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Modified Hargreaves' Method as an Alternative to the Penman-monteith Method in the Kingdom of Saudi Arabia

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Abstract: Due to the lack of standard Agro-climatic Weather Stations (AWS) in Saudi Arabia, simple conversion formulas were derived to find the average daily ET_o value per month for 29 weather stations. The Hargreaves (HRG) formula was used instead of the Penman-Monteith formula due to the ease of calculation of HRG formula, as it almost require only temperature. For each station, two formulas were derived considering both standard and non-standard AWS. Results show very good statistical representation of the formulas, with average root mean squared deviations of 0.73 and 0.57 and the mean percent errors of 1.22%, and 1.12% while considering the standard and non-standard AWS, respectively. Results also confirm the importance of temperature correction when using data from non-standard AWS, especially for the stations in the Middle to Midwest region (e.g. Arriadh, AlQassim, and Almadina); where the errors of using non-standard AWS data may be up to +24% of the correct ET_o value, which results in a massive waste of water.

Key words: Evapotranspiration; Weather stations; Hargreaves; Penman Monteith; Temperature correction.

INTRODUCTION

Estimation of reference evapotranspiration (ET_o) is important for several hydrological and agricultural sciences, like water resources management, crop-water requirements, irrigation scheduling, and land use planning.(Mardikis *et al*., 2005; and Trajkovic and Gocic, 2010,). Though, a good amount of research is done by the scientists to estimate the ET_o accurately, especially for the sensitive fields like irrigation scheduling (Trajkovic, 2007). Due to its comprehensive theoretical base, The Penman–Monteith method (PM) method is recommended by the United Nations Food and Agricultural Organisation (FAO) as the sole method to calculate (ETo) and for evaluating other ET_o calculation methods as well (Allen *et al*., 1998; and Khoob, 2008). The FAO approach to calculate ETo using the PM method was published in the FAO irrigation and drainage paper number 56, hence abbreviated as FAO-56 method. The FAO-56 PM requires measurements of air temperature, relative humidity, solar radiation, and wind speed. The FAO-56 PM equation is expressed as follows (Allen *et al*., 1998):

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \dfrac{900}{T_a + 273}\gamma U_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \quad (1)$$

Where ET_o: reference evapotranspiration [mm day^{-1}]; R_n: net radiation at the crop surface [MJ m^{-2} day^{-1}]; G: soil heat flux density [MJ m^{-2} day^{-1}]; T_a: mean daily air temperature [°C]; U_2: wind speed at 2 m height [m s^{-1}]; (e_s- e_a): vapor pressure deficit [kPa]; e_s: saturation vapor pressure [kPa]; e_a: actual vapor pressure [kPa].; e_s: slope vapor pressure curve [kPa °C^{-1}]; γ: psychrometric constant [kPa °C^{-1}]. The formulas of the equation's parameters are detailed at Allen *et al*., (1998), chapters 2 and 3. Nonetheless, the FAO-56 method requires climatic data from standard weather stations. Standard FAO56 weather stations are stations having "a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation" (ASCE-EWRI,

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2005). Allen (1996) reported that data gathered from non-standard weather station should be adjusted before using it in ET_o calculation. He suggested a method for this data-adjustment especially for temperature. On the other hand, Jia *et al*., (2007) concluded that non-standard weather stations yield to non-significant bias from the correct ET_o value, except under high wind speed conditions where the bias is significant.

In fact, the number of weather stations where there are reliable data for these parameters are limited (Trajkovic, 2007) especially for Middle-Eastern and developing countries (ElNesr, and Alazba. 2010).

Hargreaves (1975) developed a temperature-based formula to find the ET_o, as

$ET_o = 0.0135 \cdot R_s \cdot (T_a + 17.8)$, where *Rs*: the global solar radiation [same units as ET_o], T_a: the average temperature [◦c]. This formula was evaluated over time especially after Hargreaves (1981) and Hargreaves and Samani (1982) formula for estimating Rs from the temperature range (*TR*) and the extraterrestrial radiation (R_a); as,

$$R_s = k_r \cdot R_a \cdot TR^{0.5} \quad (2)$$

where k_r is an empirical coefficient depending on the station location (sometimes called coastality value). The last combined form of Hargreaves equation (HRG) is the Hargreaves and Samani (1985) formula, Eqn.(3), known as the Hargreaves-85 equation.

$$ET_o = 0.0135 \cdot R_s \cdot (T_a + 17.8) \quad (3)$$

Since the Hargreaves' formula requires very few climatic data than the PM-FAO56 method; it urges many investigators to test its reliability compared to PM method. Allen *et al*., (1998); and Sau *et al*., (2000) concluded the importance of local calibration of the HRG to ensure reliable data. Lee, (2010) found that the HRG formula provides excellent results for the Korea Peninsula after local calibration. So did Jamshidi *et al*., (2010) for different climates in Iran. Amatya *et al*., (1995) and Trajkovic, (2007) reported that in humid regions; HRG provides an overestimate to the PM values. Martínez-Cob and Tejero-Juste (2004) found that the Hargreaves method overestimated ET_o at stations with wind speeds less than 2 m/s in Spain. Gavilán *et al*., (2006) reported similar results for inland locations with low wind speeds and large daily temperature ranges, and for coastal locations with high wind speeds and small daily temperature ranges. On the other hand, for semiarid environment, the HRG method was found to underestimate the PM values in most stations of Iran (Khoob, 2008), Turkey (Benli *et al*., 2010), Australia (Azhar and Perera, 2010), and Jordan (Weiß and Menzel, 2008).

For hyper-arid regions, the HRG equation also underestimates the ET_o values for Saudi Arabia as reported by Al-Sha'lan and Salih, (1987); Salihand and Sendil, (1984); and Alazba (2004). Hence, the objectives of this paper were: 1. to investigate whether the ET_o values calculated by PM method are affected significantly by Allen (1996) temperature adjustments or not, and 2. To adjust the Hargreaves equation's parameters to use it in prediction of the the actual ET_o values from non-standard weather stations, for all zones of the Kingdom of Saudi Arabia.

