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National level assessment of soil salinization and structural degradation risks under irrigation

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Abstract

Optimal water supply of plants is key to high yields. However, irrigation in drier regions must be accompanied by soil conservation. Nationwide planning of irrigation needs spatially exhaustive, functional soil maps, which may support proper recommendations for the different areas. For supporting the Hungarian national irrigation strategy, a series of countrywide functional soil maps was created, which reveal the pedological constraints, conditions and circumstances of irrigation by the spatial modelling of the relevant functional features of the soil mantle. Irrigation can improve productivity, while its negative effects may lead to soil degradation. This paper focuses on threats, the spatial identification of potentially affected areas. The thematic maps spatially model the irrigability and vulnerability of soils. Estimation of salt accumulation hazard, and soil structure degradation risks were targeted. The salinization hazard assessment was carried out by two ways. We applied the steady state concept of critical water-table depth and a more dynamic, process-based method. To estimate soil structural degradation hazard, class-based relationships were developed based on soil profile data of MARTHA 1.0 (Hungarian Detailed Soil Hydraulic Database). Soil type, organic matter content, carbonate content, soil reaction and texture class (USDA) were taken into consideration to develop pedotransfer functions for modelling the correlations between primary soil properties and threats indicators. The new maps can help decision makers to improve land use management, and sustainable agronomy.

Keywords: functional soil map, irrigation, salt accumulation, soil structural degradation, Hungary

Introduction

Irrigation is one of the most important agri-environmental operations, which can contribute to improved productivity (EEA, 2017a). Based on the Eurostat report in 2019 the extent and ratio of irrigable and actually irrigated area were almost the same in 2003 and 2013 in Hungary. The total irrigable area in 2013 was 259,000 hectares, while the area of the irrigated lands (at least once a year) is less than 142,000 hectares, which means 54 per cent utilization. This ratio in more arid, European countries is higher, e.g. 70 per cent in Italy and 76 per cent in Greece. In some countries (e.g. Spain, Portugal, Greece, Italy), due to limited natural water resources, treated wastewater can be an alternative source for irrigation which increases both of the risk of secondary salinization (Daliakopoulos, I.N. *et al.* 2016; Elgallal, M. *et al.* 2016; Francés, G.E. *et al.* 2017) and structural degradation (Leuther, F. *et al.* 2019).

Due to climate change, water requirements for irrigation could increase by 17–27 per cent depending on crops (Esteve, P. *et al.* 2015). As a long-term forecast, the European-scale soil moisture modelling for 2021–2050 projects wetter conditions in northern, but drier ones in southern European regions, to which the territory of Hungary belongs (EEA, 2017b).

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The national statistics for the last ten years show that the acreage of irrigated areas does not exceed 3 per cent of arable lands in Hungary. The question of irrigation is becoming increasingly important for preventing soil dryness due to eventual extreme drought events. Sustaining proper soil moisture content is essential in agronomy. However, irrigation cannot be sustainable without taking care of soil conservation. According to the report of the Research Institute of Agricultural Economics) (Kemény, G. *et al.* 2018), about 800,000 hectares would be suitable for irrigation, but at present only ca 300,000 hectares have irrigation facilities.

An ongoing research aims to estimate the productivity growth due to irrigation by considering the agricultural potential of soils, where the anthropogenic management factors, which have an effect on the efficiency of production, are integrated into the form of scenarios, based on a new land evaluation system (Tóth, G. 2011; Tóth, G. *et al.* 2014). According to preliminary results, nearly two-thirds of Hungary's cropland would show significant increase in productivity as a result of irrigation, but in areas with poor productivity there is no significant increase in productivity with irrigation alone.

From the point of view of irrigation, its surplus (not absorbed by crops) water is an infiltrating supply, which contains various amounts of dissolved salts. Following the plant water uptake (transpiration) and surface evaporation, which consume the water of stored moisture, the dissolved salt of the irrigation water remains and accumulate in soil over time.

In irrigated conditions plant water uptake is equal to transpiration by definition when disregarding the water content of plants. Part of irrigation water is percolating down in the soil for several reasons, e.g. if water is available, irrigation is planned to be more than what is just necessary in saline areas, in order to make sure the present salt is leached down. Furthermore, the water distribution is not perfect and there is leaking from the canals; the vegetation cover is not perfect and in non-covered patches water is percolating without being used by plants (Szabolcs, I. *et al.* 1968, 1969a; Várallyay, Gy. 1989). Last but not least, in sub-humid conditions, as in Hungary, unplanned rainwater is added to the water and contributes to water table rise.

Irrigation may also have an effect on soil structure, hydraulic properties, nutrient flow (better water supply, more vigorous soil life), and regular irrigation may affect the depth of groundwater level and change the direction of soil formation as soil hydromorphisation, secondary salinization (Kovda, V.A. *et al.* 1973; Várallyay, Gy. 1989; Murray, R.S. and Grant, C.D. 2007). Sun, H. *et al.* (2018) examined the impacts of long-term irrigation on selected soil properties, and they found that irrigation timing affects bulk density and saturated hydraulic conductivity; while organic matter and total nitrogen decreased during their 17-year long survey. Irrigation enhanced clay dispersion in Vertisols of Northern Cameroon (Basga, S.D. *et al.* 2018). Tisdall, J.M. and Hodgson, A.S. (1990) found, also in irrigated Vertisol, low air-porosity, which could decimate soil faunal populations. Dong, L. *et al.* (2018) reported sand content decrease, and soil texture became finer under irrigation. In Europe, continental scale irrigation maps were generalized/created to estimate the irrigation water requirements (Wriedt, G. *et al.* 2008). Based on simulation performed by Riedeger, J. *et al.* (2014), the irrigation demands will increase in the future if the temperature rise. With satellite data, namely satellite soil moisture products, irrigation doses can be quantified (Brocca, L. *et al.* 2018).

