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Performance of Reference Evapotranspiration Estimation Methods at the Southern Paraná, Brazil

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Abstract— *Knowing the atmospheric potential demand (ETo) implies in quantifying the ability of vegetated surfaces in absorbing water from the soil aiming at irrigation scheduling, crop yield prediction and water balance studies at a given site. Such information is extremely useful even under non-irrigated systems, for it makes possible to adjust sowing date within the crop growing season as a function of the local soil water availability, conditioning therefore a better reclamation of rainfall regime. Crop yield is significantly affected by the atmospheric conditions in order to galvanize researchers to scrutinize the regime of physical environment variables which directly interfere into the consumption of natural resources of crops in production fields. The aim of the current work was to investigate which of the atmospheric evaporative demand estimation methods are more suitable to depict physical reality of the water loss process in order to maximize crop yield and optimize irrigation scheduling under the climatic conditions of Southern Paraná, Brazil. The following methods were tested at two distinct sites of the studied region concerning its performance, taking into account the Penman-Monteith (FAO-56) approach as a standard reference for comparison purposes: simplified Penman, modified Bowen, Hargreaves-Samani, Camargo, and Linacre. The meteorological elements used for the calculation of ETo were monitored by an automatic weather station from Campbell Scientific Inc. throughout the years of 2008 through 2013. We concluded that empirical methods showed an unsatisfactory performance, whereas those methods that took into consideration net radiation as an input variable performed better, being the latter hence to be considered for agricultural planning and also for agrometeorological studies aiming at sustainability of the regional agriculture. The simplified Penman and modified Bowen methods were more accurate for estimating ETo in order to provide irrigation scheduling and indicate local soil water status at the region in study, because dismiss information on wind regimes that govern evapotranspiration rates.*

Keywords—Potential evapotranspiration, modeling, agrometeorological studies, irrigation, sustainable agriculture.

I. INTRODUCTION

Reference evapotranspiration is a bio-meteorological element depicting in practical terms atmosphere evaporative demand with the aim of defining the ideal amount of water irrigation to be adopted at the right time throughout the crop growing season at a given site, conducting prediction studies of crop production and water balance. It is defined as the amount of water lost from the surface grown with grass or alfalfa fully covering the soil at an active development stage, with a uniform height, leaf area index of roughly 3 exposed to the prevailing atmospheric conditions under no water restriction and with a fetch sufficiently large and well irrigated to minimize advection towards the experimental area (Thornthwaite, 1948; Allen et al., 1998; Pereira et al., 2011).

Regimes of local meteorological elements condition atmosphere evaporative demand and in turn water loss rates by means of stomata along with water uptake by the roots so that the plants might perform its metabolic processes within an optimal of physiological efficiency to provide maximization of crop production. Either photosynthesis or plant transpiration takes place at a given site as a function of atmosphere evaporative demand. Being crop transpiration considered to be a physiological loss to assure photosynthetic activity and therefore primary productivity expression, it is quite pivotal to get to know potential atmospheric demand at a particular site for the purpose of planning agricultural practices in production fields.

Crop water consumption may be measured by means of high precision lysimeters. However, owing to high installation costs and management of equipment determining crop water consumption by making use of mathematical equations in conjunction with specific crop coefficients comes to being a feasible alternative to be borne in mind (Medeiros, 1998).

Silva and Rao (2006), by working with sub-irrigation lysimeters at the region of Rodelas, Bahia State, Brazil, assessed the performance of different estimation methods of reference evapotranspiration (ETo) aiming at determination of peanuts water ideal climatic demand and verified that Class A pan, Hargreaves, and Thornthwaite methods were the most appropriate for an efficient irrigation management.

Sousa et al. (2010), by scrutinizing the performance of ETo estimation methods at four irrigated perimeters belonging to the state of Sergipe by the Class A pan, Solar Radiation, Hargreaves-Samani, Linacre, and Penman-Monteith, being the latter taken as a reference in a comparative study, drew the conclusion for the region in study that the Solar Radiation approach was the one that provided the best performance.

