Evapotranspiration of a maize stand as related to soil moisture (case study)

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Abstract: The cumulative evapotranspiration of a maize stand growing at Žabčice situated in the south-east part of the Czech Republic was determined over the periods from planting to harvest in three consecutive years 1999, 2000 and 2001. In 1999, when the maize stand was sufficiently supplied with soil water, the sum of the evapotranspiration reached 279.7 mm during the period of sixteen weeks after planting. In the next year, the water regime of the maize stand was strongly influenced by significant decrease of the soil water content in the root zone, and consequently, the cumulative evapotranspiration during the same period was only 63.8% of the cumulative evapotranspiration over the comparable time interval in the season 1999. Similar reductions in the soil water content and evapotranspiration were recorded during the vegetation period 2001, as well. The mean daily sums of the evapotranspiration averaged over the periods of sixteen weeks after planting were 2.48 mm/day in 1999, but only 2.06 mm/day in 2000 and 1.73 mm/day in 2001. It followed from further analysis that the soil water availability practically did not affect the evapotranspiration, when at least 58.2% of extractable soil water was present in the root zone, but below this value, the evapotranspiration decreased linearly with the decrease in the soil water content. When the amount of available water for plants approaches the wilting point, the actual evapotranspiration is negligible.

Key words: maize, soil moisture, evapotranspiration, atmospheric factors

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1. Introduction

The daily transpiration accumulated over a given time interval usually determines the biomass production for that interval in a given climate (*de Wit, 1958; Tanner and Sinclair, 1983).* However, the evapotranspiration and its components depend on soil water content in the root zone (*Denmead and Shaw, 1962*). Consequently, one of the most common limiting environmental factors for plant growth is water supply (*Steduto and Hsiao, 1998b*). Evapotranspiration is a crucial parameter in most crop yield forecasting models (*Wallace, 1995*). The quantity of water losses by evapotranspiration must be know for correct irrigation scheduling (*Rana et al., 1997*).

For these reasons, estimations of the evapotranspiration have been recognized as important from many theoretical and practical aspects. Respecting this fact, the evapotranspiration of various field crops was frequently a subject of research. Nevertheless, most of these publications are short term studies covering the time interval of a few days to several weeks *(Hatfield et al., 1984; Choudhury et al., 1986; Bastiaanssen et al., 1997; Kjelgaard et al., 1994).* Till now, relatively few authors analysed the evapotranspiration throughout all vegetation period *(Baldocchi et al., 1981; McGinn and King, 1990; Steduto and Hsiao 1998a, 1998b).* Besides, the results based on experimental data are valid only for the geographic and climatic conditions where they were obtained, so that a generalisation is difficult, or quite impossible. Therefore the further investigation on this topic in different soil, geographic and climatic conditions is needed.

The aim of this study is to quantify the response of evapotranspiration from a maize stand to changes in soil moisture in environmental conditions of the south-east part of the Czech Republic.

2. Material and methods

The experimental data used for determination of the evapotranspiration were obtained at the experimental site of the Agricultural School Enterprise at Žabčice (49°01′N, 16°37′E, 179 m above mean sea level) serving as the research basis of the Mendel University of Agriculture and Forestry in Brno (Czech Republic).

The experimental site Žabčice is located in a warm microclimatological region with a predominantly moderate winter. During the vegetation period, the sums of mean daily air temperatures exceeding 5°C range between 2563°C and 3255°C with the average of 2871°C (*Rožnovský and Svoboda, 1995*). The growing period, as it is determined by the biological zero for maize (8°C), starts in average at March, the 3rd and ends at November, the 11th (*Šťastná, 1998*).

The region is the driest in the Czech Republic, whereby the mean annual sum of precipitation is 480 mm. During the vegetation period, the sum of precipitation ranges between 219 mm and 420 mm with the average of 321 mm (*Rožnovský and Svoboda, 1995*).

According to FAO classification, the soil is classified as calcaric fluvisol (*FAO, 1988*). The mean values of the field capacity and of the wilting point in the root zone are 38% and 21% by volume, respectively (*Šťastná and Žalud, 1999; Eitzinger et al., 2003*). The groundwater table was at a depth of about 1.8 m and its influence on the water regime of the upper soil layer 0-60 cm was neglected in this study. The field was not irrigated, so the atmospheric precipitation represented the only water resource.

