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Estimation of *Aman* Rice Evapotranspiration Using Bowen Ratio Energy Balance Method and its Comparison with Some other Methods under Bangladesh Condition

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Abstract

The study was conducted in the field laboratory of the Environmental Science Department, Bangladesh Agricultural University, Mymensingh during Aman rice season of 2005 to estimate field evapotranspiration (ET_0). The Bowen Ratio Energy Balance (BREB) method was used to estimate ET_0. A comparison between ET_0 and ET from pan evaporation (E_{Pan}) and with three other empirical methods (e.g., Penman (Ep), Priestley-Taylor (E_{PT}) and Makkink (E_{MK}) method) was also made to know whether ET_0 is agreed to other methods or not under Bangladesh condition. ET_0 varied with climatic conditions and growth stages of rice plant. It showed the highest value (7 mm d^{-1}) when Rn (17.66 MJ m^{-2} d^{-1}) and temperature (30 °C) reached its maximum values and relative humidity reached its minimum value (78%). ET_0 was also positively related to wind speed i.e. it showed increasing trend when wind speed increased. Linear regression between ET_0 and ET obtained from empirical methods and pan evaporation method indicated that the Ep and E_{PT} presented the highest agreements with ET_0 (correlation coefficient was 0.91with Ep; 0.91 with E_{PT} and 0.89 with E_{MK} and 0.74 with ET_{pan}).

Keywords: Evapotranspiration, Bowen Ratio Energy Balance Method, Pan Evaporation, Empirical Methods.

Introduction

Evapotranspiration (ET) plays an important role for computing water requirements of crops at a regional scale. A proper estimate of ET provides the vital means for computing water availability and water requirements[1] which is essential for irrigation scheduling as well as to increase water use efficiency. The procedure of ET calculation for ecological and hydrological resource planning studies plays significant role to reduce water loss[2]. ET is often limited by the currently available evaporable water, as well as by characteristics of the plant cover, climatic and soil condition. Based on these factors, two values can be distinguished, namely actual ET (AET) and potential ET (PET). The concept of AET and PET is suitable for deriving ET values for any crop. Researchers have used many empirical[3-5], micrometeorological[6], and hydrological[1,7] methods to estimate AET and PET in different parts of the world. The accuracy of any method depends heavily on the climatic condition of the study site as well as morphological and physiological characteristics of crop. The influences of micrometeorological, morphological and physiological factors on ET have been reported by some previous studies[8-11].

In Bangladesh, 79.4% lands are used for rice cultivation and therefore, estimation of ET in paddy field is very important issue for irrigation scheduling. However, evaluation of rice ET is a new research area in Bangladesh. Past research reports clearly indicate that estimation of ET of rice grown in Bangladesh using Bowen ratio energy balance method (BREB) and its comparison with some other methods is not reported so far. Although some previous studies examined the rice ET in different parts of the world, it is very important to estimate rice ET in Bangladesh condition as morphology and physiology of rice vary with rice species, geographical location and climate. Therefore, to find out the suitable method for estimating ET, the necessity of comparison among different methods is indispensible. For the comparison between AET and PET, three empirical methods (e.g., Penman, Priestly-Taylor and Makkink equations)[12-14] and pan evaporation data were used in this study. The objectives of this study were: To measure ET of *Aman* rice field using BREB method. To compare the measured ET with PET. To evaluate the performance of different methods for ET estimation under Bangladesh conditions.

Materials and Methods

Study site: The study site i.e., paddy field is situated at Bangladesh Agricultural University (BAU) Farm, Mymensingh, a northern district of Bangladesh (24.75ºN, 90.5ºE, 18 m above sea level). Soil of the experimental field is non-calcareous dark grey floodplain soil[15] with sandy loam texture. The pH value of the soil ranges from 5.9 to 6.5 (According to Soil Science Department, BAU, Mymensingh). The study site is under subtropical climate characterized by moderately high temperature and heavy rainfall during the kharif (monsoon) season (April to September) and scanty rainfall with moderately low temperature during Rabi (dry) season (October to March). In Bangladesh, there are three rice cropping seasons a year: Aus and Aman in the monsoon season, and Boro in the dry season. The present study was made during the season of Aman rice cultivation.

