Canopy structure changes and potential evapotranspiration: Possible influence of wind – throw in High Tatra Mountains

K. Kňava, V. Novák and T. Orfánus

Institute of Hydrology, Slovak Academy of Sciences, Račianska 75, 831 02 Bratislava, Slovak Republic

Abstract One of results of the wind throw in High Tatras in December 2004 was clearing of trees, covering about 12 000 hectares. The structure of the evaporating canopy was changed, followed by changes in evapotranspiration rates and their totals during the season. This article contains results of mathematical modeling of potential evapotranspiration of the three evaporating surfaces: spruce forest with three leaf area indexes (LAI = 1.5; 3.0 and 6.0), grass and bare soil. Results of mathematical modeling of potential evapotranspiration and its components– potential transpiration and potential evaporation of those different surfaces has shown significant differences in rates, totals and especially in its structure. Potential evapotranspiration rates were chosen, because they are not influenced by the soil water content and can readily demonstrate the role of canopies itself.

Key words: *potential evapotranspiration, transpiration, evaporation, soil water, mathematical modeling, soil hydrology*

Introduction

Wind throw in High Tatra Mountains in December 2004, focused attention to the problems of the impact of wind throw on environment, especially on its impact on flora, fauna, microclimate and on water transport in affected areas. Clearing of over 12 000 hectares of forest changed the plant cover structure and should influence microclimate and water transport as well. Therefore, to analyze the new interrelations in affected environment, attention was paid to estimation of basic properties of the soil – plant – atmosphere system.

Changes in evapotranspiration structure due to changes of canopy structure are important from different aspects: they influence soil water content (SWC), groundwater recharge, surface runoff and finally, microclimate.

This contribution presents basic information about the expected changes in potential evapotranspiration and its structure (potential evaporation, potential transpiration). Potential values of evapotranspiration and its structure were chosen as indicators of the role of canopies itself in evapotranspiration processes, not modified by soil water availability. The differences in canopy structure due to wind – throw can seriously affect soil water balance, evapotranspiration structure and microclimate of the impacted area.

Method

The influence of canopy structure on evapotranspiration rates and its components is extremely difficult to measure. Particular problems arise for forest canopies, because of trees dimension. The only possibility to solve this problem is to apply mathematical simulation models to calculate necessary information. Among different models known from literature - SWATRE, (Van Dam, et al., 1997); HYDRUS − ET, (Šimunek, et al., 1998, Vogel, et al., 1996) and GLOBAL (Majerčák, Novák, 1992), the last simulation model was chosen. The advantage of the GLOBAL simulation model is detailed description of the evapotranspiration process, based on results of Russian studies in the physics of atmosphere (Budagovskij, 1981).

This model, developed at the Institute of Hydrology, Slovak Academy of Sciences in Bratislava, is based on one dimensional Richards governing equation. This model allows to calculate soil water transport during the vegetation period. Daily courses, as well as daily totals of modelled characteristics can be calculated. This model provides original method of evapotranspiration and its components (transpiration, evapotranspiration) calculation, as well as improved methods of interception and root extraction patterns estimation. Evapotranspiration estimation method is in principle Penman – Monteith type, but with different method of "wind" function estimation based on Obuchov – Monin results, which substantially improves accuracy of evapotranspiration estimation. The same method is used in HYDRUS –ET model (Novák, 1995). Hydraulic conductivity is calculated using Mualem – Genuchten method, hysteresis of retention curves can be accounted for. Numerical solution of Richards equation is using Galerkin version of finite element method. This one – dimensional model can calculate soil water transport in layered soil (up to 5 layers can be used). This model was described in details by Majerčák, Novák (1992), Novák, Majerčák (1992).

Site and soil

Research site, characteristics of which were used to model potential evapotranspiration and its components was chosen as one of four official sites, which undergo intensive monitoring through couple of participating research groups. Chosen site acronym is FIRE and is located west of Starý Smokovec, north of the main road Starý Smokovec – Štrbské Pleso. This cleared area was later set on fire, so from there is its acronym FIRE. But measurements of soil characteristics showed minimum decline of the fire affected parts from non affected parts of this site. Only a top few millimeters of organic matter was fired, thus minimally changing properties of soil of studied area.

Tab. 1 Characteristics of the soil profile at site FIRE, needed as input data of the model GLOBAL.
Tab. 1 Charakteristiky profilu pôdy v lokalite FIRE, potrebné ako vstupné hodnoty do modelu GLOBAL.