MATERIAL AND METHODS

Data Used:

The most reliable weather dataset in the Saudi Arabia is the database of the Presidency of Meteorology and Environment (PME) in KSA, the official climate agency in the country. Weather stations are equipped with up-to-date monitoring devices and are subjected to regular inspection and replacement for defected devices (personal communication with the PME). This Database represents daily values of 29 meteorological stations distributed spatially over the 13 districts and temporally over a time span since 1980 to the end of 2010 for most of the stations. Details about the weather stations and associated parameters are presented in Table 1. All the PME stations are located inside airports for aviation information services; hence these stations are not standard FAO-56 weather stations, and accordingly Allen (1996) corrections of temperature were applied. The recorded climatic factors for all stations are dry bulb and wet bulb temperatures (max., min., and avg.), relative humidity (max., min., and avg.), rainfall, wind speed (average), wind direction, atmospheric pressure (sea and station levels), the cloud cover, and the actual vapor pressure. Most of the listed factors were used to find the FAO-56 ETo values.

Table 1: Kingdom of Saudi Arabia weather stations and their properties.

Station		Station Location						
ID	Name	Latitude deg. N.	Longitude deg. East	Altitude m	Coastal / Interior	Logged Years	Average Temperature°C	Coastalityvalue (kr)*
St:01	A'Dhahran	26.16	50.1	17	Coastal	30	26.48 ± 7.49	0.184
St:02	Abha	18.14	42.39	2093	Interior	30	18.60 ± 3.72	0.171
St:03	Ad Dammam	26.42	50.12	1	Coastal	10	26.72 ± 7.86	0.179
St:04	Al Ahsa	25.3	49.48	179	Interior	25	27.26 ± 8.27	0.173
St:05	Al Baha	20.3	41.63	1652	Interior	25	22.83 ± 4.92	0.178
St:06	AlJouf	29.47	40.06	671	Interior	30	22.03 ± 8.61	0.177
St:07	AlMadina	24.33	39.42	636	Interior	30	28.45 ± 7.00	0.178
St:08	AlQaisumah	28.32	46.13	358	Interior	30	25.23 ± 9.28	0.173
St:09	AlQassim	26.18	43.46	650	Interior	30	24.94 ± 8.26	0.166
St:10	AlQuraiat	31.5	37.5	560	Interior	5	20.04 ± 7.91	0.167
St:11	AlWajh	26.12	36.28	21	Coastal	30	25.00 ± 3.98	0.216
St:12	Arar	31	41	600	Interior	30	22.01 ± 9.17	0.173
St:13	ArRiyadh Middle	24.63	46.77	624	Interior	30	26.66 ± 8.10	0.181
St:14	ArRiyadh North	24.42	46.44	611	Interior	25	25.80 ± 8.12	0.167
St:15	AtTa'if	21.29	40.33	1454	Interior	30	22.92 ± 5.12	0.172
St:16	Bisha	19.59	42.37	1163	Interior	30	25.69 ± 5.40	0.158
St:17	Gizan	16.54	42.35	3	Coastal	30	30.22 ± 2.80	0.209
St:18	Hafr El-Batin	28.2	46.07	360	Interior	20	25.26 ± 9.21	0.172
St:19	Hail	27.26	41.41	1013	Interior	30	22.47 ± 8.20	0.172
St:20	Jeddah	21.3	39.12	17	Coastal	30	28.23 ± 3.50	0.197
St:21	Khamis Mushait	18.18	42.48	2057	Interior	30	19.49 ± 3.75	0.168
St:22	Makkah	21.4	39.85	213	Interior	25	30.78 ± 4.57	0.179
St:23	Najran	17.37	44.26	1210	Interior	30	25.51 ± 5.54	0.166
St:24	Rafha	29.38	43.29	447	Interior	30	23.33 ± 9.05	0.169
St:25	Sharurrah	17.47	47.11	725	Interior	25	28.57 ± 5.81	0.168
St:26	Tabuk	28.22	36.38	776	Interior	30	21.99 ± 7.53	0.170
St:27	Turaif	31.41	38.4	818	Interior	30	19.06 ± 8.27	0.173
St:28	Wadi Al Dawasir	20.5	45.16	652	Interior	25	28.15 ± 7.01	0.168
St:29	Yenbo	24.09	38.04	6	Coastal	30	27.56 ± 4.72	0.184

* The coastality value data were gathered from El-Nesr *et al.*, (2011)

Procedure:

To calculate the reference evapotranspiration values according to FAO-56 PM method, the following procedure was followed. First, the shortwave radiation was calculated according to Eqn. (2). The actual coastality values (k_r) for each station were taken from ElNesr *et al.*, (2011) as listed in Table 1, and the R_a value is calculated as shown in the appendix, Eqn. (7). Next, the rest of the parameters of Eqn. (1) were calculated using the procedures detailed in Allen *et al.*, (1998) and briefed in ElNesr and Alazba (2010). Calculations were performed for daily basis then averaged to monthly basis.

The FAO-56 PM ET_o values were recalculated after applying Allen (1996) temperature corrections by the procedure mentioned in the following steps:

1. Calculating the dew point temperature, $T_d = \frac{116.91 + 237.3\ln(e_a)}{16.78 - \ln(e_a)}$, where e_a: the actual vapor pressure $e_a = 0.005\left(RH_x e_o[T_n] + RH_n e_o[T_x]\right)$; T_n : minimum air temperature [°C]; T_x: maximum air temperature [°C]; RH_x: maximum relative humidity [%]; RH_n: minimum relative humidity [%]; $e_o[T]$: the saturation vapor pressure, and $e_o[T] = 0.611 \cdot \exp\left(17.27\,T / (T + 237.3)\right)$

2. Computing the value of $\Delta T = T_n - T_d$

3. For arid and semi - arid environments, If Δ T > 2 then maximum temperature adjustment, $T_x^{\{corr\}} = T_x - 0.5(\Delta T - 2)$, where {corr} stands for 'corrected' value. Then doing the same for T_n. It important to consider that if Δ T ≤ 2, then no correction was needed. After applying the temperature corrections, the ET_o was recalculated, and named $ET_o^{\{corr\}}$.

