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Discussion and reassessment of the method used for accepting or rejecting data observed by a Bowen ratio system

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Abstract:

The Bowen ratio energy balance method often produces extremely inaccurate magnitudes of the flux due to resolution limits of the instruments. We analysed the criteria used for rejecting inaccurate data observed using a Bowen ratio system and the resolution limit of the sensors to analytically determine the reliable values of the Bowen ratio (β) and the latent and sensible heat fluxes. The formula used to calculate the error limit of the Bowen ratio (β) was corrected based on the theory of error analysis. An example was proposed for the common case with 0.2 °C resolution limit of temperature measurement and 0.08 kP_a resolution limit of water vapour pressure measurement, to show the steps of accepting or rejecting data observed by a Bowen ratio system. The acceptance or rejection of data observed by a Bowen ratio system is a dynamic process, which should be performed based on the excluded interval of the Bowen ratio and the qualitative relationships among the data observed by a Bowen ratio system. The excluded interval of the Bowen ratio can be structured based on the accuracy of the sensors used. Data are excluded first if they do not satisfy the qualitative relationships between the vapour pressure difference, the temperature difference, Bowen ratio, and the available energy, whereas the data in the rejection region range of the Bowen ratio are excluded second. It is necessary to improve the accuracy of the temperature and humidity probes to improve the acceptance rate for data collected using the Bowen ratio system, apart from improving the observed precision of available energy.

KEY WORDS Bowen ratio; energy balance; error analysis; temperature difference; vapour pressure difference

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INTRODUCTION

The Bowen ratio-energy balance method (BREB) has been widely used since it was proposed in 1926 because it has the advantages of a clear physical concept, few parameter requirements, and a simple calculation method. It can be used to estimate the latent heat flux over large areas (~1000 m^2) and small time scales (<1 min) (Ibánñez and Castellví, 2000). It has higher precision and is often used as a criterion for test other methods for calculating evapotranspiration. It facilitates the analysis of the relationships between evapotranspiration and environmental factors, which helps to understand the internal mechanism of evapotranspiration. However, this method also has a large number of assumptions and constraints. Thus, there can be major deviations (or errors) in the data observed using the Bowen ratio system due to variability in the weather, plants, and other factors, as well as the measurement accuracy of the instrument, if the external conditions do not satisfy the conditions of use. Appropriate data processing is directly related to the measurement accuracy of the BREB. Therefore, it is necessary to accept or reject the data observed using the Bowen ratio system.

The simplest method used for accepting or rejecting the data observed by a Bowen ratio system is to eliminate the data where the temperature and humidity difference is less than or close to the probe precision (Unland *et al.*, 1996), or where the excluded interval is given directly based on the value of β (Ortega-Farias *et al.*, 1996). If the energy consumed by evapotranspiration is equal to the sensible heat supplied to the underlying surface, i.e. $\beta = -1$, the evapotranspiration tends to infinity (Todd *et al.*, 2000). In 1999, Perez *et al.* suggested that the unreasonable range for β was a dynamic variation, which was mainly influenced by the water pressure gradient and the sensor resolution (Perez *et al.*, 1999), and this method has been applied throughout the world (Peacock and Hess, 2004; Wu *et al.*, 2005; Gavilán and Berengena, 2007; Zhang *et al.*, 2008; Zhang *et al.*, 2011).

The main aim of this study is to revise the formula used to calculate the error limit of Bowen ratio β to provide a theoretical basis for accepting or rejecting data observed using a Bowen ratio system.

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ANALYSIS

Basic principle of the BREB method

According to the principle of energy conservation, the surface energy balance equation can be expressed as follows (Kang *et al*., 1994):

$$R_n = \lambda ET + H + G + A + P + M \tag{1}$$

where R_n is the net radiation flux (W/m^2), λET is the latent heat flux (W/m^2), H is the sensible heat flux (W/m^2), G is the soil heat flux (W/m^2), A is the energy exchange capacity caused horizontally by advection (W/m^2), P is the energy used by photosynthesis (W/m^2), M includes the energy conversion caused due to metabolic activities and heat storage within the plant tissue and in the canopy (W/m^2), λ is the latent heat of vaporization (J/kg), and ET is the evapotranspiration (mm).

