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Testing and Modification of Dalton's Evaporation Model

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Abstract
Knowledge of the process of evaporation is a must for project planning for irrigated areas, water requirement for basins, interstate and other litigations and international negotiations. This study was undertaken mainly to examine the effects of different meteorological parameters on pan evaporation and to develop suitable regression models to predict the rate of evaporation for different periods within a particular year. The study was undertaken to test the validity of Dalton's evaporation model for its use under the climatic condition of Udaipur region in India. This paper summarises the test results of the study made on the basis of regression model, original Dalton's model and the modified Dalton's model. It was fount that the results obtained by use of the modified model were very close to the observed rate of evaporation in the region. Variations between the estimated and observed evaporation were found to be -26.95, -4.55, -22.22 and -23.28% for Rabi season, Summer season, Kharif season and for the whole year respectively. As against this, when the modified model was used, corresponding variations were found to be +1.02, +8.20, -7.93 and -4.83% respectively. Further, the variation between the modified model predicted and observed rate of evaporation for the Rabi season of the crop year 1992-93 was found to be +7.2%. The test results indicated that the modified model could be used with a higher degree of accuracy in the region.

Keywords: *Evaporation, climate, humidity, saturated vapour pressure, regression analysis etc.*

INTRODUCTION

Evaporation of water plays an important part in most human activities designed to satisfy basic needs. The rate of evaporation from the open water surfaces can be measured by evaporimeters or open pans. However, pan evaporation data are not always available for a particular climatic region. Under such conditions prediction equations are often used for the purpose. Approaches do vary, however, for efficient design and operation of irrigation and other related projects adequate knowledge of the quantity of water that is lost through the process of evaporation is necessary (Blaney and Criddle 1958). Many evaporation models have been developed by scientists and researchers. However, such models are often used in areas with climatic condition different from that of the area in which the models were originally developed. This entails adequate testing validation of the models regarding their validity to be used under another climatic condition. In Udaipur region of India too where such models were in use were not tested and validated. It was therefore, felt necessary to determine the reliability of five such most commonly used evaporation models so as to make them useful for future prediction. This paper however, summarises test results of only Dalton's model which form the basis of the evaporation process. The model was tested and validated with the help of a data-base of twenty years (1973-1992) and on the basis of a local set of regression models. The main objective of this paper is to present the test results of regression analysis for prediction of evaporation and also the test results of original and modified Dalton's model.

Materials and Methods

The study was conducted at the College of Technology and Agricultural Engineering, Udaipur. The data required for the study were collected from the Agricultural Meteorological Station located at the Demonstration Farm of the college with good fetch in all directions. It is however, advisable to collect data from a network of stations for better accuracy and representation. The area falls under the sub-humid region of the agro-climatic zone IV-A of the state of Rajasthan in India and is situated between 24^0 35' N latitude and 73^0 42' E longitude at an altitude of about 582.17 m above mean sea level. The average rainfall in the region is about 662.0 mm and more than 80.0% of this amount is received during the Kharif season alone due to the influence of South-West monsoon. Mean values of different meteorological parameters determined on the basis of past twenty years data (1973-1992) on seasonal as well as on annual basis are presented in Table 1

Table 1. *Seasonal and annual mean values of different meteorological parameters (1973-1992)*

Parameters Period	**Temperature (°C)**	**Relative Humidity (%)**	**Sunshine (hrs/day)**	**Wind Velocity (km/hr)**	**Evaporation (mm/day)**
Rabi season	17.91	54.79	9.41	3.66	3.71
Summer season	27.90	34.23	10.31	7.07	10.11
Kharif season	27.12	66.46	6.87	6.25	5.67
Whole year	23.50	55.40	8.60	5.40	5.80

The soils of the area fall under the class sandy-clay-loam with a bulk density in the range of 1.57gm/cc to 1.62 gm/cc at depths 0-30 cm and 30-60 respectively. Infiltration rate was found to be about 2.2 cm/hr while the field capacity was found to be 21.0% on dry weight basis. Electrical conductivity was found to be 0.18 m mhos/cm at 25 C and soil pH was found to be 8.7.