The third ET_o calculation method in comparison is the HRG method, where the R_s value was calculated from Eqn. (2) followed by the ET_o calculation from Eqn. (3). Like the two previous methods, monthly ET_o values were calculated as the average of the daily calculated values.

The ET_o values calculated by HRG method were fitted to the values of both uncorrected and corrected PM values through simple linear model ($y=\alpha+bx$) to find a best fit for each station.

The resultant Hargreaves equation was compared to the original corrected and uncorrected PM values and the prediction precision was tested through statistical indices like the root mean squared deviation (RMSD), it's coefficient of variation ($RMSD_{CV}$), and the mean percent error (MPE). Equations 5 and 6 were used to calculate the RMSD and MPE.

$$\mathrm{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(F_i - A_i\right)^2} \tag{4}$$

$$\mathrm{MPE} = \frac{100}{n}\sum_{i=1}^{n}\frac{\left(F_i - A_i\right)}{A_i} \tag{6}$$

Where '*F' and* '*A*': the forecasted (estimated) and the actual (measured) values respectively; *n*: number of readings; *i*: counter.

RESULTS AND DISCUSSION

The average monthly values of PM for each station were calculated by the three mentioned methods ($PM^{\{norm\}}$, $PM^{\{Corr\}}$, and HRG methods) as illustrated in Fig. 1. The HRG method seemed to underestimate the $PM^{\{norm\}}$ method for almost all the 29 studied stations except 2 stations namely Makkah, and Gizan, in addition to AlWajh station in some months. In Makkah, HRG method overestimated the $PM^{\{norm\}}$ and $PM^{\{Corr\}}$ in all months. Makkah city has special climate (steady hot all the year), and special topography (very rugged mountains and valleys), and even special demographic nature (due to its religious characteristics, it is always occupied by pilgrims and visitors). These special circumstances render this arid city a humid-like city, as reported by ElNesr *et al*., (2011). In humid locations, HRG method always overestimates PM as discussed earlier. For similar reason, Gizan, the semi-island, behaved like humid location and the overestimation occurred. In AlWajh station, HRG method overestimated the $PM^{\{norm\}}$ in summer months (June, July, August, and September) while its underestimation occurred for the rest of the year. This could be due to the weather effects for its coastal location at the top-north of the kingdom's shore on the Red Sea and exposure to the Mediterranean Sea's weather effects as well.

For somewhat simpler explanation, Fig. 2 illustrates the annual averages of ET_o calculated by the three methods for the 29 stations. The overestimation in Gizan and Makkah is clear in Fig. 2, while the partial overestimation appeared for AlWajh station. It appears that Abha station has the least ET_o in all over the kingdom with an average annual value of 4.73 mm/d. This low value of ET_o, however, was due to the cold weather of the region due to its high altitude (2093 m above sea level, Table 1). The maximum average annual ET_o, 8.43 mm/d, was found for Sharurrah station which is the nearest urban zone to the Empty Quarter region (Rub' al Khali). The Empty Quarter region is one of the largest hyper-arid sanddesertsin the world with very high temperatures of about 47°C in normal days and up to 60°C during July and August (Smith, 2001; and Vincent, 2008).

For all of the stations except Gizan and Makkah, HRG method resulted the least ET_o value followed by the $PM^{\{Corr\}}$ and the $PM^{\{norm\}}$ methods. This could mean that ET_o values from non-standard weather stations were always overestimated if calculated from standard AWSs. This could be attributed to the temperature drop in the standard weather stations due to the surrounding vegetation cover. In some stations, however, the overestimating ratio (error) was small, like in Gizan, AlWajh, and Jeddah; where the error was around 5% (Table 2). Table 2 summarizes the error values with eight stations below 10%, between 10 and 15% for similar number of stations, between 15% and 20% for eight stations, and five stations having more than 20% error. The importance of knowing these values was to think twice when dealing with uncorrected values of PM ET_o in the stations with huge errors, especially for the top five stations of AlJouf, ArRiyadh North, AlQassim, AlMadina, and ArRiadh Middle having error values of 20.95%, 21.46%, 22.27%, 23.27%, and 23.96%, respectively.

In fact, these zones are occupied by massive agricultural projects in addition to "Wadi Al Dawasir" and unfortunately some of these agricultural projects probably use the non-standard weather data to calculate ET_o resulting up to 25% increase in water usage. This situation clearly demonstrates the importance of using standard weather stations' data in ET_o calculation especially in these areas, or to use the suggested correction formulas when the $PM^{\{norm\}}$ is calculated from non-standard weather stations (Table 3).

