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PERFORMANCE OF PAN EVAPORATION BASED METHODS UNDER ARID CLIMATE OF TANDOJAM, SINDH, PAKISTAN

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ABSTRACT

The measurement of reference evapotranspiration has a critical role in planning and managing water resources. There exist several methods to estimate this phenomenon, viz, radiation, temperature, mass transfer, pan evaporation and combination-based methods. This study was conducted with the aim to test the accuracy and suitability of nine pan evaporation-based methods under the prevailing climatic conditions of Tandojam, Sindh, Pakistan. Twenty-three years data were used and the pan evaporation based methods were evaluated against Penman-Monteith method. The results showed that only the Pereira method gave good results (BIAS=0.06; Nash Sutcliffe model efficiency=0.87) among the nine-pan evaporation based methods. The rest of the methods deviated from the reference method. Thus, Pereira is recommended to be employed in lieu of the Penman Monteith method when the complete meteorological data set is unavailable. The other methods tested in this study must be calibrated before use.

Keywords: penman-monteith, pereira method, snyder method, orang, nash sutcliffe model efficiency

INTRODUCTION

Water resources planning and management warrants accurate measurement of crop water demand. The water demand by crops is determined in terms of evapotranspiration. Accurate measurements of various physical parameters and sophisticated experimental setup like lysimeters or the soil water balance are required to determine evapotranspiration. The measurements of evapotranspiration through these methods are expensive and require trained and skilled personnel which limits their use (Snyder *et al.,* 2005; Xing *et al.,* 2008). As a result, several empirical models have been developed by researchers to compute evapotranspiration from weather data (Azhar and Perera, 2010; Antonopoulos and Antonopoulos 2017). Actually, the empirical methods determine reference evapotranspiration (ET_o) which in conjunction with crop coefficient is used to estimate actual evapotranspiration. Apart from combination (FAO-56) and other types, several pan evaporation based reference evapotranspiration have been developed and are being used worldwide to estimate this important phenomena accurately with minimum data. These empirical models were developed for a particular region in accordance with available weather data. The combination based methods require net radiation, temperature, wind speed and relative humidity data and thus, are data intensive. Whereas, the pan evaporation based methods need pan evaporation cum pan coefficient data to estimate ET_o. Literature reviewed reveal that the combination methods are superior to all other methods when the complete meteorological data is available (e.g. Gavilán, 2008; Azhar and Perera, 2010; Xystrakis, 2011). Methods require minimum data to estimate ET_o are only valid under specific climatic and agronomic conditions for the location they were developed and need to be calibrated for other location (Grismer *et al.,* 2002; Azhar and Perera, 2010). Thus, considering limited data availability, several studies pertaining to evaluation of empirical ET_o methods have been conducted. Recommendations have been given by the researchers to investigate suitability of empirical methods for a specific location before use. Against the above, this study was conducted for merely evaluating 9 pan evaporation based ET_o methods for arid climate of Tandojam, Sindh Pakistan so that suitability of the methods for computing ET_o with minimum data can be

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assessed. This study will be useful for irrigation engineers and planners for short term irrigation planning.

MATERIALS AND METHODS

Data acquisition

Pertinent weather data for twenty-three years (1990-2012) were obtained from meteorological observatory of the Drainage Reclamation Institute of Pakistan (DRIP). The data comprised maximum and minimum air temperature, relative humidity, wind speed, and sunshine duration (Table 1).

Empirical models for estimation of reference evapotranspiration

Present study evaluated 9 pan evaporation based methods relative to Penman-Monteith (PM) model for arid climate of Tandojam. The methods are detailed here after:

Combination based method

The collaborative work of International Commission for Irrigation and Drainage and the World Meteorological Organization (Allen *et al.,* 1998; Allen *et al.,* 2005) resulted in standardized equation for computing ET_o known as FAO-56 modified Penman-Monteith (PM) equation. The equation is given as Equation 1 (Table 2)

Pan evaporation-based methods

The evaporation measurement in pan is governed by the wind, radiation, humidity and temperature. An empirically derived pan coefficient is associated with the pan evaporation to compute the reference evapotranspiration. The elements that influence water loss from cropped and water surface are taken into account by this coefficient (Allen *et al.,* 1998). These methods are being employed in several countries where complete meteorological data is not available due to non-installation of expensive equipment (Stanhill, 2002; Tabari *et al.,* 2011). The pan evaporation based methods presented in Table 2 as Equations 2-9 were tested.The values of K_{pan} recommended by Doorenbos and Pruitt's (Doorenbos and Pruitt, 1977) were also tested. The ET_{pan} values for twelve months (i.e. January to December) are in the order of 3.40, 3.95, 5.96, 8.57, 10.17, 10.37, 8.96, 8.00, 7.07, 5.72, 4.53, and 3.54 mm d^{-1}. These values are average of 23 years data.

