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Running title:

Soil Water Characteristics

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Soil Water Characteristics of European SoilTrEC Critical Zone Observatories

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Abstract

Most of soil functions depend directly or indirectly on soil water retention and transmission, which explains their importance for the processes in Soil Critical Zones. Soil hydraulic properties are essential in irrigation and drainage studies for closing water balance equation, for predicting leaching of nutrients and for other agronomical and environmental applications. Soil hydraulic properties reflect the structure of soil porous system comprising pores of different geometry and sizes. The investigation comprises a detailed analytical study of soil hydraulic properties and climate conditions at 18 methodologically selected sites in Damma Glacier, Slavkov Forest, Marchfeld and Koiliaris Critical Zone Observatories of SoilTrEC project. The local moisture regimes were assessed on long-term basis by the Newhall model. The experimental data for soil water content at different potentials were used for assessing water storage capacity, pore size distribution, parameters of fitted retention curves, slope at the inflection point, and water permeability characteristics at each soil horizon. The differences of soil retention and transmission characteristics were explained by the different stages of soil profiles development, parent materials, organic matter content, and land use.

Keywords: CZO, SoilTrEC, soil water retention curve, soil pore size distribution, soil moisture regime

Introduction

The agronomical and environmental applications of soil hydraulic properties data are usually confined in irrigation and drainage planning for closing water balance equation, predicting leaching of nutrients out of the rooting zone, assessing productive potential of soils. In broader aspect the knowledge on soil and water interaction is of primary importance for evaluating and predicting "*the soil's role in water quantity and quality, and the water's role in soil quantity and quality*" (Lin, 2012). Most of soil functions depend directly or indirectly on soil water retention and transmission, which explains their importance for the processes in Soil Critical Zones (Lin et al., 2005; Kutílek, 2004; Blum, 2006; Lin, 2012; Banwart et al., 2013). Soil hydraulic properties reflect the structure of soil porous system comprising pores of different geometry and sizes (e.g., Hillel, 1980; Dexter, 1988; Kutílek, Nielsen, 1994; etc.). Well developed soil structure hierarchy is important for crop production and for minimizing environmental pollution arising from preferential flow (Dexter, 1988; Jarvis et al., 2012). The importance of soil structure explains the interest for its quantification and modelling its impact on flow and transport process (Lin et al., 2005). Soil structure was chosen as a key property for tracing the different stages of soil evolution examined in four Critical Zone Observatories (CZOs) in Europe during SoilTrEC project (Banwart et al.,2012; Menon et al., 2014). The selected eighteen sites in these CZOs reveal different natural and anthropogenic impacts on soil structure along a life cycle of soil development, comprising newly formed soils, soils used for agriculture and forestry, and soils affected by degradation. The received complex set of soil physical and chemical data (Rousseva et al., 2010) allowed to establish the mechanistic linkages between some characteristics of soil structure, such as soil aggregation, water stability of aggregates, and soil porosity with some soil chemical properties (Regelink et al., 2015).

The comparison of hydraulic properties and hence of soil structures can be realized using classifications and parameterization. There are numerous classifications describing the significance of different categories of pores for soil water functions (Brewer, 1964; Greenland, 1981; Beven, German, 1982). Volumes of macropores, plant available water, drainage aeration pores, saturated hydraulic conductivity are assessed regarding their significance for plant development and productivity, transmission of water and solution. The volume of air-filled pores at soil water suction of 5 kPa less than 10 % and saturated hydraulic conductivity less than 10 $cm.d^{-1}$ (0.4 $cm.hr^{-1}$) are among the selected soil compaction indicators (Huber et al., 2008; Schjønning et al., 2015). Corey (1977) categorized pores on physical principles as sub microscopic, capillary and macropores (non-capillary) pores. The capillary pores are subdivided into matrix (intra-aggregate, intrapedal) within soil aggregates and structural (inter-aggregate, interpedal) between aggregates (Kutílek, Nielsen, 1994). In case of the widely used simplified model of soil porous system - parallel capillary tubes, the size distribution of pores, estimated via Jurin's formula of capillary rise, can be derived from the experimental or parameterized soil water retention curves (SWRC). Physically-based approach for modelling of soil porous system is based on the assumptions of the log-normal type of pore size distribution (Kosugi, 1994). The fitted double log-normal (Kutílek, 2004; Kutílek, Jendele, 2008) and double exponential equations (Dexter et al., 2008) allow to separate the domains of structural and matrix pores. Parameterization of soil water retention curve is used also for developing pedotransfer functions (Pachepsky, Rawls, 2004; Saxton and Rawls, 2006; Toth et al., 2014) and for soil quality assessment (Dexter, 2004). The most frequently explored expression of the soil water retention function is the equation of van Genuchten (1980). It describes the sigmoidal form of a smooth curve fitted by three to five parameters to the measured data. Dexter (2004, 2006) used fitting parameters for calculation of the slope (S) of the SWRC at its inflection point Wi. The S parameter indicates the extent to which the soil porosity is concentrated into a narrow range of pore sizes and it is used as a soil quality parameter (Dexter, 2004).

Morphological descriptions of soil structure and soil layering, as well as the variability of soil properties are also important indicators for soil hydrological processes and soil stage development in landscapes (Lin et al., 2005).

Climate is the main driving factor for soil water functions. The identification of patterns in the variable soil moisture conditions can be realized via categorization of soil moisture regimes or of other components of soil water balance (Šútor et al., 1999). The most popular classification of soil temperature and moisture regime is that proposed by the USDA Soil Taxonomy (Soil Survey Staff, 1999), adopted by FAO (2006). The main criteria in this classification are related to duration and time of occurrence of periods with different level of water storage in soil moisture control section. The calculation model of Newhall (1972) is a standard method for determining the type of soil moisture regime. It is a good tool for differentiation of the pedoclimatic setting (Bonfante et al., 2010) and for assessment of the temporal variability and trends of soil moisture regime in bordering climatic zones (Dimitrov et al., 2014).

The focus of current study is on the characterization and comparison of the soil water characteristics of the eighteen sites surveyed in four CZOs in the frame of SoilTrEC project. The complex set of data for soil physical properties are analysed to estimate the influence of climate conditions, soil parent materials, soil structure, land use and other factors on soil water properties and functions.

Material and Methods

Sites

The sampling campaign carried out in 2010 year includes eighteen sites in four CZOs localized in Europe, as follows: 4 sites in Damma Glacier Forefield CZO, Switzerland - three of them representing initial stages of soil formation (D1-3), established by retreat of the glacier during the past 150 years and a referent site D4 (Bernasconi et al., 2011); 3 small catchments in the Slavkov Forest, Czech Republic which have been heavily impacted by atmospheric deposition of acid pollutants (Krám et al., 2012; Helliwell et al., 2014), representing forest soils on varying parent rock type in region which was not glaciated; 6 sites in Fuchsenbigl-Marchfeld CZO, Austria, representing chronosequence of long-term soil development under various land use including forest, grassland and cropland on fluvially deposited sediments (Fiebig et al., 2009; Lair et al., 2009); 5 sites in the Koiliaris River Basin CZO, Crete, Greece, representing decline of soil due to longstanding intensive agriculture at elevation stages from arable land in the coastal zone to manmade terraces of different ages and parent material in the uplands (Moraetis et al., 2010; 2014). Consolidated information can be found for all sites in Rousseva et al. (2010), Banwart et al. (2012) and for majority of sites in Regelink et al. (2015). Morphology of the soil profiles was described following the WRB guidelines (FAO, 2006) and the soils were classified according to the WRB (IUSS WG WRB, 2006). General description of the main sampling sites is presented in Table 1.