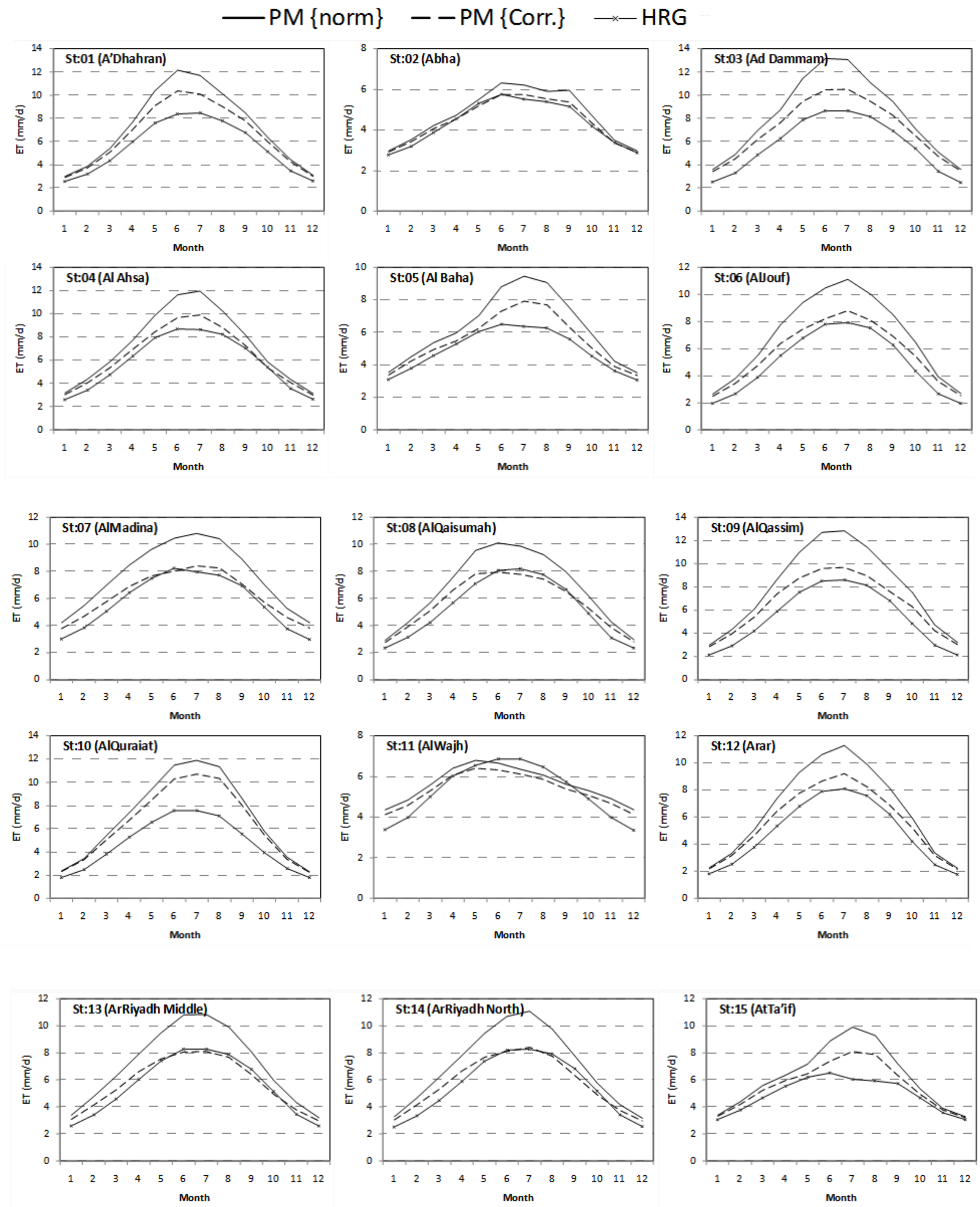

Fig. 1. (*...continued*)

