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Drought - how to quantify it?

V. NOVÁK

Institute of Hydrology, Slovak Academy of Sciences, Račianska 75, 831 02 Bratislava, Slovak Republic
(e-mail: novak@uh.savba.sk

Abstract An analysis of drought as a phenomenon and the proposal how to define and quantify lack of water in soil for plants, so called „physiological drought" is described. The presented approach is based on the theoretical considerations and empirically estimated relationships between biomass production of particular plant and 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 transpiration total, therefore potential transpiration total corresponds to the maximum possible yield. Transpiration rate, less than potential one leads to the biomass production decrease. This phenomenon can be used to define the „physiological" drought, under which the soil water content of soil root zone decreases below the so called „critical soil water content of limited availability" for plants, under which transpiration rate is going below its potential transpiration rate. Methodology is illustrated by the results of mathematical modeling of soil water dynamics of Soil – Plant – Atmosphere system, with loamy soil and maize canopy.

Key words: *physiological drought, soil water content, transpiration, biomass production, mathematical modeling, maize*

Introduction

Drought as a phenomenom means lack of water - in general. It is used frequently, but its definition is usually qualitative and sometimes contradictive. Definition of drought from 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 Tech. Dictionary (1996), drought is „a sustained period of time, with insufficient precipitation". So, drought is mentioned here as „period" of time.

There are different drought definitions which are treated it as a „state" not as a time interval in which lack of water is noted.

Meteorological drought is characterized 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. (Review of them was presented by Kandra, 2006).

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

Agronomical drought (Met. Slovník .., 1993) is a result of meteorological drought. This term seems to be not appropriate, better term for the state of water in soil below some level should be expression „soil drought". According to (Šútor et al., 2005, Šútor, 2006), soil drought performs if an average soil water content is below the SWC characterized by permanent wilting point. Better term is given by Wikipedia, characterized lack of water, that negatively affects crop production as „agricultural drought".

Physiological drought (Met. Slovník ..., 1993) sems to be better characteristics and it means the state of soil (and water in plants respectively) limiting plant growth and plant production. Its relation to different types of drought is not unambiguous; even if there is a meteorological drought, it does not mean necesarilly physiological or hydrological drought. Accordingly, the stage of physiological drought depends on plant type, especially on the ontogenesis stage of particular plant. Biomass production means usually production of the shoot parts of plants. But crop yield (known as agricultural output) means usually biomass production of final product (like grain, or roots of sugar beet). But, exact and quantitative expression of drought is difficult to formulate. It can mean quite different situation, depending on the aspect you are looking for.

Probably the most important aspect of drought is lack of soil water limiting biomass production. In this contribution it will be discussed what can be understood under „drought" from the point of view of plant production.

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

Theory

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

$$P = \frac{\Delta c_{ou}}{r_{ac} + r_{sc} + r_m} \qquad (1)$$

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

$$E_t = \frac{\Delta c_v}{r_a + r_s} \qquad (2)$$

P – photosynthesis rate, [kg m^{-2} s^{-1}]
E_t–transpiration rate, [kg m^{-2} s^{-1}]
r_{ac} , r_{sc}, r_m – resistance of boundary layer of atmosphere at the leaf surface; the resistance of the stomata and mesophyl resistance to carbon dioxide transport from atmosphere to plant, [s m^{-1}]
r_a , r_s - resistance of boundary layer of atmosphere at the leaf surface for water vapour transport; the stomata resistance to water vapour from substomatal cavity to the atmosphere, [s m^{-1}]
Δc_{ou} – the difference of the mass concentration of carbon dioxide between leaf (after carboxylation) and the atmosphere,[kg m^{-3}]
Δc_v – the difference of the mass concentration of water vapour between the leaf and atmosphere, [kg m^{-3}]

By combination of equations (1) and (2) we get

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

Resistances to CO$_2$ and water vapour transport are complex functions of an environment and they are changing with time. For particular plant, environmental properties and time seem to be reasonable to assume the constant value of the resistances ratio at the right side of the equation (3) and to express it as a constant B. Then, the photosynthesis rate P can be written as proportional to the transpiration rate E_t

$$P = B.E_t \qquad (4)$$

Equation (4) demonstrates the proportionality between photosynthesis rate and transpiration based on simplified assumptions. So, validity of equation (4) is limited by the constant B, which contains all the environmental properties (plant, soil, agrotechnics, fertilization). Parameters of atmosphere and partially of the plants are involved in the procedure of transpiration rate calculation. Of course, this procedure is an approximation. There are many empirical realtionship of this type (Hillel, Guron,1973, Hanks, Hill, 1980, Vidovič, Novák, 1987, Feddes, Raats,1995, Guron, 2004), some of them are illustrated in Fig. 1.

