Optimisation of Irrigation Regime for Early Potatoes, Late Cauliflower, Early Cabbage and Celery

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Abstract: The paper deals with optimisation of threshold suction pressure of soil water on light soils for early potatoes, early cabbage, late cauliflower and celery on the basis of results of small-plot field experiments with differentiated irrigation regime. Experiments were conducted in 2003–2005. Threshold suction pressures of soil water were identical for all crops: 15 kPa in treatment I, 30 kPa in treatment II, 60 kPa in treatment III, and 120 kPa in treatment IV. Precipitation, air temperature and relative humidity, global solar radiation, wind speed and direction were measured by an automated meteorological station. Reference and actual evapotranspiration was determined for the experimental crops according to FAO Paper No. 56 and by means of a biological curve (BC) in 2003–2005. To compare these two methods of calculation of actual evapotranspiration the soil moisture balance was found out. Based on the influence on marketable yield and proportion of the crop quality grades it is possible to determine the optimum threshold suction pressure on light loamy-sand soils in early potatoes, late cauliflower and cabbage 30 kPa and in celery 15 kPa. 80% of available soil water capacity (ASWC) corresponds to the threshold suction pressure 30 kPa, and as much as 96% of ASWC corresponds to 15 kPa. The seasonal irrigation depths determined on the basis of soil moisture balance, in which the crop evapotranspiration (ET_c) is calculated either according to FAO 56 or by the BC, are substantially different from the really achieved irrigation depths in the treatments where optimal suction pressure is maintained. For potatoes, the really achieved values of seasonal irrigation depths are nearer to the depths calculated by the BC, while for the other vegetables (cauliflower, cabbage and celery) they are more similar to the depths calculated by FAO 56 methodology. The theoretical irrigation depths calculated by the BC method sometimes differ substantially from those based on FAO 56. These differences are at maximum for cauliflower and celery and at minimum for cabbage and decrease with the decreasing irrigation depths.

Keywords: irrigation regime; early potatoes; late cauliflower; early cabbage; celery; yields; threshold suction pressures of soil water; reference evapotranspiration; actual evapotranspiration

Qualified management of irrigation regimes of crops is one of the basic conditions of irrigation profitability. It brings about great savings of irrigation water, electrical power and nitrogen fertilisers, and it enables to achieve optimum and high-quality marketable yields of crops and to reduce a risk of groundwater contamination by nitrates, pesticide residues and other xenobiotic compounds. Sanford (2003) stated that the management of irrigation regime could reduce energy consumption per unit yield by 7–32% in relation to the crop. The importance of energy savings increases with the growth of its prices that has been, and will probably be, marked.

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Scientific and in practice tested methods may be used for irrigation management. They are usually based either on the measurement of soil moisture and on its balance or on the measurement of some physiological parameters of plants. In some countries there exist organisations offering to farmers information necessary for irrigation management. Paid services usually provide daily values of potential or reference evapotranspiration, sometimes with crop coefficients, or direct instrumental measurements of soil moisture (Curwen & Massie 1994; Kohut 1996; Wolff *et al.* 1996; King & Stark 1997; Martins 2000; Specty 2006; http://weather.nmsu.edu/wcc202/; etc.). But mainly farmers in Europe use these services to a small extent. In the Czech Republic (CR) several methods for irrigation regime management were developed. The method of biological curve (Sláma 1969) is based on the balance of soil moisture according to potential evapotranspiration determined as the product of the sum of actual vapour pressures over the balance period and the coefficient of biological curve. The graphico-analytical method (Kudrna 1987) is based on an assumption that the process of organic matter formation is determined by thermodynamic laws. This method was modified by Slavík (1980) so that it would be possible to manage the irrigation regime of field crops by the prognosis of the need of supplemental irrigation rates in a decade balance period. The agrometeorological programme complex AVISO, run by a branch of the Czech Hydrometeorological Institute in Brno, is a balance method based on the computations of potential evapotranspiration by a modified procedure according to Penman and Monteith (Kohut 1996). None of these methods has been applied in practice on a larger scale.

No scientific method is currently used in the CR for the management of irrigation regimes of vegetables and field crops. Only in newly built microirrigations, mainly in orchards and vineyards, Virrib sensors of the company AMET in Velké Bílovice (http://www.amet.cz) directly measuring soil moisture are used.

Simplicity and low cost of the used method are crucial conditions for the introduction of qualified management of irrigation regimes. For the use of any method it is necessary to determine minimum soil moisture or threshold suction pressure of soil water. Their values are related to the crop and soil type. In the CR the threshold suction pressure was determined only for early potatoes on medium-heavy soils (Zavadil 2000). In extensive foreign specialised literature dealing with irrigation management threshold suction pressures were reported only in North American literature. For vegetables including potatoes (Irish potato) they were summarised e.g. by Kemble and Sanders (http://www.aces.edu/pubs/docs/A/ANR-1169) or by Sanders (http://www.nscu.edu/depts/hort/hil/hil-33-e.html). Thomas *et al.* (1970) determined optimum threshold suction pressures of soil water for cabbage while these pressures for potatoes were determined by van Loon (1981), Shock *et al.* (2001), Wilson *et al.* (2001), Kang *et al.* (2004), Shock (2004).

This paper deals with the optimisation of threshold suction pressure of soil water on light soils for early potatoes, early cabbage, late cauliflower and celery on the basis of results of small-plot field trials with differentiated irrigation regime.

