Applicability Evaluation for Reference Crop Evapotranspiration in Hebei Provence

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Abstract: Based on 53 years of daily meteorological data from 1961 to 2013 provided by 19 meteorological stations in Hebei Provence, seven algorithms of Penman-Monteith (P-M), Hargreaves-Samani (H-S), Irmark-Allen (I-A), Pristley-Taylor (P-T), Makkink (M-K), Penman-Van Bavel (PVB), 1948 Penman(48-PM) were used to calculate daily ET_0 of 3 areas in Hebei Provence. P-M was used as a standard to be compared with other 6 algorithms for estimating ET_0. The 6 algorithms were compared from the goodness-of-fit, definition and the applicability of monthly average ET_0 accumulated values. The algorithms got its scores after each comparative respects. The results show: I-A did the best work, scoring 23 points, and 48-PM ranked second, 11 points; these 2 methods can be the simplified recommendation to calculate ET_0 in Hebei Provence. The study proves that it is reasonable to value the applicability of each equation by the scoring method.

Introduction

The key to determine the water consumption of agriculture is to calculate reference crop evapotranspiration (ET_0), whose accuracy influences directly the irrigation program of crops, the reasonability of irrigation plans [1], and the whole water requirement of agriculture. ET_0 is also one of the most essential index to express the evaporation ability of atmosphere, evaluate the degree of climate drought, the water consumption of vegetation, potential productivity and the supply and demand balance of water resources [2,3]. The ways to calculate ET_0 can be divided into 3 sorts: synthesis method, temperature method and radiation method [4]. The scholars made many studies about this field with different methods in different regions. Xystrakis [5] analyzed the applicability of 13 ET_0 algorithms in Crete Island finding that Turc and Hansen method were more accurate. Azhar and Perera[6] analyzed the applicability of 10 ET_0 algorithms in the southeast of Austrilia finding that compared with the measured value, P-M method existed 21%~29% errors, Hargreaves method'errors was 18%~31%; Qingyu Sun and someone else[7] used 5 algorithms with the P-M method for standard finding that there were 9 parts (among 10 parts) more close to the results calculated by Hargreaves algorithm and FAO-24 Radiation algorithm. Zhi Li [8] also used 6 ways to calculate the applicability of loess plateau finding FAO-24 BC and Hargreaves method were better than others.

Many scholars study the applicability of different ET_0 algorithms in different regions from various evaluation aspects, but the results of each aspect usually goes to different conclusion. So it is common to summarize the study based on qualitative analysis. In this paper, based on 19 meteorological stations provided 53 years of daily meteorological data from 1961 to 2013 of Hebei Provence, 6 methods with P-M for standard were used to calculate daily ET_0 of 3 partitions, and then each method was marked from 3 evaluation aspects. In the study, some tries were made to evaluate the characteristics in quantitative analysis by scoring, and proved that it was reasonable.

Materials and Method

Study area. The study was conducted in Hebei Provence (36° 01′N~42° 37′N, 113° 04′E~119° 53′E) in the north of the North China Plain, dominated by cropland, mainly wheat and maize. The coastline of Hebei Provence is 487 km, and the area is 187700 km^2.Mean annual evaporation exceeds 565.2mm, and annual mean air temperature is 13.3℃. The terrain slopes from north west to south east. Due to the influence of terrain to ET_0, divide Hebei Provence into 3 part based on its altitude and latitude. The region where its altitude is lower than 200m belongs to Plain area, between 200m and 600m belongs to Hilly area, and above 600m belongs to Plateau area. These 3 divisions were named Part 1, Part 2 and Part 3 in turn, shown in Figure 1.

