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Regional Calibration of Hargreaves Equation in the Xiliaohe Basin

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Abstract

This paper investigates calibration of Hargreaves equation in Xiliaohe Basin. Twelve meteorologicalgauges located within Xiliaohe Basin in Northeast China were monitored during 1970 and 2014 providing continuous records of meteorological data. Taking daily ET_0 calculated by Penman-Montieth equation as the benchmark, the error of Hargreaves equation for computing ET_0 was evaluated and the investigation on regional calibration of Hargreaves equation was carried out. Results showed there was an obvious difference between the calculating results of Hargreaves and Penman-Monteith equation. The estimation of the former was obviously higher during June and September while lower during the rest time in a year. The three empirical parameters of the Hargreaves equation were calibrated using the SCE-UA (Shuffled Complex Evolution) method, and the calibrated Hargreaves equation showed an obvious promotion in the accuracy both during the calibration and verification period.

Keywords

Reference Crop Evapotranspiration, Penman-Monteith, Hargreaves, SCE-UA, Xiliaohe

1. Introduction

Reference Crop Evapotranspiration (ET_0) is an important climatic and hydrological variable, which lays the foundation for the calculation of actual evapotranspiration [1], thus accurate estimation of ET_0 is essential to ecological environment protection and planning as well as water and soil resource management. There are dozens of methods for calculating ET_0 at present which are different from each other on theoretical basis, complexity and applicable conditions. All these methods can be summarized to empirical formula method (such as Blanney-Criddle and Thornthwaite), moisture diffusion method, energy-balanced method (such as Presley-Tylor) and synthesis method. Penman-Monteith (P-M hereinafter) equation was recommended by FAO due to its rigorous physical basis and high calculating accuracy [2] [3]. However, calculation of ET_0 with this equation needs a variety of meteorological data (maximum temperature, minimum temperature, average temperature, sunshine hours, relative humidity, average air pressure and wind speed) thus it is often limited by lack of data

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when applied to data-deficiency areas. In this case, empirical methods which are more widely used for its relatively low requirement for data became a realistic choice [4].

As one of the empirical methods in calculating ET_0, Hargreaves (H hereinafter) equation has been put forward and improved by Hargreaves *et al.* since 1950s-1960s [4] [5]. The data requirement of H equation is relatively low (only maximum and minimum temperature) thus FAO-56 has recommended this equation as priority in data-deficiency areas [6]. Scholars at home and abroad have been researching the application of this equation in different areas. Wang [7] *et al*. pointed out that the annual error of H equation mainly existed between 13^{th} and 30^{th} ten-days and calibrated the equation through establishing the linear regression between results of H and P-M equation; Fan's [8] research in Manas river basin indicated there was an obvious error during April and October in the results of H equation, afterwards a calibration of parameter "*C*" was carried out with the Bayesian method to improve the accuracy; Yang [8] *et al*. calculated ET_0 in Lhasa with P-M and H equation which showed a difference in spring and rainy season, the factor of average humidity was introduced to adjust the H equation which gained a relatively accurate result; Hu [4] calibrated "*C*", "*E*", "*T*" in H equation simultaneously with the SCE-UA method in 105 stations within China, the applicability of the calibrated equation was then demonstrated in different regions of China subsequently.

In summary, there are mainly several following methods of calibrating H equation: (1) establishment of a linear regression between P-M and H results, such as reference [7]; (2) introduction of new meteorological factors to improve the accuracy, such as reference [9], which might harm the brevity of the formula's structure; (3) calibration of one of the empirical parameters in H equation (generally "*C*"), such as reference [8], however, some research pointed out that all three parameters("*C*", "*E*", "*T*") had regional variability [4] so it might not be reasonable to calibrate only one of them. Another inconvenient problem is, previous researchers basically adopted the recommended values by FAO ($a = 0.5$, $b = 0.25$) when calculating solar radiation (R_s) with Angstrom equation, which haven't yet been evaluated systematically to be reasonable [3] [10], some research indicated "*a*" and "*b*" in Angstrom equation varied a lot in China [11]. Usage of these raw values in calculation will lead to unconvinced results since the error of "*a*" and "*b*" effects ET_0 a lot.

The aim of this study is to evaluate the error of H equation using the meteorological data of 12 gauging stations in Xiliaohe Basin and to conduct an investigation into the regional calibration of 3 empirical parameters. The calibration will be achieved with the SCE-UA method [12]. The results of the study are discussed to serve as a reference of ET_0 calculation in similar continental semiarid areas.