MATERIAL AND METHODS

To optimise the threshold suction pressure of soil water field trials were conducted on plots of Research Institute of Soil and Water Conservation in Mělník locality. An experimental plot is situated at an altitude of 180–182 m above sea level, 51°21’31.8” latitude and 14°26’13.6” longitude. The soil on this plot belongs to soils of chernozemic character that were formed on a light carbonate substrate, with a slight aeolic admixture in topsoil. A dominant genetic soil representative according to the Complex Survey of Soils (Němeček *et al.* 1967) is dark Regosol (DAt 59; 1.04.01), according to the Taxonomic Classification System of Soils of the CR (Němeček *et al.* 2001) it is arenic Chernozem (CEr). Physical, hydro-pedological and agrochemical properties of soil on the experimental plot are balanced. According to Novák’s classification scale the soil on the experimental plot in the topsoil layer (0–0.3 m) is light, loamy sand with the average content of soil particles < 0.01 mm amounting to 19.4%. It has neutral to weakly alkaline soil reaction (exchange pH 7.2) and medium to high humus content (1.7% C_{ox}). Based on the criteria of evaluation of available nutrients in Mehlich III extract (Trávník *et al.* 1999), every year in spring before crop planting phosphorus content was very high (about 500 mg/kg soil), potassium content was good to high (about 250 mg/kg soil) and magnesium content was satisfactory (about 100 mg/kg soil).

Table 1. Differentiation of irrigation regime and the values of soil moisture constants

Treatment	Threshold suction pressure (kPa)	Threshold soil moisture – *TSM* (% vol.)	% *ASM*
I	15	27.1	96
II	30	24.8	80
III	60	22.6	65
IV	120	20.4	49

Θ_{FC} (field capacity) = 27.6% vol.; Θ_V (permanent wilting point) = 13.4% vol.; *ASM* (available soil moisture) = $\Theta_{FC} - \Theta_V$ = 14.2% vol.; % *ASM* = 100 × ($TSM - \Theta_V$)/*AS*

In the experiment we used early potatoes (cultivar Marabel – seed tubers were certified as C2), late cauliflower (cv. Fremont), early cabbage (cv. Zora in 2003 and 2005 and cv. Perfekta in 2004) and celery (cv. Maxim). These crop species were chosen with respect to the present assortment of crops irrigated in the CR. The experiment with each crop had 4 variants of irrigation regime. The variant without irrigation was not used in early potatoes and vegetables because their production without supplemental irrigation is not assumed. Threshold suction pressures of soil water were identical for all crops: 15 kPa in treatment I, 30 kPa in treatment II, 60 kPa in treatment III, and 120 kPa in treatment IV. Table 1 shows soil moisture contents in percentage by volume corresponding to these pre-irrigation suction pressures. Suction pressures of soil water in kPa were converted to soil moisture contents in percentage by volume by means of the pF curve (Figure 1). Field capacity (Θ_{FC}) and wilting point (Θ_W) were determined from the pF curve for the effective depth of watering to 0.3 m in early potatoes and to 0.2 m in vegetables. These soil moisture constants have the same value for both depths – Θ_{FC} = 27.6% vol. (pF 2) and Θ_W = 13.4% by vol. (pF 4.18). van Genuchten equation (1980) was used for the approximation of pF curve.

The irrigation of vegetables started immediately after planting to ensure their survival. In vegetables the irrigation regime started to be differentiated after their rooting to the effective depth of watering to 0.2 m and in potatoes after their emergence. The effective depth of watering in potatoes was 0.3 m. All crops were irrigated by microsprinkling. In 2003 we used Super Mamkad sprinklers of the Israeli company Dan Sprinklers with sprinkler intensity 4.6 mm/h at a pressure of 0.35 MPa, in

