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Evaluation of Eleven Reference Evapotranspiration Models in Semiarid Conditions

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Abstract

The objectives of this study were to evaluate the performance of the FAO Penman Monteith reference evapotranspiration model under limited data and some mine temperature methods of reference evapotranspiration (ETo) under the semiarid and arid conditions in Mali. The results showed that under limited data conditions, the FAO-PM equation achieved accurate estimation of daily ETo when solar radiation, relative humidity, and wind speed are lacking individually with root mean squared errors (RMSE) averaging 0.52, 0.56 and 0.62 mm/day, respectively. Much more accurate ETo was estimated under relative humidity and wind speed missing data conditions with RMSE varying from 0.20 to 0.58 mm/day and average RE, MBE and MAE of 6.7%, −0.25 mm/day and 0.30 mm/day. The Jensen-Haise equation systematically overestimated ETo while the Hansen, Christiansen, and Irmak, and the two Tabari's equations underestimated ETo at all weather stations. The Abtew equation showed the best performance among the selected ETo equations.

Keywords

Reference Evapotranspiration, Semiarid and Arid Climate, Mali

1. Introduction

Mean annual rainfall across the West African Sahel, varies from 100 mm to 600 mm covering 1 to 6 months with the decreasing trends from the southern limit to the northern limit [1]. The extremely high air temperature and the low relative humidity increase the Evapotranspiration demand. Evapotranspiration is the main source of water losses and one of the important parameters under the hydrological, agricultural and environmental studies [2]. Under the Sahelo-Saharan climate conditions, water resource is one of the most factors limiting food production where insufficient and erratic rainfall limits rainfed agriculture in high risk production systems in terms of water stress. The Sahel is characterized by semi-arid climate under which effective water management is, therefore, critical. Accurate crop evapotranspiration estimation is critical for the water resources management under agricultural, hydrological and environmental processes. Management of water resources in the limited available water resources environment like the west African Sahel merit primordial attention for resource sustainability and improving water use efficiency [3] [4] [5]. Crop evapotranspiration is mostly estimated by the indirect method combining crop reference evapotranspiration (ETo) with crop coefficients [6] beside the direct measurement though lysimeters [7] [8]. Different methods for estimating ETo have been developed for different parts of the globe using climatic variables such as temperature, radiation, and combined variables [9]-[14]. While most of developed ETo equations have relative accuracy and adaptability to the local environment different from where they were developed, the Penman-Monteith ETo equation was demonstrated and shown to be the most accurate and adapted to all climatic conditions [12] [15]-[20]. The applicability of the Penman-Monteith ETo equation is constrained by the number and the non-availability of the full climatic dataset (temperature, relative humidity, solar radiation, and wind speed) mostly the developing countries like the sub-Saharan African countries. Scientists have to evaluate the adaptability of simple ETo equations to the local climatic conditions. One of the Valiantzas ETo equations was shown suitable ETo estimation across Burkina Faso [4] [21], Tanzania, Kenya and Uganda [20] [22]. Djaman *et al.* [3] reported the Trabert, Mahringer, Penman 1948, Albrecht, and two of Valiantzas' equations to perform well under the semiarid condition in Senegal River Delta and their calibration to the local climatic condition had improved daily ETo [5]. Tabari *et al.* [23] reported suitability of very few ETo equation to the Iranian environment while [24] indicated good performance of the calibrated forms of two of the Valiantzas equations to the Pilbara region of Western Australia.

While different equations have been tested and calibrated for different regions and sub-regions under different climatic conditions including in Canada [25], in Iran [26] [27] [28], in China [29], in Poland [30], in Florida (USA) [31], in Southeast Australia [32], and in Senegal [3], limited studies were conducted on the adaptability of reference evapotranspiration equation to the African Sahelo-Saharan region. Therefore, it is critical to assess the adaptability of ETo models and improve them through proper calibration to the local climate conditions. Thus, the objectives of this study were to: 1) evaluate the FAO-PM ETo equation under limited data condition, 2) evaluate nine temperature reference evapotranspiration equations with comparison to the FAO-PM method, and 3) calibrate and validate the Abtew ETo equation [33] under the Malian semiarid and arid climate conditions.

2. Materials and Methods

2.1. Data and Study Area

Climatic data were collected at eleven weather stations across Mali (West Africa) for the period of 1990-2012. Maximum temperature (*Tmax*), minimum temperature (*Tmin*), maximum relative humidity (*RHmax*), minimum relative humidity (*RHmin*), wind speed (*u*2), and solar radiation (*Rs*) data were collected from Bougouni, Hombori, Koutiala, Mopti, Nara, San, Segou, Senou, Sikasso, and Tessalit (Table 1). Mali has three climatic zones: the Sudanian zone with 700 to 1000 mm of annual precipitation, the Sahelian zone which receives 200 to 400 mm of precipitation, and the Saharan zone with little or no rain. Mali is among the hottest countries in the world. Most of Mali receives negligible rainfall and droughts are very frequent. The rainy season covers generally late June to early December in the southern area. The vast northern desert part of Mali has a hot desert climate with long, extremely hot summers and scarce rainfall which decreases northwards. The central area has a hot semi-arid climate with very high temperatures year-round, a long, intense dry season and a brief, irregular rainy season.

2.2. Reference Evapotranspiration Equations

- Penman-Monteith equation (FAO-PM)

Daily grass reference evapotranspiration (ETo-Ref) was calculated using the Penman-Monteith (FAO-PM) equation [12]. The Penman-Monteith reference evapotranspiration equation for grass surface is:

Table 1. Geographic coordinates and the climatic zones of the eleven weather stations.

Weather Stations	Latitude (Degree North)	Longitude (Degree East)	Altitude (m)	Climatic zones
Bougouni	11.42	−7.5	344	Soudanian Zone
Senou	12.53	−7.95	375	
Sikasso	11.35	−5.68	284	
Koutiala	12.38	−5.47	367	Salelian Zone
Mopti	14.52	−4.1	272	
Nara	15.17	−7.28	265	
Niono	14.23	−5.98	277	
San	13.33	−4.83	284	
Segou	13.4	−6.15	289	
Hombori	15.33	−1.68	288	Sahara Zone
Tessalit	20.2	−0.98	491	

$$\mathrm{ETo} = \frac{0.408\Delta\left(Rn - G\right) + \left(\gamma Cnu2/\left(T + 273\right)\right)\left(es - ea\right)}{\Delta + \gamma\left(1 + Cdu2\right)} \tag{1}$$

where all variables are defined as described in [22]. All parameters necessary for computing ETo were computed according to the procedure developed in FAO-56 by [12].

The FAO-PM ETo model was evaluated under limited climatic data conditions for its performance and suitability under similar conditions as it is almost the case in most of the developing countries where climatic data record is not consistent and with missing variables [3] [34] [35] [36] [37].