Thirty-three-day-old seedlings were uprooted carefully from the nursery and transplanted on the well-paddled field on 10 August 2005 by using 2 seedlings hill^{-1} maintaining 15cm × 25cm spacing. Recommended doses of fertilizers were applied to the field. Irrigation was given twice, on 15 September and 25 October 2005. Drainage was also done after heavy rainfall.

Measurements of evapotranspiration rate and supporting data: Micrometeorological measurements were conducted throughout the growing season (from 1 September to 14 November 2005). Air temperature and relative humidity over rice canopy were measured at two heights, 0.75 m and 2.10 m above the ground with temperature-humidity sensor (HMP45A; Vaisala, Helsinki, Finland). Flux densities of incident and reflected solar radiation were measured with an albedo meter (MR-21; Eko, Tokyo, Japan) mounted at 1.4 m, while net radiation flux density was measured with a net radiometer (Q*6.1, Radiation and Energy Balance Systems; Seattle, WA, USA) mounted at 1.1 m. Soil heat flux density was measured with three heat flux plates (MS-81, Eko) and their average data were used. Signal output of each meteorological sensor was sampled at 10-second intervals using a data logger (CR10x; Campbell Scientific Instruments, Logan, UT, USA) and 15-minute averages were stored in a storage module (SM4M; Campbell). After removing erroneous 15-minute averages, we combined two consecutive 15-minute averages into 30-minute averages, which were used for calculating ET.

We applied the Bowen Ratio Energy Balance (BREB) method to measure evapotranspiration (ET) rate[16]. By the definition of Bowen ratio (β), sensible (H) and latent heat (lE) flux densities are given as:

$$H = \frac{1}{1+\frac{1}{\beta}}(R_n - G) \quad (1)$$

$$lE = \frac{1}{1+\beta}(R_n - G) \quad (2)$$

where: R_n is net radiation flux density (Wm^{-2}) and G is the soil heat flux density (Wm^{-2}). β was determined from the vertical gradient of air temperature and vapor pressure by using the well-known equation:

$$\beta = \left(\frac{C_p}{l}\right)(T_1 - T_2)/(q_1 - q_2) \quad (3)$$

where: T is air temperature, q is specific humidity and C_P is specific heat of moist air under constant pressure (J g^{-1} K^{-1}). Subscripts 1 and 2 indicate values at measurement height z_1 and z_2, respectively. We used constant value of C_P (1.004 J g^{-1} K^{-1}) in our experiment.

To measure leaf area index (LAI) and dry weight of aboveground biomass, five hills were randomly collected from early vegetative stage to mature stage at 7 days interval. Leaf area was measured by leaf area meter (LI3100; LI-COR Logan, UT, USA) and then LAI was calculated as: leaf area/ground area. For the estimation of dry weight, samples were dried in an oven at 80°C for 48 hours and weight was recorded.

Estimation of ET using empirical equations: To estimate potential evapotranspiration (PET), three empirical equations; Penman's equation[12], Priestly-Taylor equation[13] and Makkink equation[14] were used in this study.

According to Penman's equation, the PET (Ep) is as follows:

$$E_p = \left[\frac{\Delta}{\Delta+\gamma}\right]E_r + \left[\frac{\gamma}{\Delta+\gamma}\right]E_a \quad (4)$$

$$E_r = \frac{R_n}{l\rho_w} \quad (5)$$

$$E_a = B[e_s(T) - e_a] \quad (6)$$

Where the first and the second terms of the right-hand side of Equation (4) are PET imposed by radiation and by aerodynamic factors, respectively. Other variables: e_a is the water vapor pressure; e_s is the saturation water vapor pressure at the reference height; l is the the latent heat of vaporization (J g^{-1}); Δ is the derivative of e_s with T; γ is the psychrometric constant (γ =($C_pP/\varepsilon l$), ε is the ratio of molecular weight of water vapor to that of dry air (0.622); B (mm d^{-1} Pa^{-1}) is an empirical function of u_d (km d^{-1}) as B=0.0027 (1+u_d/100), where u_d is the 24-hour wind run (km d^{-1}) at the reference height[17]. We applied Equations (4) to (6) to estimate daily mean PET from daily mean values of the meteorological variables. B was revised as B=0.0027 (1+1.116 X 10^{-4} u), where u was daily mean horizontal wind speed (m s^{-1}) at 2 m height. As T and e_a at the reference height, we used air temperature and water vapor pressure measured at 2.10 m.

