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APPLICATION OF ENERGY AND WATER BALANCE METHODS: A COMPARATIVE STUDY ON WHEAT EVAPOTRANSPIRATION RATES

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Abstract

As a problem of water shortage in Henan Province, it is necessary to study the evapotranspiration of wheat field, in order to make reasonable allocation of agricultural water resources. Water balance method (WB) is used to measure the evapotranspiration of the point, and the energy balance (EB) method and the eddy correlation (ECV) rule is used to estimate the evapotranspiration of large scale. Through the study, the correlation coefficient of the energy balance method and water balance method was 0.99. The instantaneous value of the energy balance method was higher, but the daily average value was close to the normal level. Finally, it is pointed out that in energy balance method is used to calculate evapotranspiration calculated Bowen ration the key is usually used on a weighted average value instead of the instantaneous values of the error can be eliminated. The results show that energy balance method can fasten and continuous monitor crop evapotranspiration, which has reference significance for guiding the local agricultural water resource disposition.

Introduction

Wheat yield in Henan province accounts about 25% of the China's total wheat yield, which makes great contribution to the country's food security. In agriculture water shortage is a main problem during the wheat growth. The most effective way to solve this problem is using agricultural water resource reasonably and improving the efficiency of use of water. Only figuring out the winter wheat water consumption and its pattern can lay basis for the scientific irrigation system and reasonable water distribution in irrigation area. Evapotranspiration plays an important role in the energy distribution and hydrological cycle of farmland, and also provides the data support for the irrigation water resources allocation. The methods for research of evapotranspiration include water balance method (Huang *et al.* 2005, Liu *et al.* 2016), lysimeter method (Marek *et al.* 2016, Saseendran *et al.* 2016), the reference crop evapotranspiration method (Muniandy *et al.* 2016), energy balance method (Zhang *et al.* 2008, Dicken *et al.* 2013, Holland *et al.* 2013 and Xing *et al.* 2008, Elsawwaf *et al.* 2009), eddy covariance method (Nagler *et al.* 2005, Wolf *et al.* 2008, Uddin *et al.* 2013, Tang *et al.* 2013, Soubie *et al.* 2016) and remote sensing method (Rientjes *et al.* 2013, Cammalleri and Ciraolo 2013, Consoli and Vanella 2014, Corbari *et al.* 2015, Allam *et al.* 2016). Among these methods, the water balance method and lysimeter method are mainly used for small plots scale to test evapotranspiration. The rest of methods, which includes the reference crop evapotranspiration method, micro meteorology method and remote sensing method are mainly used for testing evapotranspiration in irrigated area. Due to the energy balance method has the advantage of measuring evapotranspiration for large scale farmland,

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easy to use as well as highest accuracy, therefore, this article chooses this method from micro meteorology method to find out the evapotranspiration of wheat field, at the same time, by applying water balance method to verify the result. Bowen ratio (Bowen 1926) was firstly raised by British physicist Bowen in 1926 during the study of surface energy balance. In 2003, Payero (Wright *et al.* 2003) proposed the guide of verification data method; Escarabajal-Henarejos *et al.* (2015) improved the accuracy of calculation of evapotranspiration by replacing thermocouples to resistance temperature detectors. This article mainly solved two problems: (i) the difference between the crop water requirement calculated by energy balance method and the crop water requirement calculated by water balance method was investigated, (ii) the water consumption law and water consumption of winter wheat during the growing season in Henan Province were verified.

Materials and Methods

Based on China flux farmland ecological flux observation stations, the experiment was carried out from October, 2013 to June, 2014, location following Qi Li Ying test base in Xinxiang county of Chinese Academy of Agricultural Sciences. The base coordinate was north latitude 35°18′ and 113°54′ east longitude, with 73.2 m altitude. Xinxiang County belongs to temperate continental monsoon climate, which has four distinctive seasons and obvious seasonal characteristics. The spring is drought and sandy; summer has abundant rain and torridity; autumn has long sunshine time and winter is cool with less rain or snow. The average temperature among these years is 14.3ºC, average range of temperature is 16.5ºC, sunshine hour is 2407 hrs, frost free days is 191 days, annual average evaporation amount is 1652.8 mm, annual average rainfall is 560.6 mm, and the inter annual rainfall is uneven, mostly from June to September that is about 75% of the total annual rainfall. Soil type is sandy loam, soil bulk density is 1.50 g/cm^3, the field capacity is 24% (percentage of dry soil weight).

