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COMPARISON OF REFERENCE EVAPOTRANSPIRATION EQUATIONS UNDER CLIMATE CHANGE CONDITIONS

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ABSTRACT

Precise estimation of crop water requirements at any region over the globe is very vital. Hence, an accurate estimation of reference evapotranspiration is very important especially in agriculture, hydrology and meteorology. The objectives of the present study were comparison of evapotranspiration estimations using different equations and FAO-56 Penman-Monteith under future climatic conditions. *Four reference evapotranspiration (ET_o) methods namely; Blaney-Criddle*, Hargreaves, Thornthwaite and FAO-56 Penman-Monteith (PM) have been used. Data of the present climate have collected from different automated meteorological stations distributed along Egypt from 1998 to 2007. While, the future climate data have chosen for the concerned RCPs scenarios: RCP2.6, RCP4.5, RCP6.0 and RCP8.5 at 2040. The results revealed that, there were statistically no significance between PM and B*laney-Criddle* only in the Delta region at P value less than 0.05 while the other equations had significant differences. There were significant differences between ET_o under current and future conditions for all studied regions. The B*laney-Criddle and* Thornthwaite equations had the lowest ET_o values under different RCPs scenarios comparing with Hargreaves and Penman-Monteith (PM) method. Generally, RCP 8.5 gave the highest ET_o values under climate change conditions.
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Keywords

Climate. Reference Evapotranspiration. Estimation. E-Pan. FAO-56 Penman-Monteith., Blaney-Criddle. Hargreaves. Thornthwaite. RCPs

1. INTRODUCTION

Evapotranspiration is a combination of two terms, evaporation from the surface of water bodies and transpiration from plants and crops. The amount of evapotranspiration depends mainly on the weather and climate conditions in addition to many other factors such as crop characteristics, management and environmental factors. This amount plays an important and major role in agriculture and hydrology, especially the hydrological cycle. Also in

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meteorology, this amount determines the formation of different cloud patterns hence controls the precipitation over different locations.

Moreover, **Haas (2002)** projected that the first order impacts of climate change on the Mediterranean hydrological systems as wetter winters and dryer summers, hotter summers and heat waves, and more variability and extreme weather events will take their toll. These impacts may induce an increase in evaporation (E) from natural and artificial water bodies and soils that reduce the available water supply (**Abu-Zeid,** 2002). Additionally; adapting to climate change will have close resonance with adapting to water scarcity and is likely to require implementation of water demand management strategies which may require capacity building and awareness raising across institutions and society. Adaptation measures on the supply-side include ways to improve rain-harvesting techniques, increasing extraction of ground water, water recycling, desalination, and improving water transportation. In addition, regular reviewing and updating of drought responses and research into improved long-term forecasting is essential to enhance Egypt's ability to cope with prolonged drought (**Agrawala, and Berg, 2002**). In addition, Due to the higher performance of FAO-56 Penman-Monteith (FAO-56 PM) model in different parts of the world when compared with other models, it has been accepted as the sole method of computing reference evapotranspiration from meteorological data (**Garcial et al., 2006 and Gavila, et al, 2006**). The result obtained from the use of Hargreaves model has been reported to produce satisfactory results in computing weekly or monthly reference evapotranspiration Hargreaves and Allen, (2003). Various methods are available to estimate evapotranspiration from standard meteorological observations. Penman-Monteith, the method which served as basis for the development of the ET_o calculator software, is considered the most physical and reliable method and is often used as a standard to verify other empirical methods (**Allen et al., 2005 and Dirk 2009**).

2. Data and methodology

Meteorological parameters, viz.: Maximum and minimum temperature, maximum and minimum relative humidity, wind speed and sunshine duration were collected from automated meteorological stations for the period 1998-2007 from automated meteorological stations distributed all over Egypt. In addition to the measurements of the reference evapotranspiration using class A pan or Epan. These stations managed and controlled by the Central Laboratory for Agriculture Climate (CLAC), the Egyptian Ministry of Agriclture. These data have been used to estimate the reference evapotranspiration over Egypt using different calculation methods. These are Blaney-Criddle, Thornthwaite, Hargreaves and FAO-56 Penman-Monteith (PM). The first two methods are based on the air temperature while the other ones are based on the solar radiation. The results from these methods are going to be compared with the measurements from FAO-56 Penman-Monteith (PM) under current and future conditions.