Thus, the following acronyms were used for ETo estimated using: 1) FAO-56 Penman Monteith equation with full data set is referred as FAO-PM ETo, 2) ETo-Rs when Rs is missing, 3) ETo-Tmin when RH is missing, 4) ETo-um when u2 is missing, 5) ETo-RsTmin when *Rs* and *RH* are missing, 6) ETo-Rsum when *Rs* and u2 are missing, 7) ETo-umTmin when u2 and RH are missing, 8) ETo-RsumTmin when Rs, RH and u2 are missing.

- Jensen and Haise [6] method:

$$\mathrm{ETo} = \left(0.025 Tmean + 0.08\right)\frac{Rs}{\lambda} \tag{2}$$

- Hansen [38] method:

$$\mathrm{ETo} = 0.7\frac{\Delta}{\Delta + \gamma}\frac{Ra}{\lambda} \tag{3}$$

- Abtew [33] method 1: Abtew

$$\mathrm{ETo} = \frac{Tmax}{K}\frac{Rs}{\lambda} \tag{4}$$

- Calibrated Christiansen [33] method:

$$\mathrm{ETo} = 0.53\frac{Rs}{\lambda} \tag{5}$$

- Droogers and Allen [39] method: Dr-Al

$$\mathrm{ETo} = 0.003\left(Tmean + 20\right)\left(Tmax - Tmin\right)^{0.4} Ra \tag{6}$$

- Hargreaves and Allen [40] method: Harg

$$\mathrm{ETo} = \left(0.0135 Tmean + 0.2403\right)\frac{Rs}{\lambda} \tag{7}$$

- Irmak [41] method:

$$\mathrm{ETo} = -0.611 + 0.149 Rs + 0.079 Tmean \tag{8}$$

- Tabari [23] method 1: Tabari 1

$$\mathrm{ETo} = -0.642 + 0.174 Rs + 0.0353 Tmean \tag{9}$$

- Tabari [23] method 2: Tabari 2

$$\mathrm{ETo} = -0.478 + 0.156 Rs - 0.0112 Tmax + 0.0733 Tmin \tag{10}$$

where, *Tmax*, *Tmin* and *Tmean* are daily maximum, minimum and mean air temperature (˚C), respectively; *Rs* is solar radiation, *Ra* is extraterrestrial radiation ($MJm^{-2}\cdot day^{-1}$), *K* is dimensionless coefficient to be determined for each location.

- Multi-model ensemble (MME)

Simple multi-model ensemble (MME) was constructed by combining all the nine the individual ensemble of ETo models with equal weights [42] [43]. Multi-model ensemble outperforms single models in their skill due to error cancellation and the nonlinearity of the skill metrics applied. Hagedorn *et al.* [43] reported that it is not usually possible to identify a "best" or a "poorest" model from a set of models, as their individual strengths and flaws typically vary with location and initialization time. In this method, MME forecasts are generated by simply pooling together the participating simple models, with all ensemble members having equal weight [43]. We assume that this procedure might solve the quantification of all aspects of all simple models uncertainties with increasing model performance as demonstrated by [44] [45] [46] [47].

2.3. Calibration of the Abtew ETo Equation

To calibrate the ETo equations, a linear regression relationship between daily PM-ETo and daily ETo estimates by the Abtew equation was determined and the calibration coefficients were then obtained by multiplying the slope of a regression line between ETo estimate by an ETo equation and the PM-ETo by its inverse to bring the slope of the regression line to the unity. And, the opposite value of the intercept was added to the new regression relationship to minimize the new intercept (as close to zero as possible). The dependent variable was ETo estimated by the PM-ETo and the independent variable was the ETo estimations by the Abtew equation. Therefore, the calibration processes tend to have a new regression relationship with a slope as unity and intercept as zero. The Abtew ETo equation was calibrated and validated using all eleven weather stations. The data from 1990 to 2003 were used for the equation calibration and data from 2004 to 2012 were used for the validation. This partitioning is due to the need of more data for training the equation as suggested by [28] [48].

2.4. Evaluation Criteria

Simple linear regression was used for models comparison with reference to the FAO-PM. Root mean squared error (RMSE), relative error (RE), mean bias error (MBE), and the absolute mean error (AME) were also used for model evaluation and calculated as follow:

$$\mathrm{RMSE} = \sqrt{\sum_{i=0}^{n} \frac{(Ei - Oi)^2}{n}} \tag{11}$$

$$\mathrm{RE} = \frac{\mathrm{RMSE}}{\mathrm{ETomean}} \times 100 \tag{12}$$

$$\mathrm{MBE} = n^{-1} \sum_{1}^{n} (Ei - Oi) \tag{13}$$

$$\text{AME} = n^{-1}\sum_{1}^{n}\left|Ei - Oi\right| \tag{14}$$

where, *Ei* is the estimated ETo with FAO-PM under limited data and the temperature ETo models; and *Oi* is ETo estimated with FAO-PM model with full dataset, at the *ith* data point and *n* is the total number of data points.

3. Results and Discussion

3.1. Performance of the FAO-PM Equation under Limited Data

The FAO-PM equation performed relatively well under limited data conditions in the semiarid and arid conditions in Mali. Under solar radiation missing, the FAO-PM (ETo-Rs) overall underestimated the daily ETo with the best performance at Nara in the Sahelian zone and Tessalit in the Sahara zone. The regression slope between FAO-PM ETo and ETo-Rs was very high and varied from 0.934 to 0.999 and the R^2 ranged from 0.68 to 0.96 (Table 2). ETo underestimation

Table 2. Comparison between FAO-PM ETo computed from full Data set and FAO-PM ETo computed with limited data when Rs, RH, and u2 are missing.

