Functional soil mapping for identification of NVZs

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SUMMARY

Functional soil mapping is a promising tool for the regionalisation of nitrate vulnerability feature of land. Our objective was to elaborate functional soil mapping approaches, which are able to provide nitrate vulnerability maps in national level as well as at regional scale for pilot areas with different geographical conditions. In both cases rather simple environmental inference models were taken into account with few but really prevailing environmental factors simulating only the dominant processes operating in the area of interest. The features of the applied methods differ in the case of the two levels, however there are common considerations, too. In two pilot areas -with different physiographical conditions- a deterministic model family was introduced for the evaluation of the land vulnerability for nitrate hazard at regional scale. For the evaluation of the nitrate leaching hazard in Hungary at a scale of 1:1M a stochastic approach was applied. Appropriate evaluation of the resulted digital functional soil maps makes the identification and designation of nitrate vulnerable zones possible, which is strictly required by Council Directive of EU on nitrate pollution of waters.

INTRODUCTION

Soil maps and more generally spatial soil information systems are designed for fulfilling various requirements and demands expressed by the society. However conception on soil map of potential user is often not well defined. Soil map can be usually considered on three different levels: map displaying (i) primary soil properties or soil classes, (ii) secondary soil properties, derived from primary properties and (iii) soil function and/or threats inferred from soil properties and external data. Primary soil maps are traditionally provided by soil surveys generally using soil mapping units. Digital soil maps using specific spatial inference models for the spatial extension of measured/observed data predicting soil properties over the full range of an area are also ranked as primary soil maps. Elaboration of soil maps with secondary soil properties, in addition to spatial inference, also requires property inference in the form of pedotransfer rules or environmental models. Soils maps can also depict soil related features in the context of soil functions and/or degradation processes. The resulted product is a functional soil map, which regionalises a specific soil function, soil threat (Dobos et al., 2006).

Recently there has been a shift in the characterization of the soils from their traditional description/classification towards their functions. Soil functions (SFs) are actually various ecologic and socio-economic roles of soils. The six key SFs (Blum 1993, CEC 2002) are as follows:

- Food and other biomass production.
- Environmental interaction: storage, filtering, and transformation.
- Biological habitat and gene pool.
- Platform for man-made structures as buildings, roads etc.
- Source of raw materials.
- Cultural heritage.

Nitrate is the most widespread contaminant of groundwater and its loading is still an unsolved environmental problem. Diffuse input by the rural economy is the main cause of this loading. Council Directive of EU (EC, 1991) on nitrate pollution of waters requires identification of nitrate polluted waters and vulnerable zones together with the establishment and implementation of action programmes in order to reduce water pollution from nitrogen compounds in vulnerable zones. One of the used specific criteria refers to groundwaters, which contain or could contain, if preventative action is not taken, nitrate concentrations greater than 50mg/l. All known areas of land contributing to nitrate pollution of these waters are to be identified for designation as Nitrate Vulnerable Zones (NVZs). Farmers located within these NVZs are required to adhere to an Action Programme of measures to reduce the amount of nitrate lost from their land to the polluted waters. Specific vulnerable zones in national territories are expected to be displayed on maps.

Designation of NVZ's, that is identification of areas with higher risk of N-leaching, can be carried out by interpreting functional soil maps representing soil's nitrate filtering function. In order to produce a map of potential nitrate leaching, data on soil are to be combined with spatial information on specific environmental factors (climate, terrain, groundwater, land use etc.) in appropriate inference models. This is just the issue what functional soil mapping is supposed to produce.

Nitrogen cycle is a complicated system since N is an ingredient of numerous organic and inorganic chemical compounds with complex transformation and transfer processes (Kovács et al. 1995), the nitrogen dynamics in soils and the processes which lead to leaching are very complex (Grignani and Zavattaro, 2000), thus it is generally difficult to quantify the environmental impacts from agricultural practices. Integration of knowledge related to environmental conditions of a certain area can be carried out in many ways: applying rather simple or really complex; deterministic or stochastic approach mapping/modelling on various (from global to local) scales.

