

Dependence of evaporation on meteorological variables at different time-scales and intercomparison of estimation methods

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Abstract:

This paper consists of two parts. In the first part, the significance of five major factors, including solar radiation, vapour pressure deficit, relative humidity, wind speed and air temperature, that control evaporation were evaluated comparatively at different time-scales using the data from Changines station in Switzerland. The comparative evaluation was made at hourly, daily, 10-day and monthly time-scales. It was found that the role of controlling variables in evaporation varied with the time-scale. The vapour pressure deficit was best correlated with pan evaporation at all time-scales, while the wind speed was least correlated with pan evaporation, especially when the time period was longer than a day. In the second part, four equations for calculating evaporation, including temperature-based methods, humidity-based methods, mass transfer methods and radiation-based methods, were compared with pan evaporation. Of these four equations, the Penman equation, representing the mass transfer method, resulted in monthly evaporation values that agreed most closely with pan evaporation values. The Romanenko equation, representing the humidity method, also compared reasonably well with pan evaporation. The Turc equation, representing the radiation method, and the Thornthwaite equation, representing the temperature method, were found to underestimate evaporation significantly, especially for cold months. © 1998 John Wiley & Sons, Ltd.

KEY WORDS evaporation; time-scale; pan evaporation; estimation methods; meteorological variables

INTRODUCTION

Evaporation estimates are essential for water balance studies, agricultural irrigation, water supply, flow forecasting and land resource planning. Of all the components of the hydrological cycle, evaporation is perhaps the most difficult component because of complex interactions between the components of the land–plant–atmosphere system. Evaporation depends on the supply of heat energy and the vapour pressure gradient, which, in turn, depend on meteorological factors such as temperature, wind speed, atmospheric pressure, solar radiation, quality of water and the nature and shape of evaporation surface (e.g. Morton, 1968). These factors also depend on other factors, such as geographical location, season, time of day, etc. Thus, the process of evaporation is rather complicated. Much of the ensuing discussion of meteorological factors is couched in terms of evaporation from a free-water surface. The rate of evaporation from a saturated soil surface is approximately the same as that from an adjacent water surface of the same temperature (e.g. Linsley *et al.*, 1982). Therefore, in many studies the estimation methods of free-water evaporation are also used for estimating potential evaporation (e.g. Panu and Nguyen, 1994; Winter *et al.*,

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1995). Moreover, the relative effect of pertinent meteorological factors is, at best, difficult to evaluate, and any conclusions must be qualified in terms of the time-scale considered.

In view of the above considerations, this paper first analyses and compares the roles of controlling variables of free-water evaporation with change of time-scale. The dominating factors affecting evaporation for different time-scales are then determined, which then forms the basis for choosing the evaporation estimation method suitable at different time-scales. In this comparative study, the time-scales considered are hourly, daily, 10-day and monthly. After that, different methods, which include temperature, humidity, mass-transfer, and radiation methods, are examined and compared.

STUDY REGION AND DATA

The Changines climatological station in the state of Vaud in Switzerland was used in this study. This station is located at a latitude of 46°24 N and a longitude of 06°14 E. Several hydrometeorological variables, including air temperature, wind speed, relative humidity, solar radiation, vapour pressure, and evaporation, among others, have been continuously recorded for the period 1990–1994. The hourly data were selected and subsequently integrated to the daily, 10-day and monthly values for use in the study. The monthly averages of the main climatic parameters and the amount of evaporation are given in Table I.

Table I. Monthly averages of the main climatic parameters and evaporation for station Changines in Switzerland (1990–1994)

Month	Temperature (°C)	Wind speed (m/s)	Vapour pressure deficit (mb)	Humidity (%)	Radiation cal/cm ² /d	E_{pan} (mm)
January	2.19	2.44	1.52	80.50	88.16	29.28
February	2.77	2.45	1.79	78.25	159.33	32.25
March	7.47	2.61	3.50	69.22	266.14	67.69
April	8.98	2.71	4.29	67.76	346.34	83.40
May	14.30	2.60	5.89	68.19	457.92	106.77
June	16.70	2.54	6.37	70.74	462.61	104.10
July	20.14	2.42	9.08	66.08	513.29	146.32
August	20.53	2.40	9.90	63.84	445.13	152.25
September	15.28	2.18	4.91	75.05	295.72	82.59
October	10.03	2.35	2.45	81.16	169.04	43.71
November	6.04	2.21	1.69	82.65	84.70	28.75
December	2.75	3.08	1.52	80.37	71.98	31.76

DEPENDENCE OF EVAPORATION ON METEOROLOGICAL VARIABLES

In order to have a better comparative evaluation, it is preferable to use dimensionless quantities. In this study, the standardized values of each variable were computed and compared by using the transformation

$$Z_i = (X_i - \mu)/\sigma \quad (1)$$

where x is a variate, i is the i th value, μ is the mean of x and σ is the standard deviation of x . The same transformation was applied to mean hourly, daily, 10-day and monthly values. The comparisons are shown in Figures 1–5.

Figure 1 shows that the vapour pressure deficit remains as a controlling factor of evaporation for time-scales varying from hourly to monthly. That is why the mass transfer methods for evaporation estimation based primarily on the vapour pressure gradient give generally good results for various time-scales (e.g. Singh and Xu, 1997a, b).