Indices	Locations	ETo-Rs	ETo-Tmin	ETo-um	ETO-RsTmin	ETo-Rsum	ETo-umTmin	ETo-RsumTmin
Regression slope	Bougouni	0.941	0.944	1.133	0.876	1.077	1.001	0.937
	Hombori	0.936	0.914	1.143	0.816	1.081	0.957	0.863
	Koutiala	0.958	0.929	1.123	0.884	1.083	0.982	0.939
	Mopti	0.971	0.905	1.084	0.877	1.056	0.942	0.914
	Nara	0.996	0.898	1.072	0.905	1.069	0.930	0.938
	Niono	0.962	0.904	1.086	0.861	1.049	0.939	0.897
	San	0.964	0.920	1.104	0.883	1.068	0.967	0.931
	Segou	0.970	0.901	1.087	0.869	1.058	0.937	0.906
	Senou	0.956	0.929	1.127	0.875	1.084	0.980	0.929
	Sikasso	0.950	0.934	1.112	0.878	1.064	0.9841	0.930
	Tessalit	0.999	0.901	1.078	0.900	1.077	0.934	0.933
	Average	0.964	0.916	1.104	0.875	1.070	0.957	0.920
R^2	Bougouni	0.70	0.95	0.92	0.64	0.67	0.96	0.65
	Hombori	0.68	0.89	0.87	0.76	0.49	0.92	0.73
	Koutiala	0.74	0.93	0.94	0.69	0.70	0.94	0.68
	Mopti	0.78	0.91	0.97	0.77	0.74	0.93	0.75
	Nara	0.85	0.91	0.99	0.81	0.82	0.92	0.80
	Niono	0.79	0.91	0.98	0.76	0.75	0.92	0.75
	San	0.75	0.92	0.96	0.73	0.70	0.94	0.71
	Segou	0.80	0.90	0.98	0.76	0.77	0.92	0.75
	Senou	0.76	0.93	0.94	0.68	0.73	0.94	0.68
	Sikasso	0.74	0.94	0.94	0.66	0.72	0.95	0.67
	Tessalit	0.96	0.94	1.00	0.92	0.96	0.95	0.91
	Average	0.78	0.92	0.95	0.74	0.73	0.94	0.73

was revealed through the MBE that average −0.18 mm/day and the MAE average of 0.38 mm/day (**Table 3**). Under missing RH conditions and when the actual vapor pressure is estimated with Tmin, ETo-Tmin basically underestimated daily ETo at lower rate of daily evapotranspiration less than 6 mm/day (**Figure 1**). The largest underestimation was observes at Nara and Tessalit when the MBE was −0.66 and −0.69 mm/day, and the MAE was 0.66 and 0.69 mm/day, respectively (**Table 3**). The least RE was observed at Bougouni (7.1%), the largest RE (12%) was observed at Nara and the average RE was 10% that showed the applicability of the method in the case of missing RH data. Large overestimation of daily ETo between 7% and 14% that averaged 10% (**Figure 1**) was obtained when the global average wind speed of 2 m/s was used (**Table 2**) with RMSE that varied from 0.51 and 0.85 mm/day, RE from 7.7% to 15.5%, and MBE from 0.44 and 0.79 mm/day (**Table 3**). However, very high R^2 varying from 0.87 and 1.0 was obtained between FAO-PM ETo with full data set and ETo-um. When Rs and RH data are missing, ETo-RsTmin underestimated the daily ETo with RMSE ranging from 0.78 to 1.08 mm/day, MBE from −0.58 to −1.01 mm/day, high RE that varied from 12.5% to 19.6% (**Table 3**). ETo overestimation average of 7% was observed in the case of missing Rs and wind speed with no geographical specificity. In this case, RE was as high as 17.6% at Bougouni and average 13.9% (**Table 3**). Under missing wind speed and RH data, ETo-umTmin had relatively low RMSE that varied from 0.20 to 0.56 mm/day and low RE always less than 10% and averaging 6.7%, MBE average of −0.25 mm/day, and MAE average of 0.30 mm/day. The lowest RE was obtained at Bougouni (4%) when the null MBE was observed and the lowest MAE of 0.14 mm/day. When the RS, RH, and u2 are missing the FAO-PM has the poorest performance at all locations across Mali with large RMSE varying from 0.64 to 0.84 mm/day, high RE averaging 13%, and MBE varying from −0.75 to −0.29 mm/day, and MAE averaging 0.59 mm/day (**Table 3**). Therefore it is not recommend using the FAO-PM equation under this condition across the semiarid and arid conditions across Mali.

The results of this study are in agreement with previous research under similar climatic conditions. Similar results were reported by [4] during their study across Burkina Faso. Rojas and Thepadia [37] reported better results of the FAO-PM ETo equation when using wind speed data from a neighboring site in northeast Louisiana compared to the adoption of the global average wind speed of 2 m/s with a mean ratio of 0.98 and MAE of 0.56 mm/day. Trajkovic and Kolakovic [8] reported that the discrepancies between ETo under full data set and ETo under limited data set increased with increasing number of estimates weather parameters. Popova *et al.* [49] reported that the ETo estimation by FAO-PM under limited data provided accurate estimates of ETo with small standard errors of estimates. In contrast, [50] showed small differences in terms of MBE varying −0.22 to 0.25 mm/day and small RMSE varying 0.06 - 0.50 mm/day when they comparing ETo-RS and FAO-PM ETo with full data set in Korea. The results are close enough to the results of [51] who indicated that under missing Rs data, temperatures could be used to derive Rs for ETo estimation

Table 3. Statistical indices for the evaluation of FAO-PM ETo computed with limited data when Rs, RH, and u2 are missing.

Indices	Locations	ETo-Rs	ETo-Tmin	ETo-um	ETO-RsTmin	ETo-Rsum	ETo-umTmin	ETo-RsumTmin
RMSE (mm/day)	Bougouni	0.60	0.34	0.75	0.80	0.85	0.20	0.67
	Hombori	0.53	0.56	0.85	1.08	0.77	0.35	0.84
	Koutiala	0.55	0.44	0.71	0.79	0.84	0.25	0.67
	Mopti	0.54	0.62	0.51	0.87	0.72	0.44	0.75
	Nara	0.47	0.74	0.47	0.80	0.71	0.56	0.70
	Niono	0.55	0.65	0.53	0.96	0.70	0.47	0.83
	San	0.57	0.52	0.62	0.83	0.81	0.31	0.70
	Segou	0.53	0.65	0.53	0.91	0.71	0.47	0.78
	Senou	0.57	0.40	0.64	0.80	0.77	0.22	0.67
	Sikasso	0.55	0.45	0.73	0.84	0.82	0.27	0.70
	Tessalit	0.28	0.75	0.51	0.78	0.59	0.58	0.64
	Average	0.52	0.56	0.62	0.86	0.75	0.38	0.72
RE (%)	Bougouni	12.4	7.1	15.5	16.5	17.6	4.1	13.9
	Hombori	9.6	10.2	15.5	19.6	13.9	6.4	15.3
	Koutiala	10.8	8.7	13.8	15.5	16.3	5.0	13.0
	Mopti	9.6	11.1	9.2	15.6	12.9	7.8	13.4
	Nara	7.6	12.0	7.7	13.1	11.5	9.2	11.5
	Niono	9.6	11.3	9.3	16.8	12.2	8.3	14.5
	San	10.5	9.6	11.5	15.3	14.9	5.8	13.0
	Segou	9.5	11.6	9.5	16.2	12.7	8.4	13.9
	Senou	11.5	8.1	12.9	16.2	15.6	4.5	13.6
	Sikasso	10.7	8.8	14.2	16.3	16.0	5.3	13.5
	Tessalit	4.4	11.9	8.1	12.5	9.4	9.2	10.2
	Average	9.7	10.0	11.6	15.8	13.9	6.7	13.3
MBE (mm/day)	Bougouni	−0.27	−0.27	0.62	−0.58	0.36	0.00	−0.29
	Hombori	−0.33	−0.49	0.79	−1.01	0.47	−0.26	−0.75
	Koutiala	−0.20	−0.36	0.61	−0.58	0.41	−0.10	−0.31
	Mopti	−0.16	−0.54	0.46	−0.70	0.31	−0.34	−0.49
	Nara	−0.02	−0.66	0.44	−0.61	0.42	−0.46	−0.41
	Niono	−0.21	−0.57	0.48	−0.80	0.28	−0.37	−0.60
	San	−0.19	−0.44	0.55	−0.63	0.36	−0.19	−0.38
	Segou	−0.17	−0.56	0.47	−0.74	0.31	−0.36	−0.53
	Senou	−0.24	−0.31	0.52	−0.58	0.30	−0.08	−0.33
	Sikasso	−0.21	−0.37	0.63	−0.62	0.42	−0.11	−0.35
	Tessalit	0.00	−0.69	0.50	−0.67	0.50	−0.48	−0.46
	Average	−0.18	−0.48	0.55	−0.68	0.38	−0.25	−0.45