Stanners and Bourdeau (1995) provided a European overview of nitrate leaching taking into consideration spatial distribution of nitrogen application, soil and climate. Boumans et al. (1999) compiled a map showing nitrate in the uppermost meter of groundwater in the Netherlands combining remote sensing, national inventories and statistics with maps of environmental factors. Olsen and Kristensen (1998) developed an assessment system for assessing risks of nitrate leaching on the regional as well as national scale, having municipalities as the level of aggregation in Denmark. 4M model (Fodor et al., 2002) which is based on CERES and CROPGRO models but enriched by several external routines using soil, crop, weather and technology inputs, has been applied to create estimation of nitrate leaching in regional scale for Hungary's Euro-regions (Kovács, 2005). Hack-Ten Broeke (1998) focused on nitrate leaching to the groundwater as a result of the land use system at farm level and translated the results to other sandy soils in the Netherlands. Bíró et al. (1998) evaluated risk assessment of nitrate pollution in a watershed level. McLay et al. (2001) investigated whether nitrate pollution could be predicted on the basis of landuse and topsoil features generating leaching risk. Lake et al. (2003) used expert knowledge to combine GIS-based evaluation of four relevant factors into a measure of vulnerability. Schnebelen et al. (2004) developed an upscaling approach for the soil-crop model STICS in order to predict the impact of agricultural practices on nitrate leaching on both plot and regional scales. Vachaud (2002) used distributed models to characterise the sensibility of nitrate leaching at catchment scale.

In can be stated in general that considerable progress has been made in the field of soil nitrogen modelling. Coupling of soil and groundwater modelling is a straightforward approach for the investigation of interactions between various processes related to the N-problem. However, although various integrated hydrological models have been developed, process-oriented modelling approaches implementing coupled N-transport and turnover in soils and groundwaters of lowland watersheds are still missing (Wriedt 2007). El-Sadek et al. (2003) modelled nitrate leaching using a field-scale quasi-two-dimensional mechanistic flow model (DRAINMOD) in combination with a GIS. Mantovi et al. (2006) used MACRO and SOILN field-scale models in order to verify the reliability of simulated water flow and nitrogen transport in their nitrate leaching study. The modelling approach of Wriedt (2006) has been a step towards bridging the gap between simple large-scale models and detailed small-scale studies, maintaining process orientation while allowing to consider landscape heterogeneity.

An important limitation of the substantial, detailed methods is the necessity of information concerning the spatial distribution of input parameters and the cost of associated measurement campaigns. Simpler (and consequently less precise) environmental models can produce results quickly, and not really seldom time is more dominant data modelling quality factor than model accuracy. For overview studies rawer but simpler model might prove to be sufficient and at the same time more economic. On the other hand complex dynamic models do not necessarily produce better results than much simpler and partly lumped models. The reasons for the disappointing results of distributed models can be attributed to the uncertainty involved in estimating and measuring the large number of input variables. There is also need for much simpler environmental inference models simulating only the dominant processes operating in the area of interest (De Roo, 1998).

MATERIALS AND METHODS

Our objective was to elaborate functional soil mapping approaches, which are able to provide nitrate vulnerability maps in national level (~ 1:1,000,000) as well as at regional scale (~ 1:50,000 - 1:25,000) for pilot areas with different geographical conditions. In both cases rather simple environmental models were used taking into account few but really dominant environmental factors. The features of the applied methods differ in the case of the two levels, however there are common considerations, too. Beside soil characteristics the effect of precipitation and the accessibility of groundwater determine the possibility of nitrate contamination of groundwater. Physico-chemical characteristics of soils represent their buffer capacity/resistance feature according to the transfer of pollution. Precipitation surplus induces nitrate pollution to move downwards. Finally, location of groundwater table determines the distance to be done by nitrate to reach the water body.

Regional scale approach

Two pilot areas were selected for the implementation (Fig 1.). The two regions differ in their environmental conditions; land use, exposure to pollution and even the two sets of data available for them are distinct. The two pilot areas are well-defined physiographical units each. Csepel Isle is enclosed by River Danube; Watershed of Tetves Creek is a thoroughly studied subcatchment of the Lake Balaton (Németh et al., 2002). A simple comparison of the two pilot areas is given in Table 1.

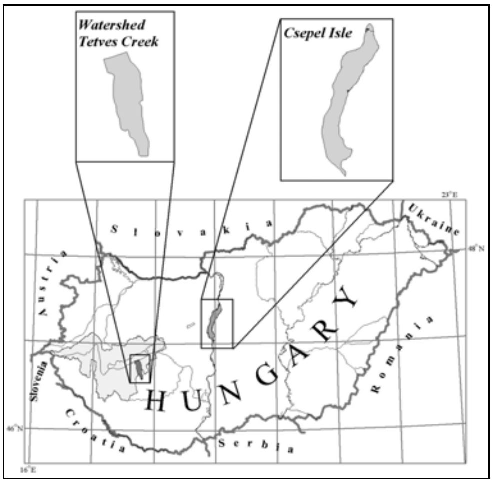


Figure 1: The location of the two pilot areas within Hungary.