Insert Table 1 near here

Climate and Hydrological Characteristics

Long-term records of temperature and precipitation data at nearby meteorological stations were used to estimate mean monthly and annual values of these parameters (Table2, Figure 1a-d). The potential evapotranspiration was calculated by Thornthweite method

(Thornthweite, 1948). According to the empirical climate classification of Köppen (Köppen, 1936; Peel et al., 2007), Damma Glacier bears the treats of polar-tundra type of climate, Lysina and Marchfeld – cold type, without dry season, and Koiliaris – temperate type with dry and hot summer (Table 2). According to genetic climatic classification (Alisov et al., 1952), the first three CZOs are situated in the belt of moderate continental type of climate at different altitudes. The annual sum of precipitation, presented in Table 2 for Slavkov Forest is representative for the Pluhův Bor and Na Zeleném catchments (S2, S3), while precipitation at the Lysina catchment (S1), situated at 140 m higher altitude, is about 1020 $mm.y^{-1}$ in average. The sites at Koiliaris watershed are also situated at different altitudes – from 10 m till 1062 m (Table 1), but all are in the conditions of subtropical, Mediterranean type of climate. The main differences between the two major climate types are: distribution of precipitation - maximum in May-June for moderate continental climate and maximum in winter for subtropical climate; colder winter and cooler summer for moderate continental climate than for subtropical climate. Differences due to the elevation are expressed in diminishing the temperature and increasing the quantities of precipitation with height, and correspondingly increasing the percentage of snow precipitation in winter. This is reflected in duration of wet and dry status of soil profiles, drainage and runoff quantities. The annual runoff in case of Damma Glacier is about 2700 $mm.yr^{-1}$ (Bernasconi et al., 2011), in Lysina and Pluhův Bor catchments 450 $mm.yr^{-1}$ and 275 $mm.yr^{-1}$, correspondingly (Krám et al., 2014; Krám, 2011; Benčoková et al., 2011), and 620 $mm.yr^{-1}$ in Koiliaris watershed (Moraetis et al., 2011; 2014).

Insert Table 2 near here

In order to estimate the influence of the climate conditions on pedoclimatic characteristics we used the approach of Soil Survey Staff (1999), adopted by FAO (2006) to characterize soil temperature regime and moisture regime in normal years (years with mean annual precipitation ± 1 standard deviation with more than 8 months with normal monthly precipitation sums). We applied the Newhall Simulation Model (Newhall, 1972) using the Java version (USDA.NRCS, 2012) of the program van of Wambeke written in BASIC (van Wambeke et al., 1986; van Wambeke, 2000) for each year from the periods pointed in Figure 1. Taking into account the limitations of the Newhall model, the obtained information on distribution of wet and dry periods in soil moisture section is used only for determining type of climate and its variability through the years and between studied CZOs.

Insert Figure 1 near here

Figure 1. Long-term average values of monthly air temperature (T°C), sums of precipitation (Prec, mm) and potential evapotranspiration (PET, mm) at Damma Glacier (**a**), Slavkov Forest (**b**), Marchfeld (**c**), Koiliaris (**d**) CZOs. Dominant type of soil temperature and moisture regimes. H – altitude of meteorological station (see Table 2).

The dominant temperature and moisture types of pedoclimate in normal years are presented for each CZO in Figure 1. The dominant temperature regimes are Cryic in Damma Glacier (100% of the years), Mesic - in Slavkov Forest (71%) and Marchfeld (100%), and Thermic (54% of the years at sea level to 100% above 380 m altitude) in Koiliaris CZO. Part (29%) of the years in the Slavkov Forest is colder – with Cryic temperature regime. Hyperthermic is the soil moisture regime in 44% of the years at sea level at Koiliris CZO.

The type of soil moisture regimes did not change at Slavkov Forest and at higher altitudes (>380 m) at Koiliaris CZOs – Udic and Xeric, respectively, in 100% of the normal years.. The dominant soil moisture regime at Damma Clacier CZO is Udic (57%), the rest (43% of normal years) are with Perudic soil moisture regime. Variable is soil moisture regime near the sea level at Koiliaris CZO – 56% of normal years are Xeric, and 44% are Ustic, regardless of the available soil water holding capacity (runs of the program with AWC=200, 100 and 50 mm). In non-normal drier years there is a tendency for increasing the cases of Aridic soil moisture regime at AWC=50 mm.

The soil moisture regime in Marchfeld CZO is more variable and depends on available soil water holding capacity (AWC). In case of AWC=200 mm (default value of the program), 53 % of the normal years are with Ustic, 29% - are Xeric and 18% - are Udic moisture regimes. Soils with lower AWC at Marchfeld CZO have different distribution of soil moisture regimes. The percents of normal years with Ustic, Xeric and Udic soil moisture regimes are 69 %, 14%, and 17% in case of AWC=100 mm, and 92%, 0%, and 8% in case of AWC=50 mm.

Soil sampling and soil physical laboratory analyses

Three soil pits were revealed at each site. One of them, named "main profile" is sampled at each soil genetic horizon. The samples from the other two profiles were sampled at selected horizons (usually 3) and the data were used for statistical analyses – e.g. spatial variability of soil aggregation parameters (Kercheva et al., 2011) or regression analyses (Regelink et al., 2014). The soil profiles were sampled from the top layer 0-5 cm following the soil genetic horizons downward. Average "disturbed" sample from each sampling depth was formed by gently breaking and mixing the excavated fresh soil by hands into aggregates finer than 15 mm. Vertically oriented cores were sampled in triplicate in 100 cm^3 metal cylinders for bulk density (ISO 11272:1998) and water retention determination. In some cases where the thickness of the layer was less than 5 cm, rings with 2 cm height and 50 cm^3 volume were used in 4 replicates. Particle density analysis was carried out with 100 cm^3 pycnometers according to ISO 11508:1998. Total porosity was calculated using the measured bulk density and particle density.

Particle-size distribution was determined after chemical dispersion of 10 g air dry soil sample (<2 mm) with 25 cm^3 of 0.4N sodium pyrophosphate ($Na_4P_2O_7$) without removal the organic matter and carbonates from the soil sample. Four sand fractions (2-1, 1-0.5, 0.5-0.25, 0.25-0.10) were determined by sieving, and the fifth sand fraction 0.10-0.05 mm was calculated. The particle fractions < 0.05, <0.02, <0.01, <0.002 mm were determined by pipette method.

Soil water retention at suction less than 30 kPa was determined using the undisturbed soil cores (100 cm^3 and 50 cm^3) by a suction plate method similar to those proposed in ISO 11274: 1998. The wetting of soil samples at 0.25 kPa on a sand bath was chosen instead of the full water saturation in order to avoid the possibility of destroying the soil structure by slaking which could occur often in sandy soils. Duration of wetting was more than 20 days. The drainage of the wetted samples at 1, 5, 10 and 30 kPa (pF 1.0, 1.7, 2.0, and 2.5) was done by suction type apparatus (Shot filters G5 with diameters of pores 1.0-1.6 μm). Equilibrium for each potential was established for 5-7 days. Soil water retention at suction 1500 kPa (pF 4.2) was determined using fine (<2 mm) earth samples by pressure membrane apparatus (Richards, 1941). In this case a correction for skeleton was applied by multiplying the measured water content by fraction of fine earth in the undisturbed soil sample, expressed on weight basis. Four points (pF 5.6, 6.13, 6.27, 6.38) at water adsorption part of the curves were determined using vapour pressure method with controlled relative humidity (75%, 35%, 25% and 16%) in exicators containing, correspondingly, saturated solution of NaCl, 50%, 55% and 60% concentrations of H_2SO_4. Correction for skeleton was also applied in these cases. The total number of soil water retention curves was 524. The variation of data was estimated by the coefficient of variations of core measurements (Cv) in each profile and by the coefficient of variation between the average values in three replicate profiles (Cv_h) at each site.