The tested cultivars were Xinmai 26, seeding at 18 October, 2013, harvested at 12 June, 2014, using 3 local farmers growing habits.

Main observation items: air temperature and humidity, net radiation, soil heat flux plate and soil temperature of two selections. Three dimensional velocity was measured by CSAT3 (Campbell, USA); using NR01 net radiation sensor (Hukseflux, Netherlands) measured air temperature and humility at two heights. There were three heat flux plate buried under surface layer of 5, 10 and 20 cm, respectively. The data acquisition system was made available from Italian E-l0G collector that collected and saved data every 10 min automatically. Soil moisture used soil drying method and TDR.

The data were reasonably tested, eliminated outliers, and the missing data were supplemented by meteorological interpolation.

Evapotranspiration measurements: (i) The equation of theoretical basis of the energy balance is:

$$R_n - G = LE + H$$

R_n is net radiation, LE is the latent heat flux between the ground and the atmosphere; H is the sensible heat flux between the ground and the atmosphere; G is the soil heat flux. Assuming Bowen ratio is b = H/LE,

$$LE \quad \frac{R_n - G}{1 + \beta}$$

Set the crop and ground surface as evaporation, based on the theory of boundary layer diffusion, the latent heat and sensible heat flux on the surface is as follows:

$$H = -\rho C_p K_h \frac{d_T}{d_z}$$

$$LE = -\frac{\rho \lambda \varepsilon}{P} K_v \frac{de}{dz}$$

assuming $K_h = K_v$, differential variation,

$$\beta = \frac{C_p P}{\lambda \varepsilon} \frac{K_h}{K_v} \frac{d_T}{d_z} = \frac{C_p P}{\lambda \varepsilon} \frac{\Delta T}{\Delta e} = \gamma \frac{\Delta T}{\Delta e}$$

where, L is latent heat of vaporization; ρ is air density; C_p is air set pressure specific heat; εis molecules of water vapor proportionally for the dry weight of air molecules; P as the atmospheric pressure; K_v, K_h, respectively stands for latent and sensible heat exchange coefficient; Z and T were temperature and humidity gradient. According to the theory of similarity, assuming $K_h = K_v$, while obtaining Bowen ratio β (the ratio of sensible heat flux and latent heat flux), divided into differential:

Measuring Rn, G, ΔT and ΔE by using (4), (5), (6), Can calculus the value of latent heat and sensible heat flux between the evaporation surface and the atmosphere.

Water balance method: The actual measurement of evapotranspiration of summer maize using water balance method:

$$W_t - W_0 = W_T + P_e + S_G + I - ET_c$$

after the compilation of the equation:

$$ET_c = W_0 - W_t + W_T + P_e + S_G + I$$

W_o and W_t are respectively soil moist layer water storage at beginning and end; W_r is the amount of water increased by toil moisture layer; P_e is effective precipitation of stored in the soil moisture layer; S_G is the amount of underground water conservancy in the period of time; I as irrigation amount; ET_c as Evaporation and transpiration in the period of time; as requirement of reference crop water, all the above units are mm. This is the 1998 World Food and Agriculture Organization recommended amendments to the formula.

Statistical and model evaluation index: There are multiple class of statistical indices, which includes summary statistics for example, mean; correlation indices, such as coefficient of determination; absolute error indicators, such as were the root mean square error, mean absolute error and mean bias error; relative error metrics, including absolute error criterion of relative value, efficiency index and composite index.

