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Regionalization of potential water storage capacity of agricultural landscape – a quantification of soil accumulation function

Tomas Orfanus, Vladimir Mikulec

Institute of Hydrology, Slovak Academy of Sciences, Racianska 75, 831 02 Bratislava, Slovak Republic, (orfanus@uh.savba.sk / Phone: +421 2 49268262, mikulec@uh.savba.sk / Phone: +421 2 49268262)

0.1 Introduction

Soil properties in their mutual combinations and relations to other components of geoecosystem define soil functions. Bedrna (2002) distinguish (i) ecological (ii) environmental and (iii) socio-economical functions. The potential of soil cover to assign its functions is evaluated as a soil quality. Bujnovsky et Jurani (1999) present stepwise approach for soil quality evaluation starting at (i) soil properties (their sum represents soil functions), through (ii) soil parameters as their quantitative representations to (iii) criteria as a way to evaluate the parameters for defined purposes. We try to quantify the parameter of water storage capacity in this paper as a property of soil water-accumulation function in the Záhorská nížina Lowland. Water-accumulation function of soil highly determines its quality, because hydrological regime and water availability for the coenoses becomes a serious problem nowadays in the whole part of Slovakian lowlands. Water deficiency during plant ontogenesis, especially in its critical phenological phases, can have harmful effect on plant condition. Individual phytocoenoses have various mechanisms of adaptability, resilience and resistance for water deficiency during their critical seasons but cultural phytocoenoses belong to the most sensitive ones. A spatial information on water storage capacity of the root zone becomes a serious thematic base for management of agricultural landscape therefore. Záhorská nížina Lowland (important agricultural area in frame of the Moravia river catchment) has been affected by agricultural activities for long time and agrocoenoses as well as cultural grassy communities present the abiding part of vegetation nowadays. It is supposed to be a landscape, which is widely sensitive for water and landuse management.

Core

Water storage capacity of soil excludes free gravitational water, which is precipitously moving through the unsaturated zone during temporal hydrological events such as rainfalls or floods. It also excludes water bound up with the solid phase of soil by high forces, which plants do not utilize for their metabolism. Water storage capacity, as a potential value, includes only water, which is available for plants for relatively longer time and can be actively used by the root system of plants. Basic information on water content relevant for the evaluation of interactions between soil and vegetation is given by so-called hydrolimits, which can be defined as borders of water availability for plants (Antal, 1999). Such hydrolimits (also called “conditioned hydrolimits” by Rehák et Jánsky 2000) are conventionally identified as points on water retention curve (WRC) at selected energetic forces related to physiologically available water (Kutílek, 1978). From this point of view, the potential water storage capacity of unsaturated zone of soil is usually defined as water volume between “field water capacity point” and “wilting point” (Kutílek, 1978). This potential source of water is renewable due to hydrological cycle. Except of mentioned field water capacity point (FWC) and wilting point (WP), conditioned hydrolimits also include critical water content at its lower limit for agrocoenoses - point of decreased water availability (DWA). However, this hydrolimit is variable depending on transpiration intensity, hydraulic conductivity of soil and plant root density. The above-mentioned hydrolimits can be defined as follows:

1. FWC – soil water content at the border between gravitational and capillary water (pF between 2.0 and 2.9)
2. WP – soil water content at which plants suffer from permanent water deficiency and they are irreversibly wilting (pF = 4.18)
3. DWA – soil water content at which water availability for plant dramatically decreases (pF = 3.1 – 3. 5)

We used pedo-transfer functions (PTF) for estimation of water storage capacity in this paper. PTFs are nowadays in the centre of interest because a direct way of obtaining soil hydrological data is very expensive and time consuming (e.g. Tietje et Tapkenhinrichs, 1993). That is reason why some alternative methods were proposed for indirect estimation of hydrophysical soil properties from relatively well-described and easily available soil properties, such as particle size distribution, bulk density or organic carbon. Most of empirical regional PTFs are based on multilinear regressions, which are used for estimation of soil retention at fixed pressures, or for prediction of some parameters of water retention curves (e.g. Šútor et Štekauerová 1999a,b; Houšková 2000, Skalová 2001). We used neural-network approach in this paper (refer e.g. Pachepsky et al., 1996; Schaap et Bouten, 1996), which was calibrated for the Záhorská nížina Lowland and applied on KPP DB structure by Orfánus et al. (2003).