SOIL CHARACTERISTICS			
	0 - 5 cm	5 - 15 cm	15 - 100 cm
θ_v	0.18	0.14	0.27
θ_{fc}	0.396	0.464	0.391
θ_s	0.704	0.658	0.622
K_s [cm d^{-1}]	1000	320	670
α	0.26749	0.20454	0.10592
n	1.17952	1.13446	1.23345

θ_v – volumetric soil water content corresponding to the wilting point [cm^{3}cm^{-3}], θ_{fc} – soil water content corresponding to the „field capacity" [cm^{3}cm^{-3}], θ_s – water content of the saturated soil [cm^{3}cm^{-3}], K_s – hydraulic conductivity of the soil saturated with water (saturated hydraulic conductivity) [m.s^{-1}], α [cm^{-1}] and n [-] – van Genuchten's equation coefficients

Basic hydropedological properties of mountainous soils in High Tatra Mountains were not known. Our study has shown, that soil properties are quite different from agricultural soils. Upper, organic layer of about 5 –10 cm thickness is followed by stony soil, typical for relicts of previous iceberg activity. Typical soil in impacted area is composed by stony boulders, diameters of which are mostly between 10 – 20 centimeters; space among boulders is filled with highly permeable sandy loam soil. The content of boulders in such a soil was tentatively estimated 40 – 60 % of total soil volume, depending on site location. Interesting and important for our calculations is, that soil hydropedological properties are similar for all the four research sites in High Tatra Mountais under study. In such a soil, water transport performs through the soil matrix only; stones are completely impermeable and their hydraulic conductivity can be taken zero. Water content and their retention capacity for water in granite stones can be taken as zero too. Soil among boulders itself is of high retention capacity; volumetric soil water content of soil saturated with water is between 0.60 – 0.80 , which is nearly twice of standard agricultural soils. Hydraulic conductivity of soil saturated with water is in the range of meters per day, so high retention capacity, together with high hydraulic conductivity can supply water at high rates to the roots of canopies and can ensure evapotranspiration rates close to the potential values. Retention curves of the soil profile, composed of the three material layers were estimated, using apparatus Soil Moisture Corp., and were approximated by Van Genuchten´s (1980) equation.

Basic soil profile characteristics are given in Tab. 1. The upper, one meter layer of the soil was taken, to model soil water transport. According to the natural soil profile composition, the modeled soil profile was divided of three layers (0 – 5 cm; 5 –15 cm and 15 –100 cm) , characteristics of which can be found in Table 1.

Canopies

Evapotranspiration of the three types of evaporating surfaces was calculated:

1) Spruce forest, about 70 years old, with height about 30 meters. Three different leaf area indexes were used for calculation, to simulate different tree densities and thus different role of trees and low vegetation in evapotranspiration structure. Table 2. shows basic canopy characteristics used, needed to simulate potential evapotranspiration rate. It is typical for coniferous forest, that its phenological characteristics are not changing during the season significantly.
2) Grass, as an alternative evaporating surface, with variable characteristics, during the season.
3) Bare soil. This kind of surface can be observed just after clearing, fire, or during short spring period. Under meteorological conditions of Slovakia it is rare case. However, this case is shown for comparison.

Another canopy characteristics used as input data were albedo, roughness coefficient (as a functions of time) and characteristics of interception processes according to the proposal by Benetin et al. (1986).

Tab. 2 Characteristics of plant canopies, needed as inputs to the model (LAI – leaf area index, dimensionless; z_o - roughness length, m; α – albedo of plant canopy, dimensionless).
Tab. 2 Charakteristiky porastov, potrebné ako vstupné hodnoty do modelu GLOBAL;(LAI – index listovej pokryvnosti; z_o – drsnosť vyparujúceho povrchu, m; α – albedo vyparujúceho povrchu.

SURFACE		LAI	z_0 (m)	α
SPRUCE FOREST	01.04. - 31.10.2006	1.5 3.0 6.0	0.3	0.15
BARE SOIL	01.04. - 31.10.2006	0.0	0.03	0.15
GRASS	01.04. - 31.05.2006	0.5	0.02	0.25
	01.06. - 30.06.2006	1.5	0.03	
	01.07. - 31.08.2006	5.0	0.05	
	01.09. - 30.09.2006	4.0		
	01.10. - 31.10.2006	0.5	0.02	

Meteorological characteristics

Meteorological characteristics for the season 2006 were used (daily precipitation total, average daily air temperature, average daily air humidity, average daily wind velocity and daily sunshine duration). There are results of measurements at meteorological station Tatranská Lomnica, run by the Institute of Geophysics, Slovak Academy of Sciences. The distance of this MS from the site FIRE is about 10 kilometers, so it was used as characteristic for FIRE site. The time interval of 220 consecutive days was modeled (April 1, - October 31, 2006).