A field of approximately 0.65 ha was planted with maize (*Zea mays* L.), the variety "STIRA" having the plant density of 12 plants/m^2 and the row spacing of 0.7 m. Agrotechnology, growth and development of maize stand was described earlier (*Chalupníková, 2001*).

The micrometeorological profile measurements of the wind speed, air temperature and relative humidity have been carried out since 1999 at this experimental site using the anemometers A100L, and thermohygrometers HMP45c. All these instruments were installed on a metallic mast at four levels above the maize stand. The levels of measurements were lifted up according to the increase in the mean height of the stand and its zero plane displacement. The profile measurements were accompanied by measurements of global radiation at a level of 12 m above the soil surface by means of the pyranometer KIPP& ZONNEN, type CM 6B. All meteorological parameters were measured automatically in intervals of 10 seconds and the results were registered as quarter-hourly averages by means of two data loggers type CN10 and CR10X, respectively.

Soil water content profiles in the soil layer 0-60 cm were determined gravimetrically by weighting soil samples before and after drying. The soil samples were taken in the time interval of a week. Daily totals of precipitation were available, as well.

Three sets of experimental data were used for further analysis. The first was obtained in 1999 during the time interval from planting on 6 May to 31 August, when the premature harvest for silage was made in the stage of milky ripeness. The next two data sets referred to the periods from planting to the stage of full ripeness in the following years 2000 and 2001. The meteorological conditions over these three consecutive years can be characterised by means of the data contained in Table 1.

Table 1. Monthly totals of the precipitation P, global radiation Q, and monthly averages of air temperature T in three consecutive years 1999, 2000 and 2001 as compared with climatic normal 1961-1990

		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
P [mm]	1999	5.0	10.6	20.8	49.8	44.4	81.6	82.4	10.4	35.6	11.2	42.4	5.6
	2000	28.6	16.8	40.5	2.4	44.6	13.6	116.6	48.4	37.8	17.6	38.4	29.1
	2001	25.3	9.5	46.0	31.6	31.8	42.0	68.6	57.6	107.0	10.6	41.2	14.8
	1961-90	24.8	24.9	23.9	32.2	62.8	68.6	57.1	54.3	35.5	31.8	36.8	26.3
Q [MJ.m^{-2}]	1999	74.9	171.6	328.2	475.2	619.0	600.9	644.7	536.6	415.1	223.3	91.0	94.0
	2000	100.8	189.6	259.4	555.3	682.5	748.5	507.2	585.2	354.4	205.3	119.9	69.4
	2001	98.8	218.8	232.4	451.1	700.0	583.5	583.1	588.9	254.0	179.0	128.5	91.9
	1961-90	84.1	148.2	285.0	420.4	563.2	605.4	613.1	519.9	344.1	205.0	90.2	62.7
T [°C]	1999	-0.7	-0.1	6.5	11.6	15.8	18.2	21.2	19.5	18.6	10.2	3.4	-0.2
	2000	-2.1	3.0	5.4	14.6	17.7	20.8	18.3	21.5	14.6	12.3	7.5	1.5
	2001	0.2	1.5	5.8	9.3	17.6	17.0	21.2	21.6	13.6	12.1	2.9	6.7
	1961-90	-2.0	0.2	4.3	9.6	14.6	17.7	19.3	18.6	14.7	9.5	4.1	0.0

The actual evapotranspiration was determined over periods of several days according to the water balance method (*Novák, 1995*). It was assumed that the groundwater level does not affect significantly the soil water regime in the upper 60 cm thick soil layer and the runoff can be neglected. Then, calculating the evapotranspiration for a certain period, the precipitation totals were balanced with the evapotranspiration and changes in the soil water content in the soil layer 0-60 cm.

With the aim to determine daily courses of evapotranspiration and its components, a mathematical model of plant water regime was used (*Huzulák and Matejka 1989a,b; Novák et al., 2005*). This simulation model was constructed in accordance with interactions existing among plants and the boundary layer of the atmosphere (*Bichele et al., 1980; Choudhury and Monteith, 1988*). Input data of this model involved hydrophysical parameters of soil, biometric characteristics of the maize stand, and meteorological elements as global radiation, wind speed, air temperature and air humidity at a reference level above the stand. The output of this model provides values of the evapotranspiration and its components.