Determination of hydrolimits as well as potential water storage capacity assumes some consequent sub-procedures, which can be summarised by following steps:

1. *Assessment of particle size distribution in the root zone of soil*

Information on particle size distribution of soils in the Záhorská nížina Lowland was obtained from 813 georeferenced records of so called selected soil profiles of complex agricultural soil survey from digital database KPP-DB (Skalský ed., 2002), which are managed by Soil Science and Conservation Research Institute (SSCRI) as a part of Information System of Soils. The percentage content of three main particle-size classes (sand, silt and clay according to USDA) was estimated as an average value up to 50 cm soil depth weighted by thickness of individual horizons identified in this 50 cm layer. The depth of the root zone was set to 50 cm because most of cultural plants have effective soil depth, from where they receive prevailing amount of water, to 50 cm (Antal, 1999). Particle size distribution as well as basic soil and hydrological parameters were spatially interpolated by "*ordinary kriging*" in GIS environment using Geostatistical Analyst for ArcGIS (Johnston et al., 2001) to obtain georeferenced rasters with pixel size 200 m.

1. *Finding parameters of WRC*

Parameters of WRC, which are essential for calculation of hydrolimits (eq. 1) and potential water storage capacity (eq. 2), were obtained by SSCBD_TH33_TH1500 subroutine (it uses contents of sand, silt and clay, bulk density and water contents related to soil water potentials of 33 and 1500 kPa as input parameters) in the *Rosetta* model (Schaap et al., 1997). This method was proposed by Orfánus et al. (2003) as an effective pedotransfer function applicable on data structures of KPP-DB. It explicitly assumes an estimation of bulk density and soil water contents at 33 and 1500 kPa potentials by multivariate regression models calibrated on 84 experimental WRC from the Záhorská nížina Lowland (Šútor et al. 2001, Orfánus et al. 2003).

1. *Calculation of hydrolimits*

Values of FWC, WP and DWA were calculated according to van Genuchten (1980) equation for analytical description of WRC (eq. 1). Retention parameters of residual moisture (Θ_r), saturated moisture (Θ_s) and shaping parameters α and n result from procedure of *Rosetta* model.

Eq.1.		[cm^3.cm^{-3}],

where θ is actual soil moisture [cm^3.cm^{-3}], h_w is soil water potential [cm], θ_s is saturated moisture [cm^3.cm^{-3}], $\theta_r$is residual moisture [cm^3.cm^{-3}], α and n are parameters of approximating function, m is equal to 1-1/n

Pressure head h_w [cm] at FWC was set to analogous value for pF = 2.0 (sandy soils), pF = 2.47 (loamy soils) and pF = 2.7 (clay soils) – adopted from Šútor et Rehák (1999). In the case of WP, pressure head was set to pF = 4.18 and finally pF = 3.25 in the case of DWA hydrolimit. Raster calculator in Spatial Analyst for ArcGIS was used for estimation of hydrolimits.

1. *Calculation of potential water storage capacity*

Water storage capacity is generally expressed in mm of equivalent height of soil water (W) according to Rehák et Janský (2000). It was estimated according to eq. 2 using raster calculator in Spatial Analyst for ArcGIS.

Eq. 2. $W = 1000\ (\Theta_{FWC} - \Theta_{WP}).h$[mm] ,

where Θ_{FWC} and Θ_{WP} are soil moistures at FWC and WP [cm^{3}cm^{-3}] and h is soil depth [0.5 m]. The raster map of potential water storage is presented in Fig. 5.