Results and discussion

There are plenty of publications presenting results of mathematical modeling of nearly any components of water balance equation during the season. Fact is, that measuring and monitoring of state variables of soil (soil water content, soil water potential) are basic data, informing about the state of soil water. But, it is nearly impossible to measure all data needed; forest evapotranspiration and its structure measurement is particular item, with specific problems especially due to trees dimensions. This is the main reason, to utilize simulation models. Simulation model GLOBAL and its part, evapotranspiration calculation was verified many times, with good results and therefore it is frequently used as a good estimate of processes under consideration (Novák, et al., 1986, Majerčák, Novák, 1992, Novák, Majerčák, 1992).

Results of mathematical modeling are daily rates of potential evapotranspiration and components of its structure – evaporation and transpiration for the part of the season 2006, starting form April 1, until December 31, 2006, for three evaporating canopies: spruce forest, grass and bare soil. As an example, daily courses of potential evapotranspiration structure of the tree canopy with LAI = 3, which represents spruce forest of medium density (Fig. 1) are shown.

Better information about the role of respective evaporating surface can be extracted from seasonal courses of cumulative daily potential evapotranspiration and components its structure – evaporation and transpiration. Potential evapotranspiration courses of spruce forest with three different LAI (1,5;3;6) are approximately the same, because of small differences in their albedo and roughness lengths. But, their structure (components) are different. For medium density of the forest (LAI = 1.5) potential transpiration (E_{tp}), and potential evaporation (E_{ep}), are approximately the same, the differences between potential evapotranspiration components are becoming higher with increasing LAI. As LAI is increasing, potential transpiration is increasing too (Fig. 2).