If the underlying surface is uniform and the area is large, the vertical gradient of the meteorological elements is much greater than the horizontal gradient, so the energy advection term A can be neglected. In addition, the sum of the P term and the M term is usually much smaller than the actual error of the main component in the energy balance equation, so the P and M terms can also be ignored under normal circumstances, and Equation (1) can be simplified to the following.

$$R_n = \lambda ET + H + G \tag{2}$$

The Bowen ratio β was introduced in 1926 to reflect the proportional relationship between the sensible heat flux and latent heat flux in the energy balance, i.e.

$$\beta = \frac{H}{\lambda E} = \gamma \frac{\Delta T}{\Delta e} \tag{3}$$

$$\gamma = \frac{C_p P_a}{0.622\lambda} \tag{4}$$

where β is the Bowen ratio; γ is the psychrometric constant (kPa/°C); C_p is the specific heat of the air at constant pressure (J/(kg·K)); P_a is the atmospheric pressure (kPa);ΔT and Δe are the temperature difference (°C) and water vapour pressure difference (kPa) at two measurement levels, respectively (Figure 1).

The expressions for λET is

$$\lambda ET = \frac{R_n - G}{1 + \beta} \tag{5}$$

Rejection region for data observed using a Bowen ratio system

If $\beta \approx -1$, using Equation (5) gives $\lambda ET = \infty$, which is clearly unreasonable. If it is assumed that the random measurement error for temperature and humidity is far less than the precision of instrument, the dynamic rejection region when β is close to −1 may be formulated based on the sensor accuracy.

If we assume that the absolute error of β is Δβ, absolute error limit is ε, the absolute error of vapour pressure difference Δe is E (Δe), the absolute error limit is δΔe, the absolute error of the temperature difference ΔT is E (ΔT), and the absolute error limit is δΔT, then

$$|\Delta\beta| \le \varepsilon \tag{6}$$

$$|E(\Delta e)| \le \delta \Delta e \tag{7}$$

$$|E(\Delta T)| \le \delta \Delta T \tag{8}$$

$$|E(\Delta e)| \approx |d \Delta e| \tag{9}$$

$$|E(\Delta T)| \approx |d\Delta T| \tag{10}$$

Because

$$\beta = \gamma \frac{\Delta T}{\Delta e}$$

So

$$\frac{\partial \beta}{\partial \Delta T} = \frac{\gamma}{\Delta e} \tag{11}$$

$$\frac{\partial \beta}{\partial \Delta e} = -\frac{\gamma \Delta T}{(\Delta e)^2} \tag{12}$$

$$d\beta = \frac{\partial \beta}{\partial \Delta T} d\Delta T + \frac{\partial \beta}{\partial \Delta e} d\Delta e \tag{13}$$

Inserting Equations (11) and (12) into Equation (13) produces

$$\begin{aligned} d\beta &= \frac{\gamma}{\Delta e} d\Delta T - \frac{\gamma \Delta T}{(\Delta e)^2} d\Delta e = \frac{\gamma}{\Delta e} d\Delta T - \gamma \frac{\Delta T}{\Delta e} \cdot \frac{d\Delta e}{\Delta e} \\ &= \frac{\gamma}{\Delta e} d\Delta T - \beta \frac{d\Delta e}{\Delta e} \end{aligned} \tag{14}$$

If $\beta = -1$

$$d\beta = \frac{d\Delta e + \gamma d\Delta T}{\Delta e} \tag{15}$$

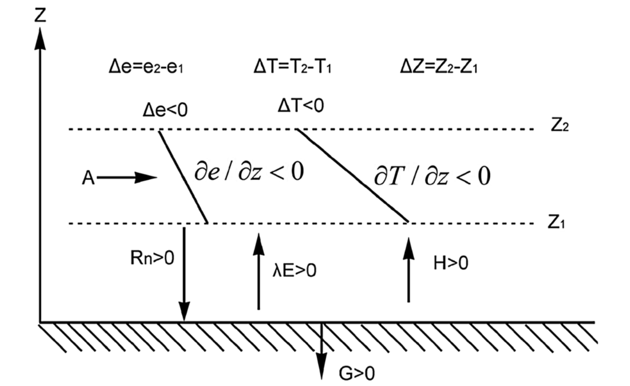

Figure 1. Schematic showing the directions of the components of the energy fluxes (modified based on Perez *et al.* (1999))

$$
\begin{aligned}
|d\beta| &= \left|\frac{d\Delta e+\gamma d\Delta T}{\Delta e}\right| = \frac{|d\Delta e+\gamma d\Delta T|}{|\Delta e|} \leq \frac{|d\Delta e|+|\gamma d\Delta T|}{|\Delta e|} \\
&\approx \frac{|E(\Delta e)|+\gamma|E(\Delta T)|}{|\Delta e|} \leq \frac{\delta\Delta e+\delta\Delta T}{|\Delta e|}
\end{aligned} \tag{16}
$$

$$
|\Delta\beta| \approx |d\beta| \leq \frac{\delta\Delta e+\gamma\delta\Delta T}{|\Delta e|}
$$

