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Zusammenfassung

Auf der Grundlage von Windkanalexperimenten und Feldmessungen, die in der Oase Al Hassa (Saudi Arabien) und in Braunschweig durchgeführt wurden, wird der Einfluß verschiedener meteorologischer Parameter auf die Evaporation der USWB Class A Pan und der keramischen Verdunstungsscheibe nach *Czeratzki* untersucht. Vergleiche mit dem tatsächlichen Pflanzenwasserverbrauch zeigen, daß Pflanzen und Geräte auf die Lufttemperatur in ähnlicher Weise reagieren. In der Reaktion auf die Windgeschwindigkeit bei Trockenheit und auf die Strahlung unterscheiden sich Pflanzen und Evaporimeter jedoch ganz erheblich. Um diese Differenzen zu kompensieren, wurden Korrekturmethoden entwickelt, mit denen es möglich ist, die Evaporimeter für die Planung von Bewässerungsprojekten, für die aktuelle Steuerung von Bewässerungsanlagen und als Hilfsmittel zur Erhöhung der Effizienz des Wassereinsatzes, allgemein also als Entscheidungshilfe des Managements im Bewässerungslandbau arider und humider Regionen einzusetzen.

Abstract

On the basis of field and windtunnel measurements in Al Hassa / Saudi Arabia and Braunschweig / Fed. Rep. of Germany, the influence of different meteorological parameters upon evaporation of the USWB Class A Pan, and of the Ceramic Evaporation Disc according to *Czeratzki* is investigated. Comparisons with the consumptive use of plants show that the reactions of plants and instruments upon air temperature are similar, whereas the reaction upon wind velocity under dry conditions and upon radiation is quite different. In order to compensate those differences, correction methods are developed, with which the data of reliable evaporimeters can be used successfully for planning purposes, for actual irrigation control and as a tool for improving water use efficiency, i. e. as a basis for improving irrigation management both in arid and humid regions.

1 Introduction

Many efforts have been made by engineers to assure a sufficient supply of water for agricultural purposes and to construct, operate and maintain irrigation schemes. But there still remains the difficult task of optimum use of the scarce water resources. *Ohlmeyer* and *v. Hoyningen-Huene* (1) have demonstrated the problems of estimation of consumptive water use of crops for the design of irrigation schemes in an economically feasible scale.

There are three fundamental ways to assess the quantity of water used by plants:

- calculation using climatological or physical formulae (*Penman*, *Bowen*-ratio, *Blaney-Criddle* etc.),
- assessment from the change of water content of the rooted zone of the soil (lysimeter, tensiometer, neutron probe, gravimetric method),
- measurements with instruments (evaporimeters), which represent simulation models of plants or canopies.

The application of formulae is not always satisfying. The simple climatological regression formulae are not transferable to different climatic conditions and lead sometimes to poor results even under the climate under which they have been developed.

Equations on a proper physical basis like the one of *Penman* (2) and the improved versions (e.g. *Rijtema* (3), *Monteith* (4)) need a quite high instrumental and calculatoric effort. But they are an important tool for planning irrigation projects.

The determination of consumptive use of water by plants by measuring the change of soil moisture, is not suitable for planning purposes, but it is a reliable aid in irrigation praxis, because of the fairly correct measurement of the water status in the root zone.

The gravimetric method involves much work for practical use, while neutron probes and lysimeters are too expensive. Unfortunately tensiometers frequently draw air at tensions higher than about 0.6 bar, which often occur in sandy soils under arid conditions when the water supply of the instrument is too little. In such cases, tensiometers have to be repaired.

As a consequence, irrigation engineers prefer to use evaporimeters of different types, if these instruments are

- inexpensive in prime costs and
- easy to operate.

The optical information about the water used plays an important psychological role, particularly for the technicians operating the instruments and for the farmer.

However, evaporimeters do not always work satisfactorily for they represent only models of plants or canopies. Due to the biological reactions not considered (e.g. stomatal regulations) and due to their different geometrical shape, they are influenced in a different way by the ecological conditions.

At the Round Table Conference on Evapotranspiration, held at Budapest in 1977 by the International Commission on Irrigation and Drainage (ICID) (5) evaporation pans were recommended as partly suitable, atmometers as not suitable instruments. This recommendation results from the fact, that due to the urgent need of evapotranspiration data evaporimeters of different types are used world-wide without knowledge of their different physical properties and their different reactions.

There is no doubt, that this judgement would have been more positive, if better correction methods had been available about the fundamental physical characteristics of both, the transpiration of canopies and the evaporation of evaporimeters. Only on the basis of such knowledge a mathematical adaption of the instrumental measurements is possible using simultaneously measured parameters, such as radiation or wind velocity.

After successful experiences with the ceramic evaporimeter (*Czeratzki* disc) and the USWB Class A Pan in the course of irrigation experiments at Hofuf/Saudi Arabia, and by means of investigations in a wind tunnel of the Agrometeorological Research Station of the German Weather Service in Braunschweig/West Germany, this physical analysis was made in order to demonstrate both, the possibilities and the limits of these instruments for irrigation engineers, farmers, meteorologists and research workers.

2 Description of the instruments

2.1 The evaporation pan

The evaporation pan is the most commonly used evaporimeter. There are a number of individual types such as the USWB Class A Pan, the USB Plant Industry Pan, the GGI 1100 and others. Due to the recommendations of the ICID (5), only the Class A Pan has been tested in the investigation presented in this report.

The shape of the Class A Pan (6) is given in Figure 1. The pan is a circular basin with a surface of one squaremeter and a depth of 25.4 cm. It is made of stainless steel and unpainted. It is used both as sunken pan and, supported on a wooden frame, with the water surface 50 cm above the earth.

The water surface is to be maintained between 5 and 7 cm below the rim of the pan. Every morning and evening the difference of the water level is to be measured using a hook gage in a stilling well. Commonly the wind velocity near the pan and the maximum and minimum water temperature is measured in addition. The anemometer is mounted on the pan platform with the center of the cups about 18 cm above the rim of the pan.

2.2 The ceramic disc *(Czeratzki* disc*)*

The ceramic disc has to be described in more detail, as it is not yet introduced world-wide as a practical evaporimeter. According to *Czeratzki* (7), the evaporating body of this instrument is the lower surface S of a horizontal porous ceramic disc, 16 cm in diameter (Fig. 2). The upper surface of the disc is covered with a coarse filter, consisting of epoxy tied sand, which supports the disc and which ensures a homogeneous water supply. The filter surface is coated with epoxy. The evaporating lower surface S has an area of 200 cm^2.

The disc is supplied (suction) with distilled water by means of a copper tube at its surface and a teflon tube from a glass cylinder, which serves as a calibrated reservoir.

Because of the lower position of the cylinder as compared to the disc, there exists a subatmospheric pressure at the surface S of the disc. A conical roof prevents intervention of rainwater (due to the negative pressure within the disc) and shields the disc against radiation. This standard version of the ceramic evaporimeter with exposition heights of 200 and 50 cm above ground is used since 1969 as an instrument for controlling irrigation in Al Hassa.

By combining the disc with a recording device a recording evaporimeter can be built. Depending on the revolving speed of the cylinder any time analysis can be made. Figure 3 represents such a type of the recording ceramic evaporimeter 1) with a small radiation shield. It is recommended to combine the evaporimeter with an anemometer.

3 Investigations concerning the physical performance of the evaporimeter

Investigations in the laboratory under controlled environmental conditions have to be made in order to determine the physical reactions of the evaporimeter and to compare them with the behaviour of natural plants. Then, field investigations have to be made to evaluate the effect of the environmental factors during day and night which may influence the results obtained.

3.1 Theoretical considerations

The amount of heat used for evaporation is the product of the quantity of evaporated water E and the specific evaporation energy, the "latent enthalpy" l . The heat energy consumed may originate from the heat G stored within the disc or within the water of the pan, from long and shortwave net radiation Rn and from the sensible heat flux H from the ambient air. Consequently, the equation of heat balance of the disc can be written as follows

$$- lE = Rn + H + G \qquad [1]$$

Under steady state conditions the ceramic disc does not change its temperature (contrary to the pan with its high thermal inertia). The heat flux from the interior of the disc is zero and the instrument has a temperature not exceeding the one of the surrounding air even at night. This is an important fact, as shown later on.

1) Manufacturer: *Thies* GmbH, 3400 Göttingen, West Germany

The energy yield from radiation Rn consists of a longwave and a shortwave part, from which a certain part is reflected. The shortwave reflection coefficient of the disc can be adapted to that of the plant colour (8).

As far as the pan is concerned, the shortwave radiation penetrates through the water surface into deeper layers of the water. Such, a considerable amount of radiation energy is absorbed. This induces an increase of the pan evaporation.

The longwave emission R_e is given by the product of the Stefan-Boltzmann Constant σ, of the fourth power of the surface temperature T and of the longwave emission coefficient

$$R_e = \epsilon \sigma T^4. \qquad [2]$$

R_e depends on the structure of the surface. In the spectral range from 8 – 14 μm, the emissivity of plants exceeds in most cases 96 %. Accordingly, the reflectivity is very small (9). It was not possible to investigate the reflection conditions of the ceramic surface, but due to its structure an emissivity of more than 95 % is to be expected. The emissivity of the open water surface of the pan also exceeds 95 %.

Both, the sensible heat flux H and the flux of latent enthalpy lE depend in the same way upon the wind velocity. The equation of H from and to a leaf, the ceramic disc and the surface of the pan can be written as

$$H = a_H \cdot (T_a - T_o). \qquad [3]$$

T_a is the air temperature and T_o is the surface temperature of the leaf, the disc or the water surface respectively. The factor a_H (heat transfer coefficient) is proportional to the inverse of the heat transfer resistance r_H. The equation describing the water vapour transfer is:

$$E = a_w \cdot (q_a - q_o), \qquad [4]$$

q_a and q_o are the water vapour concentrations in the environmental air and in the boundary layer at the water surface, in the pores of the leaf or in the disc respectively. a_w is the water transfer coefficient corresponding to the heat transfer coefficient. Its inverse value, the water transfer resistance, is composed of the atmospheric transition resistance r_H equal to the heat transfer resistance and additionally of an interior transfer resistance of the pores, r_{St}. It is zero at the free water surface of the pan. Due to the unrestricted water supply within the disc, this resistance is zero only in certain cases, e.g. when turning the disc upside down during extreme radiation (8). If the water and light supply of leaves is optimal, their interior resistance is very small too due to the stomatal opening.

In consequence the heat balance equation of the disc or the pan surface reads: [5]

$$Rn + G + a_H \cdot (T_a - T_l) + a_H \cdot l \cdot \frac{0.623}{p \cdot c_p} \cdot (e_a - E_o) = 0$$

In this form of the equation, the water vapour concentration is replaced by the saturation water vapour pressure E_o at the surface temperature and at the actual water vapour pressure e_a · c_p is the specific heat capacity of the air and p is the air pressure.

From this equation it is evident, that the evaporation of the disc and the pan is controlled by:

- the energy supply by radiation Rn and the heat flux from the interior of the body G (this term is zero for a leaf or for the disc due to their small thermal inertia),
- the air temperature (energy supply by sensible heat flux)
- the saturation deficit of the air
- the water transfer as a function of surface structure and wind velocity.

3.2 Laboratory tests

If the environmental factors radiation, temperature and humidity are equal with respect to plant canopy, disc and pan, then the water transfer coefficient a_w is the essential criterion for the physical comparability of the instruments on one hand and the plants on the other.

Due to the small size of the ceramic disc, it was possible to test this instrument in a wind tunnel. For testing, the large pan was replaced by a smaller weighable evaporimeter after *Wild* with a similar shape. However, because of the movements of the vessel, caused by the turbulence, no exact measurements could be made (these movements, which are similar to the ones under field conditions, show inpracticability of this instrument). Thirdly, a *Piche* atmometer was tested in the wind tunnel.

The heat and water coefficient of the ceramic disc has the same form as the one of the *Piche* filter paper:

$$a_w = c_1 \cdot u^{c_2}, \qquad [6]$$

where u is the wind velocity.

The factor c_1 depends on the width of the leaf in wind direction only, the exponent c_2 describes the turbidity. In the literature values of c_2 about 0.5 are given for low turbulence in laminar flow (11). *Groeber* et al. (12) assume exponents up to 0.8 if there are high inflow disturbances (edge effects). *Roth* (10) gives for the *Piche* evaporimeter

$$a_H = 2.37 \cdot u^{0.636} \text{ mW} \cdot \text{cm}^{-2}\text{K}^{-1}. \qquad [7]$$

Frankenberger (13) computed the following heat and water vapour transfer coefficient for a wet meadow:

$$a_H = 1.39 \cdot u^{0.5} \text{ mW} \cdot \text{cm}^{-2}\text{K}^{-1}. \qquad [6a]$$

In this investigation a water transfer coefficient of the ceramic disc evaporating only at the lower side, of

$$a_w = 0.62 \cdot u^{0.747} \text{ mW} \cdot \text{cm}^{-2}\text{K}^{-1} \qquad [8]$$

was developed.

The relation between the transfer coefficients of the ceramic disc and the wind velocity is shown in Figure 4 together with the curves of the *Piche* atmometer and those of various plant leaves. It is evident that amphistomatal leaves, transpiring on both sides as e.g. the uneven sugar beet leaves (after *v. Hoyningen-Huene* (14)) have much higher a_w as the even *Czeratzki* disc. The smooth maize leaves of similar size as the disc, have similar values (curve 2a) if they transpire only on the lower side. They have higher a_w values if they transpire on both sides or if they have a smaller diameter.

The dependence of the exponent on the leaf size can be explained by the disturbance of the laminar boundary layer due to the turbulence, originating from the windside edge. With increasing distance from the edge the boundary layer is rebuilt, and then protects the evaporating surface from turbulent diffusion. This fact can be made visible by a diagramme of the surface temperatures which decrease due to the energy loss by evaporation. In Figure 5 the temperature distribution on the lower side of the disc is given. It was measured by means of an infrared thermometer at a wind velocity of 3.0 m/s, an air temperature of 23° C and a relative humidity of 45 %. The lowest temperatures occur at the windwardside edge. Here the evaporation has its maximum, while the temperature increases leeward up to one degree, showing the rise of the boundary layer.

