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ESTIMATION OF EVAPOTRANSPIRATION USING STATISTICAL MODEL

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ABSTRACT

The model is valid to estimate evapotranspiration using some climatic variables such as solar radiation, relative humidity and air temperature. Correlations between evapotranspiration and some climatic variables were made to investigate direct and indirect effects of these variables on evapotranspiration. The climatic variables used in the study were air temperature, relative humidity, wind speed, sunshine hours, solar radiation and cloudiness. The results showed that while air temperature, sunshine hours and solar radiation had strong and positive correlation with evapotranspiration, relative humidity and cloudiness were negatively correlated. As for the direct effects of the climatic variables on evapotranspiration, solar radiation has the highest effect (P= 0.995) followed by relative humidity (P= 0.865), air temperature (P= 0.772), cloudiness (P= 0.250), sunshine hours (P= 0.165) and wind speed (P=-0.13) in descending order. The relative contribution of each climatic variable viz solar radiation, relative humidity, air temperature, cloudiness, sunshine hours and wind speed to evapotranspiration was respectivly 31.32, 27.23%, 24.30%, 7.87%, 5.19% and 4.09%. The relative contribution of major variables showing high direct effects i.e. solar radiation, relative humidity and air temperature was used in simultaneous equations

The low water potential value shown by Eq.[1] is suitable for upper Egypt. The high water potential value shown by Eq.[2] and optimal water potential value revealed by Eq.[3] are relevant to the Delta region.

The model was written in visual C^{++} language to be compatible with Windows 95. The model is fitted for predicting optimal water demand rates in new reclaimed land. Thus, a software package will help the decision-maker to have a prospective guideline for a water demand policy in Egypt.

Abbreviations: (ETo),Reference evapotranspiration; (ET), Evapotranspiration

1. INTRODUCTION

Water is released into the atmosphere by direct evaporation of solid and liquid water from soil and plant surfaces as well as by transpiration. Since each of these processes involve evaporation and is not easily distinguishable (Dale *et al.*, 2001), together they are called evapotranspiration (ET). ET was found to be differentially sensitive to climatic variables and to the time (month) of the year. It was most sensitive to solar radiation, air temperature and wind speed in order of decreasing sensitively (Smajstrla et al, 1987).

The daily course of transpiration rate showed a signal peak with a high value at midday and low values in the early morning and evening. Transpiration rate changed with plant development. It was obviously affected by relative humidity and air temperature (Peng *et al.* 1999).

ET is negatively correlated to relative humidity and cloudiness and positively to air temperature, wind speed, sunshine hours and solar radiation (Blindeman, 2000; Khanikar and Nath, 1998; Schmidt *et al.*, 1987).

Consumptive use (CU) includes water used in plant metabolism and direct evapotranspiration from soil and plant surfaces. Thus CU exceeds ET by the amount of water used for plant metabolism viz photosynthesis, transport of minerals, structural support, and growth. Since this difference is usually less than 1 percent, ET and CU are normally assumed to be equal (James, 1988). ET is the principal factor in determining irrigation water requirements, but losses in storage, conveyance and applying water, and the need for soil leaching are additional factors (Jensen, 1981). Irrigation water requirements was defined by Doorenbos and Pruitt (1977) as the depth of water needed to meet the water losses and crop ET in large fields. Determination of water requirement and consumptive use for Egyptian crops are important especially when a large area is to be brought under irrigation through various land reclamation projects viz. Toshky and El-Salam canal projects, which will reduce the limited water resources further. The main resource of water in Egypt is the Nile. Egypt's share from the Nile water is 55.5 billion m^3 a^{-1}. Other resources such as ground water and drainage water contribute 3.1 billion m^3 and 4.7 billion m^3 a^{-1} respectively, while rainfall in Egypt is scarce and varies from 100-200 mm a^{-1} in the North coastal area (Abd El-Hafez and El-Mowelhi, 2000). El-Gibali and Badawi (1978) estimated water consumptive use in Egypt to be 24 billion m^3 a^{-1} and water requirements was 44 billion m^3 a^{-1} using the Blany and Criddle formulae. Total water requirements under the present crop pattern stands at 24.151 billion m^3 a^{-1} for the main field crops, and may be 26.95 billion m^3 a^{-1} for all crops, while current usage of irrigation water by the agriculture sector accounts to about 49.7 billion m^3 a^{-1} (El-Mowelhi and Abou-Baker, 1995). Estimated water requirement values for the new lands in Egypt using three ET methods (Doorenbos-Pruitt, Modified Penman and Penman Monteith) were 5.686, 4.521 and 3.711 billion m^3 a^{-1} under surface, sprinkler and drip irrigation systems, respectively (Eid et al 1999). Ainer et al, (1999) found that seasonal water consumptive use by cropland amounted to 29.9 billion m^3 a^{-1} using the Penman Monteith method, and the total irrigation requirements were found to be 52.0, 43.9 and 39.2 billion m^3 a^{-1} under surface, sprinkler and drip irrigation systems, respectively. El-Marsafawy and Eid, (1999) found that total consumptive use in the Nile Valley and Delta regions amounted to about 26.9 billion m^3 a^{-1} resulting from cultivated area totaling about 5.04 million hectares in the year 1996, using the average values of four formulae i.e. Modified Penman, Penman Monteith, Doorenbos-Pruitt and Evaporation Pan. There are specific formulae that are more used than the others, i.e. Modified Penman, Penman Monteith, Doorenbos-Pruitt, Evaporation Pan, Blaney-Criddle and the radiation and the first four formulae gave ET crop estimation values close to the actual ET under Egyptian climatic conditions. The calculated reference crop ET can be used to estimate actual ET by using coefficients to account for the effect of soil moisture status, stage of growth and maturity of a crop. Crop ET can also be estimated using a coefficient that relates crop ET to evaporation as measured with pans (Pruitt, 1966; Doorenbos and Pruitt, 1977).