Soil Water Characteristics

The water retention experimental data were used to build and parameterize water retention curves and to determine pore size distribution. Volume of air-filled pores at given suction *h* is calculated as the difference between total soil porosity P_t and the measured volume of water content (θ) retained at this suction. The effective pore diameter δ corresponding to *h* is calculated by Jurin's formula:

$$\delta = 4*\sigma/h \quad (1)$$

where $\sigma = 7.29*10^{-2}$ $N.m^{-1}$ is the surface tension, *h* is in Pa. The effective diameters of pores corresponding to 5, 10, 30, and 1500 kPa, are 60 μm, 30 μm, 10 μm, 0.2 μm

The water retention experimental data at different suctions were approximated with van Genuchten equation (2) (Van Genuchten, 1980):

$$W=(W_{sat}-W_{res})*(1+(\alpha*h)^n]^{-m}+W_{res} \quad (2)$$

where W is gravimetric water content ($kg.kg^{-1}$), h – suction (hPa), W_{sat} – water content at saturation, W_{res} – residual water content ($h \rightarrow \infty$), α (hPa^{-1}), *n*, *m* – parameters. Stable results for the parameters were obtained when constraint was applied for $m=1-1/n$ (Mualem, 1976) and when the parameter W_{res} is fixed to zero in cases with negative estimation;

The parameters *Wsat, Wres*, α, and *n* of equation 2 were fitted with OriginPro 6.1 software.

The obtained parameters of Van Genuchten equation were used (Dexter 2004, 2006) to calculate slope S of the gravimetric water content against natural logarithm of the pore water suction at the inflection point W_i:

$$S = -n \cdot (W_{sat} - W_{res}) \cdot \left[1 + \frac{1}{m}\right]^{-(1+m)} \quad (3)$$

$$W_i = (W_{sat} - W_{res}) \cdot \left[1 + \frac{1}{m}\right]^{-m} + W_{res} \quad (4)$$

Dexter (2004, 2006) defined and used S as a soil physical quality parameter, as it indicates the extent to which part of the soil porosity is concentrated into a narrow range of pore sizes. According to the values of S, the soil has very good quality at $S \geq 0.050$, good - $0.050 > S \geq 0.035$, poor $0.035 > S \geq 0.020$, and very poor $0.020 > S$ (Dexter, 2004).

Soil water retention curve allows to estimate saturated hydraulic conductivity by simplified models. In this study we apply the equation of Han Han (2005), recommended by Dexter (2006):

$$K_{sat}=0.00381.\Phi^{(3-\lambda)}, m.s^{-1} \quad (5)$$

where $\Phi=\rho_b(W_{sat}-W_i)$, $\lambda=S/(\rho_b.W_i)$, ρ_b - bulk density in $g.cm^{-3}$.

The saturated hydraulic conductivity - K_{sat} is classified (Soil Survey Division Staff, 1993) as: very low $K_{sat}<0.0036$ $cm.h^{-1}$, low $0.0036<K_{sat}<0.036$ $cm.h^{-1}$, moderately low $0.036<K_{sat}<0.36$ $cm.h^{-1}$, moderately high $0.36< K_{sat}<3.6$ $cm.h^{-1}$, high $3.6< K_{sat} <36$ $cm.h^{-1}$, very high $K_{sat} >36$ $cm.h^{-1}$.

Plant available soil water holding storage in 1 m depth is classified after Dumitru et al. (2009): very low < 50 $mm.m^{-1}$, low 51-100 $mm.m^{-1}$, moderate 101-160 $mm.m^{-1}$, high 161-220 $mm.m^{-1}$, very high 221-300 $mm.m^{-1}$, extremely high >301 $mm.m^{-1}$.

Results

Examples of the soil water retention curves from the studied CZOs are presented in Figure 2. They reflect some specific features of the soil profiles: initial soil formation with very small water retention capacity (2a); profile with differentiated structure – favourable proportion of water characteristics in top layer are followed by layers with small amount of air filled pores with drainage functions (2b); highly productive soil (2c) where capacity of soil to retain and transmit water is balanced along the well developed soil profile; profile with thin top layer followed by subsoil with low retention capacity (2d).

Insert Figure 2 near here

Figure 2. Examples of soil water retention curves from the Damma Glacier (**a**), Slavkov Forest (**b**), Marchfeld (**c**), Koiliaris (**d**) CZOs.

The distribution of water content hold at different suctions, expressed by volume, allows assessing the pores size (effective pore diameters) distribution in each horizon of the eighteen main soil profiles (Figure A1÷A4). The other structural elements pointed out in these figures are the percent of gravel and fine earth on volume basis and pedality. The data of soil properties and parameters of pF curves, expressed by weight, at selected sampling depths are presented in Table 3. This way of presentation is preferable for comparing soil horizons with different bulk density,

Tables 3 near here (landscape)

The most newly formed soil profile – Leptosol (D1) in Damma Glacier CZO has very low capacity to retain water at suction greater than pF 2.5 due to course soil texture with extremely low (1%) clay content (Figure A1, Table 3a). The other two newly formed Leptosols (D2 and D3) have very thin (3 and 4 cm depth) humic horizons with high content of organic carbon (26 $g.kg^{-1}$ and 109 $g.kg^{-1}$) which enlarge porosity of soil on the account of the pores retaining water available for plants (10-0.2 μm) and pores with drainage functions (>10 μm). The reference profile D4 – Cambisol has thicker top (18 cm) and buried humic horizons with high content organic carbon (95 and 126 $g.kg^{-1}$, respectively) and high content of all categories of pores. The values of S index are high in humus rich horizons, which is due to the capacity of organic material to retain water in all categories of pores.

Three different parent rock materials at Slavkov Forest CZO (Table 1) form different type of soils with specific chemical and physical properties (Table 3b) and also with different soil porous systems. The profile of Podzol on acid igneous granite at site S1 has sandy loam texture in all horizons except in B_{th} horizon, where it is loam. The total porosity is low P_t=44-54%v except in Bth horizon, where it is P_t=60%v due to high org.C=44$g.kg^{-1}$ (Figure A2). More than half of the porosity in A horizons is occupied by macro pores (>60 µm), while the volume of pores with effective diameters between 10 and 60 µm is small (4-6%). The content of finer pores increases in the illuvial Bt horizons. The textural differentiation in Stagnosol, which is formed on ultrabasic metamorphic serpentinite at site S2 is much better pronounced than in the case of Podzol. Total porosity diminished from 68%v in top Ah horizon to 20%v in Btg horizon on the account of large pores. These horizons are characterized with high values of bulk density - 1.8 $g.cm^{-3}$ and particle density 2.9 $g.cm^{-3}$. The volume of pores filled with air (AP) at suction pF 1.7 is critically low at BE horizon (7%v) and especially in Btg horizon (3%). The olive grey (Munsell colour moist 5Y4/2) confirms the waterlogging occurrence at this site. The Cambisol (S3) formed on basic metamorphic amphibolite has the largest total soil porosity (80-56%v), with high drainage aeration pores – 33-23%v (Figure A2).

The different age for formation of studied Fluvisols (M1÷3 sites) and Chernozems (M4÷6 sites) at Marchfeld CZO as well as the agricultural land use (M4 and M5) impact the soil structure at this typical high productive region (Table 3c, Figure A3). The surface horizons of Fluvisols have about 15-20% greater total porosity than the humus (A) horizons of Chernozems. The plant available water is more than 1/3 of total porosity in all sites. Finer texture of Chernozem at Fuchsenbigl experimental station (M5) lead to increase of water retained at suction greater than pF 4.18 (unavailable water for plants) and diminishing the drainage porosity at upper horizons. The high porosity of parent material of Chernozems (C horizons) diminishes the risk of prolonged surface waterlogging.