Several scientists sought to evaluate ETo at different sites aiming at recommendation of methods more accurate and suitable for calculation as a function of availability of local meteorological data (Zhang et al., 2008; Syperreck et al., 2008; Ambas; Baltas, 2012; Nouri et al., 2012; Luo et al., 2014; Shiri et al., 2015; Ershadi et al., 2015; Qiu et al., 2015).

Faced with the aforementioned, the aim of the current manuscript was to monitor agricultural environmental variables that govern biological responses of crops grown at the region of Campos Gerais, state of Paraná, Brazil. In order to give support to irrigation planning of crops with regional economic importance, prediction of crop production and water balance studies we evaluated the performance of ETo estimation methods that most approached to calculated values obtained by the Penman-Monteith approach at the studied sites (Villa Nova and Pereira, 2006; Villa Nova et al., 2006; Villa Nova et al., 2007; Alfaro et al., 2013; Pereira et al., 2014).

II. MATERIAL AND METHODS

An automatic weather station from Campbell Scientific Inc. was installed at an experimental area belonging to the State University of Ponta Grossa – UEPG – Ponta Grossa, PR, Brazil, under the following geographic coordinates: latitude of 25º11'S, longitude of 50º08'W, and altitude of 800 m. For the municipality of Arapoti, PR, the geographic coordinates are as follows: latitude of 24º16'S, longitude of 50º06'W, and altitude of 966 m. The climatic formula according to the Köppen climate classification for both sites in study was Cfb (Alvares et al., 2014).

The following local meteorological data were monitored by the weather station over the course of the years comprised between 2008 and 2013 at both Ponta Grossa and Arapoti municipalities, state of Paraná, Brazil: air temperature and relative humidity (HMP45C Temperature and Relative Humidity Probe), precipitation (CSI model TB4), barometric pressure (CS106), wind speed and direction (MET ONE model 034B), global solar radiation flux density (pyranometer LI-200X), net radiation (NR LITE), and photosynthetic active radiation (Quantum LI-190SB).

All of the sensors were coupled to a data acquisition system; model CR-1000, from the Campbell Scientific Inc., which were programmed to perform readings with a frequency of 60 seconds storing averages at each 15 minutes.

For ETo assessments the following estimation methods were taken into account herein: Penman-Monteith (FAO Standard – 1998) (EToPM), modified Bowen (Villa Nova et al., 2007)(EToBM),simplified Penman (Villa Nova et al., 2006)(EToPS), Camargo (Camargo, 1971)(EToC), Hargreaves-Samani (Pereira et al., 2002) (EToHS), and Linacre (Linacre, 1977) (EToL).

In a study dealing with assessment of estimation methods of alfalfa maximum evapotranspiration, Santos et al. (1994) cited by Medeiros (1998) concluded that estimation for a five-day period or larger intervals showed satisfactory outcomes whilst on a daily basis it revealed uncertainties, evidencing that there is a proclivity for error stabilization from estimates obtained for a five-day period.

The Penman-Monteith approach was chosen as the standard method to estimate ETo because it demonstrates that calculated values are rather close to measured grass evapotranspiration at a given site and also points out its superiority in relation to other methods (Cai et al., 2007; Gavilan et al., 2007; Xing et al., 2008). Such a method is based on physical processes and, explicitly incorporates physiological and aerodynamic parameters into it. There are several methods reported in the literature to estimate ETo, but their performances at different agricultural environments vary, since most of them present empiricism in their conceptualization (Sentelhas et al., 2010).

By taking into consideration ETo information one might be able to determine crop coefficient or relative water consumption, which varies as a function of crop and physiological age of the plants. Such a bio-meteorological element allows for an ideal irrigation water amount determination to be applied throughout the whole crop growing season in such a way as to assure maximization of crop yield and minimization of costs of production at a farm level. ETo turns out to be a physical environmental variable of a great importance for irrigation projects that can be utilized to provide support for assessment surveys associated with climatic risks, which in turn are directly related to the zoning of sowing dates of non-irrigated farming systems.

