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Calibration of Hargreaves model for reference evapotranspiration estimation in Sichuan basin of southwest China

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ABSTRACT

Accurate estimation of reference evapotranspiration is vital to hydrological and ecological processes. The FAO-56 Penman–Monteith (PM) model has the higher accuracy for ET_0 estimation, but it requires many meteorological inputs that are not commonly available. Therefore an ideal method is needed requiring as minimal as possible input data variables without affecting the accuracy of estimation. The temperature-based models are especially interesting due to its input data, air temperature, can be monitored easily and is one of the commonly available climatic inputs. Among the temperature-based models, the Hargreaves (HG) model requiring maximum and minimum air temperature as the inputs is considered as one of the simplest and accurate ET_0 methods, but this method needed a local calibration. The present study calibrated the HG model using Bayesian theory at 19 meteorological stations in Sichuan basin of southwest China. Meteorological data during 1961–1990 were used for the calibration and data during 1991–2014 were used for the validation. The results confirmed that the locally calibrated HG model (with average RRMSE, MAE and NS of 0.284, 0.433 mm/d and 0.783) performed better than the original HG model (with average RRMSE, MAE and NS of 0.567, 0.959 mm/d and 0.134). Both of the calibrated and original HG models overestimated ET_0 at daily, monthly and annual timescale, but the calibrated HG model provided closer average values with PM ET_0, which could confirm the good performances of the calibrated HG model. Therefore, the calibrated HG model could be highly recommended for estimating ET_0 when only temperature data are available.

1. Introduction

Population growth and increasing consumption of calorie and meat-intensive diets are expected to roughly double human food demand by 2050, to meet the food security in the coming decades, considerable changes in agricultural water management are required (Mueller et al., 2012). In contrast to the growing dependence on irrigated production, water for irrigation has been reduced due to a combination of frequent droughts and competition for water resources among individual, agricultural and industrial users (Martí et al., 2015a). The high-efficient use of agricultural water is one of the effective ways to alleviate the water crisis. As the only term that appears in both water balance and surface energy balance equations (Xu and Singh, 2005), evapotranspiration (ET) plays a key role in designing and operating irrigation projects (Abdullah et al., 2015), its accurate estimation is vital to computation of crop water requirement, irrigation scheduling, water resources management and determination of the water budget (Shiri et al., 2012).

ET can be estimated using mathematical models, usually relying on reference evapotranspiration (ET_0), which is defined in terms of the FAO-56 Penman–Monteith (PM) model as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23, where the reference surface closely resembled an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water (Allen et al., 1998; Almorox et al., 2015). PM method is recommended as the sole standard approach for estimating ET_0 and validating other models (Allen et al., 1998), it can be applied in a great variety of environments and climate conditions without local calibration and has been validated using lysimeters under a wide range of climatic conditions (Landeras et al., 2008; Shiri et al., 2012). The main limitation of PM method is that it requires many meteorological inputs

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that are not commonly available, especially in developing countries (Droogers and Allen, 2002; Almorox et al., 2015). An ideal method used for estimation of ET_0 should be selected based as minimal as possible on the input data variables without affecting the accuracy of estimation (Shih, 1984; Traore et al., 2010). Thus, the temperature-based models are especially interesting due to its required input data, air temperature, can be measured easily and widely (Mendicino and Senatore, 2013; Almorox et al., 2015). Air Temperature and solar radiation explain at least 80% of ET_0 variability (Priestley and Taylor, 1972; Samani, 2000; Martí et al., 2015b), Hargreaves and Samani (1985) introduced maximum, minimum temperature and extraterrestrial radiation to calculate solar radiation, and then they established the well-known Hargreaves (abbreviated as HG) model for ET_0 estimation. It is considered as one of the simplest and accurate ET_0 estimation methods (Jensen et al., 1997), and can be applied for short-term forecasting of ET_0 using the temperature forecasts (Luo et al., 2014). Allen et al. (1998) recommended the HG model as PM alternative method for ET_0 estimation when the data set of PM model required are not fully available. Almorox et al. (2015) assessed 11 representative temperature-based methods for estimating ET_0, HG model provided the most accurate global average performance in arid, semiarid, temperate, cold and polar climates. Although its good performances have been reported, HG model is recommended for a local calibration (Allen et al., 1998; Samani, 2000; Hargreaves and Allen, 2003), and applied for five-day or longer periods calculation of ET_0 (Hargreaves and Allen, 2003). The HG model has a tendency to underestimate ET_0 under condition of high wind conditions (wind speed > 3 m/s) and to overestimate under conditions of high relative humidity or low evapotranspiration rates (Allen et al., 1998; Droogers and Allen, 2002; Xu and Singh, 2002; Zhao et al., 2012; Almorox et al., 2015), thus a local calibration of HG model suited for local daily calculation of ET_0 is highly needed.

