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REVISED FAO METHODOLOGY FOR CROP-WATER REQUIREMENTS

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Abstract

In the early 1970s, the Food and Agriculture Organization of the United Nations (FAO) developed a practical procedure to estimate crop-water requirements that has become a widely accepted standard, in particular for irrigation studies. Since its publication as FAO Irrigation and Drainage Paper, new concepts and advances in research have revealed shortcomings in the methodology and made necessary a review and revision. A consultation of experts organized by FAO recommended the adoption of the Penman-Monteith combination method as a new standard for reference evapotranspiration, and advised on procedures for calculation of the various parameters. By defining the reference crop as hypothetical with an assumed height of 0.12 m, a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extensive surface of actively growing and adequately watered green grass of uniform height, the FAO Penman-Monteith method was developed, overcoming previous deficiencies and providing values more consistent with actual crop-water-use data worldwide. Furthermore, recommendations have been developed for the use of the FAO Penman-Monteith method with limited climatic data, largely eliminating the need for any other reference evapotranspiration methods and creating a consistent and transparent basis for a globally valid standard for crop-water-requirement calculations.

1. INTRODUCTION

As part of FAO's mandate to assist its member countries to increase and sustain agricultural production, the Land and Water Development Division has been instrumental in the development of a globally accepted methodology for the prediction of crop-water requirements. The methodology published first in 1974 as No 24 in the FAO Irrigation and Drainage Series, and revised in 1977 [1] has become an international standard, extensively used worldwide.

Advances in research and the more accurate assessment of crop-water use have revealed weaknesses in the FAO No-24 methodologies [2,3,4]. The FAO Penman method was found frequently to over-predict reference evapotranspiration (ET_o) while the other FAO-recommended ET_o equations, namely the FAO Radiation, the FAO Blaney-Criddle, and the FAO Pan Evaporation methods, showed variable adherence to the reference-crop evapotranspiration standard of grass. Furthermore, the problem of using grass as a reference crop resulted in inconsistencies under different climatic conditions.

A consultation of experts and researchers was organized by FAO in May 1990 in Rome, in collaboration with the International Commission for Irrigation and Drainage and with the World Meteorological Organization, to review the FAO No-24 methodologies and to advise on the revision and updating of procedures. The panel recommended the adoption of the Penman-Monteith method and revised the definition and calculation procedures for estimating reference evapotranspiration. The report of the consultation presents the results of the review and recommendations as well as the detailed procedures for the calculation of the FAO Penman-Monteith method [5].

To follow up on the recommendations, a working group was established to carry out additional studies directed at further validation of the Penman-Monteith method and to improve or replace the original radiation and temperature methods when insufficient climatic data are available. Furthermore, a review and update were undertaken of the crop coefficients in light of the newly defined concept for the reference crop.

This paper provides a summary of the review of the various ET_o methods, presents the new recommended standard of the FAO Penman-Monteith method as a consistent and globally valid standard for crop-water-requirement calculations, and indicates how to apply the method when limited climatic data are available.

The results of the review of crop coefficients of the original FAO No-24 Manual have been consolidated into a single system of coefficients with procedures to adjust for crop height and various climatic conditions. The revised crop coefficients are reported [6] under the same topic area.

2. REVIEW OF REFERENCE EVAPOTRANSPIRATION METHODS

A large number of more or less empirical methods has been developed over the last 50 years by numerous scientists and specialists worldwide, to estimate evapotranspiration from different climatic variables. Relationships were often subject to rigorous local calibrations and proved to have limited global validity.

Based on the available research results and recommendations of experts in 1971 and 1972, four evapotranspiration methods were adopted in the FAO No-24 method to be used according to the availability of climatic data, as indicated in Table I.