ETo data calculated at the region of Campos Gerais, Paraná state, were subjected to analysis of variance along with application of F test, as well as to a simple

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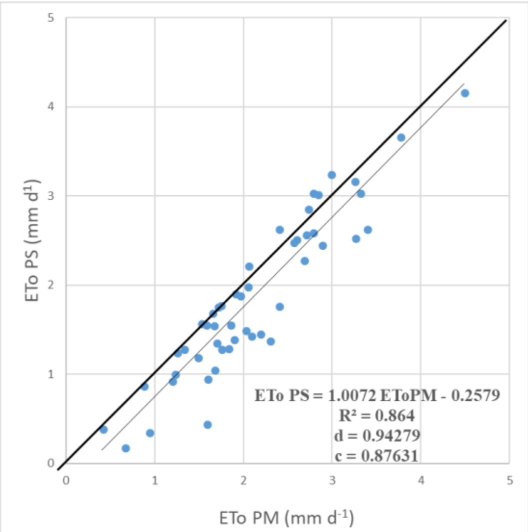
linear regression analysis study aiming at a definition of the best ETo estimation approach. Coefficients of determination (R^2) were calculated to assess precision of the estimates and agreement indices (d) proposed by Willmott et al. (1995) were determined to quantify accuracy or exactness of the studied methods.

In addition to such statistical parameters, we determined the coefficients of performance of mathematical models proposed by Camargo and Sentelhas (1997), given by the product between the Pearson correlation coefficient (r) and Willmott agreement index (d), as well as mean absolute error (MAE) of estimates in conjunction with NSE (Nash Sutcliffe Efficiency) index, which refers to a standardized index of optimization analysis of models proposed to correlate residual variance to measured variance (Nash and Sutcliffe, 1970).

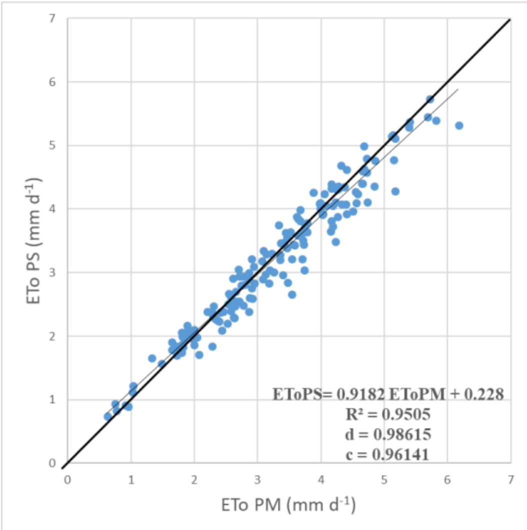
III. RESULTS AND DISCUSSION

The model proposed by Villa Nova et al. (2006) (EToPS) refers to a simplification of the method originally idealized by Penman-Monteith (FAO Standard – 1998) (EToPM) based on the fact that a considerable portion of evapotranspiration is essentially ascribed to available energy and considering that other input variables of the original equation (FAO Standard – 1998) are built in the value of S (tangent to the water vapor saturation pressure curve). Under a sensitivity analysis on different estimation methods of evapotranspiration, Ambas and Baltas(2012) concluded that solar radiation and air temperature constitute the main meteorological elements that predominately govern water loss process from soil-plant system, since air relative humidity and wind regimes affect less evapotranspiration rates.

ETo values estimated by the simplified Penman method were quite similar to those obtained by the Penman-Monteith approach for both sites in study (Figure 1), with overestimates for increasing values in conjunction with deviations lower than 1 mm day^{-1} (MAE corresponding to 0.019 and 0.041 for Ponta Grossa and Arapoti, PR, Brazil, respectively).



(A)



(B)

Fig.1: Confrontation between reference evapotranspiration estimated by the classical Penman-Monteith approach (EToPM) and potential demand calculated by the simplified Penman method(EToPS) for the period comprised between March 27, 2008 and August 22, 2011 at Ponta Grossa (A), and between August 26, 2011 and October 14, 2013 at Arapoti (B), PR, Brazil (averages of a 5-day period).