The studied Fluvisols at Koiliaris CZO (K1 and K2 sites) are with different soil water characteristics (Figure A4, Table 3d). This can be explained with the different periods for formation of the soil profiles and respectively different soil textures – silt loam and sandy loam (Moraetis et al., 2014). The Fluvisol (K1 site) with more advanced development is formed by sedimentation of finer particles in more arid conditions, while the Fluvisol at K2 site is relatively younger and formed under more intense hydrodynamic conditions (Moraetis at al., 2014). The total porosity of Fluvisol at site K1 is less than 50%v, most of which (>50% of P_t) are pores retaining water available for plants (more than 50% of total porosity), on the account of relatively low content (<10%) of pores with drainage functions. The other Fluvisol is with high capacity to transmit water – more than 60% of pores are with drainage functions and very low capacity to retain water – plant available water is less than 15%v. The soils at sites K3 and K4 are shallow Leptosol and Cambisol with organic matter content 16 and 56 $g.kg^{-1}$, respectively. The maximum content of water by weight, which can fill all pores is 0.37 and 0.52 $cm^3.g^{-1}$, correspondigly (Table 3d). This is due to the higher content of large (>10 μm) and small (<0.2 μm) pores of Cambisol (K4) due to the finer soil texture (SiCL) and higher organic content. The Cambisol at (K5 site) located at the upland with the highest altitude is similar to K4 regarding soil texture, organic content and total porosity. The water retention properties at pF 2.5 and pF 4.18 are higher at site K5 than at K4 and are distributed throughout the soil.

An integrated parameter used for comparison of soil water retention curves is the S index (slope of the curves at the inflection point W_i) (Dexter, 2004, 2006). The obtained parameters of van Genuhten equation (eq. 2) for each curve are not presented in this paper as they are used only for calculation of S (eq. 3) and W_i (eq. 4). As it is shown in the figures (2a-d), the data are well fitted by the Van Genuchten equation (2). The S values are presented in Table 3, Figure 3 and Figure 4. It is established good agreement between the average of the S values of the individual curves for each soil sample, and the S values obtained on averaged water retention data per horizon (as presented in Table 3) . The estimation of S on each individual curve allows assessing the variation of this parameter due to micro (within horizon) variability (Figure 3). The standard deviation is very high in surface horizons of profiles (D2, D3, D4) in Damma Glacier CZO and in Ah horizons of S2 and S3 profiles in Slavkov Forest CZO and much more stable in the deeper horizons. The micro variation of the soil quality index S in each horizon of the soil profiles is in average Cv=32%, 15%, 7%, and 6% for Damma Glacier, Slavkov Forest, Marchfeld and Koiliaris CZOs, and it is similar to the variability between the three replicate profiles at each site, which is Cv_h=29%, 19%, 13%, and 7% , correspondingly for these four CZOs.

Insert Figure 3 near here

Figure 3. Soil quality index S (slope at the inflection point of soil water retention curves) along the soil profiles at Damma Glacier (**a**), Slavkov Forest (**b**), Marchfeld (**c**), Koiliaris (**d**) CZOs.

The variability of S parameters is related to variability of water retention data, total porosity, bulk density, soil texture fractions, and organic matter content. The soil bulk density measurements varied in average between Cv=3% for Marchfeld and Koiliaris sites to Cv=6% and 9% for Slavkov Forest and Damma Glacier sites. The variation between the three replicate profiles of each site is Cv_h=19%, 10%, 7%, 4% in average for Damma Glacier, Slavkov Forest, Marchfeld, and Koiliaris CZOs. Changes in soil structure, presence of gravel and organic substance lead to even more variation in measurements of the water content retained at pF 2.5 (field capacity) – Cv =28%, 11%, 5%, 3% and between the three replicate profiles for the site Cv_h= 36%, 17%, 17%, 7%, in average, correspondingly for Damma Glacier, Slavkov Forest, Marchfeld, and Koiliaris CZO. The standard deviation of laboratory analyses of water content at pF 4.18 (Wilting Point) of fine earth was 0.2% (Cv=1.5%) in average, but the horizontal variation between the three profiles is estimated to be Cv_h=41%, 29%, 15%, 15%, which is close to the variation of clay content Cv_h=40%, 21%, 17%, 18% correspondingly for Damma Glacier, Slavkov Forest, Marchfeld, and Koiliaris CZO. The coefficient of variation of plant available water content (by weight) is Cv =41%, 18%, 9, 4% in average and Cv_h= 44%, 26%, 19%, 10% in average between the three profiles of particular site, correspondingly for Damma Glacier, Slavkov Forest, Marchfeld, and Koiliaris CZO. This ordering of variability can be explained with the topographical features and parent materials (Wilding et al., 1994). The reduced variability can be explained also with the domination of one of soil forming factor for long-term period (Burrough, 1993). Such domination factors can be the traditional agricultural use, low humification of plant residues and high mineralization rates of organic matter at Koiliaris CZO.

The values of S parameter increase with water content at the inflection point (W_i) as it is shown in the case of Marchfeld and Koiliaris CZO (Figure 4), but the relationship is different for C horizons. The high values of S for these coarse texture horizons are due to the narrower distribution of pore sizes and usually is not reflected in improving of other soil physically properties (Dexter et al., 2008). The comparison between water content at the inflection point and at field capacity (pF 2.52) shows that in well structured horizons these characteristic points are closely positioned.

Insert Figure 4 near here

Figure 4. Slope (S) and water content (Wi) at inflection points of soil retention curves of A horizons at each site at Marchfeld (**a**) and Koiliaris (**b**) CZOs. Data for C horizons are presented for all sites with one symbol (-).

The values of S parameters are related to transmission properties of the soil connected with the presence of structural pores. This is confirmed by the estimated (eq. 5) saturated hydraulic conductivity (Figure 5a-d), which prognosis high K_{sat} of surface horizons of younger soils, e.g. Leptosols, Cambisols, Fluvisols, where S values are also high (S>0.06). In case of Leptosols the deep water percolation is restricted by the rock parent material. The older Fluvisol at site M3 at Marchfeld CZO becomes more compacted (moderately high K_{sat}) at depth below 30-40 cm, while the Chernozems (M4-6) have moderately high K_{sat} in the surface horizons and high K_{sat} in C horizons. The K_{sat} decreases in the upper 25 cm (till BE horizon) at Podzol (S1) at Slavkov Forest CZO but remains moderately high. Below BE horizon K_{sat} increases. The horizons below the high conductive surface (Ah) horizon at Stagnosol (S2) form a thicker compacted (K_{sat}<1.5 cm.h^{-1}) layer. The upper (AO) horizons with thickness 12 cm and 7 cm at sites S1,S2 Slavkov Forest contribute to accumulation of water and restrict drying the soil profile by evaporation. The prognosed high K_{sat} (9-13 cm.h^{-1}) and moderately high K_{sat} (1-4 cm.h^{-1}) of Fluvisols at K2 and K1 sites stemmed from the consideration regarding soil profile formation and presence of pores with larger diameters at site K2.

Insert Figure 5 near here

Figure 5. Coefficient of saturated hydraulic conductivity (K_{sat}, cm.h^{-1}) estimated by eq. 5 at Damma Glacier (**a**), Slavkov Forest (**b**), Marchfeld (**c**), Koiliaris (**d**) CZOs.

The average plant available water capacity (% by volume) throughout the soil profile is very high (24%v) for the Fluvisol at site M1, high (19%) – for the Fluvisols at M2 and M3 sites, and moderate (10÷13%) – for Chernozems (M4÷M6 sites) at Marchfeld CZO. Profiles with high plant available water capacity (PAWC) at Koiliaris CZO are Fluvisols at site K1 (20%v) and Leptosols at site K3 (18%v), with moderate PAWC are Cambisols at sites K4 (11%v) and K5 (15%), and with law PAWC is the Fluvisol at site K2 (9%v). The Podzol (S1 site), Stagnosol (S2 site) and Cambisol (S3 site) at Slavkov Forest CZO are with moderate (15.9%v), high (17%v) and low (10.4%v) PAWC in average for the soil profiles. The young Leptosols at Damma Glacier CZO are with low PAWC at sites D1 (9.5%v) and D3 (8.5%), and with moderate (14%v) PAWC at site D2. Moderate is the PAWC of Cambisol at site D4 sites.