The mean monthly temperature, rainfall and radiation for the for the climate change conditions at 2040 under HadGEM2-ES model were downscaled from ClimaScope website http:// http://gisweb.ciat.cgiar.org/MarkSimGCM/ .

In this study, Egypt has been divided into several agro-climatic regions according to the average air temperature and the reference evapotranspiration from Epan.The most important agro-climatic regions are: the Delta region, represented in this study by Gharbia governorate; the Middle Egypt region represented by Menya governorate and the Upper Egypt region represented by Sohag governorate.

3. RESULTS AND DISCUSSION.

3.1 Evaluation of monthly Reference Evapotranspiration Equations under Climate change.

Tables (1 to 3) illustrates the results of monthly calculations of ET_o using Penman-Monteith, Blaney-Criddle, Thornthwaite and Hargreaves equations for the Delta, Middle and Upper Egypt regions, respectively, under different RCPs scenarios. It is obvious from the Epan measurements that, Upper Egypt had the highest values in both monthly and

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annually averages of ET_o followed by middle Egypt, while Delta had the lowest ones. The future ET_o values had the same trend as the current ET_o with a higher values

Regarding the estimated monthly average of ET_o values under different RCPs scenarios, all equations had the same trend and behavior at all agro-climatic regions. The highest values of measured and estimated ET_o for all regions were recorded during June and July months, while the lowest ones were recorded in January and February. In addition, it is noticed that ET_o values were gradually increased from January till July as the temperature increases then decreasing trend from June to December as the temperature decreases. Statistically, there were significant differences between current (ET_o estimated by the same equation)and future ET_o for the all tested equations at different climatic regions in Egypt. In addition, the highest estimated annual values of ET_o were given using Hargreaves equation, while the lowest ones were given by Thornthwaite equation at all agro-climatic regions. The RCP 8.5 scenario gave the highest ET_o at 2040s under all tested climatic regions compared to the other RCPs scenarios. These results agreed with **Ayub and Miah, (2011); Nour El-Din, (2013)**.

3.2 Trend of annual ETo under climate change under tested equations.

The average annual future ET_o values using PM, Blaney-Criddle, Hargreaves and Thornthwaite equations for the Delta, Middle and Upper Egypt regions (Tables 4 and 5). Hargreaves equation gave the highest ET_o values followed by Penman-Monteith; while the Thornthwaite gave the lowest ET_o values under all studied climatic regions. The ET_o values in the Middle Egypt region under RCPs climate change scenarios were increased compared to Delta. It is clear that the Upper Egypt region had the highest average ET_o values under future conditions than the Delta and the Middle Egypt regions. There were significant differences between all tested equations compared to the PM under different climatic regions except with Blaney-Criddle in the Delta region.

The percentage of differences ET_o values obtained through different tested equations from the corresponding values estimated through FAO-56 PM method were calculated and listed in Table 6. The estimated ET_o values from Hargreaves equation gave in higher percentage of differences as 5.7, 3.2 and 2.2 % Than PM under Delta, Middle and Upper Egypt, respectively. Whereas, Blaney-Criddle and Thornthwaite equations gave negative differences from PM method. The least among negative differences found by Thornthwaite equations under different RCP scenarios -16.7, -35.1 and -41.0 % for Delta, Middle and Upper Egypt, respectively. Generally, from Table (5) that there are gradually increasing values of annual ET_o under different tested RCPs scenarios from RCP 2.6 to RCP 8.5. These results are matched with Modi (2000), Xu and Singh (2001), and Farage et al. (2013). Moreover, Penman's combination formula is the most accurate and most physically based of the common methods used (Tabari, 2010). Penman's method is a combination of aerodynamic and energy budget methods. Although a mathematical formula is used, the input values are from meteorological observations and their relationship established from that of actual physical representation (Allen et al., 1994, Temesgen et al., 2005 and Allen et al., 2005).