According to Priestly-Taylor equation (E_{PT}) and Makkink equation (E_{MK}):

$$E_{PT} = \alpha_1\left[\frac{\Delta}{\Delta+\gamma}\right]R_n/(l\rho_w) \quad (7)$$

$$E_{MK} = \alpha_2 R_s/(l\rho_w) \quad (8)$$

where: R_s is the incident short-wave radiation flux density, α_1 and α_2 are empirically determined constants. We applied Equations-7 and 8 to estimate daily mean ET from daily mean meteorological variables.

Measurement of evaporation at the weather yard of BAU: Weather yard at BAU measures evaporation twice in a day *i.e.* early in the morning (at 6 am) and in the evening (at 6 pm). Evaporation pan is used to store water and hook gauge is used to measure the amount of evaporated water that is set on evaporation pan.

Results and Discussion

Meteorological and vegetation conditions: Meteorological conditions and plant morphological parameters in the study period are shown in Figure-1. Daily mean air temperature ranged from 21 to 30^0C (Figure-1a). Temperature was higher in the early growing season and it decreased gradually and lowers at the mature stage. It was due to the change of season *i.e.* changing of summer to winter season. Daily mean relative humidity ranged from 75-91% and that of average was 84% (Figure-1a). It showed increasing and decreasing trend throughout the growing season. Daily mean wind speed during the growing season ranged from 0.16-2.71 m s^{-1} and average wind speed was 0.8 m s^{-1} (Figure-1b). At vegetative and reproductive stage it showed the increasing and decreasing trend and at mature stage it showed lower value. Incident solar radiation ranged from 1 to 23 MJ m^{-2} d^{-1} (Figure-1c). Solar radiation was reduced by heavy rainfall and cloudy days in the periods of DOY263-276 and DOY290-295. Intensive rainfall was observed up to the middle growing stage of rice and it was 499.3, 406.6, 361.7 and 0 mm in the month of August, September, October and November, respectively.

The LAI was increased gradually from early vegetative stage (DOY 254, 30 days after transplanting) and reached its maximum value (5.24) at reproductive stage (DOY 276, approximately 60 days after transplanting), and then decreased gradually at mature stage (Figure-1d). Above ground crop biomass was maximum (2352.5 g $m^{-2)}$ at harvest (Figure-1d).

Dynamics of energy balance components: Diurnal patterns of energy balance components at vegetative (DOY 255), reproductive (DOY 280) and mature stages (DOY323) are presented in Figure-2. Air temperature was 30, 28 and 21^0C, relative humidity was 78, 84 and 81%, rainfall was 2.8, 0.0 and 0.0 mm and wind speed was 2.52, 0.26 and 0.25 m s^{-1} on DOY 255, 280 and 323, respectively. Net radiation (Rn) above the field followed the diurnal course of solar radiation. In all growing stages, it showed the peaked value at 1230h. The highest Rn was 697, 586 and 432 Wm^{-2} on 255, 280 and 323 DOY respectively. lE was the dominant form of water loss. It increased rapidly from 700h and reached its maximum values of 689, 525 and 251 Wm^{-2} just at 1230h on 255, 280 and 323 DOY, respectively and after that it gradually decreased. The maximum value of H was 81 (at 830h), 104 (at 930h) and 158 Wm^{-2} (at 1230h) on 255, 280 and 323 DOY, respectively. On DOY 255 and 280 it showed negative value at noon hours indicating soil absorbs sensible heat which is used to evaporate water. The maximum value of G was 36 Wm^{-2} (on DOY 255 and 280) at 1230 hours and that of 24 Wm^{-2} (on DOY 323) at 1130h.

Seasonal variations in energy budget components are presented in Figure-3. Rn ranged from 0.52 to 17.66 MJ m^{-2} d^{-1} and followed the similar pattern of solar radiation, lE ranged from 1.01 to 17.40 MJ m^{-2} d^{-1}, H ranged from -1.45 to 8.50 MJ m^{-2} d^{-1} and G ranged from -0.63 to 0.86 MJ m^{-2} d^{-1}. Most of the Rn was partitioned into lE as the field was in watered condition which nearly balanced the net radiation. In higher soil moisture condition, Rn is mostly partitioned as lE and small portion of Rn is consumed as H and G[18]. Some previous studies on paddy fields also reported that lE mostly balanced the net radiation[19-22].

