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SCALE RELATED PROBLEMS OF THE SOIL-PLANT-ATMOSPHERE SYSTEM

Scale dependency of soil hydrological properties as well as of meteorological data

Abstract of Ph.D. thesis

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1. INTRODUCTION

According to the global trend both the frequency and the intensity of weather extremes such as severe drought, heat waves and periods of heavy rainfall are expected to increase due to the climate change. Therefore my thesis is relevant which describes some aspects of scale-related problems of the soil-plant-atmosphere system. Specific topics were investigated with respect to soil temperature and water content as well as to observed meteorological data.

In the course of modeling, our main aim is to build up a system operating similar to physical reality, taken account of the characteristic features of the observed area. Therefore, it is essential to take into account the specification of factors, processes, aspects and their scale of validity. Furthermore, the scale of applicability of the used model also has to be determined. Scale of a characteristic feature in a concrete system represents the resolution which provides detailed characterization of temporal and spatial diversity as well as the variability of a system. **The issue of scale dependency** emerges due to diversity and variability of some characteristic features of the observed system.

Processes with temporarily variable dynamics are disintegrated into short quasistationary elements thus the continuous reality is represented as a series of discrete sessions. Furthermore, model calculations assume homogenous area at different scale (pedon, polypedon) during the simulation of processes. The **models are discrete, consequently** the results are scale dependent. Models calculate with average values ignoring the possible differences within the intervals of the temporal and spatial scale. The results of calculations might be different depending on the applied temporal and spatial scale.

The measured data such as initial and boundary conditions as well as parameter values are required to describe the concrete system as exact as possible. But, the measurement also has a kind of scale dependency. The measurements are carried out at several points and at different times of the observed object. Consequently, **measurements are discrete** as well.

Scale-related problems are caused by the fact that the reality changes both in space and time while the models and measurements are discrete, applying a certain spatial and/or temporal resolution.

Consequently, the investigations of the soil-plant-atmosphere subject could be arranged in two groups: (1) analyses of scale-related problems of modeling (2) examinations of scale related problems of measurements.

2. OBJECTIVES

The following questions were investigated in the research:

1. Does the measured saturated hydraulic conductivity depend on the sample size?
2. How does the hydraulic conductivity change after cultivation on sandy and loamy soils?
3. Is there any heterogenity of hydraulic conductivity and water repellency values within pedon scale on sandy soil and what factors may cause its water repellency?
4. Is there any difference between measured and simulated values of soil temperature as well as of soil water content at different scales as a function of crop and snow cover?
5. Are the simulated infiltration and soil evaporation results influenced by the applied soil profile discretization? Is the simulated plant phenological development effected by the frequency of meteorological data recording?
6. Is there any difference between the model result obtained with the average of different inputs and the average of model results obtained after the simulations (using different inputs)?

3. MATERIAL and METHODS

Measurements and investigations were carried out in laboratory as well as in field experiments, in irrigated and fertilized field trials, between 2009 and 2013. The experiment sites were: Csólyospálos (sandy soil), Martonvásár (sandy loam soil), Nagyhörcsök (loam soil), Őrbottyán (sandy soil) and Szurdokpüspöki (clay soil). The 4Mx crop model as well as the HYDRUS-1D hydrological model was applied in the study.

3.1. **Temporal variability of hydraulic conductivity**

Experiments investigating the process and the time required for soil re-compaction, characterized by hydraulic conductivity (K_S) and bulk density changes were carried out for different soil types: sandy soils of Csólyospálos and Őrbottyán and loam soil of Martonvásár. It is an important issue in modeling because the soil physical character is modified, the soil structure changes which affects the soil moisture storing capacity, due to cultivation. A 10×2 m weedless area was cultivated with a mini tiller in the upper 15 cm. Bulk density and hydraulic conductivity were measured in 5 repetitions before and after the tillage, as well. Later, the K_S values were determined after every major rainfall events with Mini Disk Infiltrometer (MDI) on the surface. Samples taken for measuring bulk density from 0-5 cm layer were measured in the laboratory. The measured values of K_S and bulk density were plotted against cumulative precipitation and the results were evaluated with statistical methods.