Ershadi et al. (2015), by making use of the NSE statistics to confirm the outcomes obtained from their studies, found NSE values ranging from 0.07 to 0.66 for the model idealized by Penman-Monteith, once NSE varying from 0 to 1 indicate good fittings to the model under confrontations between predicted and observed data. Such a statistical tool is based on comparison of the moment of magnitude 2 for each individual observation in relation to the moment of magnitude 2 centered on averages of observed data. Therefore, NSE index evidences the average of deviation squares for punctual observations in comparison to the variance of original data.

Under the prevailing atmospheric conditions of the current study NSE indices ranging from 0.68 to 0.94 as a function of confrontation between EToPS and EToPM at the municipalities of Ponta Grossa and Arapoti, PR, respectively, were obtained. The aforementioned statistical parameter depicted an excellent fitting of the estimates generated by the simplified Penman model, being then in consonance with calculated Willmott agreement indices (d) for both sites, as well values of performance coefficient

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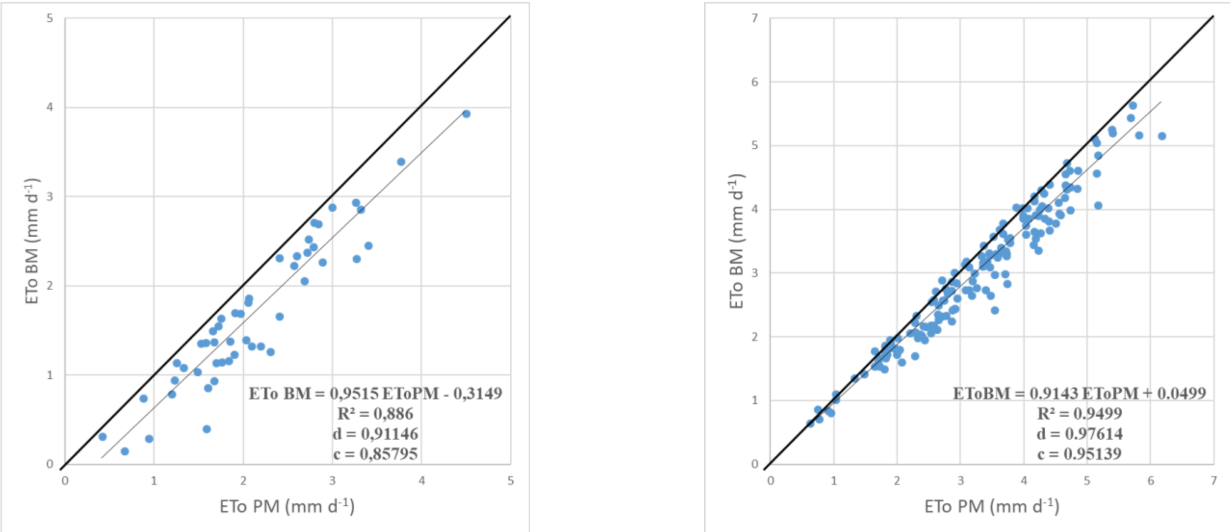
(c) considered to be classified as optimal (Camargo and Sentelhas, 1997) (Figure 1).

Energy balance approach allows for evapotranspiration estimation even under inadequate soil water supply conditions, besides turning out to be a straightforward and cheap approach (Nouri et al., 2012). Given its applicability and direct relationship with other methods often has been adopted as a reference for evapotranspiration estimation (Qiu et al., 2015).

The simplified Penman model demonstrated to be more accurate and precise than the modified Bowen approach (Villa Nova et al., 2007) at the studied sites (Figures 1 and 2). The confrontation between EToBM and EToPM provided MAE ranging from 0.026 to 0.053 mm day^{-1}along with NSE between 0.62 and 0.90 for Ponta Grossa and Arapoti, PR, respectively. Such statistical parameters apart from relating positively with Willmott agreement index (d) and model performance coefficient (c) have been considered to be optimal for both sites, and also denote a lesser sensitivity of the model to the local climatic variations by taking into account the similarity of responsiveness of such methods tested at the sites in scrutiny.



(A) (B)

Fig.2: Confrontation between reference evapotranspiration estimated by the classical Penman-Monteith approach (EToPM) and potential demand calculated by the modified Bowen method (EToBM) for the period comprised between March 27, 2008 and August 22, 2011 at Ponta Grossa (A), and between August 26, 2011 and October 14, 2013 at Arapoti (B), PR, Brazil (averages of a 5-day period).