Continued

MAE (mm/day)	Bougouni	0.45	0.27	0.62	0.69	0.73	0.14	0.54
	Hombori	0.41	0.49	0.79	1.04	0.68	0.27	0.79
	Koutiala	0.40	0.36	0.61	0.68	0.72	0.18	0.53
	Mopti	0.38	0.54	0.46	0.76	0.63	0.36	0.60
	Nara	0.32	0.66	0.44	0.68	0.63	0.47	0.56
	Niono	0.38	0.57	0.48	0.85	0.61	0.39	0.68
	San	0.40	0.44	0.55	0.71	0.71	0.23	0.55
	Segou	0.37	0.56	0.47	0.80	0.62	0.38	0.64
	Senou	0.43	0.31	0.52	0.69	0.65	0.16	0.54
	Sikasso	0.40	0.37	0.63	0.73	0.71	0.19	0.56
	Tessalit	0.18	0.69	0.50	0.69	0.53	0.50	0.52
	Average	0.38	0.48	0.55	0.76	0.66	0.30	0.59

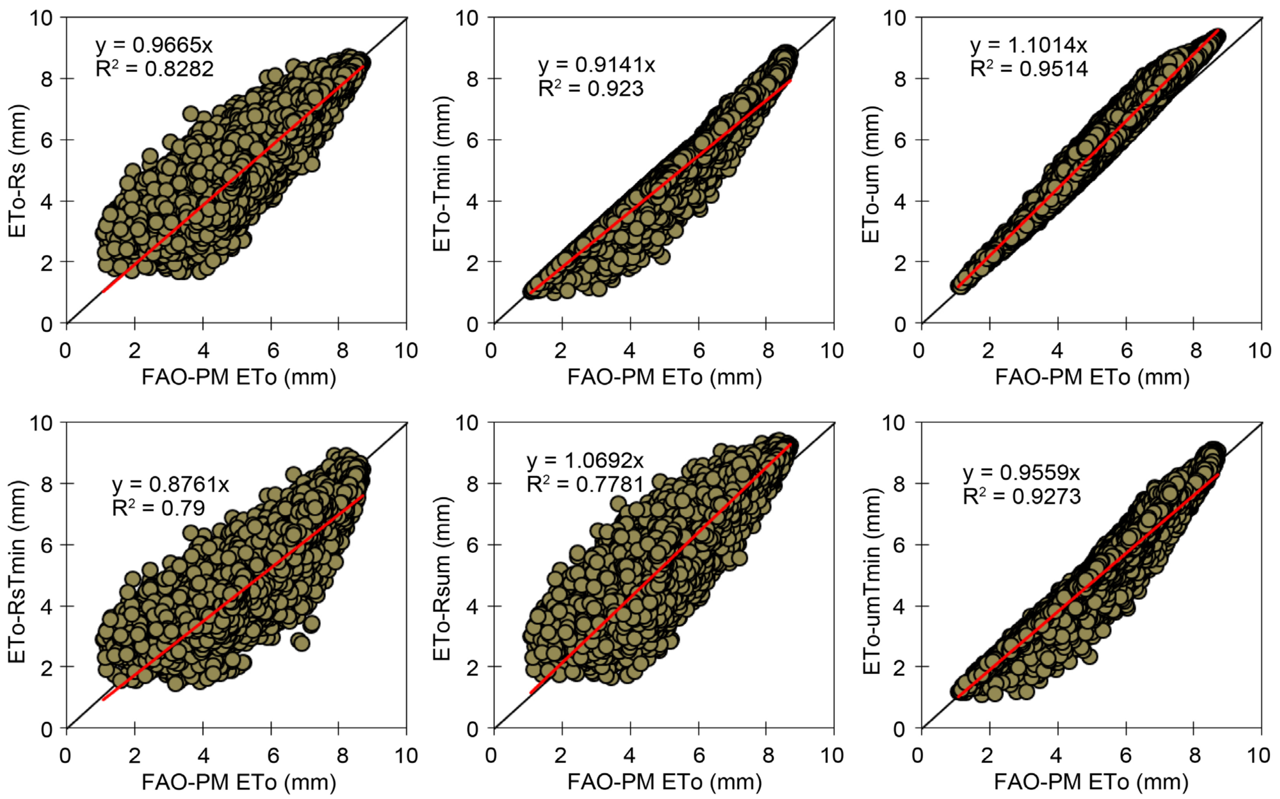

Figure 1. Relationship between the FAO-PM daily ETo computed with full data and the daily ETo by the FAO-PM under limited data conditions.

in the Mediterranean environment. They reported very high $R^2 \geq 0.98$ using this method and RMSE varying from 0.42 to 0.71 mm/day. Wang *et al.* [52] indicated accurate estimates of ETo when RH is missing in Malawi. Jabloun and Sahli [34] also reported similar results under semiarid conditions in Tunisia. These results corroborated the finding of [4] for their study under semiarid climate in Burkina

Faso. In Southern Ontario, Canada, ETo-Tmin overestimated ETo up to 12% as reported by [35]. Kwon and Choi [50] reported large RMSE of 0.6 - 0.73 mm/day under missing RH data in Korea. Under missing wind speed data, [34] reported close to unity regression slopes and very high R^2 (>0.96) in Tunisia. [4] [8] [34] [37] reported that the use of global wing speed average of 2 m/s should be replaced by the local average wind speed data that provided better estimates of ETo. Under missing RH and u2, the results of this study are in agreement with [35] who reported that under missing RH and u2, FAO-PM method showed good estimation of daily ETo in the Southern Ontario, with RMSE < 0.53 mm/day. However, when three climatic variables were mission, the results showed the poorest performance of the FAO-PM model as reported by [34] [50] [53].