2. Study Area and Data

2.1. Study Area

This case study utilizes the data obtained from 12 meteorological monitoring of 12 gauges located in Xiliaohe Basin which lies between 116˚16'E and 123˚35'E longitude and between 40˚05'N and 45˚13'N latitude with a drainage area of 13.52×10^4 km^2. The basin is characterized by high west and low east. The western part of the basin is hilly while the rest are plains (**Figure 1**). Most of the basin belongs to the arid or semi-arid areas with annual average temperature: between 4.3 and 8.2˚C; annual average sunshine hour: between 2760 and 3170 h; average relative humidity: between 43.8% and 54.2%; average wind speed: between 2.6 and 3.6 m/s; annual precipitation: between 239 to 556 mm with a spatio-temporal maldistribution, 80% of the precipitation takes place during June and September with the precipitation in hilly areas much larger than the plain areas.

Along with the increasing development intensity of water resource, grassland and desert vegetation in some parts of Xiliaohe Basin have been degrading in different degrees recently. The largest sand land in China—Horqin Sandland locates in this area with severe water resources shortage, making this land the most eco-fragile area in Northeast China. Meanwhile, the main rivers in the basin cut off occasionally which make the development of agriculture and industry more and more dependent on the exploit of groundwater. In 2001-2010, the average quantity of annual water supply in Xiliaohe Basin was between 4.8 - 5.5×10^9 m^3 in which the groundwater accounted for 70% - 80% averagely.

2.2. Data

According to research, the data of 12 meteorological gauges in Xiliaohe Basin (distribution of stations as **Figure 1**, basic situation as **Table 1**) were collected, including the following two kinds:

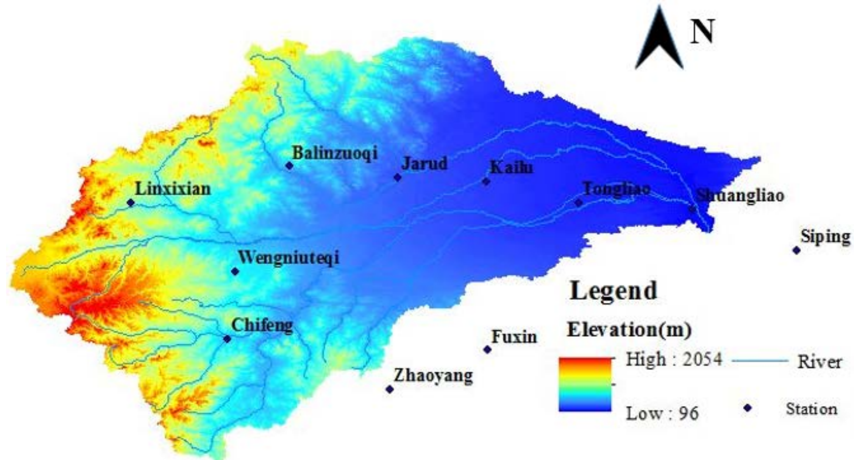

Figure 1. DEM and distribution of meteorological stations in Xiliaohe Basin.

Table 1. Basic information of 12 meteorological gauges in Xiliaohe Basin.

gauges	longitude	latitude	administrative district	gauges	longitude	latitude	administrative district
Jarud	123.9	44.7	Jarud	Shuangliao	123.5	43.5	Shuangliao
Balinzuo	119.5	43.9	Balinzuo	Siping	124.4	43.2	Siping
Changlin	124.0	44.3	Changlin	Wengniute	119.0	42.9	Wengniute
Linxi	118.1	43.6	Linxi	Chifeng	119.0	42.3	Chifeng
Kailu	121.2	43.6	Kailu	Fuxin	121.7	42.0	Fuxin
Tongliao	122.2	43.6	Tongliao	Zhaoyang	120.5	41.6	Zhaoyang

(1) Monthly radiation data from 1976-2014 for calibrating parameter "*a*" and "*b*" in Angstrom equation;

(2) Daily meteorological data (including maximum temperature, minimum temperature, average temperature, average relative humidity, sunshine hours, average air pressure, average wind speed) from Jan 1st 1970 to Dec 31st 2014 for calculating ET_0 with P-M and H equation.

