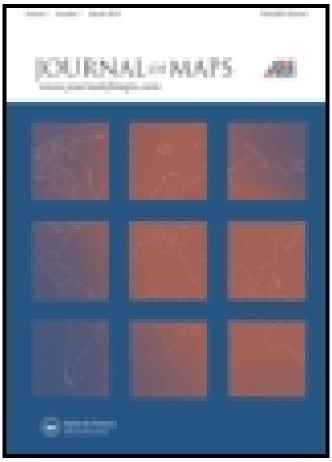

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SCIENCE

Spatial risk assessment of hydrological extremities: Inland excess water hazard, Szabolcs-Szatmár-Bereg County, Hungary

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Inland excess water hazard was regionalized and digitally mapped using auxiliary spatial environmental information for a county in Eastern Hungary. Quantified parameters representing the effect of soil, geology, groundwater, land use and hydrometeorology on the formulation of inland excess water were defined and spatially explicitly derived. The complex role of relief was characterized using multiple derivatives computed from a DEM. Legacy maps displaying inland excess water events were used as a reference dataset. Regression kriging was applied for spatial inference with the correlation between environmental factors and inundation determined using multiple linear regressions. A stochastic factor derived through kriging the residual was added to the regression results, thus producing the final inundation hazard map. This may be of use for numerous land-related activities.

Keywords: digital mapping; environmental correlation; excess water; regression kriging; risk regionalization

1. Introduction

Inland excess water is surplus surface water forming due to the lack of runoff, insufficient absorption capability of soil or the upwelling of groundwater (Rakonczai, Farsang, Mezősi, & Gál, 2011). This interrelated natural and human induced phenomenon causes several problems in the flat-land regions of Hungary, which cover nearly half of the country. The term 'inland excess water' refers to the occurrence of inundations outside the flood levee that originate from sources differing from flood overflow (Koncsos & Balogh, 2008). There is a multiplicity of definitions, which indicate the complexity of processes that govern this phenomenon (Pálfai, 2001). Most of the definitions have a common part, namely, that inland excess water is temporary water inundation that occurs in flat-lands due to both precipitation and groundwater emerging on the surface as substantial sources. More recently the over-moistening of the soil of arable land is regarded as excess-water as well, as it also causes agricultural damage.

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Unfavourable climatic conditions might cause harmful effects on areas that were formerly floodplains, but are presently used as arable land (Figure 1). Extremities of global climate change are increasingly experienced in the Carpathian Basin (Mika, 1988, Pongracz, Bartholy, Matyasovszky, & Schangler, 2003, Puskás, Gál, & Farsang, 2012). After several dry years, extreme precipitation of recent years have made seasonal and permanent waterlogging the most serious agro-environmental problem in the Great Hungarian Plain (Koncsos, 2011; Rakonczai, Ladányi, Deák, & Fehér, 2012; Figure 2). As a consequence, preventive management of land requires sufficient information on the spatial and temporal distribution of inland excess water.

In Hungary the first attempts to map inland excess lowland water hazard dates back to the early 1980s. National and regional overview maps were compiled, mainly based on event frequency records (Pálfai, 1994, 2003). Agriculture and rural development, however, require more accurate and reliable maps, both spatially and thematically. Inland excess water is a complex process whose characteristics can only be determined by taking numerous factors into consideration. The evolution of geographic information systems (GIS), together with the availability of digital spatial information on those factors which significantly affect formulation of inland excess water, promise and potentially provide a suitable environment for the compilation of maps with the expected accuracy. There have been various recent initiatives for the GIS-based mapping of different features of inland excess water phenomena in Hungary (Jolánkai, Kardos, Koncsos, Kozma, & Muzelák, 2012; Koncsos & Kozma, 2012; Mucsi & Henits, 2010; Pásztor et al., 2009; Thyll & Bíró, 1999; van Leeuwen, Mezősi, Tobak, Szatmári, & Barta, 2012; van Leeuwen et al., 2013). Several international literature sources can also be cited, in which GIS and digital elevation model (DEM)-based modelling were used to map inundation processes of floodable areas (e.g. Natale & Petaccia, 2013; Sanders, 2007).

Figure 1. Spring inundation of arable land in Szabolcs-Szatmár-Bereg county, April 2006.