GIS based mapping of soil vulnerability is composed of a hierarchical structure of models and the final map is a result of subsequent model selections (Linhart and Zucchini, 1986). On the first level the influencing factors are identified: 'which environmental parameters determine the given vulnerability feature?' On the second level the available data on the formerly selected parameters are identified: 'what kind of datum is measured and/or available at all on the given influencing parameter?' On the third level some derived factors may be calculated: 'may the input data be converted/transformed into more appropriate format?' On the forth level the mathematical model is set up: 'what is the functional relation between the vulnerability feature and the determining factors?' On the further levels the refinement of the mathematical model takes place: 'which value should be assigned to the parameters to get good/better/the best result?' This procedure induces a model family. In this context compilation of the vulnerability map is the result of iteration where data characteristics and model parameters are in interaction.

	Csepel Isle	***Watershed of Tetves Creek***
physiography	plain, island	hilly, catchment
area	248 km^2	120 km^2
dominant land use	arable land	forest, pasture
soil information	PemeTIR database	DKDIS
groundwater information	detailed, available	incomplete, derived
precipitation information	poor	poor

Table 1: Some characteristics of the pilot areas.

The following data representation of the influencing parameters was available. For the description of precipitation annual average precipitation measurements were used. In first approximation it characterizes properly the degree of induction for leaching. For better results seasonal variability in precipitation as well as effects of non-natural water input (irrigation) should be considered. For the description of groundwater table measures on its average depth were used. To achieve more precise results, seasonal changes also in this parameter should be accounted for. For the representation of resistance of soils against the transfer of nitrate pollution their physico-chemical characteristics were quantified, namely texture and organic matter content together with depth of rootable depth of soils. For better results vertical variability in these parameters should be also taken into account in the form of data by soils horizons.

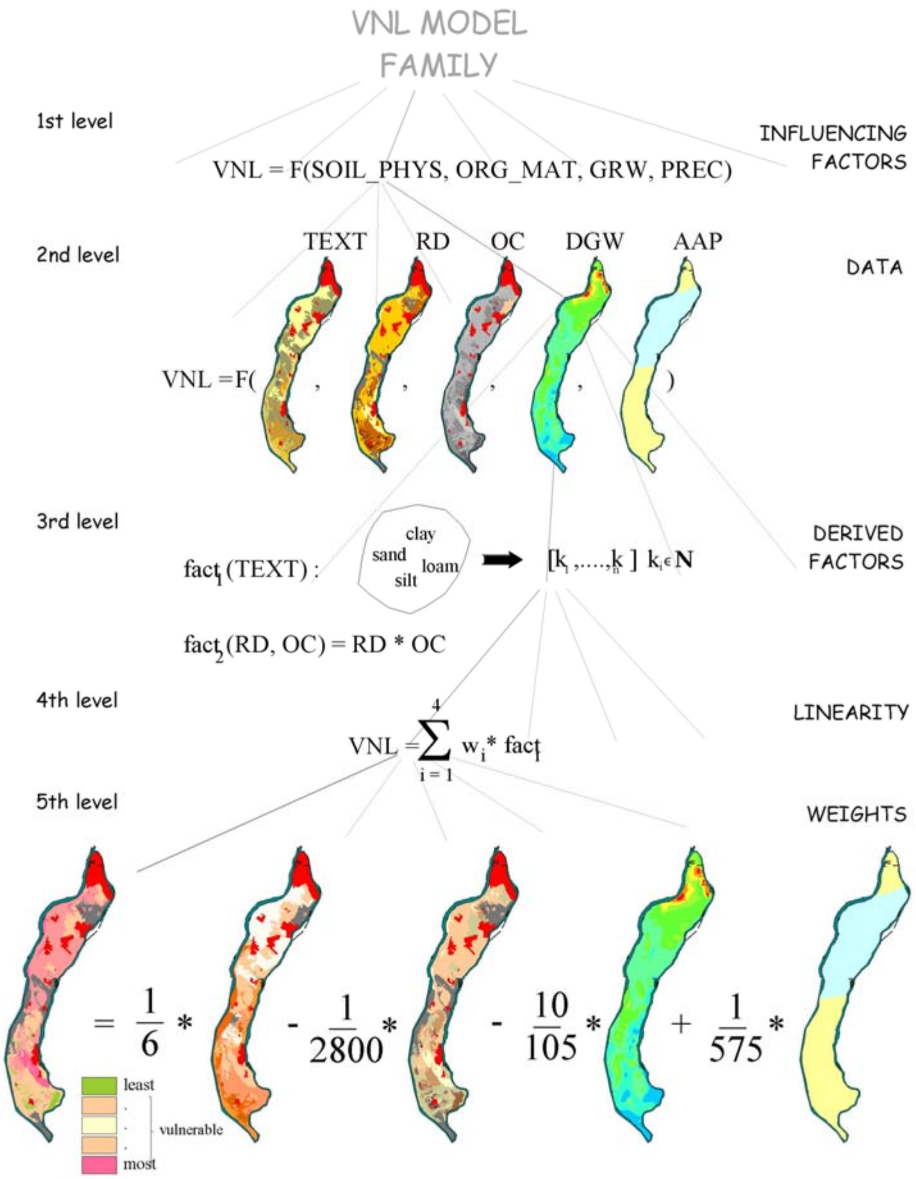
Two secondary factors were derived from the primary soil data. Organic matter content of soil is a density type parameter, consequently its product with rootable depth provides a quantity featuring column density of organic matter which is a much more proper parameter in our context. On the other hand, texture information on soil is generally (and as it was in the present case) given in categories. Thus according to their transferability, soils were described by numerical values on ordinal scale based on the knowledge of their texture properties.