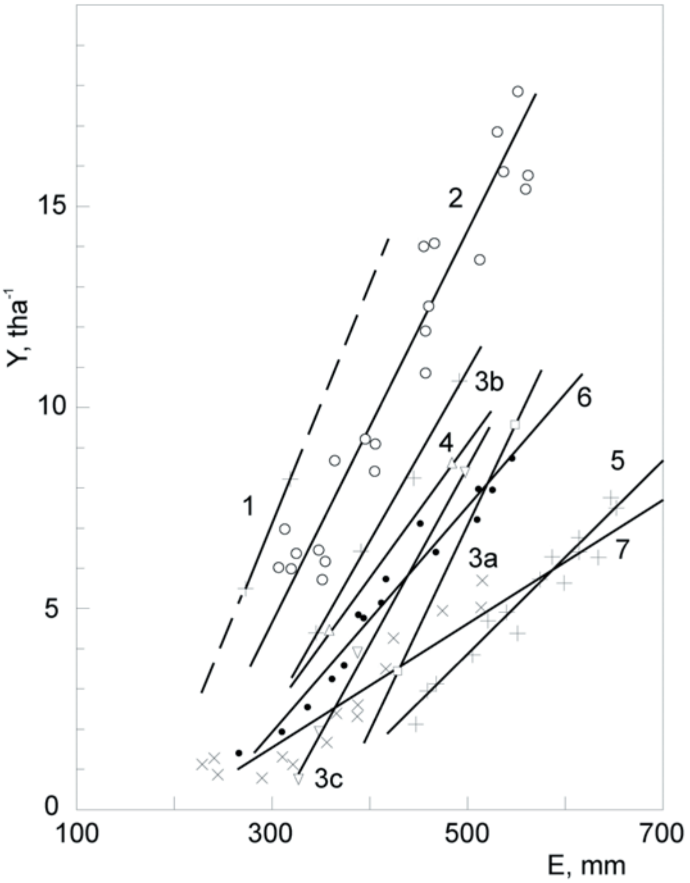

Fig.1. Empirical relationship of dry maize grains *Y* and seasonal maize evapotranspiration totals *E* during the vegetation period. 1 – Trnava (1981 – 1982), 2 – Logan, USA,(1975), 3a,3b,3c –Gilat, Izrael, (1968,1969,1970), 4 – Cherson, Ukraina, (1974 – 1978), 5 – Greenville, USA, (1978), 6 – Farmington, USA, (1978), Evans, USA, (1978).
Obr.1. Empirická závislosť hmotností suchých zŕn kukurice *Y* vo vzťahu k sumárnej transpirácii *E*, za vegetačné obdobie. 1 – Trnava (1981 – 1982), 2 – Logan, USA,(1975), 3a,3b,3c –Gilat, Izrael, (1968,1969,1970), 4 – Cherson, Ukraina, (1974 – 1978), 5 – Greenville, USA, (1978), 6 –Farmington, USA, (1978), 7 - Evans, USA, (1978).

There are existing a family of „production" models, which could be used to model production process, based on the photosynthesis modelling. They are relatively complicated, canopy oriented and their weak point is estimation of many parameters, needed as input data (Hansen et al., 1990). Therefore, even simplified, approximative models with minimum input data which can be applied for particular plant with acceptable accuracy are valuable for application. This is the case of presented approach.