Many methods of estimating ET have been proposed. The methods may be broadly classified as those based on combination theory, humidity data, radiation data, temperature data, and miscellaneous methods which usually involve multiple correlations of ET and various climatic data (Jensen 1981).

Path analysis have been used to identify important yield components in various crops including rice (Oryza sativa L.; Gravois and McNew, 1993), wheat (Triticum aestivum L.; Costa and Kronstad,1994) and soybean (Shukla *et al.*,1999). It is also used to partition the relative contribution of yield components via standardized partial-regression coefficients. The correlation coefficients can be separated into the direct and indirect influences that one variable has on another (Ball *et al.*2001).

In this study, path analysis provides a framework for identifying significant climatic variables for evapotranspiration.

2. MATERIALS AND METHODS

The last 7 years data commencing from 1973 to 1980 on ET of sugarcane crop *Saccharum officinarum* (Ministry of Water Resources and Irrigation, 1981) and 20 years data (1961-1980) of Egyptian Agroclimatology (El-Marsafawy and Eid, 1999) were utilized to study the effect of climatic variables on evapotranspiration by using some climatic variables and path coefficient analysis. Data of climate were collected from 28 agroclimatological stations. Variables of climate under study were air temperature (^{o}c), relative humidity (%), wind speed (km d^{-1}), sunshine (h), solar radiation (cal cm^{-2} d^{-1}) and cloudiness. Correlations between climatic variables on the one hand and evapotranspiration of sugarcane on the other were calculated according to Cochran and Cox (1957). The path coefficient analysis was calculated according to Wright,(1921) to interpret the influence of direct and indirect effects of each variable on evapotranspiration. The path coefficient analysis was done with and without wind speed to study the effect of the wind speed variable on direct and indirect effects of climatic variables and its influence on evapotranspiration. Then, the average direct effect for each variable involved resulting from the path analysis was used for calculation of relative contributions according to Li, (1956). The relative contribution of major variables showing direct effects was used in Eq.[1], then Eq.[1] was multiplied by the experimental constant (1.64) to obtain Eq.[2]. The experimental constant was derived by averaging the range (1.35 to 1.92) reported by Ainer et al, (1999), El-Marsafawy et al, (1999), Eid et al, (1999), El-Mowelhi and Abuo-Baker, (1995) and El-Gibali and Badawi, (1978). This experimental constant represents the overall ratio of water requirements (water losses and ET of crop, Doorenbos and Pruitt,

1977) to ET of crop, (James, 1988) under Egyptian conditions. This ratio suggests the highest evapotranspiration in Egypt. Eq.[3] was calculated averaging Eq.[1] and Eq.[2].