1. *Functional delimitation*

Water storage capacity was evaluated separately for (i) soil textural classes, (ii) genetic soil units (according to Morfogenetic Classification System of Soils (Collective, 2000) and (iii) pedo-ecological regions (Džatko, 2002). Soil genetic unit polygons as well as PE-region polygons were derived form georeferenced digital database of pedoecological units (PEU-DB) managed by SSCRI. Textural classes were classified according to USDA triangle (Soil Survey Staff, 1996) and identified by logical queries on sand, silt and clay rasters and consequently vectorised. Average values of water storage and hydrolimits up to 0.5 m soil depth for evaluated polygons (i-iii) were obtained as an average of raster cell values for overlaying polygons using ”*zonal analysis*” tool in Spatial Analyst for ArcGIS.

Záhorská nížina Lowland, its agricultural landscape respectively, was evaluated for long-term water storage capacity in the root zone in three separate steps as realized below. Geospatial rasters of hydrophysical properties with pixel size 200 x 200 m (crucial scale 1: 250,000) was used for the root zone up to 50 cm depth.

1. *Water storage in pedo-ecological regions*

The highest mean water storage capacity was estimated in the root zone of Myjavská niva region (over 57 mm) and Unínska-Senická pahorkatina region (more than 56 mm). Both pedo-ecological regions have also the highest water contents by hydrolimits for cultural coenoses - FWC more than 26 vol. %, DWA more than 19 vol. % and WP over 14 %. Prevailing part of agricultural landscape of the Záhorská nížina Lowland is found in Bor, Záhorské pláňavy and Dolnomoravská niva regions (74 %), which store noticeably smaller amounts of water in the root zone.

1. *Water storage in individual textural classes*

Water storage in the unsaturated zone of soils highly varies over the study area. It is known that its variability principally depends on particle size composition and bulk density of soil. Sandy (lp) and loamy-sandy (lh) soils reach the lowest values of hydrolimits and cultural plants begin to wilt at soil water content approximately 6-8 vol. % here. Regardless to low wilting point values, these soils, which cover more than 40 % of the study area, are potentially endangered by drought because available water is bound by weak forces and water storage capacity of the root zone is less than 50 mm therefore. Soil water is highly mobile in all directions in such soils. Texturally heavier soils occur in regions of Dolnomoravská niva, Záhorské pláňavy, Myjavská niva, Unínska and Senická pahorkatina. The highest water storage capacity, averagely from 55 to 60 mm, was estimated in silt-loamy (ssh) and silt-clay-loamy (ssi) soils, which occur mostly in Chvojnícka pahorkatina and Myjavská niva regions. However, mentioned textural classes cover only approximately 11 % of the study area and their asset to the total water storage of the region is not so high. The most frequent medium heavy soils are those of sandy-loamy (sp) and loamy (sh) classes, which cover approximately 36 % of the study area. They potentially store about 53–55 mm of water up to 50 cm depth.

1. *Water storage in individual genetic soil units*

From ecological point of view it is also interesting to follow potential water storage as a function of soil types because they are still considered to be a general indicator of soil quality and suitability for cultural coenoses. Mollic fluvisols (mollic gleysols) together with arenic regosols cover dominant part of Dolnomoravská niva and Myjavská niva regions, or Bor region respectively. They together represent nearly 60 % of agricultural landscape in the Záhorská nížina Lowland. Arenic regosols have low water storage capacity for cultural coenoses in the root zone. Similar values have mollic fluvisols or fluvisols and it is especially due to their sandy profile constitution. On the other hand the most suitable conditions for water storage were estimated in the root zone of luvisols in the Chvojnícka pahorkatina region (over 57 mm). Chernozems belong among soils with relatively low water storage in average however, these soils have high minimum values. Regosols, mollic fluvisols, fluvisols and luvisols show high difference between water storage minimum and maximum. It is especially because these soil types differ in textural composition of profiles.

Conclusions

It is evident that water storage capacity and relevant hydrolimit values highly depend on particle size composition of soil – on textural classes respectively. High variability of granular texture involved by high diversity of quaternary sediments in the Záhorská nížina Lowland influences spatial pattern of water bound in the root zone of soil. Especially sandy soils are known for low storage capacity of soil water and cultural coenoses can suffer from drought during longer dry periods. Optimal conditions for cultural phytocoenoses are estimated in silt-loamy substrate, where potential water storage bound in the unsaturated zone create a good assumption for effective water management. It means that after sufficient saturation of the root zone by rainfall or flood event, there is enough available water for plants even during relatively longer dry period.