Transpiration is frequently used as an indicator of the soil water resurces. Relative transpiration as an index of the soil water resources state was published by Budagovskij and Grigorieva (1991) as the ratio of transpiration E_t and the potential transpiration E_{tp}:

$$\eta_p = E_t / E_{tp} \qquad (5)$$

The equation (5) is characterizing the availability of soil water within the range (0;1) and the expression (6) can be noted as drought index in the range (0;1); $\eta_d = 0$ means „absolute" drought, $\eta_d = 1$ means full, unlimited availability of soil water to plant.

$$\eta_d = 1 - \eta_p \qquad (6)$$

The critical soil water content of limited water availability concept

The „critical soil water content of limited water availability“, (θ_{la}), is characterizing an average soil water content of the soil layer at which the transpiration rate starts to decrease followed by biomass production decrease (Novák, Havrila, 2006). In the above mentioned soil layer roots are located; usually upper one meter layer is considered. The core of the estimation method is based on an analysis of the relationship between relative transpiration rate and average soil water content of the root zone, as it is presented in Fig.2.

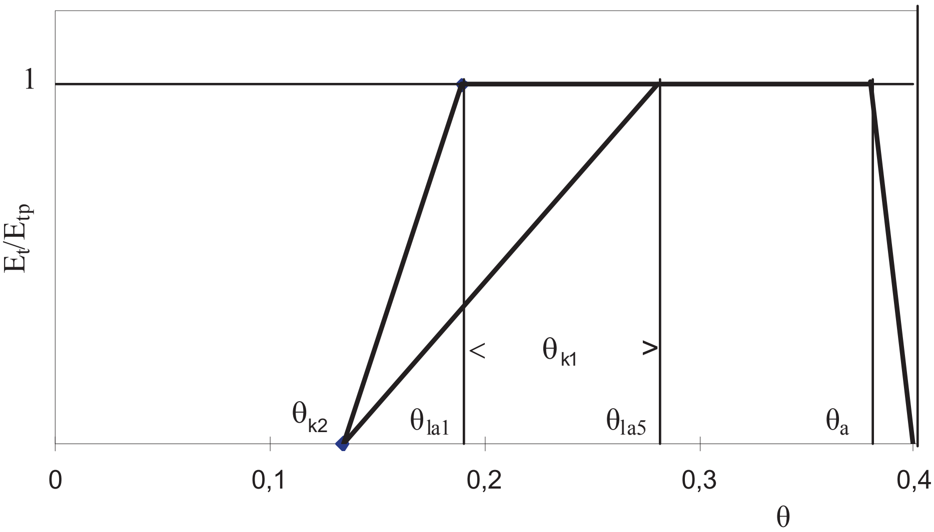

Fig. 2. Relative transpiration and the soil water content of the upper one meter soil layer $E_t / E_{tp} = f(\theta)$, where $\theta_{la5} - \theta_{la1}$ is the range of the „critical soil water contents of limited availability“ for plants, θ_{k1}, for the range of daily transpiration totals $1 \leq E_t \leq 5$ mm/day at the site Most pri Bratislave.
Obr. 2. Relatívna transpirácia v závislosti na obsahu vody vo vrchnej, metrovej vrstve pôdy $E_t / E_{tp} = f(\theta)$, kde $\theta_{la5} - \theta_{la1}$ je rozsah „kritických vlhkostí pôdy so zníženou dostupnosťou pre rastliny” , θ_{k1}, v rozsahu denných úhrnov transpirácie $1 \leq E_t \leq 5$ mm/deň v lokalite Most pri Bratislave.

The principle of θ_{la} evaluation is briefly characterized using Fig. 2. It follows from analysis that maximum plant production can be reached if transpiration total per vegetation period of particular canopy is maximum, i.e. potential one. From it follows that any transpiration rate below its potential value decreases plant growth. A decrease in soil water content in the soil root zone below θ_{la} has to result in a decrease in biomass production too. Therefore, the soil water content of the soil root zone below this value can be declared as soil water content corresponding to the state characterized as „physiological drought“.

Method 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 empirical equations (Novák, 1990):

$$\theta_{la} = \theta_{k1} = \frac{1}{\alpha} + \theta_{k2} \tag{7}$$

$$\theta_{k2} = 0.67 \,.\, \theta_v \tag{8}$$

$$\alpha = -2.27\, E_{tp} + 17.5 \tag{9}$$

where θ_{k1}, θ_{k2} are the so called „critical“ soil water contents, (SWC), indicating the beginning and the end of the transpiration decrease rate range, θ_v is 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 it is also a function of the Soil – Plant – Atmosphere

Continuum (SPAC) properties. Transpiration rate, which strongly influences critical soil water content θ_{k1} is function of meteorological properties. Sensitivity analysis of 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 potential transpiration rate, followed by the air temperature.