The modified Bowen method overestimated reference evapotranspiration in relation to the classical FAO Penman-Monteith approach, agreeing with the outcomes reported by Zhang et al. (2008) who also obtained evapotranspiration rates way above those ones determined by the energy balance – Bowen ratio approach – in comparison to the Standard FAO estimation method.

By evaluating the performance of the Hargreaves-Samani approach at Ponta Grossa and Arapoti municipalities, we came up with for both sites values of angular coefficients of the regression equation rather close to 1. The need for a preliminary local calibration of the Hargreaves-Samani model to meet regional atmospheric demands has been the target of concern on the part of scientists from all over the world, such as Shiri et al. (2015) and Luo et al. (2014).

In general, the Hargreaves-Samani approach overestimated evapotranspiration at 0.5 mm day^{-1} in relation to the FAO Standard model at the region of Campos Gerais of Paraná. This is because such a model was developed for dry climate regions, generating then overestimates of ETo at humid climate regions. By scrutinizing NSE values for the specific-studied sites (0.57 and 0.63, respectively, for Ponta Grossa and Arapoti, PR), it was possible to conclude that such a model could not be generally utilized to calculate ETo without local preliminary calibrations (Figure 3).

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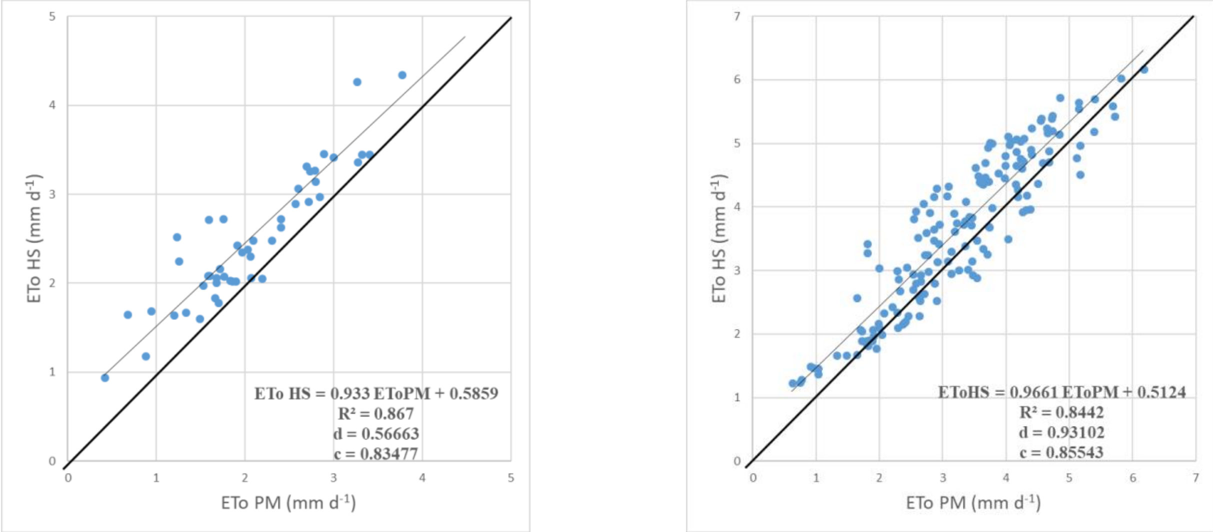
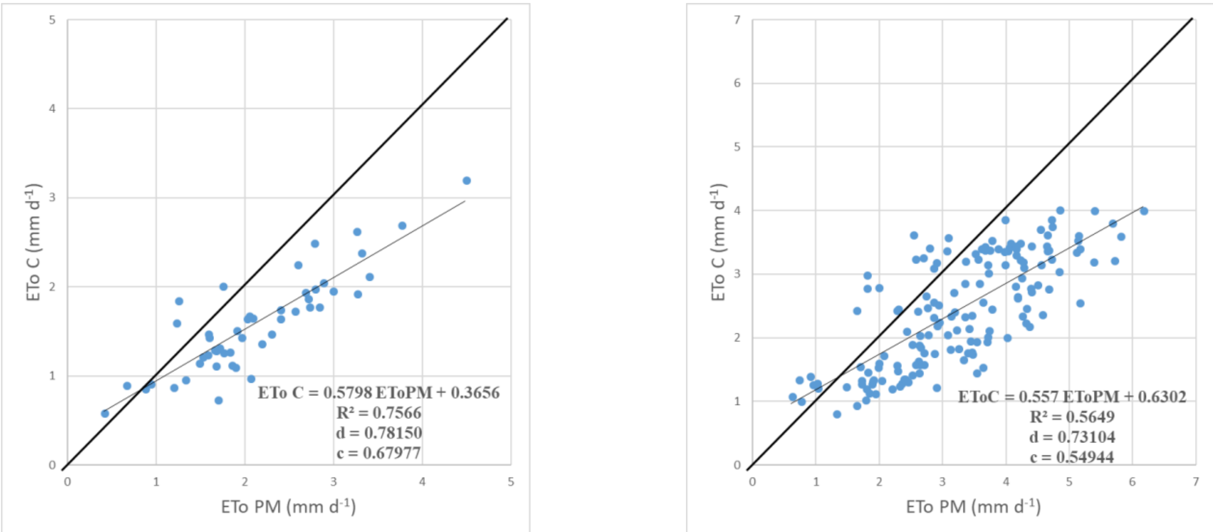