Therefore,

$$
\varepsilon = \frac{\delta\Delta e+\gamma\Delta T}{|\Delta e|} \tag{17}
$$

Equation (17) shows that the rejection region of β is a dynamic rejection region surrounded by the curve of $\beta = -1 \pm \varepsilon$, which depends on the system accuracy and the measured vapour pressure difference, Δe.

The types of rejection regions with a different Bowen ratio β are shown in Table I.

DISCUSSION

A functional relationship exists between indirect measurement values and direct measurement values, so we set

$$
\mathrm{y} = \mathrm{f}(\mathrm{x}_1, \mathrm{x}_2, \cdots\cdots, \mathrm{x}_\mathrm{n}) \tag{18}
$$

Table I. Types of rejection regions with a different Bowen ratio β

Type	Rejection region for the Bowen ratio β		
A	Rn-G>0	Δe<0	β<-1+ε
B	Rn-G>0	Δe>0	β>-1−ε
C	Rn-G<0	Δe<0	β>-1−ε
D	Rn-G<0	Δe>0	β<-1+ε

Note: Δe is vapour pressure at the upper measurement level minus vapour pressure at the lower measurement level, that is, $\Delta e = e_2 - e_1$ (modified based on Perez *et al.* (1999))

where y is the direct measurement value, x_i is the indirect measurement value, and i = 1, 2, ···, n.

Taking the total differential of Equation (18) yields (Mathematics Department of Tongji University, 1978)

$$
dy = \frac{\partial f}{\partial x_1}dx_1 + \frac{\partial f}{\partial x_2}dx_2 + \cdots + \frac{\partial f}{\partial x_n}dx_n \tag{19}
$$

If differential dy, dx_1, dx_2, …, dx_n are substituted by absolute error Δy, Δx_1, Δx_2, …, Δx_n in the equation above,

$$
\Delta y = \frac{\partial f}{\partial x_1}\Delta x_1 + \frac{\partial f}{\partial x_2}\Delta x_2 + \cdots + \frac{\partial f}{\partial x_n}\Delta x_n \tag{20}
$$

where Δy, Δx_i, and the partial derivative $\frac{\partial f}{\partial x_i}$ of Equation (20) can be positive or negative, so the positive term may offset the negative term on the right of the equation above.

The absolute value of the absolute error of a function or an indirectly measurement value y is (Li and Hu, 2008)

$$
|\Delta y| = \left|\frac{\partial f}{\partial x_1}\Delta x_1 + \frac{\partial f}{\partial x_2}\Delta x_2 + \cdots + \frac{\partial f}{\partial x_n}\Delta x_n\right| \tag{21}
$$

According to the nature of the absolute value of the inequality, we have

$$
\begin{aligned}
|\Delta y| &= \left|\frac{\partial f}{\partial x_1}\Delta x_1 + \frac{\partial f}{\partial x_2}\Delta x_2 + \cdots + \frac{\partial f}{\partial x_n}\Delta x_n\right| \\
&\leq \left|\frac{\partial f}{\partial x_1}\Delta x_1\right| + \left|\frac{\partial f}{\partial x_2}\Delta x_2\right| + \cdots + \left|\frac{\partial f}{\partial x_n}\Delta x_n\right| \\
&= \left|\frac{\partial f}{\partial x_1}\right|\cdot|\Delta x_1| + \left|\frac{\partial f}{\partial x_2}\right|\cdot|\Delta x_2| + \cdots + \left|\frac{\partial f}{\partial x_n}\right|\cdot|\Delta x_n|
\end{aligned} \tag{22}
$$