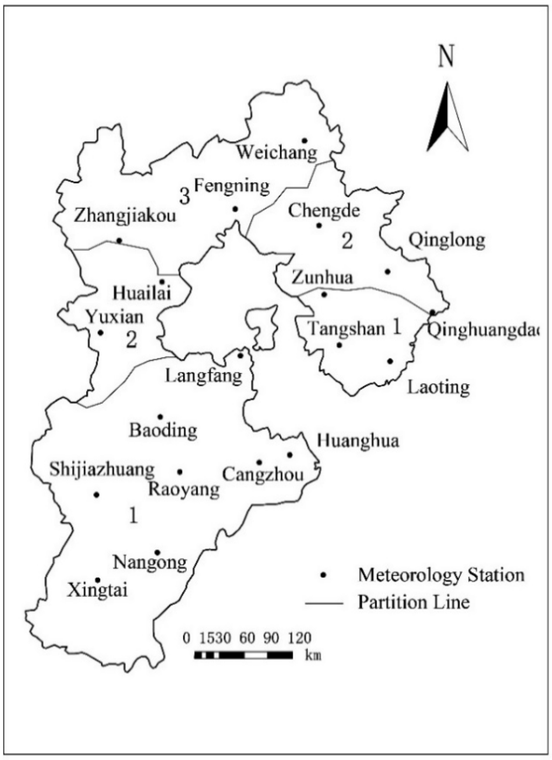

Fig.1 Area division and stations distribution in Hebei Provence

Data Materials. The daily meteorology data from 1961 to 2013 form 19 meteorology stations in Hebei Provence were provided by National Meteorological Information Center. The missing daily data was replenished by linear interpolation method. The daily meteorology data includes daily maximum temperature, daily minimum temperature, daily average temperature, average relative humidity, sunshine time, wind speed at 2m height (calculated by U_{10}). The information and distribution of 19 meteorology stations was showed in Figure 1.

Study Method

Expressions of Methods. Penman-Monteith method, 1998, is based on energy balance and aerodynamics, and its equation can be expressed as [7]:

$$ET_{0-PM} = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} U_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \quad (1)$$

Where, $ET_{0\text{-}PM}$, daily ET_0 calculated by P-M method(mm/d); Δ, the slope of the saturation vapour pressure temperature relationship(kPa/℃); R_n, the net radiation($MJ \cdot m^{-2} \cdot d^{-1}$); G, the soil heat flux represents the vapour pressure deficit of the air($MJ \cdot m^{-2} \cdot d^{-1}$); γ, the psychrometric constant(kPa/℃); T, the mean daily air temperature (℃); U_2, the wind speed at 2m height(m/s); e_s, the saturation vapour pressure(kPa); e_a, the actual vapour pressure (kPa).

Hargreaves-Samani method, 1950s, is based on the conditions of heat and radiation, and its equation can be expressed as [9]:

$$ET_{0-HS} = C_0 \left(T_{\max} - T_{\min}\right)^{0.5} \left(T_{mean} + 17.8\right) R_a \tag{2}$$

Where, $ET_{0\text{-HS}}$, daily ET_0 calculated by H-S method(mm/d); C_0, transformation coefficient,0.0023; T_{max}, daily maximum temperature(℃); T_{min}, daily minimum temperature(℃); T_{mean}, daily average temperature (℃); R_a, extraterrestrial radiation($MJ \cdot m^{-2} \cdot d^{-1}$).

Irmark-Allen method, 2003, is based on the conditions of heat and the net radiation. This method is widely used in moist area, and its equation can be expressed as [7]:

$$ET_{0-IA} = 0.489 + 0.289 R_n + 0.023 T_{mean} \tag{3}$$

Where, $ET_{0\text{-IA}}$, daily ET_0 calculated by I-A method(mm/d); the other parameters are same with formula（2）.

Priestley-Taylor method, 1972, is based on evaporation balance and the information of wet lands. This method is also widely used in moist area, and its equation can be expressed as [10]:

$$ET_{0-PT} = \alpha \frac{\Delta}{\Delta + \gamma} \left(R_n - G\right) \tag{4}$$

Where, $ET_{0\text{-PT}}$, daily ET_0 calculated by P-T method(mm/d); α, experience coefficient, 1.26; the other parameters are same with formula（1）.

Marrink method, 1957, is only based on the solar radiation, and it was proved to have good adaptability in cold area. And its equation can be expressed as [8]:

$$ET_{0-MK} = \frac{0.61}{2.45} \frac{\Delta}{\Delta + \gamma} R_s - 0.12 \tag{5}$$

Where, $ET_{0\text{-MK}}$, daily ET_0 calculated by M-K method(mm/d); R_s, solar radiation, $MJ \cdot m^{-2} \cdot d^{-1}$; the other parameters are same with formula（1）.