3.2. Evaluation of the Selected ETo Equations

The tested ETo equations had different performance at the eleven weather stations in Mali. The Jensen-Haise equation systematically overestimated ETo at all sites (**Table 3**) with RMSE ranging from 1.6 to 2.0 mm/day, the RE within the range of 26.3% to 37.6% averaging 32.1%, and average AME of 1.55 mm/day (**Table 5**). The highest overestimation was recorded at Bougouni, Senou and Sikasso, all under the Sudanian climate. The Hansen, Christiansen, and Irmak ETo equations had similar performance and slightly underestimated ETo (**Table 4**). The regression slope varied from 0.79 to 0.94, from 0.76 to 0.92, and from 0.79 to 0.95 for the Hansen, Christiansen, and Imak equations, respectively, and the RMSE varied from 0.52 to 1.44 mm/day, from 0.63 to 1.66 mm/day, and from 0.45 to 1.43 mm/day for the respective ETo equations (**Table 5**). The relative error averaged 17%, 19%, and 15% under the Hansen, Christiansen, and Imak equations while the MBE averaged −0.75, −0.85, and −0.69 mm/day for the respective equations. These three ETo equations had the best performance at Bougouni under the Sudanian climate and the worst performance at Nara under the Sahelian climate.

The Abtew dimensionless coefficient K varied with locations and was 58.67, 57.75, and 57.55 at Bougouni, Senou, Sikasso, respectively, in the Soudanian zone; 57.54, 55.58, 55.08, 55.96, 56.94, 55.37 at Koutiala, Mopti, Nara, Niono, San, and Segou, respectively, for the Sahelian Zone; and 57.97 and 56.31 at Hombori and Tessalit, respectively, for the Sahara zone. Overall, there was not particular correlation between K and the geographical coordinates of the weather stations. However, good correlation between K values and the latitudes of the weather stations was found only for the Sahelian zone (K = 30.864 × Altitude − 1438.5 with R^2 = 0.63) and this relation could be introduced into the original Abtew equation for regionalization under the Sahelian conditions. The Abtew equation showed the best performance among the ETo equations, slightly better than the [39] (Dr-Al) and [40] (Harg.) equations (**Table 4** and **Table 5**). The regression slopes varied from 0.98 to 1.03, from 0.91 to 0.99, and from 0.90 to 1.07 for the Abtew, Dr-Al and Harg equations with average R^2 of 0.86, 0.74 and 0.79, and

Table 4. Comparison between FAO-PM ETo computed from full data set and ETo computed with selected models.

Indexes	Locations	Jensen-Haise	Hansen	Abtew	Christiansen	Dr-Al	Harg	Irmak	Tabari 1	Tabari 2	MME
Regression slope	Bougouni	1.354	0.936	0.994	0.919	0.981	1.065	0.945	0.803	0.815	0.979
	Hombori	1.336	0.915	0.993	0.896	0.906	1.045	0.903	0.779	0.785	0.951
	Koutiala	1.313	0.896	0.997	0.873	0.979	0.896	0.906	0.766	0.774	0.947
	Mopti	1.245	0.831	0.989	0.820	0.946	0.970	0.847	0.719	0.717	0.899
	Nara	1.196	0.790	0.985	0.761	0.959	0.922	0.794	0.672	0.659	0.860
	Niono	1.260	0.843	0.989	0.817	0.929	0.977	0.845	0.718	0.719	0.900
	San	1.283	0.871	0.991	0.850	0.965	1.000	0.876	0.745	0.745	0.925
	Segou	1.251	0.836	0.990	0.809	0.938	0.968	0.846	0.713	0.718	0.897
	Senou	1.322	0.898	0.993	0.903	0.970	1.031	0.907	0.767	0.777	0.949
	Sikasso	1.324	0.916	0.995	0.757	0.973	1.043	0.928	0.788	0.798	0.963
	Tessalit	1.209	0.791	0.982	0.873	0.958	0.927	0.782	0.666	0.647	0.858
Average		1.28	0.87	0.99	0.84	0.95	0.99	0.87	0.74	0.74	0.92
R^2	Bougouni	0.89	0.79	0.91	0.66	0.64	0.86	0.72	0.74	0.52	0.90
	Hombori	0.82	0.80	0.83	0.76	0.75	0.82	0.84	0.80	0.78	0.86
	Koutiala	0.83	0.72	0.88	0.55	0.68	0.72	0.65	0.65	0.44	0.85
	Mopti	0.76	0.70	0.83	0.55	0.77	0.75	0.68	0.65	0.50	0.82
	Nara	0.73	0.69	0.80	0.57	0.82	0.74	0.73	0.66	0.55	0.81
	Niono	0.79	0.72	0.84	0.57	0.77	0.78	0.72	0.67	0.56	0.84
	San	0.78	0.70	0.86	0.55	0.73	0.77	0.65	0.64	0.45	0.83
	Segou	0.77	0.65	0.84	0.46	0.75	0.75	0.60	0.58	0.40	0.79
	Senou	0.86	0.75	0.88	0.59	0.67	0.84	0.69	0.69	0.52	0.87
	Sikasso	0.86	0.74	0.90	0.73	0.65	0.82	0.62	0.67	0.39	0.86
	Tessalit	0.83	0.88	0.85	0.58	0.92	0.88	0.95	0.87	0.90	0.92
Average		0.81	0.74	0.86	0.60	0.74	0.79	0.71	0.69	0.55	0.85

MBE of −0.05, −0.25 and −0.05 mm/day for the respective ETo equations. The Abtew equation obtained the least relative errors that averaged 9.83% and AME of 0.41 mm/day. They showed better performance under the Sudanian and Sahelian semiarid climates. The Tabari 1 and Tabari 2 ETo equations did not show good performance under the Sudano-Sahelo semiarid and Saharan arid conditions in Mali. Both equations systematically underestimated daily ETo across the study area with RMSE that averaged 1.53 and 1.54 mm/day, MBE of −1.42 and −1.41 mm/day, and AME of 1.42 and 1.42 mm/day, respectively. The Tabari ETo equations showed the best performance with the lowest RMSE of 1.04 and 1.01 mm/day and the lowest AME of 0.93 and 0.86 mm/day at Bougouni in the Sudanian semiarid climate zone (**Table 5**). It can be deducted that the Abtew ETo equation was revealed the best among the nine temperature ETo equations which obtained the best evaluation indices across the study area. Therefore, it

Table 5. Statistical indices summary for the reference evapotranspiration equations evaluation.