The next step was the set up of the mathematical model. As a first approximation, general linear model was used as it is commonly used in multivariate methods.

$$V=\sum_{i=1}^{4} w_i * F_i \quad \text{, where}$$

V is the measure of vulnerability, F_i is the ith factor and w_i is its corresponding weight. To get final result, w_I should be determined/defined in formula. In the simplest case role of the four (original or derived) factors can be considered uniform. In this case weights merely help to standardize factors that is to make their scale comparable. Fig. 2 shows the steps how the final map was derived for Csepel Isle.

A crucial step of the procedure is the zonalization/regionalization of the vulnerability categories. There are numerous difficulties emerging at this point. The derived vulnerability values are numerical, but they do not represent physical values.



VNL: vulnerability to N-leaching;
SOIL_PHYS: physical properties of soil; ORG_MAT: organic matter; GRW: groundwater; PREC: precipitation;
TEXT: (soil) texture; RD: rootable depth; OC: organic matter content
DGW: depth to groundwater; AAP: annual average precipitation

Figure 2: Deduction of the vulnerability map for Csepel Isle.

The minimum and maximum values can be interpreted on a relative scale and neither in the case of the two pilot areas can be compared. There are no reference data, which could be used for transformation of these values to physical values. There are no threshold values for the different measures of vulnerability. Since generally there are no straightforward mathematical rules to solve this problem, spatial categorization (zoning) of the land according to its sensitivity might be required by decision-makers.

This lack of formal completion of the procedure can be more or less explained by the fact, that designation of final NVZs can be assisted rather than solved by GIS, because final decision is always policy dependent. In any case there are some opportunities to advance in the solution of this problem. One of them has been applied completing the ’pure’ mapping procedure in our other soil function mapping approach used at national scale.

National scale approach

In our small-scale approach N-leaching hazard was mapped in Hungary at a scale of 1:1M. A stochastic environmental model was elaborated for the evaluation of the land vulnerability. Three influencing factors proved to be relevant represented by applicable and available spatial information.

- Hungarian soils were classified into nine main soil water management categories according to their hydrophysical properties (Várallyay et al., 1980). The categories characterize infiltration rate, permeability, and hydraulic conductivity, field capacity and water retention features of Hungarian soils.
- Input map of ’Annual average precipitation’ is based on data collected by the National Meteorological Institute and registered by meteorological stations for the period of 1951-1980.
- Map of ’Groundwater depth’ is based on data collected in the frame of groundwater observation well network of Scientific Research Center for Water Resources and registered for the period of 1961-1980. The scale of this map is also 1:1,000,000 and covers non-mountainous region of the country.

To complete our objectives, the maps of various factors, as different layers, were overlaid. From mathematical/statistical point of view units of the resulted map are elements of a multidimensional factor space. Statistical behaviour of the intersected mapping units in this three-dimensional feature space was then studied. Since the number of units does not necessarily reflect their extent, their areas were used as weights in the statistical analysis.