Our objective was to present a nationwide map series of the most important risks of irrigation, e.g. salinization and structural degradation, in order to delineate the areas where special attention must be paid to the practice so that it remains sustainable.

Methods

Data sources used in the evaluation processes

– Hungarian Soil Information and Monitoring System (SIMS, 1995) is a nationwide soil monitoring programme, which provides soil information from 1,235 locations. Due to the standardized methodology and the accredited laboratory measurements, SIMS is the most unified and thematically detailed, up-to-date soil-related database in Hungary.

– Groundwater Depth and Quality Monitoring Network Data of General Directorate of Water Management (OVF) contain, among others, specific electrical conductivity of water (μS/cm), measured 1–4 times per year at 8,095 sites.
– Digital Kreybig Soil Information System (DKSIS – Pásztor, L. *et al*. 2010, 2012) is the most detailed spatial dataset related to soils covering the whole country. It simultaneously contains two types of geometric datasets: soil mapping units (SMUs) and sampling plots. In the present paper, we applied plots with pH and salt content data, as well as SMU layer with physical and chemical soil property categories. Physical soil categories were attributed according to water retention capability, permeability and infiltration rate; chemical categories were derived from pH and calcium carbonate content of soils.
– Hungarian Detailed Soil Hydraulic Database (MARTHA 1.0 – Makó, A. *et al.* 2010) was developed to collect information on measured soil hydraulic and physical characteristics in Hungary. Recently, this has become the largest and most detailed national hydrophysical database. However, it was not elaborated for mapping purpose, the countrywide sampling was not representative, neither systematic nor random, its data originate from experts' data collections.
– Digital, Optimized, Soil Related Maps and Information in Hungary (DOSoReMI.hu) database collects novel soil property- and soil type maps as well as functional soil maps, compiled by up-to-date digital soil mapping methods. In the present paper, we applied clay, silt, sand and calcium carbonate content maps.
– Climate was represented by average annual precipitation, average annual temperature, annual evaporation and average annual evapotranspiration layers compiled by the Hungarian Meteorological Service with 0.5′ resolution (Szentimrey, T. and Bihari, Z. 2007). We calculated Aridity Index, which is ratio of annual precipitation to annual potential evapotranspiration.
– CORINE Land Cover Database (CLC50 – Büttner, G. *et al.* 2004) is a national land cover database elaborated on the basis of the CORINE nomenclature of the European Environment Agency (EEA), and adapted to fit the characteristics of Hungary.
– MODIS satellite images were involved in the mapping process. Red, near-infrared (NIR) bands from two dates (16.03.2012 and 07.09.2013) as well as NDVI images providing information from 16 day periods of two dates (03.2012 and 09.2013) represented different phases and states of vegetation. Spatial resolution of the images is 250 m (NASA LP DAAC, 2015).
– Digital Elevation Model (EU-DEM 2015) and its morphometric derivatives were applied as environmental auxiliary layers. Channel Network Base Level, Elevation, Multiresolution Index of Ridge Top Flatness – MRRTF, Multiresolution Index of Valley Bottom Flatness – MRVBF, SAGA Wetness Index, and Vertical Distance to Channel Network were used in the mapping process. The terrain features were calculated from the DEM in SAGA GIS (Conrad, O. *et al.* 2015) environment.
– Lithology was represented by the Geological Map of Hungary 1:100,000 (Gyalog, L. and Síkhegyi, F. 2005). The units of the map were correlated with the nomenclature of parent material defined in the FAO Guidelines for soil description (Bakacsi, Zs. *et al.* 2014).

Mapping potential irrigation possibilities based on the critical groundwater level concept

The assessment approach targeted to evaluate the possibility of irrigation based on the steady state concept of critical water table depth, further developing the ideas used for the irrigation planning of the 1960s in the region of river

Tisza (Szabolcs, I. *et al.* 1968, 1969a, b) and extending the principles to national scale producing the „Map of irrigation possibilities". Critical water-table level is a groundwater depth value, which is based on theoretical calculations and practical experiences (Polynov, E. 1930; Szabolcs, I. *et al.* 1968). Over this level the rise of a particular saline groundwater may result in harmful salt accumulation (secondary salinization) of the root zone, where most damage is caused. As a consequence, the higher the salt content of the groundwater and the clay percent of given profile, the deeper is the critical water-table level. Examining a particular case, the critical water-table level is affected by the stratification of the soil layer, but not at national scale. *Figure 1.* shows the conceptual model of the evaluation. Limitations for depth, salt content and profile are based on Szabolcs, I. *et al.* (1968, 1969a, b).

Because of its large spatial representativity, the nationwide mapping of soil salinity was based on DKSIS legacy soil profile data, and it was carried out by regression kriging (RK – Hengl, T. 2009). This method permits that environmental factors with exhaustive spatial extension, such as climatic, vegetation-, topographic, soil- and geologic layers can be taken into consideration for the spatial interpolation/extrapolation of the reference data. For delineating the different regions in the „Map of irrigation possibilities" we used thematic layers of (i) properties and water regime categories, (ii) salt content of soil and soil chemistry, (iii) dissolved salt quantity and quality in groundwater. According to soil salinity content categories, the areas were delineated as 1. proposed, 2. conditionally proposed, 3. not proposed for irrigation development.

In some cases, Szabolcs, I. *et al.* (1968, 1969a, b) applied numerical threshold values, and in others relied on their experience, using the geographical and/or genetic soil classification in each category (e.g. based on this, the Hajdúság microregion loess-mantled alluvial fan belongs to the "proposed" category).

We used maximum pH and average salt content of soils down to 150 cm depth. The threshold values were chosen to ensure harmonization with the data set of Szabolcs, I.