(A) (B)

Fig.3: Confrontation between reference evapotranspiration estimated by the classical Penman-Monteith approach (EToPM) and potential demand calculated by the Hargreaves-Samani method (EToHS) for the period comprised between March 27, 2008 and August 22, 2011 at Ponta Grossa (A), and between August 26, 2011 and October 14, 2013 at Arapoti (B), PR, Brazil (averages of a 5-day period).

The model proposed by Camargo (1971) takes into consideration environmental variables governing evapotranspiration rates at a given site, such as daily extraterrestrial solar radiation, expressed in mm day^{-1}, daily mean air temperature and number of days for the period in analysis. Such a model replaced in the Thornthwaite nomogram the annual calorific index (I) with a thermal index (T), which corresponds to the mean air temperature throughout the period and location in study (Camargo and Camargo, 2000; Carvalho et al., 2011).

By comparing the performance of Camargo method with the FAO Standard approach at the bay of the river Jacupiranga, located in São Paulo state, Brazil, Borges and Mendiondo (2007) observed a good correlation between both potential demand estimation methods, having the Camargo approach showed high reliability indices and being opportune to highlight herein that such a model turns out to be more suitable to assess evapotranspiration rates at hot climate regions. When tested under the climatic conditions of Palotina, PR, Brazil, the aforementioned method presented good results that might be confirmed by the model performance index c (Syperreck et al., 2008).



(A) (B)

Fig.4: Confrontation between reference evapotranspiration estimated by the classical Penman-Monteith approach (EToPM) and potential demand calculated by the Camargo method (EToC) for the period comprised between March 27, 2008 and August 22, 2011 at Ponta Grossa (A), and between August 26, 2011 and October 14, 2013 at Arapoti (B), PR, Brazil (averages of a 5-day period).