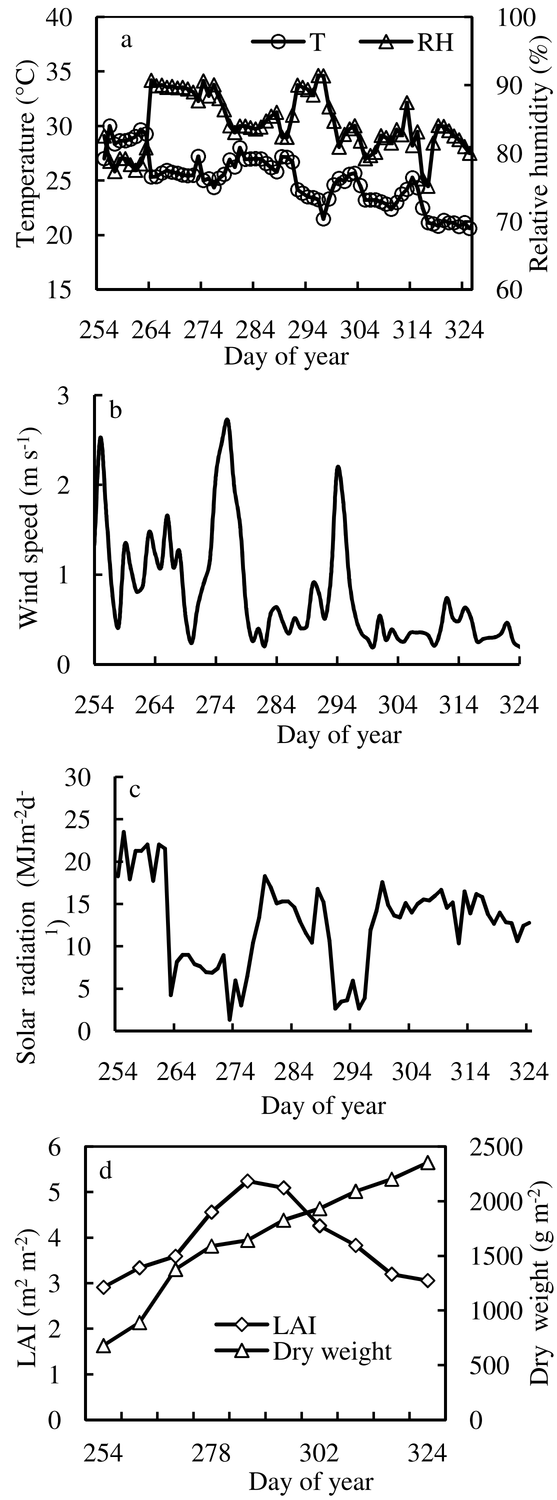

Figure-1
Seasonal variations in (a) air temperature (T) and relative humidity (RH), (b) wind speed (c) incident solar radiation flux density, (d) leaf area index (LAI) and biomass dry weight of rice

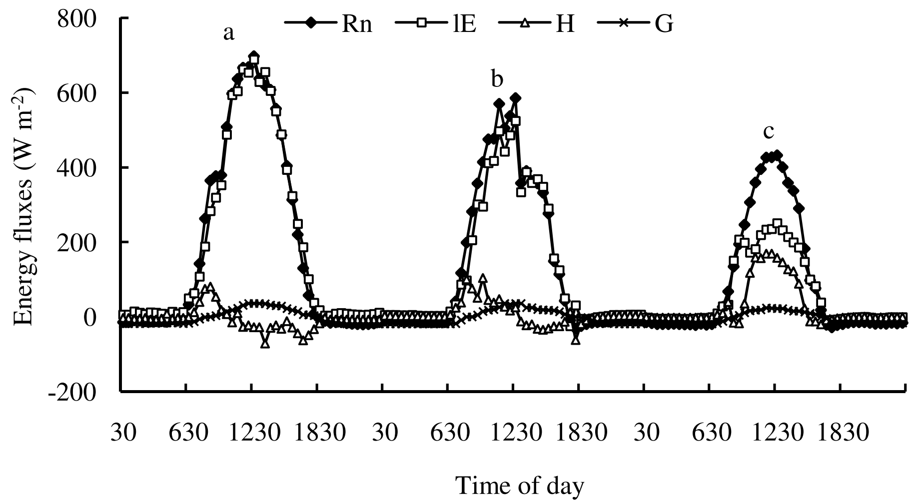

Figure-2
Diurnal variations in surface energy budget components on selected periods of Aman rice cultivation: (a) vegetative stage, (b) reproductive stage and (c) mature stage

