Using the Sensitivity of Biomass Production to Soil Water for Physiological Drought Evaluation

Viliam NOVÁK

Institute of Hydrology, Slovak Academy of Sciences, Bratislava, Slovakia

Abstract: The analysis of drought as a phenomenon and the proposal of how to define and quantify the deficiency of water in soil for plants, so called physiological drought, are described. The presented approach is based on the theoretical considerations supported by empirically estimated relationships between the biomass production of a particular plant and the transpiration total of this plant during its vegetation period. This relationship is linear and is valid for particular plant and environmental conditions (nutrition, agrotechnics). Optimal plant production can be reached for maximum seasonal transpiration total, therefore the potential transpiration total corresponds to the maximum possible yield. The transpiration rate lower than the potential one leads to a biomass production decrease. This phenomenon can be used to define the physiological drought, under which the soil water content in the root zone decreases below the so called critical soil water content of limited availability for plants, under which the transpiration rate drops below its potential transpiration rate. Methodology is illustrated on the basis of the results of mathematical modelling of soil water movement in Soil – Plant – Atmosphere system, with loamy soil and maize canopy.

Keywords: physiological drought; soil water content; transpiration; biomass production; mathematical modelling; maize

Drought as a phenomenom generally means the lack of water. It is used frequently but its definition is usually qualitative and sometimes contradictive. The definition of drought from the Encyklopedia Wikipedia sounds „A drought is an extended period of months or years when a region notes a deficiency in its water supply“. Acording to Multilingual technical dictionary on irrigation and drainage (ICID 1996), drought is „a sustained period of time, with insufficient precipitation“. Thus, drought is mentioned here as period of time.

There are different drought definitions which treat it as a state, not as a time interval at which the lack of water is noted.

Meteorological drought is characterised by low precipitation totals during the period studied, together with air temperature, evapotranspiration, wind velocity, and air humidity, and is expressed by different climatological indexes.

Hydrological drought is defined as a lack of water in streams and rivers, usually in relation to the number of days with the water level or discharge below some defined values. The same criteria can be applied for groundwater (Burger 2005) and springs.

Agronomical drought (Sobíšek *et al.* 1993) is a result of meteorological drought. This term seems not to be appropriate, a better term for the state of water in soil below some critical level is

Supported by the Slovak Grant Agency VEGA, Grant No. 2/7091/27 and the Slovak Grant Agency APVV, Grant No. 51-030205.

soil drought. According to (Šútor *et al.* 2005; Šútor 2006), soil drought arises if the average soil water content in the defined soil layer is below the soil water content (SWC) characterised by permanent wilting point. A better term is given by Wikipedia, characterised deficiency of water that negatively affects the crop production as agricultural drought.

The expression physiological drought (Sobíšek *et al.* 1993) seems to be a better characteristic to specify the water deficiency for plants and it means the state of soil (and water in plants, respectively), limiting the plant growth and production. Its relation to different types of drought is not unambiguous; even if the meteorological drought exists, it does not necessarily mean physiological or hydrological drought. Accordingly, the stage of physiological drought depends on the plant type, especially on the ontogenesis stage of a particular plant. The biomass production means usually the production of the shoot parts of plants. But the crop yield (known as agricultural output) means usually the biomass production of the final product (like grain, or roots of sugar beet). However, the exact and quantitative expression of drought is difficult to formulate. It can mean quite different situations, depending on the aspect you are looking from.

Transpiration is frequently used as an indicator of the soil water resources. Relative transpiration as an index of the soil water resources state was presented by Budagovskij and Grigorieva (1991) as the ratio of transpiration E_t (M/L^2T), and the potential transpiration E_{tp}, (M/L^2T):

$$\eta_p = E_t/E_{tp} \qquad (1)$$

Eq. (1) characterises the availability of the soil water within the range (0; 1), and expression (2) can be noted as the drought index in the range of (0; 1); $\eta_d = 1$ means absolute drought, $\eta_d = 0$ means full, unlimited availability of the soil water for plants.

$$\eta_d = 1 - \eta_p \qquad (2)$$

Probably the most important aspect of drought is the lack of the soil water limiting the biomass production. This contribution will discuss what can be understood under drought from the point of view of the plant production.