The profile distributions of water, stored at field capacity and at wilting point, are shown in Figure 6a-d for each site at the studied four CZOs. These characteristics are important for closing the soil water balance. The differences between the soils are better understood when comparing the maximum quantities of available water which can be stored at rooting depth (Table 4). As it is shown in Table 4 the possibility of soil profile to retain water is very different due to the thickness of soil profiles and due to structural characteristics described above. The profiles with maximum plant available water stored at rooting depth in studied CZOs are Cambisols at site D4 of Damma Glacier CZO – 40 mm, Stagnosol at site S2 of Slavkov Forest – 114 mm, Fluvisols at site M2 and M3 of Marchfeld CZO – 136 mm and 130 mm, Fluvisol at site K1 of Koiliaris CZO – 92 mm and Cambisols at site K5 – 126 mm. Shallow soils (D1÷D3, K2÷K4) retain less than 25 mm available water for plants.

Insert Table 4 near here

Insert Figure 6 near here

Figure 6. Water storage in main soil profiles at Wilting Point (pF 4.2) and at Field Capacity (pF 2.5) at Damma Glacier (**a**), Slavkov Forest (**b**), Marchfeld (**c**), Koiliaris (**d**) CZOs.

Discussion

The soil hydraulic functions at studied 18 sites from 4 CZOs were compared on the basis of soil hydraulic properties and climate conditions. According to the genetic climatic classification (Alisov et al., 1952) Damma Glacier, Slavkov Forest and Marchfeld CZOs are located in the belt of moderate continental type of climate at different altitudes. The hydrothermal conditions at these CZOs create three combinations of the dominant soil temperature and moisture regimes: Cryic - Udic, Mesic - Udic, and Mesic – Ustic, respectively. The water balance in Damma Glacier and Slavkov Forest CZO is positive throughout the year, while in Marchfeld CZO it is negative in summer time. The steep slope of the terrain and the positive water balance provoke high runoffs in snow free time of the year in Damma Glacier CZO and Slavkov Forest CZO. The subsurface water discharge can be resticted to some extent by the biological crust in Damma Glacier CZO and litter layers (between 7 and 15 cm) in Slavkov Forest CZO, which are hydrophobic when are dry. Marchfeld CZO is characterized with more variable soil moisture regime throught the normal years. This variability of climate conditions increases the risk for droughts especially for soils with lower available water holding capacity. The sites at Koiliaris watershed are also situated at different altitudes but all are in the conditions of subtropical, Mediterranean, type of climate. The dominant soil temperature regime is Thermic and the dominant soil moisture regime is Xeric. More variable is the pedoclimate at sea level sites. The Xeric soil moisture regime in Koiliatis CZO creates conditions for runoff and drainage in winter time at sites with shallow soil profiles. As the selected sites are natural and manmade terraces where the soil water erosion is restricted, the hydraulic properties of the soil profiles reflect the influence of parent material, vegetation/land use and other pedogenetic factors (Moraetis at al., 2015).

The characteristics of soil hydraulic properties related to different age of soil development (Damma Glacier and Marchfeld CZOs), vegetation cover/land use (Marchfeld and Koiliaris CZOs) and parent materials (Slavkov Forest and Koilaris CZOs) were presented and discussed for each CZO in the Results section of this paper. The texture classes of studied soil horizons differ significantly – loamy sand, sandy loam, sandy clay loam, loam, silt loam, silt clay loam. Some of them contain gravel. The organic matter content as the other factor which influences the hydraulic properties is well represented from very low to very high values. The surveyed soil profiles in each CZO were referred to more than one soil groups according to WRB. Occurence of Leptosols, Cambisols and Fluvisols studied at least in two CZOs from different climatic regions allows to discuss the similarities and differences of soil hydraulic properties in each of these groups.

Leptosols: Damma Glacier CZO (D1, D2, D3) and Koiliaris CZO (K3)

The studied Leptosols represent different stages of soil formation. The initial soil formation in Damma Glacier CZO is localized in a small area between the exposed rocks and cliffs as a fine layer (profiles D1, D2, and D3). This stage of soil evolution is manifested with almost lack of clay fraction in the soil texture, domination of sand, and high rates of skeletal performance. This explains the very low soil water sorption and retention capacity which in the case of the youngest profile manifested via CR horizon. The soil evolution along the chronosequence (from 7-13 years till about 110-130 years) extending from the face of the glacier is expressed in increasing the depth of the soil profiles, formation of thin surface (AC) horizon in the topsoil, capable to retain more water, slightly increasing of the fine texture fractions. All studied properties have high spatial variation. The studied Leptosol (profile K3) in Koiliaris CZO was developed during longer period (about 550 years) under different environmental conditions with human interference, as it is on manmade cultivated terrace. The spatial variability of soil physical properties of K3 site in Koiliaris CZO is lower than that of Leptosols in Damma Glacier. This variability reduction is explained with the domination for long-term period of degradation processes related to intensive agriculture use and high mineralization rates at K3 site. The profiles differ regarding the amount and size distribution of pores. The soil pore space is very high (0.8 to 2.9 $cm^3.g^{-1}$) in the thin surface layers of D2 and D3, and drop to about 0.30 $cm^3.g^{-1}$ in C horizons. In the top AC horizon of K3 the total porosity is about 0.40 $cm^3.g^{-1}$. The proportions of pores with drainage functions (δ>10μm), pores holding plant available water (0.2 μm <δ<10μm), pores holding unavailable for plant water (δ<0.2 μm) to total porosity of top AC horizons are 7:2:1 in Damma Glacier and 4:4:2 in Koiliaris. This reflects in very high values of S (>0.05) for coarse texture horizons of Damma Glacier due to the narrower distribution of pore sizes, while S in top horizons is 0.05 in K3. This is reflected in higher capacity of K3 to store water in the rooting depth – 25 mm, while the Leptosols at Damma Glacier store less than 17 mm plant available water.

Cambisols: Damma Glacier CZO (D4), Slavkov Forest CZO (S3), Koiliaris CZO (K4, K5)

The comparison of Cambisols studied in three of the CZOs showed that the texture is coarser in D4 site at Damma Glacier, and finer in K4 and K5 sites at Koilaris CZO. The organic matter content of surface Ah horizons content is highest in S3 (Slavkov Forest CZO), followed by D4 (Damma Glacier CZO), and lowest in K4 and K5 (Koiliaris CZO). Total porosity is more than 0.50 $cm^3.g^{-1}$. The proportions of pores with drainage functions (δ>10μm), pores holding plant available water(0.2 μm <δ<10μm), pores holding unavailable to plant water (δ<0.2 μm) to total porosity are almost the same in all studied Cambisols - 6:2:2, with the exception of K5, where they are 4:3:3. The top horizons of these soils is also characterized with very high values of S due to their transmission properties. The difference in rooting depth is of primary importance for water retention capacity of studied profiles. The plant available water holding capacity of the Cambisol (S3) at Slavkov Forest CZO is 83 mm, more than twice higher than the reference profile D4 at Damma Glacier. The profile with highest thickness and plant water holding capacity (126 mm) is profile K5 – manmade terrace at non-cultivated condition, which is a good example for the constructive human impact.