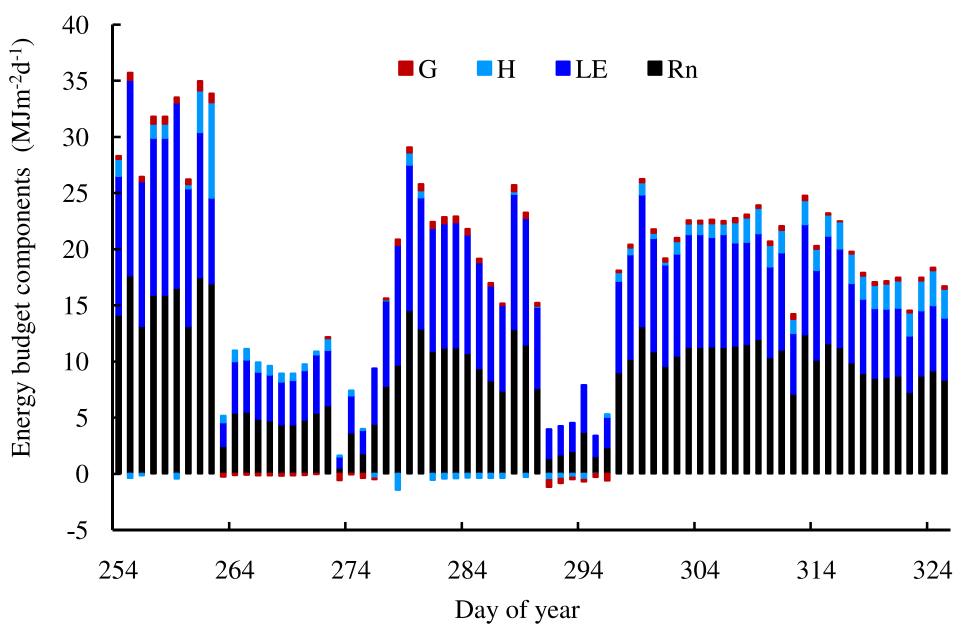

Figure-3
Seasonal variations in surface energy budget components

Comparison of observed evapotranspiration rate with those estimated using empirical equations and pan evaporation: Seasonal variations in observed ET (ET_0), estimated ET from Penman's equation (Ep), Priestly-Taylor equation (E_{PT}) and Makkink equation (E_{MK}) and ET from pan evaporation (E_{pan}) from vegetative stage to mature stage are presented in Figure-4. ET_0 as well as estimated and pan evaporation ET showed increasing and decreasing trend throughout the growing season. Fluctuation in ET may be happened due to fluctuation in meteorological parameters. All of the estimated ET showed the similar seasonal trend as of observed ET. The ET_0 ranged from 0 to 7 mm d^{-1} throughout the study period. The values of ET range from 4.4 to 14.3 mm d^{-1} in South and Southeast Asian rice field[3]. Results of studies on water management for lowland rice reported that ET ranges from 4 to 9 mm d^{-1} in most Asian rice field[23]. Some researchers found that ET of rice field varied between 4 and 9 mm d^{-1} [24,25]. ET_0 was higher at vegetative stage and lower at mature stage. Net radiation and temperature was also higher and relative humidity was lower at vegetative stage and vice-versa condition was found at mature stage indicating the climatic influence on ET_0. ET_0 also influenced by plant growth stage. It reached its maximum value at vegetative stage due to higher transpiration from rice plant.

Linear regressions between the values from observed ET by BERB method and the values from empirical equations and pan evaporation are presented in Figure-5a and 5b. The performance of Penman and Priestley-Taylor methods was higher (coefficients of determination 0.83) in calculating ET in the studied area. The Makkink method also showed better performance (coefficients of determination 0.80). However, this method overestimated the ET in the studied climatic condition. ET_{pan} showed poorer performance (coefficients of determination 0.56) compared to other empirical methods.

Conclusion

The observed ET in this study using the BREB method indicated that the radiant energy mostly used to evaporate water and showed a small seasonal variation. ET obtained from other methods showed the similar seasonal pattern with that of observed ET. The Penman and Priestley-Taylor equations are feasible for calculating ET in the studied region when necessary instrumental support for field observation is unavailable.