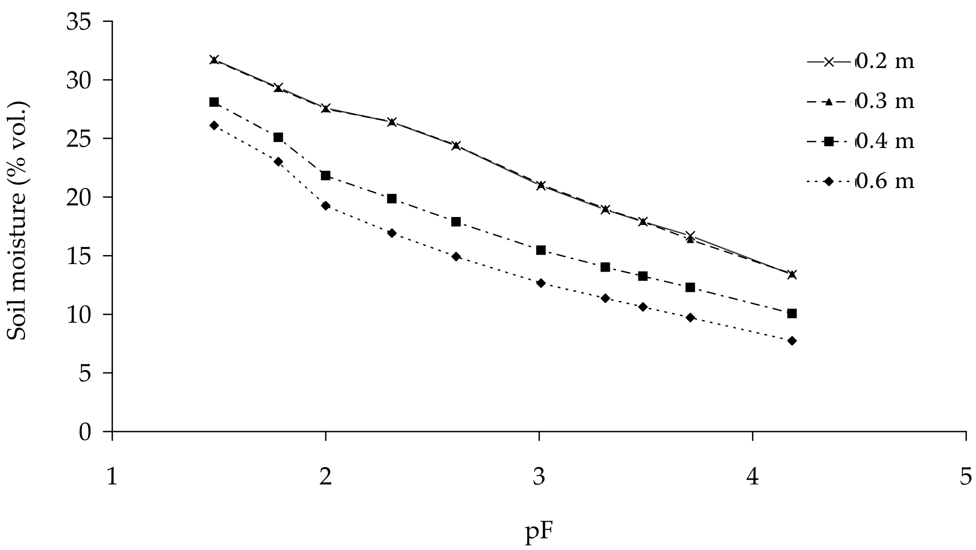

Figure 1. pF curves, experimental plot in Mělník-Neuberk locality

2004 and 2005 impact circular microsprinklers with sprinkler intensity 7.3 mm/h at a pressure 0.35 MPa were employed. The amount of water consumed for irrigation was measured with water meters at each treatment separately. The irrigation regime was adjusted with respect to the need of protective sprayings against diseases and pests, hoeing and weeding. The date of irrigation was indicated when the suction pressure of 15 kPa was reached in treatment I, 30 kPa in treatment II, 60 kPa in treatment III, and 120 kPa in treatment IV. Irrigation rates were calculated so that the water content in soil would be filled up to the field capacity and water losses during microsprinkling would be compensated. Suction pressures of soil water were measured automatically with Watermark sensors of Irrometer Co. (http://www.irrometer.com/agcat.htm#WM) in one-hour intervals at a depth of 0.3 and 0.6 m under potatoes and at a depth of 0.2 and 0.4 m under vegetables. At each depth 3 sensors were placed ca. 0.5 m apart for the reason of non-uniform sprinkler intensity and soil heterogeneity. Watermark sensors were used because they measure suction pressures of soil water to 200 kPa and are cheap compared to the other sensors, which is one of the main conditions for their use in practice in the CR. Data were recorded with dataloggers of the company Environmental Measuring Systems in Brno (EMS Brno) (http://www.emsbrno.cz). The irrigation regime was managed according to suction pressures of soil water at 7.00 a.m. If one value of suction pressure was markedly different from the others, it was left out.

An automated meteorological station of EMS Brno Company was used for meteorological measurements. It registered precipitation, air temperature and relative humidity, global solar radiation, wind direction and speed. To determine potato yield 8 rows by 15 hills were harvested, and 8 rows by 15 individuals were harvested to determine vegetable yield. One replication always consisted of two rows. Crop yields were expressed as weight. Besides total yield the proportion of the size categories of potato tubers (< 3, 3–5 and > 5 cm) in yield and the proportion of the quality grades of vegetables in yield were determined. Vegetables were included in grades according to criteria defined by the respective Czech technical standards: ČSN 46 3112 Cauliflower (2000), ČSN 46 3113 Head Cabbage and Head Savoy Cabbage (2000) and ČSN 46 3120 Fresh Vegetables – Root Vegetables (1995). Yields were evaluated by one-factor analysis of variance on a significance level $\alpha = 0.05$.

Reference evapotranspiration (ET_o) was determined in accordance with the FAO 56 paper (Allen *et al.* 1998). Actual vapour pressure (e_a) was calculated from maximum and minimum relative air humidity (RH_{max} and RH_{min}) and minimum and maximum air temperature (T_{min} and T_{max}). For all crops used in the experiment actual evapotranspiration (ET_c) was calculated according to FAO 56 (1) and by means of the biological curve (Sláma 1969) (2).

$$ET_c = ET_o \times K_c \qquad (1)$$

where:

K_c – simple crop coefficient (Allen *et al.* 1998)

$$ET_c = e_a \times K_b \qquad (2)$$

where:

e_a – actual vapour pressure computed from average daily air temperature and its average daily relative humidity

K_b – experimentally determined coefficient of biological curve for the particular temperature groups given in ČSN 75 0434 (1994)

To compare these two methods of ET_c computation the soil moisture balance was found out. The assumed allowable soil moisture deficit (ASMD) is based on ČSN 75 0434. For potatoes to flowering and 2 weeks before harvest it is 40% and in the interim period 30%, for cauliflower, cabbage and celery in the first 30 days from planting it is 30% and later until harvest 40%. Each irrigation rate equalled the amount of water necessary to fill up the water content in soil to the depth of irrigation to field capacity.

RESULTS AND DISCUSSION

Figures 2 and 3 show weather conditions in the growing seasons (months IV–IX) of 2003–2005. The year 2003 was the driest one and the year 2005 was the wettest one. The amount of precipitation for months IV–IX (239.8 mm) was lower by 37.4 mm than in 2004 and by 150.4 mm compared to 2005 (Table 2). The amount of precipitation over the growing season of crops was lowest in 2003 and highest in 2005 (Table 3). In 2003 ET_o was the highest – it was higher by 103 and 102 mm, respectively, compared to 2004 and 2005 (Table 2,

