence, the calibrated Turc method can be used to estimate ETos when full meteorological variables are not available. Higher RMSE values for calibrated Mak, Har and PT methods showed that they may cause greater error for calculating ETo in Beijing region.

3.2 Relationships between ETo and meteorological variables

Figure 2 shows the relationships between standard daily ETo and daily meteorological variables, including daily mean air temperature, wind speed, relative humidity, net radiation and vapor pressure deficit (VPD). Based on the determination coefficient (R^2) of the regression lines, saturated vapor pressure deficit was firstly close to ETo (R^2=0.82), followed by net radiation (R^2=0.77), and air temperature (R^2=0.59). Relationships between ETo and relative humidity and wind speed were insignificant (F>0.05). Liu and Pereira[40] found that radiation and air temperature were two key factors influencing ETo in Xiongxian and Wangdu in Hebei Province in north China, which is in agreement with this finding.

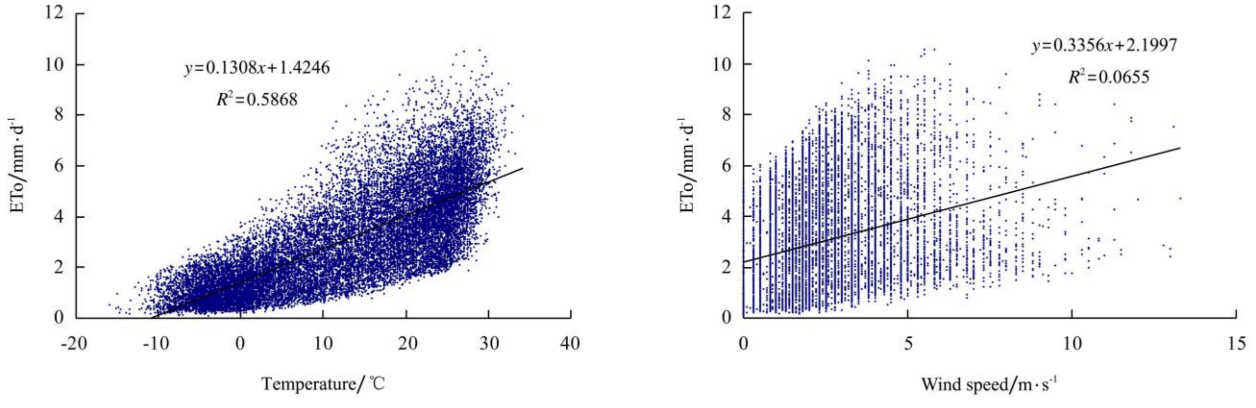
3.3 Empirical ETo methods for Beijing area

Results in Figure 2 showed that the vapor pressure deficit and net radiation were the first two factors affecting ETo in Beijing. Therefore, we developed two empirical methods to calculate ETo. They were VPD-based method and VPD-radiation combined method. Considering climate variation in the past 57 years, meteorological data from 1951-1959, 1970-1979 and 1990-1999 were used to develop these methods, and data from 1960-1969, 1980-1989 and 2000-2007 were used to validate them. The developed empirical methods were:

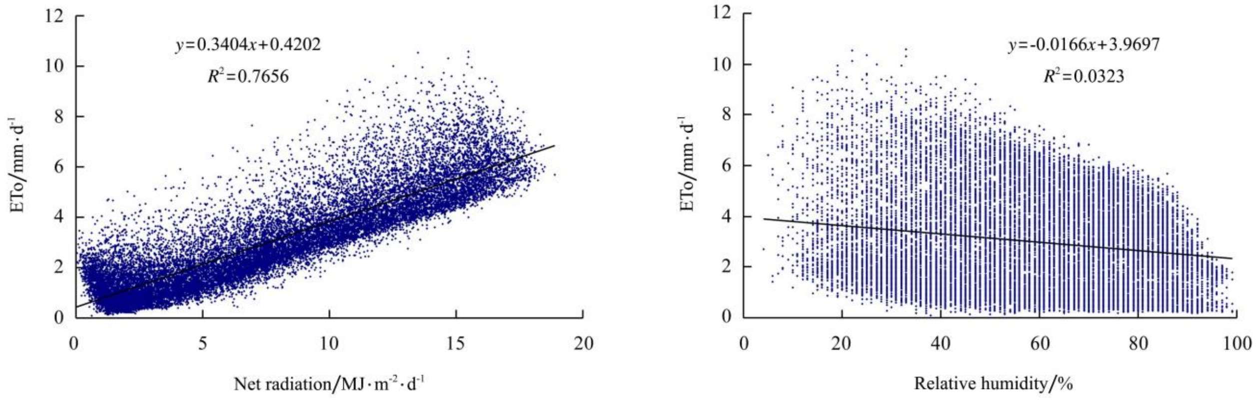
$$ETo = 0.659 + 3.688VPD \quad (R^2=0.81) \tag{18}$$