- The FAO modified Penman was an adaptation of the original Penman method and included a revised wind function, derived from lysimeter data at various locations worldwide.
- The FAO radiation method was based on the Makkink method, developed originally for the humid conditions in the Netherlands. By introducing a correction coefficient for wind and humidity conditions, its validity was extended to a wider range of climatic conditions.
- The Blaney-Criddle method, introduced in the early 1950s in the arid western United States, found broad application in irrigation studies and was adapted as the FAO Blaney-Criddle method for a wider range of climatic conditions by introducing a correction factor that can be determined from estimates of humidity, wind and sunshine conditions.
- The pan evaporation method has been widely adopted on agro-meteorological stations; the measured evaporation of water in a standardized container has been extensively used as an ET_o parameter and is applied in many irrigation studies and in real-time irrigation scheduling. A pan factor is required, however, to correct the evaporation from a free water surface to the evapotranspiration of a green-grass cover. The method has been consolidated in FAO No-24 by standardization of the pan factor for various climatic conditions and environments.

A key element in the procedures for determining crop-water requirements (ET_{crop}) was the introduction of the crop coefficient standardized for the various growth stages. These coefficients were given for a large number of crops with detailed calculation procedures, providing an easy and uniform method that has become the accepted standard.

The large number of ET_o-estimation methods with various locally adapted or modified parameters has become confusing for the common user. To evaluate the performance of the various estimation procedures under different climatological conditions, a major study was undertaken under the auspices of the Committee on Irrigation Water Requirements of the American Society of Civil Engineers (ASCE).

The ASCE study reported by Jensen et al. [4] analyzed the performance of twenty different methods, using detailed procedures to assess the validity of the methods compared to a set of carefully screened lysimeter data from eleven locations with variable climatic conditions. The study proved to be revealing and showed the widely varying performance of the methods under different climatic conditions. Table II shows their performance, classified for humid and arid conditions.

TABLE I. Climatic data required for the FAO evapotranspiration methods [1]

Method	Temperature	Humidity	Wind Speed	Sunshine	Evaporation
FAO Blaney Criddle	*[a]	O[b]	O	O	
FAO Radiation	*	O	O	*	
FAO Penman	*	*	*	*	
Pan Evaporation		O	O	O	*

[a]Measured data essential.
[b]Estimation required.

In a parallel study commissioned by the European Community, a consortium of European research institutes evaluated the performance of various evapotranspiration methods using data from various lysimeter studies in Europe [7]. It confirmed the overestimation by the Modified Penman method introduced in FAO No-24, and the variable performance of the other methods depending on the degree of adaptation to local conditions. The comparative studies may be summarized as follows.

- The Penman methods require local calibration of the wind function to achieve satisfactory results.
- The Radiation methods provide good results in humid climates where the aerodynamic term is relatively small, but performance in arid conditions is erratic and underestimates evapotranspiration.
- Temperature methods remain empirical and require local calibration in order to achieve satisfactory results. A possible exception is the Hargreaves method [8], which has shown reasonable ET_0 results with global validity.
- Pan evapotranspiration methods clearly reflected the shortcomings of predicting crop evapotranspiration from open-water evaporation. The methods are susceptible to the micro-climatic conditions under which the pans are operating and their performance proves erratic.
- The excellent performance of the Penman-Monteith approach both in arid and humid climates was convincingly shown in the ASCE and the European studies.

3. THE FAO PENMAN-MONTEITH EQUATION

The comparative studies and much other research have confirmed the superior performance of the Penman-Monteith approach. By introducing aerodynamic and canopy resistance in the combination method, better simulation of wind and turbulence effects and of the stomatal behavior of the crop canopy was achieved [9]. Earlier difficulties related to the estimation of the resistance values have been largely overcome by progress in research and reliable estimates of the two parameters for a range of crops including the reference crops, grass and alfalfa.

The FAO experts reached unanimous agreement in recommending the Penman-Monteith approach as the best-performing method to estimate evapotranspiration of a reference crop, and adopted the estimates for bulk surface and aerodynamic resistance as elaborated by Allen et al. [2] as standard values for the reference crop.