In this paper, the index mainly contains mean, determination coefficient (R^2), mean deviation error (EDE), root mean square error (RMSE), relative deviation error and relative root mean square error, determination coefficient R^2 as:

$$R^2 = \left[\frac{\sum_{i=1}^{N} (O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{N} (O_i - \overline{O})^2} \sqrt{\sum_{i=1}^{N} (P_i - \overline{P})^2}} \right]^2$$

where, N as the quantity of measured value, Oi and Pi, respectively as measured and predicted values, overbar stands for the mean. Mean deviation error MBE and relative mean deviation error RBE are defined as:

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(O_i - P_i)$$

$$RBE = \frac{MBE}{\bar{O}} \times 100$$

The root mean square error RMSE and the relative root mean square error RSE are defined as

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{N-1}}$$

$$RSE = \frac{RMSE}{\bar{O}} \times 100\%$$

degree of fitting IA:

$$IA = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(\left|O_i - \bar{O}\right| + \left|P_i - \bar{P}\right|)^2}\right]$$

Results and Discussion

Daily energy allocation model

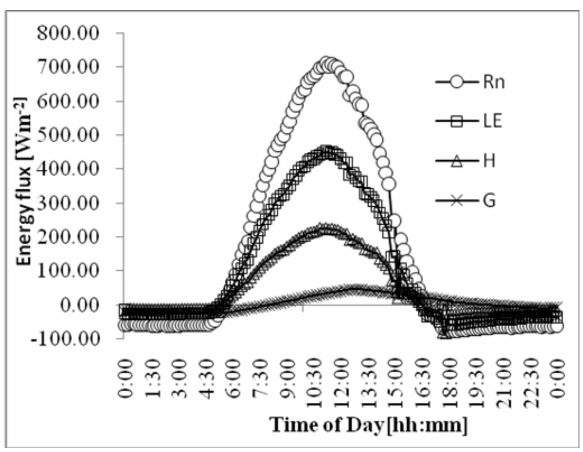

Fig. 1. Components of energy fluxes including actual latent heat flux (LE), actual sensible heat flux (H), soil heat flux (G) and net radiation (Rn) under advective conditions (DOY 104, 29 April, 2013).

Fig. 1 shows the energy distribution in wheat field on 29 April, from the figure, solar net radiation from 0:00 to 4:00 is –60 W/m^2 after 400, it began to increase, at 5:40 became positive and still growing, until at 11:30 reached the maximum 708.36 Wm^{-2} then gradually reduced.

Around 17:00, it dropped to negative, until 19:00 reached the minimum –77.38 Wm^{-2} then stayed around –62 Wm^{-2}. Soil heat flux began to decrease from 0:00 to 5:00, whereas the minimum –23.33 Wm^{-2}, after that started to increase. At 8:00 arrived at positive and increasing progressively, at 13:00 it came at maximum 45.59 Wm^{-2}, then decreased steadily, around 23:00 got the minimum –10.15 Wm^{-2}, then rose. There was a same variation trend between latent heat of evaporation and sensible thermal evaporation and solar net radiation. Compared to soil heat flux and the net radiation, it could be seen that the time of maximum of soil heat flux was 90 min later than solar net radiation, which was caused by the lag of energy on the surface redistribution of farmland.

Evapotranspiration process analysis: Fig. 2 shows the winter wheat daily evapotranspiration variation, it states evapotranspiration of green stage is 2.5 mm/d, evapotranspiration of winter wheat increases gradually after turn green, evapotranspiration of joint stage is 3.7 mm/d, evapotranspiration of filling stage is 4.6 mm/d, evapotranspiration at milky stage is 2.9 mm/d. Till it reaches filling stage, evapotranspiration becomes decrease. Compared evapotranspiration for each stage, during heading and grain filling is the maximum, joint stage is the second; turning green stage and milking stage stay flat essentially. After turning green stage, plant population began to recover and growth with the temperature increased, so evapotranspiration raised; after joint stage, leaf area index of wheat increased rapidly, evapotranspiration was dominated by transpiration; turned into heading filling stage, wheat arrived at a key period of vegetative growth and reproductive growth, which had the maximum evapotranspiration; then went to milky stage, the leaves turned yellow, and evapotranspiration decreased.