$$ETo = 02.373VPD + 0.189Rn \quad (R^2=0.98) \tag{19}$$

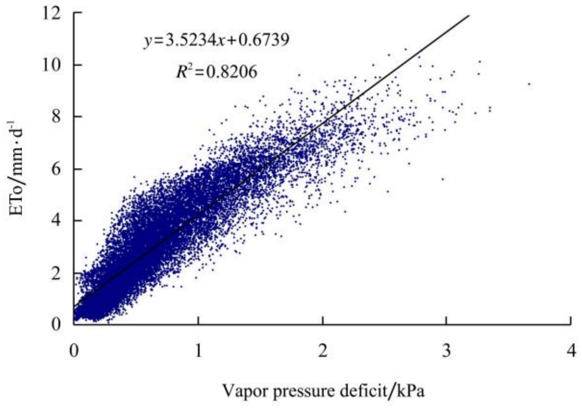
where, *ETo* is daily evapotranspiration, mm/day; *VPD* is daily mean vapor pressure deficit, kPa; and *Rn* is daily net radiation, MJ/m^2/day.



a. Temperature　　b. Wind speed



c. Net radiation　　d. Relative humidity



e. Vapor pressure deficit

Figure 2　Relationships between daily ETo and mean daily air temperature, wind speed, net radiation, relative humidity and vapor pressure deficit (total data sets of 21032 in each figure)

The statistical results of method developing and validation processes were listed in Table 3. It can be seen that the combined method (Equation (19)) performed well for calculating ETo with determination coefficient of 0.93, coefficient of efficiency of 1.0, MBE of 0.04 mm/day, and RMSE of 0.52 mm/day. These statistical parameters for Equation (19) were similar to those from calibrated Penman and DP methods (Table 2) and KP method (Table 1). RMSE for VPD-based method were 0.83 mm/day, higher than those for calibrated Penman and DP method (Table 2) and KP method (Table 1). While when only vapor pressure deficit is available, this method can be an attractive alternative to the more complex methods.

Table 3 Statistical results on Equations (18) - (19) in developing and validating processes

	Experiential methods	Linear relationship between standard ETos and predicated ETos	Determination coefficient of the linear relationships between standard ETos and predicated ETos, R^2	MBE (mm d^{-1})	RMSE (mm d^{-1})
Method developing processes	Equation (18)			0.000	0.803
	Equation (19)			-0.030	0.480
Method validating processes	Equation (18)	$Y = 1.015X$	0.813	0.193	0.833
	Equation (19)	$Y = 1.004X$	0.931	0.036	0.522

Note: X is standard ETo calculated with PM method; Y is predicated ETo calculated with Equations (18) to (19).

4 Conclusions

Potential ETo in Beijing was calculated by seven widely used methods and compared with the standard ETos calculated using FAO-56 Penman-Monteith method. ETo estimated by KP method was the most close to standard ETo and, hence can be directly used in Beijing region. Penman and DP methods overestimated ETo by 15%-16%, while locally calibrated Penman and DP methods performed well and may be used in this region. Turc method underestimated ETo by 62%, but is linearly related to the standard ETo with higher R^2 of 0.86. Considering only few climatic variables being needed, the Turc method was locally calibrated and the calibrated method showed a good performance for estimating ETo and Mak; PT and Har methods underestimated ETo by 6% to 26% respectively, with low determination coefficient and greater RMSE, hence they are not suitable in this region.

In Beijing region, ETo was firstly sensitive to vapor pressure deficit, followed by net radiation and temperature. Therefore, the VPD-based and VPD-radiation-combined ETo methods were developed by using local data. Statistical results showed that the two empirical methods performed well for estimating ETo, hence they can be used as attractive alternatives to the more complex PM method when only vapor pressure and net radiation are available.

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[References]

[1] David M S, Jennifer M J. Utility of Penman–Monteith, Priestley–Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. Journal of Hydrology, 2005; 308(1-4): 81-104.

[2] Yuan B Z, Jie S, Kang Y, Soichi N. Response of cucumber to drip irrigation water under a rain-shelter. Agricultural Water Management, 2006; 81: 145-158.