Fluvisols: Marchfeld CZO (M1, M2, M3), Koiliaris CZO (K1, K2)

The Fluvisols at Marchfeld CZO are with most favorable soil hydraulic characteristics as result of environmental conditions where the balance of humification and aerobic status for biological activity are at high rates. Total porosity of top horizons is about 0.7 $cm^3.g^{-1}$ and decreases with depth to about 0.40 $cm^3.g^{-1}$. The proportions of pores with drainage functions (δ>10μm), pores holding plant available water(0.2 μm <δ<10μm), pores holding unavailable to plant water (δ<0.2 μm) to total porosity show well balanced hydraulic functions of structured soils - 4:5:1 (M1), 4:4:2 (M2), 5:3:2 (M3). The total porosities of Fluvisols at Koliaris CZO are about 0.3 to 0.4 $cm^3.g^{-1}$. The size distribution of soil pores is different for profiles K1 and K2. Fluvisol at K1 has greater retention capacity (the respective proportions are 1:6:3 and S≈0.05 in top horizon, and 3:5:2, S=0.04 in depth), while the coarser texture of profile K2 determines better water transmission properties (proportions 6:3:1 and S>0.05). The climate and vegetation/land use interactions can be explored on profiles M3 and K1 which have the same texture class – SiL, but the content of organic matter at K1 is more than two times lower than at M3. This lead to significantly lower quantity of macro pores. The reason of low organic matter content can be the high mineralization rates during the summer and low humification of plant residues as well under intensive agricultural use of the lowlands since centuries at Koiliaris. From the other hand the trees at site M3 create root biopores which aslo contribute to formation of larger pores.

The integrated S parameter is suitable for comparison of land use impact on soil quality of top horizons with similar texture, as are the Chernozems in this study. The soil quality of A horizons under forest is quantified as very good, while the soil quality under agricultural land is of lower class – good.

Conclusion

The paper presented the soil water characteristics of the eighteen sites in Damma Glacier, Slavkov Forest, Marchfeld and Koiliaris Critical Zone Observatories surveyed in the frame of SoilTrEC project. Data and parameters of the soil water retention curves were used for assessing and comparing the storage capacity, pore size distribution and water permeability characteristics of soil profiles formed at different environmental conditions and evolution stages. The soil water retention data are well fitted by the van Genuhten's equation. The integrated index S – slope at the inflection point is used for comparison the soil physical quality of top horizons and assessment of the spatial variation. Soil water functions at different sites were analyzed regarding soil hydraulic properties and climate characteristics. Soil moisture regime was assessed on long-term basis by the Newhall model. The obtained information can be used for testing soil water simulation models, for impact assessment of natural and anthropogenic factors, and for comparison with analogous environmental setting in other locations.

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Appendix

Insert Figure A1 here

Figure A1. Distribution (%) of water hold at different suctions and pedality of main profiles' horizons. Damma Glacier Forefield CZO, Switzerland. Pedoclimate Cryic, Udic. **a) D1**, Damma Glacier CZO. H=2059 m. Nudlithic Leptosol; **b) D2**, Damma Glacier CZO. H=2015 m. Lithic Leptosol (Dystric); **c) D3**, Damma Glacier CZO. H=1964 m. Haplic Leptosol (Dystric); **d) D4**, Damma Glacier CZO. H=2019 m. Haplic Cambisol (Ruptic, Dystric, Skeletic).

Insert Figure A2 here

Figure A2. Distribution (%) of water hold at different suctions and pedality of main profiles' horizons. Slavkov Forest CZO, Czech Republic. Pedoclimate Mesic, Udic. **a) S1**, Slavkov Forest CZO. Lysina catchment. H=891 m. Albic Podzol formed on granite; **b) S2**, Slavkov Forest CZO. Pluhův Bor catchement. H=772 m. Luvic Endogleyic Stagnosol formed on serpentinite; **c) S3**, Slavkov Forest CZO. Na Zeleném catchment. H=759 m. Leptic Cambisol formed on amphibolite.

Insert Figure A3 here

Figure A3. Distribution (%) of water held at different suctions and pedality of main profiles' horizons. Fuchsenbigl-Marchfeld CZO, Austria. Pedoclimate Mesic, Ustic. **a) M1**, Marchfeld CZO. H=157 m. Epigleyic Fluvisol under rare willow trees; **b) M2**, Marchfeld CZO. H=156 m. Haplic Endogleyic Fluvisol under mixed deciduous forest; **c) M3**, Marchfeld CZO. H=157 m. Mollic Endogleyic Fluvisol under mixed deciduous forest; **d) M4**, Marchfeld CZO. H=155 m. Haplic Chernozem under old cropland; **e) M5**, Marchfeld CZO. H=148 m. Epicalcic

Chernozem under cropland Fuchsenbigl, former arable, grassland from 5 years; **f) M6**, Marchfeld CZO. H=165 m. Epicalcic Chernozem under rare oak forest.

Insert Figure A4 here

Figure A4. Distribution (%) of water hold at different suctions and pedality of main profiles' horizons. Koiliaris CZO, Crete, Greece. Pedoclimate Thermic, Xeric. **a) K1**, Koiliaris CZO. H=10 m. Epicalcic Endogleyic Fluvisol under intensively cultivated irrigated area with vegetable crops. Parent material – sedimentary rock; **b) K2**, Koiliaris CZO. H=9 m.Epicalcic Fluvisol under intensively cultivated irrigated area with olive trees last 20 years. Parent material – sedimentary rock; **c) K3**, Koiliaris CZO. H=555 m.Haplic Leptosol. Manmade terrace with olive trees last ~20 years. Parent material – acid metamorphic rock (schist); **d) K4**, Koiliaris CZO. H=465 m.Endoleptic Cambisol. Manmade terrace with non-tilled olive trees (~50 years old). Parent material – platy limestone; **e) K5**, Koiliaris CZO. H=1062 m.Bathyleptic Cambisol. Abandoned terrace with permanent grassland and sparse tree/shrub cover. Parent material – cherty limestone.

Table 1. Location and description of sites. D - Damma Glacier Forefield CZO; S - Slavkov Forest (1 - Lysina, 2 - Pluhuv Bor, 3 - Na Zelenem) CZO, M - Fuchsenbigl-Marchfeld CZO; K - Koiliaris River Basin CZO.

Site ID	Location Lat/Lg	Alt., m	Age, years	Parent rock material	Soil Group (WRB)	Land use Vegetation
D1	46°38.2' N /08°27.6'E	2059	7-13	Aare Granite	Nudlithic Leptosol	scattered pioneer plants
D2	46°38.3' N /08°27.8'E	2015	60-80	Aare Granite	Lithic Leptosol (Dystric)	pioneer plants
D3	46°38.4' N /08°28.0'E	1964	110-130	Aare Granite	Haplic Leptosol (Dystric)	pioneer plants
D4	46°38.5' N /08°28.5'E	2019	10000	Aare Granite	Haplic Cambisol (Ruptic, Dystric, Skeletic)	grass and shrubs
S1	50°02.2'N/12°39.6'E (Lysina)	891	n.d.	IA: Acid igneous Granite	Folic Albic Podzol (Skeletic)	Norway spruce (Picea abies)
S2	50°03.8'N/12°46.9'E (Pluhův Bor)	772	n.d.	UM1: Ultrabasic metamorphic: Serpentinite	Luvic Endogleyic Stagnosol (Albic, Eutric, Clayic)	Norway spruce (Picea abies)
S3	49°59.8'N/12°42.5'E (Na Zeleném)	759	n.d.	MB5: Basic metamorphic: Amphibolite	Leptic Cambisol (Dystric, Skeletic)	Norway spruce (Picea abies)
M1	48°07.7'N/16°43.6'E	157	<50	Alluvial sediments	Epigleyic Fluvisol (Calcaric, Siltic)	rare willow trees (Ortha-Island)
M2	48°08.0'N/16°39.7'E)	156	50-400	Alluvial sediments	Haplic Endogleyic Fluvisol (Calcaric, Siltic)	mixed deciduous forest
M3	48°08.7'N/16°41.6'E	157	400-800	Alluvial sediments	Mollic Endogleyic Fluvisol (Calcaric, Siltic)	mixed deciduous forest
M4	48°09.5'N/16°41.1'E	155	>2500	Alluvial sediments	Haplic Chernozem (Calcaric, Humic, Siltic)	old cropland
M5	48°11.7'N/16°44.7'E	148	>2500	Alluvial sediments	Epicalcic Chernozem (Siltic)	cropland Fuchsenbigl, former arable, grassland from 5 years
M6	48°17.0'N/16°39.8'E	165	>15000	Alluvial sediments	Epicalcic Chernozem (Arenic)	Forest Markgrafneusiedl, rare oak forest
K1	35°26.9'N/24°08.3'E	10	2400	UF2:sedimentary rock (unconsolidated)	Epicalcic Endogleyic Fluvisol (Siltic)	Intensively cultivated area with vegetable crops and under irrigation
K2	35°26.7'N/24°08.2'E	9	1400	UF1: sedimentary rock (unconsolidated)	Epicalcic Fluvisol (Arenic)	Intensively cultivated area with olive trees last 20 years under irrigation
K3	35°23.4'N/24°05.6'E	555	n.d.	MA4: acid metamorphic rock schist	Haplic Leptosol (Eutric, Skeletic)	Manmade terrace with olive trees last ~20 years
K4	35°25.2'N/24°06.1'E	465	n.d.	SO1: Sedimentary rock,consolidated, carbonatic,organic – platy limestone	Endoleptic Cambisol (Colluvic, Eutric, Escalic)	Manmade terrace with non-tilled olive trees (~50 years old)
K5	35°21.7'N/24°04.3'E	1062	580	SO1: Sedimentary rock,consolidated, carbonatic,organic – cherty limestone	Bathyleptic Cambisol (Colluvic, Eutric, Escalic)	Abandoned terrace with permanent grassland and sparse tree/shrub cover