In addition, the existing aerodynamic term and formulated the Penman-Monteith evapotranspiration model. Jensen et al. (1990) found that radiation methods considerably underestimated evapotranspiration for rates greater than 4 mm/day. **George et al. (2002)** have developed decision support system for estimating reference evapotranspiration using Temperature, Radiation and Combination methods (**Hidalgo et al., 2005, Irmak et al., 2003**). Among these methods, Penman-Monteith method is taken as standard method for comparison with other methods (**Temesgen et al., 2005**).

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Table 1. Estimated monthly average of ET_o using Penman-Monteith, Blaney-Criddle, Thornthwaite, and Hargreaves methods for Delta region.

Delta										
	PM					Thornthwaite				
		RCP's scenarios					RCP's scenarios			
	Current	2.6	4.5	6.0	8.5	Current	2.6	4.5	6.0	8.5
Jan	1.95	2.10	2.09	2.05	2.14	2.25	2.20	2.20	2.19	2.28
Feb	2.12	2.46	2.46	2.44	2.53	2.28	2.23	2.23	2.23	2.32
Mar	2.63	3.35	3.34	3.31	3.44	2.28	2.82	2.82	2.81	2.92
Apr	4.46	4.57	4.55	4.52	4.70	3.09	3.60	3.60	3.59	3.74
May	5.78	5.71	5.69	5.69	5.92	3.93	4.38	4.38	4.37	4.55
Jun	6.43	6.97	6.86	6.76	7.03	5.45	5.44	5.43	5.43	5.64
Jul	6.25	6.92	6.96	6.88	7.16	5.88	5.89	5.88	5.87	6.11
Aug	5.85	6.70	6.73	6.66	6.92	4.99	5.11	5.10	5.10	5.30
Sep	5.84	5.79	5.77	5.75	5.98	4.78	4.73	4.73	4.72	4.91
Oct	5.52	5.30	5.25	5.21	5.42	4.11	4.20	4.19	4.19	4.35
Nov	3.34	3.75	3.73	3.70	3.85	3.08	3.42	3.41	3.41	3.55
Dec	2.50	2.77	2.76	2.73	2.83	2.43	2.56	2.56	2.55	2.65
Avg.	4.39	4.70	4.68	4.64	4.83	3.71	3.88	3.88	3.87	4.03
P(F<=f)		*	*	*	*		*	*	*	*
	0.0%	7.1%	6.7%	5.7%	10.0%	0.0%	4.6%	4.4%	4.3%	8.5%
	Hargreaves					Blaney and criddle				
		RCP's scenarios					RCP's scenarios			
	Current	2.6	4.5	6.0	8.5	Current	2.6	4.5	6.0	8.5
Jan	2.60	2.89	2.89	2.88	3.00	2.79	3.04	3.03	3.03	3.15
Feb	2.80	3.04	3.04	3.03	3.15	2.82	3.24	3.23	3.23	3.36
Mar	3.30	3.72	3.71	3.71	3.86	3.51	4.20	4.19	4.19	4.35
Apr	4.90	5.03	5.02	5.01	5.22	3.63	4.98	4.97	4.96	5.16
May	5.88	6.07	6.06	6.05	6.30	4.31	5.92	5.91	5.90	6.14
Jun	6.12	6.59	6.58	6.57	6.84	5.66	6.56	6.55	6.54	6.80
Jul	6.23	7.14	7.13	7.12	7.40	5.66	6.57	6.57	6.56	6.82
Aug	5.60	6.99	6.99	6.98	7.26	5.50	6.36	6.35	6.35	6.60
Sep	5.72	6.35	6.34	6.33	6.58	4.97	5.65	5.65	5.64	5.87
Oct	4.24	4.63	4.63	4.62	4.80	4.35	4.96	4.96	4.95	5.15
Nov	3.67	3.85	3.84	3.84	3.99	3.48	4.17	4.17	4.16	4.33
Dec	3.28	3.32	3.32	3.31	3.45	2.98	3.13	3.13	3.12	3.25
Avg.	4.53	4.97	4.96	4.96	5.15	4.14	4.90	4.89	4.89	5.08
P(F<=f)		*	*	*	*		*	*	*	*
	0.0%	9.7%	9.6%	9.4%	13.8%	0.0%	18.4%	18.2%	18.1%	22.8%