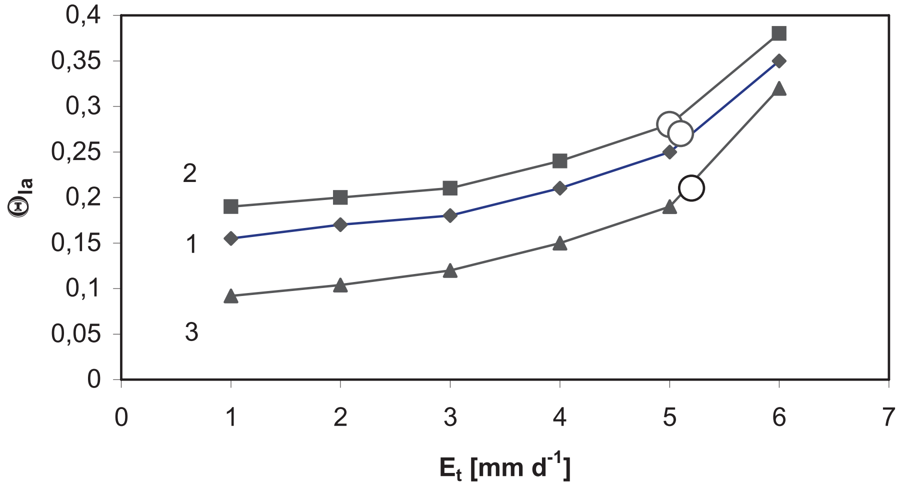

Fig. 3. Critical soil water content of limited availability for maize θ_{la} , corresponding to the transpiration rate E_t of the three soils. Circles are denoting values of θ_{pla} estimated according to the equation (10). Trnava (1)- chernozem on loess, Láb (2) – sandy soil , Most pri Bratislave (3) - loamy soil.
Obr. 3. Kritické vlhkosti pôdy so zníženou dostupnosťou pre kukuricu θ_{pla} , zodpovedajúce rýchlosti transpirácie E_t pre tri druhy pôd. Krúžkami sú označené hodnoty θ_{la} vypočítané rovnicou (10). Trnava (1)- černozem na spraši, Láb (2) – piesočnatá pôda , Most pri Bratislave (3) – hlinitá pôda.

Fig. 3 presents SWC corresponding to the critical soil water content of limited availability to plants of three soils as they depend on the transpiration rate $\theta_{la} = f\,(E_t)$. From the analysis it follows a strong dependence 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 decrease in daily transpiration rate during days with maximum energy input (hot days) limited by lack of the soil water is limiting biomass production much more significantly than during cold days.
In Fig.3 (denoted by circles), it could be seen soil water contents corresponding to "point of limited availability" (θ_{pla}) calculated according to frequently used empirical equation (Kutílek, 1978)

$$\Theta_{pla} = 0{,}6\;(\theta_{fc} - \theta_v) \qquad (10)$$

It can be seen that SWC corresponding to the "point of limited availability" (θ_{pla}) is in the rage of SWC estimated by the proposed method, but its values are corresponding to the high transpiration rates, which are rare. Realistic transpiration rates under conditions of South Slovakia are usually 2 – 3 mm/day.

Proposed estimation method of the critical SWC of limited availability for plants θ_{la} is physically and physiologically clearly interpreted and can be easily calculated using equations (7 - 9). It is not a constant value, but it changes, depending on the transpiration rate. For practical purposes it is possible to use the critical SWC (θ_{la}) corresponding to the daily average transpiration rates.

Results - an illustrative example

Application of the above described method of „physiological drought“ estimation will be illustrated on results of measurement and modelling at the experimental site of Most pri Bratislave, with loamy soil and maize canopy. As a tool, simulation model HYDRUS – ET (Šimůnek, et al., 1997) was used,

with modified Penman – Monteith method to calcualte evapotranspiration and its components (Majerčák, Novák, 1992). Calculations were made for 31 seasons nad maize canopy. Basic soil characteristics can be found in papers by Havrila, Novák (2006) and Novák, Havrila (2006).
Maximum (V_{max}) and minimum (V_{min}) daily values of soil vater content in 0 - 50 cm upper layer of soil with maize canopy, calculated by mathematical model HYDRUS –ET, during 31 seasons for Most pri Bratislave site, as well as SWC corresponding to the basic soil water hydrolimits (wilting point, critical SWC of limited availability and field capacity) are in Fig.4. It can be noted that during this period, there was no the state when the SWC of the upper 50 cm soil layer was below permanent wilting point. There were found periods, when SWC was below critical soil water content of limited availability (V_{la}), which corresponds here to the potential (highest) rates of transpiration.