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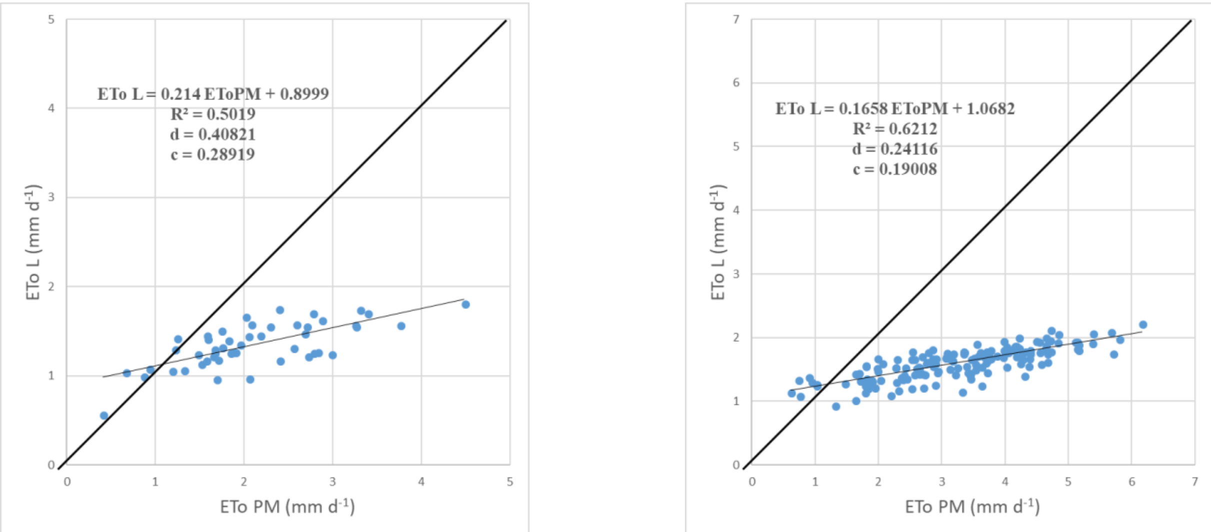
Scrutiny on the relationships between EToPM and EToC values demonstrates that the dispersion of the data around the trend line is greater than that promoted by other tested methods (Figure 4). The method of Camargo (1971) revealed to be adequate to estimate ETo at a monthly scale, and for such a reason it showed more pronounced fluctuations in a daily basis when compared to the FAO Standard approach. The values of Willmott agreement index (d) were corresponding to 0.782 and 0.731 for Ponta Grossa and Arapoti, PR, respectively, in conjunction with a model performance index (c) of 0.679 and 0.549, respectively, classified as sufferable according to performance criteria proposed by Camargo and Sentelhas (1997). NSE value for the municipality of Ponta Grossa was of -0.64, whereas for the municipality of Arapoti was of -0.66, a point that restricts its utilization at the region of Campos Gerais of Paraná for five-day periods due to its lower precision as opposed to that one provided by the modified Bowen and simplified Penman methods.

The method proposed by Linacre (1977) is a mere simplification of the original Penman method. The term that expresses the difference between mean air temperature and dew point temperature present in such a method may be estimated as a function of local altitude, mean air temperature and extreme air temperatures, as well as by the difference between mean air temperatures of the most hot and cold months in a monthly basis (Carvalho et al., 2011).

Mendonça et al. (2003) compared rates of reference evapotranspiration measured at weighting lysimeters with calculated values of ETo obtained from different estimation methods at the Northern Rio de Janeiro state, Brazil. The outcomes coming from such a correlation study indicated that for the 10-day periods the coefficients of determination (R^2) were of 0.82 for the Penman-Monteith, Linacre and Jensen-Haise methods. Nevertheless, high correlations between observed and calculated ETo values revealed that the latter came to being the most appropriate estimation method for the hot climate regions, highlighting according to Henrique and Dantas (2007) that Linacre and Thornthwaite methods did not generate satisfactory results to estimate ETo in a daily basis.

Henrique and Dantas (2007) found variations of ETo estimates obtained by the Linacre approach ranging from 2.0 to 2.5 mm day^{-1}, whose values were quite similar to those calculated by the same method at both studied sites. For the region of Campos Gerais of Paraná, EToL rates did not surpass 3.0 mm day^{-1}. The observed values of Willmott agreement index (c) yoked to the confrontation between EToPM and EToL were of 0.408 and 0.241 at Ponta Grossa and Arapoti, PR, respectively, in conjunction with model performance indices (c) of 0.289 and 0.190, having been therefore classified as terrible according to Camargo and Sentelhas (1997). The NSE value for Ponta Grossa was of -16.03, whilst for Arapoti it was corresponding to -59.07, which denotes a conspicuous unfeasibility of application at both specific-sites in study (Figure 5).