The first equation was calculated as follows:

$$\mathbf{Et_{o1}} = \frac{Sr(RCsr).T(RCt)}{Rh(RCrh)} \quad \textbf{[1]}$$

where $\mathbf{Et_{o1}}$ is reference evapotranspiration in mm d^{-1}, S_r is solar radiation in mm^{-1} = $(\frac{cal\ cm - 2\ d - 1}{585} x10)$ (Jemes, 1988), RC_{sr} is relative contribution of solar radiation =0.3132 (Table 3), T is air temperature (^{o}c) multiplied by its coefficient = $(\frac{Max.. \quad Min.}{2}) x0.025 \quad 0.08$ (El-Shafei, 1972), RC_t is relative contribution of air temperature =0.2430 (Table 3), R_h is relative humidity (%), RC_{rh} is relative contribution of relative humidity =0.2723 (Table 3).

The second equation was calculated as follows:

$$\mathbf{ET_{o2} = ET_{o1}\ X\ E_c} \quad \textbf{[2]}$$

where E_c is the experimental constant = 1.64

The third equation was calculated as follows:

$$\mathbf{Et_{o3}} = \frac{(ET_{o}1 \quad ET_{o}2)}{2} \quad \textbf{[3]}$$

The reference evapotranspiration methods (ET_o) used to test and evaluate simultaneous equations were Penman-Monteith and Doornbos-Pruitt (Doornbos and Pruitt 1977).

2.1. Program description

ET_o program,which is derivative of Eq.[1], Eq.[2] and Eq.[3], is written in visual C^{++} language, Windows 95 compatible, and will fit on a 3.5-in disk. Copies of ET_o are registered by the Egyptian Cabinet, Egypt. The registration No. is 823/8 and can be purchased for a modest fee by contacting Dr.A. Z. El-Bably, Dep. of Water Requirements and Field Irrigation, Agric. Res. Center, Sakha, Kafr El Sheikh, Egypt.

3. RESULTS AND DISCUSSION

3.1. Correlation coefficient study

Data in Table 1 indicate that evapotranspiration is positively correlated to air temperature, wind speed, sunshine hours and solar radiation and negatively to relative humidity and cloudiness. The positively correlated indicate that when air temperature, wind speed, sunshine hours and solar radiation increase, evapotranspiration increases. However, negative correlation shows that evapotranspiration decreases with increasing relative humidity and cloudiness (Blindeman, 2000; Khanikar and Nath, 1998 ; Schmidt *et al*., 1987 and Riou *et al*., 1987).

3.2. Path coefficient analysis:

Data presented in Table 2 show the direct and indirect effects of all climatic variables with and without wind speed on evapotranspiration.

Table 1. The Correlations between evapotranspiration and climatic variables under study.

Variables	Evapotranspiration	Air temperature	Relative humidity	Wind speed	Sunshine hours	Solar radiation	Cloudiness
Evapotranspiration	1	0.961	-0.559	0.727	0.911	0.844	-0.838

3.2.1. Air temperature

Data presented in Table 2 show that the direct effect of air temperature on water consumptive use is high (P= 0.773). Total effect including direct and indirect effects (ry_1) was 0.961, while, the direct effect of air temperature, in the absence of wind speed, on water consumptive use is high (P= 0.770). The importance of air temperature variable in evaporation process is distinct with its high direct effect (James, 1988 and Jensen, 1974).

3.2.2. Relative humidity

Direct influence of relative humidity on evapotranspiration was very high (P= 1.05) with total effect (ry_2) as -0.559. When the total effect is negative but the direct effect is positive and high,indirect effects are undesirable, while the direct effect should be considered (Singh and Kakkar, 1977). In the absence of wind speed, the direct effect of relative humidity on water consumptive use was 0.685. The direct effect of relative humidity was reduced from 1.05 to 0.685 due to wind speed effect.

3.2.3. Wind speed

Data presented in Table 2 show that the direct effect of wind speed was negative (P= -0.134) to evapotranspiration. The indirect effect of air temperature, relative humidity, sunshine hours, solar radiation and cloudiness were 0.645, -0.795, -0.038, 1.231 and -0.182 respectively. The total effect (ry_3) is 0.727. When the total effect (ry_3) is positive, but the direct effect is negative, the indirect effect seems to be the cause of correlation. In such situations, indirect casual factors such as air temperature and solar radiation are to be considered in selection (Singh and Chaudhary, 1985).