Penman method, 1948, is the simplify calculation of Penman-Monteith method with no horizontal transport of water vapor. Its equation can be expressed as [11]:

$$ET_{0-48PM} = \frac{\Delta\left(R_n - G\right) + 6.43\gamma\left(1 + 0.536 U_2\right)\left(e_s - e_a\right)}{\lambda\left(\Delta + \gamma\right)} \tag{6}$$

Where, $ET_{0\text{-48PM}}$, daily ET_0 calculated by 48-PM method(mm/d); λ, latent heat of vaporization, 2.45 MJ/kg; the other parameters are same with formula（1）.

Cornelius Van Bavel improved the experience coefficient of Penman method, and named the new algorithm Penman-Van bavel method. Its equation can be expressed as [12]:

$$ET_{0-PVB} = \frac{\dfrac{eps \times R_n}{\lambda} + \dfrac{e_s - e_a}{r_s}}{eps + 1} \tag{7}$$

$$eps = 1.005 \times \left(0.920 - 0.002632 T_{mean} + 0.003075 T_{mean}^2\right), \quad r_s = \frac{80.8}{u_2 + 0.1}$$

Where, $ET_{0\text{-PVB}}$, daily ET_0 calculated by PVB method(mm/d); T_{mean} is same with formula（2）; the other parameters are same with formula（1）.

Assessments

Goodness-of-fit was evaluated by comparing ET_0 of P-M with other 6 models. If results perfectly predicted the data, observed-versus-predicted points would lie on line x=y. Evaluation parameters, root mean square error (RMSE) and Nash-Sutcliffe coefficient (C_D), were used to characterize the deviation of the calculated values form the results of P-M method. The tow equations are:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(ET_0' - ET_{0-PM}\right)^2}{n-1}}, \qquad C_D = 1 - \frac{\sum_{t=1}^{n}\left(ET_0' - ET_{0-PM}\right)^2}{\sum_{t=1}^{n}\left(ET_{0-PM} - \overline{ET_{0-PM}}\right)^2}$$

Where, n, the sample number; ET_0', ET_0 of each method(mm/d); ET_{0-PM}, daily ET_0 calculated by P-M method(mm/d); $\overline{ET_{0-PM}}$, the average of daily ET_0 calculated by P-M method(mm/d).

Scores of the Methods

Evaluating the goodness-of-fit of 6 models firstly, and then defining 6 degrees: best, better, good, normal, poor, poorer. The goodness-of-fit scores were 3, 2, 1, 0, -1 and -2 in turn. The models were compared from 3 evaluative aspects: the goodness-of-fit, definition and the applicability of monthly average ET_0 accumulated values. First, the 6 methods were rank from best to poorer, then the 6 algorithm got corresponding scores. Ultimately, according the total scores they got from 3 evaluative aspects, the different goodness-of-fit of 6 models was showed out in Hebei Provence.

Result and Analysis

Goodness-of-fit of Methods (①): the equation in goodness-of-fit and determination coefficient between 6 methods and P-M are listed in sheet-1. In Part 1, algorithms' gradients(K) of M-K and PVB were 1.247 and 1.036, and ET_{0-MK} and ET_{0-PVB} were bigger than ET_{PM}; ET_{0-HS}, ET_{0-IA}, ET_{0-PT} and ET_{0-48PM} were lower （0.797, 0.98, 0.921, 0.849）. The K of PVB and I-A were closer to 1 showing better applicability. In Part 2, except the M-K (bigger than P-M), other 5 methods were lower, and K of PVB and I-A (0.979, 0.879) were more close to 1; the K of H-S was the smallest (0.718). In Part 3, ET_{0-MK} and ET_{0-PVB} were bigger than ET_{0-PM}, with the K 1.233 and 1.086; ET_{0-HS}, ET_{0-IA}, ET_{0-PT} and ET_{0-48PM}, (0.786, 0.959, 0.935, 0.845), were smaller than ET_{PM}. I-A and P-T method were close to1. The applicability of I-A and P-T method were better while H-S method was the worst. Every algorithm's coefficient of determination was bigger than 65%.