[3] Liu H J, Kang Y H. Sprinkler irrigation scheduling of winter wheat in the North China Plain using a 20 cm standard pan. Irrigation Science, 2007, 25(2): 149-159.

[4] Liu H J, Cohen S, Tanny J, Lemcoff J H, Huang G. Estimation of banana (Musa sp.) plant transpiration using a standard 20 cm pan in a greenhouse. Irrigation and Drainage System, 2008; 22(3-4): 311-323.

[5] Liu H J, Yu L, Luo Y, Wang X, Huang G. Responses of winter wheat *(Triticum aestivum* L.) evapotranspiration and yield to sprinkler irrigation regimes. Agricultural Water Management, 2011; 98: 483-492.

[6] Yu W, Kitamura R, Kato K, Li L, Fukui H. A computer program for automatic watering based on potential evapotranspiration by penman method and predicted leaf area in miniature pot rose production. Agricultural Sciences in China, 2010; 9(3): 370-377.

[7] Liang L Q, Li L J, Liu Q. Temporal variation of reference evapotranspiration during 1961-2005 in the Taoer River basin

of Northeast China. Agricultural and Forest Meteorology, 2010; 150(2): 298-306.

[8] Allen R G, Perreira L S, Raes D, Smith M. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56, Food and Agriculture Organization of the United Nations, 1998, Rome.

[9] Penman H L. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society of London (Series A), 1948; 193: l20-145.

[10] Hargreaves G H, Samani Z A. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture, 1985; 1(2): 96-99.

[11] Turc L. Estimation of irrigation water requirements, potential evapotranspiration: a simple climatic formula evolved up to date. Annual Agronomy, 1961; 12: 13-49.

[12] Priestley C H B, Taylor R J. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review, 1972; 100(2): 81-92.

[13] Makkink G F. Testing the Penman formula by means of lysimeters. International Journal of Water Engineering, 1957; 11(3): 277-288.

[14] Doorenbos J, Pruitt W O. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper No.24, Food and Agriculture Organization of the United Nations, 1977, Rome.

[15] Pei B X. Measurement and calculation of evaporation and evapotranspiration. China Meteorological Press, Beijing, 1989, pp. 6-7. (in Chinese with English abstract)

[16] Wright J L. Derivation of alfalfa and grass reference evapotranspiration. In: Evapotranspiration and Irrigation Scheduling, Camp CR, Sadler EJ, Yoder RE. Process International Conference, ASAE, San Antonio, TX, 1996, pp 133-140.

[17] Alexandris S, Kerkides P. New empirical formula for hourly estimations of reference evapotranspiration. Agricultural Water Management, 2003; 60:157-180.

[18] Fan J, Shao M A, Wang Q J. Comparison of many methods for calculating reference evapotranspiration in the Loess Plateau of China. Transactions of Chinese Society and Agricultural Engineering, 2008; 24(3): 98-102. （in Chinese with English abstract）

[19] Chiew F H S, Kamaladasa N N, Malano H M, McMahon T A. Penman-Monteith. FAO-24 reference crop evapotranspiration and class-A pan data in Australia. Agricultural Water Management, 1995; 28(1): 9-21.

[20] Abdelhadi A W, Hata T, Tanakamaru H, Tada A, Tariq M A. Estimation of crop water requirements in arid region using Penman–Monteith equation with derived crop coefficients: a case study on Acala cotton in Sudan Gezira irrigated scheme. Agricultural Water Management, 2000; 45(2): 203-214.

[21] Lecina S, Martínez-Cob A, Pérez P J, Villalobos F J, Baselga J J. Fixed versus variable bulk canopy resistance for reference evapotranspiration estimation using the Penman-Monteith equation under semiarid conditions. Agricultural Water Management, 2003; 60(3): 181-198.

[22] Angel U, Imma F, Antonio M, José C. Comparing Penman-Monteith and Priestley-Taylor approaches as reference evapotranspiration inputs for modeling maize water-use under Mediterranean conditions. Agricultural Water Management, 2004; 66(3): 205-219.

[23] Fooladmand H R, Haghighat M. Spatial and temporal calibration of Hargreaves equation for calculating monthly ETo based on Penman-Monteith method. Irrigation and Drainage, 2007; 56: 439-449.

[24] Fooladmand H R, Ahmad S H. Monthly spatial calibration of Blaney–Criddle equation for calculating monthly ETo in south of Iran. Irrigation and Drainage, 2009; 58: 234-245.