This contribution presents a method for the physiological drought evaluation, depending on the relationship between seasonal transpiration (evapotranspiration) totals of particular plants and plant production (Havrila & Novák 2006).

THEORY

The rate of photosynthesis, expressed by the carbon dioxide consumption by plant, can be approximatively expressed by the equation (Bierhuizen & Slayter 1964):

$$P = \frac{\Delta c_{ou}}{r_{ac} + r_{sc} + r_m} \qquad (3)$$

Transpiration rate can be expressed by van Honert's (1948) equation

$$E_t = \frac{\Delta c_v}{r_a + r_s} \qquad (4)$$

where:

P – photosynthesis rate (M/L^2T)

r_{ac}, r_{sc}, r_m – resistance of the boundary layer of atmosphere on the leaf surface; the resistance of the stomata and mesophyl resistance to carbon dioxide transport from the atmosphere to plant (T/L)

r_a, r_s – resistance of the boundary layer of the atmosphere on the leaf surface for water vapour transport; the stomata resistance to water vapour from the substomatal cavity to the atmosphere (T/L)

Δc_{ou} – difference of the mass concentration of carbon dioxide between leaf (after carboxylation) and the atmosphere (M/L^3)

Δc_v – difference of the mass concentration of water vapour between the leaf and the atmosphere (M/L^3)

By combination of Eqs (3) and (4) we obtain

$$\frac{P}{E_t} = \frac{r_a + r_s}{r_{ac} + r_{sc} + r_m} \frac{\Delta c_{ou}}{\Delta c_v} \qquad (5)$$

Resistances to CO_2 and water vapour transport are complex functions of the environment and they change with time. For a particular plant, the environmental properties and time seem to be reasonable to assume the constant value of the resistances ratio on the right side of Eq. (5) and to express it as a dimensionless constant B. Then, the photosynthesis rate P can be written as proportional to the transpiration rate E_t

$$P = B \times E_t \tag{6}$$

Then, the potential (maximum) photosynthesis rate P_p can be expressed as directly proportional to the potential transpiration rate E_{tp}

$$P_p = B \times E_{tp} \tag{7}$$

Eqs (6) and (7) demonstrate the proportionality between photosynthesis and the transpiration rate based on simplified assumptions. So, the validity of Eq. (5) is limited by the validity of the assumption concerning parameter *B*, considered to be constant. This parameter contains all the environmental properties (plant, soil, agrotechnics, fertilisation). The parameters of the atmosphere and, partially, of the plants are involved in the procedure of the transpiration rate calculation. There are many empirical relationships of this type for crops (Hillel & Guron 1973; Hanks & Hill 1980; Vidovič & Novák 1987; Feddes & Raats 2004), some of them are illustrated in Figure 1. The scattering of the points in these relationships reflects the environmental conditions changes, not fulfilling the assumption of *B* as a constant value.

The ratio of Eqs (4) and (5) leads to

$$\frac{P}{P_p} = \frac{E_t}{E_{tp}} \tag{8}$$

If $E_t = E_{tp}$, then $P = P_p$; or expressing it in the terms of yields for $E_t = E_{tp}$, $Y = Y_p$; Y_p means the upper limit of the possible range of yields (M/L^2), not limited by the soil water. For the given site conditions, it depends mainly on the weather conditions, changing over seasons. The minimum possible yield is difficult to estimate or characterise simply by some minimum seasonal transpiration total.

There exists a family of the production models, which can be used to model the production process, based on the photosynthesis modelling. They are relatively complicated, canopy oriented, and their weak point is the necessity to estimate many parameters, needed as the input data (Hansen *et al.* 1990; Supit & Van Den Groot 2003). Therefore, even simplified, approximative models with minimum input data, which can be applied to a particular plant with acceptable accuracy, are valuable for the application. This is the case of the approach presented – to evaluate the influence of the soil water content on the crop yield.