Regression Analysis

Since a physical basis was needed for predicting evaporation in the region, multiple linear regression analysis was carried out and suitable regression models were developed both for seasonal prediction and yearly prediction with evaporation as the predicted variable and temperature, relative humidity, sunshine and wind velocity as predictor variables. For this purpose, the whole year was divided into three seasons prevailing in the region on the basis of standard weeks as given below.

Rabi season	42^{nd} week (mid October)	to	11^{th} week (mid March)
Summer season	11^{th} week (mid March)	to	22^{nd} week (May end)
Kharif season	22^{nd} week (May end)	to	42^{nd} week (mid October)

Regression analysis was carried out to develop seasonal and yearly prediction equations. Regression coefficients, standard errors and constant values were determined and underlying regression model was developed for each case. Computed’t’ values were compared with standard‘t’ values to examine significance.

The Dalton's Model

The fundamental principle of evaporation from a free water surface was enunciated by John Dalton, an English chemist, meteorologist and physicist in the year 1882, according to which, evaporation is a function of the difference in the vapour pressure of the water body and the vapour pressure of the surrounding air. The concept may be mathematically presented as follows:

E **= f (w) (e_s-e_d)** where,

E = Evaporation rate, mm/day

e_s = Saturated vapour pressure at mean air temperature, mm Hg

e_d = Saturated vapour pressure at mean dew point temperature (Actual vapour pressure in the air), mm Hg

f (w) = **0.26(1.0 + 0.54W_2)** = Wind function

W_2 = Wind velocity at 2.0 m from the ground, m/sec

Saturated vapour pressure values were obtained from standard tables and actual vapour pressure values were obtained by multiplying the relative humidity values to the saturated vapour pressure values at air temperature. Since, data on wind run were obtained at a height of 3.0 m from the ground surface, a correction factor of 0.93 was applied to convert the same to data on wind run at 2.0 m from the ground surface so as to meet the analytical requirement of the equation representing the wind function. Seasonal and yearly values of each of the components of the model were calculated based on the background data of twenty years to determine the evaporation rate for each season and for the whole year alike. Estimated values were compared with the observed values to determine the deviations. The causes of deviation were examined for the purpose of validating the model. The model after being validated was put to use again to estimate seasonal and yearly evaporation. Further, the validated model was used to predict the rate of evaporation for the Rabi season of the crop year 1992-93 to test its suitability. The predicted value was then compared with the observed value of evaporation.

Results and Discussion

Test results of regression analysis

For the purpose of the present study multiple linear regression analysis was carried out to establish relationship between the predicted variable evaporation and the predictor variables, temperature, relative humidity, sunshine and wind velocity at 95.0% level of confidence. Multiple linear regression models were only developed for the purpose of the study, since the use of complex logarithmic, quadratic and cubic regression models did no significantly improve the estimation of evaporation as calculated from a linear regression (Baier et al. 1965). The test results are presented in Table 2 to Table 5.

Table 2. *Meteorological parameters influencing evaporation and their statistical values (Rabi season)*

Predictor variable, Xi	Regression coefficient, Bi	Standard error	t-value
Temperature(T), °C	0.09	0.02	3.95
Relative humidity(H), %	-0.08	0.02	-4.27
Sunshine(S), hrs/day	0.67	0.22	3.10
Wind velocity at 3.0m(W), km/hr	0.26	0.13	2.05
Constant (C)	-0.44	3.02	-0.14
Coefficient of correlation, R(adjusted) = 0.9873	Coefficient of determination, R^2(Adjusted) = 0.9747		
Standard error = 0.18 mm/day	Predicted variable : Evaporation(E), mm/day		

Prediction model (Rabi season), E = C + f(B,X) = -0.44 + 0.09(T) - 0.08(H) + 0.67(S) + 0.26(W)

Table 3. *Meteorological parameters influencing evaporation and their statistical values (summer season)*

Predictor variable, Xi	Regression coefficient, Bi	Standard error	t-value
Temperature(T), °C	0.43	0.06	7.51
Relative humidity(H), %	-0.10	0.02	-5.57
Sunshine(S), hrs/day	-0.45	0.28	-1.63
Wind velocity at 3.0m(W), km/hr	0.49	0.16	3.03
Constant (C)	2.88	2.86	1.01

Coefficient of correlation, R(Adjusted) = 0.9972	Coefficient of determination, R^2(Adjusted) = 0.9942
Standard error = 0.16 mm/day	Predicted variable : Evaporation(E), mm/day