The model was verified in different soil and climatic conditions for various stands. The verification carried out for a maize stand showed that the model is able to simulate the hourly sums of the evapotranspiration with the mean error of 0.06 mm/h (*Matejka, 1995*) which is quite acceptable for the purpose of this study. This conclusion is supported also by a comparison of seasonal patterns of the cumulative evapotranspiration simulated by the model and simultaneously calculated from the soil water balance equation at the experimental site Žabčice (Fig. 1).

Daily sums of the potential evapotranspiration were estimated by the reference evapotranspiration ET_0 calculated according to the FAO56 Penman-

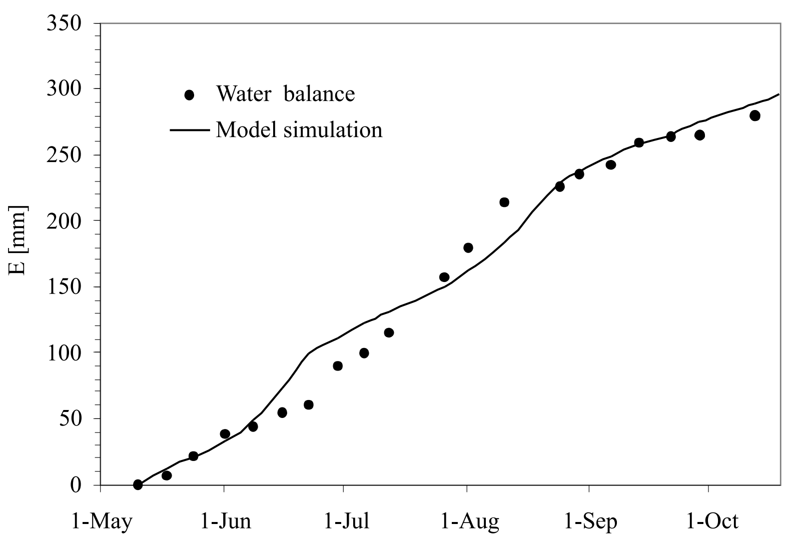

Fig. 1. The cumulative evapotranspiration of the maize stand determined by the method of the water balance and by means of the mathematical model during the growing season 2000.

Monteith equation (*Allen et al., 1998*)

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\,[37/(T_h + 273.16)]\,U_2 VPD}{\Delta + \gamma(1 + 0.34)U_2} \qquad (1)$$

where R_n is the net radiation, G soil heat flux, T_h mean hourly air temperature, U_2 wind speed, VPD vapour pressure deficit, Δ means the saturation slope vapour pressure curve and γ is the psychrometric constant.

3. Environmental factors

In the vegetation period of 1999, the meteorological conditions were ideal for growth of the maize stand. The sufficient precipitation amounts and their suitable time distribution created favourable conditions for the canopy development (Table 1). The sum of the global radiation and the average of air temperature calculated over the growing period exceeded corresponding normal values (*Svoboda and Brotan, 2003*). During the growing period, the monthly totals of the precipitation exceeded the corresponding normal values, except for August, when only 10.4 mm of precipitation has fallen. Nevertheless, the maize stand was well supplied with soil water over the whole analysed period.

As to the air temperature and the incoming solar radiation, the vegetation periods 2000 and 2001 seem to be very similar to the situation in the year 1999. However, there is a significant difference in the time distribution of precipitation. The monthly totals of precipitation in April, May and June 2000 fell dramatically, especially in April 2000, when the measured monthly sum of the precipitation represented 2.4 mm, which is 7.8% of the long-time climatic normal only. Similarly, there was a deficit in precipitation also in the first half of the year 2001. Consequently, the values of soil moisture during the whole growing periods in 2000 and 2001 were lower in comparison with the situation in 1999 (Fig. 2).

Besides, the extremely high evaporative demands of the atmosphere, that were recorded in the vegetation periods 2000 and 2001, brought to intensive evapotranspiration, especially at the beginning of the vegetation period, which resulted in rapid decrease of the soil water content in the root zone. Consequently, a few dry periods occurred in the growing periods 2000