Table 1. Twenty-three years (1990-2012) month-wise average weather data at DRIP, Tandojam

Month	Temperature (^{0}C)			Relative humidity (%)	Sun shine (hour)	Wind speed (Km day^{-1})
	Maximum	Minimum	Mean			
January	24.0	9.10	16.55	68	8.40	21.82
February	27.4	11.4	19.40	64	8.80	18.71
March	33.2	16.0	24.60	58	9.20	21.38
April	38.3	21.2	29.75	54	9.70	35.18
May	40.4	25.4	32.90	61	10.2	50.77
June	38.9	27.2	33.05	67	8.60	64.13
July	36.3	26.9	31.60	74	7.20	52.55
August	35.1	26.2	30.65	77	8.10	32.96
September	35.2	24.4	29.8	75	9.30	48.54
October	35.5	19.8	27.65	69	9.50	13.36
November	31.1	14.9	23.00	64	9.00	16.03
December	25.5	10.7	18.10	67	8.20	18.71

Statistical analysis

Following statistical test were applied to infer from comparative results of pan evaporation methods and PM method.

(1) The coefficient of determination (R^2), (2) regression coefficients, (3) Root mean square error (RMSE), (4) BIAS, and (5) Nash Sutcliffe model efficiency (Krause *et al.,* 2005).

$$Y = mx + c \tag{1}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \bar{O})(E_i - \bar{E})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(E_i - \bar{E})^2}} \right)^2 \tag{2}$$

$$Root\ mean\ square\ error(RMSE) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - E_i)^2} \quad (3)$$

$$BIAS = \frac{\sum_{i=1}^{n}(E_i - O_i)}{\sum_{i=1}^{n} O_i} \quad (4)$$

$$Index\ of\ agreement\ (d) = 1 - \frac{\sum_{i=1}^{n}(O_i - E_i)^2}{\sum_{i=1}^{n}(|E_i - \bar{O}\ | + |O_i - \bar{O}\ |)^2} \quad (5)$$

$$Model\ efficiency\ (ME) = 1 - \frac{\sum_{i=1}^{n}(O_i - E_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (6)$$

Where *O* stands for observed reference evapotranspiration and *E* represents estimated reference evapotranspiration by the different methods

Table 2. Reference evapotranspiration empirical models

(1) Combination based method

$$ET_o = \frac{0.408\ \Delta\ [R_n - G] + \gamma \frac{900}{T+273}}{\Delta + \gamma\ [1 + 0.34u_2]} u_2 [e_s - e_a] \quad (7)$$

Readers are referred to the work of Allen *et al.* (1998 and 2005) for more details of this method.

(2) Pan evaporation based methods

Cuenca (1989)

$$ET_o = ET_{pan}\ x[\ 0.475 - (0.000245u_2)\ (0.00516RH)\ (0.00118F) - \ (0.000016RH^2) - (0.00000101F^2) - (0.000000008\ RH^2 u_2) - \ (0.00000001\ RH^2\ F)] \quad (8)$$

Allen and Pruitt (1991)

$$ET_o = ET_{pan}\ x\ [0.108 - (0.000331u_2) + (0.0422 ln(F)) + (0.1434\ ln(RH)) - (0.000631((ln(F))^2\ ln(RH))] \quad (9)$$

Snyder (1992)

$$ET_o = ET_{pan}\ x\ [0.482 + [0.24ln\ (F)] - (0.000376u_2) + (0.0045RH)] \quad (10)$$

Pereira (Pereira *et al.,* 1995)

$$ET_o = \ ET_{pan}\ \times\ [0.85\ \times\ [(\Delta\ +\ \gamma)\ \div\ [\Delta\ +\ \gamma(1 + 0.33u_2)] \quad (11)$$

Orang (1998)

$$ET_o = ET_{pan}\ x\ [0.51206 - (0.000321u_2) + (0.002889RH) + (0.03188\ ln(F)) - (0.000107RH\ ln(F))] \quad (12)$$