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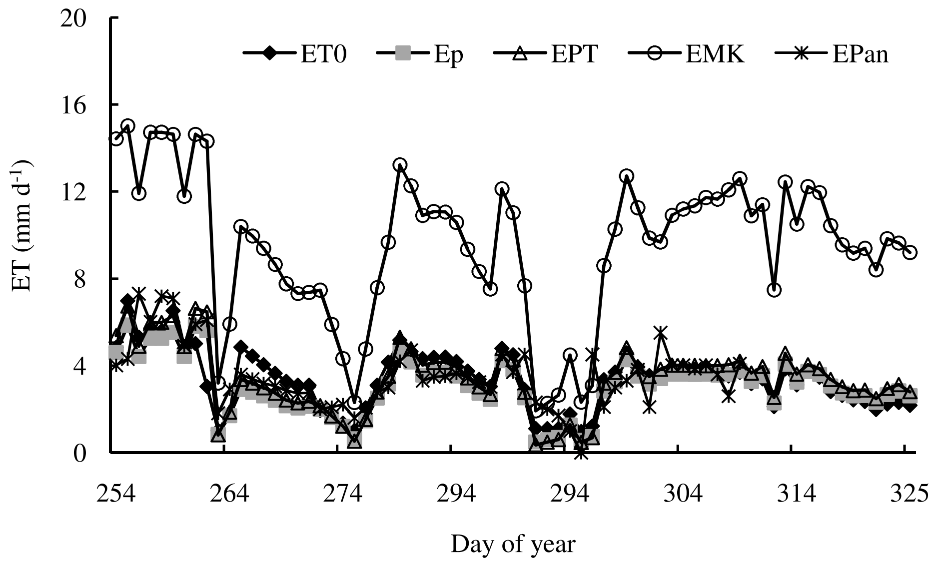

Figure-4
Seasonal variations in evapotranspiration rate

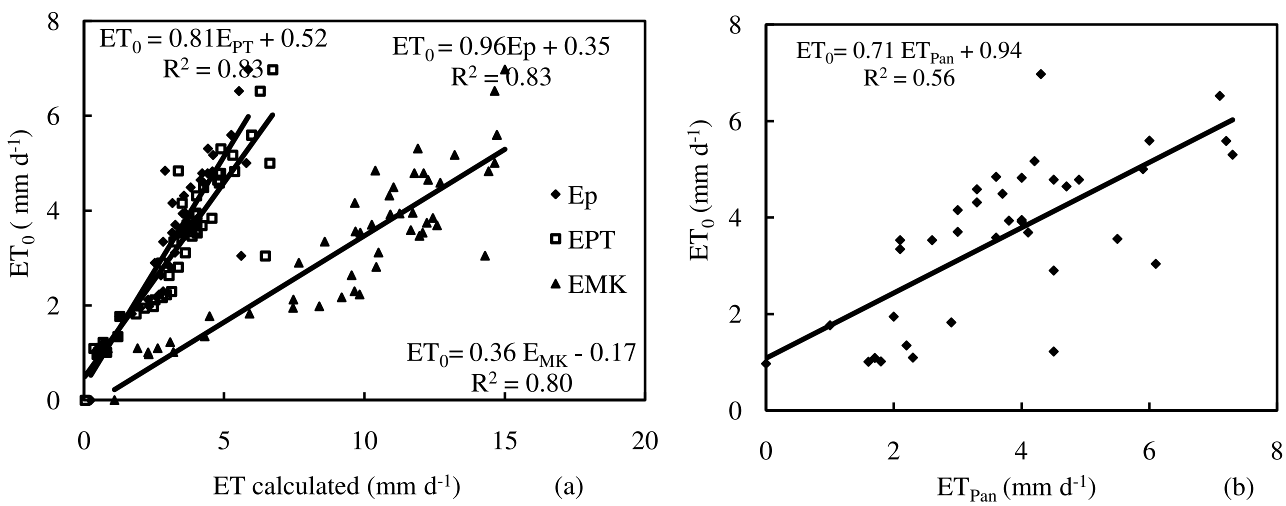

Figure-5
Relationship between: (a) ET_0 with E_P, E_{PT} and E_{MK} (b) ET_0 and E_{Pan}

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