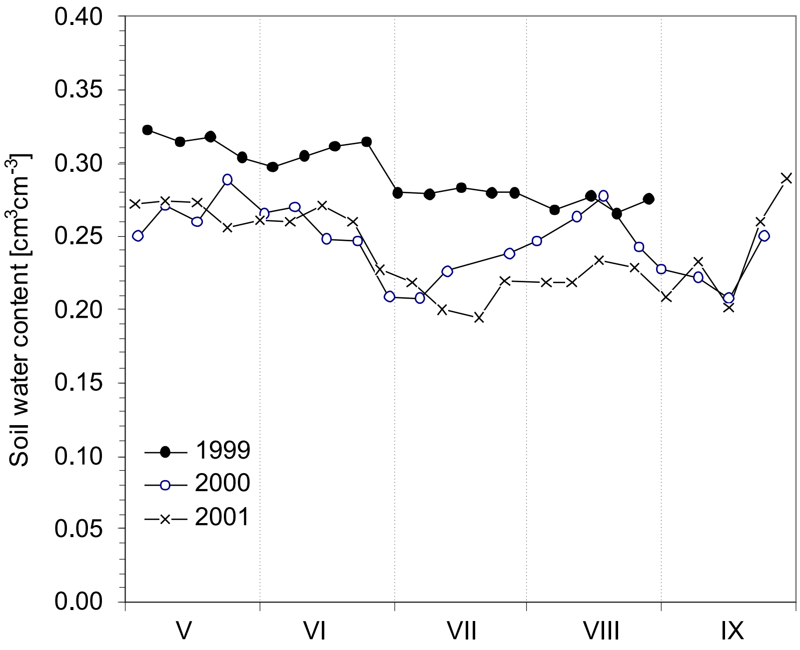

Fig. 2. Seasonal changes in the volumetric water content in the soil layer 0-60 cm below the maize stand during the growing seasons of three consecutive years 1999, 2000 and 2001.

and 2001, when the soil water availability decreased dramatically, and soil moisture in the root zone approached the wilting point, particularly in the beginning of July 2000 and in the middle of July 2001 (Fig. 2).

4. Results and discussion

The weekly sums of the actual evapotranspiration were determined according to the method of the water balance during the periods from May to August in 1999 and from May to September in 2000 and 2001. The seasonal changes in the cumulative evapotranspiration over the periods of sixteen weeks after planting in each of the analysed seasons are graphically presented in Fig. 3.

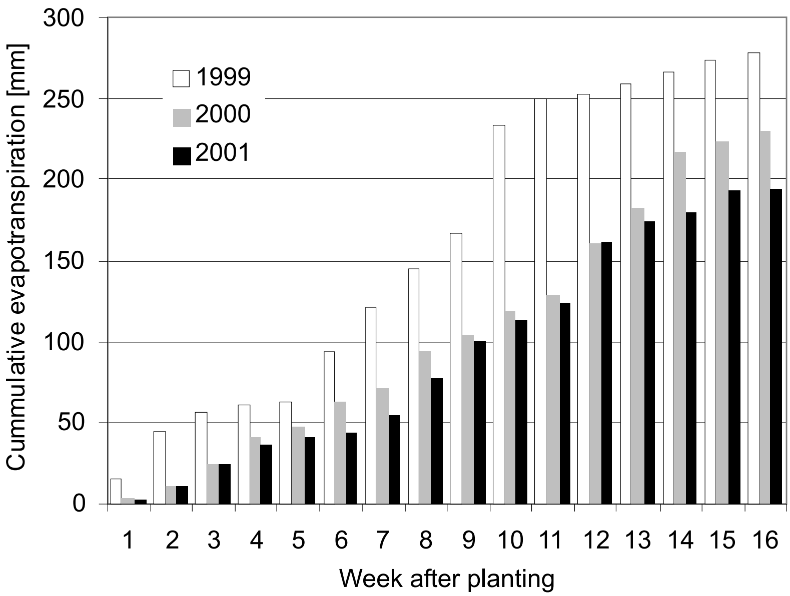

Fig. 3. The cumulative evapotranspiration of a maize stand during sixteen weeks after planting in three consecutive years 1999, 2000 and 2001.

In 1999, during the period of sixteen weeks after planting, the sum of the actual evapotranspiration reached 277.9 mm, while the total amount of precipitation during the same time interval was 229.5 mm. In the next year, the sum of the actual evapotranspiration over the corresponding period fell to 230.3 mm and the precipitation total of 213.6 mm was recorded for these sixteen weeks. Similarly reduced values of the cumulative evapotranspiration were determined also in the period of sixteen weeks after planting in 2001, when the sums of the evapotranspiration and precipitation were 194.3 mm and 174.8 mm, respectively. The mean daily sums of the evapotranspiration averaged over the periods of sixteen weeks after planting were 2.48 mm/day in 1999, but only 2.06 mm/day in 2000, and 1.73 mm/day in 2001.