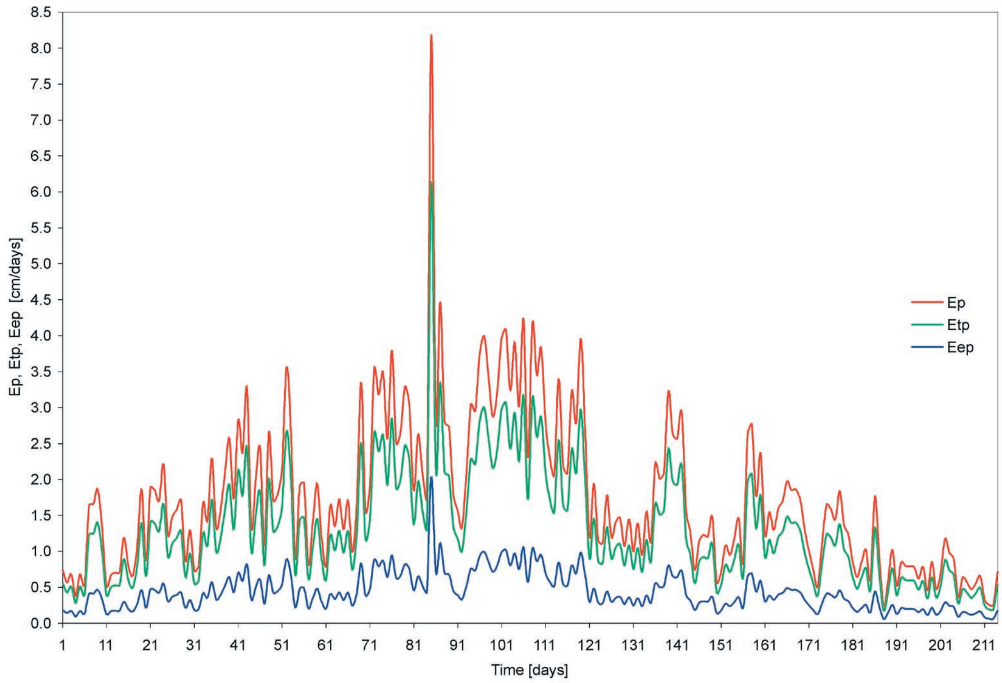

Fig. 1 Seasonal courses of potential evapotranspiration (E_p), potential transpiration (E_{tp}) and potential evaporation (E_{ep}) daily totals for spruce forest, of LAI = 3, calculated using GLOBAL simulation model for FIRE site in High Tatras. April 1, - December 31, 2006.
Obr. 1 Ročný chod denných úhrnov potenciálnej evapotranspirácie (E_p), potenciálnej transpirácie (E_{tp}) a potenciálneho výparu (E_{ep}) smrekového lesa, s LAI = 3, vypočítaný pomocou simulačného modelu GLOBAL , pre lokalitu FIRE vo V. Tatrách. 1.4. – 31.12. 2006.

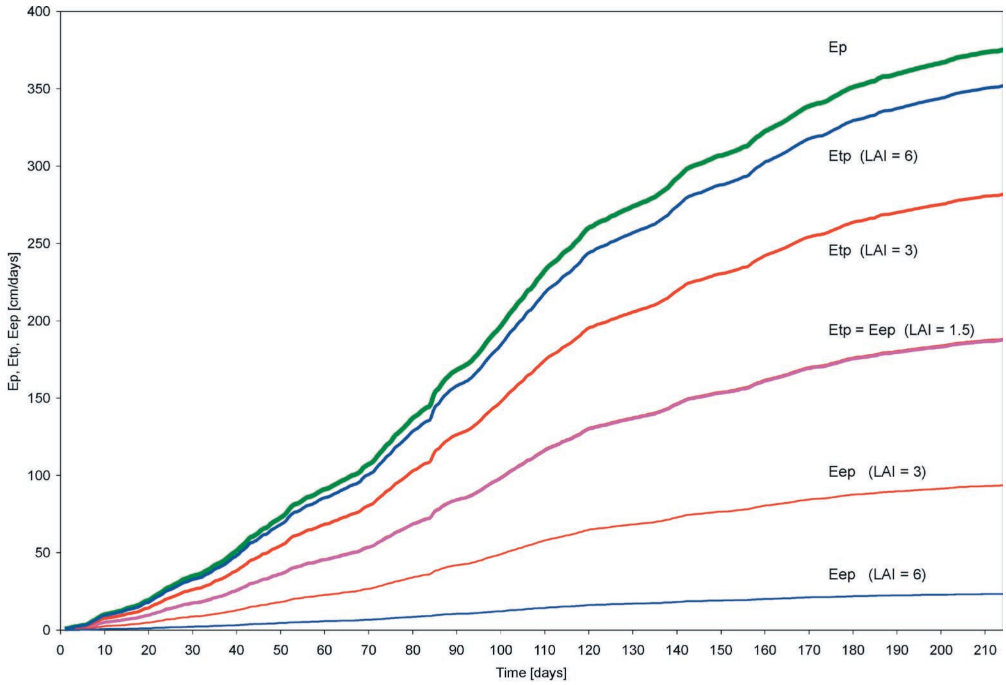

Fig. 2 Cumulative daily potential evapotranspiration totals (E_p) of spruce forest and components of its structure - potential evaporation (E_{ep}) and potential transpiration (E_{tp}) for different leaf area indexes (LAI) during the part of the season 2006, starting form April 1, until December 31, 2006. High Tatra, site FIRE.
Obr. 2 Kumulatívne denné úhrny potenciálnej evapotranspirácie (E_p) smrekového lesa a zložiek jeho štruktúry – potenciálneho výparu (E_{ep}) a potenciálnej transpirácie (E_{tp}) vypočítané modelom GLOBAL pre rozdieľne hodnoty indexov listovej pokryvnosti (LAI) pre lokalitu FIRE vo V. Tatrách. 1.4. – 31.12. 2006.

Important finding resulting from this analysis is: the higher LAI of the canopy is (up to some critical density of the forest), the higher forest (tree) biomass production rate can be expected. This result can be drawn from known empirical (linear) relationship between transpiration rate and biomass production rate (Hanks, Hill, 1980, Havrila, Novák, 2006, Novák, 2007 –this conference).

Seasonal courses of cumulative daily potential evapotranspiration (E_p), and components of its structure – evaporation (E_{ep}), and transpiration (E_{tp}), of dense grass canopy can be seen in Fig. 3. Relatively low transpiration rate (E_{tp}), at the beginning of the vegetation period is becoming higher than evaporation rate during the later stage of vegetation period.