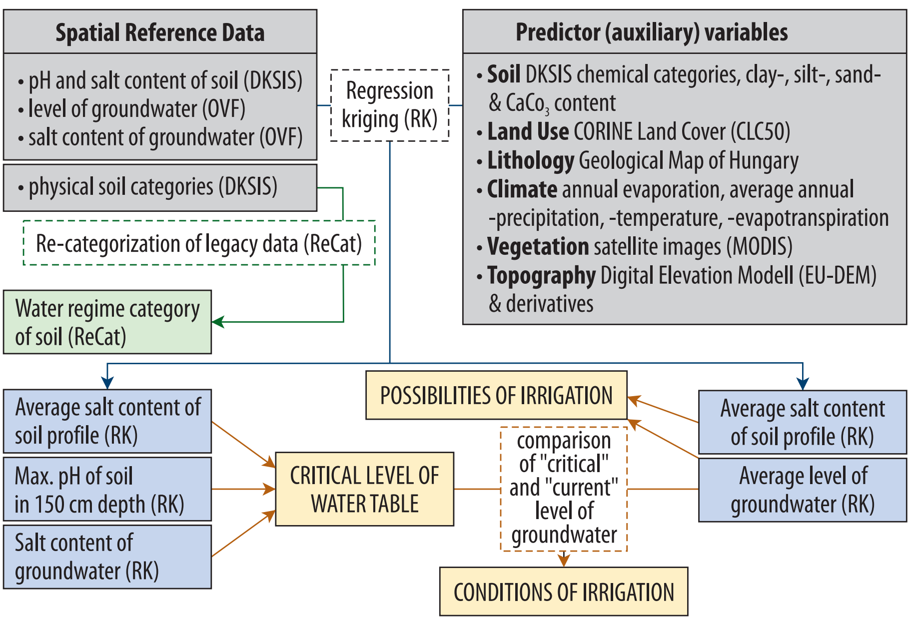

Fig. 1. The conceptual model of critical water-table level-based evaluation

et al. (1968) and the data on the Szarvas plot map (Szabolcs, I. *et al.* 1969b). After the separation of areas that were conditionally suitable for irrigation, the conditions were determined based on the relationship of current "average" and critical groundwater level. The "average" level of groundwater was considered as the mean value calculated from daily groundwater depth records (collected between 2000 and 2013) of the Groundwater Depth Monitoring Network of General Directorate of Water Management limited for the growing season (from April to October). After spatial and error filtering 1,936 observation points remained, whose data were used for further analysis. For spatial inference, proper, spatially exhaustive, auxiliary predictor variables were selected (see *Figure 1*).

Electrical conductivity of groundwater is provided by the Groundwater Quality Records of General Directorate of Water Management. After spatial and error filtering 7,793 well-data remained from the 8,095 sites. We converted their electrical conductivity values into salt content (mg/l) according to the practically accepted approach; using 0.5 as an empirical multiplier applied by OVF Water Quality Laboratory practice (it means that 2,000 μS/cm approximately equals to 1,000 mg/l).

The water regime category map originates from legacy polygon-based map of properties (DKSIS). The legacy map was re-categorized in order to match the water regime categories of soil according to Szabolcs, I. *et al.* (1969a). Salt content, and average level of groundwater as well as soil pH and soil salinity maps were compiled by regression kriging (RK). All mentioned final map products were prepared with 250 m grid size.

The condition of irrigation was determined by the comparison of the 'current' and the 'critical' depth of the water table, because water level shallower than the critical level may result in undesirable processes, such as salinization and alkalinisation. The critical depth of the water table was calculated based on average salt content of the soil profile, the water regime category of soil, salt content of the groundwater and soil pH values.

Evaluation of predicted salt accumulation in the topsoil

The dynamic approach for the prediction of salt accumulation risk is based on the quantification of the salt accumulation processes focusing on the topsoil (0–30 cm), resulting in the „Salinization risk map". Involving the factors which mainly determine the present salinity status of soils, a regression model was set up and, assuming certain water-table rise, the predicted soil salinity status was estimated. The relative differences between the „present" and „predicted" salinity values constituted the basis for vulnerability classification. Based on the main factors of salt accumulation in the topsoil, estimation algorithm was established by multivariate linear regression for salt content of topsoil providing information on the importance of the affecting, background, independent factors. Using monitoring observations, the trend type changes in the depth and salt content of groundwater were also taken into consideration.

Due to large inter-annual changes, for expressing the vulnerability of areas to salinization, the available current soil salt content map is not suitable, but the salt accumulation processes covering longer periods must be quantified. The method used is the determination of the numerical weight (regression coefficients) of the most important factors influencing salt accumulation. First, the multivariate regression equation was developed on the SIMS data (for 670 points) to quantify the effect of processes on the present salt status, in the second step, using the same regression equation, the effect of the assumed groundwater level caused by irrigation was calculated and mapped *(Figure 2)*. The relative differences between the „present" and „predicted" maps constituted the basis for vulnerability classification.

Furthermore, we calculated the areal distribution of salinization risk (vulnerability) categories within the soil productivity classes. The soil type map has been reclassified according to the productivity categorization of MÉM NAK (1979).