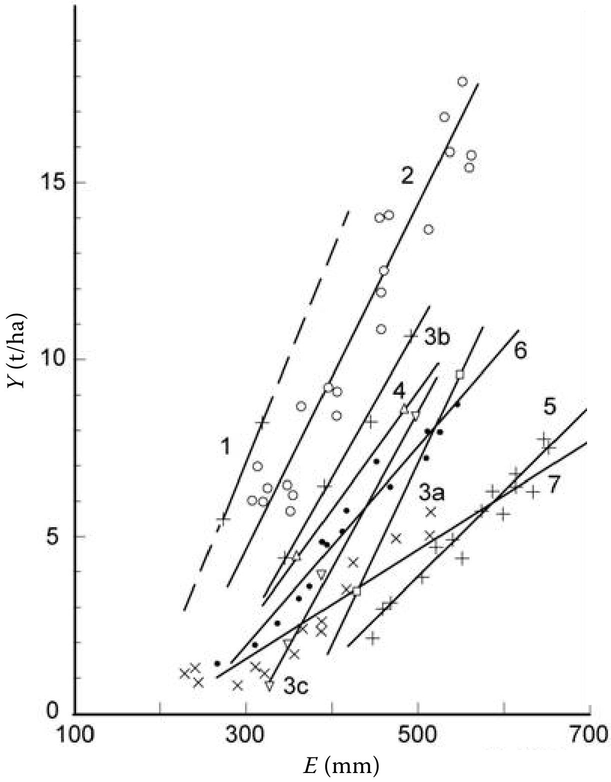

Figure 1. Empirical relationship of dry maize grains *Y* and seasonal maize evapotranspiration totals *E* during the vegetation period; 1 – Trnava (1981–1982) (Vidovič & Novák 1987); 2 – Logan, USA (1975); 3a, b, c – Gilat, Israel, (1968, 1969, 1970); 4 – Cherson, Ukraina, (1974–1978); 5 – Greenville, USA (1978); 6 – Farmington, USA (1978);7 – Evans, USA (1978); items 2–7 are compiled from Hanks and Hill (1980)

The critical soil water content of limited water availability concept

The critical soil water content of limited water availability (θ_{la}) characterises the average soil water content of the soil layer at which the transpiration rate starts to decrease, which is followed by a biomass production decrease (Novák & Havrila 2006). In the above mentioned soil layer, roots are located; usually the upper layer of one meter is considered. The core of the estimation method is based on an analysis of the schematic relationship between the relative transpiration rate and the average soil water content of the root zone (Novák 1990).

The principle of θ_{la} evaluation is briefly characterised in Figure 2. It follows from the analysis that maximum plant production can be reached if the transpiration total per vegetation period of the

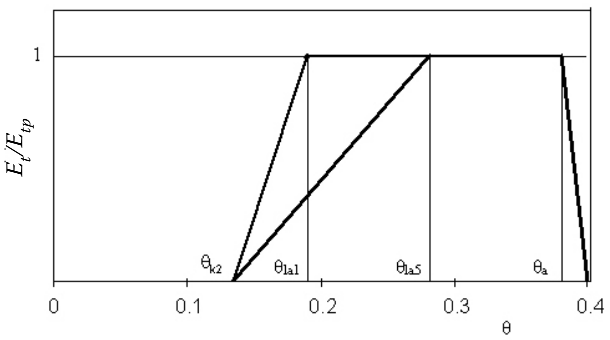

Figure 2. Relative transpiration rate and the soil water content of the upper one meter soil layer, $E_t/E_{tp} = f(\theta)$, where (θ_{la5}, θ_{la1}) is the range of the critical soil water contents of limited availability for plants, for the range of daily transpiration totals $1 \leq E_t \leq 5$ mm/day at the site Most pri Bratislave (Novák & Havrila 2006)

respective canopy is maximum, i.e. the potential one. From this it follows that any transpiration rate below its potential value decreases the plant growth. A decrease in the soil water content in the soil root zone below θ_{la} results in a decrease in the biomass production as well. Therefore, the soil water content of the soil root zone below this value can be declared as the soil water content corresponding to the state characterised as physiological drought.