Table1 Imitative equation and determination coefficient between 6 ET_0 methods and P-M in Hebei Provence

Method	H-S	I-A	P-T	M-K	48-PM	PVB
Part 1	y=0.797x+0.29 R^2=0.8018	y=0.986x−0.25 R^2=0.7828	y=0.921x+0.67 R^2=0.7852	y=1.247x+0.28 R^2=0.8522	y=0.849x−0.12 R^2=0.9958	y=1.036x+0.55 R^2=0.7858
Part 2	y=0.718x−0.90 R^2=0.7609	y=0.879x+0.42 R^2=0.6956	y=0.860x+1.16 R^2=0.6970	y=1.182x+0.65 R^2=0.7818	y=0.826x−0.12 R^2=0.9810	y=0.979x+1.02 R^2=0.6916
Part 3	y=0.786x+0.75 R^2=0.7934	y=0.959x+0.26 R^2=0.7600	y=0.935x+1.03 R^2=0.7629	y=1.233x+0.57 R^2=0.8341	y=0.845x−0.11 R^2=0.9918	y=1.086x+0.88 R^2=0.7548

Definition of the Methods (②): RMSE and C_D of 6 methods are listed in sheet-2. In Part 1, RMSE and C_D of PVB and M-K were 1.3553mm/d, 0.6523 and 1.2743mm/d, 0.6270; RMSE of PVB was the biggest while C_D of M-K was the smallest; deviation of PVB was bigger. RMSE of P-T, H-S, I-A and 48-PM decreased while C_D increased; the precision of these increased in turn. In Part 2, RMSE and C_D of PVB were 1.3692mm/d and 0.3768. RMSE of PVB was biggest while C_D was smallest. RMSE of P-T, H-S, I-A and 48-PM decreased while C_D increased. The precision of algorithms in Part 3 was the same with that in Part 1; the precision of PVB, M-K, P-T, H-S, I-A and 48-PM increased in turn.

Table2 Comparison ET_0 accuracy among 6 simplification calculations and P-M in 3 divisions in Hebei Provence

Evaluation	Parameter	H-S	I-A	P-T	M-K	48-PM	PVB
Part 1	RMSE	0.9141	0.8706	1.2424	1.2743	0.7498	1.3553

	（mm/d）						
	C_D	0.7161	0.7537	0.6961	0.6270	0.8381	0.6523
Part 2	RMSE （mm/d）	1.1095	0.9805	1.3140	1.3107	0.8816	1.3692
	C_D	0.5909	0.6805	0.4261	0.4290	0.7417	0.3768
Part 3	RMSE （mm/d）	0.9086	0.8654	1.2349	1.2667	0.7453	1.3472
	C_D	0.7302	0.7552	0.5016	0.4756	0.8185	0.4069

Applicability of Monthly Average ET0 Accumulated Values of the Methods (③)： monthly average ET_0 accumulated values of P-M method in Part 1, Part 2, Part 3 and Hebei were 867.55mm, 954.80mm, 931.78mm and 918.04mm. As Figure 2 shows: the values of I-A, H-S and 48-PM were higher than P-M in Part 1, and their deviation values were 95.24mm, 103.10mm and 199.00mm while the values of P-T, PVB and M-K were lower than P-M, and their deviation values were 161.67mm, 203.91mm and 245.22mm. In Part 2, the value of 48-PM was higher than P-M in excess of 248.36mm while the values of I-A, H-S, P-T, PVB and M-K were lower than P-M, and their deviation values were 25.07mm, 26.88mm, 281.83mm, 316.87mm and 324.43mm. In Part 3, the value of 48-PM was higher than P-M in excess of 211.99mm; the values of I-A, H-S, P-T, M-K and PVB were lower than P-M, and the deviation values were 45.63mm, 49.65mm, 288.76mm, 325.43mm and 332.83mm. In Hebei the values of I-A, H-S and 48-PM were higher than P-M in excess of 8.18mm, 8.86mm and 219.78mm, while the values by P-T, PVB and M-K method were lower than P-M and the deviation values were 244.09mm, 284.54mm and 298.36mm.