The mean daily totals of evapotranspiration from the field with maize reported by other authors are a little greater than it was at Žabčice, particularly 4.2 mm/day (*Jara et al., 1998*), or 4.67 mm/day (*Kjelgaarg et al., 1994*). However, these mean values were obtained in different soil and climatic conditions for shorter periods when canopies were closed and fully developed.

It can be seen from Fig. 3 that the differences in the cumulative evapotranspiration between years 1999 and 2000, or 2001, arose immediately after planting. The sum of the actual evapotranspiration over three weeks after planting was 56.0 mm in 1999 but only 25.0 mm in 2000 and 25.1 mm in 2001. This significant reduction of the actual evapotranspiration in early development stages of the maize canopy can be explained as a result of different initial soil moisture at planting. While at planting in 1999 the mean soil moisture in the 0-60 cm soil layer was 32.4% of volume, the corresponding values in next two years were 27.2% and 25.1% of volume only. However, the greatest differences in the cumulative evapotranspiration during seasons 1999 and 2000 occurred in 10th and 11th weeks after planting (15th – 21st July 1999 and 12th – 18th July 2000, respectively). Over these periods, the mean soil moisture in 2000 and 2001 approached the wilting point, while in 1999 the maize canopy was sufficiently supplied with soil water.

Similar results were presented by *Steduto and Hsiao (1998a, 1998b)* for a maize stand growing in similar soil and climatic conditions. They found the reduction of the evapotranspiration of water stressed plants in the non-irrigated treatment in the 16th week after planting about 60% in comparison with the evapotranspiration from the irrigated part of the experimental maize field.

To compare in more detail the evapotranspiration over two consecutive years with different soil water regime, the decades between 15th and 24th July were selected from growing periods of years 1999 and 2000 for further analysis. The maize stand was during these decades in the same stage of development (flowering of panicles identified at 50% of plants on 19th July 1999 and 16th July 2000, respectively).

For the selected decades, the hourly sums of the actual evapotranspiration were calculated using the mathematical model of the plant water regime (*Huzulák and Matejka, 1989a,b; Huzulák and Matejka, 1996; Novák et al., 2005*). Simultaneously, the potential evapotranspiration was determined with a time step of one hour according to the FAO56 Penman-Monteith equation (*Allen et al., 1998*). Then, daily totals of the actual and potential evapotranspiration were calculated. To reduce the influence of atmospheric factors on evapotranspiration rates, the relative evapotranspiration, defined as the ratio between actual and potential evapotranspiration, on the soil moisture was analysed.

The significant differences in the relative evapotranspiration during selected decades are obvious (Fig. 4). The mean value of the relative evapotranspiration averaged over the decade was 0.92 in 1999 and 0.45 in 2000, respectively. The obtained results can be compared with data reported by *Tomlain (1979)* who found out that the long-time averaged value of the relative evapotranspiration equals 0.60 for July at the climatic station Brno, which is about 15 km away from Žabčice. Hence, during the decade 15th – 24th of July, 1999, the actual evapotranspiration of the maize stand approached the potential evapotranspiration, while within the same decade in the next year the maize stand suffered the strong water stress. Since atmospheric factors have only a small effect on the relative evapotranspiration, and the maize stand was in the same stage of its development, the differences in the relative evapotranspiration between compared decades had to be caused by differences in the soil water content.

The reduction of actual evapotranspiration in seasons 2000 and 2001 has been manifested also for the corresponding monthly sums of actual

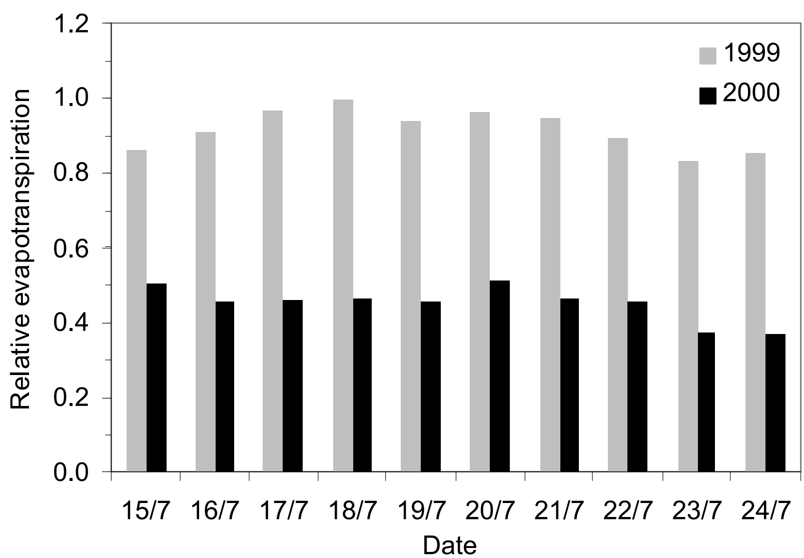

Fig. 4. Daily sums of the relative evapotranspiration during the decades between 15th and 25th of July in hydrologically contrasting years 1999 and 2000.