3.2. Spatial heterogeneity of soil hydraulic properties

The spatial variability of hydraulic conductivity and water repellency were examined in a 1 m^2 area divided into 100 10×10 cm cells at Őrbottyán and Csólyospálos experimental sites. Systematic sampling method was applied in each cell to determining the water repellency and K_S value with MDI.

The soil water repellency index was measured with Water Drop Penetration Time (WDPT) method at both pilot sites. The category of water repellency was determined with the classifying method of Dekker and Ritsema in each cell. According to the necessary time (t) of water drop infiltration, 5 categories are distinguished: (1) wettable or nonwater repellent (t< 5 s); (2) slightly (t=5 – 60 s); (3) strongly (t=60 – 600 s); (4) severely (t=600 – 3600 s); (5) extremely water repellent (t> 3600). The humic acid and fulvo acid content of the investigated soils were determined because the soil water repellency is influenced by the quality and quantity of Dissolved Organic Carbon. We demonstrated the effect of water repellency on hydraulic conductivity measurement.

3.3. Scale dependency of K_S measurement

100 cm^3 and 5650 cm^3 samples were investigated in 5 repetitions to determine the saturated hydraulic conductivity with laboratory methods on sandy (Őrbottyán), loamy (Nagyhörcsök) and clay (Szurdokpüspöki) soils. K_S values of were compared with paired t-test to prove the significant difference between the two sapling methods with more than 1 order of magnitude size difference.

3.4. Modeling problems of meteorological data recording

The plant phenological development is determined by the amount of daily thermal time. According to our hypothesis, its value depends on the air temperature input data. Thus, the daily and cumulative thermal times were calculated in two ways by the 4Mx model using the meteorological data measured at Őrbottyán in 2010. Firstly, the 5 minute resolution temperatures data were used to calculating the thermal times, secondly, sinusoidal diurnal course were assumed from minimum and maximum daily temperatures values. The anomalies were investigated with graphical method.

3.5. Modeling of soil temperature with different resolution and concepts

Measured and simulated soil temperature form 5 different depths (5, 10, 20, 40, and 60 cm) were compared for the Őrbottyán experimental site between 25.04.2010 and 04.10.2011. Temperature data were recorded every 15 minutes. Simulations were carried out by HYDRUS-1D and 4Mx models. The canopy and leaf area indices (LAI) were investigated under fertilized or control treatments. Models were calibrated by minimizing the difference between the simulated and observed LAI values. 4Mx is a daily-step deterministic model that simulates plant growth as well as soil processes with decimeter resolution using empirical equations. HYDRUS-1D is a mechanistic model that simulates the water and solutes transport in the soil with centimeter resolution. The hydrology model requires more sink and initial terms and plant input data to calculate the heat transport of soil layers. Site-specific measured data were used as inputs for both models. Measured and simulated soil temperature values were compared with t-test.

3.6. Comparison of measured and simulated soil water contents in field experiment

The measured and simulated soil water content (SWC) were compared for different depths (0-10, 0-30, 30-60, 60-80 and 0-80 cm) at Őrbottyán between 31.03.2010 and 18.04.2013. Simulations were carried out with HYDRUS-1D with centimeter and decimeter resolutions. The soil water content was measured 47 times in 10 cm resolution down to 80 cm depth during the investigated period. The differences between measured and simulated SWC were evaluated with variance analyses.

3.7. Spatial scale related problems of modeling infiltration and evaporation

Still, several models use decimeter resolution of the soil profile. According to our hypothesis, the above mention resolution is not adequate to simulate the soil evaporation and infiltration. The top soil layer was defined to 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 cm thick in the soil module of 4Mx model which input data were measured at Őrbottyán between 01.06.2012 and 07.07.2012.

Surface run off, infiltration and soil evaporation rate were simulated as a function of discretization of the top soil layer after a 42 mm rainfall followed by a dry month.