It is seen from Figure 2 that wind speed is more or less a controlling factor for hourly data only. The degree of dependence of evaporation on wind speed, however, decreases as the time-scale increases. For time steps

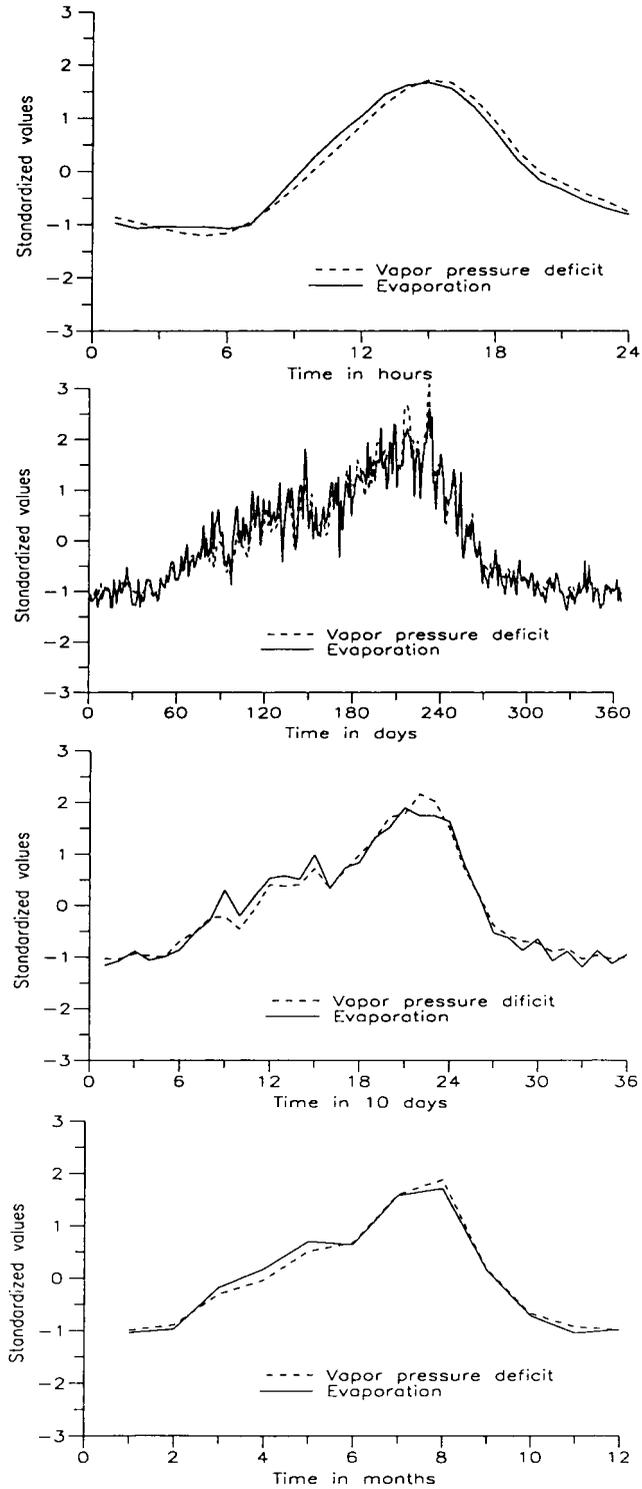


Figure 1. Dependence of evaporation on vapour pressure deficit at different time-scales (mean values calculated for the period 1990–1994)