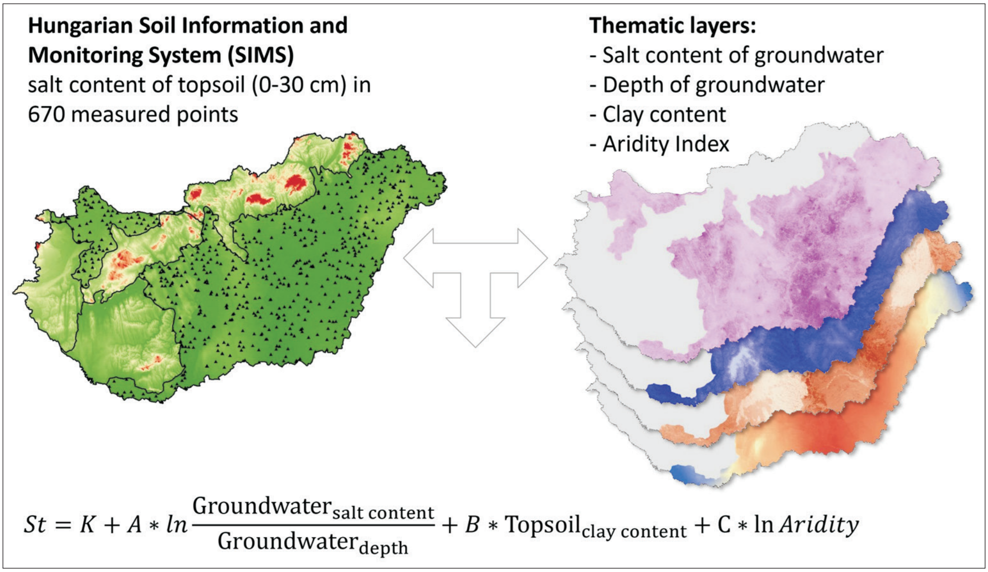

Fig. 2. Conceptual model of processes-based evaluation. In the equation St is topsoil salt concentration; K is constant; A, B and C are regression coefficients, all fitted parameters. Aridity is ratio of annual precipitation to annual potential evapotranspiration.

Estimation of risk of structural degradation

Differential porosity changes (e.g. ratio of macro-pores) within a given soil textural class could be taken as primary indicators of structural degradation and affect the soil water regime, while the accompanying changes in bulk density can indicate the susceptibility for compaction (Rajkai, K. *et al.* 2018). Using profile (MARTHA 1.0) and map-based soil physical databases (www.dosoremi.hu see in Pásztor, L. *et al.* 2017), pedotransfer functions were elaborated for finding correlations between descriptive soil parameters and indicators.

Concerning the nationally available thematic soil maps and the content of MARTHA soil hydraulic database, the main taxonomic soil type, according to Stefanovits, P. *et al.* (1999), organic matter content, carbonate content, pH value and texture classes (USDA) were selected as variables in calculations.

During the assessment of vulnerability for structural degradation, it was supposed, that soils with good structure are not liable to soil compaction. We were looking for a soil-specific index, which can describe this structure stability properly. We examined different structure stability indices (Reynolds, W.D. *et al.* 2002, 2008, 2009; Dexter, A.R. 2004; Ghiberto, P.J. *et al.* 2015; Rajkai, K. *et al.* 2015; De Melo, T.R. *et al.* 2018) derived from MARTHA database, to decide which is the most suitable to describe vulnerability of soil for structural degradation. The relative field capacity (*RFC*) value, the ratio of field capacity to saturated water content (Reynolds, W.D. *et al.* 2008), was finally selected as an indicator for degradation risk. *RFC* is dimensionless, it can indicate the optimum soil structural condition and pore volume distribution. It is calculated, as follows:

$$RFC = \Theta_{pF2.0} / \Theta_{pF0},$$

where $\Theta_{pF2.0}$ is volumetric soil moisture content at pF = 2 tension; Θ_{pF0} is volumetric moisture content at saturation (maximum water capacity = total porosity). *RFC* values can range between

0 and 1. Reynolds, W.D. *et al.* (2009) found that 0.6 ≤ *RFC* ≤ 0.7 values indicate optimum pore volume distribution, and so optimal water- and air-capacity. In case of lower *RFC* values, there are less macro-pores to retain water; while higher *RFC* values show absence of macro-pores, worse air- and water permeability. In both cases, soil productivity may decrease (e.g. less available water or anaerobic conditions for plant roots; limited bacterial nitrification because of waterlogging or lack of air) (Doran, J.W. *et al.* 1990; Reynolds, W.D. *et al.* 2002).

For estimating the vulnerability to soil degradation, the soils were investigated according to the effect of the sum of the basic soil properties considered by the structural properties (Classification and Regression Tree, CRT – Breiman, L. *et al.* 1984). Effects of soil tillage or improper agricultural practice on soil structure could not be taken into account by this classification.

Firstly, we selected data of upper (0–30 cm) plough layers from MARTHA database (except peat soils). Saturated water content and field capacity were estimated (pred_pF0 and pred_pF2.0) from basic soil parameters with pedotransfer functions (SPSS, Classification and Regression Tree, CRT). Category variables were texture class (TX USDA) and soil taxonomic main type of the Hungarian Genetic Classification, ca equivalent classification level to soil orders of USDA Soil Taxonomy (MT), while continuous variables were organic matter content (OM), calcium carbonate content (carb), soil reaction (pH water). After filtering, 710 samples remained for further analysis. An example for the established regression trees is presented in *Figure 3*.

Structural degradation and soil compaction are closely related issues. From predicted water capacity values relative field capacity was estimated (pred_RFC). Pred_RFC was compared with bulk density value and with literature data (Linn, D.M. and Doran, J.W. 1984; Skopp, J. *et al.* 1990; Olness, A. *et al.* 1998; Reynolds, W.D. *et al.* 2002). Categories of vulnerability to soil degradation, considering soil texture, were determined, as follows: 1. highly vulnerable, 2. moderately vulnerable, 3. less vulnerable. In sandy soils too low pred_RFC refers to structural degradation (more macro-pores, worse water retention); while in case of clayey soils too high pred_RFC mean soil compaction caused by structural degradation (less macro-pores, worse air permeability).

Based on the national digital soil property maps, a new map of pred_RFC was created. The algorithm for creating categories of vulnerability to structural degradation was prepared in R 3.4.0 program (R Core Team, 2017).

Results and discussion

Salt accumulation hazard, secondary salinization

We performed the two types of calculations to gain the maps of risks of irrigation. First, we present the one produced with the steady state model. The evaluation takes into account the salt content of the soil and the groundwater together with the average depth of the groundwater table during the growing season (from April to October) to fulfil the requirements of the critical water-table level evaluation concept (see *Figure 1*).