A method for the estimation of the critical soil water content of limited water availability (θ_{la}), was described earlier (Novák 1990; Novák & Havrila 2006). It can be expressed by the following empirical equations (Novák 1990):

$$\theta_{la} = \theta_{k1} = \frac{1}{\alpha} + \theta_{k2} \quad (9)$$

$$\theta_{k2} = 0.67 \times \theta_v \quad (10)$$

$$\alpha = -2.27\, E_{tp} + 17.5 \quad (11)$$

where:

θ_{k1}, θ_{k2} – so called critical volumetric soil water contents, (SWC), indicating the beginning and the end of the transpiration decrease rate range

θ_v – SWC of the permanent wilting point (Kutílek & Nielsen 1994)

Coefficient α depends on the potential evapotranspiration (transpiration) rate E_{tp}. It follows, that SWC, corresponding to the critical SWC of limited availability for plants, does not depend on the soil properties only but is also a function of the Soil – Plant – Atmosphere Continuum (SPAC) properties. The transpiration rate, which strongly influences the critical soil water content θ_{k1}, is a function of meteorological properties. Sensitivity analysis of the transpiration process, as it is quantitatively described by Penman – Monteith equation (Monteith 1965) and was performed by Novák *et al.* (1997), documented the primary importance of net radiation on the potential transpiration rate, followed by the air temperature.

The SWC corresponding to the critical soil water content of limited availability to plants of three soils, as they depend on the transpiration rate $\theta_{la} = f(E_t)$, are presented in Figure 3. From the analysis, a strong dependence is obvious of critical SWC of the limited availability θ_{la} on the transpiration rate, and it increases with the transpiration rate. It is a fact that the decrease in the daily transpiration rate during the days with maximum energy input (hot days) limited by the lack of the soil water limits the biomass production much more significantly than during cold days.

In Figure 3 (denoted by circles), the water contents can also be seen corresponding to the point

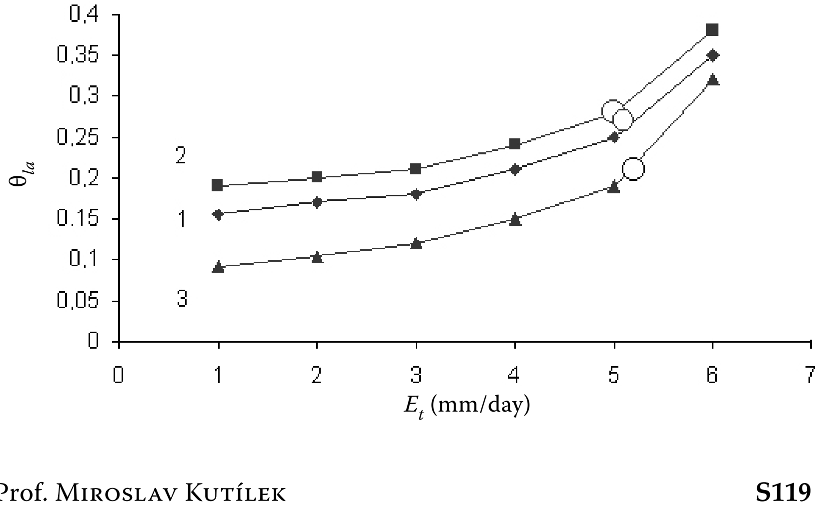

Figure 3. Critical soil water content of limited availability for maize θ_{la}, corresponding to the transpiration rate E_t of three soils. Circles denote the values of θ_{pla} estimated according to the Eq. (12); 1 – Chernozem on loess at Trnava, 2 – sandy soil at Láb, 3 – loamy soil at Most pri Bratislave

of limited availability (θ_{pla}) which is frequently used in irrigation management practice, calculated according to the frequently used empirical equation (Kutílek 1978)

$$\theta_{pla} = \theta_v + 0.6\,(\theta_{fc} - \theta_v) \qquad (12)$$

Now, the physiological meaning of this popular term can be simply demonstrated. It can be seen that SWC corresponding to the point of limited availability (θ_{pla}) is in the range of SWC estimated by the proposed method, but its values correspond to high transpiration rates, which are rare. The average summer transpiration rates under the conditions of South Slovakia are 2–3 mm/day.