Cumulative frequency curves of maximum (V_{max}) and minimum (V_{min}) daily values of soil water content in 0 - 50 cm upper layer of soil with maize canopy are in Fig. 5. In 60 per cent of seasons analyzed, the V_{la} was estimated to be below the critical level.
Interesting is Fig. 6., presenting the diagram in which can be seen number of days *n* during the vegetation period of maize with soil water content of the upper 50 cm soil layer less than 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 permanent lack of water neded for maximum biomass production.

Cumulative frequency curves number of days *n* during the vegetation period of maize with soil water content of the upper 50 cm soil layer less than soil water content corresponding to the „critical SWC of limited availability“ of soil water to plants V_{la} , (V_{la}= 0.28), calculated by mathematical model HYDRUS –ET, during 31 seasons is in Fig. 7. Data from Fig.6. were used. Only four vegetation periods of maize were wet enough, to ensure optimum soil water content for maximum biomass production.

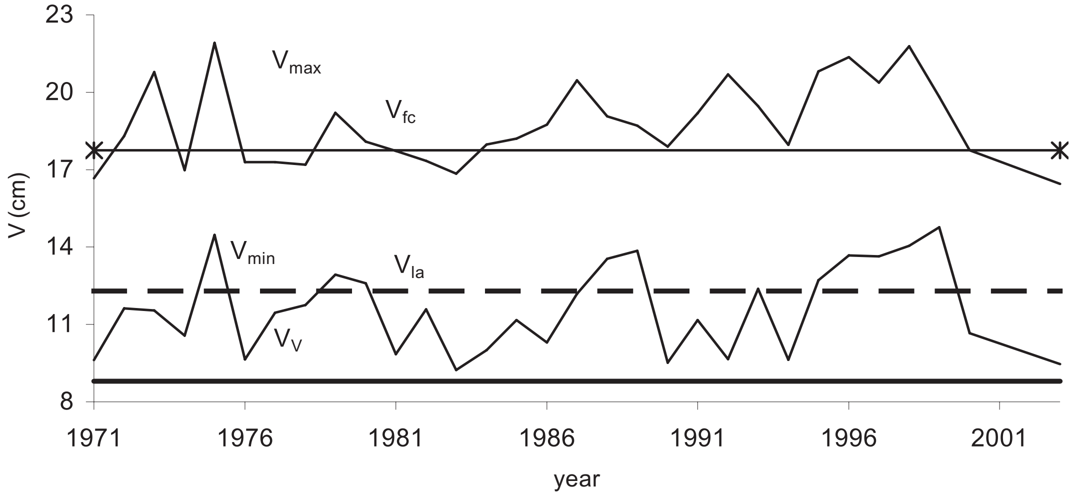

Fig.4. Maximum (V_{max}) and minimum (V_{min}) daily values of soil vater content of the 0 - 50 cm upper layer of soil with maize canopy, calculated by mathematical model HYDRUS –ET, during 31 seasons. Soil water contents (SWC), corresponding to the basic soil water characteristics (wilting point, SWC of limited availability and field capacity) are presented too. (Most pri Bratislave site).
Obr.4. Maximálne (V_{max}) a minimálne (V_{min}) denné hodnoty obsahu vody vo vrstve pôdy 0 - 50 cm pod povrchom pôdy s porastom kukurice vypočítané modelom HYDRUS – ET za 31 vegetačných období kukurice. Na obrázku sú naznačené obsahy vody v pôde, zodpovedajúce základným hydrolimitom pôdy V_{fc}, V_{la}, V_v, (Most pri Bratislave).