Map of irrigation possibilities *(Figure 4)* delineates regions with the best condition for irrigation (proposed for irrigation) and areas where the irrigation also possible, but the potential harmful salt accumulation processes must handle by farmers (conditionally for irrigation) The map shows that most of the agricultural land in Hungary is suitable for irrigation, respecting certain aspects.

Considering the relative position of the calculated critical water-table depth and the long term (between 2000 and 2013) average of the groundwater level in the growing season, when the surplus water requirements supposed to be the highest, we compiled the maps of irrigation conditions. Map shows the necessary operations to maintain irrigation *(Figure 5).* Three categories have been distinguished: 1. level of groundwater have to be sunken, 2. rise of groundwater level have to be hindered, 3. level of groundwater have to be regularly controlled, as follows:

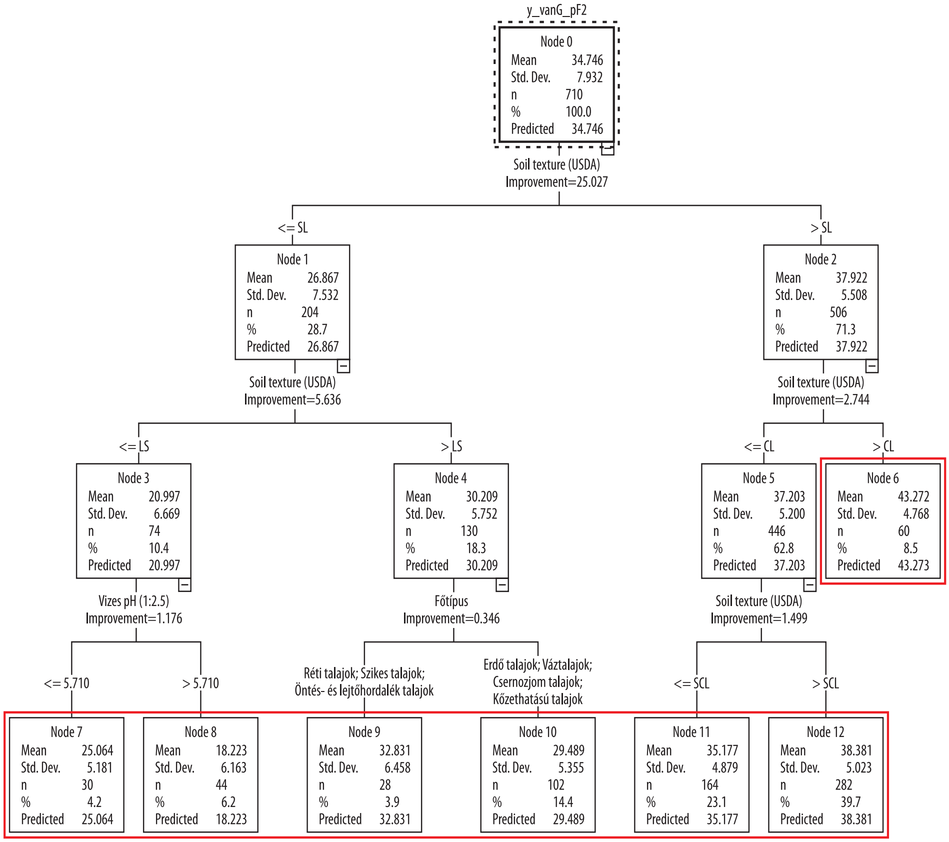

Fig. 3. Water content estimation, an example for pF = 2, classes definition based on soil main type, soil reaction (pH water) and texture class (USDA). M = predicted mean value of the node; STD = standard deviation; n = number of samples, % = percentage of samples used at the node; I = improvement; SL = sandy loam; LS = loamy sand; CL = clay loam; SCL = sandy clay loam. The relation signs in context of the USDA texture classes can be interpreted by the following sequence built in the model: 1 = sand; 2 = loamy sand; 3 = sandy loam; 4 = loam; 5 = sandy clay loam; 6 = sandy clay; 7 = silty clay; 8 = silt; 9 = silty clay loam; 10 = clay loam; 11 = silty clay; 12 = clay.

Lowering the groundwater level is recommended, where the average depth of the groundwater level is shallower than the critical groundwater level.

It is recommended to *prevent rise of groundwater level*, where the average water level of the groundwater level is 0–1 m below the critical ground water level.

Regular monitoring of groundwater level is recommended, where the average depth of the groundwater level is at least 1 m below the critical groundwater level.

The process-based method to compile an irrigation risk map, evaluates the relative differences between the „present" and „predicted" salt status of topsoil. Five vulnerability categories have been distinguished on the "Salinization risk map" (*Figure 6*), as follows:

Non-vulnerable areas: Particularly less clayey (typically sandy) areas and where salinity of groundwater is typically low and there is no salt in the topsoil.

Slightly vulnerable areas: Areas bordering non-vulnerable areas with not significant soil salinity.

Moderately vulnerable areas: These areas are located between the non-vulnerable and vulnerable areas, including typical