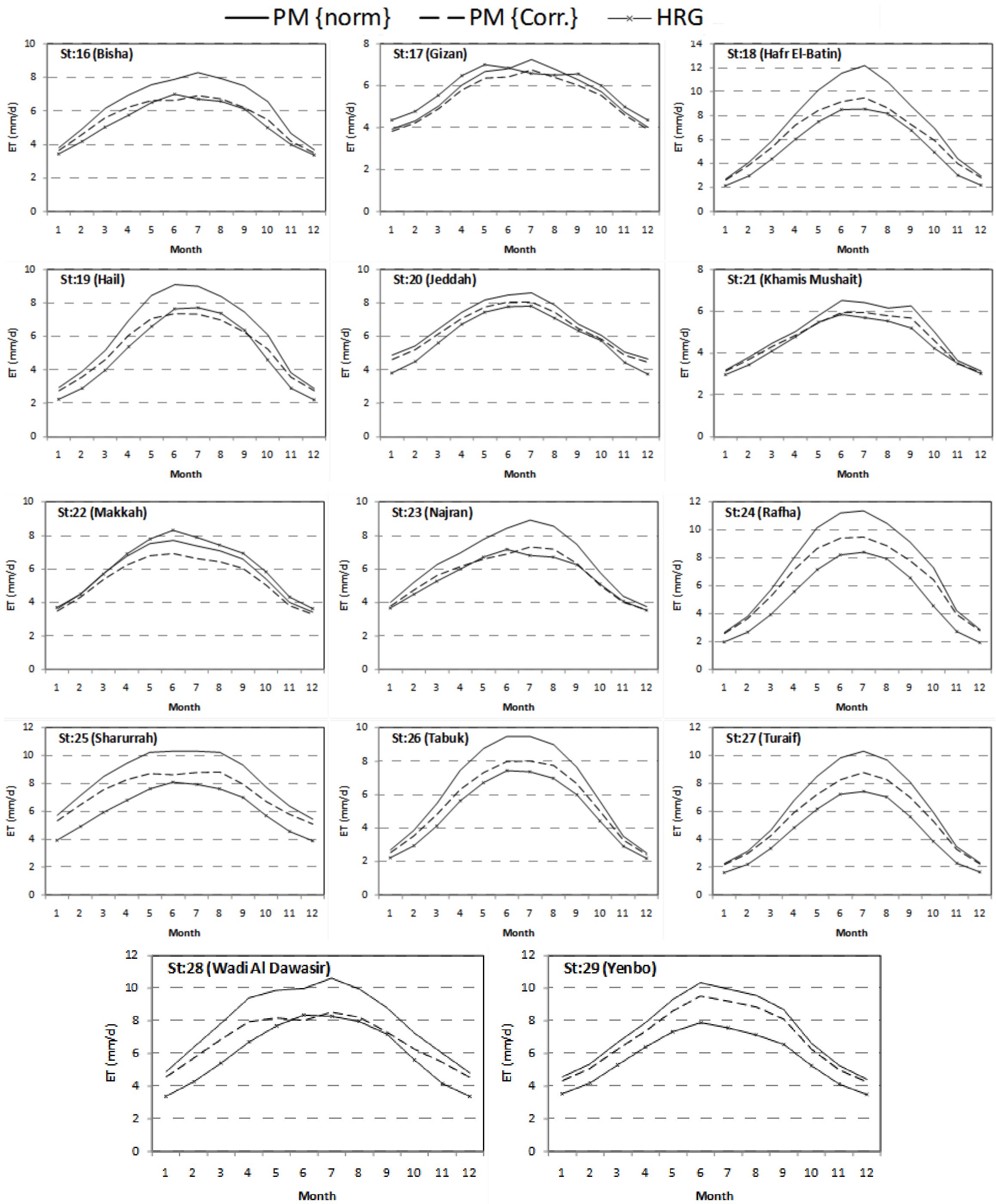

Fig. 1: Monthly ET_o values of the studied stations, calculated by methods of PM$^{\{norm\}}$,PM$^{\{Corr\}}$, and HRG.

For most of the small to medium size projects' landowners and agronomists in the KSA, it is not easy to compute the ET_o by PM equation, however, HRG equation requires less parameters, and minimum efforts to calculate the ET_o. The HRG equation, however, underestimates the PM value in most regions in the kingdom and hence the correction formulas suggested by Allen *et al*., (1998) were derived for all of the studied stations (Table 4). Because of the different scenarios in the agricultural projects, two formulas were derived for each station, one for each scenario. The first scenario's formula is applied when the climatic data (which is used to calculate HRG value) was obtained from the standard AWS. In this case, both PM and HRG were calculated without temperature correction, so HRG value can easily be calculated, and the corresponding PM value was computed through the related formula in Table 4. On the other hand, the second scenario's formula is applied when the climatic data was obtained from non-standard AWS, so the HRG value was calculated by un-corrected data but the resulting PM value is corrected to the standard conditions.

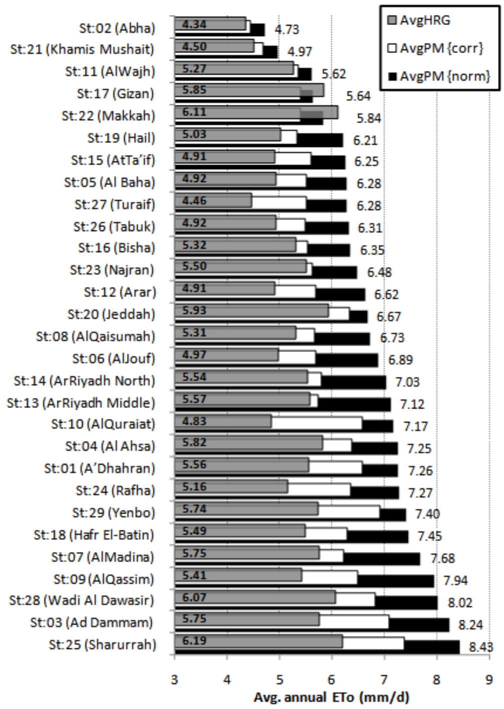

Fig. 2: Average annual ET_o (mm/d)for the studied stations sorted ascending from top to bottom. Numbers outside series indicate $PM^{\{norm\}}$ values, while numbers inside series indicate HRG values.

Table 2: Percent of error between the corrected ETo value and the normal ETo value.

Station	Error %
St:17 (Gizan)	4.36
St:11 (AlWajh)	5.01
St:20 (Jeddah)	5.24
St:21 (Khamis Mushait)	6.19
St:02 (Abha)	6.37
St:29 (Yenbo)	7.01
St:22 (Makkah)	8.23
St:10 (AlQuraiat)	8.86
St:01 (A'Dhahran)	10.53
St:15 (AtTa'if)	11.75
St:04 (Al Ahsa)	13.78
St:05 (Al Baha)	13.83
St:27 (Turaif)	14.28
St:25 (Sharurrah)	14.34
St:24 (Rafha)	14.41
St:16 (Bisha)	14.62
St:26 (Tabuk)	15.09
St:23 (Najran)	15.38
St:03 (Ad Dammam)	16.12
St:12 (Arar)	16.37
St:19 (Hail)	16.77
St:28 (Wadi Al Dawasir)	17.50
St:18 (Hafr El-Batin)	18.35
St:08 (AlQaisumah)	18.77
St:06 (AlJouf)	20.95
St:14 (ArRiyadh North)	21.46
St:09 (AlQassim)	22.27
St:07 (AlMadina)	23.27
St:13 (ArRiyadh Middle)	23.96

Table 3: Calculation formulas of PM {Corr} when the PM{norm} is known.