TABLE II. Performance of various ET_o methods [4]

Method	Humid			Arid		
	Rank no.	Over est.[a]	Stand error[b]	Rank no.	Over est.[a]	Stand error[b]
Combination						
Penman-Monteith	1	+4%	0.32	1	-1%	0.49
FAO-24 Penman (c=1)	14	+29%	0.93	6	+12%	0.69
FAO-24 Penman (corrected)	19	+35%	1.14	10	+18%	1.1
FAO -PPP-17 Penman	4	+16%	0.67	5	+6%	0.68
Penman (1963)	3	+14%	0.60	7	-2%	0.70
Penman 1963, VPD #3	6	+20%	0.69	4	+6%	0.67
1972 Kimberley Penman	8	+18%	0.71	8	+6%	0.73
1982 Kimberley Penman	7	+10%	0.69	2	+3%	0.54
Businger-van Bavel	16	+32%	1.03	11	+11%	1.12
Radiation						
Priestley Taylor	5	-3%	0.68	19	-27%	1.89
FAO-Radiation	11	+22%	0.79	3	+6%	0.62
Temperature						
Jensen-Haise	12	-18%	0.84	12	-12%	1.13
Hargreaves	10	+25%	0.79	13	-9%	1.17
Turc	2	+5%	0.56	18	-26%	1.88
SCS Blaney-Criddle	15	+17%	1.01	15	-16%	1.29
FAO Blaney-Criddle	9	+16%	0.79	9	0%	0.76
Thornwaite	13	-4%	0.86	20	-37%	2.4
Pan evaporation						
Class A Pan	20	+14%	1.29	17	+21%	1.54
Christiansen	18	-10%	1.12	16	-6%	1.41
FAO Class A	17	-5%	1.09	14	+5%	1.25

[a]Over- or under-estimation as percentage from eleven lysimeter data locations, corrected for reference type.
[b]Weighted standard error of estimates, mm/day.

The adoption of fixed values for crop-surface resistance and crop height required an adjustment of the concept of reference evapotranspiration that was redefined as follows.

Reference evapotranspiration is the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height (12 cm), a fixed crop surface resistance (70 s m^{-1}) and albedo (0.23), closely resembling the evapotranspiration from an extensive surface of green grass-cover of uniform height, actively growing, completely shading the ground and with adequate water.

Thus defined, the Penman-Monteith equation used for 24-h calculations of reference evapotranspiration and using daily or monthly mean data can be simplified as follows,

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

where

ET_o	is the reference crop evapotranspiration (mm d^{-1}),
R_n	is the net radiation at the crop surface (MJ m^{-2} d^{-1}),
G	is the soil heat flux (MJ m^{-2} d^{-1}),
T	is the average air temperature (°C),
U_2	is the wind speed measured at 2 m height (m s^{-1}),
(e_a-e_d)	is the vapour pressure deficit (kPa),
Δ	is the slope of the vapour pressure curve (kPa $°C^{-1}$),
γ	is the psychrometric constant (kPa $°C^{-1}$), and
900	is the conversion factor.

Full details of the FAO Penman-Monteith method and procedures for determining the various parameters, algorithms, recommended values and units are already published [10,11].

The FAO Penman-Monteith equation can be adapted to hourly ET_o calculations, of relevance in detailed research studies and for automatic weather stations, by replacing the conversion factor 900 in the equation by 37, equal to 900/24. Net radiation and soil heat flux are determined for hourly values by adjusted formulas for incoming radiation and heat flux. Comparison of hourly measured and calculated values and summations of hourly and 24-hour calculations showed good agreement [11].

A key element in the development of the FAO Penman-Monteith equation is the assumption of the reference crop as hypothetical, with a fixed surface-resistance value. Many studies on various crops have shown, however, that the resistance factor, which represents stomatal behaviour, is affected by climatic conditions. Solar radiation, air temperature, vapour-pressure deficit, day-length and wind affect the crop resistance to different degrees and in different directions. The study commissioned by the European Community showed increasing resistance values for lower latitudes and recommended a variable factor [7].

Further studies have been undertaken by the FAO working group to evaluate this aspect [12,13]. Results have not been conclusive and often contradictory. The original recommendation made by the FAO expert panel of a surface resistance of 70 s m^{-1} for a hypothetical grass crop is therefore maintained as a valid and standardized approximation.