***** Significant at P < 0.05***

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Table 2. Estimated monthly average of ET_o using Penman-Monteith, Blaney-Criddle, Thornthwaite, and Hargreaves methods for Middle Egypt region

Middle Egypt										
	PM					**Thornthwaite**				
		RCP's scenarios					**RCP's scenarios**			
	Current	**2.6**	**4.5**	**6.0**	**8.5**	Current	2.6	4.5	6.0	8.5
Jan	2.71	2.92	2.88	2.85	2.97	2.05	2.23	2.22	2.22	2.31
Feb	3.36	3.58	3.61	3.58	3.67	2.08	2.42	2.42	2.41	2.51
Mar	4.21	4.67	4.62	4.62	4.73	2.20	3.16	3.16	3.16	3.28
Apr	5.95	6.80	6.78	6.78	6.94	3.15	3.72	3.72	3.71	3.86
May	7.47	8.28	8.27	8.36	8.47	4.20	4.64	4.64	4.63	4.82
Jun	8.10	8.81	8.78	8.77	8.99	5.80	5.28	5.28	5.27	5.48
Jul	7.98	8.22	8.26	8.21	8.42	6.09	6.11	6.10	6.09	6.33
Aug	7.61	8.06	8.07	8.02	8.22	5.18	5.43	5.43	5.42	5.64
Sep	7.26	7.76	7.71	7.75	7.92	4.88	4.78	4.78	4.77	4.96
Oct	6.39	6.56	6.45	6.46	6.69	4.16	4.19	4.19	4.18	4.35
Nov	4.83	4.87	4.85	4.81	5.01	2.95	3.17	3.17	3.16	3.29
Dec	3.15	3.34	3.33	3.30	3.40	2.25	2.52	2.51	2.51	2.61
Avg.	5.75	6.16	6.13	6.13	6.29	3.75	3.97	3.97	3.96	4.12
P(F<=f)		*	*	*	*		*	*	*	*
	0.0%	7.0%	6.6%	6.5%	9.3%	0.0%	6.0%	5.8%	5.7%	9.9%
	Hargreaves					**Blaney and criddle**				
		RCP's scenarios					**RCP's scenarios**			
	Current	2.6	4.5	6.0	8.5	Current	2.6	4.5	6.0	8.5
Jan	2.81	2.99	2.98	2.98	3.10	3.28	3.41	3.41	3.40	3.54
Feb	3.49	3.67	3.67	3.67	3.81	3.31	3.74	3.74	3.73	3.88
Mar	4.38	4.79	4.78	4.78	4.97	3.57	4.42	4.41	4.41	4.59
Apr	6.19	6.97	6.97	6.96	7.24	4.19	5.36	5.35	5.35	5.56
May	7.77	8.49	8.47	8.46	8.80	5.04	6.27	6.27	6.26	6.51
Jun	8.42	9.03	9.02	9.01	9.37	6.21	6.71	6.71	6.70	6.97
Jul	8.30	8.43	8.42	8.41	8.75	6.14	6.63	6.62	6.61	6.88
Aug	7.92	8.26	8.25	8.24	8.57	5.95	6.40	6.39	6.38	6.64
Sep	7.55	7.95	7.94	7.93	8.25	5.37	5.69	5.68	5.67	5.90
Oct	6.64	6.72	6.71	6.70	6.97	4.67	5.03	5.03	5.02	5.22
Nov	5.02	4.99	4.99	4.98	5.18	3.84	4.14	4.14	4.13	4.30
Dec	3.28	3.43	3.42	3.42	3.55	3.26	3.47	3.47	3.46	3.60
Avg.	5.98	6.31	6.30	6.30	6.55	4.57	5.11	5.10	5.09	5.30
P(F<=f)		*	*	*	*		*	*	*	*
	0.0%	5.5%	5.4%	5.2%	9.4%	0.0%	11.8%	11.7%	11.5%	16.0%