evapotranspiration (Table 2). The most significant reduction of the actual evapotranspiration from the analyzed maize stand, in comparison with long-time averaged data (*Tomlain, 1991*), occurred in May and June 2000 and 2001, when the stand was in early stages of its development.

Table 2. Monthly totals of the actual evapotranspiration in mm/month during the period May – September in three consecutive years 1999, 2000 and 2001, compared with the long-time averages of the actual evapotranspiration monthly sums for a grass (*Tomlain, 1991*)

	V	VI	VII	VIII	IX	V-VIII
1999	59.6	83.2	114.0	22.9		279.7
2000	41.9	55.8	79.9	62.6	61.1	240.2
2001	41.2	65.2	72.7	60.5	28.4	239.6
1951-1980	78.0	87.0	76.0	58.0	36.0	299.0

With the aim to quantify the influence of changes in soil moisture on the evapotranspiration of the maize stand, the relationship between evapotranspiration and soil water content in the soil layer 0-60 cm was determined. For this purpose, the clear days and the overcast days were selected from the growing seasons of years 1999 and 2000. The daily sums of the actual and potential evapotranspiration were calculated for these selected days using the mathematical model and the Penman method, respectively. Based on these data, the relationships between the relative evapotranspiration and the soil water content in the root zone for seasons 1999 and 2000 were compared (Fig. 5). The sloping part of the graph was fitted by a regression line.

The interpretation of the dependence presented in Fig. 5 can be based on the frequently used simplified conception (*Baunworth and Mack, 1987; Feddes et al., 1988; Novák, 1995; Shaozhong et al., 2000*). According this idea, the dependence of the relative evapotranspiration on the soil moisture is schematically described in a simplified form as a broken line with two breaking points at the soil water content W_1 and W_2. The values W_1 and W_2 were determined as points of intersection of the regression line with levels where the relative evapotranspiration is equal to zero or unity, respectively.

It follows from the Fig. 5 that the critical values of the volumetric soil

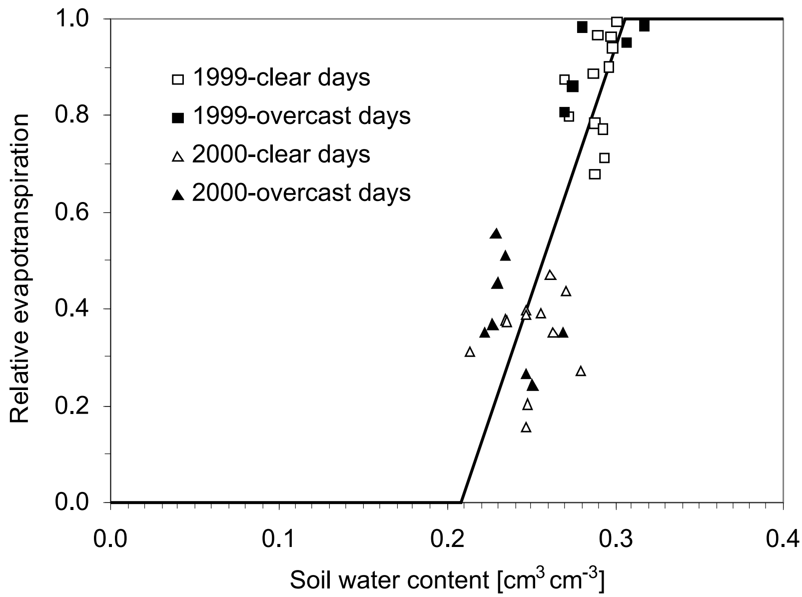

Fig. 5. The relationship between the volumetric water content in the soil layer 0-60 cm and the relative evapotranspiration of the maize stand for clear days and overcast days selected from two consecutive years 1999 and 2000.