(A) (B)

Fig.5: Confrontation between reference evapotranspiration estimated by the classical Penman-Monteith approach (EToPM) and potential demand calculated by the Linacre method (EToL) for the period comprised between March 27, 2008 and August 22, 2011 at Ponta Grossa (A), and between August 26, 2011 and October 14, 2013 at Arapoti (B), PR, Brazil (averages of a 5-day period).

The unsatisfactory performance of the Linacre method at the studied region is attributed to the mild prevailing local climate, with normal annual mean temperature of Arapoti being quite lower than that observed in Ponta Grossa besides the fact that such a method does not estimate ETo with a high precision for short periods of time.

A crucial point to be borne in mind concerning the choice of potential demand estimation methods at a given site is directly related to the time scale required. Usually empirical methods, such as Thornthwaite and Camargo, estimate ETo quite well in a monthly basis, whereas either physical or combined approaches involving net radiation assessments lead to better estimates of ETo in a daily scale (Pereira et al., 2007).

A matrix correlation analysis between potential demand estimation methods for the studied locations (Tables 1 and 2) evidenced more consistent precision and accuracy for both modified Bowen and simplified Penman methods in comparison to the FAO Penman-Monteith approach, as well as the agreement degree between Camargo and Linacre methods.

The observed correlations between the Penman-Monteith FAO Standard method and the modified Bowen, simplified Penman, and Hargreaves-Samani methods were superior to 0.90 ($p<0.0001$), described as being almost perfect according to Souza et al. (2010), whereas for the Camargo and Linacre methods such correlations ranged from 0.70 to 0.90 ($p<0.0001$), classified as very high for the specific-sites in study.

By making use of the same analogy on the comparison of potential demand estimation methods, high correlations between modified Bowen and simplified Penman methods were observed (>0.99; $p<0.0001$), as well as between Camargo and Linacre approaches (>0.80; $p<0.0001$). However, such a correlation considerably decreases whenever two methods groups (one based on net radiation and other on air temperature) are to be compared.

Table.1: Correlation matrix between reference evapotranspiration estimated by the classical Penman-Monteith approach (EToPM) and potential demand calculated by the simplified Penman (EToPS), Camargo (EToC), Hargreaves-Samani (EToHS), modified Bowen (EToBM) and Linacre (EToL) methods, throughout the period comprised between March 27, 2008 and August 22, 2011 at Ponta Grossa, PR, Brazil (averages of a 5-day period).

	EToPM	*EToPS*	*EToC*	*EToHS*	*EToBM*	*EToL*
EToPM	1.0000					
EToPS	0.9295	1.0000				
EToC	0.8698	0.8282	1.0000			
EToHS	0.9311	0.8705	0.9482	1.0000		
EToBM	0.9413	0.9981	0.8568	0.8899	1.0000	
EToL	0.7084	0.5100	0.8039	0.7170	0.5520	1.0000

All correlation coefficients showed to be statistically significant by the Student t Test at 1% probability level.

Table.2: Correlation matrix between reference evapotranspiration estimated by the classical Penman-Monteith approach (EToPM) and potential demand calculated by the simplified Penman (EToPS), Camargo (EToC), Hargreaves-Samani (EToHS), modified Bowen (EToBM) and Linacre (EToL) methods, throughout the period comprised between August 26, 2011 and October 14, 2013 at Arapoti, PR, Brazil (averages of a 5-day period).

	EToPM	*EToPS*	*EToC*	*EToHS*	*EToBM*	*EToL*
EToPM	1.0000					
EToPS	0.9749	1.0000				
EToC	0.7516	0.7838	1.0000			
EToHS	0.9188	0.9268	0.9232	1.0000		
EToBM	0.9746	0.9973	0.8100	0.9357	1.0000	
EToL	0.7882	0.7433	0.8886	0.8475	0.7772	1.0000

All correlation coefficients showed to be statistically significant by the Student t Test at 1% probability level.

IV. CONCLUSIONS

It is possible to evaluate atmosphere evaporative demand for agrometeorological investigation purposes by means of reference evapotranspiration estimation methods scrutinized at the region of Campos Gerais of Paraná, Brazil.

The simplified Penman and modified Bowen methods had the best performance and are to be recommended for agricultural planning purposes at the studied region, for dismiss meteorological information with regard to wind regimes.

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