Additional investigations were made about the instrumental behaviour of the disc. When comparing several *Czeratzki* discs, no differences were found for all wind velocities tested. Also a change of the height difference (up to one meter) between disc and water table induced no change in evaporation.

When changing the exposition of the disc to the wind, distinct effects appeared. Particularly a deviation from the horizontal position caused a significant increase in evaporation. The streamlines were no more parallel to the disc and induced higher turbulence. If the disc was turned upside down (again parallel streamlines) the evaporation was 37 % higher than in normal position. This effect is not explained yet. The same effect was found by *Czeratzki* et al. (8) during field measurements in Tunesia.

3.3 Use of the ceramic disc as a physical plant model

Evaporimeters are thought of as models of plant canopies, which allow to simulate the water loss of the soil.

Due to the physical properties of the disc, especially due to the similar aerodynamic properties, the disc can be used as a model of single leaves or of plants. Since the models have no stomatal regulation the various influences of the ecological conditions on one hand and the physiological events on transpiration on the other hand can be separated.

From preliminary results of experiments with a corn canopy in Germany, it is known that the evaporation of a disc, mounted in the upper canopy level, evaporates as much as the canopy as a whole, if all stomata of the leaves are open. If the instrument is mounted at lower levels, the evaporation of the disc can be compared with the transpiration of single leaves, if the size of the leaf and the disc are taken into consideration. In this case the evaporimeter can be used to investigate the influence of the physical conditions within the canopy upon evapotranspiration, with respect to the distance of the canopy edge or to the distance from the canopy surface.

Figure 6 and Figure 7 are examples for the applicability of the disc as a plant model. In Figure 6 the relative mean evaporation of discs 0.6 m above soil surface in various distances from the windside edge of the canopy is given. If the evaporation rate outside the canopy is taken as 100 %, it decreases to 75 % one meter, and to 50 % about six meters from the edge.

In Figure 7 the daily run of the disc evaporation, used as a plant model within a canopy is compared with the actual evapotranspiration of the maize canopy, calculated from the heat balance (*Bowen*-ratio method) (20). The actual transpiration has its maximum during the morning hours, when the water supply of the plants is still sufficient and when the stomata are open. Lateron the actual transpiration decreases. Until afternoon the humidity of the air decreases and the potential evaporation of the ceramic plant model increases.

The results of similar analyses shall be presented in more detail in a further publication (20).

3.4 Climatological investigations about the properties of evaporimeters

The physical investigations demonstrated that the evapotranspiration from vegetated surfaces as well as the evaporation from evaporimeters depends on three effective meteorological systems:

- the first describes the energetical processes, including the parameters radiation, soil heat flux and air temperature,
- the second describes the acceptability of the atmosphere towards water vapour, including the parameters humidity of the air or saturation deficit,
- the third system represents the water vapour transport or the replacing of humid by dry air masses. This system includes the wind velocity and the eddy diffusivity.

These parameters do not act separately but appear in various combinations and reciprocal effects. Consequently, besides physical investigations in the laboratory, also climatological investigations in the field have to be made in order to test the instruments, to compare one with the other and, particularly, to compare the measurements with the actual evapotranspiration of natural vegetated surfaces during various seasons of the year.

For these studies three sets of data were used:
- data from Hofuf as published in (1)
- data gained at Hofuf in 1977
- data measured in Braunschweig (Federal Republic of Germany).

For the investigation of the stochastical connections between evapotranspiration and meteorological parameters, a statistical approach was used, which takes into consideration the influence of the single effective components and additionally the interconnections between them, using a quadratic formulation, as proposed by *Schneider* (14). This is necessary, because many parameters are not acting singularely but become effective only in combination with other parameters. An example is the mutual effect of temperature and wind velocity in advective processes.

The application of the least square method yields an n-dimensional regression area ("reaction area") that contains all the information about the behaviour of the individual parameters as well as their mutual effects. The general mathematic expression is:

$$Y = a_0 + \Sigma a_i \cdot x_i + \Sigma a_{ik} \cdot x_i \cdot x_k \qquad [9]$$

The target value Y is the evaporation of the instrument, x_i are the effective meteorological parameters and a_i are the regression factors. The sum of the products $a_i x_i$ expresses the independent linear regression, while the sum of the products of $a_{ik} \cdot x_i x_k$ (i = k) describes the non-linear effects. $a_{ik} x_i x_k$ ($i \neq k$) represents the mutual effects. The result is a n-dimensional quadratic hyperbola of the reaction area of the evapotranspiration Y. The n-1 other axes are the influencing parameters. Due to the mutual effects $a_{ik} x_i x_k$ ($x_i \neq x_k$) the main axes of the hyperbola are not rectangular and not parallel to the axes of x_i. Therefore, the inclination of the area, which shows the effects of an alteration of the independent parameters upon the evapotranspiration, is not rectangular to the axes.

Only the reaction Rx_i upon an individual factor x_i can be expressed through the partial differential equation

$$Rx_i = \frac{\partial y}{\partial x_i} \qquad [10]$$

The real inclinations in other directions must be calculated after a rotation of the coordinates of the whole system into the direction of the main axes of the hyperboloid. So, the effect of any individual component may be devided into three additive terms containing the coefficients a_i and a_{ik} respectively of a linear term x_i as well as of a quadratic term $x_i \cdot x_k$. The quadratic term describes the mutual reactions between the two factors. The type of the conic section of the quadratic hypersurface can be found by means of the eigenvalues of the quadratic equation. The square roots of the eigenvalues correspond to the length of the main axis, whereas the vectors show their directions. This direction is considered to be the main effective direction of the parameters. Therefore, only slight changes in the magnitude of a parameter result in a relatively large change of reaction.

By means of lysimeterdata of consumptive use, which are published in (1), and of data of pan and disc evaporation measured at Hofuf in winter 1970/71 and summer 1971 on the one hand and of climatological parameters on the other hand the influence of the various meteorological parameters upon both, actual evapotranspiration of canopy and evaporation of instruments was analysed, using the statistical method described above. From the three acting systems as described in 3.1, the following effective meteorological parameters which can easily be measured, are used:

- the daily sum of global radiation,
- air temperature 2 m above ground measured at 2 p.m. (maximum),
- relative humidity at the same level at 2 p.m.
- daily mean wind velocity.

This combination appeared to be an optimum after several tests using also other parameters or combinations of parameters. The multiple regression coefficients R between measurements and calculated reaction areas was found quite high (R = 0.95 to 0.99) using the 4 parameters mentioned above.

R did not increase when more parameters were included.

The two parameters of the energy system, temperature and radiation, can substitute each other to some extent for the omission of one of them reduced the multiple correlation coefficient between regression surface and measurement only from 0.97 to 0.94. But R decreased rapidly, if both or any other parameter was omitted.

The results of these calculations are three regression formulae of the type as shown in eq. [9] for disc, pan and canopy. In tables 1, 2 and 3 the regression coefficients a_i and a_{ik} are listed.

Table 1: Coefficients of pan evaporation reaction area.

Subscripts: 1 = radiation (KJ/cm²day),
2 = temperature (°C),
3 = wind (m/s),
4 = saturation deficit (%)
Multiple correlation coefficient R = 0.99

a_0 = −1,5309			
a_1 = −2,4162	a_2 = −1,2186	a_3 = 1,2460	a_4 = 0,4923
a_{11} = 1,3372	a_{12} = −1,1304	a_{13} = 1,8267	a_{14} = 0,1316
	a_{22} = 0,0075	a_{23} = 0,2035	a_{24} = 0,0085
		a_{33} = 0,2509	a_{34} = −0,0575
			a_{44} = −0,0054

Table 2: Coefficients of disc evaporation reaction area

Subscripts: 1 = radiation (KJ/cm^2d),
2 = temperature (°C),
3 = wind (m/s),
4 = relative humidity (%).
Multiple correlation coefficient R = 0.95

a_0 = 2,1426			
a_1 = 1,7096	a_2 = 0,2510	a_3 = −0,3649	a_4 = 0,0675
a_{11} = 1,1240	a_{12} = 0,1340	a_{13} = −0,9819	a_{14} = 0,0769
	a_{22} = 0,0138	a_{23} = 0,0889	a_{24} = −0,0095
		a_{33} = 0,3631	a_{34} = −0,0456
			a_{44} = 0,0017

Table 3: Coefficients of the alfalfa AET reaction area

Subscripts: 1 = radiation (KJ/cm^2d),
2 = temperature (°C),
3 = wind (m/s),
4 = saturation deficit (%).
Multiple correlation coefficient R = 0.98

a_0 = 47,1338			
a_1 = −20,9530	a_2 = −0,6152	a_3 = 3,1849	a_4 = −0,6833
a_{11} = 2,5614	a_{12} = 0,3200	a_{13} = 1,5105	a_{14} = 0,3580
	a_{22} = 0,0266	a_{23} = 0,1319	a_{24} = −0,0074
		a_{33} = 0,1211	a_{34} = −0,0661
			a_{44} = 0,0031

They are valid for evaporation data in mm/day. Figure 8a shows one part of the regression area: the reaction of evaporation from the disc and of actual evapotranspiration from an alfalfa canopy upon temperature and humidity. Figure 8b represents the corresponding area of Class A Pan and alfalfa. In all three cases (alfalfa, pan and disc), the evaporation increases exponentially with increasing saturation deficit and increasing temperature. This striking similarity does not exist, if the three evaporating surfaces due to wind velocity and radiation are compared.

Figure 9 shows the reaction areas as functions of global radiation and saturation deficit. The high radiation absorption of the pan in contrast to the canopy (as mentioned earlier in the theoretical discussion of the physical properties of the instruments) is demonstrated by the far higher evaporation of the pan as compared to the canopy at all radiation values.

The reaction area of the alfalfa canopy, pan and ceramic disc at constant conditions concerning radiation and saturation deficit is shown in Figure 10. Again the same characteristical increase of evaporation with increasing temperature is evident. Increasing wind velocity has striking different effects on the canopy on the one hand and on the instruments on the other hand. While both instruments show an exponential increase of evaporation with increasing daily mean wind velocity, the evaporation of the alfalfa canopy shows an only slight increase at low wind velocities and a constant evapotranspiration or even a slight decrease at mean windspeeds higher than 4 m/s. This effect is caused by the additional stomatal resistance against water vapour flux from the leaves (particularly during night time) and by the different extent of the evaporating areas.

Particularly in arid regions warm and dry air masses are advected to the wet surfaces and induce an increasing evapotranspiration rate (oasis effect).

With increasing length of the wet surface over which the air moves water vapour is accepted and the air becomes cooler. As a result the oasis effect decreases with increasing field size. The small surfaces of the evaporimeters show the highest oasis effect. As a consequence the smallest evaporimeter, the *Piche* atmometer, has the highest wind dependence as compared to other evaporating surfaces. Figure 10 demonstrates that the larger pan is slightly less effected by the wind as the disc. Both of them react by far more intensively on wind than the large alfalfa canopy. In this fact lies the main difference between the evaporation of the instruments and the consumptive use of canopies.

These effects can be quantified, if the eigenvalues and eigenvectors of the reaction area are used. The succession of eigenvalues is a measure of the stochastical effectiveness. To every eigenvalue there belongs an eigenvector, consisting of the four components radiation, temperature (2 p.m.), saturation deficit (2 p.m.) and mean wind velocity. In an earlier publication (1) it is referred to the original data. In this investigation a computer with expanded capacity was used. So a greater number of better comparable parameters could be taken into account. Additionally the data were standardized with respect to the range of their variation in order to obtain dimensionless inputvalues and in order to be in a position to evaluate the influence of the units.

In Table 4, 5 and 6 the eigenvalues and eigenvectors of the pan and the disc reaction areas are listed in comparison to the reaction area of the alfalfa evapotranspiration. According to the sequence of the eigenvalues e_1, e_2, e_3 and e_4 the eigenvector E_1 has the highest influence upon evapotranspiration. Because of the components of this vector, its direction corresponds in the case of the pan (Tab. 4) into the direction of the temperature and wind axes. The components of radiation and humidity are relatively small. That means that due to the main slope of the area the main influence upon pan evaporation is induced by the mutual effect of temperature (E_{12} = 0.6687) and wind (E_{13} = 0.6598). According to the second eigenvalue the influence of the saturation deficit (E_{24} = 0.7119) in combination with the wind (E_{23} = 0.5366) comes second. The influence of the radiation runs third only.

The influence of the temperature upon the evapotranspiration of the alfalfa canopy is strikingly strong (Tab. 6 E_{12} = 0.7867). The mutual effect with the wind and with other parameters is less important (E_{13} = 0.3577).

Second comes the mutual effect of humidity E_{24}, temperature E_{22} and radiation E_{21}, whereas the individual

effect of the wind E_{43} ranges in the last position. The eigenvectors of disc evaporation are very similar to those of the pan (Tab. 5). The main influence is the mutual effect of wind and temperature (E_{12} = 0.631, E_{13} = 0.607).
The influence of saturation deficit ranks next (E_{24} = 0.66) while the global radiation is on the last position (E_{41} = 0.818).

Table 4: Eigenvalues e_i and Eigenvectors E_i of pan reaction area

e_1 = 1.3661 e_2 = – 0.6246 e_3 = – 0.3120 e_4 = 0.2639

	E_1	E_2	E_3	E_4
1 radiation	– 0.3173	– 0.1045	– 0.6118	0.7170
2 temperature	0.6687	– 0.4408	0.3209	0.5054
3 wind	0.6598	0.5366	– 0.5208	– 0.0742
4 satur. def.	– 0.1298	0.7119	0.5015	0.4742

Table 5: Eigenvalues e_i and Eigenvectors E_i of disc reaction area

e_1 = 0.00892 e_2 = 0.00670 e_3 = 0.00126 e_4 = 0.00126

	E_1	E_2	E_3	E_4
1 radiation	– 0.32539	0.45999	– 0.11461	0.81816
2 temperature	0.63152	0.59380	– 0.47566	– 0.14932
3 wind	0.60759	0.01489	0.72036	0.33419
4 satur. def.	– 0.35513	0.65998	0.49160	– 0.44342

Table 6: Eigenvalues e_i and Eigenvectors E_i of alfalfa reaction area

e_1 = 2.2021 e_2 = 0.7577 e_3 = – 0.2547 e_4 = – 0.0569

	E_1	E_2	E_3	E_4
1 radiation	– 0.3807	0.5475	0.3911	0.6343
2 temperature	0.7867	0.5759	0.1771	– 0.1341
3 wind	0.3577	– 0.1412	– 0.5966	0.7044
4 satur. def.	– 0.3288	0.5904	– 0.6780	– 0.2890

Formula of reaction area:

$$V = \Sigma a_i x_i + \Sigma a_{ii} x_i^2 + \Sigma a_{ik} x_i x_k + a_o$$

This analysis shows, that the difference of the readings of evaporimeters on the one hand and the real evapotranspiration or consumptive use of well irrigated crops on the other hand is mainly caused by the wind velocity, because it induces the transport of dry and warm desert air across the fields of the oasis. If the surrounding land would be irrigated too, these air masses would cool down because of moistening by evaporation. So, the intensity of the oasis effect depends also on the humidity of the air, however, this effect is much less striking as shown in Figures 9 and 10. The different behaviour of living plants and of the instruments on radiation with its thermal and photosynthetically active effects, causes additional reactions, particularly at low radiations, e.g. at night. The air temperature has nearly the same effect on transpiration from the canopy and on evaporation from the instruments.