The data above basically came from "daily dataset of Chinese climate data" and "monthly dataset of Chinese radiation data" in National Meteorological Information Center, a spot of missing data (mainly average wind speed and average relative humidity) were interpolated with the pre and post data.

3. Methodology

3.1. P-M Equation and Its Parameter Calibration

In this study, daily ET_0 calculated by P-M equation is set as a standard, the form and calculation steps of P-M equation see reference [13]. It is not advisable to use the recommended value (a = 0.5, b = 0.25) for the sake of reliability of results since parameter "*a*" and "*b*" in Angstrom equation varied a lot in China. Theoretical astronomical radiation R_a was calculated according to formula (1), parameter "*a*" and "*b*" of each station were gained by establishing linear regression between theoretical and measured astronomical radiation (see formula (2)).

$$R_a = 37.6 d_r \left(\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s\right) \tag{1}$$

$$R_S = R_a \left(a + b\frac{n}{N}\right) \tag{2}$$

where d_r is the solar-terrestrial relativedistance, kPa^0C^{-1}; ω_s is the angle of sunset, rad; δ is the magnetic declination of the sun, rad; R_a is the monthly astronomical radiation, $MJ/(m^2 \cdot d)$; n, N are actual and theoretical sunshine hours respectively, h/d; a and b are the parameter remains to be calibrated.

3.2. H Equation and Its Calibration Method

H equation was put forward based on the two empirical Equations (3)-(4) [14], formula (5) is gained by merging formula (4) and formula (3):

$$ET_{0\text{-H}} = 0.0135 R_s \left(\frac{T_{\max} + T_{\min}}{2} + T\right) \tag{3}$$

$$R_s = K_{RS} R_a \left(\frac{T_{\max} + T_{\min}}{2}\right)^E \tag{4}$$

$$ET_{0\text{-H}} = C R_a (T_{\max} - T_{\min})^E \left(\frac{T_{\max} + T_{\min}}{2} + T\right) \tag{5}$$

where $ET_{0\text{-H}}$ is the ET_0 calculated by H equation, mm/d; $T_{\max}$, $T_{\min}$, T are daily maximum, minimum, average temperature respectively, ˚C; K_{RS} is an empirical coefficient; "C", "E", "T" are 3 parameters of H equation which are recommended as 0.0023, 0.5, 17.8.

The SCE-UA algorithms which is capable of global optimization is adopted to calibrate "C", "E", "T" of each station at Xiliaohe Basin, the calibrating steps are as follows:

(1) Division of the research time. The daily meteorological data (1970-2014) is divided into calibrating and verification period according to the ratio of 5:1, thus the former is from 1970-2005, the latter is from 2006-2014.

(2) Definition of the range of "C", "E", "T". According to analysis, debugging and reference [4], the range of 3 parameters are set to be: $C \in [5\times10^{-5}, 0.02]$, $E \in [0.02, 2.0]$, $T \in [2.0, 75.0]$.

(3) Definition of the objective function.Maximization of function F (Nash-Sutcliffe efficiency coefficient, see formula (6)) and minimization of function G (total relative error, see formula (7)) are set to be the optimization target of SCE-UA algorithm.

$$F = 1 - \frac{\sum_{t=1}^{n} [ET_{0\text{-H}}(t) - ET_{0\text{-PM}}(t)]^2}{\sum_{t=1}^{n} [ET_{0\text{-PM}}(t) - \overline{ET_{0\text{-PM}}}]^2} \tag{6}$$

$$G = \frac{\sum_{t=1}^{n} [ET_{0\text{-H}}(t) - ET_{0\text{-PM}}(t)]}{\sum_{t=1}^{n} ET_{0\text{-PM}}(t)} \tag{7}$$

where $ET_{0\text{-H}}(t)$, $ET_{0\text{-PM}}(t)$ are the t^{th} day's ET_0 calculated by H and P-M equation respectively, $\overline{ET_{0\text{-PM}}}$ is the mean daily value of the $ET_{0\text{-PM}}(t)$ in the given period.

(4) Operation of the algorithms. Output of the calibration results of parameters.