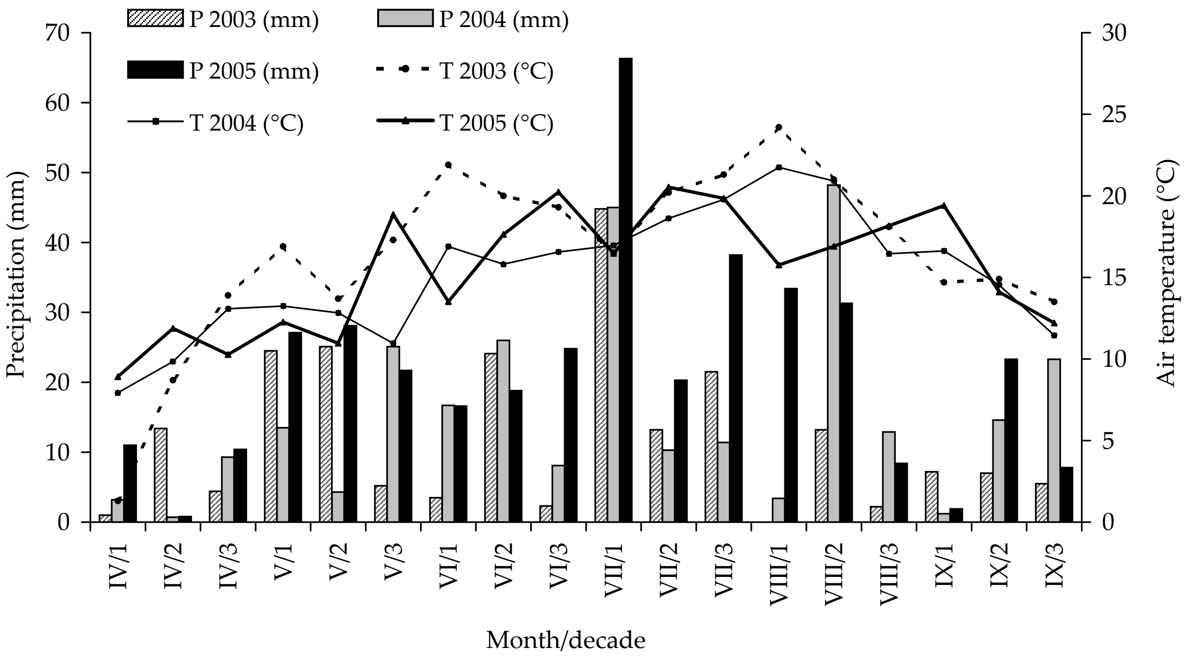

Figure 2. Comparison of average daily temperatures of air (T) and precipitation amounts (P) for the decades of growing seasons in 2003–2005

Figure 3). The same applied to ET_c (Figure 4). Generally higher ET_c of cabbage in 2004 was caused by the use of cv. Perfekta with longer growing season than in cv. Zora planted in 2003 and 2005.

The depth of precipitation and its distribution in the growing season of crops made it possible to markedly differentiate seasonal irrigation depths between the treatments in 2003 and 2004 in all

Table 2. Average values of temperature of air (T) and its relative humidity (RH), global radiation (R_g), wind speed (u_2), soil temperature at a depth 0.1 m (T_s), precipitation amount (P) and reference evapotranspiration (ET_o) for months IV–IX

Year	T (°C)	RH (%)	R_g (W/m^2)	u_2 (m/s)	T_s (°C)	P (mm)	ET_o (mm)
2003	15.2	65.8	185.6	1.7	19.0	239.8	678.6
2004	15.2	68.6	176.9	1.7	18.8	277.2	575.6
2005	15.4	70.9	183.8	1.6	18.1	390.2	577.0

Table 3. Precipitation amounts in the growing season of crops

Year	Early potatoes		Late cauliflower		Early cabbage		Celery	
	GS	P (mm)	GS	P (mm)	GS	P (mm)	GS	P (mm)
2003	26.3.–14.7. (111 days)	148	3.7.–2.10. (91 days)	87	22.4.–24.6. (64 days)	103	29.4.–2.10. (188 days)	218
2004	1.4.–28.7. (119 days)	174	7.7.–11.10. (96 days)	157	21.4.–20.7. (91 days)	158	5.5.–29.9. (177 days)	262
2005	7.4.–26.7. (111 days)	256	7.7.–26.9. (81 days)	185	20.4.–22.6. (64 days)	124	12.5.–19.9. (160 days)	333