**** Significant at P < 0.05***

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Table 3. Estimated monthly average of ET_o using Penman-Monteith, Blaney-Criddle, Thornthwaite, and Hargreaves methods for Upper Egypt region.

Upper Egypt										
	PM					Thornthwaite				
		RCP's scenarios								
	Current	2.6	4.5	6.0	8.5	Current	2.60	4.50	6.00	8.50
Jan	3.23	3.81	3.77	3.72	3.88	2.16	2.26	2.26	2.26	2.35
Feb	4.27	4.35	4.41	4.39	4.49	2.19	2.36	2.35	2.35	2.44
Mar	5.33	5.82	5.78	5.78	5.93	2.36	3.56	3.56	3.55	3.70
Apr	7.85	8.13	8.12	8.12	8.31	3.57	4.73	4.72	4.72	4.90
May	9.59	9.77	9.81	9.87	10.03	4.81	6.12	6.11	6.10	6.35
Jun	10.27	10.63	10.61	10.63	10.89	6.56	6.65	6.65	6.64	6.90
Jul	10.31	10.58	10.65	10.65	10.91	6.84	6.85	6.84	6.83	7.10
Aug	10.43	10.53	10.56	10.51	10.76	5.72	5.88	5.87	5.87	6.10
Sep	8.58	9.88	9.82	9.88	10.10	5.42	5.52	5.51	5.51	5.73
Oct	7.17	8.44	8.32	8.36	8.64	4.52	4.76	4.75	4.75	4.94
Nov	5.56	6.34	6.32	6.26	6.51	3.16	3.45	3.45	3.45	3.58
Dec	3.77	4.05	4.05	4.01	4.13	2.35	2.46	2.46	2.45	2.55
Avg.	7.20	7.70	7.69	7.68	7.88	4.14	4.55	4.54	4.54	4.72
P(F<=f)		*	*	*	*		*	*	*	*
	0.0%	6.9%	6.8%	6.7%	9.5%	0.0%	9.9%	9.8%	9.7%	14.0%
	Hargreaves					Blaney and criddle				
		RCP's scenarios								
	Current	2.60	4.50	6.00	8.50	Current	2.60	4.50	6.00	8.50
Jan	3.16	3.91	3.90	3.90	4.05	3.27	3.59	3.59	3.59	3.73
Feb	3.79	4.46	4.46	4.45	4.63	3.30	3.87	3.87	3.86	4.02
Mar	5.02	5.97	5.96	5.96	6.19	3.61	4.64	4.64	4.63	4.82
Apr	8.72	8.34	8.33	8.32	8.65	4.35	5.61	5.60	5.60	5.82
May	10.50	10.02	10.01	10.00	10.39	5.29	6.54	6.53	6.52	6.78
Jun	10.88	10.89	10.88	10.87	11.30	6.49	7.08	7.07	7.06	7.35
Jul	10.89	10.84	10.83	10.82	11.25	6.34	6.89	6.88	6.87	7.15
Aug	10.43	10.79	10.78	10.77	11.20	6.13	6.74	6.73	6.72	6.99
Sep	9.28	10.12	10.11	10.10	10.50	5.52	6.01	6.01	6.00	6.24
Oct	5.47	8.65	8.64	8.63	8.98	4.77	5.29	5.28	5.27	5.48
Nov	4.56	6.49	6.48	6.48	6.74	3.87	4.37	4.37	4.36	4.54
Dec	3.25	4.15	4.15	4.14	4.31	3.25	3.59	3.59	3.59	3.73
Avg.	7.16	7.89	7.88	7.87	8.18	4.68	5.35	5.35	5.34	5.55
P(F<=f)		*	*	*	*		*	*	*	*
	0.0%	10.1%	10.0%	9.9%	14.3%	0.0%	14.3%	14.2%	14.0%	18.6%

***** Significant at $P < 0.05$***

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Table 4. comparison of Average annual estimated ET_o under major agro-meteorological regions using Penman-Monteith, Blaney-Criddle,Thornthwaite and Hargreaves equations.