3.2.4. Sunshine hours

Table 2 show that when wind speed was included in the analysis the direct effect of sunshine hours was -0.051, while, the indirect effect of air temperature and solar radiation was high showing positive values 0.697 and 1.398, respectively. When the total effect (ry_3) is positive, but the direct effect is negligible, the indirect effect seems to be cause of correlation. In such situations, indirect casual factors such as air temperature and solar radiation are to be considered simultaneously for selection (Singh and Chaudhary, 1985).

3.2.5. Solar radiation

Data in Table 2 reveal that solar radiation has the highest direct effect (P= 1.459) on evapotranspiration through high evaporation (James,1988, Jensen, 1974 and El-Shafei, 1972). When the direct effect is equal or higher to its total effect, the use of solar radiation variable would be highly effective (Singh and Chaudhary, 1985). The total effects (ry_5) were 0.849 in analysis with wind speed and 0.842 in the absence of wind speed. The direct effect of solar radiation on evapotranspiration was quite low in the absence of wind speed (0.530). This explains the contribution of wind speed to water evaporation due to solar radiation. (Wang and Boulard, 2000).

3.2.6. Cloudiness

Data presented in Table 2 showed that cloudiness gives a low positive direct effect to evapotranspiration with value of 0.300, and total of direct and indirect effect was -0.838.

3.2.7. Residual effect

Data in Table 2 indicate that overall residual effect was 0.1620, the climatic variables explain only about 83.80% of the variability in the evapotranspiration. This indicates that 16.20% effect has been estimated by other some minor variables which have not been connected with the present study.

It is evident that wind speed plays an important role in enhancing water evaporation with its impact on major environmental factors affecting evapotranspiration such as air temperature, relative humidity and solar radiation (Ruan *et al.*, 1999). Afors, (1986) showed that when wind speed increases, the potential evapotranspiration increases.

Table 2. Values of the direct and indirect effects of all climatic variables under study with and without wind speed on evapotranspiration.

Nature of influence and association	All climatic variables with wind speed evapotranspiration	All climatic variables without wind speed evapotranspiration	Overall mean
Temperature vs evapotranspiration			
Direct effect (py_1)	**+0.773**	**+0.770**	**+0.772**
Indirect effect via			
- Relative humidity	-0.719	-0.466	-0.593
- Wind speed	-0.112	0.000	-0.056
- Sunshine hours	-0.046	+0.344	+0.149
- Solar radiation	+1.309	+0.476	+0.893
- Cloudiness	-0.244	-0.163	-0.204
Total (Direct and Indirect) effects (ry_1)	**0.961**	**0.961**	**0.961**
Relative humidity vs evapotranspiration			
Direct effect (py_2)	**+1.050**	**+0.680**	**+0.865**
Indirect effect via			
- Temperature	-0.529	-0.527	-0.528
- Wind speed	+0.101	0.000	+0.051
- Sunshine hours	+0.039	-0.295	-0.128
- Solar radiation	-1.312	-0.478	-0.895
- Cloudiness	+0.092	+0.061	+0.077
Total (Direct and Indirect) effects (ry_2)	**-0.559**	**-0.559**	**-0.558**
Wind speed vs evapotranspiration			
Direct effect (py_3)	**-0.134**		**-0.134**
Indirect effect via			
- Temperature	+0.645	Not calculated	+0.645
- Relative humidity	-0.795		-0.795
- Sunshine hours	-0.038		-0.038
- Solar radiation	+1.231		+1.231
- Cloudiness	-0.182		-0.182
Total (Direct and Indirect) effects (ry_3)	**0.727**		**0.727**
Sunshine hours vs evapotranspiration			
Direct effect (py_4)	**-0.051**	**+0.380**	**+0.165**
Indirect effect via			
- Temperature	+0.697	+0.695	+0.696
- Relative humidity	-0.814	-0.527	-0.671
- Wind speed	-0.101	0.000	-0.051
- Solar radiation	+1.398	+0.508	+0.953
- Cloudiness	-0.217	-0.145	-0.181
Total (Direct and Indirect) effects (ry_4)	**0.912**	**0.911**	**0.911**
Solar radiation vs evapotranspiration			
Direct effect (py5)	**+1.459**	**+0.530**	**+0.995**
Indirect effect via			
- Temperature	+0.693	+0.691	+0.692
- Relative humidity	-0.946	-0.613	-0.780
- Wind speed	-0.113	0.000	-0.057
- Sunshine hours	-0.049	+0.364	+0.158
- Cloudiness	-0.195	-0.130	-0.163
Total (Direct and Indirect) effects (ry_5)	**0.849**	**0.842**	**+0.845**
Cloudiness vs evapotranspiration			
Direct effect (py_6)	**+0.300**	**+0.200**	**+0.250**
Indirect effect via			
- Temperature	-0.628	-0.628	-0.628
- Relative humidity	+0.322	+0.209	+0.266
- Wind speed	+0.081	0.000	+0.041
- Sunshine hours	+0.037	-0.275	-0.119
- Solar radiation	-0.950	-0.345	-0.648
Total (Direct and Indirect) effects (ry_6)	**-0.838**	**-0.839**	**-0.838**
Residual effect	**0.1934**	**0.1305**	**0.1620**