GS = growing season, P = precipitation

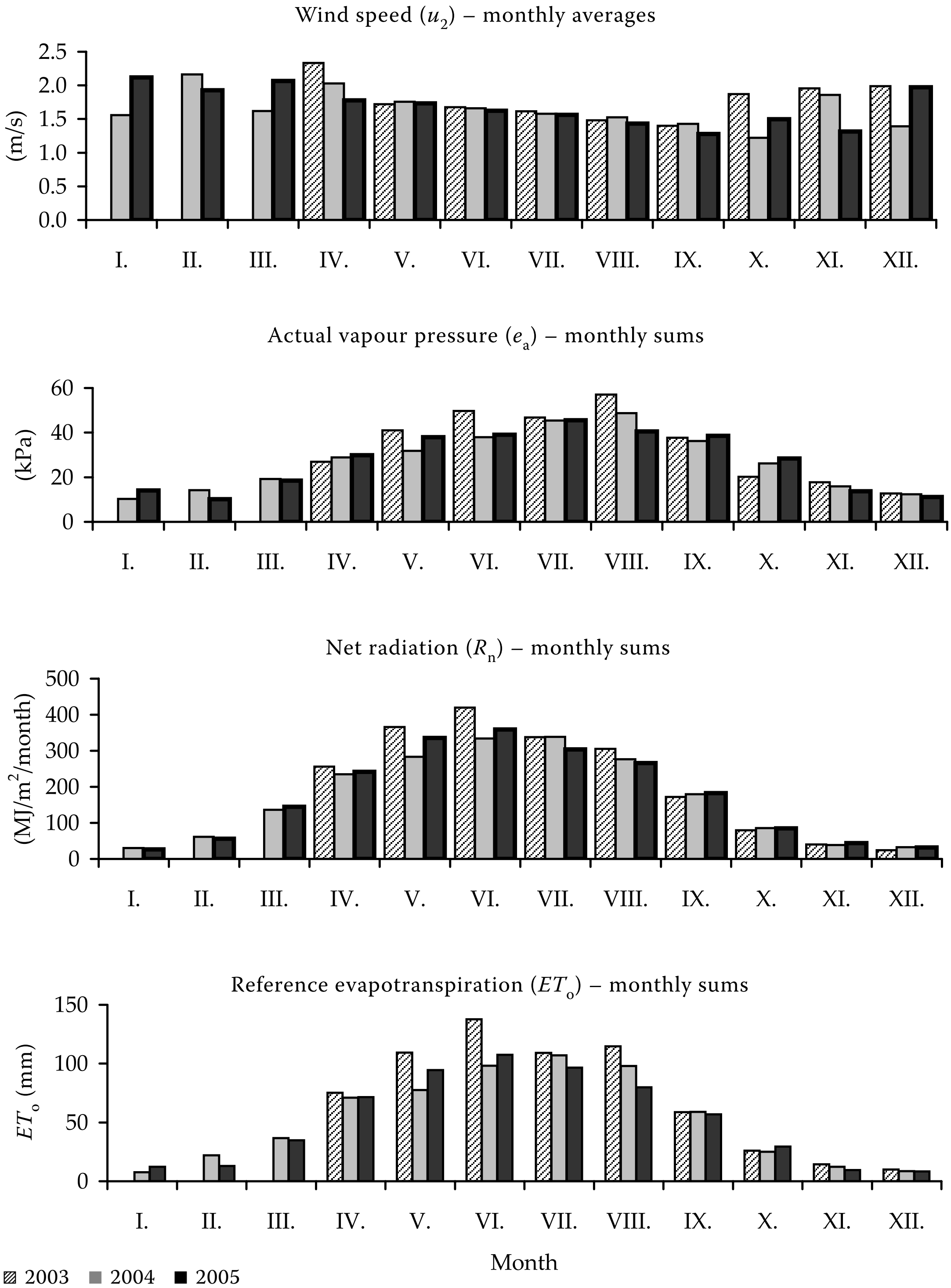

Figure 3. Monthly averages of wind speed and monthly sums of actual vapour pressure, net radiation and reference evapotranspiration

crops, in 2005 only in potatoes (Table 4). In all years marketable yields of all crops were highest in treatment I with the highest irrigation depth (Tables 5–8). There was a statistically significant difference between treatments I and II (pre-irrigation suction pressure 15 and/or 30 kPa) only in potato yield in 2003, in cabbage yield in 2004, when cv. Perfekta was planted, and in celery root

Table 4. Theoretical and actual seasonal irrigation depths (*SID*)

Crop	Year	Theoretical *SID* (mm)		Real *SID* (mm)			
		according to *BC*	according to ET_c	treatment I	treatment II	treatment III	treatment IV
Early potatoes	2003	205	269	176	100	28	0
	2004	117	195	134	85	60	0
	2005	124	173	151	125	57	20
Late cauliflower	2003	470	206	231	199	147	125
	2004	318	137	185	127	100	78
	2005	202	120	165	154	123	115
Early cabbage	2003	238	176	146	135	77	38
	2004	167	138	129	93	61	50
	2005	123	120	80	70	48	44
Celery	2003	712	426	278	186	66	28
	2004	376	264	155	127	117	43
	2005	255	206	126	108	47	47

According to *BC* – calculation of evapotranspiration by means of biological curve (Sláma 1972)
According to ET_c – calculation of evapotranspiration in accordance with FAO 56 (Allen *et al.* 1988)

yield in all years (Table 9). The difference in cauliflower yields between treatments I and II was insignificant in all years. The yields of all crops in treatments III and IV except cauliflower yield in treatment III in 2005 were significantly lower in all three years than in treatments I and II. The effect of seasonal irrigation depth on the proportion of quality grades of the harvested crop is not unambiguous. In potatoes in the year 2003 with low precipitation as well as in 2004 the proportion of marketable product (tubers > 5 cm in diameter) was much higher in treatments I and II than in treatments III and IV. In 2005 the highest proportion of marketable tubers was recorded in treatment I while there were not any marked differences between the other treatments (Table 5). The same situation was in cauliflower with the proportion of the quality grade "choice" in total yield (Table 6). In 2003 the proportion of quality grades of cabbage heads (Table 7) was adversely influenced in treatments I and II by bursting of heads caused by the late termination of irrigation. In 2004 and 2005 the seasonal irrigation depth did not significantly influence the proportions of cabbage head quality grades. In all treatments the proportion of choice quality was > 90%, in 2004 in treatments I and II it was even 100%. In all years the differentiation of seasonal irrigation depths in celery had a great influence on root yield but a small influence on the proportion of quality grades of the crop (Table 8). A significant reduction in the proportion of quality grade I roots was recorded only in treatment IV in 2005 – by about 20% compared to treatments I and II. In treatments III and IV celery roots and cabbage heads were smaller compared to treatments I and II, but their quality was high.

Based on the influence on marketable yield and proportion of the crop quality grades it is possible to determine the optimum threshold suction pressure on light loamy-sand soils to be 30 kPa in early potatoes, late cauliflower and cabbage and 15 kPa in celery. 80% of available soil water capacity (ASWC) corresponds to the threshold suction pressure 30 kPa, and as much as 96% of ASWC corresponds to 15 kPa (Table 1).