Delta				
	PM	Hargreaves	Thornthwaite	Blaney and
Current	4.39	4.53	3.71	4.14
2.6	4.70	4.97	3.88	4.90
4.5	4.68	4.96	3.88	4.89
6.0	4.64	4.96	3.87	4.89
8.5	4.83	5.15	4.03	5.08
Avg.	4.65	4.91	3.87	4.78
		*	*	N. S
	0.0%	5.7%	-16.7%	2.8%
Middle Egypt				
	PM	Hargreaves	Thornthwaite	Blaney and
Current	5.75	5.98	3.75	4.57
2.6	6.16	6.31	3.97	5.11
4.5	6.13	6.30	3.97	5.10
6.0	6.13	6.30	3.96	5.09
8.5	6.29	6.55	4.12	5.30
Avg.	6.09	6.29	3.95	5.03
		*	*	*
	0.0%	3.2%	-35.1%	-17.4%
Upper Egypt				
	PM	Hargreaves	Thornthwaite	Blaney and
Current	7.20	7.16	4.14	4.68
2.6	7.70	7.89	4.55	5.35
4.5	7.69	7.88	4.54	5.35
6.0	7.68	7.87	4.54	5.34
8.5	7.88	8.18	4.72	5.55
Avg.	7.63	7.80	4.50	5.26
		*	*	*
	0.0%	2.2%	-41.0%	-31.1%

***** Significant at P < 0.05***

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Table 5. Average annual estimated ET_o under different agro-meteorological regions using Penman-Monteith, Blaney-Criddle,Thornthwaite and Hargreaves equations.

	Delta				
		RCP's scenarios			
	Current	2.6	4.5	6.0	8.5
PM	1602	1715	1709	1694	1762
Hargreaves	1653	1813	1811	1809	1881
Thornthwaite	1355	1417	1415	1413	1470
Blaney and criddle	1510	1788	1786	1784	1855
Avg.	1530	1683	1680	1675	1742
	0.0%	10.0%	9.8%	9.5%	13.8%
	Middle Egypt				
		RCP's scenarios			
	Current	2.6	4.5	6.0	8.5
PM	2099	2247	2239	2236	2294
Hargreaves	2183	2303	2300	2298	2390
Thornthwaite	1368	1450	1448	1446	1504
Blaney and criddle	1667	1864	1862	1860	1934
Avg.	1830	1966	1962	1960	2031
	0.0%	7.5%	7.2%	7.1%	11.0%
	Upper Egypt				
		RCP's scenarios			
	Current	2.6	4.50	6.0	8.5
PM	2627	2809	2805	2804	2877
Hargreaves	2614	2879	2875	2872	2987
Thornthwaite	1511	1661	1659	1657	1723
Blaney and criddle	1709	1954	1951	1949	2027
Avg.	2115	2326	2323	2320	2404
	0.0%	9.9%	9.8%	9.7%	13.6%

**** Significant at** $P < 0.05$*

4. Conclusion

The knowledge of evaporation has become more and more important during the last decades because of the increased use of irrigation on farmlands. Estimating an exact value for evaporation over an area is very hard due to the unsecure parameters you have to take into account.

The expected climate changes in Egypt according to the RCPs scenarios will cause an increase in annual ET_o depending on the climatic region. This study compared different empirical equations to calculate evapotranspiration under current and future conditions. The radiation equations (Penman montieth and Hargreaves) are more accurate than

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temperature equations (Plany – Criddle and Thornthwaite). Further studies could be done to compare the water requirements of different economical crops under current and future conditions.