FAO-56 (Allen *et al.,* 1998)

$$ET_o = ET_{pan}\ x\ [\ 0.108 - (0.0286u_2\ ) + \ (0.0422\ ln(F)) + (0.1434ln(RH) - (\ 0.000631\ (ln(F))^2\ ln(RH)] \quad (13)$$

Raghuwanshi and Wallender (George, 2012)

$$ET_o = ET_{pan} x\ [0.5944 + 0.024X_1 - 0.0583X_2 - \ 0.1333X_3 - \ 0.2083X_4 + 0.0812X_5 + \ 0.1344X_6] \quad (14)$$

Modified Snyder (Tabari, 2011)

$$ET_o = ET_{pan}\ x\ [0.5321 - (0.0003u_2) + (0.0249\ ln(F)) + (0.0025RH)] \quad (15)$$

Symbols List
ET_o is the reference evapotranspiration in mm d^{-1}
R_n is net radiation at the crop surface in MJ m^{-2} d^{-1}
G is soil heat flux density in MJ m^{-2} d^{-1}
T is air temperature at 2 m height in °C
u_2 is wind speed at 2 m height in m s^{-1} in PM method and FAO-56 Pan method while in remaining pan evaporation methods, it is in km d^{-1}
e_s is saturation vapor pressure in kPa
e_a is actual vapor pressure in kPa
e_s - e_a is the saturation vapor pressure deficit in kPa
RH is the mean daily relative humidity in %
F is the upwind fetch distance of low-growing vegetation (m) - the value of 1000 m was used in this study as there were crops around the meteorological observatory
Δ is the slope of vapor pressure curve in kPa $°C^{-1}$
γ is the psychrometric constant in kPa $°C^{-1}$
X_1 is the ln of the fetch distance (F) in m
X_2, X_3 and X_4 are the wind speed categories of 175-425,425-700, and >700 km d^{-1} , respectively, and are assigned values of one to zero depending upon their occurrence (zero for wind speed < 175 km d^{-1})
X_5 and X_6 are the relative humidity categories of 40 to 70% and >79%, respectively (a zero value for these variables represent a relative humidity <40%).

RESULTS AND DISCUSSION

Nine pan evaporation based methods were contrasted to evaluate their performance against Penman-Monteith (PM) method. The reference evapotranspiration computed by PM method varied from 1.82 to 5.43 mm d^{-1}. The ET_o determined by PM method were used as yard stick values for comparison purpose. The comparison results are discussed in subsequent paragraphs.

Performance of pan evaporation based methods

The results regarding the statistical analysis of pan evaporation based methods are compared in Figure 1 and summarized in Table 3. The results show that Pereira method produced evapotranspiration estimates similar to PM method (m = 1.11, *c* = 0.3164, R^2 = 0.929, RMSE = 0.44 mm d^{-1}, ME = 0.87 and *d* = 0.96). The Pereira method tended to over estimate the evapotranspiration by 6 %. Sentelhas and Folegatti (2003) evaluated various pan evaporation methods and also rated Pereira method as best method for ET_o estimation. The remaining methods showed greater scatter compared to PM method for climatic conditions of Tandojam. The Doorenbos and Pruitt (BIAS= -0.35), Allen (BIAS= -2.19) and Raghuwanshi and Wallender (BIAS = -0.31) under estimated the ET_o to a great extent. Whereas Modified Snyder, Cuenca, Snyder, Orang, FAO-56 (Allen *et al.,* 1998), showed departure from reference method by over estimating ET_o in the order of 56, 57, 338, 57 and 57 %. The exorbitant error was exhibited by Allen (RMSE= 8.61 mm d^{-1}) and Snyder (RMSE= 13.43 mm d^{-1}). George (2012) also reported that the evapotranspiration prediction by Snyder, FAO-56, Cuenca and Raghuwanshi is statistically inaccurate. The under prediction of ET_o by some methods, namely, Allen and Doorenbos is also evident from the research work of Tabari *et al.* (2011) and Grismer *et al.* (2002). It is note worthy (Figure 1) that except Pereira method all other methods showed departure from reference method in computing ET_o for more than or at least five months (for example: the deviating values for Cuenca have been circled). Based on study results, only Pereira method can be used for prevailing conditions of Tandojam, while other tested methods require local calibration before use especially for the deviating months. The value of R^2 is close to 1 for almost all methods but all other statistical criteria reflect difference between reference values and values computed by tested methods. The exception is Pereira method. This also shows the importance of using different statistical criteria for assessing empirical models. Krause *et al.* (2005) stated that a model which systematically over or under predicts all the time will still result in good R^2 values close to 1.0