A possibility of comparing threshold suction pressures with their values reported in literature is very scarce for vegetables. Kemble and Sanders (http://www.aces.edu/pubs/docs/A/ANR-1169) or Sanders (http://www.nscu.edu/depts/hort/hil/hil-33-e.html) reported the threshold suction pressure of 35 kPa for potatoes (Irish potato), 34 kPa for cabbage and cauliflower, and 25 kPa for

Table 5. Yields of early potatoes

Year	Treatment	Parameter	Tuber size (cm)			Total
			< 3	3 to 5	> 5	
2003	I.	yield (t/ha)	3.3	9.7	57.3	70.2
		proportion (%)	4.7	13.8	81.6	100.0
	II.	yield (t/ha)	1.1	6.0	49.2	56.3
		proportion (%)	2.0	10.6	87.3	100.0
	III.	yield (t/ha)	2.0	11.7	16.9	30.5
		proportion (%)	6.5	38.3	55.2	100.0
	IV.	yield (t/ha)	3.1	12.5	8.3	23.8
		proportion (%)	12.9	52.3	34.8	100.0
2004	I.	yield (t/ha)	1.1	20.7	60.0	81.8
		proportion (%)	1.4	25.3	73.3	100.0
	II.	yield (t/ha)	0.3	22.7	60.5	83.4
		proportion (%)	0.3	27.2	72.5	100.0
	III.	yield (t/ha)	0.0	22.2	45.9	68.1
		proportion (%)	0.0	32.6	67.4	100.0
	IV.	yield (t/ha)	10.1	13.4	18.4	41.8
		proportion (%)	24.1	32.0	44.0	100.0
2005	I.	yield (t/ha)	1.1	19.2	49.4	69.7
		proportion (%)	1.6	27.5	70.9	100.0
	II.	yield (t/ha)	2.4	22.8	40.5	65.6
		proportion (%)	3.6	34.7	61.7	100.0
	III.	yield (t/ha)	1.0	18.4	38.6	58.0
		proportion (%)	1.7	31.8	66.5	100.0
	IV.	yield (t/ha)	1.0	18.3	28.3	47.5
		proportion (%)	2.0	38.5	59.5	100.0

celery. However, Thomas *et al.* (1970) recorded the highest yields of cabbage at the threshold suction pressure of soil water in the upper 61 cm amounting to 80–160 kPa. Yields decreased after its value 360 kPa was reached. Compared to the results of our experiments, these values are too high. In the soil conditions of experimental plot a statistically significant depression of cabbage yield occurred at the suction pressure of water 30 kPa (Table 5). Optimum threshold suction pressures of soil water for potatoes reported in literature usually range from 20 to 60 kPa (van Loon 1981; Zavadil 2000; Shock *et al.* 2001; Wilson *et al.* 2001; Kang *et al.* 2004; Shock 2004). Compared to the optimum threshold suction pressures of soil water cited in literature the values we measured were usually somewhat lower. It can probably be explained by different hydrophysical properties of soil. The plots where experiments were conducted in other countries had heavier soils with higher field capacity than on our experimental plot. The effect of cultivar probably played its role in potatoes. In our experiment we used an early cultivar unlike the experiments conducted abroad. ASWC corresponding to pre-irrigation suction pressures of soil water for crops used in the experiment are

Table 6. Yields of late cauliflower

Year	Treatment	Parameter	Quality grade				Total
			choice	1st quality	2nd quality	non-standard	
2003	I.	yield (t/ha)	37.0	3.5	0.7	0.3	41.5
		proportion (%)	89.2	8.3	1.7	0.8	100.0
	II.	yield (t/ha)	38.5	2.9	1.1	0.4	42.8
		proportion (%)	90.0	6.7	2.5	0.8	100.0
	III.	yield (t/ha)	26.4	5.0	1.1	0.8	33.4
		proportion (%)	79.2	15.0	3.3	2.5	100.0
	IV.	yield (t/ha)	14.4	4.1	3.3	1.8	23.6
		proportion (%)	60.8	17.5	14.2	7.5	100.0
2004	I.	yield (t/ha)	25.7	2.6	2.6	3.4	34.3
		proportion (%)	75.0	7.5	7.5	10.0	100.0
	II.	yield (t/ha)	28.4	4.8	2.1	0.9	36.3
		proportion (%)	78.3	13.3	5.8	2.5	100.0
	III.	yield (t/ha)	18.8	5.0	3.2	2.7	29.7
		proportion (%)	63.3	16.7	10.8	9.2	100.0
	IV.	yield (t/ha)	15.6	3.1	3.9	2.1	24.6
		proportion (%)	63.3	12.5	15.8	8.3	100.0
2005	I.	yield (t/ha)	29.3	2.4	1.9	3.4	37.0
		proportion (%)	79.2	6.6	5.0	9.2	100.0
	II.	yield (t/ha)	24.0	6.5	3.1	3.4	36.9
		proportion (%)	65.0	17.5	8.3	9.2	100.0
	III.	yield (t/ha)	23.4	8.5	1.8	2.7	36.5
		proportion (%)	64.2	23.3	5.0	7.5	100.0
	IV.	yield (t/ha)	21.9	7.3	1.4	3.1	33.8
		proportion (%)	65.0	21.6	4.2	9.2	100.0

mostly higher than ASWC reported in literature. The reasons are likely the same as in threshold suction pressures of soil. E.g. Kemble and Sanders (http://www.aces.edu/pubs/docs/A/ANR-1169) or Sanders (http://www.nscu.edu/depts/hort/hil/hil-33-e.html) reported 70% ASWC for potatoes and celery and 60% for cabbage and cauliflower, ČSN 75 0434 (1994) 60–70% for early potatoes but only 40% for late potatoes before flowering and 50% after flowering, Sláma (1972) 60% for medium-early potatoes, Novotný *et al.* (1990) 75–80% for cabbage and 80% for celery in the period of intensive growth of celery root. According to Rybáček *et al.* (1988) ASWC in potatoes is related to the importance of irrigations in their developmental period. It is about 40% in an important period, 66% in a critical period and as much as 80–90% in a very critical period. King and Stark (1997) drew a conclusion that in general the content of available soil water should be maintained between 65% and 85% (in relation to developmental stage) during the active growth period in order to achieve optimum potato yields.