Indexes	Locations	Jensen-Haise	Hansen	Abtew	Christiansen	Dr-Al	Harg	Irmak	Tabari 1	Tabari 2	MME
RMSE (mm/day)	Bougouni	1.82	0.52	0.37	0.63	0.59	0.52	0.45	1.04	1.01	0.31
	Hombori	1.97	0.63	0.48	0.72	0.66	0.55	0.60	1.27	1.23	0.43
	Koutiala	1.75	0.72	0.44	0.85	0.57	0.50	0.63	1.29	1.27	0.44
	Mopti	1.65	1.05	0.60	1.17	0.61	0.65	0.97	1.66	1.69	0.72
	Nara	1.61	1.44	0.77	1.61	0.61	0.88	1.36	2.10	2.20	1.02
	Niono	1.74	1.06	0.60	1.21	0.67	0.62	0.99	1.70	1.71	0.72
	San	1.74	0.88	0.51	1.00	0.58	0.57	0.80	1.47	1.49	0.57
	Segou	1.65	1.09	0.57	1.26	0.65	0.63	0.99	1.71	1.69	0.74
	Senou	1.79	0.71	0.44	0.86	0.60	0.49	0.62	1.28	1.25	0.43
	Sikasso	1.71	0.61	0.37	0.71	0.58	0.49	0.54	1.13	1.12	0.38
	Tessalit	1.77	1.42	0.86	1.66	0.55	0.81	1.43	2.18	2.29	1.01
Average		1.74	0.92	0.56	1.06	0.61	0.61	0.85	1.53	1.54	0.62
RE (%)	Bougouni	37.60	10.74	7.66	13.04	12.16	10.78	9.28	21.43	20.87	6.31
	Hombori	35.82	11.45	8.77	13.06	11.91	9.92	10.96	23.03	22.36	7.84
	Koutiala	34.06	14.01	8.49	16.64	11.15	9.83	12.21	25.04	24.76	8.66
	Mopti	29.48	18.85	10.72	21.03	10.94	11.66	17.35	29.66	30.27	12.94
	Nara	26.29	23.54	12.48	26.31	9.89	14.30	22.13	34.30	35.85	16.56
	Niono	30.38	18.49	10.49	21.20	11.80	10.83	17.27	29.70	29.83	12.63
	San	32.18	16.27	9.46	18.56	10.81	10.61	14.79	27.18	27.69	10.65
	Segou	29.33	19.46	10.16	22.35	11.50	11.30	17.58	30.35	30.17	13.18
	Senou	34.78	13.74	8.64	16.66	11.69	9.61	12.05	24.98	24.33	8.43
	Sikasso	34.78	12.41	7.57	14.48	11.81	10.04	10.98	23.01	22.72	7.65
	Tessalit	28.29	22.73	13.70	26.49	8.81	12.93	22.80	34.80	36.61	16.19
Average		32.09	16.52	9.83	19.07	11.13	11.07	15.22	27.59	27.77	11.00
MBE (mm/day)	Bougouni	1.69	−0.30	−0.07	−0.36	−0.06	0.31	−0.21	−0.93	−0.85	-0.09
	Hombori	1.79	−0.48	−0.09	−0.58	−0.52	0.22	−0.52	−1.22	−1.18	-0.29
	Koutiala	1.58	−0.52	−0.08	−0.61	−0.09	0.13	−0.43	−1.17	−1.12	-0.26
	Mopti	1.31	−0.88	−0.13	−0.97	−0.30	−0.19	−0.82	−1.55	−1.55	-0.56
	Nara	1.11	−1.29	−0.18	−1.44	−0.28	−0.52	−1.24	−2.00	−2.07	-0.88
	Niono	1.42	−0.89	−0.13	−1.02	−0.41	−0.16	−0.85	−1.59	−1.57	0.58
	San	1.49	−0.68	0.10	−0.78	−0.18	0.00	−0.62	−1.35	−1.34	-0.40
	Segou	1.37	−0.90	−0.11	−1.03	−0.34	−0.18	−0.81	−1.58	−1.53	-0.57
	Senou	1.62	−0.51	−0.09	−0.61	−0.13	0.15	−0.42	−1.17	−1.10	-0.25
	Sikasso	1.58	−0.39	−0.07	−0.44	−0.11	0.22	−0.30	−1.01	−0.94	-0.16
	Tessalit	1.08	−1.34	−0.27	−1.48	−0.32	−0.56	−1.36	−2.09	−2.23	-0.95
Average		1.46	−0.75	−0.10	−0.85	−0.25	−0.05	−0.69	−1.42	−1.41	−0.35

Continued

AME (mm/day)	Bougouni	1.71	0.41	0.27	0.50	0.45	0.44	0.38	0.93	0.86	0.24
	Hombori	1.83	0.52	0.36	0.61	0.60	0.44	0.54	1.22	1.18	0.34
	Koutiala	1.60	0.59	0.32	0.70	0.44	0.41	0.52	1.17	1.12	0.36
	Mopti	1.41	0.92	0.46	1.02	0.48	0.53	0.85	1.55	1.55	0.62
	Nara	1.37	1.31	0.59	1.46	0.49	0.70	1.25	2.00	2.07	0.90
	Niono	1.50	0.93	0.46	1.06	0.54	0.50	0.88	1.59	1.58	0.63
	San	1.53	0.75	0.38	0.85	0.45	0.47	0.68	1.35	1.34	0.48
	Segou	1.45	0.95	0.43	1.08	0.52	0.50	0.86	1.58	1.54	0.63
	Senou	1.65	0.58	0.31	0.70	0.47	0.39	0.52	1.17	1.10	0.35
	Sikasso	1.60	0.49	0.27	0.57	0.45	0.40	0.44	1.01	0.95	0.30
	Tessalit	1.43	1.34	0.70	1.49	0.46	0.64	1.36	2.09	2.23	0.95
Average		1.55	0.80	0.41	0.91	0.48	0.49	0.75	1.42	1.41	0.53

could be used as the most adapted and specific ETo for the Sudanian, Sahelian, and Saharan climate in Mali. However, with 10% of RE, it should be adjusted to the Malian climate to improve its performance using proper calibration to the local conditions.