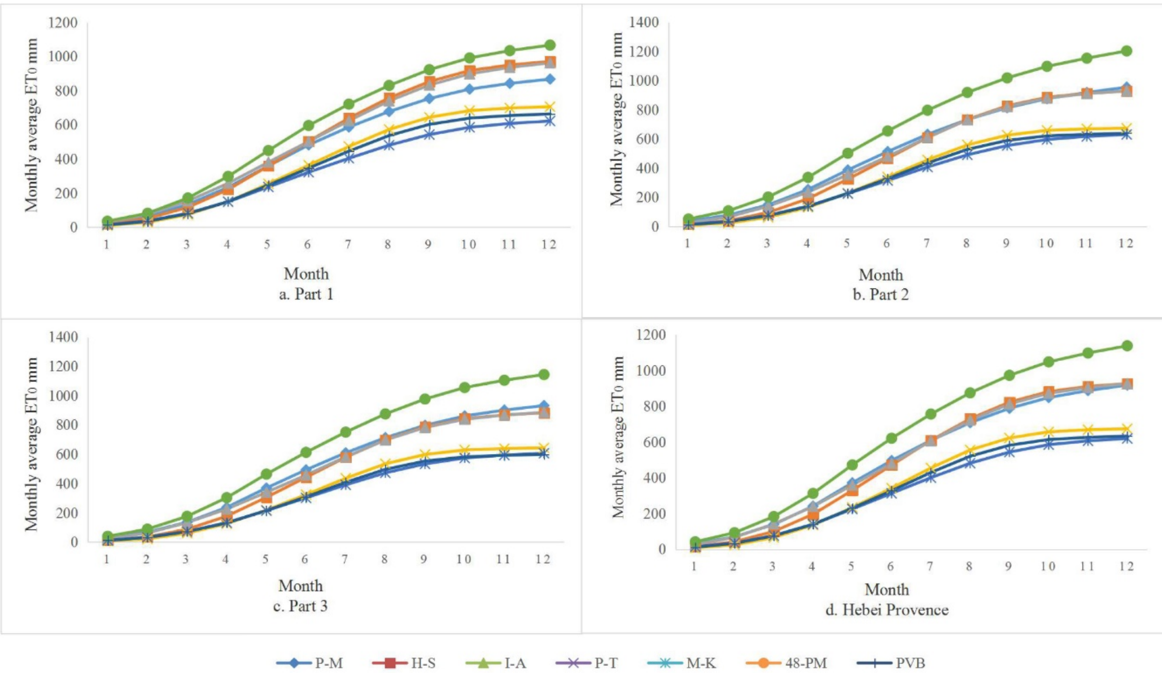

Fig.2 Monthly average ET_0 accumulated values comparison among 6 simplification calculations

Table.3 3 evaluative aspects scores of 6 simplification calculations in 3 divisions

Part	evaluative aspect	H-S	I-A	P-T	M-K	48-PM	PVB
1	①	-1	3	1	-2	0	2
	②	1	2	0	-1	3	-2
	③	2	3	1	-2	0	-1
2	①	-2	2	1	-1	0	3
	②	1	2	-1	0	3	-2

	③	2	3	0	-2	1	-1
	①	-1	3	2	-2	0	1
3	②	1	2	0	-1	3	-2
	③	2	3	0	-1	1	-2
total		5	23	4	-12	11	-4

the Scores of Methods

According to the analyses of 3 evaluative aspects in the 3 divisions, the scores of 6 simplification calculations were showed in table 3. It showed: the scores of M-K, PVB, P-T, H-S, 48-PM and I-A method were -12, -4, 4, 5, 11 and 23 respectively indicating that taking the P-M method as the standard, I-A method was the best fit one among the 6 methods considering the goodness-of-fit, definition and the applicability of monthly average ET_0 accumulated values; the accuracy and applicability of I-A method was higher than any other methods; 48-PM method was the second; M-K method was for the worse grade, and only scored -12 points.

Conclusions

The conclusions are as follows: (1) I-A and PVB were better than others in the goodness-of-fit; (2) I-A and 48-PM were better when analyzing the RMSE and CD; (3) I-A and H-S were better in the 3 divisions when analyzing monthly average ET_0 accumulated values; (4) the applicability of I-A was the best among 6 methods with the highest score; 48-PM ranked second and M-K was the last; (5) the scoring method was reasonable in estimating the applicability of methods, and it got the same conclusion compared with qualitative analysis; and the scoring mechanism for this method would be more consummate in subsequent studies.

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