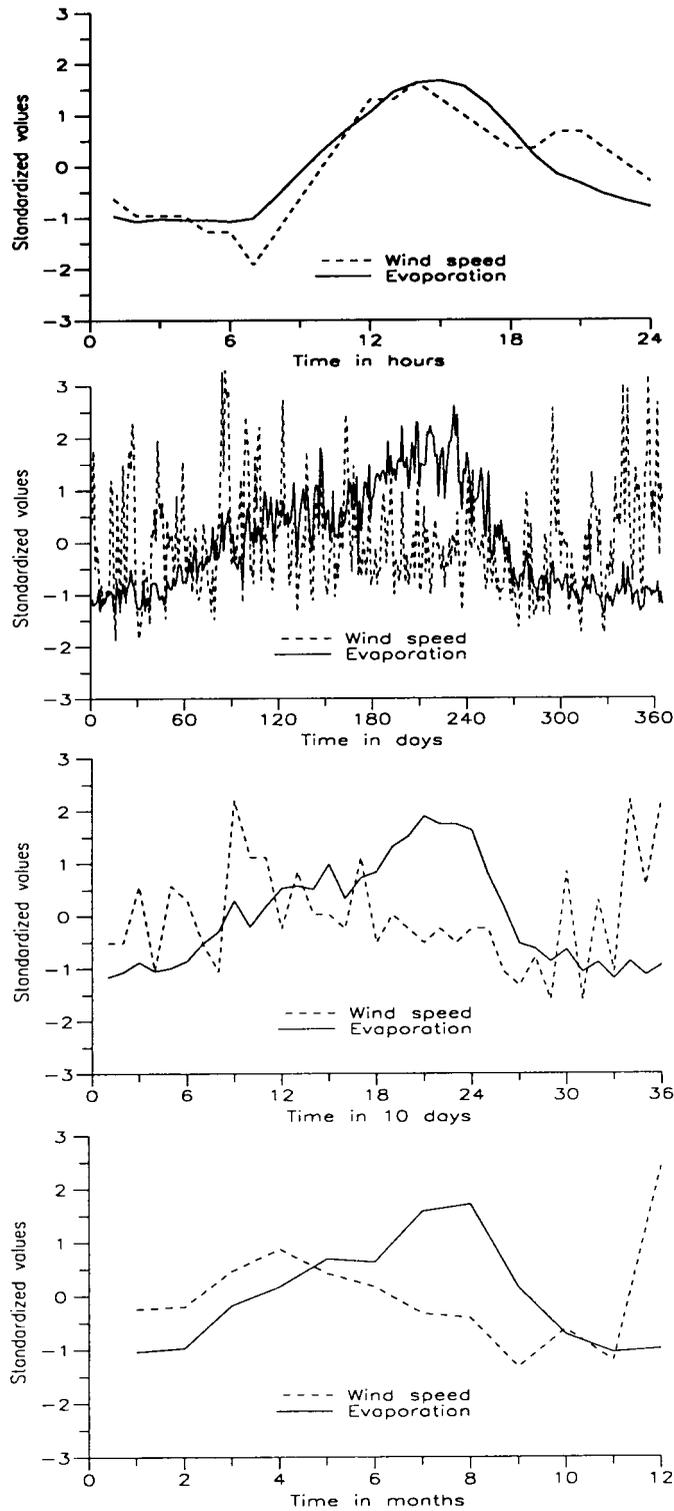


Figure 2. Dependence of evaporation on wind speed at different time-scales (mean values calculated for the period 1990–1994)

that are longer than, say, one day wind speed no longer remains a significant factor. This finding is in agreement with the statement of Linsley *et al.* (1982): 'If radiation exchange and all other meteorological elements were to remain constant over a shallow lake for an appreciable time, the water temperature and evaporation rate would become constant. If the wind speed were then suddenly doubled, the evaporation rate would also double momentarily. The increased rate of evaporation would immediately begin to extract heat from the water at a more rapid rate than what could be replaced by radiation and conduction. The water temperature would approach a new, lower equilibrium value, and evaporation would diminish accordingly. On a long-term basis, a change of 10% in wind speed will change evaporation only 1 to 3%, depending on other meteorological factors'.

In general, the relative humidity is a good indicator of evaporation (Figure 3). However, it is seen that its importance decreases as the time-scale increases. Systematic differences can be clearly seen for time-scales longer than 10 days, especially in spring and autumn months.

The dependence of evaporation on radiation is shown in Figure 4 for various time-scales. The mean diurnal pattern of change at the site shows how evaporation continues to rise following the peak in solar radiation at 12 am. The best agreement exists at a daily time-scale but the agreement at the 10-day and monthly scales is also good.

Figure 5 shows how the role of air temperature varies with time-scale. At the hourly scale, a good agreement exists between air temperature and evaporation, especially during daytime when much of the evaporation takes place. This agreement is still good on a daily base with some notable difference in autumn (days 250–320). This systematic difference increases with the increase of time-scale. It is readily apparent, at the monthly scale, that there is a time lag of about one month between evaporation and air temperature, especially in spring and autumn.

EVAPORATION ESTIMATION METHODS

There are many equations available for calculating evaporation. The wide range of data type and the expertise needed to use the various equations correctly makes it difficult for many hydrologists to select the most suitable equation to use for a given study. Estimates of evaporation can be made based on water budget methods, temperature methods, humidity methods, radiation methods, mass transfer (or aerodynamic) methods or combination (energy budget and aerodynamic) methods. The accuracy of the water budget methods depends on the accuracy with which the budget terms are evaluated. The most difficult and unreliable term to measure or estimate is the seepage rate term, especially at short time-scales, and therefore this method was not used in the study. The energy budget-based methods account for incoming and outgoing energy balanced by the amount of energy stored in the system. The accuracy of the evaporation estimate is highly dependent on the reliability and precision of a number of measurements involved in radiation measurements. Because of the detailed requirements for meteorological data this method was not used in the study either.

Based on the foregoing discussion and the availability of meteorological data as mentioned in the section on data, a temperature-based method, a humidity-based method, a radiation-based method and a mass transfer method were selected for investigation of their suitability for estimation of evaporation. The equations for each of these methods are shown in Table II. The climatological data requirements for each selected method are given in Table III.

RESULTS AND DISCUSSIONS

Evaluation of the methods involved calculating monthly estimates of evaporation for each of the four selected equations and calculations were done for five years (1990–1994) at the location represented by Changines in Switzerland. This location was selected because of the availability of the corrected pan evaporation records of the same length as other meteorological records, since one means of evaluating methods for estimating evaporation is to compare the estimates with references such as pan evaporation values.