The seasonal irrigation depths determined on the basis of soil moisture balance, in which the crop evapotranspiration (ET_c) is calculated either according to FAO 56 (Allen *et al.* 1998) or by the biological curve method (Sláma 1969), are

Table 7. Yields of early cabbage

Year	Treatment	Parameter	Quality grade choice	Quality grade 1st quality	Quality grade non-standard	Total
2003	I.	yield (t/ha)	25.7	21.9	27.6	75.2
		proportion (%)	34.2	29.2	36.7	100.0
	II.	yield (t/ha)	16.9	21.2	34.4	72.5
		proportion (%)	23.3	29.2	47.5	100.0
	III.	yield (t/ha)	9.2	26.1	10.7	46.0
		proportion (%)	20.0	56.7	23.3	100.0
	IV.	yield (t/ha)	0.4	21.7	1.2	23.3
		proportion (%)	1.7	93.3	5.0	100.0
2004	I.	yield (t/ha)	90.6	0.0	0.0	90.6
		proportion (%)	100.0	0.0	0.0	100.0
	II.	yield (t/ha)	85.3	0.0	0.0	85.3
		proportion (%)	100.0	0.0	0.0	100.0
	III.	yield (t/ha)	73.2	1.9	0.0	75.1
		proportion (%)	97.5	2.5	0.0	100.0
	IV.	yield (t/ha)	69.0	2.4	0.6	72.0
		proportion (%)	95.8	3.3	0.8	100.0
2005	I.	yield (t/ha)	46.4	0.4	0.8	47.6
		proportion (%)	97.5	0.8	1.7	100.0
	II.	yield (t/ha)	44.1	1.1	0.4	45.6
		proportion (%)	96.7	2.5	0.8	100.0
	III.	yield (t/ha)	27.4	0.0	2.8	30.2
		proportion (%)	90.8	0.0	9.2	100.0
	IV.	yield (t/ha)	27.5	0.0	1.7	29.2
		proportion (%)	94.2	0.0	5.8	100.0

substantially different from the really achieved irrigation depths in the treatments where optimal suction pressure is maintained (Table 4). For potatoes, the really achieved values of seasonal irrigation depths are nearer to the depths calculated by the BC, while for the other vegetables (cauliflower, cabbage and celery) they are more similar to the depths calculated by FAO 56 methodology. The theoretical irrigation depths calculated by the BC method sometimes differ substantially from those based on FAO 56. These differences are at maximum for cauliflower and celery and at minimum for cabbage and decrease with the decreasing seasonal irrigation depths. A probable cause of these differences is that the coefficients of biological curves were not correctly estimated. The consequence of using the BC coefficients according to the Czechoslovak standard ČSN 75 0434 (1994) for irrigation management of cauliflower and celery would be, especially in dry years, that unnecessarily high irrigation rates are applied, which could increase the risk of leaching of nitrates, pesticides and other pollutants to subsurface waters. A revision, based on a more accurate determination of the BC coef-