3.3. Evaluation Methods of Calculation Accuracy

This article basically investigates the calculating accuracy of pre-and-post calibration of H equation with the following statistical variables: absolute error (*BE*, see formula (8)) and relative error (*RE*, see formula (9)) of each month. Additionally, a wilcoxon test is used to detect whether there is an obvious difference between calculating results of P-M and H equation.

$$BE(i) = ET_{0\text{-H}}(i) - ET_{0\text{-PM}}(i) \tag{8}$$

$$RE(i) = \frac{ET_{0\text{-H}}(i) - ET_{0\text{-PM}}(i)}{ET_{0\text{-PM}}(i)} \tag{9}$$

where i is the ordinal number of month, i = 1, 2, 3, ⋯, 12; $ET_{0\text{-H}}(i)$, $ET_{0\text{-PM}}(i)$ are the average ET_0 of the i[st] month calculated by H and P-M equation respectively in the given period, $BE(i)$, $RE(i)$ are absolute error and relative error of ET_0 calculated by H equation.

4. Results and Discussion

4.1. Parameter Calibration of Angstrom Equation

Parameter "*a*" and "*b*" of 12 meteorological gauges are calibrated using the monthly radiation data of Xiliaohe Basin during 1976-2014 (see **Table 2**). As is seen from **Table 2**, "*a*" and "*b*" of 12 gauges all deviate from the recommended value (a = 0.25, b = 0.5), in which "*a*" varies around the recommended value while "*b*" is basically smaller. The mean value of "*a*" and "*b*" are 0.27 and 0.37 respectively which verifies the necessity of the calibration.

4.2. Error of H Equation before Calibration

According to the daily meteorological data of 12 gauges between 1970-2014, average daily ET_0 of 12 stations is calculated and compared using the P-M and H equation respectively. The average value of absolute and relative error by H equation in each month can be seen in **Table 3**. Compared with the standard value, the results of H equation are obviously larger during June and September while smaller in the rest months of year. In July and August when the crop water requirement reaches the most, the absolute error of H equation also reach the largest, both over 20 mm.

In order to demonstrate the error of H equation before calibration, Average daily ET_0 calculated by P-M and H equation in Jarud can be seen **Figure 2**. The results of the two methods show some certain consistence in the variation trend: a rise between January and June and a decline between June and December. However, the results of H equation are obviously larger than the standard value (P-M equation) during June and September while smaller in the rest time of year.

Table 2. Calibrated *a* and *b* of 12 meteorological gauges in Xiliaohe Basin.

gauge \ parameter	*a*	*b*	gauge \ parameter	*a*	*b*
Jarud	0.24	0.46	Shuangliao	0.26	0.41
Balinzuo	0.22	0.44	Siping	0.35	0.27
Changling	0.29	0.39	Wengniute	0.22	0.42
Linxixian	0.27	0.37	Chifeng	0.25	0.38
Kailu	0.20	0.45	Fuxin	0.32	0.30
Tongliao	0.25	0.39	Zhaoyang	0.39	0.18

Table 3. Average deviation of Hargreaves equation in each month before calibration (12 gauges, 1970-2014).

Month	*BE*/mm	*RE*/%	Month	*BE*/mm	*RE*/%
Jan	−10.86	−61.95	Jul	21.28	16.04
Feb	−11.40	−41.25	Aug	21.25	18.45
Mar	−14.61	−23.89	Sep	9.16	10.70
Apr	−15.23	−13.73	Oct	−6.15	−9.36
May	−5.24	−3.34	Nov	−10.06	−31.32
Jun	14.29	10.19	Dec	−9.48	−51.62

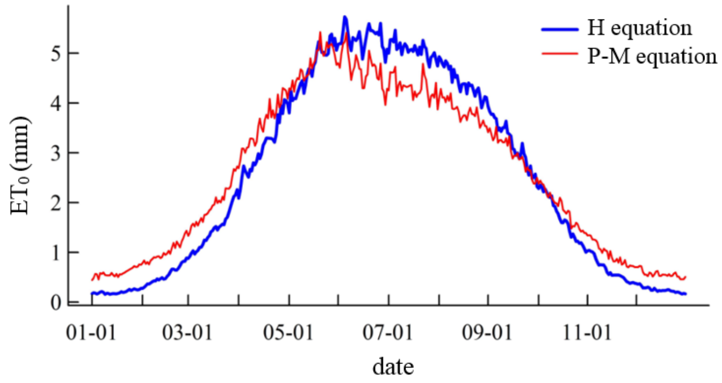

Figure 2. Average daily ET_0 calculated by P-M and Hargreaves equation (Jarud).