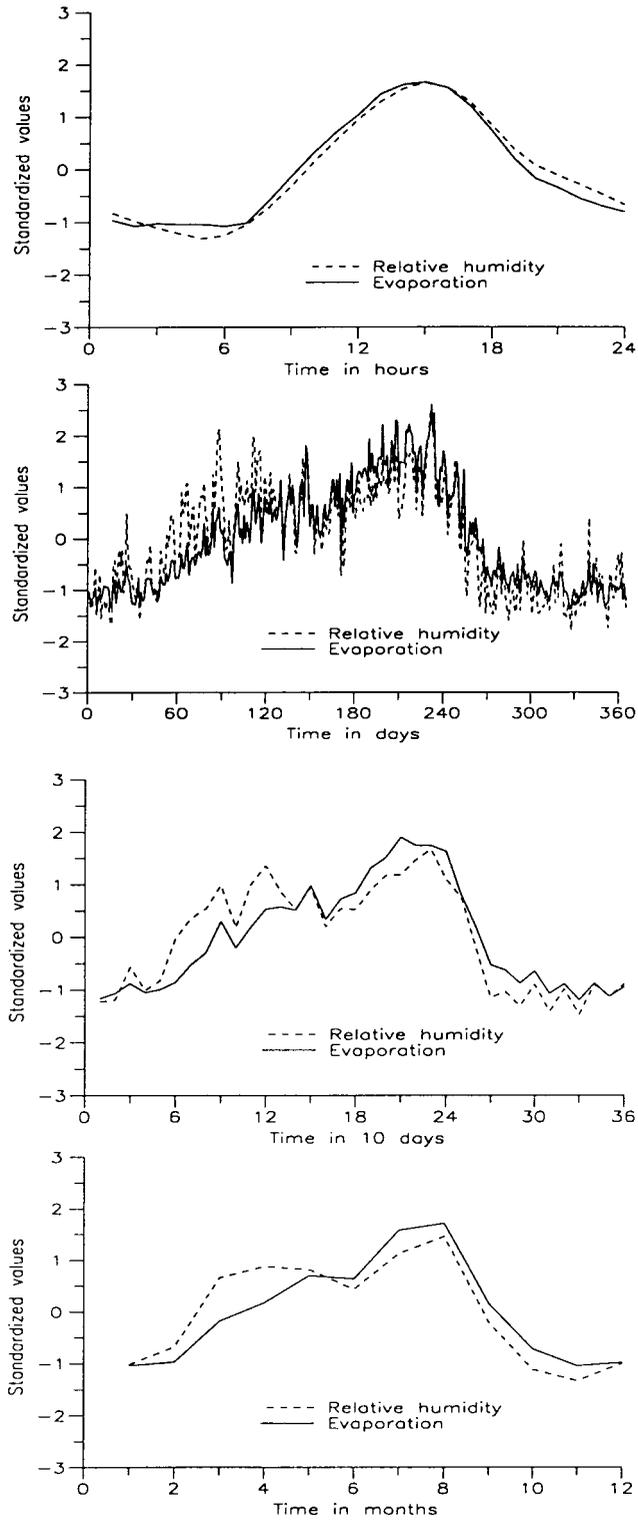


Figure 3. Dependence of evaporation on relative humidity at different time-scales (mean values calculated for the period 1990–1994)

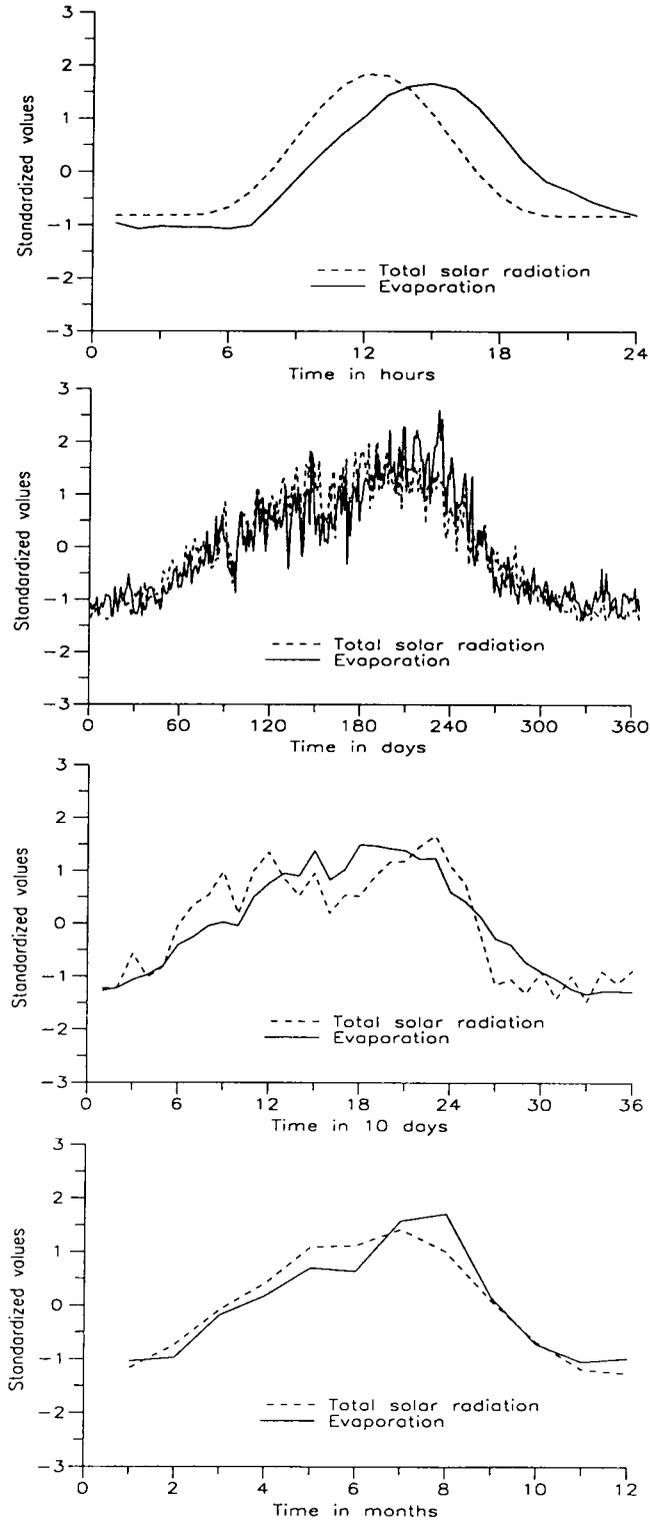


Figure 4. Dependence of evaporation on total solar radiation at different time-scales (mean values calculated for the period 1990–1994)