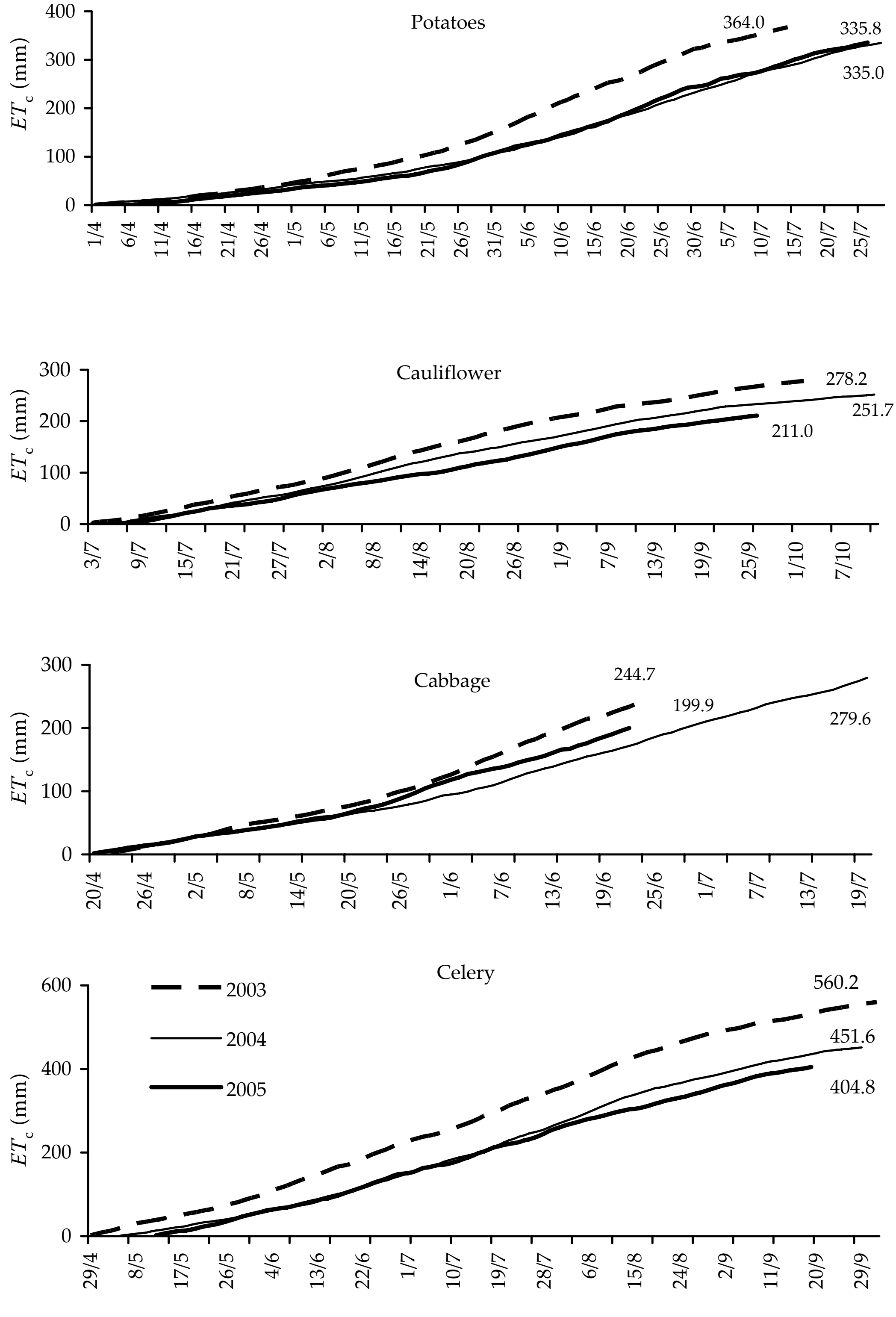

Figure 4. Mass curves of actual evapotranspiration (ET_c)

ficients, would be a necessary precondition for any future sound use of the BC method for crop irrigation management. For a more exact determination of the BC coefficients, it would be necessary to re-evaluate the archival data on irrigation experiments carried out in the 1950's and in the first half of the 1960's. Some supplementary experiments might also be needed. It might be difficult to find funding

Table 8. Yields of celery

Year	Treatment	Parameter	Quality grade			Total
			1st quality	2nd quality	non-standard	
2003	I.	yield (t/ha)	39.9	13.0	2.8	55.7
		proportion (%)	71.7	23.3	5.0	100.0
	II.	yield (t/ha)	23.5	7.6	0.3	31.3
		proportion (%)	75.0	24.2	0.8	100.0
	III.	yield (t/ha)	16.4	2.5	0.2	19.1
		proportion (%)	85.8	13.3	0.8	100.0
	IV.	yield (t/ha)	10.9	3.2	0.2	14.4
		proportion (%)	75.8	22.5	1.7	100.0
2004	I.	yield (t/ha)	50.2	6.3	2.0	58.4
		proportion (%)	85.8	10.8	3.3	100.0
	II.	yield (t/ha)	44.0	6.3	3.6	53.9
		proportion (%)	81.7	11.7	6.7	100.0
	III.	yield (t/ha)	38.3	1.0	0.3	39.6
		proportion (%)	96.7	2.5	0.8	100.0
	IV.	yield (t/ha)	13.4	1.4	2.1	17.0
		proportion (%)	79.2	8.3	12.5	100.0
2005	I.	yield (t/ha)	43.7	0.8	0.8	45.2
		proportion (%)	96.7	1.7	1.7	100.0
	II.	yield (t/ha)	28.3	0.5	1.3	30.0
		proportion (%)	94.2	1.7	4.2	100.0
	III.	yield (t/ha)	21.3	2.2	0.4	23.8
		proportion (%)	89.2	9.2	1.7	100.0
	IV.	yield (t/ha)	19.1	4.2	1.9	25.1
		proportion (%)	75.8	16.7	7.5	100.0

and capacity for this undertaking. Therefore, it is only little probable that the coefficients could be improved at all.

CONCLUSIONS

On the basis of the results of field experiments, it is possible to estimate the optimum threshold suction pressure on light loamy-sand soils as 30 kPa for early potatoes, late cauliflower and cabbage and 15 kPa for celery. The seasonal irrigation depths, if the irrigation management is controlled by soil suction, are lower than those calculated by the FAO 56 method (Allen *et al*. 1998). Therefore, the crop irrigation management by means of suction sensors can bring about important savings of irrigation water while high marketable yields of the crops are achieved.

Taking into account the incorrectly estimated coefficients of biological curves of some crops and, on the other hand, reasonable prices of automated weather stations, the use of the FAO 56 method is recommended if the soil water balance is to be taken as the basis of irrigation management.

Table 9. Statistical evaluation of yields on a significance level α = 0.05

Crop	Year	Compared treatments					
		I and II	I and III	I and IV	II and III	II and IV	III and IV
Early potatoes	2003	**	***	***	***	***	**
	2004	*	***	***	***	***	***
	2005	*	***	***	**	***	***
Late cauliflower	2003	*	***	***	**	***	***
	2004	*	***	***	***	***	***
	2005	*	*	**	*	**	*
Early cabbage	2003	*	***	***	***	***	***
	2004	**	***	***	***	***	*
	2005	*	***	***	***	***	*
Celery	2003	***	***	***	***	***	***
	2004	**	***	***	***	***	***
	2005	***	***	***	***	***	*

*insignificant difference (calculated α > 0.05); **significant difference (calculated α 0.05–0.005); ***highly significant difference (calculated α < 0.005)

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