Prediction model (Summer season), E = C + f(B,X) = 2.88 + 0.43(T) - 0.10(H) - 0.45(S) + 0.49(W)

Table 4. *Meteorological parameters influencing evaporation and their statistical values (Kharif season)*

Predictor variable, Xi	Regression coefficient, Bi	Standard error	t-value
Temperature(T), °C	0.56	0.09	6.54
Relative humidity(H), %	-0.13	0.03	-5.40
Sunshine(S), hrs/day	-0.07	0.13	-0.55
	0.15	0.11	1.32
Constant (C)	-1.12	3.25	-0.34

Coefficient of correlation, R(Adjusted) = 0.9906	Coefficient of determination, R^2(Adjusted) = 0.9812
Standard error = 0.36 mm/day	Predicted variable : Evaporation(E), mm/day

Prediction model (Kharif season), E = C + f(B,X) = -1.12 + 0.56(T) - 0.13(H) - 0.07(S) + 0.15(W)

Table 5. *Meteorological parameters influencing evaporation and their statistical values (Whole year)*

Predictor variable, Xi	Regression coefficient, Bi	Standard error	t-value
Temperature(T), °C	0.19	0.04	4.78
Relative humidity(H), %	-0.03	0.02	-1.56
Sunshine(S), hrs/day	0.63	0.14	4.66
Wind velocity at 3.0m(W), km/hr	0.87	0.12	7.25
Constant (C)	-7.18	2.42	-2.97

Coefficient of correlation, R(Adjusted) = 0.9934	Coefficient of determination, R^2(Adjusted) = 0.9869
Standard error = 0.36 mm/day	Predicted variable : Evaporation(E), mm/.day

Prediction model (Whole year), E = C + f(B,X) = -7.18 + 0.19(T) - 0.03(H) + 0.63(S) + 0.87(W)

It is evident from the above analysis that there exists a strong relationship between the selected meteorological parameters and evaporation as indicated by the coefficients of correlation and determination. The standard errors obtained indicate that the results predicted by the regression models would contain error ranging from 0.16 mm/day to 0.36 mm/day.

Test results of Dalton's model

Estimated values of each of the components of the model and the resulting rates of evaporation on seasonal and yearly basis are presented in Table 6

Table 6. *Evaporation estimated by Dalton's model*

Components → Periods ↓	**Saturated vapour pressure at mean air temperature, e_s (mm Hg)**	**Relative humidity (%)**	**Saturated vapour pressure at dew point temperature, e_d (mm Hg)**
1	2	3	4
Rabi season	15.38	54.79	8.43
Summer season	28.20	34.23	9.65
Kharif season	26.85	66.46	17.85
Whole year	21.68	55.40	12.01

Vapour pressure deficit, (e_s -e_d) (mm Hg)	Wind velocity at 3.0 m (m/sec)	Correction factor	Wind velocity at 2.0 m, W_2 (m/sec)
5	6	7	8
6.95	1.02	0.93	0.95
18.55	1.97	0.93	1.83
9.00	1.74	0.93	1.62
9.67	1.51	0.93	1.40

Wind function, f(w) $=0.26(1.0+0.54W_2)$	Estimated pan evaporation, E (mm/day)	Observed pan evaporation, Ep (mm/day)	Variation (%)
9	10	11	12
0.39	2.71	3.71	-26.95
0.52	9.65	10.11	-4.55
0.49	4.41	5.67	-22.22
0.46	4.45	5.80	-23.28

It is evident from the results that the values of evaporation estimates with the help of Dalton's model for the seasons and for the whole year lag behind the values of evaporation observed with the help of a standard United States Weather Bureau Class A pan. The estimated values of evaporation have been found to differ from the observed pan evaporation values by -26.95, -4.55, -22.22, and -23.28% for Rabi season, Summer season, Kharif season and yearly estimates respectively. This indicates that, the rate of evaporation is not only a function of vapour pressure and wind velocity but also of various other factors not included in the model. Nevertheless, the basic principle of evaporation put forward by Dalton that, evaporation is a function of vapour pressure gradient , can hardly be challenged due to the fact that vapour pressure deficit is nothing but the result of the integrated effect of all other meteorological parameters to a large extent. The discrepancy in the result obtained may be attributed to the vapour pressure deficit term and also the wind function term. Vapour pressure deficit ideally needs to be determined by finding the difference between the saturated vapour pressure at the temperature at the water surface and the saturated vapour pressure at the dew point temperature. Since, vapour pressure values at the temperature of the water surface were not available, saturated vapour pressure values at mean air temperature were taken. The values of the saturated vapour pressure at dew point temperature obtained by multiplying the saturated vapour pressure values at mean air temperature by the relative humidity values for each case. Further, the discrepancy in the result is attributed to the wind function term. It is evident that the same wind function term cannot be used for all the regions and for all the seasons due to the fact that wind velocity pattern, surface roughness and history which determine the wind function term vary from place to place and from season to season. This finding justifies the finding of Al-Nakshabandi (1974).