Station	Formula	r^2
St:01 (A'Dhahran)	PM {cor} = 0.821 × PM {norm} + 0.610	0.995
St:02 (Abha)	PM {cor} = 0.851 × PM {norm} + 0.420	0.989
St:03 (Ad Dammam)	PM {cor} = 0.744 × PM {norm} + 0.964	0.990
St:04 (Al Ahsa)	PM {cor} = 0.781 × PM {norm} + 0.713	0.993
St:05 (Al Baha)	PM {cor} = 0.758 × PM {norm} + 0.758	0.987
St:06 (AlJouf)	PM {cor} = 0.734 × PM {norm} + 0.639	0.994
St:07 (AlMadina)	PM {cor} = 0.701 × PM {norm} + 0.849	0.988
St:08 (AlQaisumah)	PM {cor} = 0.731 × PM {norm} + 0.748	0.977
St:09 (AlQassim)	PM {cor} = 0.689 × PM {norm} + 1.023	0.983
St:10 (AlQuraiat)	PM {cor} = 0.874 × PM {norm} + 0.319	0.995
St:11 (AlWajh)	PM {cor} = 0.925 × PM {norm} + 0.155	0.993
St:12 (Arar)	PM {cor} = 0.774 × PM {norm} + 0.566	0.990
St:13 (ArRiyadh Middle)	PM {cor} = 0.683 × PM {norm} + 0.879	0.985
St:14 (ArRiyadh North)	PM {cor} = 0.697 × PM {norm} + 0.886	0.983
St:15 (AtTa'if)	PM {cor} = 0.735 × PM {norm} + 0.997	0.978
St:16 (Bisha)	PM {cor} = 0.744 × PM {norm} + 0.815	0.977
St:17 (Gizan)	PM {cor} = 0.895 × PM {norm} + 0.357	0.996
St:18 (Hafr El-Batin)	PM {cor} = 0.736 × PM {norm} + 0.811	0.983
St:19 (Hail)	PM {cor} = 0.750 × PM {norm} + 0.663	0.988
St:20 (Jeddah)	PM {cor} = 0.919 × PM {norm} + 0.207	0.997
St:21 (Khamis Mushait)	PM {cor} = 0.858 × PM {norm} + 0.415	0.987
St:22 (Makkah)	PM {cor} = 0.850 × PM {norm} + 0.429	0.996
St:23 (Najran)	PM {cor} = 0.720 × PM {norm} + 0.954	0.955
St:24 (Rafha)	PM {cor} = 0.787 × PM {norm} + 0.633	0.993
St:25 (Sharurrah)	PM {cor} = 0.741 × PM {norm} + 1.125	0.956
St:26 (Tabuk)	PM {cor} = 0.797 × PM {norm} + 0.451	0.993
St:27 (Turaif)	PM {cor} = 0.798 × PM {norm} + 0.483	0.994
St:28 (Wadi Al Dawasir)	PM {cor} = 0.698 × PM {norm} + 1.227	0.962
St:29 (Yenbo)	PM {cor} = 0.889 × PM {norm} + 0.336	0.995

The coefficient of determination, r^2, for all stations in both scenarios was extremely high and encouraging i.e. an average value *of about* 0.92 with values ranging from 0.72 to 0.98. Only two stations, AlWajh and Sharurrah, had r^2 <0.80, nine stations had 0.80< r^2 <0.90, and eighteen stations with r^2>0.90. The calculated error measures (Table 5), however, indicate an acceptable precision of the derived formulas. The RMSD for 'scenario 1' ranged between 0.36 to 1.19, with an average value of 0.73, while it got better results for 'scenario 2' as it ranged from 0.28 to 0.86 with an average value of 0.56. These deviations are reasonable and acceptable, especially when taking into account the excellent MPE values that range from 0.11% to 3.02% with average value of 1.22% for 'scenario 1', and 0.03% to 2.75% with average value of 1.12% for 'scenario 2'.

To validate the formulas reliability, four stations were selected, one from each geographic zone; 'Tabuk' from the North, 'Arriadh-Middle' from the Middle, 'AlAhsa' from the east, and 'Jeddah' from the South-West. For each station, the measured vs. predicted values of PM ET_o were plotted, Fig. 3, for both of the studied scenarios. The graphs show the closeness of the points to the 45° line, with some bias for AlAhsa for ET_o values>12mm/d while the rest of the stations show very good representation of the efficiency for the predicted formulae. These good values of the validation indices (in Table 5) confirm the reliability of the presented formulae.

Table 4: Conversion formulas between HRG and PM values for the studied stations.

Stations	Scenario 1*		Scenario 2**.	
	Formula	r^2	Formula	r^2
St:01 (A'Dhahran)	PM {norm} = 1.450×HRG - 0.806	0.9482	PM {cor} = 1.203×HRG - 0.124	0.9643
St:02 (Abha)	PM {norm} = 1.144×HRG - 0.241	0.9192	PM {cor} = 0.988×HRG + 0.155	0.9349
St:03 (Ad Dammam)	PM {norm} = 1.449×HRG - 0.097	0.9496	PM {cor} = 1.097×HRG + 0.784	0.9730
St:04 (Al Ahsa)	PM {norm} = 1.313×HRG - 0.395	0.8603	PM {cor} = 1.041×HRG + 0.309	0.8815
St:05 (Al Baha)	PM {norm} = 1.559×HRG - 1.396	0.8538	PM {cor} = 1.200×HRG - 0.393	0.8696
St:06 (AlJouf)	PM {norm} = 1.335×HRG + 0.258	0.9552	PM {cor} = 0.979×HRG + 0.833	0.9473
St:07 (AlMadina)	PM {norm} = 1.226×HRG + 0.630	0.9253	PM {cor} = 0.853×HRG + 1.325	0.9013
St:08 (AlQaisumah)	PM {norm} = 1.183×HRG + 0.447	0.9172	PM {cor} = 0.857×HRG + 1.115	0.8799
St:09 (AlQassim)	PM {norm} = 1.419×HRG + 0.258	0.9163	PM {cor} = 0.994×HRG + 1.112	0.9318
St:10 (AlQuraiat)	PM {norm} = 1.631×HRG - 0.712	0.9748	PM {cor} = 1.431×HRG - 0.332	0.9778
St:11 (AlWajh)	PM {norm} = 0.637×HRG + 2.259	0.7167	PM {cor} = 0.616×HRG + 2.099	0.7790
St:12 (Arar)	PM {norm} = 1.376×HRG - 0.137	0.9553	PM {cor} = 1.065×HRG + 0.459	0.9460
St:13 (ArRiyadh Middle)	PM {norm} = 1.260×HRG + 0.099	0.9192	PM {cor} = 0.860×HRG + 0.948	0.9054