The results of this study showed better performance of the Hargreaves and Abtew under the semiarid and arid climate in Mali than under the Western Australian semiarid climate where [24] reported RMSE of 0.94 mm/day, MBE of −0.38 mm/day and RE of 17% for the Hargreaves equation while the Abtew equation induced 14% of relative error, RMSE of 1.014 mm/day and MBE of −0.4 mm/day. Contradictory, the Irmak's model performed well with the lowest value of MBE of 0.27 mm/day at Pantnagarin India among twenty ETo models [54]. The performance of Jensen-Haise equation at Tessalit is in agreement with [55] who reported large discrepancies when using this equation under extremely arid condition like the Saharan arid climate at Tessalit. Similar to the results of this study, the Jensen-Haise equation presented also the highest RMSE of 1.63 mm/day with a relative error over 40% in the State of Rio de Janeiro, Southeast of Brazil [56]. However, [57] reported that the Jensen-Haise equation was the best among 23 ETo methods evaluated under the extremely arid climate conditions in the central Saudi Arabia. Kingston *et al.* [58] reported the uncertainty of the Jensen-Haise that provided the highest estimate of ETo at 20˚N, but the lowest ETo between 50˚S - 60˚S and [59] reported that Hansen equation was one of the best two performing ones with the least average monthly error in Greece. While the Hargreaves equation showed overall good performance under the semiarid and arid climates in Mali similar to the results of [60] in eastern arid and semiarid regions of Iran, it overestimated ETo under humid climate in northeast Louisiana's [37]. Jensen–Haise model showed inaccurate estimation of ETo at California wit RMSD of 4.5 mm/day, and 2.36 mm/day at Bushland (Texas) and Davis (California), respectively, [19]. Under semiarid conditions in the Southern

Spain, the Hargreaves equation achieved large values of the MBE ranging from 0.74 to 1.13 mm/day and RMSE from 0.46 to 1.65 mm/day representing large maxima under- and overestimation of 24.5% and 22.5%, respectively [61]. Sabziparvar and Mirgaloybayat [61] reported good performance of Irmak equation with comparison to FAO-PM model at coastal sites in Iran with low altitude and high relative humidity.

3.3. Simple Multi-Model Ensemble (MME)

The simple multi-model ensembles (MME) achieved better performance than every single equation of the group of nine ETo equations (Figure 2 and Figure 3). The regression slope between FAO-PM ETo and MMEs ETO estimates varied from 0.858 to 0.979 with very high R^2 greater than 0.79 (Figure 3, Table 4). While the RMSE varied from 0.37 to 2.29 mm/day for all temperature methods, it ranged between 0.31 and 1.02 mm/day for the MMEs (Table 5). The MMES also achieved the lowest RE within the range of 6.3% - 16.2% while RE varied from 8.49 to 36.61 % for the group of the equations. The Abtew, Hargreaves and Droogers-Allen equations had performed better than the MMEs. The Jensen-Haise, Chriatiansen, Tabari 1 and Tabari 2 equations were revealed the worst compared the MMES (Table 5). Overall, the MMEs method improved the accuracy of the daily ETo estimation across Mali and could be used when a selection of some ETo equation should be used for Eto estimation under inaccurate and or limited data conditions. The MME method was successful applied by

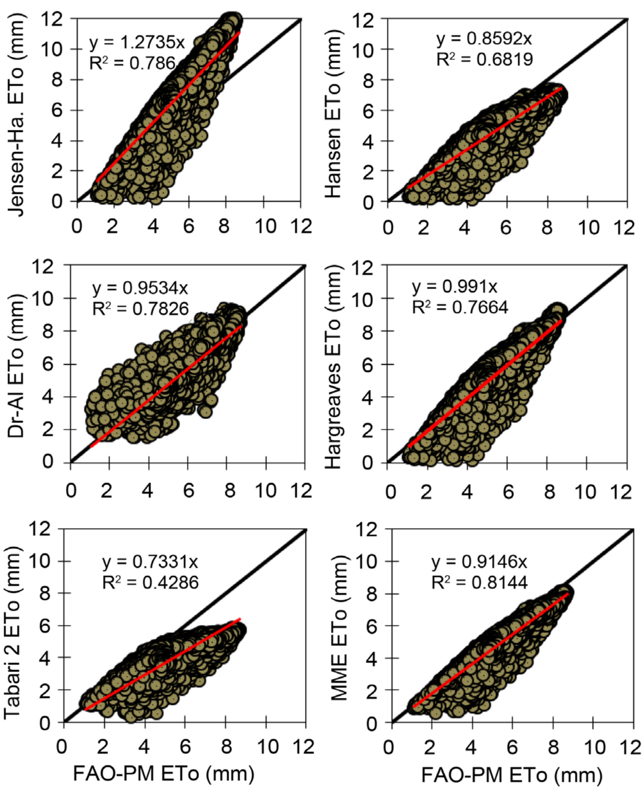

Figure 2. Relationship between the daily FAO-PM ETo estimates and the daily ETo computed by the ETo models under evaluation.

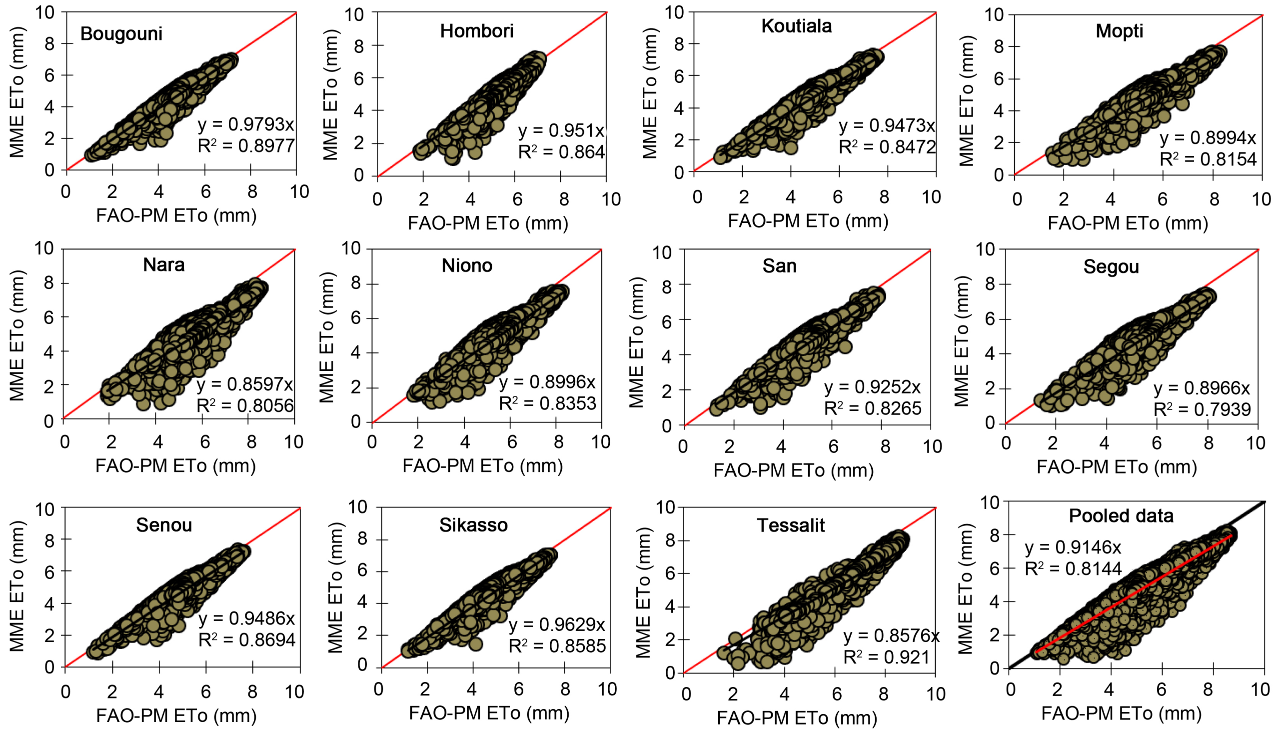

Figure 3. Relationship between the daily FAO-PM ETo estimates and the daily MME ETo estimates at all weather stations (1990-2012).