In any case, there are marked differences between the transpiration of canopies and the evaporation of instruments, but only gradual differences between the evaporimeters.

4 The correction of evaporimeter data

Since evaporimeters such as pans and atmometers are currently used there is need for a correction in order to reduce the mostly too high evaporation values.

4.1 Correction using a constant reduction factor

Commonly only a constant factor is applied for multiplication with the evaporimeter readings. In arid regions a "pan-factor" of 0.75 and a "disc factor" of about 0.68 is used. In humid regions these factors are higher due to the smaller oasis effect. In Central Europe a disc-factor of 0.75 is about correct. In very humid climates the disc factor can reach 1.0 if the daily mean relative humidity is 70 % or more.

By comparing the consumptive use values of alfalfa and the evaporation of pan and disc, *Ohlmeyer* et al. (1) evaluated the mean reduction factors for the Al Hassa Oasis and compared them with correction factors of the *Blaney-Criddle*-formula (17) and the *Penman*-formula (2). According to Table 7 the mean pan factor is 0.75 and the mean disc factor is 0.67. The corrections needed for the formulae were 1.36 ± 0.27 for *Blaney-Criddle* and 1.27 ± 0.11 for *Penman* respectively. In comparison the monthly mean instrument factors have a very small standard deviation of only ± 0.06. Furthermore there is nearly no seasonal variation, whereas the formulae-corrections, as shown in Figure 11 have a maximum of 1.68 in summer for the *Blaney-Criddle*-correction and a minimum of 0.93 in winter.

The reason is, that the high advection energy in summer is not regarded when using this formula. The more sophisticated *Penman*-formula, which includes the advection using a wind-temperature-product-term shows a much smaller seasonal variation with a maximum of 1.54 in November and two minima of about 1.10 in the spring and in the late summer. There is no seasonal variation of the pan and disc factor.

Figure 12 shows the dependence of pan and disc evaporation on temperature and humidity, after correction with the mean reduction factors. Again, the similarity of both instruments is obvious. There is no reason to see principal differences between both, evaporimeters (pan) and atmometers (ceramic disc, *Piche* atmometer).

The only difference existing is caused by the size of the evaporating surfaces and their exposition to the meteorological conditions. However, there exist principal differences between canopies and evaporimeters (or atmometers). For the improvement of the reliability of the instruments corrections have to be developed which consider these differences as analysed by physical or statistical methods. The development of new types of instruments will not lead to any essential progress (5).

Table 7: Consumptive use coefficients K_i

growth period	*Blaney-Criddle* K_b	*Penman* K_p	Class A pan K_{pa}	*Czeratzki* disc K_c
3.11.70–25.11.70	0.93	1.24	0.73	0.73
26.11.70–23.12.70	1.02	1.54	0.75	0.69
24.12.70–21. 1.71	0.95	1.35	0.74	0.66
22. 1.71–24. 2.71	1.24	1.28	0.77	0.70
25. 2.71–21. 3.71	1.42	1.18	0.75	0.65
22. 3.71–16. 4.71	1.21	1.10	0.89	0.82
17. 4.71–10. 5.71	1.51	1.18	0.79	0.71
11. 5.71– 4. 6.71	1.59	1.26	0.80	0.72
5. 6.71–29. 6.71	1.68	1.33	0.70	0.67
30. 6.71–24. 7.71	1.68	1.29	0.75	0.66
25. 7.71–18. 8.71	1.56	1.32	0.72	0.59
19. 8.71–12. 9.71	1.52	1.09	0.67	0.55
13. 9.71– 7.10.71	1.55	1.26	0.68	0.66
8.10.71– 2.11.71	1.15	1.35	0.70	0.63
average	1.36	1.27	0.75	0.67
variation	0.27	0.11	0.06	0.06

4.2 Correction due to different radiation effects

The difference in radiation effects is due to two processes:

- physically because of the different absorption of radiation energy, which is partly used for vaporization (latent heat of evaporation)
- physiologically due to the closing of the leaf pores (stomata) when the light (photosynthetic active radiation) is reduced at sunset to sunrise. The instruments, on the other hand are still able to evaporate, if there is enough energy available and if the air is dry enough.

The difference in the physical process of radiation absorption (see Fig. 9) is partly compensated by the sensible heat flux from the air, which increases, if the evaporating surface is cooled down below the air temperature by evaporation. More effective is the remaining evaporation at night. Particularly the pan with its high thermal inertia evaporates intensively at night.

This effect can be avoided, if only the evaporation during daytime is used. That is easily possible when registration devices are used. Otherwise, the morning and evening reading, e.g. at 6 a.m. and 6 p.m. can be taken. As shown in Table A 1, Table A 2 and Table A 3 the correlation coefficient between pan and alfalfa evapotranspiration increases from 0.93 to 0.97 and in case of the disc from 0.92 to 0.97. As this correction is very effective, its application can be recommended. In this case, however, then a mean pan-factor of 1.03 (instead of 0.75), and a mean disc-factor of 0.84 (instead of 0.65 or of 0.67) must be applied.

4.3 Correction due to different exposition to wind, humidity and temperature

In general, the ceramic disc is mounted at an elevation of 1.7 to 2.0 m above ground, whereas the water table of the pan lies 0.5 m above the grass surface. As a result, the instruments are differently exposed to the meteorological parameters if compared to the canopies. Particularly the wind velocity increases with increasing height. Also the humidity and the temperature are alterated.

According to the typical gradients of the meteorological parameters *Bornholdt* (16) stated strong evaporation differences when increasing mounting heights in lower levels as compared to higher levels for all kinds of evaporimeters.

The evaporation of both, Class A Pan and ceramic disc was examined in normal position and closer to the ground in order to evaluate the effects of different positions. The values of pan 0.5 m, pan 0,0 m and of the disc 2.0 m and 0.5 m are given in Table A 4 and A 5.

Placing the ceramic disc in the lower height is not very effective, as the correlation does not improve (see Tab. A 6). Only the absolute values are much closer to the evapotranspiration of alfalfa. This is caused by two contrary effects:

- In the normal position the disc reacts more on large scale climatic effects than on changes in the small scale of the canopy. This is an advantage of the lower position, particularly if in the upper atmosphere air masses with different climatic conditions are advected and if the canopy creates its own climate.
- On the other hand the climate near the ground reacts very intensively and fast upon physiological changes of the canopy. For instance: if the plants are stressed by heat or by soil moisture depletion, they close their stomata and reduce their actual transpiration. Consequently, the humidity of the canopy atmosphere decreases and the potential evaporation of the instrument increases, because there is no stomatal regulation. Additionally, several plants (particularly sugar beet or vegetables) change their shape in case of water stress due to the wilting process (hanging leaves). Then, the instrument in its fixed height is exposed to the increasing wind velocity, and its evaporation increases even more.

Consequently a position of the instrument near the canopy surface can be recommended at best, if the surrounding vegetation is always well watered and does not change its height and its water supply. In this case the mean reduction factor (disc factor) of 0.67 increases up to 1.0. If the canopy can not be irrigated in short periods with small water quantities, it is more favourable to mount the instrument in the normal height and to reduce the readings according to the recommendations given in 4.2 and 4.4. This also has the advantage, that the data are more representative for a larger area.

The placing of the pan at the level 0.0 m has even more disadvantages. The thermal inertia of this instrument increases, caused by the contact with the soil. Therefore the correlation between pan and alfalfa decreases from 0.93 in normal position to 0.92 if the pan is digged in. The absolute values are much lower than those of alfalfa.

4.4 Correction due to the wind velocity

In the preceeding chapters the influence of the variability of wind velocity was found to be the most important factor, which induces the difference between potential evapotranspiration of a canopy and the potential evaporation of all kinds of evaporimeters. Because the different influences (such as temperature and radiation) are less important or (such as humidity of the air) relatively constant within one climate, correction functions should be derived with respect to the different influence of the wind velocity. This is possible because all Class A Pans can be equipped with a wind counter (6) and normal agrometeorological stations include different types of anemometers.

For the climate of the Al Hassa Oasis functions are derived which base on the data as used before. So it is possible to correct the pan and disc readings with regard to the mean wind speed measured in 2 m or in the level of the pan respectively.

The result is a quadratic correction formula for the disc (2 m) and anemometer (in 2 m).

$$ET_{real} = -0.39 - 0.372\,v + 0.0946\,v^2 + 1.062\,E_{disc} + 0.0042\,E_{disc}^2 - 0.1215\,v\,E_{disc} \qquad [11]$$

for the pan, regarding wind speed in 2 m:

$$ET_{real} = -0.89 - 0.015\,v + 0.076\,v^2 + 1.092\,E_{Pan} + 0.0163\,E_{Pan}^2 - 0.1525\,v\,E_{Pan} \qquad [12]$$

and for the pan, regarding the wind speed in 0.5 m:

$$ET_{real} = -0.65 + 1.701\,v + 0.0577\,v^2 + 0.754\,E_{Pan} + 0.0204\,E_{Pan}^2 - 0.3657\,v\,E_{Pan} \qquad [13]$$

In Table A 7, A 8 and A 9 the measured actual evapotranspiration of the alfalfa canopy, of the corrected pan and disc evapotranspiration values by equations [11], [12] and [13] "real evapotranspiration" (E_{real}) are shown. From Figures 13, 14 and 15 the reduced standard deviations after correction are evident.

The correlation between these 3-days values of E_{real} and the measured actual evapotranspiration increases from 0.92 to 0.97 in case of the disc and from 0.93 to 0.96 (using the 2 m or 0.5 m wind reduction) in case of the pan.

In Figures 16, 17 and 18 the reduction curves are drawn. These diagrams are recommended for practical use. Every morning the irrigation farmer only has to read the water loss of one evaporimeter and the mean windspeed of the preceeding 24 hours to estimate the real evapotranspiration of a well watered dense and green canopy. For instance if the disc evaporation has been 15 mm and the wind speed (2 m height) 3 m/s or 260 km/day then the real evapotranspiration is 10.7 mm/d. In Figures 19 and 20 the uncorrected and the reduced values are compared with the measured values of alfalfa. The high effectivity of this way of correction is striking. This method even holds for longer irrigation periods, as prooved in Figures 21 and 22. There are only slight deviations between the cumulative evapotranspiration values of the canopy and of the corrected evaporimeter data.

4.5 Verification of the wind reduction method

The proposed correction was also tested using evapotranspiration values of other years and other crops, as far as reliable information about the consumptive water use of these crops were available. The consumptive use values of sorghum of 1975, as published in (19) were compared with uncorrected and reduced data of disc and pan evaporation, Table A 10. In spite of the fact, that the sorghum canopy was protected against wind by a shelter, the corrected values simulate the consumptive use of the canopy much better than the original data. Due to the windbreak effect the average values of the canopy are much lower (8.6 mm/d) than the corrected disc and pan values (11.6 and 9.8 mm/d resp), which are representative for the real evapotranspiration of open fields. But the unreduced values (15.1 and 12.6 mm/d) are uncomparably higher. The fact that the correlation coefficient increases from 0.74 (disc) to 0.79 and from 0.72 to as much as 0.86 (pan) is also evident from Figure 23 and proves the considerable improvement which can be attained even for crops, which grow under artificially changed wind conditions.

5 The practical use of evaporimeters

In the preceding chapters the design, the physical properties and the climatological basis of the application of evaporimeters are shown. However, a successful application of the instruments requires the consideration of several practical points.

5.1 Installation and management of evaporimeters

The agrometeorological station shall be representative for the surrounding area. At least fifty meters of the fields in the mean wind direction should be normally irrigated in order to create a satisfying fetch, and to avoid additional oasis effects. The instruments shall not be set up behind obstacles or windbreaks, nor shall they be exposed to local intensifications of the wind field between obstacles (jet effects). Correspondingly no station should be established within an orchard or between buildings. The lawn shall be kept short, particularly around the pan. The plot should be fenced in, in order to avoid animals interfering with the instruments.

Every week the pan has to be cleaned and the disc has to be grinded, its ceramic surface lowered below the water level of the vessel until water drips out and rinses dirt particles out.

To avoid the growth of algae, copper vitriol can be added to the distilled water of the disc. This poison, on the other hand, can be dangerous in the open water of the pan.

The reading should be taken every morning at the same time, before the evaporation becomes intensive. It is practical to combine this time with the check of the other climatic data. At Hofuf the reading time is 6 a.m. and, in addition, 6 p.m.

5.2 Comparison of different evaporimeters

During the laboratory and field tests different types of evaporimeters were used:

- the evaporation balance after *Wild*,
- the *Piche* evaporimeter,
- the ceramic disc according to *Czeratzki* in several positions
- the Class A Pan in several positions.

Because of the oscillations of the *Wild* balance in the wind, it was not possible to obtain reliable results neither in the wind tunnel nor in the open field. The installation in a weather screen created additional problems because of the special climate within the hut.

The *Piche* atmometer, which is preferred in the French speaking countries, possesses qualities not very different of the ceramic disc, but it has two disadvantages in comparison with the latter:

- because of the small size of the evaporating filter paper the wind dependency is striking (Fig. 4)
- the filter paper is very sensitive against mechanical disturbances caused by wind, by insects or by touching.