The pan factor used in the wind function term plays an important role in this regard. The main reason for using a pan factor is aerodynamic, but an equally strong reason lies in the differences in energy exchanges between the water surface and the atmosphere. This imposes a marked seasonal effect on the factor as mentioned by Penman (1965) in reference to the study of Lake Hefner. The empirical constants in the wind function depend also on the nature of the surface over which wind movement takes place and hence are required to be determined locally; where this has not been done, the use of inappropriate constants have found to cause the reliability of estimates of evaporation to be low. This has proved to be true in the present context too as evidenced by the results.

Modification of the Model

Keeping in view the importance of the pan factor and the empirical constants, a regression analysis was further carried out to determine the exact value of the pan factor and the values of the empirical constants associated with the wind function. The analysis gave rise to the following values to represent the modified wind function term.

Pan factor = 0.50
Empirical constants = 1.0 **and 0.10**
Modified wind function, f (w) = 0.50**(1.0 + 0.10W_2)** where,
W_2 = Wind velocity at 2.0 m above the ground surface, m/sec
The modified model may now be represented as follows:
E = f (w). (e_s -e_d)

The terms in the modified model bear the same unit of measurement as in the original model. Based on these modifications, evaporation rates for all the three seasons and for the whole year alike were re-estimated for the period 1973-1992 to check the suitability of the modified model. The results are presented in Table 7

Table 7. *Evaporation estimated by modified Dalton's model*

Components **Periods**	**Saturated vapour pressure at mean air temperature, e_s (mm Hg)**	**Relative humidity (%)**	**Saturated vapour pressure at dew point temperature, e_d (mm Hg)**
1	2	3	4
Rabi season	15.38	54.79	8.43
Summer season	28.20	34.23	9.65
Kharif season	26.85	66.46	17.85
Whole year	21.68	55.40	12.01

Vapour pressure deficit, (e_s -e_d) (mm Hg)	**Wind velocity at 3.0 m (m/sec)**	**Correction factor**	**Wind velocity at 2.0 m, W_2 (m/sec)**
5	6	7	8
6.95	1.02	0.93	0.95
18.55	1.97	0.93	1.83
9.00	1.74	0.93	1.62
9.67	1.51	0.93	1.40

Modified wind function, f(w) =0.50(1.0+0.01W_2)	**Estimated pan evaporation, E (mm/day)**	**Observed pan evaporation, Ep (mm/day)**	**Variation (%)**
9	10	11	12
0.54	3.75	3.71	+1.02
0.59	10.94	10.11	+8.20
0.58	5.22	5.67	-7.93
0.53	5.52	5.80	-4.83

It is evident from the new set of results that the modified model has been able to predict the rate of evaporation with a better degree of accuracy. The variations obtained for each case are well within the acceptable limit. The discrepancy in the result is due mainly to the vapour pressure deficit term for causes mentioned earlier. There is further scope of modifying the wind function term based on wind profile theory that includes a roughness parameter by assuming that the roughness parameter is constant with time and the same for all free water surfaces. A solution satisfactory for all circumstances is not found and fundamentally it cannot be expected to exist. Hence, it is suggested that different wind functions terms be developed for different seasons based on local data base as longer as possible.