Assuming that the error limit of X_i is δX_i, there are

$$
|\Delta x_i| \leq \delta x_i \tag{23}
$$

Equation (22) reduces to

$$
|\Delta y| \leq \left|\frac{\partial f}{\partial x_1}\right|\delta x_1 + \left|\frac{\partial f}{\partial x_2}\right|\delta x_2 + \cdots + \left|\frac{\partial f}{\partial x_n}\right|\delta x_n \tag{24}
$$

and the error limit ε of y is

$$
\varepsilon = \left|\frac{\partial f}{\partial x_1}\right|\delta x_1 + \left|\frac{\partial f}{\partial x_2}\right|\delta x_2 + \cdots + \left|\frac{\partial f}{\partial x_n}\right|\delta x_n. \tag{25}
$$

For the function

$$
\beta = \gamma\frac{\Delta T}{\Delta e}
$$

Equation (25) yields

$$\varepsilon = \left|\frac{\partial \beta}{\partial \Delta T}\right|\delta \Delta T + |\frac{\partial f}{\partial \Delta e}|\delta \Delta e \quad (26)$$

Substituting Equations (11) and (12) into Equation (26) yields

$$\begin{aligned}\varepsilon &= |\frac{\partial \beta}{\partial \Delta T}|\delta \Delta T + |\frac{\partial f}{\partial \Delta e}|\delta \Delta e \\ &= |\frac{\gamma}{\Delta e}|\delta \Delta T + |-\frac{\gamma \Delta T}{(\Delta e)^2}|\delta \Delta e \\ &= |\frac{\gamma}{\Delta e}|\delta \Delta T + |-\frac{\gamma \Delta T}{\Delta e}\frac{1}{\Delta e}|\delta \Delta e \\ &= |\frac{\gamma}{\Delta e}|\delta \Delta T + |-\beta \frac{1}{\Delta e}|\delta \Delta e\end{aligned}$$

When $\beta = -1$, $\varepsilon = \frac{\delta \Delta e + \gamma \delta \Delta T}{|\Delta e|}$, which is above Equation (17).

The error and error limit are two different concepts. Perez *et al.* (1999) confused the two concepts. According to the theory of error analysis, the absolute error of β is Δβ and can be calculated by the following equation

$$\Delta \beta = \beta - \beta^* \quad (27)$$

where β* is the approximation of β.

It can be seen from Equations (26) and (27) that $\varepsilon \neq \Delta\beta$, and Δβ can be positive or negative, whereas ε must be positive.

The expression (17) for the error limit ε of the Bowen ratio β presented in this paper is different from expression (28), which was proposed by Perez *et al.* in 1999:

$$\varepsilon = \frac{\delta \Delta e - \gamma \delta \Delta T}{\Delta e} \quad (28)$$

The denominator of Equation (17) is the absolute value of the vapour pressure difference, whereas the denominator of Equation (28) is the vapour pressure difference. The vapour pressure difference can be either positive or negative. Thus, there is an essential difference between the two equations. Furthermore, the numerator of Equation (17) is Δe plus γδΔT, whereas the numerator of Equation (28) is Δe minus γδΔT. Thus, the two equations are fundamentally different.

The idea of determining the rejection region for the Bowen ratio β proposed by Perez *et al.* (1999) was excellent, but the equation used to calculate the error limit of the Bowen ratio β was incorrect.

EXAMPLE

Experimental site and measurements

Research was conducted during August–October, 2011, at the Aksu National Field Research Station for Agro-ecosystems (ANFRSA) (80°51′E, 40°37′N), Xinjiang Uygur Autonomous Region, China, which is located in a new oasis in an alluvial plain where the three main headstreams (i.e. the Aksu, Yeerqiang, and Hetian Rivers) of the Tarim River meet. It covers an area of about 20 ha. The elevation of the station is 1024 m. Compared with other sites at the same latitude, this site has hot summers, cold winters, low precipitation, and high evaporation, with an annual mean temperature of 11.3°C, annual mean precipitation of 45.7 mm, an annual frost-free period of 207 days, annual sunshine duration of 2950 h, annual mean total solar radiation of 6000 MJ/m^2, and annual mean evaporation of 2110.5 mm. The soil is categorized as medium loam. The soil dry bulk density is 1.43–1.53 g/cm^3, the field moisture capacity is 0.28–0.32 m^3/m^3, and the saturated moisture content is 0.43–0.50 m^3/m^3.

A BREB system was used. The Bowen ratio instrument (Campbell Scientific Inc, USA) comprised a data collector (CR1000-XT), temperature and humidity sensor (083D-1-6), net radiometer (NRLITE), wind speed and direction sensor (010C-1-L35), and two soil heat flux plate (HFP01-L-L35). It was installed at the center of a cotton field in ANFRSA. The field was located within a large, flat, drip-irrigated area. The requirement of fetch is satisfied.