Monthly average ET_0 of Jarud calculated by H equation and its error can be seen in **Table 4**. Compared with the results of P-M equation, the annual absolute error of H equation is −97.9 mm, generally smaller than P-M results; the relative error of each month is between −70.9% and 14.1%. During April and October when the crop water requirement reaches the most, the absolute and relative error of H equation are relatively larger: −23.6 - 19.8 mm and −24.4% - 14.1% respectively. A Wilcoxon test shows a significant difference between monthly ET_0 calculated by H and P-M equation except in June and September.

4.3. Parameter Calibration of H Equation

4.3.1. Calibration Results

With the daily meteorological data during 1970-2005, parameter "*C*", "*E*", "*T*" of 12 gauges are calibrated using SCE-UA method. Distribution of the calibrated parameters are shown in **Figure 3**. 3 parameters of all the gauges deviate from the recommended value by FAO in which most gauges show a smaller "*C*" and "*E*" than recommended while all the gauges show a larger "*T*". The average value of calibrated parameters ("*C*", "*E*", "*T*") are 0.00071, 0.42, 39.65 respectively, with C_v 0.37, 0.28, 0.52. In general, parameter "*T*" shows the largest discrete degree while "*E*" shows the smallest.

4.3.2. Accuracy Characteristics after Calibration

The average relative error of ET_0 (absolute value) in each month within the verification period are drawn in the boxplot type, as is shown in **Figure 4**. A significant difference can be seen between the accuracy of H equation in each month before calibration with the relative error below 20% during Apr and Oct while between 20% and 60% during the rest months of year; meanwhile, an improvement in the accuracy of calibrated H equation can be seen in each month compared with the original equation before calibration, which is obvious in Jan-Mar and Nov-Dec. A higher and more stable accuracy can be obtained after the calibration of H equation, which means that it is feasible to calibrate "*C*", "*E*", "*T*" simultaneously.

In order to demonstrate the efficiency of calibration, daily ET_0 of Jarud calculated by 3 equations (namely calibrated H equation, uncalibrated equation, P-M equation) in calibration and verification period are shown in **Figure 5(a)** and **Figure 5(b)** respectively. As is seen in **Figure 5**, the results of H equation are larger during June and September while smaller in the rest time of year before calibration in both periods, there is an obvious difference between the results of the two equations; however the results of calibrated H equation are much closer to the standard value.

The monthly comparison of ET_0 between P-M and H equation (before & after calibration) during 1970-2014 can be seen in **Table 5**. There is an obvious decrease in the absolute and relative error after calibration, especially in Jan to Apr and Oct to Dec. The average relative error of each month decreases from −19.44% to 5.41% which shows an obvious improvement; a Wilcoxon method is used to detect the difference of each month with P value of each month all exceeding 0.001 which shows there is no obvious difference between the monthly ET_0 calculated by the calibrated H equation and P-M equation, thus the calibrated H equation can be used to calculate the monthly ET_0 in the replacement of P-M equation.

Table 4. Result statistics of monthlyET_0 calculated by P-M and Hargreaves method (Jarud, 1970-2014).

Month	$ET_{0\text{-}PM}$ / mm	$ET_{0\text{-}H}$ / mm	BE/mm	RE/%	Wilcoxon test
1	20.7	6.0	−14.7	−70.9	significant
2	32.5	16.0	−16.5	−50.8	significant
3	68.7	46.9	−21.8	−31.7	significant
4	118.3	94.7	−23.6	−19.9	significant
5	163.4	146.3	−17.1	−10.5	significant
6	153.8	162.2	8.4	5.5	insignificant
7	140.1	159.9	19.8	14.1	significant
8	123.6	139.9	16.3	13.2	significant
9	101.1	100.2	−0.9	−0.9	insignificant
10	74.1	56.0	−18.1	−24.4	significant
11	37.5	20.9	−16.6	−44.3	significant
12	21.0	8.0	−13.1	−62.2	significant
Sum	1054.78	956.91	−97.87	−283.17	-

Notes: $ET_{0\text{-}PM}$ and $ET_{0\text{-}H}$ are ET_0 calculated by P-M and H equation respectively.