Prediction of evaporation rate for Rabi season (1992-93)

As discussed earlier, the model was modified based on a data base of twenty years (1973-92). However, it was felt necessary to apply the model for future prediction and for this the rate of evaporation for the Rabi season of the crop year 1992-93 was predicted. The result is presented in Table 8

Table 8. *Evaporation predicted by modified Dalton's model (Rabi season, 1992-93)*

Components **Periods**	**Saturated vapour pressure at mean air temperature, e_s (mm Hg)**	**Relative humidity** **(%)**	**Saturated vapour pressure at dew point temperature, e_d (mm Hg)**
1	2	3	4
Rabi season	15.25	54.65	8.33

Vapour pressure deficit, (e_s -e_d) (mm Hg)	**Wind velocity at 3.0 m (m/sec)**	**Correction factor**	**Wind velocity at 2.0 m, W_2 (m/sec)**
5	6	7	8
6.92	0.79	0.93	0.74

Modified wind function, f(w) =0.50(1.0+0.01W_2)	**Estimated pan evaporation, E (mm/day)**	**Observed pan evaporation, Ep (mm/day)**	**Variation (%)**
9	10	11	12
0.53	3.67	3.42	+7.20

It is clear from the above table that there is an over-estimation of 0.25 mm/day of evaporation accounting for a variation of +7.20% between predicted and observed rate of evaporation. The variation in the result may be considered to be minor as far as daily rate of evaporation is concerned. However, while estimating the total water loss over the season that spreads over 147 days, this variation may be of importance, as this would exaggerate the picture of actual water loss through the process of evaporation, leading to over application of water.

The discrepancy in the result may be attributed to the vapour pressure deficit term and the wind function term. While modifying the wind function term it was considered to be a function of wind velocity alone as they are better correlated than any other parameter. However, studies carried out by Wartena (1973) reveal that the wind function term is not only determined by the wind speed but also by surface roughness, atmospheric stability and a function of the roughness to the windward side. Further, a single wind function to suite all conditions those exist over a year and from season to season is practically impossible to arrive at. Hence, it is advisable to determine different wind function terms individually for each season by considering the factors discussed above to obtain better results of evaporation rate. This justifies the finding of Singh et al. (1981). It is further suggested that data on meteorological parameters be collected from as many stations as possible within the region under consideration for validation of the model and for better representation. This is due to the fact that, evaporation and for that matter all meteorological parameters vary spatially and observations in a single meteorological station cannot describe the evaporation occurring at all sites in the region (Davenport 1967).

Estimation of evaporation by regression model

The rate of evaporation for the Rabi season of the crop-year 1992-93 was also calculated with the help of the regression model developed for the season and compared with the actual rate of evaporation as presented in Table 9

Table 9. *Evaporation estimated by regression model for the Rabi season, 1992-93*

Temperature(T) (°C)	Relative humidity(H) (%)	Sunshine(S) (hrs/day)	Wind velocity at 3.0 m (Km/hr)
17.70	54.65	9.40	2.84

Evaporation**, E = -0.44 + 0.09(T) - 0.08(H) + 0.67(S) + 0.26(W)**

= -0.44 + 0.09(1`7.70) - 0.08(54.65) + 0.67(9.40) + 0.26(2.84) = 3.82 mm/day

The regression model overestimates the rate of evaporation by 0.40mm/day. This is due to the error inherent in the model. This may be attributed to the fact that in developing the model only the above mentioned parameters were taken into consideration while, factors like topography, soil heat flux, water quality were not considered.

CONCLUSIONS

Based on the study and in light of the foregoing discussion the following specific conclusions are drawn.

1. Regression analysis carried out to study the relative effects of the meteorological parameters on evaporation reveals that among all the parameters, relative humidity has the maximum of retarding effect on evaporation, while temperature and wind velocity have been found to have positive effect on the rates of evaporation.
2. The regression models developed for the purpose of the study could be used as a physical basis only to compare model predicted results.
3. The modified model can be used for predicting the rate of evaporation both for short-term as well as long-term purposes. However, proper care must be taken while evaluating the vapour pressure deficit term.
4. The wind function term if developed individually for each season and for the whole year alike would provide higher accuracy in the results.
5. There is further scope for development of calculation procedure based on this study from turbulent transfer mechanism. This finding compares well with the finding of Wartena (1974).
6. In general, it is concluded that adequate testing and validation of any evaporation model is a prerequisite before the model is put to use. Further, any such testing and validation must always be based on a data-base as longer as possible to minimise error in evaluating various terms and

coefficients associated with the model and for validation of the model itself.

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