An illustrative example

The application of the method of physiological drought estimation described above will be illustrated on the results of modelling at the experimental site of Most pri Bratislave, with maize canopy. As a tool, the simulation model HYDRUS-ET (Šimůnek *et al.* 1997) was used, together with the modified Penman-Monteith method to calcualte evapotranspiration and its components (Majerčák & Novák 1992). The calculations were made for 31 seasons and maize canopy.

Silty loam soil at this site can be characterised as Haplic Chernozem (FAO 1998), it is relatively homogeneous. The basic soil characteristics can be found in Table 1 (Havrila & Novák 2006; Novák & Havrila 2006).

Figure 4 presents the diagram in which the number of days n can be seen during the vegetation period of maize with the soil water content in the upper soil layer of 50 cm below the soil water content corresponding to the critical soil water content of limited availability to plants V_{la} (V_{la} = 0.28) for 31 vegetation periods. The dryest growing season for maize canopy was found in 2003, with a permanent lack of water, i.e physiological drought was evaluated during the whole vegetation period.

Table 1. Soil characteristics (Most pri Bratislave)

θ_v (–)	0.18
θ_{la} (–)	0.28
θ_{fc} (–)	0.35
θ_s (–)	0.4
K (m/s)	5.62×10^{-7}
α (–)	0.0577
n (–)	1.299

θ_v – soil water content corresponding to the wilting point, θ_{la} – soil water content corresponding to the point of limited availability of soil water to plants, θ_{fc} – soil water content corresponding to the field capacity, θ_s – water content of saturated soil, K – hydraulic conductivity of soil saturated with water (saturated hydraulic conductivity), α, n – van Genuchten's equation coefficients

Cumulative frequency curves number of days n during the vegetation period of maize with the soil water content in the upper soil layer of 50 cm below the soil water content corresponding to the critical SWC of limited availability of the soil water to plants V_{la} (V_{la} = 0.28), calculated by means of the mathematical model HYDRUS-ET, during 31 seasons is given in Figure 5. The data from Figure 4 were used. Only four vegetation periods of maize were wet enough to ensure optimum soil water content for maximum biomass production.

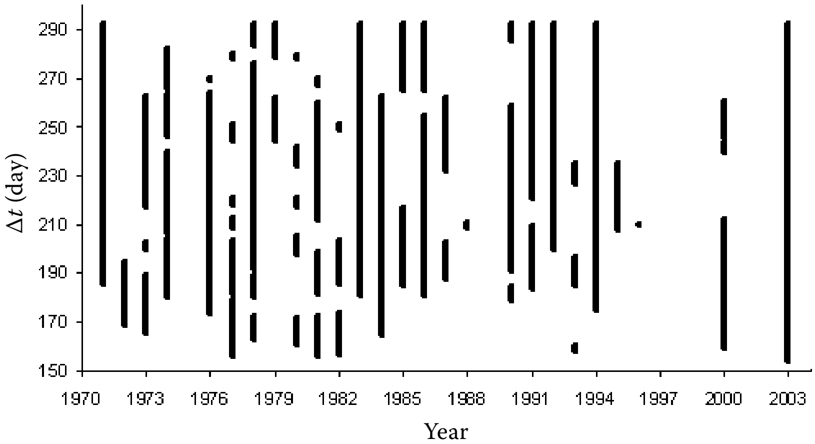

Figure 4. Number of days n during the vegetation period of maize with soil water content in the upper soil layer of 50 cm lower than soil water content corresponding to the critical soil water content of limited availability for plants V_{la} (V_{la} = 0.28 cm of water layer) for 31 vegetation periods (Most pri Bratislave)