Table 3. Statistical analysis of pan evaporation based methods with respect to PM method

Methods	Statistical Criteria			
	RMSE (mm d^{-1})	BIAS	d	ME
Doorenbos and Pruitt	1.47	0.35	0.80	-0.39
Cuenca	2.30	0.57	0.66	-2.42
Allen and Pruitt	8.61	-2.19	0.12	-47.0
Snyder	13.43	3.38	0.14	-115.6
Pereira	0.44	0.06	0.96	0.87
Orang	2.32	0.57	0.66	-2.49
FAO-56 (Allen *et al.*, 1998)	2.30	0.57	0.66	-2.43
Raghuwanshi and Wallender	1.20	-0.31	0.76	0.06
Modified Snyder	2.29	0.56	0.66	-2.39

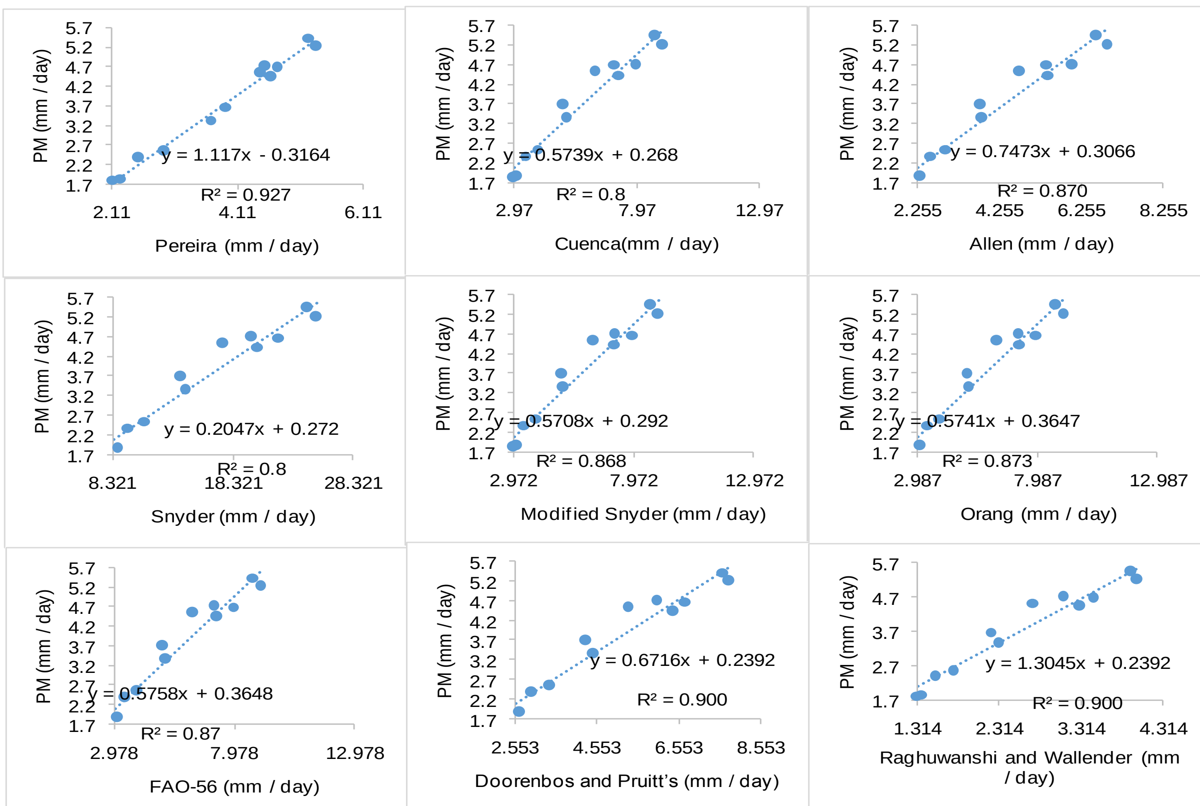

Figure 1. Relationship between reference evapotranspiration computed by PMM and PEBM

CONCLUSION

This study evaluated 9 Pan evaporation-based methods under arid climatic conditions of Tandojam, Sindh, Pakistan. The comparative results showed that the Pereira method (R^2 = 0.929) correlated well with FAO-56 method under the arid climatic conditions of Tandojam. The remaining Pan evaporation methods showed poor performance in estimating reference evapotranspiration. The poor performance of the methods can be attributed to the constants of the pan coefficients equations. Thus, it is inferred that these methods must be calibrated before use.

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