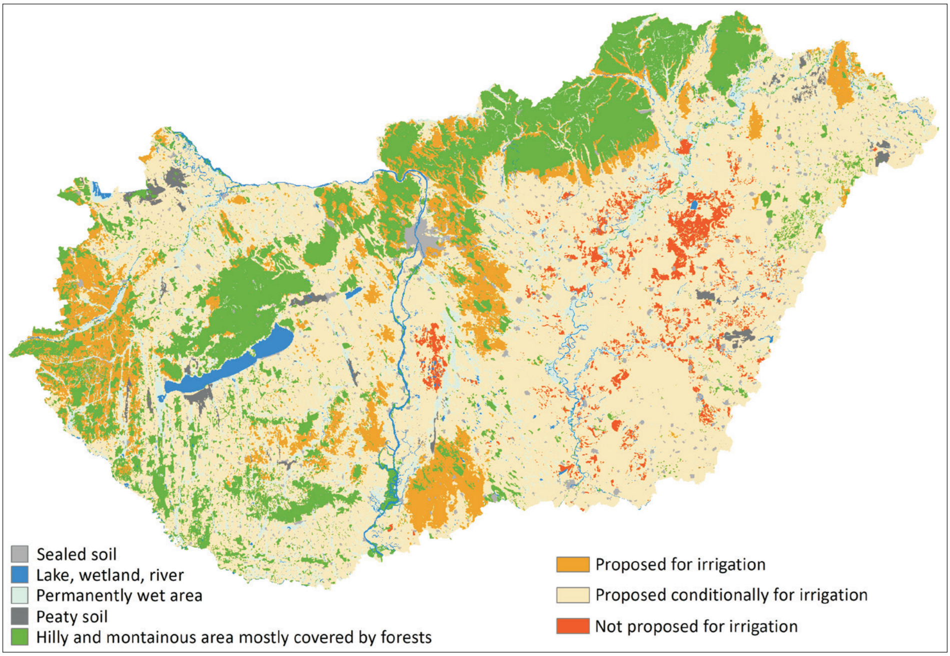

Fig. 4. Map of irrigation possibilities

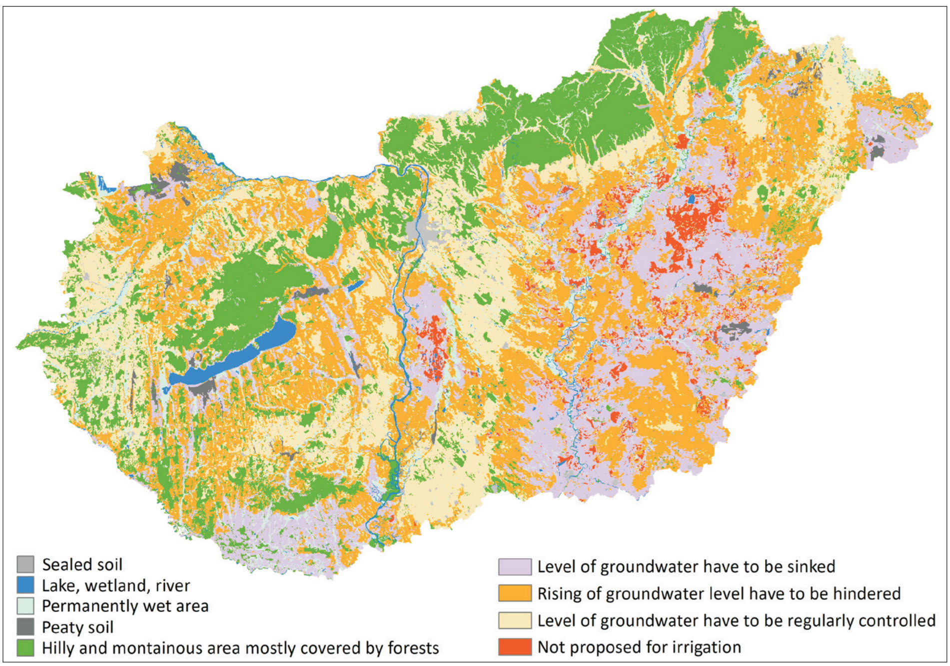

Fig. 5. Irrigation conditions. Map shows the necessary operations to maintain irrigation.

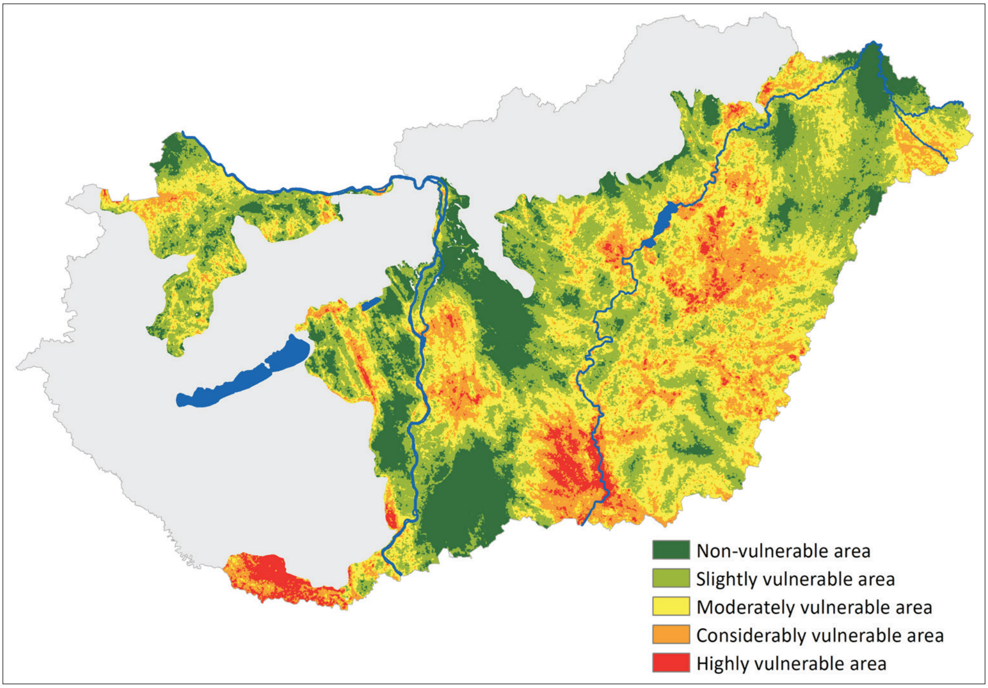

Fig. 6. Salinization risk map

plain regions, mainly in the areas of Tisza, Hortobágy-Berettyó and Körös rivers and have either high clay content, salt content in groundwater or shallow water-table. Certain areas have some salinity in the topsoil.