[62] and [63] who reported more than 10% reduction in model uncertainty under was achieved under MME when estimating irrigation water requirement through multi-model ensemble. Wang *et al.* [64] also reported the outperformance of the multiple models in a nowcast system for the monitoring of the current state of soil water.

3.4. Calibration and Validation of the Abtew Equation

The Abtew ETo equation was revealed the best among the selected equations with a regression slope between the FAO-PM ETo estimates and the original Abtew ETo of 0.9898 and high R^2 of 0.86 (**Figure 4(a)**) All weather stations combined, the simple linear regression between the daily FAO-PM ETo estimates and the calibrated Abtew ETo estimates for the 1990-2003 period is presented in **Figure 4(b)**. The regression showed the good fitness of the calibration with regression slope of 1.0035 close to unity and $R^2 = 0.89$ (**Figure 4(b)**). The validation of the calibrated Abtew equation is presented in **Figure 4(c)**. With a regression slope of almost unity (1.0288) and the R^2 equal to 0.92, the calibrated equation showed good performance and can be used for ETo estimation under the Sudanian, Sahelian, and Saharan climates in Mali. Further, the calibration process improved the RMSE of the ETo estimates from an average of 0.55 mm/day to 0.31 mm/day representing 41% improvement. The highest improvement of 63% by calibration was achieved at Tessalit while the lowest improvement of 30% was achieved at Sikasso (**Table 6**). The calibrated Abtew

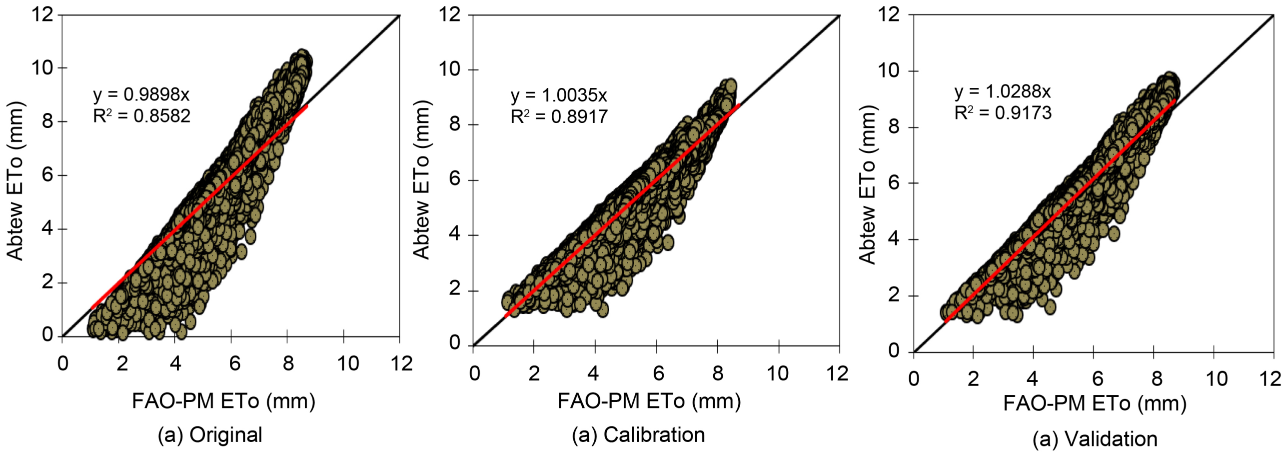

Figure 4. Relationship between (a) the original Abtew ETo estimates and the FAO-PM ETo estimates for the 1990-2012 period; (b) Calibrated Abtew ETo estimates and the FAO-PM ETo estimates for the 1990-2003.

Table 6. Improvement of the RMSE of the calibrated Abtew ETo equation.

Weather	RMSE (mm/day)		Improvement
stations	Original	Calibration	(%)
Bougouni	0.37	0.22	40.54
Hombori	0.48	0.24	50.00
Koutiala	0.44	0.29	34.63
Mopti	0.60	0.36	39.59
Nara	0.77	0.41	46.79
Niono	0.60	0.35	41.67
San	0.51	0.32	36.77
Segou	0.57	0.39	31.58
Senou	0.44	0.29	34.09
Sikasso	0.37	0.26	29.73
Tessalit	0.86	0.32	62.79
Average	0.55	0.31	40.74

equation performed as well during the calibration period as the validation period with the RMSE of the ETo estimated was 0.32 mm/day. The results of this study corroborated with the findings of [65] who reported that the Abtew model showed the best overall performance with respect to the data from all available climate stations of Central Greece, and [29] in Gansu Province, northwest China. Djaman *et al.* [5] reported the good fitness of the Abtew equation with FAO-PM equation under the semiarid climate in Tanzania and Kenya. Xu *et al.* [48] also have concluded that the simple Abtew equation can be used in the state of Vaud in Switzerland when other meteorological data except solar radiation are not available. The Calibrated Abtew equation to be used under the semiarid and arid climates in Mali climate is recommended for the study area.

4. Summary and Conclusion

The FAO-PM ETo equations using missing climatic data and nine temperature reference evapotranspiration methods were evaluated for their accuracy relative to FAO-PM equation under the Sudano-Sahelo-Saharan climate across Mali for the period of 1990-2012. The results showed that under limited data conditions, the FAO-PM equation showed good performance when solar radiation (Rs), relative humidity (RH), and wind speed (u2) are lacking solely and when both relative humidity and wind speed data are missing with RMSE varying lower than 0.58 mm/day and average relative error of 6.7%. The Abtew ETo equation that requires solar radiation and maximum temperature showed the best performance across all three climatic zones in Mali. The Jensen-Haise equation systematically overestimated ETo while the Tabari's two equations underestimated ETo. The Irmak, Hargreaves, Hansen, Christiansen performed relatively well in the study area. With 41% improvement of the performance of the best performing Abtew equation, a new form of the Abtew equation is recommended for ETo estimation across Mali and similar climatic conditions. Also in the case of non-available u2 and RH data, the simplified forms of the FAO-PM equation is recommended for use for reasonable ETo estimation across Mali.

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