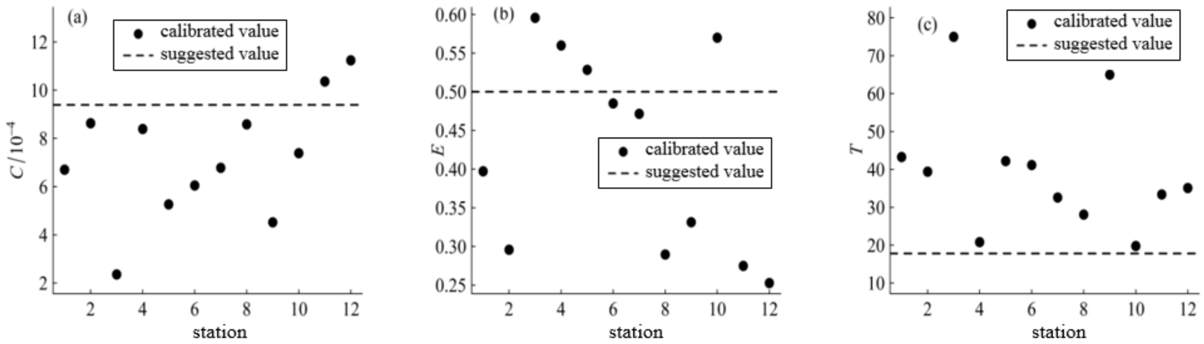

Figure 3. Distribution of calibrated paremeters of Hargreaves Equation.

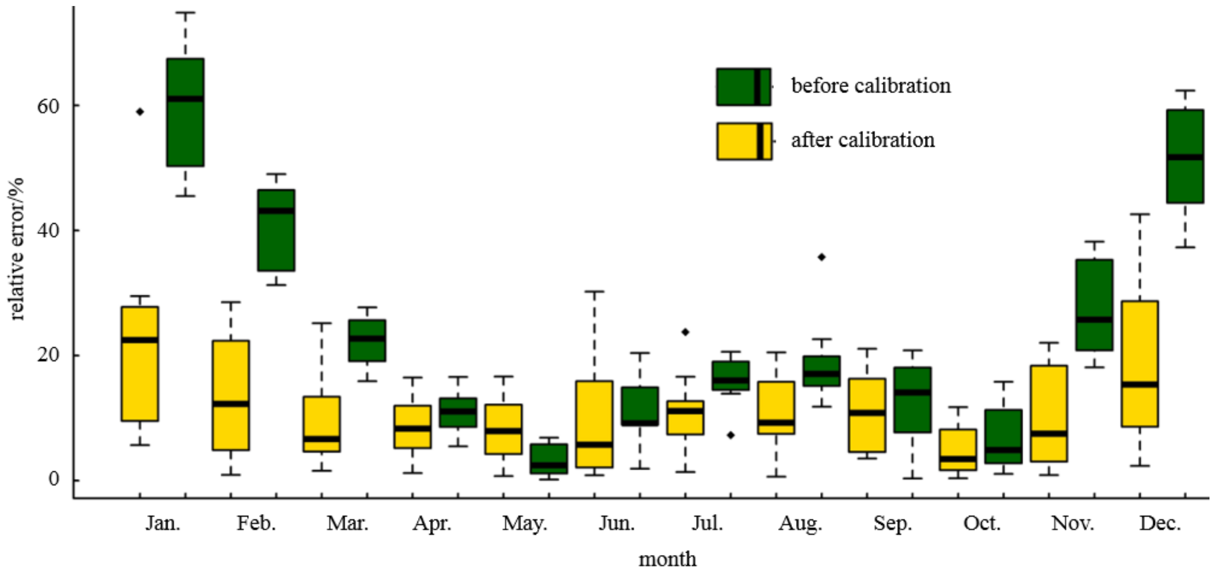

Figure 4. Boxplots of Monthly ET_0 relative error between pre-and-post calibration of Hargreaves equation.