Applying pure clustering techniques where there is no a priori rule to define the (optimum) number of groups, one needs some measure of the reality of the groups found by the partitioning algorithm. Finding the extreme value of an information theoretic criterion can provide the best fitting model and the best partition of the sample. Many model selection procedures may be found in the literature. Most of them take the form of a penalized likelihood, where a penalty term is added to the log-likelihood in order to compromise between the goodness-of-fit and the number of parameters. The ancestor of these models was developed by Akaike (1972) and we also turned to it, since it provides a versatile procedure for statistical model identification. The definition of Akaike's Information Criterion (AIC) is:

$$AIC=-2\ln(\text{maximum likelihood})+2(\#\text{ of parameters}).$$

One of the most desirable properties of AIC is that (as it penalizes for large degrees of freedom) it tends to adopt simpler models and achieves a principle of parsimony. As AIC is basically an estimator of the risk of a model selection, it should be minimized to select among the alternative possibilities, that is the smaller is AIC the better is the classification. Its estimate can be computed by ,

$$AIC(\text{estimated})=n\ln(R)+2p,$$

where n is the number of objects to be grouped, p is the number of estimated parameters and R is the residual sum of squares of deviation from the fitted model (Akaike, 1974). For the determination of optimal classification, a sequence of non-hierarchical clustering was carried out and AIC(estimated) was calculated for each partition.

RESULTS

Estimated AIC function for our dataset showed two local minima at 5 and 12 categories respectively. The 12-class solution in our scale provides too detailed thematic resolution, which might require more complex, e.g. multi-level or multi-furcated explanation. Consequently, merely the 5-class solution was further studied. The identification of vulnerability categories was facilitated by displaying the resulted categories of the units on the intersected map. The different categories showed well recognizable patterns. Analysing their geographical distribution and extent, it was also possible to rank the resulted categories into a one-parameter sequence from severe hazard to the case of no hazard.

To test applicability of the procedure, two further degradation processes were considered. Susceptibility of soils to physical degradation (SSPD) and susceptibility of soils to acidification (SSA) were formerly evaluated by analogous methods resulting in specific soil degradation maps for Hungary (Várallyay et al., 1989a,b) providing suitable reference for the outcome of our method.

In the classic approach the eight categories of the SSPD map were determined using six soil factors (genetic soil type, soil reaction and carbonate status, soil texture, organic matter content, rootable depth, hydrophysical properties). Our stochastic procedure also provided eight categories as optimum solution. After the identification and cross-correlation of the stochastic and deterministic classes 76% spatial coincidence was experienced.

In the classic approach the six categories of the SSA map were defined based on the various combinations of six soil factors (soil reaction and carbonate status, soil texture, organic matter content, rootable depth, hydrophysical properties, parent material). Interpretation of the result of our procedure did not prove to be as straightforward as in the case of SSPD. Taking into consideration that one of the soil factors (namely soil reaction and carbonate status) directly defines three of the susceptibility categories, this factor and the respective three categories were excluded and the analysis was repeated, but neither this way three-category solution resulted, optimum classification was experienced at ten classes. However cross-tabulation and spatial analysis of the result allowed merging these ten categories into three. Spatial coincidence of these three merged stochastic and the respective deterministic categories proved to be 81%. Consequently, the ten stochastic categories can be considered as refined subclasses of the traditionally used classes.

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BIBLIOGRAPHY

Akaike H., Use of an information theoretic quantity for statistical model identification. In: Proc. 5th Hawaii Int. Conf. System Sciences: 249-254, 1972.

Akaike H., A new look at the statistical model identification. IEEE Transactions on automatic control AC-19: 716-723, 1974.

Bíró T., Thyll Sz., Tamás J., Risk assessment of nitrate pollution in lower watershed of the Berettyó River. In: Gy. Filep (ed.) Soil water environment relationships. Wageningen – Debrecen: 239-247, 1998.

Blum, W.E.H., Soil Protection concept of the Council of Europe and Integrated Soil Research. In: H.J.P. Eijsackers, T. Hamers (eds.) Soil and Environment Vol I, Integrated soil and sediment research: a basis for proper protection. Kluwer Academic Publisher, Dordrecht: 37-47, 1993.

Boumans L., Drecht G., Fraters D., Nitrate in shallow groundwater of the sandy regions of the Netherlands, In: Proc. of Conference Spatial Statistics for Production Ecology, Vol. 1. International Statistical Institute, 1999.