water content for the analysed maize field are $W_1 = 0.306$ cm^{3}cm^{-3} and $W_2 = 0.199$ cm^{3}cm^{-3}. Expressing the soil water content as the amount of available water for plants, the first critical value corresponds with $W_1 =$ 58.2% of available water. As a result of the simplification of the relationship between the relative evapotranspiration and soil moisture, the second critical point is less than the wilting point. Consequently, the value of W_2 has no real interpretation in this case, and it cannot be expressed as a fraction of extractable water. Similar situation can arise quite often when the relationship between the potential and actual evapotranspiration, actually presented by a logistic function with sigmoidal shape, is simplified to a form consisting of three linear parts. In connection with this fact, only the threshold soil moisture W_1 is usually determined in the literature (*Irvine et al., 1998; Lagergreen and Lindroth, 2002; Girona et al., 2002*).

The position of points in graph in Fig. 5 clearly manifests the differences in the soil water availability between compared seasons. Since atmospheric factors have only a small effect on the relative evapotranspiration, the differences in the relative evapotranspiration over analysed seasons in years 1999 and 2000 can be explained as a result of differences in the soil water content.

The effect of changes in soil moisture on the evapotranspiration has been an issue of several studies. *Novák (1995)* found out in a maize stand that the volumetric soil water content below 0.27-0.31 cm^3cm^{-3} limits the evapotranspiration. *Steduto and Hsiao (1998a, 1998b)* analysed the evapotranspiration from a maize stand growing under different soil water regimes in soil conditions of the clay loam. Their results attest to the fact that the actual evapotranspiration practically equals the potential evapotranspiration for the volumetric soil water content exceeding 0.27-0.29 cm^3cm^{-3}.

The results presented in this study together with data of other authors led to conclusions that, in given soil conditions, the decrease of the soil water content below 0.28-0.30 cm^3cm^{-3} has as a result the reduction of the actual evapotranspiration. Since the soil water content did not reach this value during the prevailing part of the growing periods 2000 and 2001, the actual evapotranspiration from the maize stand at Žabčice was in these seasons significantly reduced in comparison with the season 1999, as well as in comparison with long-time averaged data.

Seasonal changes in the soil water content affect the evapotranspiration simultaneously with other environmental factors. Soil water status and atmospheric vapor pressure deficit are important environmental parameters that influence plant gas exchange (*Xue et al., 2004*). In connection with this, it is necessary to emphasize that the periods of soil drought in July 2000 and 2001 were accompanied by very dry air. It can be illustrated by extremely high values of the vapour pressure deficit with daily maxima in a few days exceeding 40 hPa. Consequently, the reduction of the evapotranspiration caused by shortage of the soil moisture was partially compensated by the low air humidity, which brought to high evaporative demands of the atmosphere. Similar increase of the evapotranspiration associated with rising in the vapour pressure deficit has been reported also by other authors (*Turner et al., 1984; Dai et al., 1992; Bunce, 1996; Xue et al., 2004*). All these results led to conclusion that the vapour pressure deficit in the air is an important environmental factor, which together with soil moisture affects the gas exchange between vegetation and the atmosphere (*Calvet*

2000; Gucci et al., 1996; Leonardi et al., 2000; Habermann et al., 2003). Finally, the high evaporative demands of the atmosphere accelerating the evapotranspiration have, as a result, intensive drying of the surface soil layers, which has been manifested by dry periods occurring during the growing periods of years 2000 and 2001.

5. Conclusions

During the selected three consecutive growing seasons the investigated maize stand transpirated under changing environmental conditions, and its water regime was strongly influenced by significant decrease in the soil water content recorded during the growing seasons of years 2000 and 2001.

It was shown that the soil water availability practically did not affect the evapotranspiration, when at least 58.2% of extractable soil water was present in the rooting zone, but below this value, the evapotranspiration decreased linearly with the decrease in the soil water content. The actual evapotranspiration was negligible when the amount of available water for plants approached zero.

Because of a lack of available water in the root zone, the evapotranspiration during the period of sixteen weeks after planting in the season 2000 was only 63.8% of the evapotranspiration in comparable time interval in the preceding year 1999, when the canopy was well supplied with soil water.

A very important factor, affecting the soil and plant water regime during the growing period, is the soil water content at the time of planting. Its low values accompanied by extremely high evaporative demands of the atmosphere in years 2000 and 2001 seem to be the immediate cause resulting in the intensive drying of the soil.

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