The net radiation (Rn) was measured using a net radiometer (NRLITE) mounted 2.5 m above the soil ground between the upper and lower arms. The soil heat flux (G) was measured using heat flux plates (HFP01-L-L35), which were buried at a depth of 3 cm in the middle of a wide line under plastic film and in the middle of a bare line between plastic film. The temperature and humidity were measured using two integrated temperature–humidity probes inside a radiation shield (083D-1-6). The heights of the two fixed measurements were 2.0 and 3.5 m above the soil ground. The speed and direction were measured using a speed and direction sensor (010C-1-L35). All data were collected using a data-logger (CR1000-XT) every 5 s, and the 10 min averages were calculated and stored. Measurements were collected continuously between day of year (DOY) 212 and DOY 243.

Determining the acceptable data observed using the Bowen ratio system based on the qualitative relationship among data. The qualitative relationships among Δe, ΔT, β, and Rn-G are shown in Table II. We recorded 13 249 group data using the Bowen ratio system between August and October 2011, of which 6552 group data satisfied the qualitative relationship among the data, i.e. the acceptance rate was 49.45%. Of these, 1131 group data were a-class data with an acceptance rate of 8.54%, 4465 group data were b-class data with an acceptance rate of 33.70%, two group data were c-class data with an acceptance rate of 0.02%, 0 group data were d-class data with an acceptance rate of 0.00%, 0 group data were e-class data with an

Table II. Qualitative relationships among Δe, ΔT, β, and Rn-G

Data category	Available energy (Rn-G)	Vapour pressure difference	Bowen ratio	Latent heat	Sensible heat
A	Rn-G > 0	$\Delta e < 0$	$-1 < \beta \leq 0$	$\lambda ET > 0$	$H \leq 0$
B	Rn-G > 0	$\Delta e < 0$	$\beta > 0$	$\lambda ET > 0$	$H > 0$
C	Rn-G > 0	$\Delta e > 0$	$\beta < -1$	$\lambda ET < 0$	$H > 0$
D	Rn-G < 0	$\Delta e < 0$	$\beta < -1$	$\lambda ET > 0$	$H < 0$
E	Rn-G < 0	$\Delta e > 0$	$-1 < \beta \leq 0$	$\lambda ET < 0$	$H \leq 0$
F	Rn-G < 0	$\Delta e > 0$	$\beta > 0$	$\lambda ET < 0$	$H < 0$

Note: Δe is vapour pressure at the upper measurement level minus vapour pressure at the lower measurement level, that is, $\Delta e = e_2 - e_1$ (modified based on Perez *et al*. (1999))

acceptance rate of 0.00%, and 954 group data were f-class data with an acceptance rate of 7.20%.

Determining that data observed using the Bowen ratio system that fell in the rejection region. The temperature measurement range of the temperature and humidity sensors (083D-1-6) was −50°C to 50°C, the temperature accuracy was ± 0.1°C, and water vapour pressure accuracy was 0.04 kPa.

Inserting $\delta\Delta e = 0.08$ kPa and $\delta\Delta T = 0.2$°C into Equation (17) produces

$$\varepsilon = \frac{0.0932}{|\Delta e|} \tag{29}$$

Of the 6552 group data that satisfied the qualitative relationship among data, 3684 group data were in the A Class rejection region, two group data were in the B Class rejection region, 0 group data were in the C Class rejection region, and 357 group data were in the D Class rejection region, while 2509 group data remained after excluding data in the A Class to D Class rejection regions.

According to these principles and steps, the Bowen ratio data were strictly trade-offs. The acceptance rate for data observed using the Bowen ratio system during August–October, 2011 was 18.94%.

CONCLUSIONS

(1) Accepting or rejecting the data observed using a Bowen ratio system is a dynamic process, which should be conducted based on the rejection region of the Bowen ratio and the qualitative relationships among the vapour pressure difference, the temperature difference, the Bowen ratio, and the available energy.
(2) The steps used for accepting or rejecting data are as follows: data that do not satisfy the qualitative relationships among the vapour pressure difference, the temperature difference, the Bowen ratio, and the available energy are excluded first, and then the data that fall in the rejection region of the Bowen ratio are excluded second.
(3) It is necessary to increase the accuracy of the temperature and humidity probes to improve the acceptance rate for data observed using the Bowen ratio system, apart from improving the observed precision of available energy.

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