Commission of the European Communities. Towards a Thematic Strategy for Soil Protection. 179 final, Brussels, 2002.

De Roo A. P. J., Modelling runoff and sediment transport in catchments using GIS. Hydrological processes 12: 905-922, 1998.

Dobos E., Carré F., Hengl T., Reuter H.I., Tóth G., Digital soil mapping as a support to production of functional maps. EUR 22123, Office for Official Publications of the European Communities, Luxemburg.

EC 391L0676 Council Directive 91/676/EEC. (1991). The protection of waters against pollution caused by nitrates from agricultural sources. Official Journal L 375 , 31/12/1991, pp. 0001 – 0008

El-Sadek A., Feyen J., Radwan M, El Quosy D., Modeling water discharge and nitrate leaching using DRAINMOD-GIS technology at small catchment scale. Irrigation and Drainage 52: 363 – 381, 2003.

Fodor N., Máthéné-Gáspár G., Pokovai K., Kovács G.J., 4M - software package for modelling cropping systems. European J. of Agr 18/3-4: 389-393, 2002.

Grignani C., Zavattaro L., A survey on actual agricultural practices and their effects on the mineral nitrogen concentration of the soil solution. Europ. J. Agron. 12: 251-268, 2000.

Hack-Ten Broeke M.J.D., Nitrate leaching to groundwater at experimental farm 'De Marke' and other Dutch sandy soils. Netherlands journal of agricultural science, 49: 195-205, 2001.

Kovács G.J., Ritchie J.T., Németh T., Testing simulation models for assessment of crop production and nitrate leaching in Hungary. Agricultural Systems 49(4): 385-397, 1995.

Kovács G.J., Applying models to decision support tools. In: J.L. Hatfield (ed.) The Farmers' Decision: Balancing Economic Successful Agriculture Production with Environmental Quality Soil and Water Conservation Society, Ankeny, Iowa, USA. Chapter 5: 77-112, 2005.

Lake I.R., Lovett A.A., Hiscock K.M., Betson M., Foley A., Sünnenberg G., Evers S., Fletcher S., Evaluating factors influencing groundwater vulnerability to nitrate pollution: developing the potential of GIS. J. of Environ. Manage 68(3): 315-328, 2003.

Linhart H., Zucchini W., Model selection. Wiley, New York. 1986.

Mantovi P., Fumagalli L., Beretta G.P., Guermandi M., Nitrate leaching through the unsaturated zone following pig slurry applications. Journal of Hydrology 316: 195–212, 2006.

McLayC.C., Dragten R., Sparling G., Selvarajah N., Predicting groundwater nitrate concentrations in a region of mixed agricultural land use: a comparison of three approaches. Environ. Pollut. 115(2): 191-204, 2001.

Németh T., Szabó J., Pásztor L., Bakacsi Zs., Elaboration of a complex GIS application in a catchment area. Water Science and Technology, 45:133-140, 2002.

Olsen P., Kristensen P., Using a GIS system in mapping risks of nitrate leaching and erosion on the basis of SOIL/SOIL-N and USLE simulations. Nutrient Cycling in Agroecosystems 50: 307-311, 1998.

Schnebelen N., Nicoullaud B., Bourennane H., Couturier A., Verbeque B., Revalier C., Bruand A., Ledoux E., The STICS model to predict nitrate leaching following agricultural practices. Agronomie 24: 423-435, 2004.

Stanners D., Bourdeau P. (eds.), Europe's Environment. The Dobris Assassment. EEA, 1995.

Vachaud G., Chen T., Sensitivity of a large-scale hydrologic model to quality of input data obtained at different scales; distributed versus stochastic non-distributed modelling. Journal of Hydrology 264: 101-112, 2002.

Várallyay Gy., Szűcs L., Rajkai K., Zilahy P., Murányi A., Magyarországi talajok vígazdálkodási tulajdonságainak kategóriarendszere és 1:100.000 méretarányú térképe (in Hungarian). Agrokémia és Talajtan, 29. 77-112, 1980.

Várallyay Gy., Leszták M., Susceptibility of soils to physical degradation in Hungary. Soil Technology 3. 289-298, 1989a.

Várallyay Gy., Rédly M., Murányi A., Map of the susceptibility of soils to acidification in Hungary. In: Ecological Impact of Acidification. Proc. Symp. Eco-systems, Oulu, Finland. Budapest.: 79-94, 1989b.

Wriedt G., Rode M., Modelling nitrate transport and turnover in a lowland catchment system. Journal of Hydrology (in press)