Because the water reservoir is above the paper, water easily drips out and may falsify the readings.

Worldwide, the evaporation pan is the most used evaporimeter. The East-European countries use pans with diameters up to twelve meters, quadratic or circular, digged in or openly exposed. In other countries, particularly in the USA and in the arid zones, the American Class A Pan is commonly used. As this instrument is easy to construct and because it needs no distilled water (opposed to the ceramic disc or the *Piche* tube), it is prefered in developing countries. An additional advantage is the slightly lower advection effect due to the larger suface. But the pan has also several disadvantages. The open water surface often is used as a water place by animals (e.g. birds), people use it sometimes for washing their hands. The pan is easily polluted by dust after sandstorms or by algae in warm regions. Under humid conditions considerable errors may be caused by splashing rainwater. The error, caused by its high thermal inertia, is well known. Sometimes it is tried to make corrections on the basis of readings of a maximum and a minimum thermometer floating in the pan. However, there nearly exist no instructions, how to apply such corrections. The cost of the pan, including thermometers and anemometers is relatively high.

Also the ceramic disc has several disadvantages. The most important ones are the high advectional effects as compared to the pan and the need to use distilled water. Internationally the instrument is only seldomly used as it is fabricated in Germany only. The advantages of the disc are the reliable performance of the instrument, the little pollutability of the evaporating surface (facing downward) and the transportability of the relatively small instrument. The disc can be placed at every desired elevation within and above the canopies. Last but not least the cost is low, even if it is set up in combination with a wind counter in order to obtain reliable data, or if it is designed as a recording evaporigraph.

5.3 Application of evaporimeter data

If the type of evaporimeter is selected corresponding with the conditions of the area and if it is set up in a correct way, the instrument can be used for three purposes:

- for assessing the forthcoming evapotranspiration in different seasons for planning purposes
- for estimating the actual water use of various crops, and
- for calculating the most efficient irrigation water quantity referring to the relation of water use and yield.

5.3.1 Application for planning purposes

Evaporimeters set up in places representative for a larger region, are valuable tools for climatological investigations and for prediction of consumptive water use. After *Ohlmeyer* et al. (1) the *Penman* and the *Blaney-Criddle*-formulae lead to results, which are too low, because they do not regard the advective processes in a correct way. The uncorrected evaporimeter data overestimate the consumptive use, because they overreact upon advection. However, after the wind reduction the corrected evaporimeter data conform with the real evaporation and form a basis for more reliable consumptive use predictions.

But not only the seasonal change of consumptive use is important for planning purposes. Since canals and pipelines, pumps and drainages must be designed for extreme cases, irrigation engineers have to know the frequency of normal, high and low evaporation rates. Figure 24 shows the relative frequencies of evaporation (corrected disc values) in four seasons. In winter a narrow peak of evapotranspiration rates of 3 mm/day occurs in about 24 % of all days, whereas rates of 1.0 mm/day and of 6 mm/day are transpirated in only 5 % of all days. The variations in the other seasons are more diffuse. The highest evaporation rates are to be expected in the summer months with 12 mm in 10 % of all days and not less than 17 mm in 2 % of the days. Spring and fall show a similar distribution with peaks at about 7 mm/day.

5.3.2 Application for different crops

According to the long vegetation period of alfalfa, this crop is very suitable for deriving estimations of ETA/ETP relations. Most of the other canopies have very distinct phaenological phases, in which the actual transpiration increases (in the early stages) or decreases (in the ripening stages). The duration of constant maximum transpiration (when the crop is well developed and covers the ground) is quite different and often very short. Most of the ETA/ETP relations refer to this stage. Therefore, additional plant reduction factors are necessary, which do not depend on the soil or the meteorological conditions. The most commonly used crop factors are derived by *Hargreaves* (18) (Tab. A 11). These factors are to be multiplied by the uncorrected data of the Class A Pan. In Table A 12 the corresponding crop factors with respect to the disc are listed. They are derived from the *Hargreaves* values according to the investigation presented in this paper. They have to be multiplied by the uncorrected 24-hour readings of the ceramic disc after *Czeratzki*, mounted at a height of 2 meters. Since *Hargreaves* made no reduction due to wind velocity and did not advise, for which velocities his tables are valid, new tables had to be developed which are applicable after wind reduction in order to obtain reliable results. By comparing the measurements of ETA at Hofuf with the data of Table A 1, it appears, that the *Hargreaves*-factors are derived at mean wind speeds between 1.5 and 2.5 m/s, measured at 2 meters. With respect to this, crop reduction factors were computed for pan (Tab. A 13) and disc (Tab. A 14).
They have to be applied after wind reduction.

5.3.3 Application for control of water use efficiency

Sound irrigation planning and scheduling neither aims at supplying the canopies with water with respect to their consumptive use nor to obtain maximum yields. More important is a high water use efficiency particularly in countries with high water deficit.

The productivity of the water applied to the fields can be controlled using evaporimeters, as shown in previous reports (1) (19). In Figure 25 the dry matter yield of alfalfa is shown in relation to water application rate, measured in multiples of disc evaporation (unreduced readings), as published by *Ohlmeyer* et al. (1). At low water supply an increase of application rates cause an enormous increase of yield, whereas irrigation rates higher than 75 % of the disc evaporation did not lead to equivalent increases of yield. Figure 26 shows directly the water productivity according to *Hussain* (19) as a function of water application rates. The optimum water supply of sorghum was found to be between 80 % and 100 % of disc evaporation.

It can be expected, that further investigations using the corrected values of pan or disc evaporation rates will yield more precise results.

6 Summary and conclusions

The results of the investigations presented in this report can be summarized as follows:

1. It is evident from theoretical and wind tunnel investigations that both, evapotranspiration of single plants and canopies and evaporation of open water surfaces and porous media are controlled by three main physical processes:

   - energy supply by radiation, energy flux or heat fluxes from the interior of soil, water or instrument body and from the surrounding air to the evaporating surface,
   - saturation deficit of the air,
   - air exchange due to wind velocity and turbulence.

   Additionally the plant or canopy transpiration is controlled by physiological events, particularly by stomatal regulations.

2. Evaporimeters can be used as physical plant models without stomatal reduction of evaporation, if they fulfill certain minimum conditions concerning the three processes, mentioned above.

3. From fundamental climatological field experiments and statistical investigations of the reaction area and their mathematical properties (e.g. eigenvectors), it can be shown, that these conditions are fulfilled well in temperature response, less in humidity, poorly in radiation response and least in wind speed dependency.

4. Corrections regarding particularly radiation and wind effects are needed for all evaporimeters. Manipulations, as e.g. different exposition to wind, are not usefull. A very simple means for effective improvement is the utilization of daytime evaporation data only. A correction of the data of the Class A Pan and of the ceramic disc due to wind velocity using a correction graph, derived from alfalfa measurements, is very efficient, even for different wind expositions (e.g. in a sheltered field).

5. The data of reliable evaporimeters such as pan and disc, if they are well maintained, can be used successfully for planning purposes, for actual irrigation control and as a tool for improving water use efficiency.

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Appendix
Figures and Tables

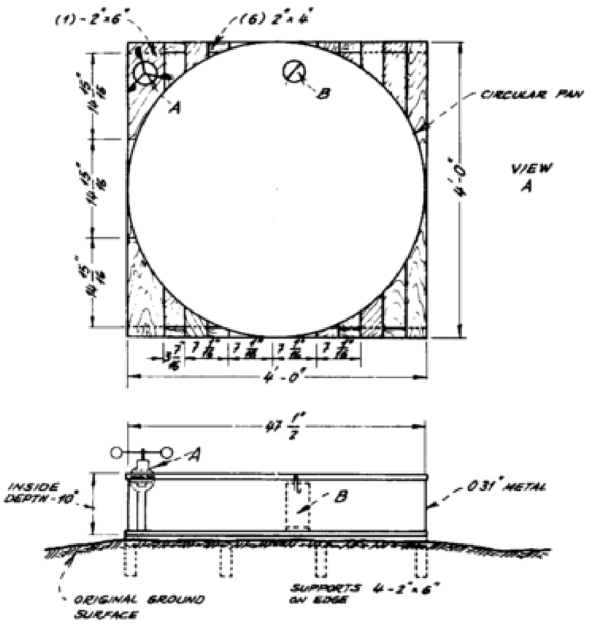

Fig. 1: USWB Class A Pan with anemometer A and stilling well B

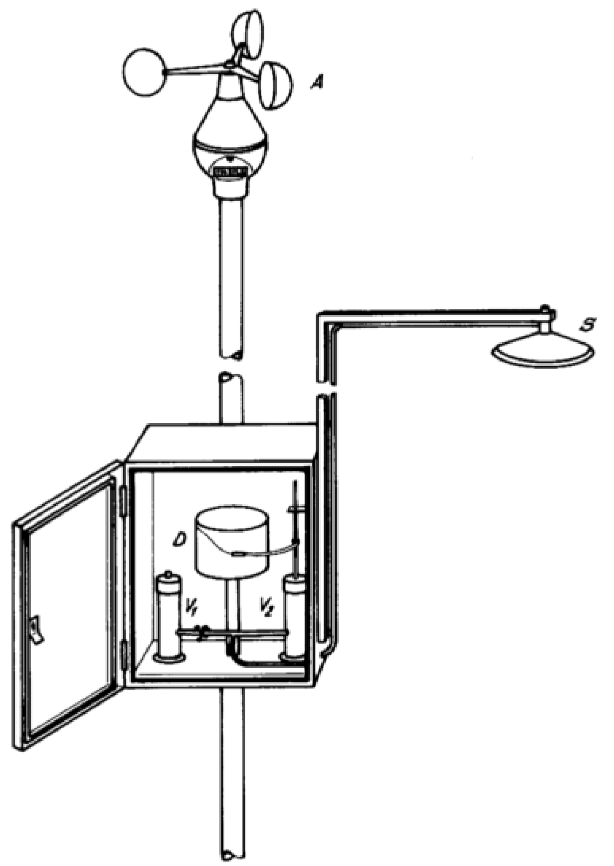

Fig. 3: Recording ceramic disc with small radiation shield S, two water supply vessels V_1, V_2, recorder drum D and counting anemometer A

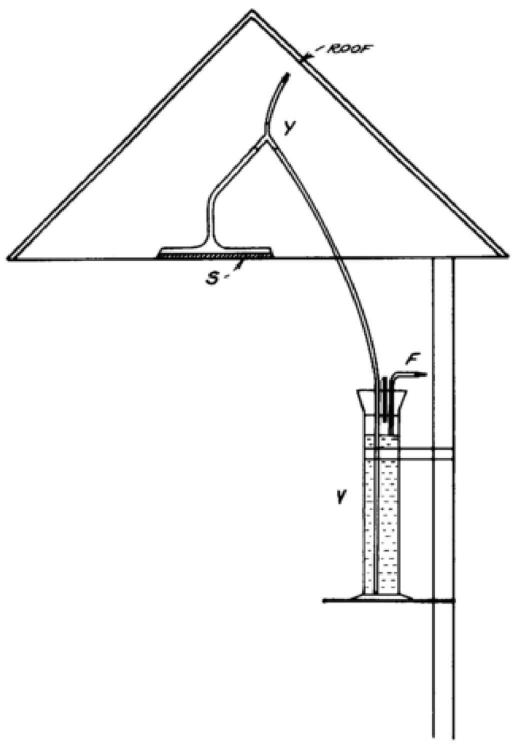

Fig. 2: Ceramic disc after *Czeratzki,* standard type
S = evaporating surface of the disc,
Y = air collector, F = water supply,
V = calibrated cylinder

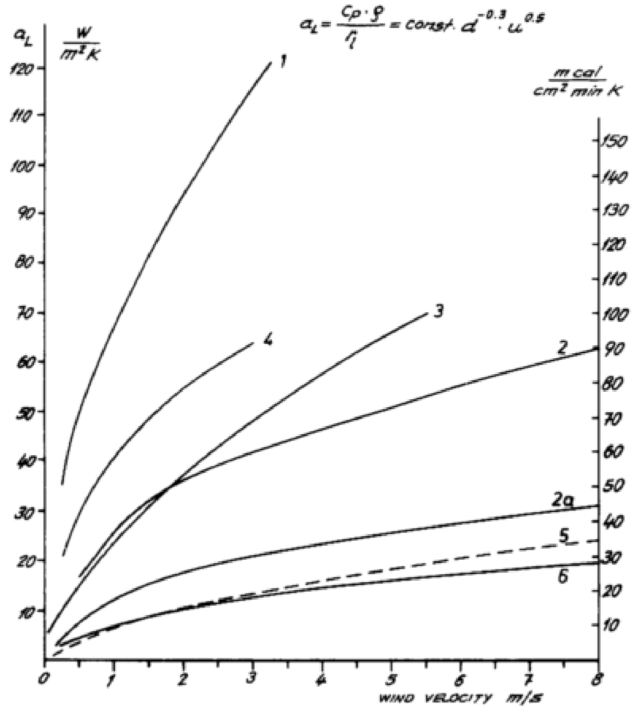

Fig. 4: Heat transfer coefficients α_H and water transfer coefficients α_W of various surfaces
(after *v. Hoyningen-Huene* (13))

1 = α_H of a leaf model 0.5 cm diameter (11)
2 = α_H of a leaf model 15 cm diameter (11)
2a = α_W of a leaf model 15 cm diameter, transpiration only at the lower side
3 = α_H of the *Piche* atmometer (10)
4 = α_H of a sugar beet leaf (14)
5 = α_W of the ceramic disc
6 = α_H of a meadow (13)

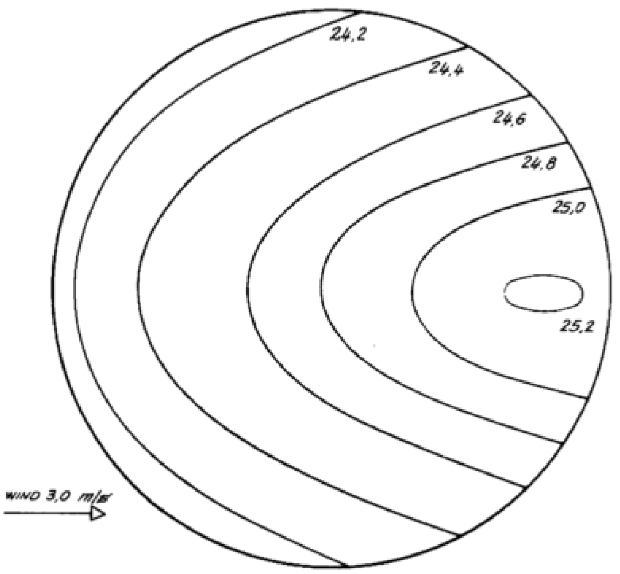

Fig. 5: Distribution of surface temperature on the disc (wind tunnel measurement)