3.8. Modeling problem of simulation technics due to spatial heterogeneity

The changing of soil water content was simulated in 1 m depth sandy soil layer with HYDRUS-1D model for the Őrbottyán experimental site. The hydraulic conductivity was measured with Guelph permeameter in 5 repetitions. Measured Ks values were used for the simulations. The following rainstorm intensities were simulated: 0.0125, 0.025, 0.04, 0.05 mm/sec. The model simulations were carried out in two ways. (a.) The measured saturated hydraulic conductivity values were averaged before the simulation (*Interpolate first, Calculate later; IC*) and this single value was used in a simulation or (b.) the model results obtained with the 5 different measured K_S data were averaged after the simulations (*Calculate first, Interpolate later; CI*). The results were compared with simple statistical methods.

4. RESULTS and DISCUSSION

4.1. Temporal variability of hydraulic conductivity

In the field experiments, it could be detected that the hydraulic conductivity (K_S) and bulk density were changed with the cumulative precipitation after cultivation. The soil at the pilot area of Csólyospálos was re-compacted to the original state within two months. At the Őrbottyán and Martonvásár experimental sites, a thin crust layer was formed on the soil surface which resulted in a fast decrease of saturated hydraulic conductivity within few weeks, but the bulk density measurements did not support the rapid re-compaction of the disturbed system. Based on the results, the consideration of the temporal variability of hydraulic conductivity as well as of bulk density after cultivation as a function of precipitation in model calculations is indispensable. Soil hydraulic conductivity and bulk density are not constant over time, as assumed in most hydrological and crop models. Therefore, the development of these models to take into account the spatial heterogenity and temporal variability of these input data is indispensable as well.

4.2. Spatial heterogeneity of soil hydraulic properties

The spatial heterogeneity of 1 m^2 soil surface was experimentally identified for two hydraulic properties although, this area is usually considered as a 'homogeneous' soil mapping unit (pedon). The measurements showed that the saturated hydraulic conductivity had 1.5 an 0.5 order of magnitude difference within 1 m^2 at Csólyospálos and Őrbottyán, respectively. The results of a model simulation could be influenced by the considerable variability of K_S values because both 4Mx and HYDRUS-1D are sensitive to the saturated hydraulic conductivity input parameter.

The sandy soils of Csólyospálos and Őrbottyán pilot areas were investigated with Water Drop Penetration Time Test. The Őrbottyán soil was found to be a non-repellent one. Our investigations showed that the soil of Csólyospálos was strongly or even severely water repellent at some points. Our findings weren't confirmed the hypothesis that the humic acid to fulvo acid ratio is a good indicator of the soil water repellency. Therefore, I assumed that the soil water repellency at Csólyospálos could be attributed to the large quantity of non-degraded organic compounds. Generally, delayed infiltration was observed with the Mini Disk Infiltrometer (MDI) at Csólyospálos experimental site. A possible reason for it could be that the soil was partially or totally repellent under the MDI. First, K_S values were determined based on raw infiltration data collected during the total measurement time then, raw data recorded after the start of the rapid infiltration was used for determining the K_S. A half order of magnitude difference was detected between the results of the two methods. On water repellent soils, the actual measurements should be started after the beginning of the rapid infiltration in order to obtain more precise saturated hydraulic conductivity values with MDI. I concluded that the Mini Disk Infiltrometer could be applied for non-repellent soils (e.g. Őrbottyán). If the area is heterogeneous, dry lenses may remain in the soil during infiltration and some of the precipitation may run off and infiltrate in the neighboring area. Consequently the bulk large scale water repellency can be less than the mean of small-scale values.

4.3. Scale dependency of K_S measurement

Determination of the saturated hydraulic conductivity from five 100 cm^3 and five 5650 cm^3 undisturbed soil samples were compared for three soil types: sandy soil of Őrbottyán (Fodor et al., 2011), silt soil of Nagyhörcsök (Fodor et al., 2011) and clay soil of Szurdokpüspöki. The method of 5650 cm^3 sample is considered to be more precise due to (a) the larger sample volume, (b) the guaranteed saturation and (c) the controlled boundary conditions during the determination of the K_S. The K_S values, measured on the large samples could give the best estimation of the saturated hydraulic conductivity values of the investigated soils according to our working hypothesis. Significant differences were found both in the average and the in standard deviation of the measured hydraulic conductivity values for each soil. It was proved that the value of saturated hydraulic conductivity was influenced by the applied calculation method as well as by the sampling volume.