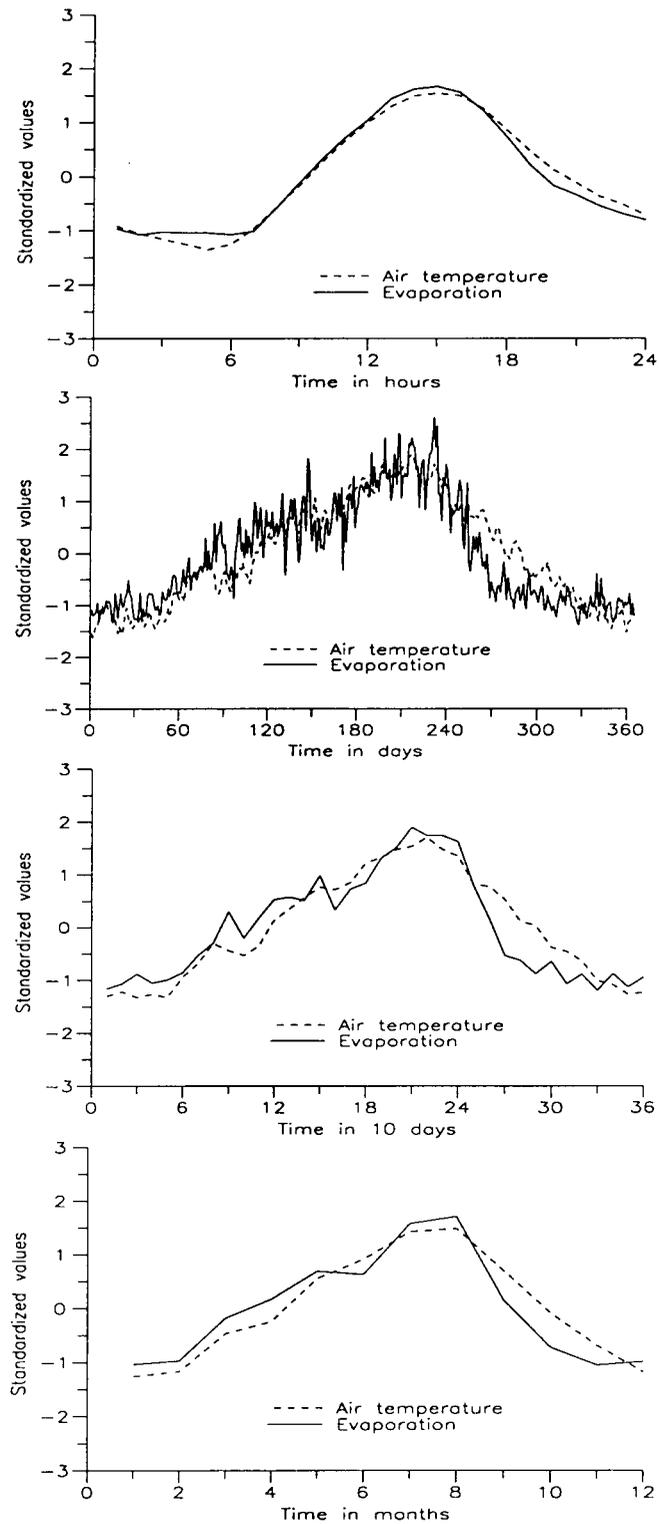


Figure 5. Dependence of evaporation on air temperature at different time-scales (mean values calculated for the period 1990–1994)

Table II. Selected equations for calculation of potential evaporation or evaporation

Method	Reference	Equation	Developed for
Temperature	Thornthwaite (1948)	$PET = 1.6 \left(\frac{10T_a}{I} \right) a$	cm/month
Humidity	Romanenko (1961)	$PET = 0.0018(25 + T_a)^2(100 - hm)$	mm/month
Mass transfer	Penman (1948)	$ET = 0.35(1 + 0.24u_2)(e_0 - e_a)$	mm/day
Radiation	Turc (1961)	$ET = 0.013 \left(\frac{T_a}{15 + T_a} \right) (R_s + 50)$	for $hm > 50$
		$ET = 0.013 \left(\frac{T_a}{15 + T_a} \right) (R_s + 50) \left(1 + \frac{50 - hm}{70} \right)$	mm/day

T_a = air temperature in °C, hm = relative humidity in %, u_2 = wind speed at 2 m height in m/s, e_0 and e_a = saturation and actual vapour pressure in mb, R_s = total solar radiation in cal/cm²/day, PET = potential evaporation and ET = free water evaporation

Table III. Climatological data requirements for various methods

Methods	Temperature	Wind speed	Humidity	Vapour pressure	Solar radiation
Thornthwaite	Y*				
Romanenko	Y		Y		
Penman		Y		Y	
Turc	Y				Y

* Y means, the indicated data needed

Table IV. Mean annual and seasonal estimated evaporation using selected methods

Season	E_{Pan} (mm)	E_{Thr} (mm)	Error* (%)	E_{Rom} (mm)	Error (%)	E_{Pen} (mm)	Error (%)	E_{Tur} (mm)	Error (%)
Winter	93.29	27.13	-70.92	83.88	-10.09	87.12	-6.61	26.56	-71.53
Spring	257.86	134.12	-47.99	213.83	-17.08	243.56	-5.55	200.69	-22.17
Summer	402.67	276.96	-31.22	351.50	-12.71	436.31	8.35	352.83	-12.38
Autumn	155.05	137.83	-11.11	144.90	-6.55	152.77	-1.47	117.89	-23.97
Annual	908.87	576.04	-36.62	794.11	-12.63	919.76	1.20	697.97	-23.20

Note: Thr = Thornthwaite method; Rom = Romanenko method; Pen = Penman method; Tur = Turc method. %Error = $\{100(\text{estimated} - E_{Pan})/E_{Pan}\}$

Mean annual and seasonal values

Mean annual and seasonal values of evaporation were computed using various methods and pan evaporation for the period of 1990–1994 and the calculated values are shown in Table IV. It can be seen that the mean annual differences between the pan evaporation and the four estimation methods ranges from 1.2 to 36.6%, with the best estimates obtained by the Penman method and the worst by the Thornthwaite method. The mass transfer method (Penman) and the humidity method (Romanenko) gave much better estimates than the Thornthwaite and Turc methods, which relate directly to the air temperature. As far as the mean seasonal values for each methods are concerned, the differences between the pan evaporation and Thornthwaite and Turc methods became even bigger, with these two methods giving values for evaporation that are too low.