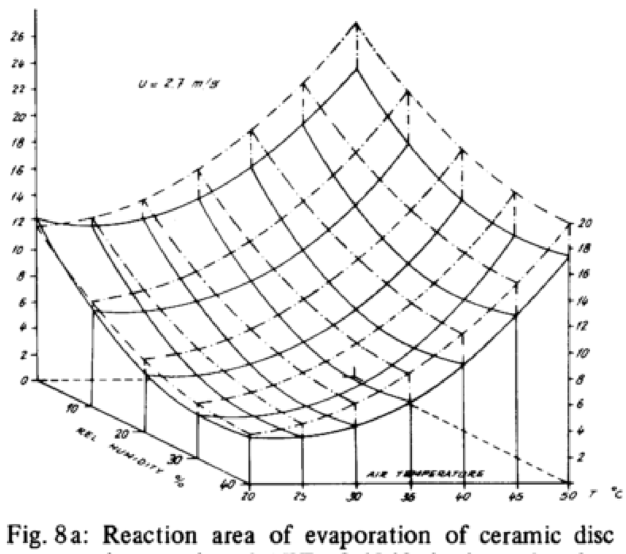

Fig. 8a: Reaction area of evaporation of ceramic disc (–·–·–) and AET of alfalfa (—) as related to temperature and rel. humidity at 2 pm Hofuf 1970/71

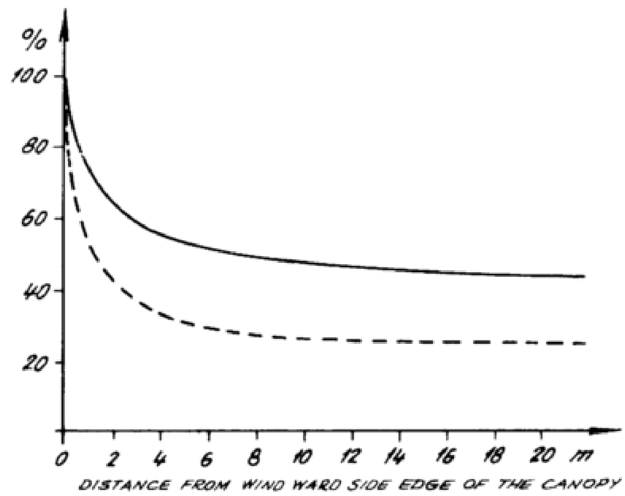

Fig. 6: Decrement of potential evaporation of ceramic discs (—) and of wind velocities (– – – –) in percent of the measurements outside of the canopy both measured in 60 cm height in a maize canopy

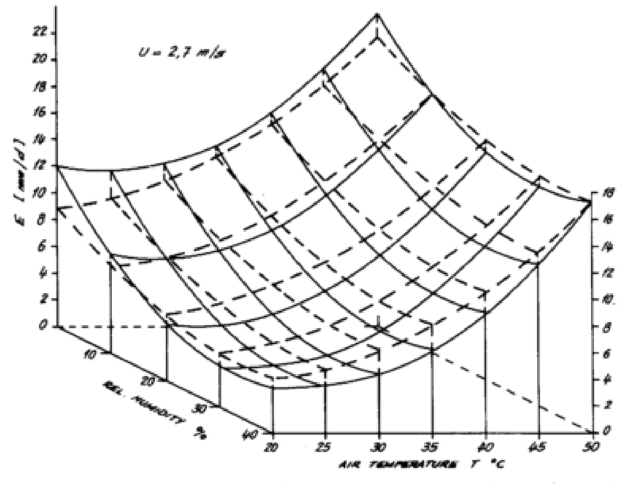

Fig. 8b: Reaction area of pan evaporation (– – –) and AET of alfalfa (—) as related to temperature and rel. humidity at 2 pm Hofuf 1970/71

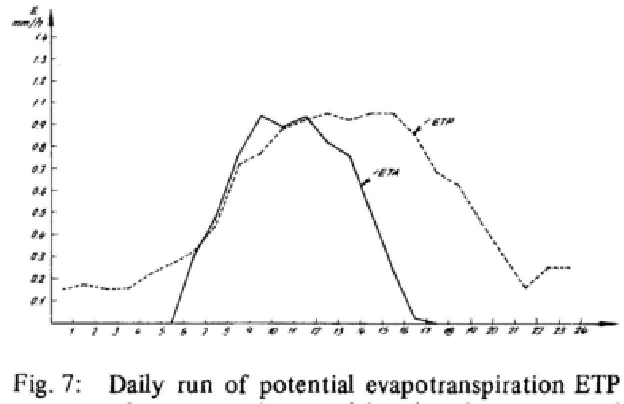

Fig. 7: Daily run of potential evapotranspiration ETP of a ceramic plant model within the canopy and actual evapotranspiration ETA of a maize canopy one day after irrigation Hofuf 5. 8. 1977

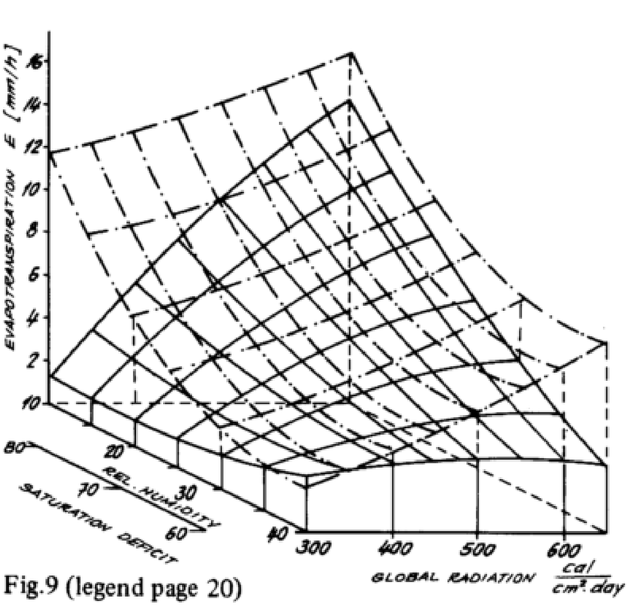

Fig.9 (legend page 20)

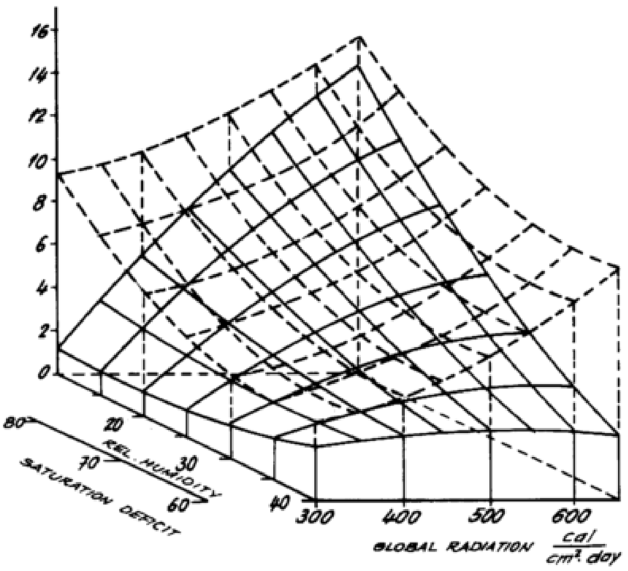

Fig. 9: Reaction areas of disc evaporation (–·–·–) and AET of alfalfa (—), left part, and of pan evaporation (– – –) and AET of alfalfa (—), right part, as related to radiation and relative humidity, respectively saturation deficit, Hofuf 1970/71

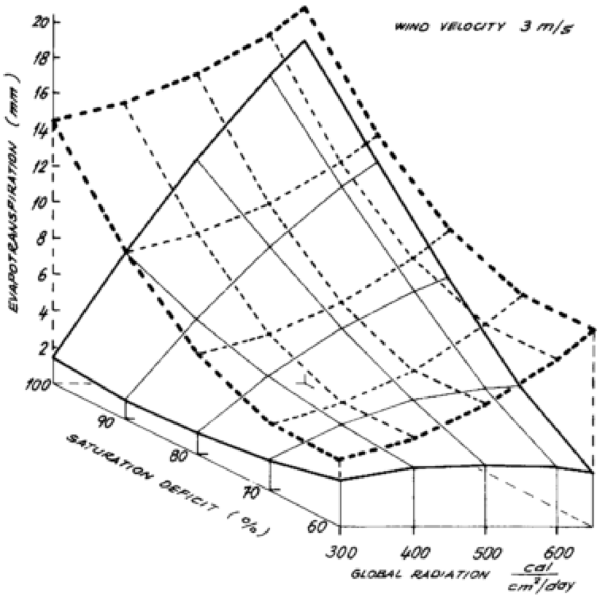

Fig. 10b: Reaction area of pan-evaporation (– – –) and AET of alfalfa (—) as related to global radiation and saturation deficit, Hofuf 1970/71

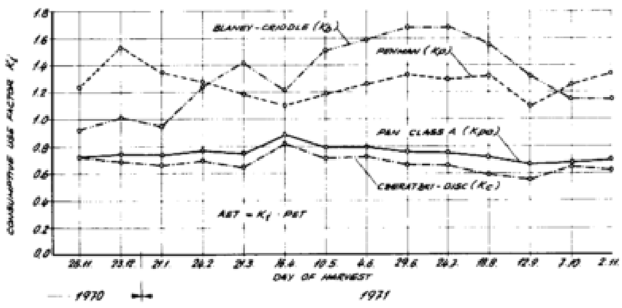

Fig. 11: Annual variation of the consumptive use factors K_i, computed from selected methods for the estimation of AET after *Ohlmeyer* (1)

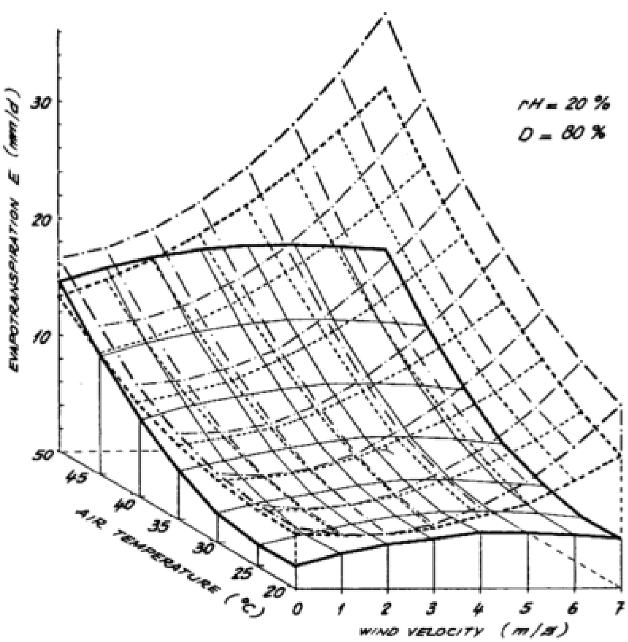

Fig. 10a: Reaction area of evaporation of pan (– – –), ceramic disc (–·–·–) and AET of alfalfa as related to wind velocity and temperature Hofuf 1970/71

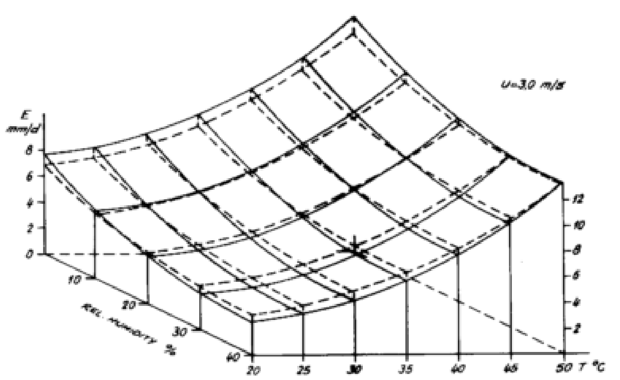

Fig. 12: Evaporation of ceramic disc (—) and pan (– – –) after correction with the constant disc factor (0.67) and pan factor (0.75), as related to noon temperature and humidity, Hofuf 1970/71

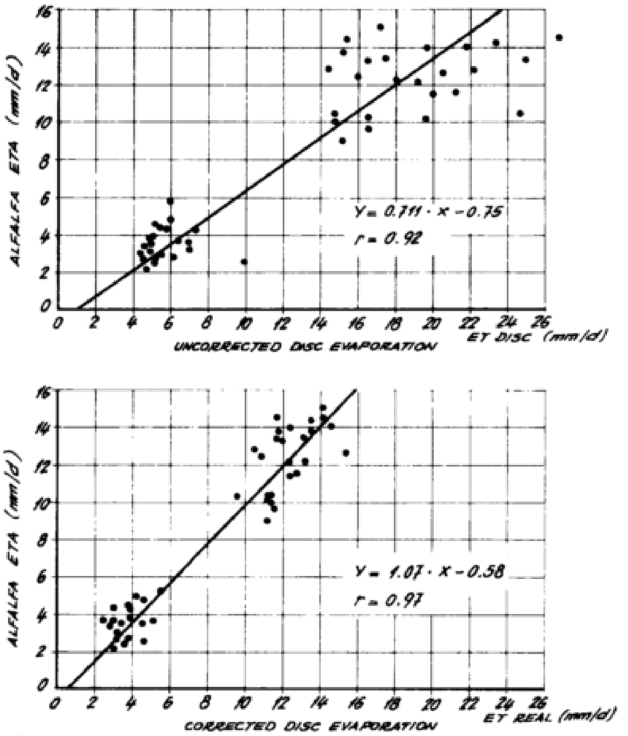

Fig. 13: Correlation between uncorrected (ET disc), corrected (ET real) disc evaporation and consumptive use of alfalfa (ETA) correction according to a daily mean wind speed measured at hight of 2,0 m