Considerably vulnerable areas: Most of these areas are salt-affected to some lesser degree than the most saline next category.

Highly vulnerable areas: Most of these areas are currently sodic and/or saline in topsoil. These areas are under the influence of shallow water-table, the salt content of groundwater is high and the soil salt content increases as a result of increasing water-table levels.

Comparison of the "Salinization risk map" *(Figure 6)* with the "Map of irrigation possibilities" (see *Figure 4*) shows that the two approaches give similar results, generally. The territory proposed for irrigation is close the same as the non-vulnerable regions. Moderately vulnerable and slightly vulnerable category (see *Figure 6*) cover 70 per cent of the „to be irrigated conditionally" areas. The sum of highly vulnerable and considerably vulnerable categories covers 20 per cent of it. About 63 per cent of the „not proposed" region belongs to moderately vulnerable or slightly vulnerable category.

The pattern shown in the „Salinization risk map" reflects mainly the independent water-table depth and salinity maps; but effect of clay content and aridity is not dominant. Tóth, T. *et al.* (2002) and Castrignano, A. *et al.* (2008) proved the effect of soil fineness, Zhou, D. *et al.* (2013) considered aridity as influential parameter.

The spatial distribution of salinization risk categories along soil productivity classes

Soil productivity classes serve crop production purposes. Their definition includes basic soil characteristics (taxonomic soil type and soil properties). The lower class number refers to higher production potential. Soil productivity class map was derived from the national soil type map of Hungary (Pásztor, L. *et al.* 2018).

The productivity class V. involves the already salt-affected regions, this class will not be discussed in the further evaluation. Combining the salinization risk and soil productivity maps, we get the regional distribution of the vulnerability categories within the individual productivity classes *(Table 1).*

The productivity class I. covers the most fertile areas, with deep soils and very good water management and nutrient supply, their cultivation is relatively easy ("chernozems-class" in short term). About 30 per cent of its territory belongs to the moderately vulnerable category, on the Csongrádi-sík (Csongrád Plain) geographical microregion in largest extension (*Figure 7.* represents the mentioned locations). More vulnerable is the southern part of Hajdúhát microregion, the loess-part of South Kiskunság microregion and some parts of the Solti-sík (Solt Plain) microregion, which delineates mostly the meadow chernozem areas within the class.

The productivity class II. represents mostly forest soils with good water management and nutrient supply. Less than 20 per cent of its area is vulnerable to secondary salinization, mostly on the southern part of the Pápa-Devecseri-sík (Pápa-Devecser Plain) microregion.

The productivity class III. involves rather heavy soils ("clayey meadow soils") lying on deeper areas of the Great Hungarian Plain, with large water retention but weak conductivity affected by unfavourable excess water, periodically. This group is the most vulnerable to secondary salinization, about 65 per cent of its territory belongs to the moderately/considerable or highly vulnerable categories. Its vulnerable territories follow mostly the riverside areas, the former floodplains along the Tisza, Körös, Maros and Dráva rivers and extend remarkable in the marshy Hanság, Kis-Sárrét and Szatmári-sík (Szatmár Plain) microregions.

Loose sandy soils belong to productivity class IV. The low amount of fine clay particles and organic matter causes low water-holding capacity in these soils that is prone to drought. Through its large amount of macropores, the dissolved nutrients can easily be leached out from the profile. They occupy mostly uplifted geographic position; therefore, the ratio of vulnerable areas is relatively small within this class. The most vulnerable territories concentrate in the eastern part of the Dorozsma-Majsai homokhát (Dorozsma-Majsa Sand Ridge) microregion.

Soil compaction and vulnerability for structural degradation

The estimates for the stability of the soil structure against long-term irrigation have not been incorporated into the national level analysis of soil conditions before. In the estimation of vulnerability, the soils have been grouped according to the effect of all the basic soil properties on the structural properties. The medium or strong vulnerability of the soil structure to degradation is not considered as a negligible cause for irrigation, but the stability of the structure is more dependent on the proposed intensity of irrigation *(Figure 8).*

Table 1. Areal distribution of salinization risk (vulnerability) categories within the soil productivity classes

Vulnerability category	Soil productivity class (area, ha)				
	Chernozems	Forest soils	Heavy soils	Sandy soils	Salt-affected soils*
Non-vulnerable	368,995	95,004	125,086	286,872	10,615
Slightly vulnerable	670,522	82,664	562,325	387,789	145,049
Moderately vulnerable	507,682	34,074	709,640	151,408	327,737
Considerably vulnerable	185,586	5,570	466,777	56,157	216,932
Highly vulnerable	14,431	1,903	131,352	25,529	38,722

*More details are provided in the text.