Table 2. Climatic characteristics of the studied CZOs. T_{hot},T_{cold} – mean air temperature at hottest and coldest month.

CZO	Damma Glacier	Slavkov Forest	Marchfeld	Koiliaris		
MTO station	Guetsch	Mariánské Lázně	Gross-Enzersdorf	Kalives /*Souda	Samonas	Prsichro pigadi
Lat/Lg	46.7'N/8.6°E	49.98°'N/12.7°E	48.1°N/16.7°E	35.4°N/24.2°E *35.5°N/24.2°E	35.4°N/24.1°E	35.4°N/24.0°E
Altitude, m	2336	700	157	24/146	385	1000
Period	1982-2009	1967-2011	1960-2012	1974-2012 *1976-2004	1974-2012	1974-2012
T_{hot}, ^{o}C	9.6	15.3	20.3	*26.4	25.3	22.4
T_{cold}, ^{o}C	-5.3	-3.1	-0.5	*11.2	10.0	7.1
T_{mean} annual, ^{o}C	1.5	5.9	10.3	*18.3	17.2	14.2
PET, mm.yr^{-1}	400	538	680	*967	876	750
P, mm.yr^{-1}	1892	835	552	677	763	1175
Snow cover, days	180	120	33			100-140
Köppen climate type	Polar – tundra (ET)	Cold - without dry season, warm summer (Dfb)	Cold, without dry season, warm summer (Dfb)	Temperate, dry and hot summer, (Csa)	Temperate, dry and hot summer, (Csa)	Temperate, dry and hot summer, (Csa)

Table 3a. Soil characteristics and hydraulic properties of selected top and sub layers of the main soil profiles studied at Damma Glacier CZO.

OC – organic carbon; BD – bulk density; P_t – total porosity; FC – field capacity (pores filled with water at pF 2.5); WP – wilting point (pores filled with water at pF 4.18); PAWC – plant available water holding capacity; $AP_{pF1.7}$, air filled pores at tension pF 1.7; S – slope of water retention curve at inflection point; W_i – water content at inflection point.

ID Site	Soil group	Hor.	Depth, cm	Gravel, %	Texture class	Sand, %	Silt, %	Clay, %	OC, $g.kg^{-1}$	BD, $g.cm^{-3}$	P_t, $cm^3.g^{-1}$	FC, $cm^3.g^{-1}$	WP, $cm^3.g^{-1}$	PAWC, $cm^3.g^{-1}$	$AP_{pF1.7}$, $cm^3.g^{-1}$	S (-)	W_i, $g.g^{-1}$
D1	Leptosol	CR	0-5	16	LS	79	20	1	2.2	1.46	0.31	0.07	0.01	0.06	0.14	0.07	0.15
D2	Leptosol	AC	0-3	0	SL	53	46	2	25.9	0.82	0.83	0.28	0.08	0.20	0.33	0.16	0.56
		CR	3-12	44	SL	68	31	1	5.8	1.54	0.27	0.10	0.02	0.17	0.13	0.04	0.15
D3	Leptosol	Ah	0-4	0	SL	59	37	4	108.8	0.32	2.96	0.98	0.24	0.74	1.24	0.53	1.97
		AC	4-7	24	LS	84	15	1	8.3	1.39	0.34	0.07	0.03	0.04	0.17	0.07	0.17
		C	7-15	20	LS	79	21	1	4.9	1.67	0.22	0.04	0.01	0.03	0.11	0.05	0.10
D4	Cambisol	Ah	0-5	4	SL	53	39	8	94.9	0.36	2.43	0.93	0.34	0.59	1.13	0.33	1.51
		AC	5-11	31	LS	74	23	3	30.0	1.03	0.63	0.21	0.08	0.13	0.25	0.10	0.38
		2A	11-18	9	L	44	42	14	125.7	0.63	1.17	0.46	0.25	0.21	0.53	0.11	0.61

Table 3b. Soil characteristics and hydraulic properties of selected top and sub layers of the main soil profiles studied at Slavkov Forest CZO.

ID site	Soil group	Hor.	Depth, cm	Gravel, %	Texture class	Sand, %	Silt, %	Clay, %	OC, $g.kg^{-1}$	BD, $g.cm^{-3}$	P_t, $cm^3.g^{-1}$	FC, $cm^3.g^{-1}$	WP, $cm^3.g^{-1}$	PAWC, $cm^3.g^{-1}$	$AP_{pF1.7}$, $cm^3.g^{-1}$	S (-)	W_i, $g.g^{-1}$
S1	Podzol	AE	0-5	41	SL	72	25	3	25.6	1.34	0.36	0.15	0.03	0.12	0.17	0.04	0.14
		E	8-13	44	SL	70	27	4	8.4	1.48	0.30	0.09	0.01	0.08	0.17	0.03	0.09
		BE	20-25	42	SL	55	28	17	28.6	1.44	0.31	0.13	0.05	0.08	0.15	0.03	0.12
		Bth	35-40	37	L	47	30	23	43.8	1.03	0.60	0.30	0.08	0.22	0.22	0.07	0.30
		Bts	50-54	40	SCL	54	26	20	36.0	1.20	0.46	0.25	0.07	0.18	0.16	0.06	0.24
		B	60-65	44	SL	59	25	16	14.3	1.35	0.37	0.14	0.04	0.10	0.19	0.04	0.18
S2	Stagnosol	Ah	0-5	4	SiL	33	54	13	43.8	0.82	0.85	0.30	0.07	0.22	0.39	0.10	0.37
		AE	5-12	25	SiL	38	52	10	19.1	1.49	0.31	0.16	0.04	0.12	0.11	0.04	0.16
		BE	12-32	23	L	43	49	8	7.1	1.76	0.21	0.14	0.04	0.10	0.04	0.04	0.14
		Btg1	38-43	22	L	45	38	17	4.7	1.76	0.22	0.17	0.08	0.11	0.02	0.03	0.15
		Btg2	57-62	29	SL	53	29	19	2.1	1.81	0.21	0.18	0.09	0.09	0.02	0.03	0.16
S3	Cambisol	Ah	0-7	6	L	44	41	15	254.7	0.40	2.75	0.91	0.54	0.37	1.19	0.42	1.53
		A	18-23	28	L	42	46	13	31.2	1.01	0.62	0.25	0.12	0.17	0.24	0.09	0.39
		B	40-45	35	L	45	39	17	13.8	1.25	0.45	0.15	0.08	0.09	0.24	0.06	0.27

Table 3c. Soil characteristics and hydraulic properties of selected top and sub layers of the main soil profiles studied at Marchfeld CZO.