4.4. **Modeling problems of meteorological data recording**

The scale-dependence of the calculated daily thermal time was also investigated at the Őrbottyán pilot area. The sinusoidal diurnal course which is based on minimum and maximum daily temperatures values is an idealized case where daily temperature anomalies could be overlooked while these anomalies could be taken into account if fine resolution (e.g. 5 minute) temperature data would be used. Consequently, daily thermal time values could be over- or underestimated if only daily-step temperature data is used for the calculations. The difference between the cumulative thermal time values calculated with the two investigated methods could be more than 10% during a 10-days period. It could induce significant modeling error as plant phenological development is based on the daily thermal time which is usually calculated by using only two daily temperature data.

4.5. **Modeling of soil temperature with different resolution and concepts**

Considerable differences in the leaf area indices were observed in different treatments of the experiment at the end of the canopy development at the Őrbottyán study site. The well-developed (with high LAI) vegetation reduces both the average soil temperature and its diurnal amplitude therefore, considering the LAI values are important in soil temperature modeling (Sándor and Fodor, 2012a).

Measured soil temperatures data were compared to simulated soil temperature calculated by models with different spatial resolution and concept. Neither HYDRUS-1D nor 4Mx simulated adequately the heat transport in the soil, although HYDRUS-1D provided more accurate soil temperature estimations. Soil temperature values calculated by the HYDRUS-1D and the modified 4Mx model were not found to be significantly different. In spite of the fact that the spatial resolution of the 4Mx model is one order of magnitude larger than that of the HYDRUS-1D, the modified 4Mx simulation results did not deviate from measured data to such an extent that could be expected according to the resolution and concept difference. The seasonal snow cover could significantly modify the freezing of soil as it builds up an isolating layer. The drop of soil temperature was moderated under the snow cover with low thermal conductivity. Thus, I propose to develop the 4Mx model to eliminate the above mentioned discrepancy.

4.6. Comparison of measured and simulated soil water contents in field experiment

According to our investigations insignificant differences were found between the soil water content values simulated with the cm- and the decimeter resolution versions of HYDRUS-1D.
Statistically significant differences between the measured and simulated (HYDRUS-1D) soil water contents were observed under different weather conditions such as extreme rainy weather in 2010 or severe drought period in 2012. The series of measured and calculated soil water content were similar, if the distribution of weather condition was average (without long dry or wet spells) such as in 2011. Simulated water content values may significantly differ from measured values during prolonged extreme weather conditions the frequency of which is expected to increase in the future.

4.7. Spatial scale related problems of modeling infiltration and evaporation

The infiltration and the soil evaporation were simulated with 4Mx model where the top most soil layer was defined to 10, 9, 8, 7, 6, 5, 4, 3, 2, 1 cm thick. During the simulated evaporation following a rainstorm event the 1 cm thick upper layer was dried out sooner than the 10 cm thick layer though, the total water content of the 0-10 cm layer was considerably higher in the first case. As a consequence, significant differences were obtained owing to the model resolution during the simulation of evaporation. Depending on whether the surface layer thickness was defined to 1 cm, or 10 cm, the simulated water content changes showed major difference as a function of time. The spatial resolution of the model could be a source of error (or at least uncertainty).
The hydraulic conductivity is drastically decreased if the 1 cm thick uppermost layer dried out. Consequently, the upward flow is stopped so the amount of evaporation is reduced. This process can protect the soil and plants from drying and withering in nature conditions. Therefore, considering the mentioned process is important in modeling.

4.8. Modeling problem of simulation technics due to spatial heterogeneity

Spatial heterogeneity related modeling problems were investigated with HYDRUS-1D using data from the Őrbottyán experimental site. Depending on whether the measured saturated hydraulic conductivity values were averaged before the simulation (IC) or the model results obtained with the different measured K_S data were averaged after the simulations (CI), considerably different infiltration and surface runoff results were obtained. The CI method is recommended, despite the fact that it requires more calculation from the user, because the IC method may hide the effect of spatial heterogeneity that appears even on pedon scale.

5. MAIN RESULTS

1. The hydraulic conductivity and bulk density were changing with the cumulative precipitation after soil cultivation both in sandy and silt soils.

2. The Őrbottyán soil was found to be non-repellent. The soil at Csólyospálos was strongly or even severely water repellent at some points.