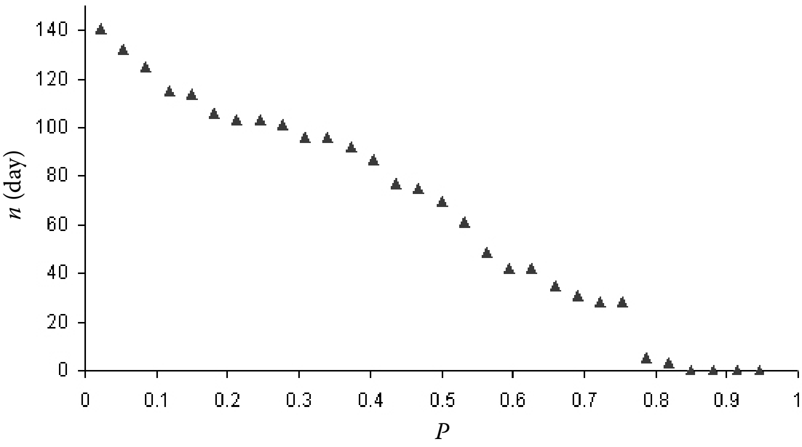

Figure 5. Cumulative frequency curve for number of days n during the vegetation period of maize with soil water content in the upper soil layer 50 cm lower than soil water content corresponding to the SWC of limited availability of soil water for plants V_{la} (V_{la} = 0.28 cm of water layer), calculated by mathematical model HYDRUS-ET, during 31 seasons (Most pri Bratislave site)

CONCLUSIONS

In this paper, a proposal is presented how to define drought from the biomass production point of view, often declared as physiological drought. This approach is based on the theoretical considerations supported by the empirical relationship between the biomass production of particular plants and the transpiration total of the respective plants during the vegetation period. This relationship is linear and valid for particular plant and environmental conditions (site, nutrition, agrotechnics).

Physiological drought is defined as a state of water expressed by the water content in the soil root zone limiting the plant production. The SWC of the root zone, below which the biomass production is decreased and the transpiration rate is lower than the potential transpiration rate, was denoted as the critical soil water content of limited availability for plants.

The core of the method is presented for the calculation of the critical soil water content of limited availability for plants. It is the function of soil properties but it also strongly depends on the transpiration rate. It means, the lower is the transpiration rate the longer are preserved optimal conditions for the plant production.

Optimal plant production can be reached for maximum transpiration total, therefore the potential transpiration total corresponds to maximum possible yield under the given conditions. The transpiration rate which is lower than the potential one leads to a biomass production decrease.

Another consequence of this analysis is the recognition that the state noted as physiological drought interpreted by means of SWC is not characterised by some universal value, but it depends on the plant type on the particular site, especially on the position of its vegetation period within the season. Relatively less sensitive to the lack of water can be winter cereals, however, more sensitive are maize, sugar beet, and generally the plants growing during the summer, hot period.

This paper presents a simple method for physiological drought evaluation, using the ratio of transpiration to the potential transpiration rate; drought can be considered when this ratio is below one. This method also allows estimating the average soil water content in the root zone corresponding to this state.

References

Bierhuizen J.F., Slayter B. (1964): An apparatus for the continuous and simultaneous measurement of photosynthesis and transpiration under controlled environmental conditions. CSIRO Austr. Div. Land Research Tech. Paper, No. 24.

Budagovskij A.I., Grigorieva N.I. (1991): The way to improve effectiveness of soil water resources utilisation. Vodnyje resursy, **1**: 131–142. (in Russian)

Burger F. (2005): Concept and identification of hydrological drough – the groundwater deficit. Acta Hydrologica Slovaca, **6**: 3–10. (in Slovak)

FAO (1998): World Reference Base for Soil Resources. World Soil Resources Reports No. 84. FAO, Rome.