4. USE OF FAO PENMAN-MONTEITH WITH LIMITED CLIMATIC DATA

A main reason to recommend the use of different ET_o methods has been the limited availability of full climatic data, in particular, sunshine, humidity and/or wind data are often lacking. To further standardize the use of the FAO Penman-Monteith method, additional studies have been undertaken to provide recommendations when limited meteorological data are available, as outlined below.

4.1. Wind data

Measured wind data are often lacking, or prove unrepresentative for the crop because of different microclimatic conditions at the agro-meteorological station. Such wind-speed differentials can be large on a day-to-day basis, whereas mean monthly values may be more consistent.

If no wind data are available, estimates can be made of average wind-speed values for ET_o calculations from global values on a monthly basis. Wind-speed data from the nearest station can be used for that purpose. The FAO CLIMWAT database [14] contains mean monthly readings from more than 3,200 stations, and allows estimates on wind data for many locations worldwide. In a further simplification, a worldwide average can be taken, based on CLIMWAT data, as follows.

$$U_2 = 2\ m\ s^{-1}$$

For windy conditions, wind speed can be approximated by an average value of 260 km day^{-1} or 3 m s^{-1} and, for low-wind conditions, values of 90 km day^{-1} or 1 m s^{-1} can be taken.

4.2. Humidity data

The radiation method was introduced in FAO No-24 to accommodate users in humid climates with measured data on temperature and radiation and with estimates for wind and humidity. Other studies [15,16] have shown that daily minimum temperature, which is more commonly available, allows reasonable estimates of the dew-point temperature. Under more arid climates greater deviations may occur, with minimum temperature 1 to 3 degrees above dew point when the weather station is surrounded by well-watered or irrigated vegetation, representing the reference condition. Actual vapour pressure (e_d) can be estimated [17] from the minimum daily temperature (T_{min}) using the following relationship.

$$e_d = 0.611 \exp\left(\frac{17.27\ T_{min}}{T_{min} + 237.3}\right)$$

ET_o values determined according to the FAO Penman-Monteith method using humidity estimates from minimum temperatures and standardized wind values (2 m s^{-1}) were improved over those made using a standard temperature formula [16].

4.3. Radiation data

Temperature methods, such as Blaney-Criddle, Turc, and Hargreaves, have remained popular because of their lack of radiation data and relatively easy calculation procedures. Studies have been undertaken by the FAO working group to correlate radiation and sunshine duration with minimum and maximum temperatures [15,18] and with rainfall [19]. Analogous to the relationship established in the Hargreaves method [8], radiation can be approximated [16] for inland stations from incoming extraterrestrial radiation (R_a) and the temperature deficit ($T_{max} - T_{min}$), using the following relationship.

$$R_s = 0.17 \frac{P}{P_o} (T_{max} - T_{min})^{0.5} R_a$$

For higher elevations, a barometric correction (P/P_o) needs to be applied, where P_o is the barometric pressure at sea level. For coastal stations, a coefficient of 0.19 proved better, while for island stations a simple relationship could be established as follows.

$$R_s = (-4 + 0.7\,R_a)$$

The correlations proved to be weak on a global basis and better ET_0 estimates were obtained when using R_s data from the nearest station with comparable climatic conditions.

5. CONCLUSIONS

The FAO-Penman-Monteith equation is recommended as the standard method for estimating reference and crop evapotranspiration. The new method has been proven to have global validity as a standardized reference for grass evapotranspiration and has found recognition by the International Commission for Irrigation and Drainage and by the World Meteorological Organization.

Procedures have been established to estimate missing climatic data that allow the FAO Penman-Monteith method to be used under all conditions. This eliminates the need for any other methods and will increase the transparency and consistency of reference and crop-water requirement studies.

The change of ET_0 definition to a hypothetical crop with fixed parameters has, to a large extent, eliminated problems related to the previous requirements in measuring a living reference ET_0, and will further facilitate the calibration of crop coefficients for the estimation of crop-water use.

It is hoped that the new FAO publication on revised procedures for crop-water requirements, which will shortly be published, will indeed become a globally accepted reference .

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