Seasonal courses of cumulative daily potential evapotranspiration (E_p), of bare soil is higher than this from grass canopy (Fig.3). The main reason of the higher value of potential evapotranspiration (E_p), of bare soil in comparison to grass is significantly lower value of bare soil roughness length.

Tab. 3 Seasonal totals of potential evapotranspiration (E_p), and components of its structure potential transpiration (E_{tp}), and potential evaporation(E_{ep}), of three different evaporating surfaces).
Tab. 3 Ročné úhrny denných hodnôt potenciálnej evapotranspirácie (E_p), a zložiek jej štruktúry potenciálnej transpirácie (E_{tp}), a potenciálneho výparu (E_{ep}), troch rozdieľnych vyparujúcich povrchov.

SURFACE		**SPRUCE FOREST**		**GRASS**	**BARE SOIL**
LAI	1.5	3	6	VARIABLE	0
E_p	375.24	375.24	375.24	407.71	475.24
E_{tp} (mm)	187.87	281.68	351.91	237.91	0
E_{ep}	187.37	93.56	23.33	169.80	475.24
E_{tp} / E_p	0.50	0.75	0.94	0.58	0.00
E_{ep} / E_p	0.50	0.25	0.06	0.42	1.00

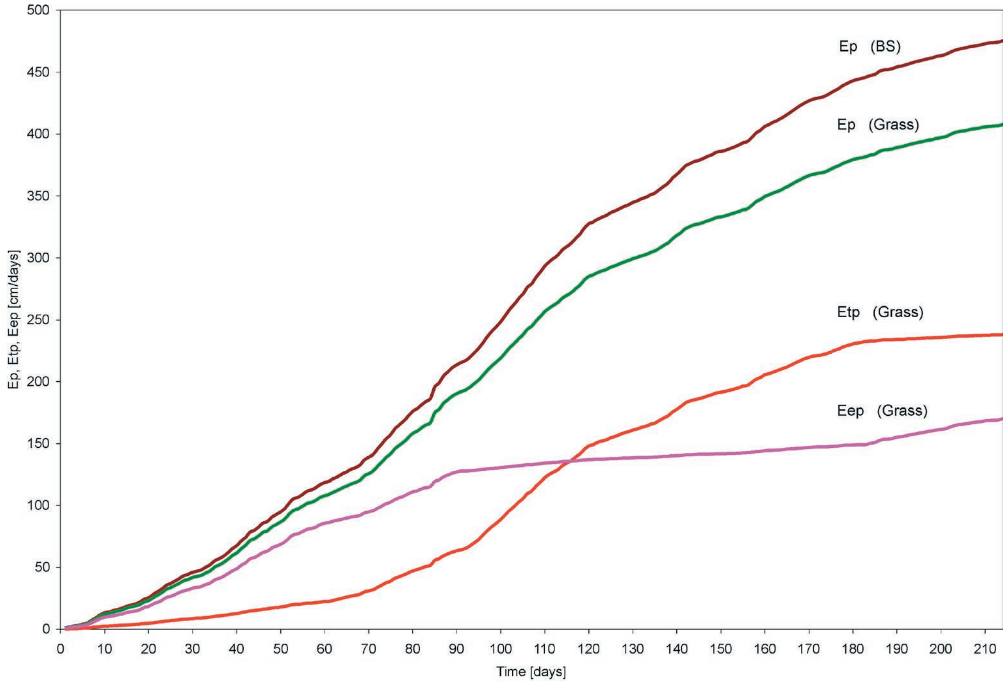

Fig. 3 Cumulative daily potential evapotranspiration totals (E_p) of bare soil (BS) and grass and components of its structure - potential evaporation (E_{ep}) and potential transpiration (E_{tp}) during the part of the season 2006, starting form April 1, until December 31, 2006. High Tatra, site FIRE.

Obr. 3 Kumulatívne denné úhrny potenciálnej evapotranspirácie (E_p) a zložiek jej štruktúry – potenciálneho výparu (E_{ep}) a potenciálnej transpirácie (E_{tp}) vypočítané modelom GLOBAL pre holú pôdu a trávu s rozdieľnymi hodnotami indexov listovej pokryvnosti (LAI) pre lokalitu FIRE vo V. Tatrách. 1.4. – 31.12. 2006.