The soil water repellency at Csólyospálos could be attributed to the large quantity of non-degraded organic compounds.

According to our investigations on water repellent soils at Csólyospálos, the Mini Disk Infiltrometer could not be applied for determining the hydraulic conductivity. If the MDI was used for determining the K_S on water repellent soils, only the raw data recorded after the start of the rapid infiltration should be used.

The spatial heterogeneity of K_S and water repellency within pedon scale (1 m^2) were significant reaching 3 order of magnitude difference.

3. Based on the results, the 100 cm^3 sampling unit was not representative on clay soil. The method using 5650 cm^3 samples is proposed to determine the saturated hydraulic conductivity more accurately. The measured value of saturated hydraulic conductivity was significantly influenced by the measuring method and the size of the sample.

4. Daily thermal time calculated by using two daily temperature extremes is valid only for an idealized case, and hinders the observation of anomalies. While these anomalies could be taken into account if 5 minute temperature data would be used. Consequently, daily thermal time values could be over- or underestimated if only daily-step temperature data is used for the calculations. It could induce significant modeling error as plant phenological development is based on the daily thermal time.

5. Based on the results, the seasonal snow cover and canopy could significantly modify the soil temperature dynamics. The thermal module of 4Mx was improved to eliminate the above mentioned discrepancy.

6. Insignificant differences were found between the soil water content values simulated with the cm- and the dm resolution versions of HYDRUS-1D. The series of measured and calculated soil water content were similar, if the yearly distribution of precipitation was average. Statistically significant differences between the measured and simulated (HYDRUS-1D) water contents were observed during extreme weather conditions.

7. During the simulation of infiltration and evaporation, considerable differences were obtained owing to the different discretization (1 cm or 10 cm) of the surface layer.

8. For heterogeneous areas, it is more practical to average the model results obtained with different inputs instead of carrying out one single simulation with the averaged inputs.

PUBLICATIONS RELATED TO THE TOPIC OF DISSERTATION

Orfánus, T., Dlapa, P., Fodor, N., Rajkai, K., **Sándor, R.,** Nováková, N. (2014): How Severe and Subcritical Water Repellency Determines the Seasonal Infiltration in Grassland and Cultivated Sandy Soils. *Soil and Tillage Research*, 135, 49-59. ***(IF= 2,367)***

Sándor, R., Rajkai, K., Fodor, N. (2013): *Homoktalaj nedvesség és hőmérséklet dinamikája növénytermesztési kísérlet kezeléseiben.* II. ATK Days, Martonvásár, p. 246-251. 08.11.2013.

Sándor, R., Fodor, N. (2012)*:* Simulation of soil temperature dynamics with models using different concepts. *The Scientific World Journal,* vol. 2012, Article ID 590287, 8 pages, 2012. doi:10.1100/2012/590287 ***(IF= 1,73)***

Lichner, L., Holko, L., Zhukova, N., Schacht, K., Rajkai, K., Fodor, N., **Sándor R.** (2012): Plants and biological soil crust influence the

hydrophysical parameters and water flow in an aeolian sandy soil. *J. Hydrol. Hydromech.*, 60, 309–318. ***(IF= 0,653)***

Sándor, R., Fodor, N. (2012): *A hőmérséklet modellezésének néhány léptékfüggő problémája*. In: Környezettudományi Doktori Iskolák Konferenciája 2012. Budapest, 30.08.2012-31.08.2012, pp. 46-54. (ISBN:978-963-284-242-4)

Lichner, L., Kovácik, L., Drongová, Z., Orfánus, T., **Sándor, R.,** Fodor, N., Rajkai, K. (2012): *Plants and biological crust influence the hydrophysical parameters of a sandy soil.* 27.07.2012-22.07.2012, Leipzig, Conference of Hydropedology. Germany

Fodor, N., **Sándor, R.**, Orfánus, T., Lichner, L., Rajkai, K. (2011): Evaluation method dependency of measured saturated hydraulic conductivity. *Geoderma* 165, 60–68. ***(IF= 2,318)***

Sándor, R., Fodor, N. (2011): *Some scale-related problems of crop modeling.* XV. Geomatematikai Ankét és IV. Horvát-Magyar Geomatematikai Konferencia, Mórahalom, 28.02011. 05. 26-28.