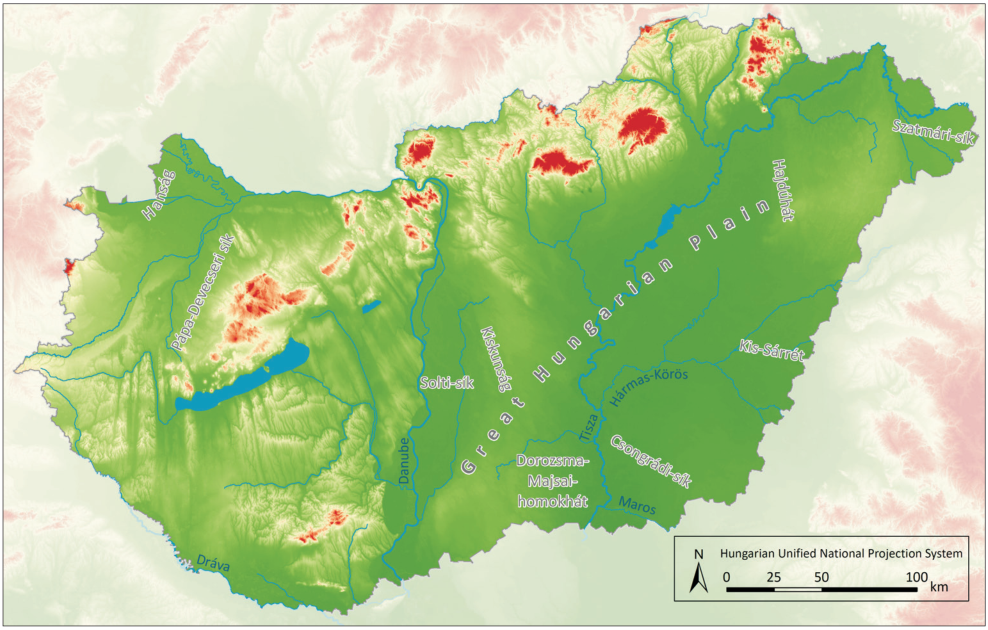

Fig. 7. Relief and hydrography overview map of Hungary with the locations mentioned in the salinization risk (vulnerability) results section

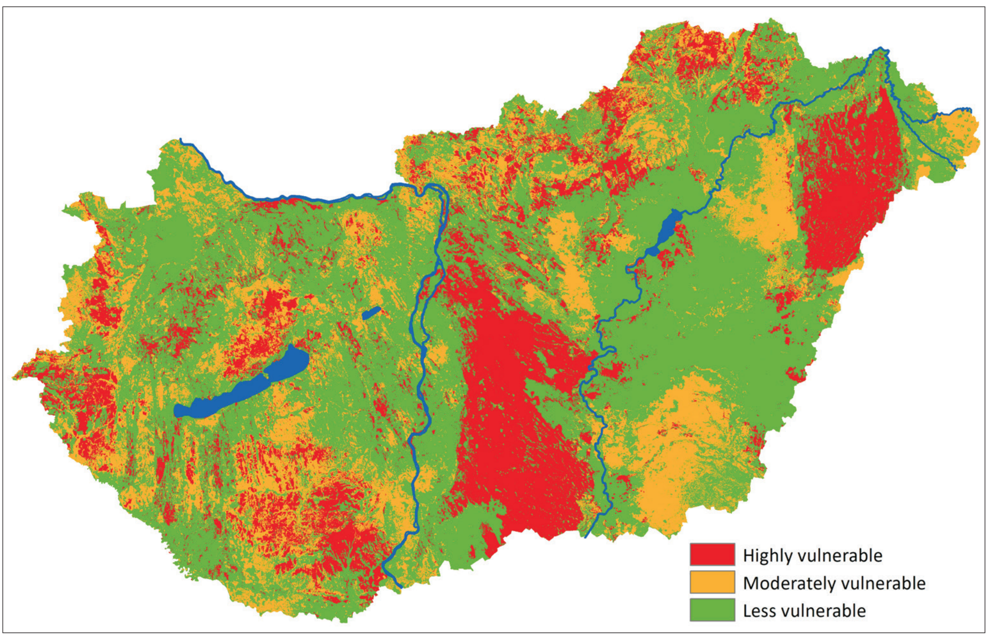

Fig. 8. Vulnerability of soils for structural degradation

Three categories were distinguished on the map of "Vulnerability of soils for structural degradation":

1. Highly vulnerable soils for structural degradation: these are the soils whose structure can easily degrade as a result of even short-term low-dose irrigation; they become prone to compactness, disaggregation, crusting. After that structural elements break down, fine particles (clay and fine silt fraction) move/are leached down into deeper/lower soil horizons, fill the pores, promoting soil compaction.

2. Moderately vulnerable soils for structural degradation: these are the soils whose structure may degrade due to longer and/or more intense irrigation. Soil can disaggregate, crusting and compaction can occur. Those soils belong to this group, which have medium strong structure, medium textured. Their colloids and humus contents are between the two other categories.

3. Less vulnerable soils for structural degradation: these are the soils that retain their good structural status through longer and/or intense irrigation; they tend to be less susceptible to slaking and compaction and disaggregation. Those soils belong here, which are mainly rich in colloids and humus, strongly structured, and heavy-medium textured.

This index of vulnerability to structural degradation is only one point of view to indicate soil's liability to physical failure. The index shows on which soil structural degradation can occur due to even a little amount of irrigation water, and which soils are more resistant.

If we examine current structural conditions of soils, and what can be the result of long-term irrigation, we will get another point of view. For example, an upper layer of humus-rich sandy soil has weak structure, its structure elements easily fail even after a small dose of irrigation water, and there is a decreasing volume of micro-pores. However, this structure failure is not excessive, RFC value does not drop much; we can have similar yield on this soil with continuous irrigation and nutrients supply. In case of a chernozem soil with good structure, as the result of continuous irrigation, with unsuitable doses, soil structural units can disaggregate slowly, and this change would be drastically great/harmful (in structural condition, water- and air-management). Consequently, the rate of harmful effects can be very diverse, and contrasting opinions might be formed on it.

Comparison of the vulnerability map for structural degradation with the map of conditions for irrigation shows that the half of the areas proposed for irrigation are highly or moderately vulnerable for structural degradation.

Conclusions

Nationwide planning of irrigation can be made only if we have spatially exhaustive maps and recommendations for the different areas. The presented irrigation risk estimations focus on soil-related threats and aim to support national level decision-making. We applied both of steady state and process based calculation methods for the spatial identification of potentially affected areas. Novelty of this study lies in:

– to actualize and spatially extend the earlier developed critical-level based calculation method in digital data processing and mapping environment,
– to develop two calculation methods for mapping salinization risk,
– to incorporate estimations for the stability of the soil structure against long-term irrigation, which have not been used in national level analysis before.

The computational framework shown is suitable for compiling more detailed maps, which can serve the local demands better, if additional data with sufficient thematic and spatial resolution are available.

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