Džatko (2002) proposed a hierarchical division of agricultural landscape into pedo-ecological regions with aim to coordinate evaluation of agricultural landscape. We used evaluation on the level of pedo-ecological region, which is defined as a complex of several pedo-ecological subregions on genetically homogenous area, such as hilly countries, plateaus, valleys etc. According to definition there is no high difference in soil conditions, climate and relief within a pedo-ecological region and it represents individual, relatively homogenous area. That is reason why we decided for such evaluation of cultural landscape as for water retention. Classified pedo-ecological regions represent different geomorphological and quaternary-geological units and they differ in water storage capacity therefore. Generally Unínska and Senická pahorkatina as well as Myjavská niva regions seem to store potentially higher water content in the root zone. On the other hand Bor region is highly demanding for optimization of water management because water storage in unsaturated root zone is low.

It is difficult to describe exactly relations between soil genetic units, as basic representatives of soil cover, and water retention abilities in the root zone. Regardless we offer general view on mean water storage capacity in the root zone of main soil types in the study area. The level of soil classification and its generalization was chosen with respect to the crucial scale of georeferenced spatial outputs provided by KPP-DB. Some uncertainty logically occurs therefore mainly at regosols and mollic fluvisols (mollic gleysols), which have very low mean value of water storage capacity although the range between maximum and minimum values is very high. Used generalised level of soil map is not sufficient enough to differ between regosols or mollic fluvisols developed from loamy sediments and sandy substrate. We can summarize that the soil types, which describe rather soil genesis and processes than soil texture, do not directly indicate water storage; on the other hand information on water regime is needful for understanding of production potential of individual soil types in particular region as a base for consequent land use evaluations.

Water storage capacity as it is expressed by eq. 2 specifies potential long-term water content in the root zone of soil, which is available for cultural coenoses. It is necessary to emphasize its potential character. The actual state of moisture conditions of the root zone depends on regimes of individual components of hydrological cycle (rainfall, snowmelt, floods, plant-root uptake, evapotranspiration, lateral flow, unsaturated zone – ground-water flows) and therefore even soils with high potential water storage capacities can suffer from water deficiency under unfavourable state of hydrological cycle components. Hence mollic fluvisols (mollic gleysols) despite their relatively low potential water capacity have usually good moisture regime owing to permanent water supply by ground water.

Discussion

Objective methods for evaluation of potential water storage capacity of unsaturated zone are usually based on its direct monitoring. However, such a monitoring system in Slovakia was realized only in some target areas (Žitný ostrov, East-slovakian Lowland) and it is also not sufficient enough to provide data necessary for determination of water storage in the unsaturated zone over these areas. That is main reason why the quantification of water storage capacity in the unsaturated zone (or its part) must be done indirectly as it is presented in this study.

Georeferenced spatial information on soil quality regerding to AFS using retention parameters (water storage capacity and hydrolimits) is doubtlessly very important for geoecology. It is the main criterion for evaluation of actual water supply accumulated in the root zone of the agricultural region. It can be used as one of strategic criteria for distributed crop management, stress index estimation, predicting soil erosion and many others. Retention and hydraulic soil aspects become very important nowadays with respect to protection of ground water against pollution. From this point of view, the knowledge on spatial distribution of potential water storage capacity of hydraulically active part of soil profile is of high importance for detecting the most pollution-endangered areas. Furthermore it can be used in process of evaluation of drought- or flood-threat in the landscape. Summarizing we can say that knowledge on potential water storage capacity of soils in target region is crucial for its environmental multi-risk assessment.

Water storage capacity is a quantitative parameter of AFS, however, it must be mentioned that it presents only one approach for AFS evaluation. Regarding to purposeful nature of AFS, it should be evaluated by purposeful indicators (e.g. other indicators for AFS can be used with respect to distributed crop management and others for evaluation of potential pollution-endangered areas).

Translated by the authors

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