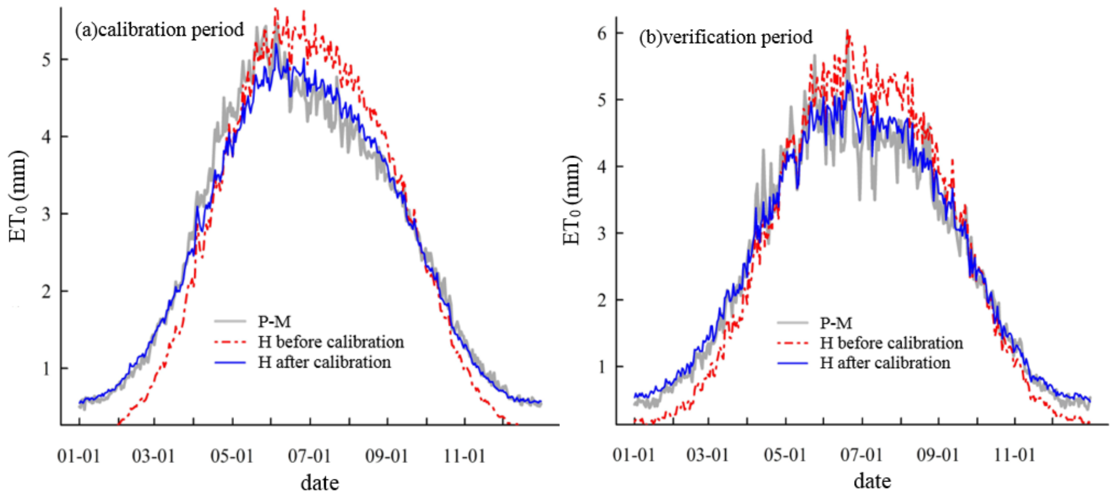

Figure 5. Daily ET_0 Comparisons between pre-and-post adjustment of Hargreaves equation (Jarud).

Table 5. Monthly ET_0 Comparisons between pre-and-post calibration of Hargreaves equation (Jarud).

month	$ET_{0\text{-PM}}$/mm	before calibration				after calibration			
		$ET_{0\text{-H}}$/mm	BE/mm	RE/%	Wilcoxon Test	$ET_{0\text{-H}}$/mm	BE /mm	RE /%	Wilcoxon Test
1	18.01	5.98	−12.03	−66.79	significant	22.66	4.66	25.87	insignificant
2	31.20	16.10	−15.10	−48.39	significant	34.86	3.67	11.76	insignificant
3	65.10	47.48	−17.62	−27.07	significant	68.50	3.40	5.23	insignificant
4	108.50	93.79	−14.71	−13.56	significant	107.00	−1.50	−1.38	insignificant
5	155.62	147.10	−8.53	−5.48	insignificant	149.27	−6.36	−4.08	insignificant
6	150.21	163.60	13.39	8.91	significant	157.32	7.11	4.74	insignificant
7	138.77	163.29	24.52	17.67	significant	154.29	15.52	11.18	insignificant
8	130.95	146.79	15.84	12.09	significant	140.45	9.50	7.25	insignificant
9	100.73	104.26	3.52	3.50	insignificant	103.74	3.01	2.99	insignificant
10	68.78	57.91	−10.87	−15.80	significant	66.37	−2.42	−3.51	insignificant
11	34.74	21.47	−13.27	−38.20	significant	32.23	−2.51	−7.23	insignificant
12	18.42	7.34	−11.08	−60.16	significant	20.09	1.68	9.11	insignificant
mean	85.08	81.26	−3.83	−19.44	-	88.32	3.23	5.41	-
Total	1021.02	975.09	−45.93	−233.28	-	1059.78	38.76	64.90	-

5. Conclusions

Based on the meteorological and radiation data of 12 gauges in the Xiliaohe Basin, this study analyzes the error of H equation by setting daily ET_0 calculated by P-M equation as a standard. The empirical parameters of H equation at each gauge are calibrated with the SCE-UA method and the accuracy characteristics of H equation before and after calibration are compared and evaluated. The results of the study provide conclusions that:

(1) The H and P-M equation show some certain consistence in the variation trend of daily ET_0 while a significant difference can be detected between the calculating values of the two equations. To be specific, results of H equation are obviously higher than the standard value during June and September while lower during the rest time of year.

(2) According to calibration results, 3 parameters of all gauges deviate from the recommended value by FAO

in which most stations show a lower "*C*" and "*E*" than recommend while all the gauges show a higher "*T*". A significant advancement in accuracy during Jan-Mar and Nov-Dec can be seen after calibration accompanied by certain-degree advancement during April and October. In a word, a better and more stable accuracy can be obtained to calculate ET_0 with the calibrated H equation in the replacement of the P-M equation.

The research conclusions above show clearly the necessity and feasibility to calibrate the empirical parameters of H equation. However, in consideration of the significant difference between calibrated parameters of different gauges in the same basin, there is an urgent need to study the regional law of distribution to explore whether this phenomenon is attributed to the different meteorological conditions of each gauge. Also, this issue can be further studied in a larger scale to draw more universal conclusions.

Acknowledgments

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