[25] Paulo C S, Terry J G, Eduardo A S. Evaluation of FAO Penman-Monteith and alternative methods for estimating reference evapotranspiration with missing data in Southern Ontario, Canada. Agricultural Water Management, 2010; 97(5): 635-644.

[26] Jabloun M, Sahli A. Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data, Application to Tunisia. Agricultural Water Management, 2008; 95: 707-715

[27] Lovelli S, Perniola M, Arcieri M, Rivelli A R, Tommaso T D. Water use assessment in muskmelon by the Penman-Monteith “one-step” approach. Agricultural Water Management, 2008; 95(10): 1153-1160.

[28] Fooladmand H R. Evaluation of Blaney-Criddle equation for estimating evapotranspiration in south of Iran. African Journal of Agricultural Research, 2011; 6(13): 3103-3109.

[29] Richard L S, Shu G, Morteza O, Sara S. Calculation and simulation of evapotranspiration of applied water. Journal of Integrative Agriculture, 2012; 11(3): 489-501.

[30] Kashyap P S, Panda R K. Evaluation of evapotranspiration estimation methods and development of crop-coefficients for potato crop in a sub-humid region. Agricultural Water Management, 2001; 50: 9-25.

[31] Kumar R, Jat M K, Shankar V. Methods to estimate reference crop evapotranspiration - a review. Water Science and Technology, 2012; 66(3): 525-35.

[32] Mao F, Zhang G Z, Xu X D. Several methods of calculating the reference evapotranspiration and comparison of their results. Quarter Journal of Applied Meteorology, 2000; 11(suppl. Vol.): 128-136. (in Chinese with English abstract)

[33] Peng S Z, Xu J Z. Comparison of reference crop evapotranspiration computing methods. Journal of

Irrigation and Drainage, 2004; 23(6): 5-9. (in Chinese with English abstract)

[34] Li X J, Li Q S. Study on calculating methods for reference crop evapotranspiration in northeastern China. Journal of Geographical Science, 2004; 24(2): 212-216.

[35] Er-Raki S, Chehbouni A, Ezzahar J, Khabba S, Lakhal E K, Duchemin B. Derived crop coefficients for winter wheat using different reference evpotranspiration estimates methods. Journal of Agricultural Science and Technology, 2011; 13: 209-221.

[36] Zhai L, Feng Q, Li Q, Xu C. Comparison and modification of equations for calculating evapotranspiration (ET) with data from Gansu province, northwest China. Irrigation and Drainage, 2010; 59: 477-490.

[37] Bois B, Pieri P, Leeuwen C V, Wald L, Huard F, Gaudillere J P, et al. Using remotely sensed solar radiation data for reference evapotranspiration estimation at a daily time step. Agricultural and Forest Meteorology, 2008; 148: 619-630.

[38] Liang L Q, Li L J, Zhang L. Sensitivity of the reference crop evapotranspiration in growing season in the West Songnen Plain. Transactions of Chinese Society and Agricultural Engineering, 2008; 24(5): 1-5. (in Chinese with English abstract)

[39] Bakhtiari B, Liaghat A M. Seasonal sensitivity analysis for climatic variables of ASCE penman-monteith model in a semi-arid climate. Journal of Agricultural Science and Technology, 2011; 13: 1135-1145.

[40] Liu Y, Pereira L S. Calculation methods for reference evapotranspiration with limited weather data. Journal of Hydraulic Engineering, 2001; 3(3): 11-17. (in Chinese with English abstract)

[41] Gao G, Chen D L, Ren G Y, Chen Y, Liao Y M. Spatial and temporal variations and controlling factors of potential evapotranspiration in China: 1956-2000. Journal of Geographical Science, 2006; 16(1): 3-12.

[42] Huo Z, Dai X, Feng S, Kang S, Huang G. Effect of climate change on reference evapotranspiration and aridity index in arid region of China. Journal of Hydrology, 2013; 492: 24-34.

[43] Cheng W X, Hu C B, Zhang X Q. Study on evaporation from farm land and water consumption of plant. China Meteorological Press, Beijing, 1994, pp. 6-7. (in Chinese)

[44] Landeras G, Ortiz-Barredo A, Lo ́pze J J. Comparison of artificial neural network models and empirical and semi-empirical methods for daily reference evapotranspiration estimation in the Basque Country (Northern Spain). Agricultural Water Management, 2008; 95: 553-565.

[45] Li Y L, Cui J Y, Zhang T H. Comparative study on calculation methods of reference evapotranspiration. Journal of Desert Research, 2002; 22(4): 372-376. (in Chinese with English abstract)