In the past decades, many researchers have put much effort on calibration of HG model (e.g. Gavilan et al., 2006; Tabari and Talaee, 2011; Berti et al., 2014; Shiri et al., 2014, 2015; Martí et al., 2015b; Cobaner et al., 2016; Xu et al., 2016), but these calibrations were site-specific and cannot be extrapolated to other sites where weather conditions are totally different (Martí et al., 2015b), and some calibrated HG models are more complicated compared with the original HG model (Martinez and Tejero, 2004; Yang and Zhang, 2009; Talaee, 2014). Moreover, using historical data to calibrate HG model directly ignores the continuity of climate change over the time, this may lead good performances of calibrated HG model in the calibrated years, but when data set extends, instability of the calibrated HG model may appear. To reduce this instability, a suitable method for the calibration should be taken into account.

During January to April in 2010, a severe drought happened in southwest China, which affected more than 60 million people and caused more than 23.66 billion CNY (3.6 billion USD) economic losses (Feng et al., 2014a). Therefore, efficiently irrigation water management and water allocation are needed to improve water use efficiency in southwest China. The aim of the present work was to locally calibrate HG model in a humid area of southwest China, the Bayesian algorithm was utilized to adjust the 3 parameters of HG model, the main objective is to improve the applicability of HG model for the accurate estimation of ET_0, and enhance precision irrigation level and increase of water use efficiency (Zhang et al., 2013).

2. Material and methods

2.1. Study area and data set

The weather data were obtained from 19 meteorological stations located in Sichuan basin, southwest China. Sichuan basin is one of the major food production areas in China, with an area of about 0.26 million km^2, a population of 90 million. The famous Dujiangyan Irrigation Project supplying irrigation water for about 7.0 thousand km^2 irrigated farmland is in the center of Sichuan basin. According to Köppen climate classification, the study area is characterized as warm temperate climate with dry winter (Zhu and Li, 2015), with mean annual air temperature, relative humidity and precipitation of 17.4 °C, 79% and 1123 mm, respectively (Table 1).

Daily meteorological variables, including maximum (T_{max}), minimum (T_{min}) and mean (T_{mean}) air temperature at 2 m height, mean relative humidity (RH), wind speed at 10 m height (U_{10}), sunshine duration, were obtained at 19 meteorological station in Sichuan basin (Fig. 1) during 1961–2014. The data set with good quality were obtained from the National Climatic Centre of the China Meteorological Administration.

2.2. FAO-56 Penman-Monteith model

Experimental techniques for measuring ET_0, such as lysimeters or eddy covariance systems, were in absence for the study

Table 1
Meteorological stations and mean meteorological variables of Sichuan basin.

Station	Station code	WMO Number	Longtitude	Latitude	Altitude	U_{10}	T_{mean}	RH	R_s	P_r
			(°E)	(°N)	(m a.s.l.)	(m/s)	(°C)	(%)	(MJ/m^2 d)	(mm/yr)
Mianyang	1	56196	104.73	31.45	522.7	0.9	16.5	77.2	12.1	909.9
Dujiangyan	2	56188	103.67	31.00	698.5	0.9	15.4	80.1	11.2	1199.1
Chengdu	3	56187	103.82	30.70	539.3	0.9	16.3	80.9	11.8	903.4
Yaan	4	56287	103.00	30.00	627.6	1.2	16.4	78.4	11.5	1722.6
Leshan	5	56386	103.75	29.57	424.2	0.9	17.4	80.0	11.9	1294.3
Guangyuan	6	57206	105.85	32.43	513.8	1.1	16.3	68.3	12.5	964.1
Bazhong	7	57313	106.73	31.87	417.7	0.6	17.0	77.9	12.7	1125.5
Langzhong	8	57306	105.95	31.59	382.6	0.8	17.1	76.6	12.4	1027.2
Nanchong	9	57411	106.10	30.77	309.7	0.9	17.6	79.1	12.4	1011.9
Suining	10	57405	105.55	30.50	355.0	0.7	17.5	80.7	12.4	968.9
Neijiang	11	57504	105.05	29.59	347.1	1.2	17.7	80.2	12.5	1040.7
Luzhou	12	57602	105.43	28.90	334.8	1.1	17.9	82.5	12.5	1125.1
Yibin	13	56492	104.60	28.60	340.8	0.7	18.1	80.5	11.9	1096.3
Xuyong	14	57608	105.43	28.17	377.5	0.9	18.0	79.5	12.5	1135.4
Daxian	15	57328	107.50	31.20	344.9	1.0	17.3	78.8	12.5	1198.2
Wanxian	16	57432	108.40	30.80	186.7	0.5	18.9	80.6	12.7	1184.3
Liangping	17	57426	107.80	30.69	454.5	0.9	17.2	80.9	12.7	1242.1
Fuling	18	57522	107.40	29.75	273.5	0.6	18.7	79.5	12.3	1100.6
Shapingba	19	57516	106.50	29.60	259.1	1.0	19.0	78.9	12.0	1092.9
Average	/	/	/	/	/	0.9	17.4	79.0	12.2	1123.3