Table V. Average monthly estimated evaporation using selected methods

Season	E_{Pan} (mm)	E_{Thr} (mm)	Error (%)	E_{Rom} (mm)	Error (%)	E_{Pen} (mm)	Error (%)	E_{Tur} (mm)	Error (%)
January	29.28	7.54	-74.24	26.05	-11.03	27.25	-6.93	7.32	-74.99
February	32.25	9.92	-69.24	30.72	-4.74	28.87	-10.46	12.36	-61.67
March	67.69	30.57	-54.85	58.44	-13.68	61.59	-9.02	40.67	-39.92
April	83.40	37.95	-54.50	67.14	-19.49	75.38	-9.61	58.85	-29.44
May	106.77	65.60	-38.55	88.25	-17.34	106.59	-0.17	101.17	-5.24
June	104.10	78.62	-24.48	91.71	-11.91	109.35	5.05	106.43	2.24
July	146.32	98.13	-32.93	124.73	-14.75	156.98	7.29	130.55	-10.78
August	152.25	100.21	-34.18	135.06	-11.29	169.98	11.65	115.85	-23.91
September	82.59	70.82	-14.24	73.40	-11.12	80.97	-1.96	68.25	-17.36
October	43.71	43.22	-1.12	41.82	-4.32	43.06	-1.47	35.14	-19.61
November	28.75	23.79	-17.25	29.68	3.23	28.74	-0.04	14.50	-49.57
December	31.76	9.67	-69.56	27.11	-14.65	31.00	-2.39	6.88	-78.33
Annual	908.87	576.04	-36.62	794.11	-12.63	919.76	1.20	697.97	-23.20

Mean monthly values

The test results of the average monthly evaporation calculated by the four methods and the corresponding pan evaporation are presented in Table V together with the percentage error of the estimates. The percentage error is also plotted in Figure 6. From an examination of Table V and Figure 6, it is readily apparent that the Penman and Romanenko methods, which are based on vapour pressure deficit and relative humidity, produced the least error at the Changines station, while the Thornthwaite and Turc methods produced very big errors for cold months. The Thornthwaite and Turc methods were found to underestimate evaporation consistently. It is apparent from this figure that the percentage error curves exhibit a high degree of curvature. In other words, there is a wide range of error in obtaining estimates of evaporation.

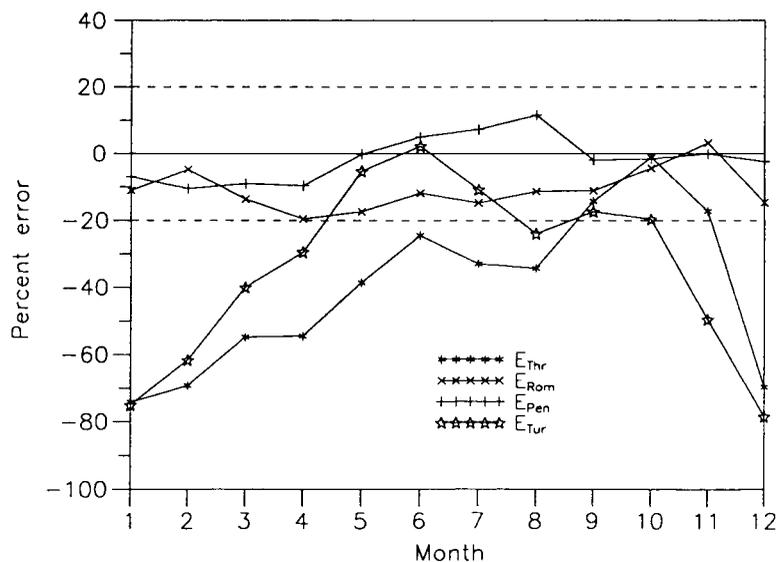


Figure 6. Variation of percentage error in evaporation estimates at Changines station using different methods (Thr = Thornthwaite; Rom = Romanenko; Pen = Penman; Tur = Turc)

Correlation between methods

The computed monthly evaporation values for five years (1990–1994) from the different methods were analysed to correlate with pan evaporation using a linear regression equation:

$$Y = mX + c \quad (2)$$

where Y represents E_{Pan} and X is the E_t estimated from temperature (Thornthwaite), humidity (Romanenko), radiation (Turc) or mass transfer (Penman) method, and m and c are constants representing the slope and intercept, respectively. The results of regression together with the cross-correlation (r^2) between the pan evaporation and the evaporation from other methods are presented in Figure 7.

It can be seen from Figure 7 that the correlation (r^2) between pan evaporation and the temperature-based and radiation-based methods was lower. The vapour pressure deficit and humidity-based methods resulted in the highest correlation with pan evaporation. In addition, higher values of the intercept c were observed in the relation between pan evaporation and temperature and radiation-based methods. Clearly, the Thornthwaite and Turc methods significantly underestimated evaporation.