Tab. 3 presents seasonal totals of cumulative daily potential evapotranspiration (E_p), and components of its structure – evaporation (E_{ep}), and transpiration (E_{tp}), for all the three canopies. Some aspects of the different LAI influence were described before. We would like to focus attention on the differences in seasonal cumulative daily potential evapotranspiration (E_p) totals. The highest potential evapotranspiration is evaporation from bare soil (475 mm), followed by the E_p of grass; the lowest value is evapotranspirated by spruce forest. There are two main reasons of it:

- interception of precipitation, which is high for trees
- decreasing velocity coefficient of turbulent movement for water vapour from evaporating surface to the atmosphere with increasing roughness length (Fig.4).

The first reason is obvious; but the second one results from the theory of Monin, Obuchov (1954), which is incorporated in the evapotranspiration calculation procedure (Budagovskij, 1981, Novák, 1995).

The relationship between velocity coefficient of turbulent movement of water vapour from evaporating surface to the atmosphere D and roughness length z_o (Fig.4) shows significant increase of D with decreasing z_o. This phenomenon significantly increases evapotranspiration from smooth surfaces, like water, bare soil or smooth plant canopies, like cereals an grass. On the contrary, evapotranspiration is decreasing from rough surfaces, like from trees and shrubs, as it is seen from results obtained by modeling. Sensitivity of the potential evapotranspiration on roughness length is significant for $z_o < 0{,}1$ m; this value is typical for shrubs and trees (Novák, 1995). Analyzing the modified Penman – Monteith equation, it can be seen, that the second term of the numerator of the right side of this equation (including term D) is additive to the radiation part of numerator and therefore increases the calculated value of potential evapotranspiration.

Results of modeling, presented, can help us to understand, what could be expected, if canopy structure changes will be done, the wind – throw is not necessary the only reason; land use can lead to comparable results. Mathematical model as a tool to obtain information about evapotranspiration rates and its structure is often the only possibility to obtain such a data. On the other side, every simulation model is an approximation of reality and results of modeling are approximation too.

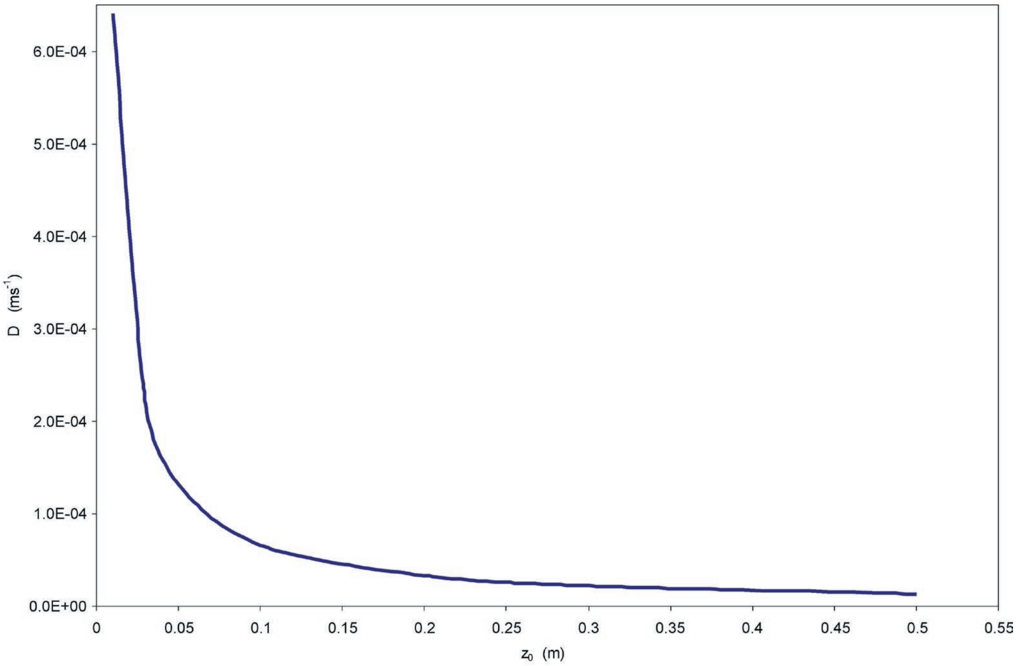

Fig. 4 The relationship between velocity coefficient of turbulent movement of water vapour from evaporating surface to the atmosphere *D* and roughness length z_o, calculated according to Obuchov – Monin (1954) theory.
Obr. 4 Závislosť medzi koeficientom rýchlosti turbulentného pohybu vodnej pary z vyparujúceho povrchu doatmosféry *D* a drsnosťou vyparujúceho povrchu z_o, vypočítaná podľa teórie Obuchova – Monina (1954).