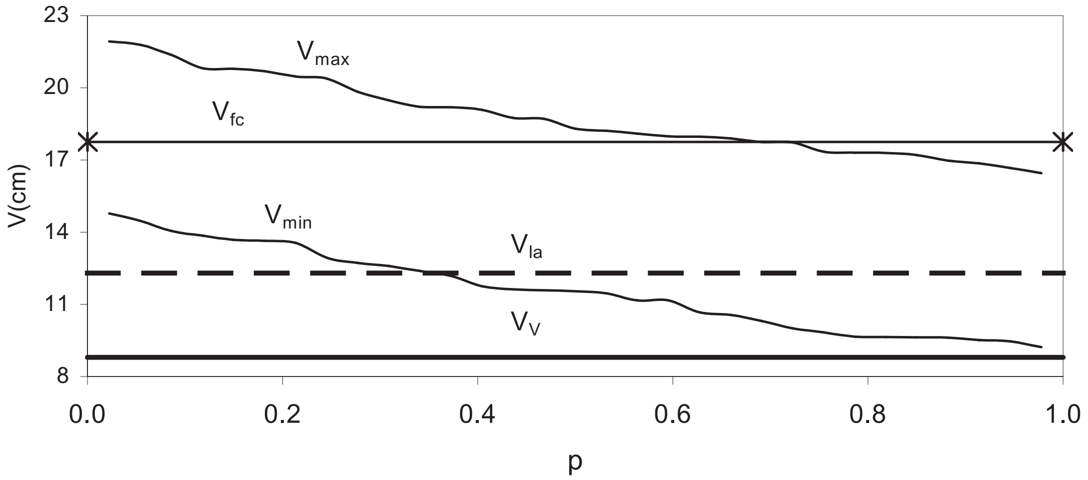

Fig.5. Cumulative frequency curves of maximum (V_{max}) and minimum (V_{min}) daily values of soil water content in 0 - 50 cm upper layer of soil with maize canopy, calculated by mathematical model HYDRUS –ET, during 31 seasons, corresponding to the basic soil water characteristics (wilting point, SWC of limited availability and field capacity) Most pri Bratislave site.
Obr.5. Čiary prekročenia maximálnych (V_{max}) a minimálnych (V_{min}) denných hodnôt obsahu vody V vo vrstve pôdy 0 - 50 cm pod povrchom pôdy s porastom kukurice vypočítané modelom HYDRUS – ET za 31 vegetačných období kukurice. Na obrázku sú naznačené obsahy vody v pôde, zodpovedajúce základným hydrolimitom pôdy V_{fc}, V_{la}, V_v, (Most pri Bratislave).