Table 4: Continue

St:14 (ArRiyadh North)	PM {norm} = 1.256×HRG + 0.082	0.9218	PM {cor} = 0.878×HRG + 0.927	0.9126
St:15 (AtTa'if)	PM {norm} = 1.661×HRG - 1.916	0.8247	PM {cor} = 1.269×HRG - 0.645	0.8704
St:16 (Bisha)	PM {norm} = 1.241×HRG - 0.252	0.8754	PM {cor} = 0.927×HRG + 0.608	0.8615
St:17 (Gizan)	PM {norm} = 1.110×HRG - 0.848	0.8618	PM {cor} = 1.011×HRG - 0.505	0.8885
St:18 (Hafr El-Batin)	PM {norm} = 1.346×HRG + 0.062	0.9324	PM {cor} = 0.992×HRG + 0.852	0.9178
St:19 (Hail)	PM {norm} = 1.109×HRG + 0.643	0.9111	PM {cor} = 0.832×HRG + 1.140	0.9026
St:20 (Jeddah)	PM {norm} = 0.945×HRG + 1.074	0.9089	PM {cor} = 0.877×HRG + 1.141	0.9245
St:21 (Khamis Mushait)	PM {norm} = 1.152×HRG - 0.221	0.8811	PM {cor} = 1.011×HRG + 0.129	0.9081
St:22 (Makkah)	PM {norm} = 0.906×HRG + 0.310	0.8822	PM {cor} = 0.765×HRG + 0.723	0.8676
St:23 (Najran)	PM {norm} = 1.314×HRG - 0.744	0.8290	PM {cor} = 0.949×HRG + 0.396	0.7988
St:24 (Rafha)	PM {norm} = 1.314×HRG + 0.492	0.9164	PM {cor} = 1.037×HRG + 1.005	0.9150
St:25 (Sharurrah)	PM {norm} = 1.175×HRG + 1.150	0.7623	PM {cor} = 0.885×HRG + 1.893	0.7516
St:26 (Tabuk)	PM {norm} = 1.321×HRG - 0.190	0.9703	PM {cor} = 1.057×HRG + 0.283	0.9695
St:27 (Turaif)	PM {norm} = 1.358×HRG + 0.220	0.9584	PM {cor} = 1.091×HRG + 0.628	0.9649
St:28 (Wadi Al Dawasir)	PM {norm} = 1.040×HRG + 1.708	0.8617	PM {cor} = 0.717×HRG + 2.471	0.8098
St:29 (Yenbo)	PM {norm} = 1.345×HRG - 0.316	0.9263	PM {cor} = 1.207×HRG - 0.012	0.9402

* Scenario 1: If HRG was calculated from Standard Agro-climatic Weather Stations (SAWS).

** Scenario 2: If HRG was calculated from Non-standard agro-climatic weather station.

Table 5: Models evaluation parameters of the defined scenarios.

Station	Tested on	Scenario 1*		Scenario 2*	
	. . . Months	RMSD	MPE	RMSD	MPE
St:01 (A'Dhahran)	368	0.743	-0.55%	0.508	-0.64%
St:02 (Abha)	369	0.368	-0.60%	0.283	-0.45%
St:03 (Ad Dammam)	131	0.759	-0.32%	0.416	-0.39%
St:04 (Al Ahsa)	307	1.193	-1.62%	0.861	-1.43%
St:05 (Al Baha)	306	0.817	-1.45%	0.589	-1.04%
St:06 (AlJouf)	368	0.644	-1.46%	0.514	-1.36%
St:07 (AlMadina)	368	0.666	-0.74%	0.539	-0.74%
St:08 (AlQaisumah)	369	0.775	-1.90%	0.690	-2.06%
St:09 (AlQassim)	368	1.039	-2.02%	0.652	-1.83%
St:10 (AlQuraiat)	67	0.554	-0.11%	0.456	-0.30%
St:11 (AlWajh)	367	0.518	-0.83%	0.424	-0.62%
St:12 (Arar)	367	0.692	-1.29%	0.592	-1.67%
St:13 (ArRiyadh Middle)	369	0.790	-1.31%	0.588	-1.37%
St:14 (ArRiyadh North)	308	0.779	-1.18%	0.579	-1.25%
St:15 (AtTa'if)	365	0.954	-1.35%	0.610	-0.89%
St:16 (Bisha)	368	0.599	-1.00%	0.475	-0.86%
St:17 (Gizan)	368	0.442	-0.54%	0.356	-0.40%
St:18 (Hafr El-Batin)	245	0.870	-1.73%	0.712	-1.87%
St:19 (Hail)	367	0.709	-1.81%	0.560	-1.61%
St:20 (Jeddah)	369	0.439	-0.44%	0.368	-0.35%
St:21 (Khamis Mushait)	367	0.450	-0.81%	0.342	-0.54%
St:22 (Makkah)	307	0.546	-1.00%	0.493	-0.97%
St:23 (Najran)	368	0.764	-1.31%	0.610	-1.19%
St:24 (Rafha)	365	0.950	-3.02%	0.756	-2.75%
St:25 (Sharurrah)	306	0.992	-1.48%	0.769	-1.17%
St:26 (Tabuk)	369	0.448	-0.95%	0.363	-0.86%
St:27 (Turaif)	367	0.609	-1.56%	0.448	-1.43%
St:28 (Wadi Al Dawasir)	306	0.770	-1.09%	0.643	-1.04%
St:29 (Yenbo)	369	0.602	-0.57%	0.483	-0.43%
Summary		0.730	-1.22%	0.557	-1.12%

* refer to Table 4 footnote for definitions

Conclusions:

In case of absence of non-standard AWS, it is recommended to use the temperature correction procedure suggested by Allen (1996) for calculating ET_o. A severe increase of ET_o values may reult (up to +24%), however, when considering the non-standard AWS. It is also recommended to use the suggested modified Hargreaves formulas instead of using the FAO56 PM method for small to middle size farms in the cases where the landowners are incapable to deal with FAO56 PM Method. It is also recommended to use the modified Hargreaves formulas when some of the important weather factors are missing like wind-speed and relative humidity. To make it easy, three types of formulas were introduced in this paper, 1- formulas to convert non-standard to standard PM value. 2- formulas to convert HRG value to PM value when the HRG values were calculated from non-standard AWS. 3- same as 2, but when HRG values were calculated from standard AWS.