Modifications to equations

Many equations for calculating evaporation have constants or coefficients that were specified by those who developed or modified the equations to satisfy their particular needs. It is generally accepted that empirical formulae, as used in this study, may be reliable in the areas and over the periods for which they were developed, but large errors can be expected when they are extrapolated to other climatic areas without recalibrating the constants involved in the formulae. Accordingly, modifications were made to the original equations used here to improve results. The constant values of 1.6, 0.0018, 0.35 and 0.013 used in the Thornthwaite, Romanenko, Penman and Turc equations, respectively, were recalibrated and the new values obtained were 2.3, 0.0021, 0.34 and 0.015, respectively. The mean seasonal and annual values calculated by these equations with the calibrated constant values are shown in Table VI and the same regression analysis was done for the monthly values of evaporation (Figure 8). Comparison between Table IV and Table VI and between Figures 7 and 8 shows that the mean annual evaporation determined by the Thornthwaite, Turc and Romanenko equations improved greatly, while the seasonal bias is still a big problem for the Thornthwaite and Turc methods. One of the reasons, as discussed in the section on dependence of evaporation, is that there exists a time lag between monthly air temperature and pan evaporation.

Table VI. Mean annual and seasonal estimated evaporation using selected methods

Season	E_{Pan} (mm)	E_{Thr} (mm)	Error (%)	E_{Rom} (mm)	Error (%)	E_{Pen} (mm)	Error (%)	E_{Tur} (mm)	Error (%)
Winter	93.29	39.85	-57.28	96.92	3.89	84.64	-9.27	30.65	-67.15
Spring	257.86	196.99	-23.61	247.10	-4.17	236.60	-8.24	231.56	-10.20
Summer	402.67	406.79	1.02	406.19	0.87	423.86	5.26	407.11	1.10
Autumn	155.05	202.44	30.56	167.45	8.00	148.41	-4.28	136.02	-12.27
Annual	908.87	846.07	-6.91	917.66	0.97	893.51	-1.69	805.34	-11.39

SUMMARY AND CONCLUSIONS

Five major factors that control evaporation, i.e. solar radiation, vapour pressure deficit, relative humidity, wind speed and air temperature, were compared at different time-scales using the data from Changines station in Switzerland. Comparisons were made at hourly, daily, 10-day and monthly time-scales. It was shown that the role of variables controlling evaporation varies with time-scale. In general, vapour pressure

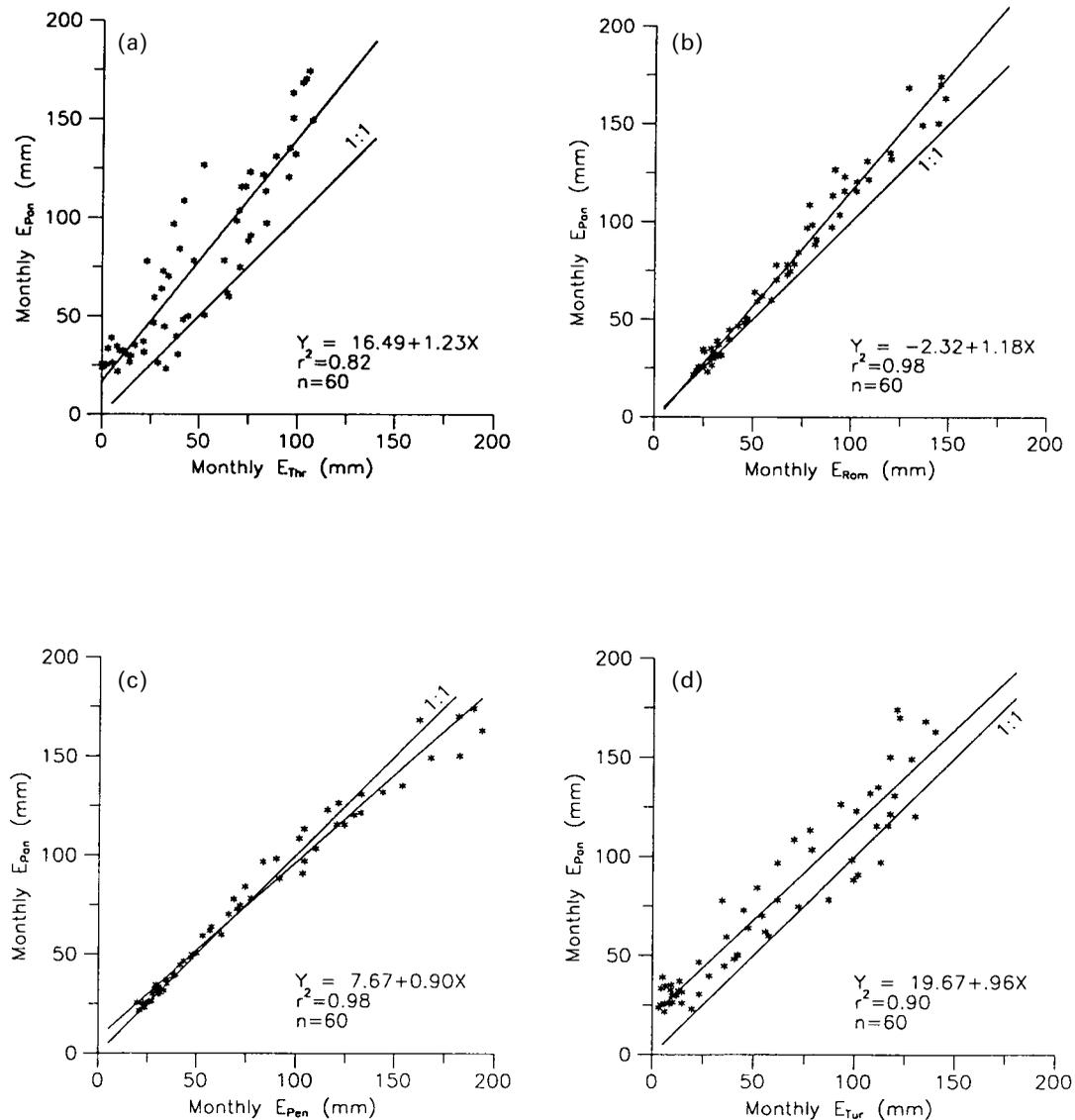


Figure 7. Comparison of estimated E_i with pan E_i for (a) the Thornthwaite equation, (b) the Romanenko equation, (c) the Penman equation and (d) the Turc equation

deficit has the best correlation with pan evaporation at all time-scales. Relative humidity and air temperature are better correlated with pan evaporation at short time-scales; at the monthly time-scale there exists a time lag between air temperature and pan evaporation. Compared with other factors, wind speed has the least correlation with pan evaporation. Solar radiation does not have the best correlation with pan evaporation, and its significance is less than vapour pressure deficit and relative humidity.