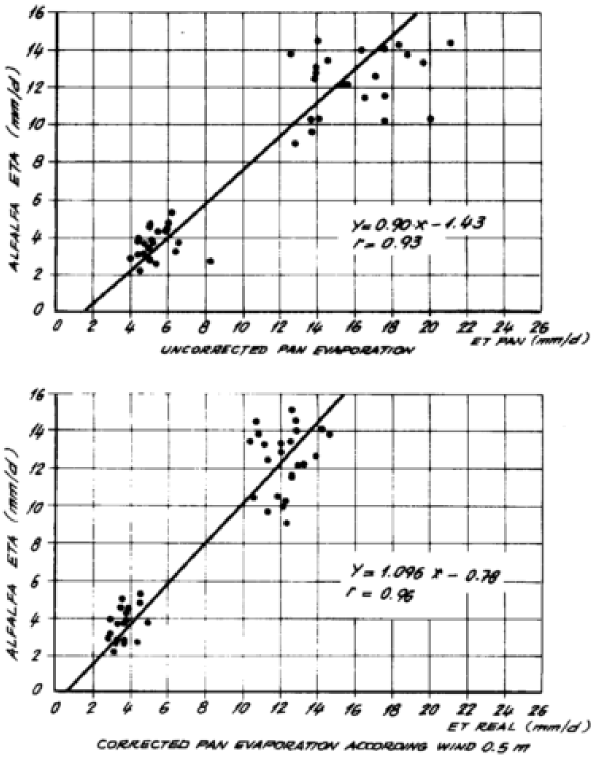

Fig. 15: Correlation between uncorrected (ET pan), corrected (ET real) pan evaporation and consumptive use of alfalfa (ETA) correction according to a daily mean wind speed measured at a hight of 0.5 m

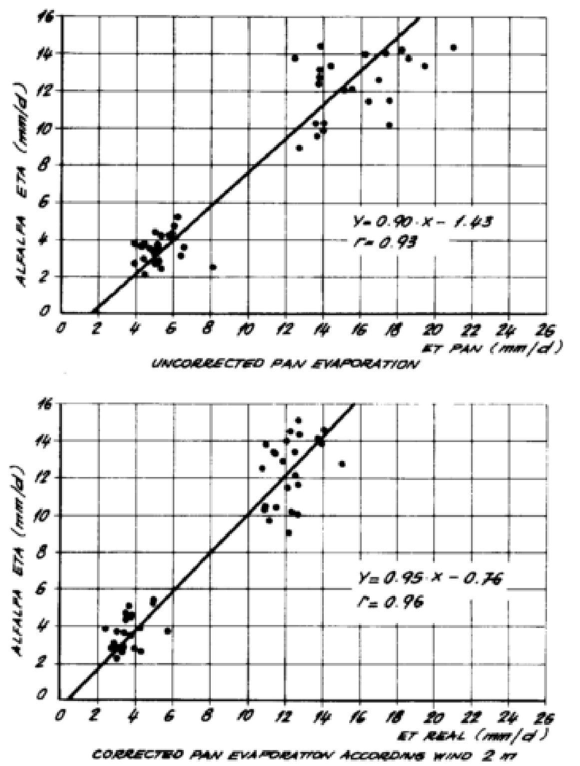

Fig. 14: Correlation between uncorrected (ET pan), corrected (ET real) pan evaporation and consumptive use of alfalfa (ETA) correction according to a daily mean wind speed measured at a hight of 2 m

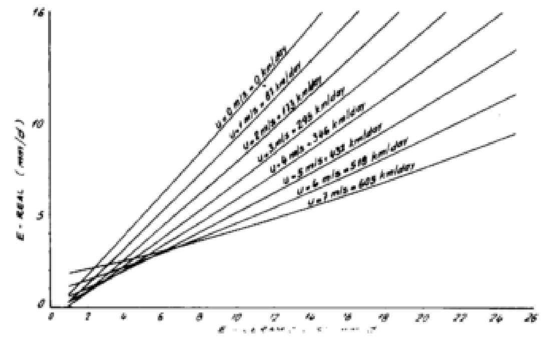

Fig. 16: Correction diagram for calculating real evapotranspiration from ceramic disc (2 m) and mean daily wind velocity (2 m)

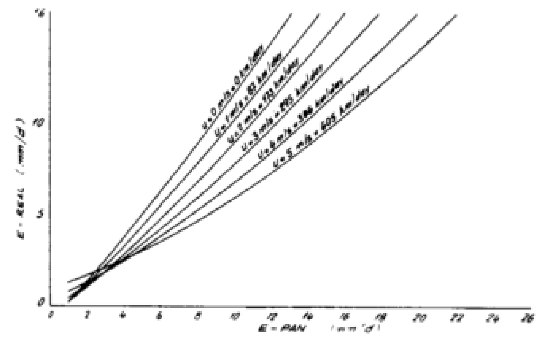

Fig. 17: Correction diagram for calculating real evapotranspiration from pan values and mean daily wind velocity (2 m)

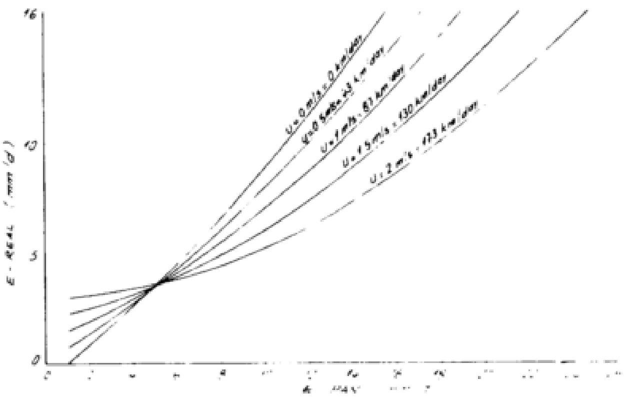

Fig. 18: Correction diagram for calculating real evapotranspiration from pan values and mean daily wind velocity (0.5 m)

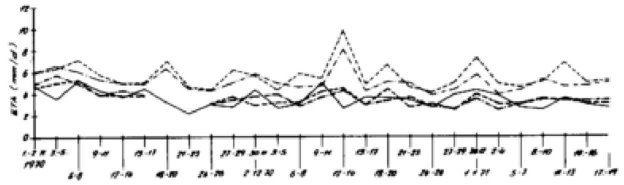

Fig. 19: Comparison between actual evapotranspiration of an alfalfa canopy (—), evaporation of the ceramic disc, unreduced (–·–) and after correction (**–·–**), and evaporation of the pan, unreduced (– – –), and after correction (**– – –**) Hofuf / Saudi Arabia, winter 1970/71

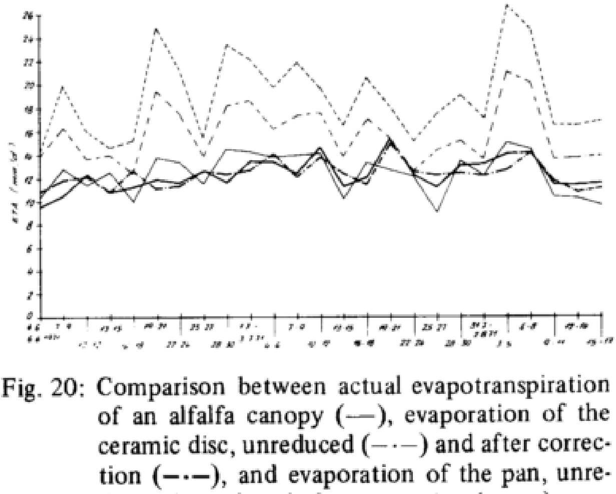

Fig. 20: Comparison between actual evapotranspiration of an alfalfa canopy (—), evaporation of the ceramic disc, unreduced (–·–) and after correction (**–·–**), and evaporation of the pan, unreduced (– – –) and after correction (**——**) Hofuf / Saudi Arabia, summer 1971

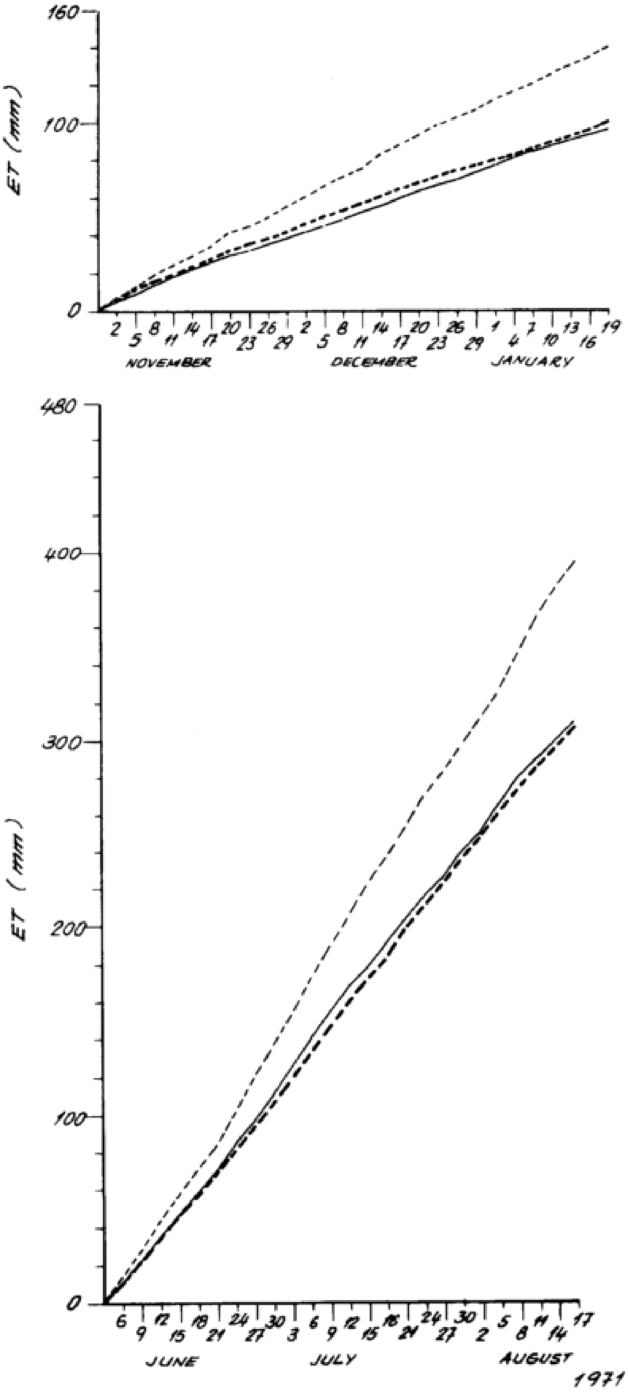

Fig. 21: Cumulative values of evapotrinsparation of alfalfa (—), pan uncorrected (– – –) and pan after wind correction (**– – –**) during winter and summer periods

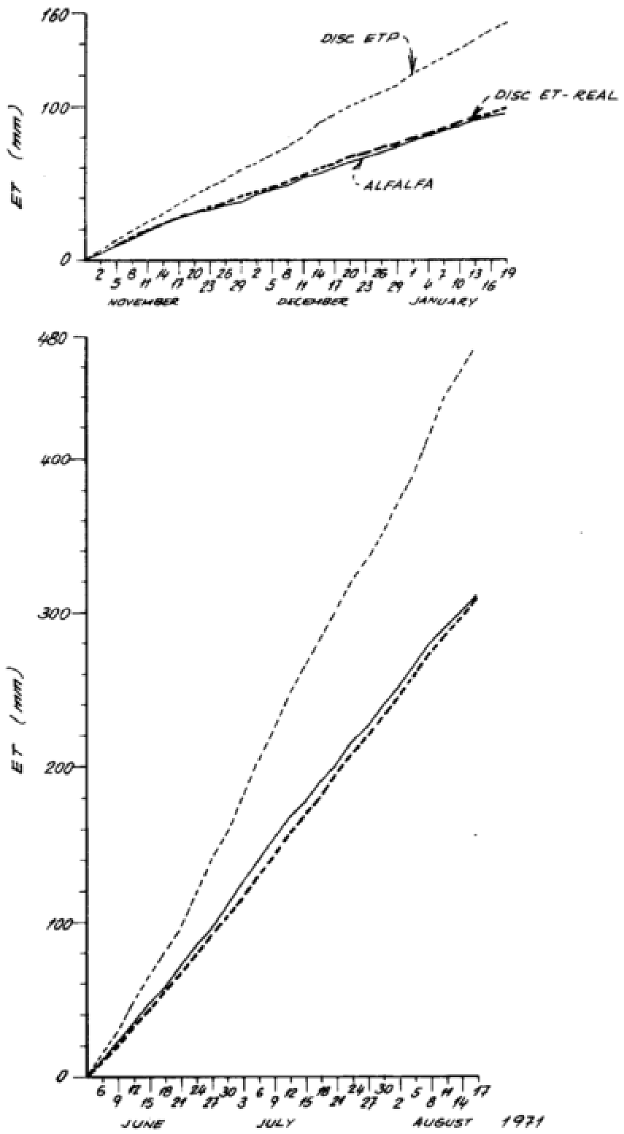

Fig. 22: Cumulative values of evapotranspiration of alfalfa (—), disc uncorrected (– – –) and disc after wind correction (**– – –**) during winter and summer periods

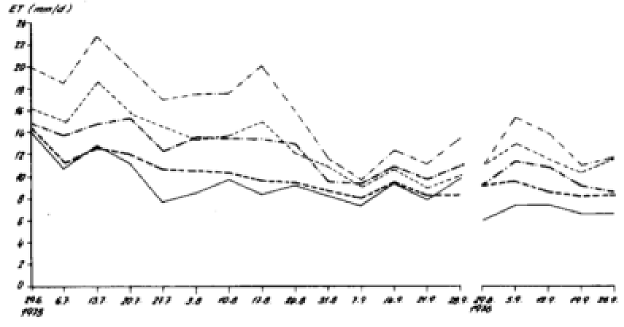

Fig. 23: Comparison of actual evapotranspiration of a sheltered sorghum canopy (—), evaporation of an unsheltered disc, unreduced (– · –) and after correction (**– · – · –**), and evaporation of an unsheltered pan, unreduced (– – –) and after correction (**– – –**) Hofuf 1975 and 1976