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6. Appendix

6.1 Potential Evaporation

6.1.1 Epan (class A pan)

The used A pan was circular with a diameter of 1.21 m and depth of 255 mm which gives it a volume of about 0.3 m^3. The basin is put on a 150 mm high wooden frame due to air circulation around the basin. The water level is kept about 50 mm below the rim, due to allowance of percolation and the need of water. The water level is measured every day; the value of A pan was modified.

$$ET_o = Kp.\ Epan \quad (1)$$

Epan = pan evaporation in mm/day and represents the mean daily value of the period considered

Kp = pan coefficient (0.85 under Egyptian conditions)

6.1.2 FAO- 56 PM Equation

The ET_o was estimated according to Allen *et al.* (1994). The FAO Penman – Monteith method to estimate reference crop evapotranspiration is as follows

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (2)$$

Where

ET_o = reference evapotranspiration (mm day-1),
Rn = net radiation at the crop surface (MJ m-2 day-1),
G = soil heat flux density (MJ m-2 day-1),
T = mean daily air temperature at 2 m height (°C),
U_2 = wind speed at 2 m height (m s-1),
e_s = saturation vapor pressure (kPa),
e_a = actual vapor pressure (kPa),
e_s-e_a = saturation vapor pressure deficit (kPa),
Δ = slope vapor pressure curve (kPa $°C^{-1}$),
γ = psychrometric constant (kPa $°C^{-1}$).

6.1.3 Hargreaves Method

The Hargreaves method (Hargreaves and Samani 1985) of computing daily reference evapotranspiration is another empirical approach that was used in cases where the availability of weather data is limited. The method was developed in Davis, California from a lysimeter study on Alta fescue grass. The original Hargreaves formula calculates reference evapotranspiration from solar radiation and temperature as follows

$$ET_o = 0.0135 \frac{R_s}{\lambda}(T + 17.8) \quad (3)$$

Where

ET_o = Reference evapotranspiration, (mm/day),
λ = Latent heat of vapourization, (MJ/kg) (2.45 MJ/kg),

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R_s = Solar radiation, ($MJ/m^2\ d^{-1}$),
T = Mean air temperature, (^oC).

6.1.4 Thornthwaite

Thornthwaite (1948) and Thornthwaite and Mather (1957) developed an expression for PET in terms of mean air temperature and number of monthly daylight hours:

$$ET_o = 16 N_m \left(\frac{10 \bar{T}_m}{I} \right)^a \tag{4}$$

Where

ET_o = reference evapotranspiration (mm day^{-1}),
c = location coefficient dependent upon daylight hours (latitude and month)
T = mean monthly temperature in ºC
I = heat index described by Eq. 5
a = location dependent coefficient described by Eq. 6

In order to determine (*a)* and monthly ET_o, a heat index ***I*** must first be computed:

$$I = \sum_{j=1}^{j=12} \left[\frac{Tj}{5} \right]^{1.514} \tag{5}$$

Where

T_j = the mean monthly temperature during month j (ºC) for the location of interest. Then, the coefficient ***a*** can be computed as follows:

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.792 \times 10^{-2} I + 0.49239 \tag{6}$$

The procedure for calculation of monthly ET_O is to:

1. Calculate I for all the months in which the mean monthly temperature is above 0°C (Equation 5); for the Prairies this can be considered to be April through October;
2. Use Equation 6 to obtain *a;*
3. Use Equation 4 with the monthly air temperature and the appropriate day length factor to obtain ET_o.

2.1.5 Blaney-Criddle formula:

This formula, based on another empirical model, requires only mean daily temperatures T (C) over each month. Then:

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$$ET_o = p.(0.46.T + 8) \text{ mm/day} \quad (7)$$

Where ET_o reference evapotranspiration (mm day^{-1}), *p* is the mean daily percentage (for the month) of total annual daytime hours.