3.3. Relative contribution

Table 3 shows that climatic variables such as solar radiation, relative humidity, air temperature, cloudiness, wind speed and sunshine hours contributed respectively 31.32%, 27.23%, 24.30%, 7.87%, 4.09% and 5.19%. Solar radiation contributes the most, followed by relative humidity, air temperature, cloudiness, sunshine hours and wind speed respectively. Parkhurst *et al.*, (1998) and Smajstrla *et al.*, (1987) reported that ET_p is the most sensitive to solar radiation. In addition to, relative humidity, maximum temperature and wind speed are the other most significant parameters that control pan evaporation (Khanikar and Nath, 1998).

Table 3. Average direct effects of climatic variables and its relative contribution (RC%) under study on evapotranspiration.

Climatic variables	Direct effects	RC (%)
Solar radiation	0.995	31.32
Relative humidity	0.865	27.23
Air temperature	0.772	24.30
Cloudiness	0.250	7.87
Sunshine hours	0.165	5.19
Wind speed	0.130	4.09
Total	3.177	100.0

3.4. Simultaneous Equations

Data in Table 4 show that ET_o rate is low in Dec. and Jan. and gradually increase from Feb. to June and then again decline. The ET_o rate was obviously affected by solar radiation, relative humidity and air temperature (Pen et al, 1999). Estimated values of Eq. [2, (El-Bably H)] closely matched to Penmen-Monteith and Doorenbs-Pruitte methods in the Delta. Omar and Eid, (1999) found that the Doorenbos-Pruitt method gives the best estimation followed by the Penman Monteith in the Delta. However, estimated values of Eq. [3, (El-Bably L)] closely agreed with Doornobs-Pruitte and Penmen-Monteith methods in Upper Egypt (Table 5). Rayan et al , (1999) has reported the Penman-Monteith and Doorenbos-Pruitt formulae as better for estimating ET crop in Upper Egypt.

The ET_o model showed that estimated ET_o every 12 days in July was 4.35, 7.13 and 5.74 cm in the Delta region using El-Bably L, H and O respectively (Fig. [1]). The ET_o model could be used to schedule irrigation under different irrigation methods i.e. surface, sprinkler and drip.

Table 4. Average agroclimatological data and estimated values of ET_o using empirical methods and Eqs. [2]and [3] (El-Bably H & O) in Delta.

Months	Air temperature	Relative humidity	Wind speed	Sunshine	Solar radiation	ETo mm d^{-1}			
	^oC	%	km d^{-1}	h	cal cm^{-2} d^{-1}	Penman-Monteith	Doorneb-Pruitt	El-Bably H	El-Bably O
January	12.8	70	97.9	7.0	274	1.80	1.85	1.22	0.98
February	13.5	67	115.2	7.7	345	2.44	2.49	1.68	1.35
March	15.6	63	123.9	8.6	436	3.42	3.44	2.55	2.05
April	19.1	57	112.3	9.6	517	4.42	4.43	3.95	3.18
May	23.4	54	109.4	10.60	576	5.42	5.42	5.55	4.47
June	25.4	55	109.4	11.9	625	6.01	5.99	6.37	5.12
July	26.7	60	97.9	11.6	610	5.87	5.85	5.94	4.78
August	26.6	62	95.0	11.3	579	5.54	5.55	5.45	4.39
September	25.2	64	83.5	10.3	508	4.58	4.71	4.41	3.55
October	22.8	65	80.6	9.3	413	3.42	3.63	3.24	2.60
November	19.5	68	83.5	8.0	316	2.38	2.50	2.06	1.66
December	15.1	71	86.4	6.6	252	1.81	1.77	1.27	1.02