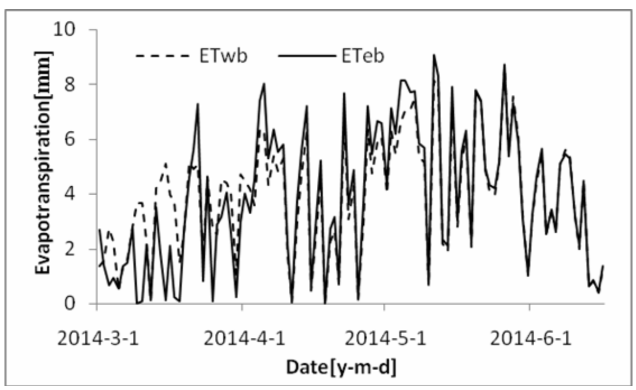

Fig. 2. Daily value of evapotranspiration computed by water balance (WB) and energy balance (EB) during the growing period in 2013.

Error analysis was made (Table 1) for water balance and energy balance method, from the chart, it shows:

1. From turning green stage to harvest stage, the mean of evapotranspiration for water balance method and energy balance method is 3.95 and 3.90 mm/d;
2. The evapotranspiration from energy balance method is small, which has the same conclusion with Qiang *et al.* (2009), about 0.05 mm/d smaller daily on average;
3. From energy balance method, the mean deviation is 0.04 mm/d and root mean square error is 1.10 mm/d;
4. The fitting degree of energy balance method is 0.94, which is less than 1.

Table 1. Statistics and error analysis between two instantaneous values of evaporation.

Parameter	Water balance method	Energy balance method
Mean	3.94627	3.901536
Standard error	0.20466	0.246139
Median	4.177956	3.614054
Standard deviation	2.117015	2.546079
Variance	4.481753	6.482518
Kurtosis	–0.73521	–1.06667
Skewness	0.004878	0.125613
Region	8.637714	9.056414
Minimum value	0.01599	0.013694
Maximum value	8.653704	9.070108
Sum	422.2508	417.4643
Maximum value	8.653704	9.070108
Minimum value	0.01599	0.013694
Confidence (95%)	0.405757	0.487994
Mean deviation error	0	0.043324
Relative mean deviation	0	1.10%
Root mean square error	0	1.096719
Relative root mean square error	0	27.79%
Fitting degree	1	0.942849

From the analysis above, it can be approved that energy balance method has high accuracy to calculate evapotranspiration, and also easy to use.

The evapotranspiration of wheat was compared daily scale and 10 min scale. From the table, we can read the maximum of daily scale evapotranspiration was 9.07 mm, converted 10 minutes scale to daily instantaneous value of evapotranspiration; the maximum was 30 mm that has the same result of Li *et al.* (2008). The reason behind is LE value in day time has positive and peak but night time LE becomes negative, the daily LE value is the average of day time and night time, therefore, the evapotranspiration value calculated by daily is less than the value calculated by 10 minutes scale. This is the datagram of daytime energy and night time energy:

The method of getting β: When using energy balance method to obtain evapotranspiration, assuming the measurement of LE and G could meet the experiment requirements, and then the calculated accuracy of LE depended on β, from the calculation, we can see β has a complex variation that has positive and negative. Therefore, here we used the method Zhu (1980) recommended to do the math.

The reasons for two measurement methods are different: Water balance method mainly focuses on evapotranspiration within a single plot; on the other hand, Bowen ratio concentrates on a large scale of farmland to measure evapotranspiration. The instruments requirements of Bowen ratio include the underlying surface remains flat, observation is in large area, the crop growth stay uniform with large area; in addition, Bowen ratio should minimize affections of accuracy such as air flow, pseudo temperature and green state effect. However, water balance method requires less strict than Bowen ratio.

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