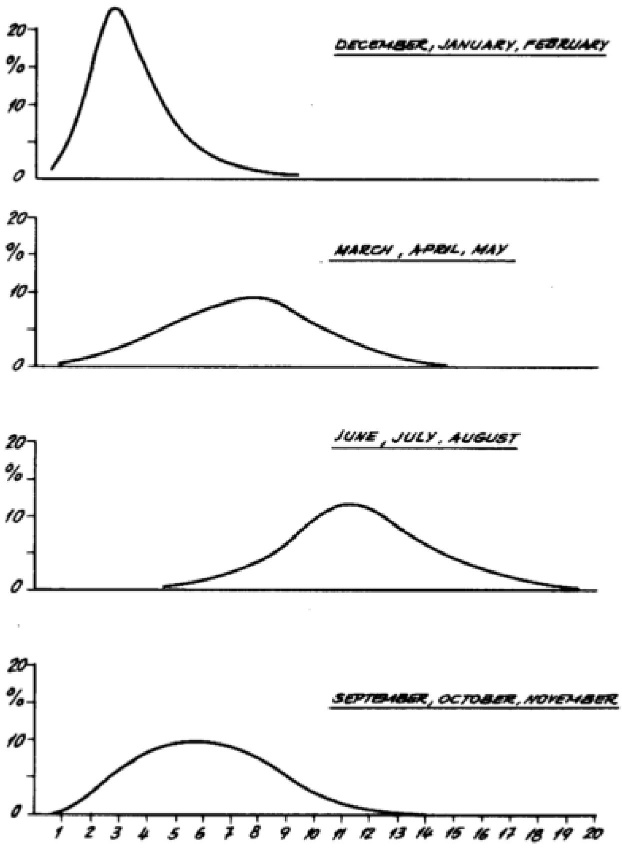

Fig. 24: Frequency distribution of reduced disc evaporation in four seasons (Hofuf 1969 – 1971)

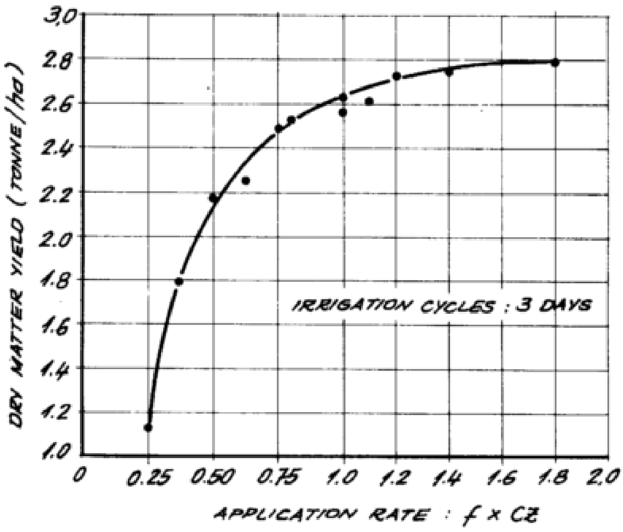

Fig. 25: Dry matter yield of alfalfa as related to water application in multiples (f) of ceramic disc evaporation (cz) corresponding to *Ohlmeyer* et al. (1)

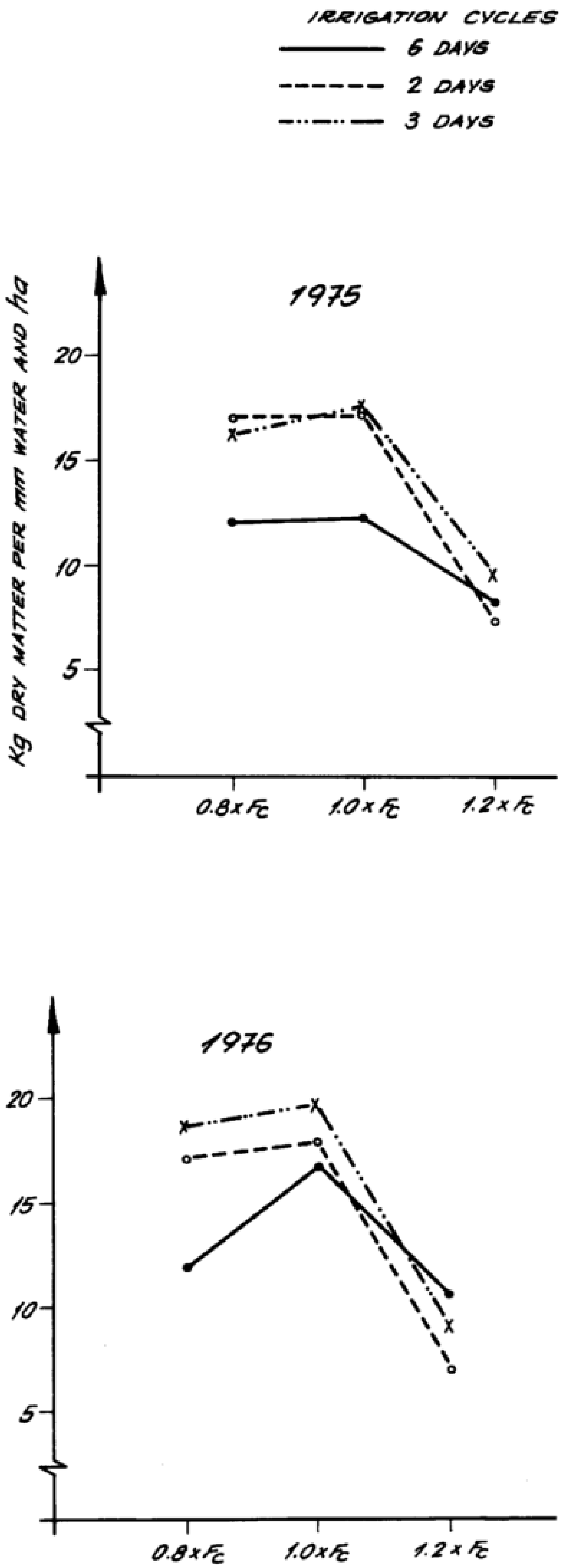

Fig. 26: Productivity of water related to various irrigation treatments and dry matter yield of sorghum according to *Hussain* (19)

Tab. A 1: Actual evapotranspiration of alfalfa and evaporimeter values 24-hour and 6 am – 6 pm readings: Winter 1970/1971

Date	ETA Alfalfa 24 h mm/d	ETP Disc 2 m 24 h mm/d	ETP Disc 2 m 6am-6pm mm/d	ETP Pan 0,5 m 24 h mm/d	ETP Pan 0,5 m 6am-6pm mm/d
01.-02.11.1970	4.8	6.0	5.0	6.1	4.3
03.-05.	3.7	6.4	5.2	6.6	4.6
06.-08.	5.3	7.2	5.9	6.2	4.3
09.-11.	4.3	5.8	5.0	5.4	3.8
12.-14.	3.8	5.0	4.5	5.1	4.2
15.-17.	4.5	5.1	4.4	5.0	3.4
18.-20.	3.2	7.0	5.6	6.4	4.6
21.-23.	2.2	4.7	4.3	4.5	2.8
24.-26.	3.0	4.4	3.8	4.4	2.8
27.-29.	2.8	6.2	5.3	5.1	3.8
30.11.-02.12.	4.4	5.4	4.3	5.9	3.8
03.-05.	2.7	4.4	3.6	5.0	3.7
06.-08.	3.1	5.9	4.4	4.7	2.9
09.-11.	5.0	5.5	4.3	4.8	3.5
12.-14.	2.6	9.9	6.4	8.1	5.1
15.-17.	3.7	4.9	3.4	4.3	2.9
18.-20.	3.6	6.6	4.4	5.2	3.3
21.-23.	3.4	4.6	3.6	5.0	3.9
24.-26.	2.8	4.1	3.5	3.9	2.6
27.-29.	3.9	5.0	3.8	4.4	2.9
30.12.-01.01.71	4.3	7.3	5.1	5.8	3.6
02.-04.	3.8	4.9	4.0	3.9	2.7
05.-07.	2.7	4.6	4.0	4.4	3.1
08.-10.	2.5	5.1	4.7	5.3	3.9
11.-13.	3.6	6.9	5.1	4.7	3.3
14.-16.	2.9	5.0	4.1	4.8	3.4
17.-19.	2.7	5.2	3.8	5.1	3.6

Tab. A 2: Actual evaporation of alfalfa and evaporimeter values 24-hour and 6 am – 6 pm readings: Summer 1971

Date	ETA Alfalfa 24 h mm/d	ETP Disc 2 m 24 h mm/d	ETP Disc 2 m 6am-6pm mm/d	ETP Pan 0,5 m 24 h mm/d	ETP Pan 0,5 m 6am-6pm mm/d
04.-06.06.1971	10.4	14.7	10.9	14.0	10.3
07.-09.	12.9	14.4	14.5	13.8	11.4
10.-12.	11.5	20.0	12.9	16.4	10.6
13.-15.	12.5	16.0	11.5	13.7	10.5
16.-18.	10.0	14.7	11.9	14.0	9.9
19.-21.	13.8	15.2	18.3	12.5	14.8
22.-24.	13.4	24.9	15.9	19.5	14.0
25.-27.	11.6	21.2	12.4	17.5	10.4
28.-30.	14.5	15.4	16.5	13.9	13.0
01.-03.07.1971	14.3	23.4	16.8	18.2	14.8
04.-06.	13.8	22.1	15.7	28.6	12.8
07.-09.	14.0	19.7	15.3	16.2	12.7
10.-12.	14.1	21.8	15.1	17.3	14.0
13.-15.	10.2	19.6	12.7	17.6	10.7
16.-18.	13.3	16.5	14.9	13.8	12.7
19.-21.	12.7	20.5	14.1	17.0	12.0
22.-24.	12.2	18.0	11.8	15.5	10.1
25.-27.	9.0	15.1	13.9	12.7	11.3
28.-30.	13.5	17.5	14.9	14.4	11.9
31.07.-02.08.71	12.2	19.1	12.7	15.2	9.9
03.-05.	15.1	17.1	16.5	13.6	12.6
06.-08.	14.5	26.7	17.6	21.0	14.1
09.-11.	10.4	24.6	13.2	20.0	10.6
12.-14.	10.3	16.5	13.1	13.6	11.0
15.-17.	9.7	16.5	13.1	13.7	9.8

Tab. A 3: Actual evapotranspiration of alfalfa and evaporimeter values 24-hour and 12-hour (6 am to 6 pm) readings. Statistical data for summer and winter period.

	ETP Disc 2.0 m mm/d	ETP Disc 0,5 m mm/d	ETP Pan 0,5 m mm/d	ETP Pan 0,0 m mm/d
Average	12.0	9.2	10.3	7.6
Correl. coefficient	0,92	0.97	0.93	0.97
Slope of regress. line	0.60	0.89	0.77	1.05
Intercpt of regr. line	0.56	-0.34	-0.11	0.14
Mean reduction factor	0.65	0.84	0.76	1.03

Tab. A 4: Actual evapotranspiration of alfalfa and evaporimeter values in different hights. Winter 1970/1971. 24-hour-readings

Date	ETA Alfalfa mm/d	ETP Disc 2,0 m mm/d	ETP Disc 0,5 m mm/d	ETP Pan 0,5 m mm/d	ETP Pan 0,0 m mm/d
01.-02.11.1970	4.8	6.0	4.5	6.1	4.0
03.-05.	3.7	6.4	5.0	6.6	4.3
06.-08.	5.3	7.2	5.4	6.2	3.9
09.-11.	4.3	5.8	4.5	5.4	3.4
12.-14.	3.8	5.0	3.8	5.1	3.8
15.-17.	4.5	5.1	3.8	5.0	3.2
18.-20.	3.2	7.0	5.3	6.4	3.9
21.-23.	2.2	4.7	4.1	4.5	2.9
24.-26.	3.0	4.4	3.4	4.4	2.8
27.-29.	2.8	6.2	4.7	5.1	3.2
30.11.-02.12.70	4.4	5.4	4.4	5.9	4.1
03.-05.	2.7	4.4	3.3	5.0	3.8
06.-08.	3.1	5.9	4.5	4.7	3.2
09.-11.	5.0	5.5	4.1	4.8	3.1
12.-14.	2.6	9.9	7.7	8.1	5.7
15.-17.	3.7	4.9	3.6	4.3	3.3
18.-20.	3.6	6.6	4.9	5.2	3.5
21.-23.	3.4	4.6	3.6	5.0	3.5
24.-26.	2.8	4.1	4.0	3.9	2.5
27.-29.	3.9	5.0	3.5	4.4	2.6
30.12.-01.01.71	4.3	7.3	5.4	5.8	4.1
02.-04.	3.8	4.9	3.8	3.9	2.8
05.-07.	2.7	4.6	3.6	4.4	2.9
08.-10.	2.5	5.1	4.0	5.3	3.0
11.-13.	3.6	6.9	5.3	4.7	3.1
14.-16.	2.9	5.0	3.9	4.8	3.2
17.-19.	2.7	5.2	3.9	5.1	3.1

Tab. A 5: Actual evapotranspiration of alfalfa and evaporimeter values in different hights. Summer 1971. 24-hour-readings

Date	ETA Alfalfa mm/d	ETP Disc 2,0 m mm/d	ETP Disc 0,5 m mm/d	ETP Pan 0,5 m mm/d	ETP Pan 0,0 m mm/d
04.-06.06.1971	10.4	14.7	11.8	14.0	9.9
07.-09.	12.9	14.4	11.3	13.8	9.5
10.-12.	11.5	20.0	15.0	16.4	11.2
13.-15.	12.5	16.0	12.0	13.7	9.2
16.-18.	10.0	14.7	11.2	14.0	9.3
19.-21.	13.8	15.2	11.2	12.5	8.8
22.-24.	13.4	24.9	19.0	19.5	13.6
25.-27.	11.6	21.2	15.9	17.5	12.4
28.-30.	14.5	15.4	12.4	13.9	9.6
01.-03.07.1971	14.3	23.4	14.7	18.2	12.0
04.-06.	13.8	22.1	16.5	18.6	12.6
07.-09.	14.0	19.7	14.7	16.2	10.7
10.-12.	14.1	21.8	16.4	17.3	11.8
13.-15.	10.2	19.6	14.8	17.6	12.1
16.-18.	13.3	16.5	11.8	13.8	9.5
19.-21.	12.7	20.5	15.4	17.0	11.6
22.-24.	12.2	18.0	13.2	15.5	10.4
25.-27.	9.0	15.1	11.2	12.7	11.0
28.-30.	13.5	17.5	12.4	14.4	9.6
31.07.-02.08.71	12.2	19.1	13.7	15.2	10.8
03.-05.	15.1	17.1	12.0	13.6	9.0
06.-08.	14.5	26.7	19.7	21.0	14.5
09.-11.	10.4	24.6	17.9	20.0	14.0
12.-14.	10.3	16.5	11.9	13.6	9.2
15.-17.	9.7	16.5	12.8	13.7	9.6

Tab. A 6: Actual evaporation of alfalfa and evaporimeter values. Evaporimeter exposition in different heights. Statistical data for summer and winter period.