Feddes R.A., Raats P.A.C. (2004): Parameterising the soil – water – plant root system. In: Feddes R.A., De Rooij G.H., van Dam J.C. (eds): Unsaturated Zone Modelling: Progress, Challenges and Applications. Kluwer Publ., Doortrecht-Boston-London, 95–144.

ICID (1996): Multilingual technical dictionary on irrigation and drainage. 2nd revised Ed. ICID–CIID, New Delhi.

Hanks R.J., Hill R.W. (1980): Modelling crop responses to irrigation in relation to soils, climate and salinity. Inter. Irrig. Inform. Center, Publ. No. 6, Bet Dagan.

Hansen S., Jensen H.E., Nielsen N.E., Svensen H. (1990): DAISY: A Soil Plant System Model. Danish Simulation Model for Transformation and Transport of Energy and Matter in the Soil – Plant – Atmosphere System. The National Agency for Environmental Protection, Copenhagem.

Havrila J., Novák V. (2006): The method of soil water extraction by plants estimation for plant production purposes. Journal of Hydrology and Hydromechanics, **54**: 15–25. (in Slovak)

Hillel D., Guron Y. (1973): Realation between evapotranspiration rate and maize yield. Water Resources Research, **9**: 743–748.

Kutílek M. (1978): Hydropedology. SNTL–ALFA Publishers, Praha. (in Czech)

Kutílek M., Nielsen D.R. (1994): Soil Hydrology. Catena Verlag, Cremlingen-Destedt.

Majerčák J., Novák V. (1992): Simulation of the soil – water dynamics in the root zone during the vegetation period: I. Simulation model. Journal of Hydrology and Hydromechanics, **40**: 299–315.

Monteith J.L. (1965): Evaporation and Environment. Symposia of the Society for Experimental Biology, **29**: 205–234.

Novák V. (1990): Estimation of critical soil water contents to evapotranspiration. Počvovedenie (Soviet Soil Sci.), **2**: 137–141. (in Russian)

Novák V., Havrila J. (2006): Method to estimate the critical soil water content of limited availability for plants. Biologia, **61** (Suppl. 19): S289–S293.

Novák V., Hurtalová T., Matejka F. (1997): Sensitivity analysis of the Penman type equation for calculation of potential evapotranspiration. Journal of Hyrology and Hydromechanics, **45**: 176–186.

Sobíšek B. (ed.) (1993): Meteorological Dictionary. Academia, MŽP ČR, Praha. (in Czech)

Supit I., Van Den Groot E. (eds) (2003): Updated System Description of the WOFOST Crop Growth Simulation Model as Implemented in the Crop Growth Monitoring System Applied by the European Comission. Treemail Publishers, Heelsum.

Šimůnek J., Huang. K., Šejna M., Van Genuchten Th. M., Majerčák J., Novák V., Šútor J. (1997): The HYDRUS-ET Software Package for Simulating the One-dimensional Movement of Water, Heat and Multiple Solutes in Variably-saturated Media. Version 1.1. Institute of Hydrology, Slovak Academy of Sciences, Bratislava.

Šútor J. (2006): Soil drought prognosis. Acta Hydrologica Slovaca, **7**: 176–182. (in Slovak)

van Honert T. H. (1948): Water transport in plants as a catenary proces. Discus. Faraday Society, **3**: 146–153.

Šútor J., Gomboš M., Mati R. (2005): Soil drought quantification and its interperetation. Acta Hydrologica Slovaca, **6**: 299–306. (in Slovak)

Vidovič j., novák v. (1987): Maize yield as it depends on canopy evapotranspiration. Rostlinná výroba, **33**: 663–670. (in Slovak)

Corresponding author:

Ing. Viliam Novák, DrSc., Institute of Hydrology, Slovak Academy of Sciences, Račianska 75, 831 02 Bratislava, Slovakia

tel.: + 421 249 267 279, fax: + 421 244 259 404, e-mail: novak@uh.savba.sk