Four equations for calculating evaporation, including temperature-based, humidity-based, mass transfer and radiation-based methods, were compared with pan evaporation. Of the four original equations evaluated, the Penman equation for the mass transfer method resulted in monthly evaporation values that agreed most closely with pan evaporation values. The Romanenko equation, a humidity-based method, also

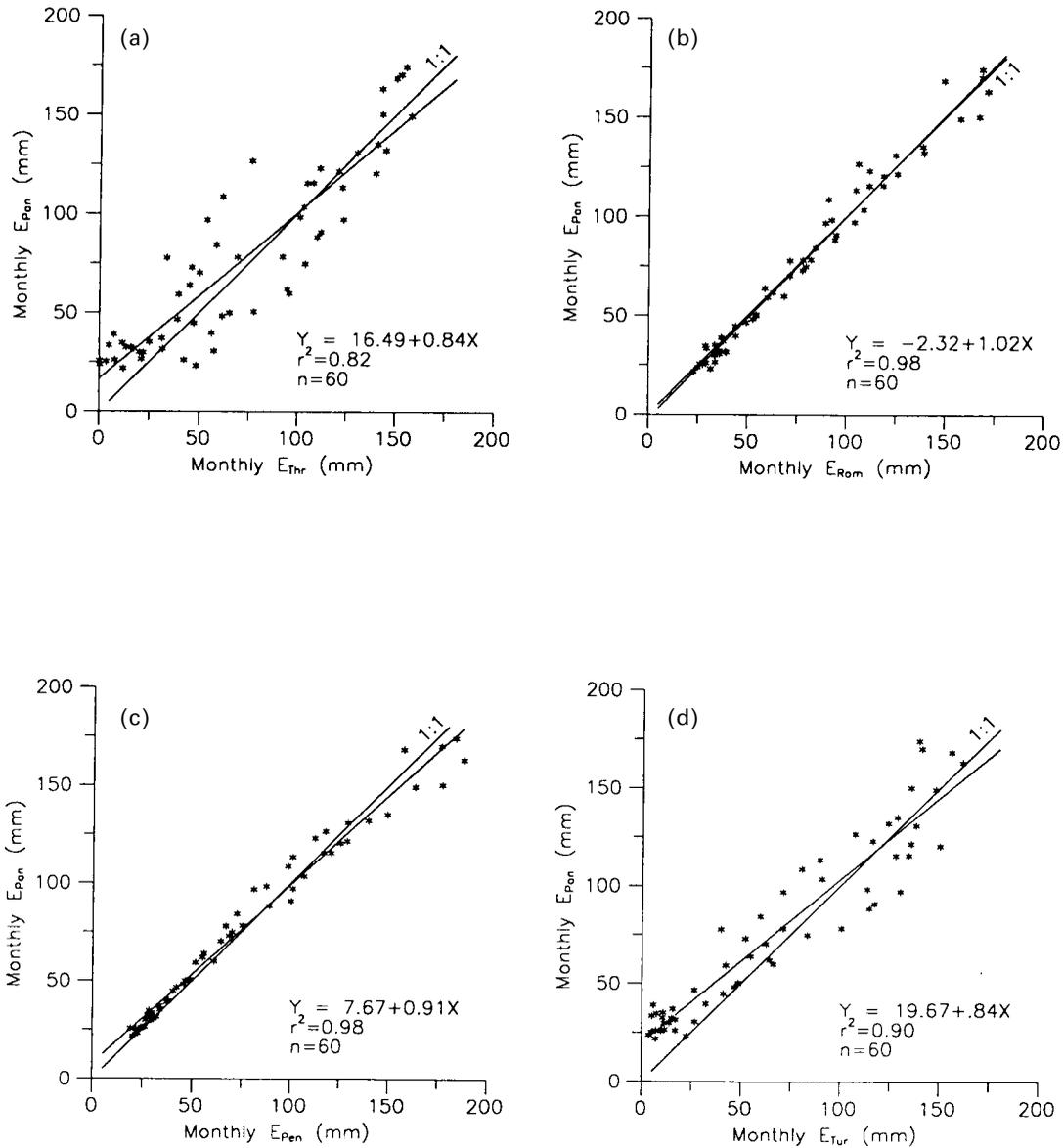


Figure 8. Comparison of pan E_t with estimated E_t with calibration constant from (a) the Thornthwaite equation (b) the Romanenko equation, (c) the Penman equation and (d) the Turc equation

compared reasonably well with the pan evaporation, while the radiation-based Turc equation and the temperature-based Thornthwaite equation were found to underestimate evaporation significantly, especially for cold months. By substituting recalibrated constant values for the original constant values, all four equations worked well for determining mean annual evaporation values. As far as the seasonal and monthly values are concerned, the Thornthwaite and Turc equations showed significant bias, compared with pan evaporation. The mass transfer-based Penman equation and the humidity-based Romanenko equation of humidity method are good choices for calculating evaporation in the study region.

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