Lichner, L., Orfánus, T., Czachor, H., Rajkai, K., Fodor, N., **Sándor, R.** (2010): *Ponded infiltration into water repellent soil in field and laboratory conditions.* 18th International Poster Day – Transport of Water, Chemicals and Energy in the Soil-Plant-Atmosphere System, Bratislava, 2010. 11. 11.

Sándor, R., Fodor, N., Rajkai, K. 2010. *Növénytermesztési modellezés néhány léptékfüggő problémája.* LII. Georgikon Days, National Scientific Conference, Keszthely, Hungary. http://sandbox.georgikon.hu/napok-old/?p=temak&page=56&q=&ev=ANY&szekcio=ANY

Sándor, R., Fodor, N., Rajkai, K. (2010): *Some scale related problems of the soil-plant-atmosphere system.* In: Lukács Gábor (szerk.) Gazdaságosság és/vagy biodiverzitás? 52. Georgikon Napok: 2010.09.30-2010.10.01, Keszthely, Magyarország. Pannon Agrártudományi Egyetem Georgikon Mezőgazdaságtudományi Kar, p. 93. (ISBN:978-963-9639-38-6, 978-963-9639-39-3)

Sándor, R., Fodor, N., Rajkai, K. (2010): *A bizonytalanság megjelenése a hidraulikus vezetőképesség mérésekben.* In: Kovács Gyula, Gelencsér Géza, Centeri Csaba (szerk.) Az Élhető Vidékért Környezetgazdálkodási Konferencia. 2010.09.22-24. Siófok, Magyarország. Törökkoppány: Koppányvölgyi Vidékfejlesztési Közhasznú Egyesület, pp. 89--. (ISBN: 978-963-08-0034-1)

PUBLICATIONS NOT DIRECTLY RELATED TO THE TOPIC

Tóth, T., Balog, K., Szabó, A., Gribovszki, Z., **Sándor, R.** (2013): *Factors affecting solute accumulation under forested plots in a sandy region.* COST Action FA0901, Workshop and Conference, Utilization and protection of halophytes and salt-affected landscapes, Abstract Book, pp. 44. Ed: Tibor Tóth, András Szabó, RISSAC CAR HAS, Budapest, 04.09.2013–06.09.2013.

Tóth, T., Balog, K., Szabó, A., Miklay, G., **Sándor, R.** (2013): *Apaj agronomy Stop (Poster)* COST Action FA0901, Workshop and Conference, Utilization and protection of halophytes and salt-affected landscapes, Budapest, 04.09.2013–06.09.2013.

Sándor, R. Füzy, A., Tóth, T. (2013): *Apaj profile Stop-1.* COST Action FA0901, Workshop and Conference, Utilization and protection of halophytes and salt-affected landscapes, Budapest, 04.09.2013–06.09.2013.

Sándor, R. Füzy, A., Tóth, T. (2013): *Apaj profile Stop-2.* COST Action FA0901, Workshop and Conference, Utilization and protection of halophytes and salt-affected landscapes, Budapest, 04.09.2013–06.09.2013.

Orfanus, T., **Sandor, R.** (2011): *Hydraulické vlastnosti lesných pôd v Tatrách a ich možný vplyv na tvorbu odtoku.* In: Šír M., Tesař, M: Hydrologie malého povodí 2011. Ústav pro hydrodynamiku AVČR, Praha Česká republika.

Sándor, R., Sümegi, P. (2009): New preliminary data for evolution of the Holocene Hungarian Mollusc fauna. *Malakológiai Tájékoztató*. 27: 9-12.

Sándor, R. (2009): Palaeoecological investigations on the core-sequence of the Vörös Marsh at Császártöltés. XIII. Geomatematikai Ankét és II. Horvát-Magyar Geomatematikai Konferencia, Mórahalom, 21.05.2009–23.05.2009.

Sándor, R. (2009.): *A császártöltési Vörös-mocsár felszínfejlődési rekonstrukciója.* Országos Tudományos Diákköri Konferencia, Szombathely, pp. 173. 07.04.2009–09.04.2009.