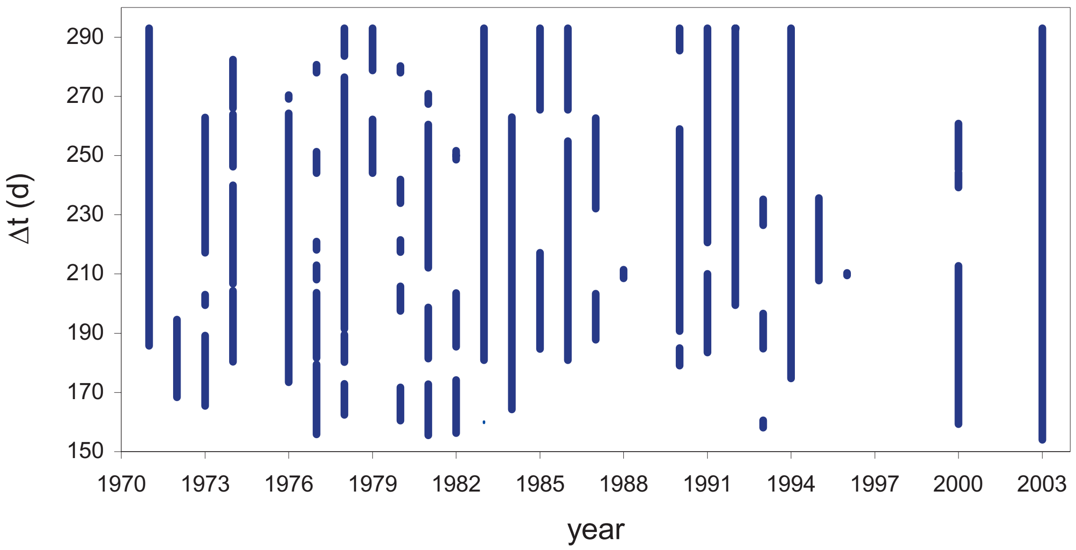

Fig.6. Number of days *n* during the vegetation period of maize with soil water content of the upper 50 cm soil layer less than soil water content corresponding to the „SWC of critical soil water content of limited availability" to plants V_{la}, (V_{la}= 0.28 cm of water layer) for 31 vegetation periods, (Most pri Bratislave).
Obr.6. Počet dní *n* počas vegetačných období kukurice s obsahom vody vo vrchnej 50 cm vrstve pôdy nižšom ako obsah vody korešpondujúci „kritickej vlhkosti pôdy so zníženou dostupnosťou vody pre rastliny" V_{la}, (V_{la}= 0.28 cm vrstva vody), počas 31 vegetačných období kukurice, (Most pri Bratislave).

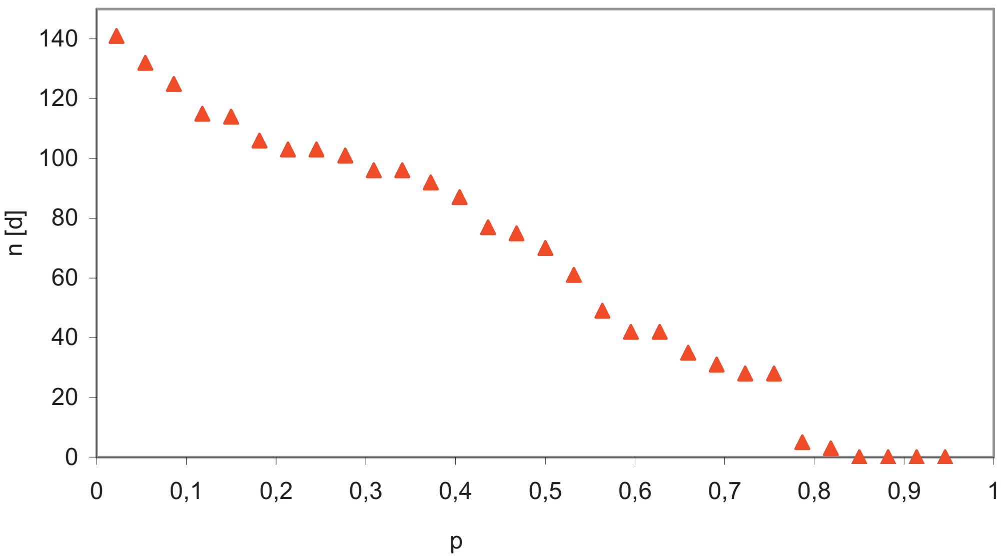

Fig.7. Cumulative frequency curves for number of days *n* during the vegetation period of maize with soil water content of the upper 50 cm soil layer less than soil water content corresponding to the „SWC of limited availability" of soil water to plants V_{la} , (V_{la}= 0.28 cm of water layer), calculated by mathematical model HYDRUS –ET, during 31 seasons,(Most pri Bratislave site).
Obr.7. Empirická čiara prekročenia počtu dní *n* počas vegetačných období kukurice s obsahom vody vo vrchnej 50 cm vrstve pôdy nižšom ako obsah vody korešpondújúci vlhkosti pôdy pri „kritickom obsahu vody zníženej dostupnosti vody pre rastliny V_{la}, (V_{la}= 0.28 cm vrstva vody), počas 31 vegetačných období kukurice, (Most pri Bratislave).

Conclusions

Drought is generally defined as a „lack of water", but it can be quantified from its impact only. In this paper a proposal is presented how to define „drought" from point of view biomass production. The presented approach is based on the theoretical consideration and empirical relationship between biomass production of particular plants and transpiration total of this plant during its vegetation period. This relationship is linear and valid for particular plant and environmental conditions (nutrition, agrotechnics).

Optimal plant production can be reached for maximum transpiration total, therefore potential transpiration total corresponds to maximum possible yield in given conditions. Transpiration rate, less than potential one leads to the biomass production decrease.

This phenomenon can be used to define the so called „physiological" drought, under which the soil water content of soil root zone decreases below the so called „critical soil water content of limited availability" for plants, under which transpiration rate is below potential transpiration rate.

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

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

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