	ETP Disc 2,0 m mm/d	ETP Disc 0,5 m mm/d	ETP Pan 0,5 m mm/d	ETP Pan 0,0 m mm/d
Average	12.0	9.0	10.3	7.0
Correl. coefficient	0.92	0.92	0.93	0.92
Slope of regress. line	0.60	0.83	0.77	1.08
Intercpt of regr. line	0.56	0.37	-0.11	0.18
Mean reduction factor	0.65	0.87	0.76	1.11

Tab. A 7: Actual evapotranspiration of alfalfa, uncorrected evaporimeter values and evaporimeter values after correction acc. Fig. 16, 17 and 18 (= ET-REAL)

Date	ETA Alfalfa mm/d	ETP Disc mm/d	ET-REAL Disc Corr. mm/d	ETP Pan mm/d	ET-REAL Pan Corr. Wind 0,5 m mm/d	ET-REAL Pan Corr. Wind 2,0 m mm/d
01.-02.11.1970	4.8	6.0	4.6	6.1	4.5	5.0
03.-05.	3.7	6.4	5.2	6.6	5.0	5.8
06.-08.	5.3	7.2	5.5	6.2	4.6	5.0
09.-11.	4.3	5.8	3.9	5.4	3.9	3.9
12.-14.	3.8	5.0	3.9	5.1	3.8	4.3
15.-17.	4.5	5.1	3.8	5.0	3.6	3.9
18.-20.	3.2	7.0	4.2	6.4	4.8	4.3
21.-23.	2.2	4.7	3.0	4.5	3.1	3.1
24.-26.	3.0	4.4	3.0	4.4	3.2	3.1
27.-29.	2.8	6.2	3.8	5.1	3.7	3.4
30.11.-02.12.70	4.4	5.4	3.0	5.9	3.9	3.8
03.-05.	2.7	4.4	3.2	5.0	4.4	4.0
06.-08.	3.1	5.9	3.2	4.7	2.9	2.9
09.-11.	5.0	5.5	4.2	4.8	3.6	3.7
12.-14.	2.6	9.9	4.6	8.1	3.7	4.3
15.-17.	3.7	4.9	3.0	4.3	3.6	3.1
18.-20.	3.6	6.6	4.5	5.2	3.4	3.4
21.-23	3.4	4.6	2.8	5.0	3.8	3.7
24.-26.	2.8	4.1	3.1	3.9	2.9	2.8
27.-29.	3.9	5.0	2.5	4.4	3.0	2.5
30.12.-01.01.71	4.3	7.3	4.0	5.8	3.8	3.6
02.-04.	3.8	4.9	3.0	3.9	2.9	2.5
05.-07.	2.7	4.6	3.1	4.4	3.1	3.1
08.-10.	2.5	5.1	3.6	5.3	3.2	3.4
11.-13.	3.6	6.9	3.4	4.7	3.4	3.4
14.-16.	2.9	5.0	3.1	4.8	3.5	3.3
17.-19.	2.7	5.2	3.1	5.1	3.6	3.4

Tab. A 8: Seasonal variation of consumptive use of alfalfa ETA and of unreduced evaporation ratels of pan and disc and of real evaporation of pan and disc after correction due to Fig. 16, 17 and 18 (= ET-REAL).

Date	ETA Alfalfa mm/d	ETP Disc mm/d	ET-REAL Disc Corr. mm/d	ETP Pan mm/d	ET-REAL Pan Corr. Wind 0,5 m mm/d	ET-REAL Pan Corr. Wind 2,0 m mm/d
04.-06.06.1971	10.4	14.7	9.6	14.0	10.5	10.9
07.-09.	12.9	14.4	10.5	13.8	12.0	11.9
10.-12.	11.5	20.0	12.5	16.4	12.6	12.2
13.-15.	12.5	16.0	10.9	13.7	11.3	10.8
16.-18.	10.0	14.7	11.3	14.0	12.1	12.7
19.-21.	13.8	15.2	11.9	12.5	10.8	11.0
22.-24.	13.4	24.9	11.7	19.5	11.4	11.4
25.-27.	11.6	21.2	12.7	17.5	12.6	12.7
28.-30.	14.5	15.4	11.7	13.9	10.7	12.3
01.-03.07.1971	14.3	24.4	13.5	18.2	13.8	12.7
04.-06.	13.8	22.1	13.5	18.6	14.6	14.0
07.-09.	14.0	19.7	12.4	16.2	12.8	12.1
10.-12.	14.1	21.8	14.6	17.3	14.2	13.8
13.-15.	10.2	19.6	11.3	17.6	12.2	12.4
16.-18.	13.3	16.5	12.0	13.8	12.0	11.5
19.-21.	12.7	20.5	15.4	17.0	13.9	15.1
22.-24.	12.2	18.0	12.3	15.5	13.2	12.5
25.-27.	9.0	15.1	11.2	12.7	12.4	12.2
28.-30.	13.5	17.5	13.1	14.4	12.5	12.5
31.07.-02.08.71	12.2	19.1	13.2	15.2	12.9	12.2
03.-05.	15.1	17.1	14.1	13.6	12.6	12.7
06.-08.	14.5	26.7	14.2	21.0	12.8	14.1
09.-11.	10.4	24.6	11.4	20.0	11.8	11.7
12.-14.	10.3	16.5	11.4	13.6	11.1	10.8
15.-17.	9.7	16.5	11.6	13.7	11.3	11.1

Tab. A 9: Actual evapotranspiration of alfalfa ETA, of unreduced evaporation rates of pan and disc ETP and of evaporation of pan and disc after correction (ET-REAL)

	ETP Disc mm/d	ET-REAL Disc corr. wind 2m mm/d	ETP Pan ~~corr.~~ mm/d	ET-REAL Pan corr. wind 0.5m mm/d	ET-REAL Pan corr. Wind 2 m mm/d
Average	12.0	9.8	10.3	7.8	7.8
Correl. coefficient	0.92	0.97	0.93	0.96	0.96
Slope of regress. line	0.60	1.00	0.77	0.01	0.99
Intercept of regress. line	0.58	0.10	0.11	0.08	0.01
Mean reduction factor	0.65	1.00	0.76	1.00	1.00

Tab. A 10: Seasonal variation of consumptive use sheltered sorghum canopy ETA and of unreduced evaporation rates of pan and disc and of real evaporation of pan and disc after correction due to Fig. 16 and 17 (ET-REAL)

Grwth period	Wind 2 m m/s	ETP Pan mm/d	ET-REAL Pan mm/d	ETP Disc mm/d	ET-REAL Disc mm/d	ETA Sorghum mm/d
23.-29.06.1976	3.23	16.0	13.8	19.8	14.4	14.6
30.06.-06.07.	2.92	14.9	11.0	18.4	13.6	10.5
07.-13.	4.04	18.6	12.4	22.4	14.7	12.3
14.-20.	2.90	15.6	11.9	19.9	15.2	11.0
21.-27.	3.13	14.3	10.4	16.8	12.0	7.5
28.07.-03.08.	2.42	13.2	10.4	17.4	13.5	8.2
04.-10.	2.82	13.7	10.2	17.5	13.3	9.4
11.-17.	3.80	14.8	9.6	20.1	13.3	8.0
18.-24.	2.16	11.9	9.4	15.9	12.7	8.9
25.-31.	1.90	10.6	8.5	11.6	9.3	7.6
01.-07.09.	0.89	8.9	7.9	9.7	9.1	6.8
08.-14.	1.40	10.6	9.1	12.2	10.8	8.8
15.-21.	1.56	8.8	8.0	11.1	9.4	7.6
22.-28.	2.13	10.6	8.2	13.4	10.7	9.6
23.-29.08.1977	1.73	10.8	9.1	10.8	9.1	5.9
30.08.-05.09.	2.70	12.8	9.5	15.3	11.3	7.4
06.-12.	2.10	11.4	8.6	13.7	10.8	7.5
13.-19.	1.76	10.3	8.3	10.9	9.8	6.7
20,-26.	2.62	11.4	8.3	11.6	8.5	5.7
Average		12.6	9.8	15.1	11.6	8.6
Correlation coeffecient		0.72	0.86	0.74	0.79	

Tab. A 11: Crop consumptive use coefficient for Class A Pan (after *Hargreaves*) 0.50 m, 24-hours readings. The coefficients are to be multiplied by pan evaporation values if no wind correction is made.

Crop \ Percentage of crop growing season	0	10	20	30	40	50	60	70	80	90	100
Alfalfa	0.55	0.60	0.70	0.80	0.90	0.95	0.95	0.95	0.90	0.80	0.65
Beans	0.20	0.30	0.40	0.65	0.85	0.90	0.90	0.80	0.60	0.35	0.20
Corn	0.20	0.30	0.50	0.65	0.80	0.90	0.90	0.85	0.75	0.60	0.50
Sorghum, Grain	0.20	0.35	0.55	0.75	0.85	0.90	0.85	0.70	0.60	0.35	0.15
Grain, spring	0.15	0.20	0.25	0.30	0.40	0.55	0.75	0.85	0.90	0.90	0.30
Grain, winter	0.15	0.25	0.35	0.40	0.50	0.60	0.70	0.80	0.90	0.90	0.30
Potetoes	0.20	0.35	0.45	0.65	0.80	0.90	0.95	0.95	0.95	0.90	0.90
Sugar beets	0.25	0.45	0.60	0.70	0.80	0.85	0.90	0.90	0.90	0.90	0.90

Tab. A 12: Crop consumptive use coefficients for *Czeratzki* disc 2 m, 24-hour readings. The coefficients are to be multiplied by disc evaporation if no wind correction is made.

	Percentrage of crop growing season										
	0	10	20	30	40	50	60	70	80	90	100
Crop											
Alfalfa	0.49	0.53	0.62	0.71	0.80	0.84	0.84	0.84	0.80	0.71	0.58
Beans	0.18	0.27	0.36	0.58	0.76	0.80	0.80	0.71	0.53	0.31	0.18
Corn	0.18	0.27	0.44	0.58	0.71	0.80	0.80	0.76	0.67	0.53	0.44
Cotton	0.09	0.18	0.36	0.49	0.67	0.80	0.80	0.76	0.67	0.49	0.31
Grain Sorghum	0.10	0.31	0.49	0.67	0.76	0.80	0.76	0.62	0.53	0.31	0.13
Grain spring	0.13	0.18	0.22	0.27	0.36	0.49	0.67	0.76	0.80	0.80	0.22
Grain winter	0.13	0.22	0.31	0.36	0.44	0.53	0.62	0.71	0.80	0.80	0.27
Potatoes	0.18	0.31	0.40	0.58	0.71	0.80	0.84	0.84	0.84	0.80	0.80
Sugar beets	0.22	0.40	0.53	0.62	0.71	0.76	0.80	0.80	0.80	0.80	0.80

Tab. A 13: Crop consumptive use coefficient for Class A Plan 0.50 m, 24-hours reading. The coefficients are to be multiplied by pan evaporation after wind reduction.

	Percentage of crop growing season										
	0	10	20	30	40	50	60	70	80	90	100
Crop											
Alfalfa	0.81	0.88	1.04	1.18	1.33	1.40	1.40	1.40	1.33	1.18	0.95
Beans	0.29	0.45	0.59	0.95	1.25	1.33	1.33	1.18	0.90	0.52	0.29
Corn	0.29	0.45	0.74	0.95	1.18	1.33	1.33	1.25	1.11	0.88	0.74
Grain Sorghum	0.29	0.52	0.81	1.11	1.25	1.33	1.26	1.04	0.88	0.52	0.21
Grain spring	0.22	0.29	0.36	0.45	0.59	0.81	1.11	1.26	1.33	1.33	0.43
Grain winter	0.22	0.36	0.52	0.59	0.74	0.88	1.04	1.19	1.33	1.33	0.42
Potatoes	0.31	0.52	0.66	0.95	1.18	1.33	1.40	1.40	1.40	1.33	1.33
Sugar beets	0.36	0.52	0.88	1.04	1.30	1.26	1.33	1.33	1.33	1.33	1.33

Tab. A 14: Crop consumptive use coefficients for ceramic *Czeratzki* disc, 2 m, 24-hours readings. The coefficients are to be multiplied by disc evaporation after wind reduction.

	Percentage of crop growing season										
	0	10	20	30	40	50	60	70	80	90	100
Crop											
Alfalfa	0.81	0.88	1.02	1.19	1.34	1.40	1.40	1.40	1.33	1.19	0.98
Beans	0.29	0.45	0.60	0.97	1.26	1.33	1.33	1.10	0.88	0.52	0.29
Corn	0.29	0.45	0.73	0.97	1.18	1.33	1.33	1 26	1.12	0.88	0.73
Grain Sorghum	0.29	0.52	0.81	1.12	1.26	1.33	1.26	1.04	0.88	0.52	0.21
Grain spring	0.21	0.29	0.36	0.45	0.60	0.81	1.12	1.26	1.33	1.33	0.45
Grain winter	0.21	0.36	0.52	0.60	0.73	0.88	1.04	1.18	1.33	1.33	0.45
Potatoes	0.29	0.52	0.67	0.97	0.67	1.33	1.40	1.40	1.40	1.33	1.3
Sugar beets	0.36	0.67	0.88	1.04	1.18	1.26	1.33	1.33	1.33	1.33	1.33