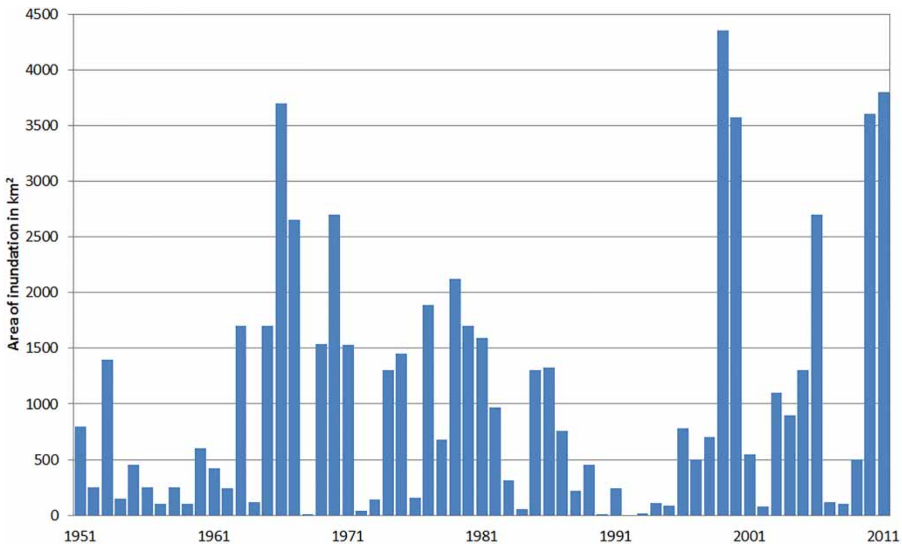

Figure 2. Estimated area of land affected by excess inland water in Hungary.
Source: Pálfai (2006) and VKKI.

Numerous digital environmental mapping methods (e.g. Franklin, 1995; Goovaerts, 2000; Hengl, 2009; Moran & Bui, 2002) have been developed to integrate geostatistical and data mining tools with detailed spatial information available for various environmental factors, providing ancillary data for these prediction techniques. These methods are mainly used in soil mapping, forming a wide community of digital soil mapping (DSM; Boettinger, Howell, Moore, Hartemink, & Kienast-Brown, 2010; Hartemink, Mcbratney, & Mendonça-Santos, 2008; Lagacherie, Mcbratney, & Voltz, 2007). The activity of DSM goes beyond mapping primary and secondary soil properties, with the regionalization of further levels of soil-related features (processes, functions and services) targeted (Minasny, Malone, & Mcbratney, 2012).

In our paper a significantly revised and improved version (inspired by our DSM experiences) of our earlier approach (hereafter cited as CEWHI1) – implemented in several counties of the Great Hungarian Plain, and published in various forms, mostly in Hungarian (e.g. Bozán, Pálfai, Pásztor, Kozák, & Körösparti, 2005; Bozán et al., 2009; Pálfai et al., 2004; Pásztor et al., 2009) – is presented.

2. Materials and methods

Szabolcs-Szatmár-Bereg County is located in the north-eastern tip of Hungary (Figure 3). It borders Ukraine, Slovakia and Romania with a total land area of 5936 sq. km. The area is crossed by the Tisza and its tributaries, which are the most important rivers of the county. The Upper Tisza and Nyírség are the dominant landscape regions of the county. The Upper Tisza region is an alluvial plain, where Holocene clay and silt sediments are deposited on Pleistocene gravel. Typical landscape elements are abandoned meanders, ox-bow lakes, levees, marshes and fens. The best known fen is the Ecsedi-láp, which resulted from floods of the Szamos and Kraszna rivers, but was subsequently drained at the end of the nineteenth century. The alluvial fan of the Nyírség was formed by rivers in the Pleistocene, and was covered by sand (and partly loess) in the Würm glacial period. At present the dominant landscape elements are: fixed and semi-fixed sand

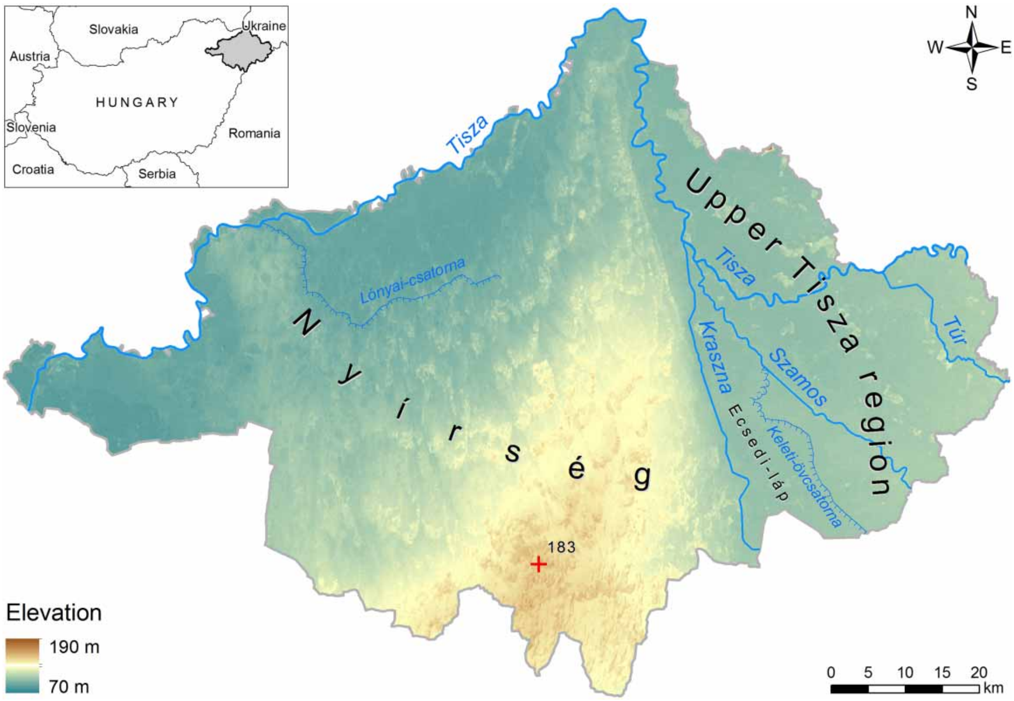

Figure 3. Topographic conditions of Szabolcs-Szatmár-Bereg County.

forms, dunes, deflation depressions and erosion-deflation lakes. The northern part of the Nyírség is covered by sandy forest soils, whilst the southern areas have loose wind-blown sand. Alluvial and meadow soils are found in the Upper Tisza region.