Conclusions

Potential evapotranspiration of the three evaporating surfaces – spruce forest with three leaf area indexes (LAI = 1.5; 3.0 and 6.0); grass and bare soil was estimated for the season 2006 by mathematical modeling, using simulation model GLOBAL. Components of its structure were calculated too; potential transpiration and potential evaporation. Potential values of them were estimated, to characterize the influence of canopies itself on evapotranspiration, not influenced by soil water content.

Under identical weather conditions the highest cumulative potential evapotranspiration (for the time interval April 1, - December 31, 2006) was estimated for bare soil (475 mm), followed by grass (407 mm) and by spruce forest (375 mm). The main reason of it is the roughness length of canopies. The highest roughness length was estimated for forest, followed by grass and by bare soil (Tab.2). It is strongly influencing velocity coefficient of turbulent transport of water vapour from evaporating surface to the atmosphere; the higher roughness length is, the lower potential evapotranspiration is calculated.

The structure of potential evapotranspiration is changing too; the higher is LAI the higher is the ratio of potential transpiration to potential evapotranspiration.

Important finding resulting from this analysis is: the higher LAI of the canopy is, the higher forest (tree) biomass production rate can be expected. This result can be drawn from widely accepted linear relationship between transpiration rate and biomass production rate.

Preliminary results, presented in this article has shown, that the changes in evaporating canopy structure can lead to the changes of water balance equation structure and to the changes of biomass production. Wind throw can be no only reason of it; land use can lead to similar results.

Acknowledgement

Authors are is grateful to the Slovak Grant Agency APVV (Grant No. 51 - 030205) for partial support of this work.

Literature

Benetin,J., Novák, V., Šoltész, A., Štekauerová, V. 1986. Intercepcia a jej vplyv na vodnú bilanciu vegetačnej pokrývky. Vodohosp. Čas.34, č.1., 3 –20.

Budagovskij, A.I. 1981. Evaporation of soil water. In.: Physics of soil water. Nauka, Moskva.

Dam, J.C. van, Huygen J.,Wesseling, J.G.,Feddes, R.A.,Kabat, P.,van Walsum, P.E.V., Groenendijk, P. And van Diepen, C.A. 1997. Theory of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the Soil – water – Atmosphere – Plant environment. Report 71, Dept of Water Resources, Wageningen Agricultural University.

Technical Document 45, DLO Winand Starring Centre, Wageningen, pp.166.

Hanks, R.J., Hill, R.W. 1980. Modeling crop responses to irrigation in relation to soils, climate and salinity. IIIC Publication, No.6, Ketterpress Enterpr., Jerusalem, pp.66.

Havrila,J., Novák, V. 2006. Metóda určenia režimu odberu vody z pôdy rastlinami pre potreby produkcie biomasy. J. Hydrol. Hydromech. 54, 2006,1,15 – 25.

Majerčák, J., Novák, V.1992. Simulation of the soil – water dynamics in the root zone during the vegetation period. I. The mathematical model. Vodohosp. čas., 40, 299 – 315

Monin, A.J., Obuchov, A.H. 1954. Basic relationships of the turbulent mixing in the boundary layer of atmosphere. Trudy Geofiz. Inst., 24 (151), 163 – 186, (In Russian).

Novák, V., Majerčák, J. 1992. Simulation of the soil – water dynamics in the root zone during the vegetation period. II. The course of state variables of soil water below the maize canopy. Vodohosp. čas., 40, 380 – 397

Novák, V., 1995. Evaporation of Water in Nature. (In Slovak). VEDA, Bratislava.

Novák, V. 2007. Drought - how to quantify it ? (This issue).

Šimůnek, J., K. Huang., M. Šejna, Th. M. van Genuchten, J. Majerčák, V. Novák, and J. Šutor. 1998. 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.

van Genuchten, M.Th. 1980. A closed - form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892 – 898.

Vogel,T., Huang,T.K., Zhang,R. and M.Th. van Genuchten.1996. The HYDRUS code for simulating one dimensional water flow, solute transport , and heat transport in variably –saturated media. Version 5.0, Research Report 140, U.S.Salinity Laboratory, Riverside, CA.