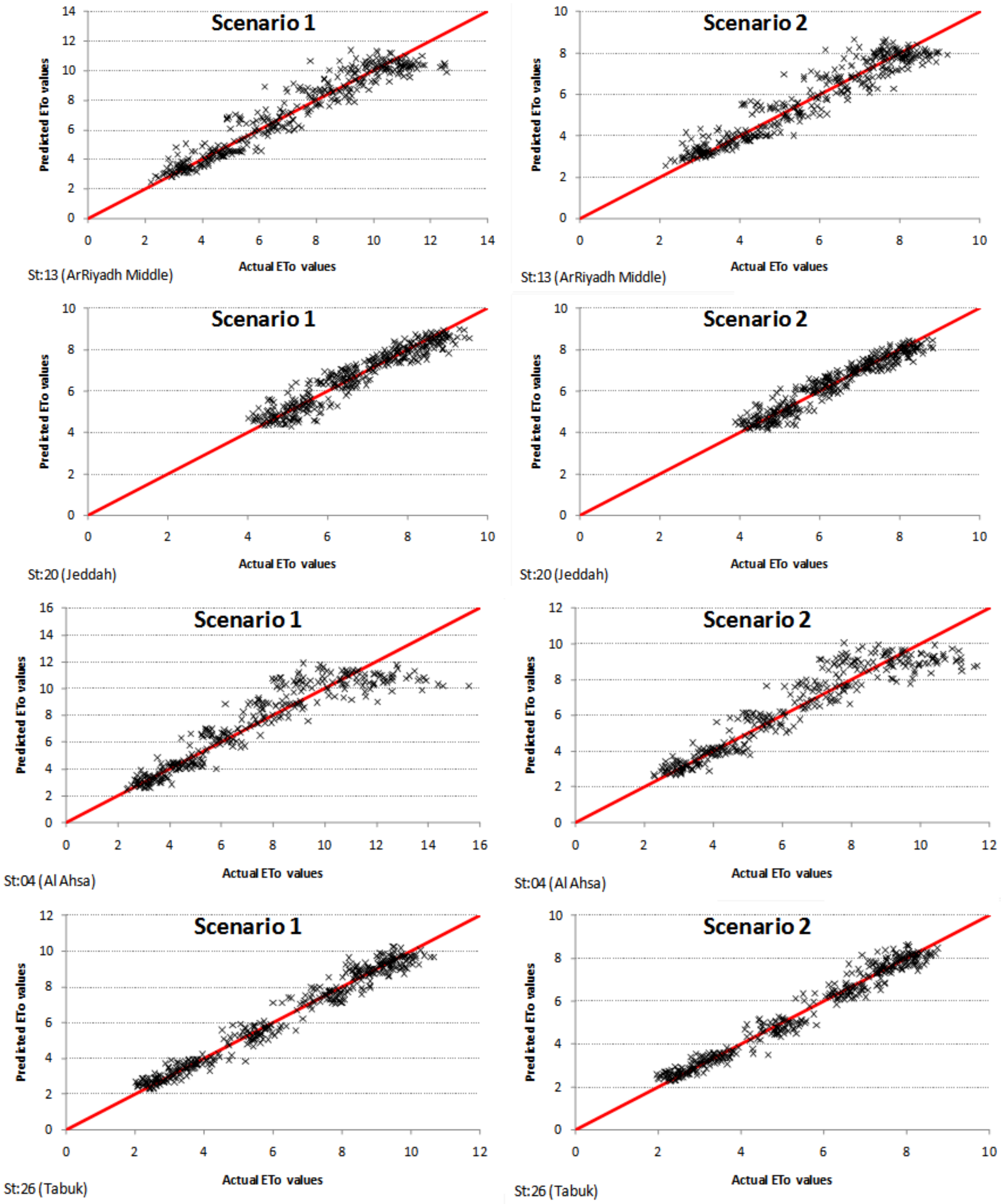

Fig. 3: Actual vs. Predicted values of ET_o for four of the studied stations in both scenarios.

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Appendix

The Extraterrestrial radiation R_a [MJ m^{-2} h^{-1}] is calculated as follows (Allen *et al.*, 1998)

$$R_a = 37.6\, d_r \left(\omega_s \sin\varphi \sin\delta + \sin\omega_s \cos\varphi \cos\delta\right) \tag{7}$$

Where d_r: relative distance Earth to Sun { $d_r = 1 + 0.033\cos\left(0.0172\, J\right)$ }, δ: solar declination [rad] { $\delta = 0.409\sin\left(0.0172J - 1.39\right)$}, φ: latitude [rad], ω_s: sunset hour angle [rad]. $\left\{\omega_s = \arccos\left(-\tan\varphi\tan\delta\right)\right\}$.

All properties depend on the Julian day number (J) which is calculated by the formula:

$J = \text{int}\left(\frac{275}{9}M + D - 30\right) \mapsto \text{if}\,(M > 2)\begin{pmatrix}\text{And LeapYear} \rightarrow \text{Subtract 1}\\ \text{AndNot LeapYear} \rightarrow \text{Subtract 2}\end{pmatrix}$ where M: month of the year, D: day of the month. Julian day ranges from 1 to 366 (in leap year).

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