ID site	Soil group	Hor.	Depth, cm	Gravel, %	Texture class	Sand, %	Silt, %	Clay, %	OC, $g.kg^{-1}$	BD, $g.cm^{-3}$	P_t, $cm^3.g^{-1}$	FC, $cm^3.g^{-1}$	WP, $cm^3.g^{-1}$	PAWC, $cm^3.g^{-1}$	$AP_{pF1.7}$, $cm^3.g^{-1}$	S (-)	W_i, $g.g^{-1}$
M1	Fluvisol	ACkg	0-5	0	SiL	31	61	8	24.8	0.94	0.70	0.45	0.08	0.37	0.17	0.12	0.37
		Ckg	15-20	0	SiL	24	60	6	17.6	1.09	0.56	0.26	0.04	0.22	0.09	0.15	0.32
M2	Fluvisol	Ahk	0-5	0	SiL	27	65	8	36.7	0.93	0.71	0.43	0.12	0.31	0.20	0.10	0.37
		Ak	5-10	0	SiL	29	63	9	28.4	1.10	0.53	0.37	0.10	0.27	0.10	0.09	0.32
		ACk	35-40	0	L	45	46	9	15.4	1.23	0.45	0.21	0.06	0.15	0.16	0.06	0.24
		Ckg	60-65	0	SL	65	30	5	11.0	1.22	0.45	0.13	0.03	0.10	0.18	0.09	0.22
M3	Fluvisol	Ahk	0-5	0	L	43	47	10	43.5	0.95	0.69	0.37	0.14	0.23	0.24	0.08	0.36
		Ak	12-17	0	SiL	30	56	14	27.8	1.07	0.56	0.28	0.12	0.16	0.24	0.06	0.27
		ACk	40-45	0	SiL	14	68	18	18.1	1.19	0.47	0.26	0.09	0.17	0.17	0.05	0.22
		Ck1	65-70	0	SiL	32	54	15	10.7	1.36	0.37	0.18	0.06	0.12	0.12	0.05	0.21
M4	Chernozems	Apk	5-10	0	L	43	38	19	16.1	1.50	0.30	0.18	0.08	0.10	0.08	0.04	0.19
		ACk1	30-35	0	L	45	37	19	20.7	1.52	0.29	0.17	0.08	0.09	0.08	0.04	0.19
		Ck	70-75	0	SL	72	21	7	10.5	1.38	0.36	0.07	0.03	0.04	0.11	0.12	0.20
M5		Ak	2-7	0	SL	58	26	16	19.1	1.66	0.23	0.15	0.07	0.08	0.02	0.03	0.16
		A'k	25-30	0	SL	56	27	18	14.8	1.58	0.26	0.15	0.08	0.07	0.04	0.04	0.18
		ACk	45-50	0	L	39	36	24	6.9	1.40	0.35	0.19	0.10	0.09	0.10	0.04	0.21
		Ck	70-75	0	SL	61	28	11	5.6	1.40	0.34	0.09	0.04	0.05	0.10	0.08	0.19
M6		Ah	0-5	0	SL	57	32	12	23.4	1.40	0.34	0.25	0.08	0.17	0.05	0.05	0.20
		A'	5-10	0	SL	56	30	14	14.0	1.46	0.31	0.20	0.06	0.14	0.06	0.05	0.19
		BCk1	58-63	4	SL	62	24	14	8.7	1.33	0.38	0.11	0.05	0.06	0.19	0.05	0.20
		Ck1	85-90	23	SL	70	20	10	5.6	1.37	0.37	0.09	0.04	0.05	0.19	0.05	0.18

Table 3d. Soil characteristics and hydraulic properties of selected top and sub layers of the main soil profiles studied at Koiliaris CZO.

ID site	Soil group	Hor.	Depth, cm	Gravel, %	Texture class	Sand, %	Silt, %	Clay, %	OC, $g.kg^{-1}$	BD, $g.cm^{-3}$	P_t, $cm^3.g^{-1}$	FC, $cm^3.g^{-1}$	WP, $cm^3.g^{-1}$	PAWC, $cm^3.g^{-1}$	$AP_{pF1.7}$, $cm^3.g^{-1}$	S (-)	W_i, $g.g^{-1}$
K1	Fluvisol	Apk	0-5	1	SiL	23	62	15	15.2	1.47	0.31	0.26	0.09	0.17	0.01	0.05	0.21
			5-10	1	SiL	22	62	15	14.4	1.34	0.38	0.26	0.09	0.17	0.06	0.06	0.26
		ACk	29-34	3	SiL	21	60	19	7.8	1.48	0.31	0.22	0.08	0.14	0.05	0.05	0.20
		Ck1	45-50	5	SiL	20	60	20	4.6	1.60	0.26	0.21	0.07	0.14	0.02	0.04	0.17
K2	Fluvisol	ACpk	0-5	0	SL	64	30	6	16.5	1.24	0.44	0.17	0.04	0.13	0.10	0.09	0.28
		Ck1	5-10	0	SL	66	29	4	14.3	1.24	0.43	0.16	0.04	0.12	0.08	0.11	0.28
		Ck2	55-60	0	SL	64	30	6	4.4	1.38	0.36	0.10	0.03	0.07	0.10	0.10	0.22
K3	Leptosol	ACp	0-5	23	SL	53	40	7	15.8	1.34	0.37	0.20	0.06	0.14	0.11	0.06	0.23
			5-10	24	SL	56	36	8	19.4	1.27	0.42	0.19	0.05	0.14	0.17	0.05	0.23
K4	Cambisol	Ah	0-5	23	CL	20	52	28	55.7	1.10	0.52	0.24	0.12	0.12	0.22	0.06	0.24
		AC	5-10	24	SiCL	16	50	34	37.9	1.20	0.44	0.18	0.10	0.08	0.23	0.05	0.23
K5	Cambisol	Ah	0-5	0	SiCL	10	60	30	50.1	1.06	0.56	0.36	0.18	0.18	0.14	0.07	0.36
		AC1	7-12	0	SiCL	12	57	31	21.6	1.21	0.46	0.27	0.15	0.12	0.14	0.05	0.28
		AC2	40-45	0	SiCL	9	58	33	20.8	1.07	0.57	0.29	0.17	0.12	0.24	0.06	0.34

Table 4. Plant available water holding capacity (PAWC, mm) in rooting depth of main profiles at each CZO.

ID site	Soil group	Horizons	Depth, m	PAWC, mm
D1	Leptosol	CR	0 - 0.06	5
D2	Leptosol	AC, CR	0 - 0.12	17
D3	Leptosol	Ah, AC, C	0 - 0.15	13
D4	Cambisol	Ah,AC, 2A	0 - 0.18	40
S1	Podzol	AE, E, BE, Bth, Bts	0 - 0.54	95
S2	Stagnosol	Ah, AE, BE, Btg	0 - 0.66	114
S3	Cambisol	Ah, A, B, BC	0 - 0.50	83
M1	Fluvisol	ACkg, Ckg	0 - 0.22	53
M2	Fluvisol	Ahk, Ak, ACkg, Ckg	0 - 0.70	136
M3	Fluvisol	Ahk, Ak, ACkg, Ckg	0 - 0.70	132
M4	Chernozem	Apk, ACk	0 - 0.44	63
M5	Chernozem	A, Ak	0 - 0.45	50
M6	Chernozem	A	0 - 0.56	65
K1	Fluvisol	Apk, ACk	0 - 0.41	92
K2	Fluvisol	Acpk	0 - 0.05	8
K3	Leptosol	ACp	0 - 0.14	25
K4	Cambisol	Ah, AC	0 - 0.10	16
K5	Cambisol	Ah, AC	0 - 0.90	126