Table 5. Average agroclimatological data and estimated values of ET_o using empirical methods and Eqs. [1]and [3] (El-Bably L & O) in Upper Egypt

Months	Air temperature	Relative humidity	Wind speed	Sunshine	Solar radiation	ETo mm d^{-1}			
	°C	%	km d^{-1}	h	cal cm^{-2} d^{-1}	Penman-Monteith	Doorneb-Pruitt	El-Bably L	El-Bably O
January	14.5	52	118.1	9.2	359	2.73	2.71	1.45	1.92
February	15.8	47	144.0	9.9	433	3.69	2.50	2.09	2.75
March	19.3	38	167.1	10.0	498	5.06	4.41	3.52	4.65
April	24.1	30	164.2	10.4	555	6.29	5.41	6.02	7.95
May	28.2	29	184.3	11.4	605	7.57	6.26	7.82	10.33
June	30.2	32	187.2	12.2	635	8.13	6.70	7.90	10.43
July	29.2	36	164.2	12.1	628	7.44	6.34	6.75	8.91
August	30.3	38	164.2	11.8	606	7.34	6.28	6.38	8.42
September	28.2	43	193.0	10.8	542	6.75	5.46	4.73	6.24
October	25.6	49	161.3	10.1	464	5.15	4.43	3.26	4.30
November	20.7	52	144.0	9.5	387	3.83	3.36	2.12	2.80
December	16.1	55	123.9	9.2	344	2.87	2.69	1.43	1.89

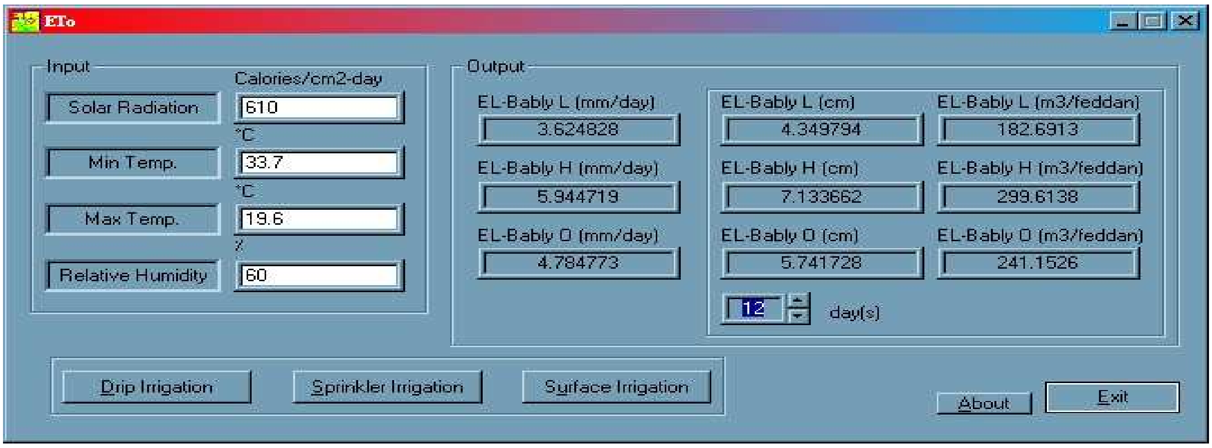

Fig. 1. Estimated ET_o using Eq.[1], Eq.[2], Eq.[3] (El-Bably L ,H and H) in Delta region.

4. CONCLUSION

The climatic variables, air temperature, sunshine hours and solar radiation were positively and highly correlated to evapotranspiration. Relative humidity and cloudiness were negatively correlated. Solar radiation has the highest direct effect (P= 0.995) on evapotranspiration followed by relative humidity (P= 0.865), air temperature (P= 0.772), cloudiness (P= 0.25), sunshine hours (P= 0.165) and wind speed (P=-0.130). The climatic variables solar radiation, relative humidity, air temperature, cloudiness, sunshine hours and wind speed had relative contribution of 31.32%, 27.23%, 24.30%, 7.87%, 5.19% and 4.09% respectively on evapotranspiration. The evapotranspiration(ET) becomes low when wind speed decreases due to its descending direct effect for relative humidity and solar radiation. In general, the low water potential value shown by Eq.[1] is suitable for upper Egypt. The high water potential value shown by Eq.[2] and optimal water potential value revealed by Eq.[3] are relevant for the Delta region.

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