Three significant differences can be found in the proposed mapping approach as compared to CEWHI1.

(1) In CEWHI1 the environmental correlation between inundation frequency and the determining factors was studied on a regular 1 km × 1 km square grid. The aggregation of the spatially more detailed information caused a significant bias. Therefore, we used virtual point sampling: 1000 points were randomized in geographical space, representing virtual sampling locations. Conditional generalization was applied, prescribing a minimum spacing of 100 metres (twice the cell size applied in the spatial modelling) between the generated points and excluding built-up areas and open water surfaces. The values of the dependent (predicted) and independent (predictor) variables were identified at the randomized locations and their records were used in multiple linear regression analysis. The randomization process was repeated 100 times and the best performing set was retained.

(2) In CEWHI1 the risk of inundation was simply identified as the result of the multiple linear regression equation even though the coefficient of determination was sometimes low (typically $R^2 < 0.35$, with varying values for the different target areas). Regression-kriging (RK; Hengl, Heuvelink, & Rossiter, 2007) is a spatial prediction technique that combines the regression of the dependent variable on auxiliary variables with kriging of the regression residuals. It is mathematically equivalent to the interpolation method

variously called universal kriging and kriging with external drift. Based on numerous soil mapping examples (e.g. Hengl, Heuvelink, & Stein, 2004; Illés, Kovács, & Heil, 2011; Knotters, Brus, & Voshaar, 1995; Odeh, Mcbratney, & Chittleborough, 1995; Pásztor et al., 2014; Szatmári & Bartha, 2013), the authors realized that RK could provide an appropriate solution to the concern about the insufficient results of CEWHI1. Essentially, RK respects the fact that neither environmental correlation nor geostatistical interpolation alone is able to account for all spatial variation, that is to produce approximately perfect map products. They can be used as complementary spatial inference approaches, where one can improve the other's drawbacks.

(3) In CEWHI1 each affecting environmental factor was represented by a single variable. As a consequence, the complex role of terrain was rather poorly accounted for by the application of a sole, but meaningful parameter. By the introduction of RK and the application of novel GIS tools, the set of ancillary variables could be extended. In addition to relief intensity alone, further relevant morphometric features were introduced into the prediction phase of the method: profile and plan curvature, relative slope position, topographic wetness index, closed depression and channel network base level (SAGA, 2008).

The representation of the further five affecting environmental factors has not been changed, as the digital data for these factors have not shown comparable improvement. The effect of soil on the formation of inland excess water was modelled and spatially represented by the soil's water management characteristics, i.e. soil water conductivity. The effect of (agro)geology was modelled and spatially represented by a complex index, taking into consideration the depth and thickness of the uppermost aquitard. The effect of groundwater was modelled and spatially represented by the standard depth of groundwater, i.e. the average of its ten highest values within the last 50 years. The groundwater parameter came from well observations, thus it had to be interpolated, which was performed using co-kriging with elevation as a spatial co-variable (Chung & Rogers, 2011). The effect of land use was modelled and spatially represented by a numeric coefficient based on the National CORINE Land Cover database (CLC50; Büttner et al., 2004) and individually attributed to its categories using expert judgement. The effect of hydrometeorology on the formation of inland excess water was modelled and spatially represented by a humidity index (10% possibility of occurrence of root square of sum of monthly weighted precipitation and sum of monthly weighted potential evapotranspiration ratio).

A map displaying the relative frequency of inland excess water events was also compiled. Its source was the seasonal mapping of areas damaged by inland excess water. Data were provided by the responsible Water Directorates for 12 years from the period between 1962 and 2010. The majority were various (in extent, scale, accuracy, etc.) hand-drawn maps displaying inundation events. For the latter periods some digitally preprocessed or geo-referenced remotely sensed datasets were available. Paper maps were digitized and the full dataset integrated in to the final reference map (Figure 4). 'Vagueness' or inaccuracy is present in both reference data sources. The inaccuracy of hand-drawn inundation maps originates mainly from their compilation process: the used base maps show great diversity and the identification of waterlogged areas on these maps did not follow strict rules. As a consequence, the identified mapping units cannot be treated as real 'ground truth', just its approximation with varying spatial accuracy. Nevertheless remotely sensed data cannot be considered as absolute reference either, as they originate from temporally single observations, thus showing just a – not definitively representative – snapshot of a process.

Multiple linear regression analysis (MLRA) was used for modelling the joint effect of the selected environmental factors on inundation. First, principal component analysis (PCA) was performed on the affecting environmental auxiliary information and the resultant principal

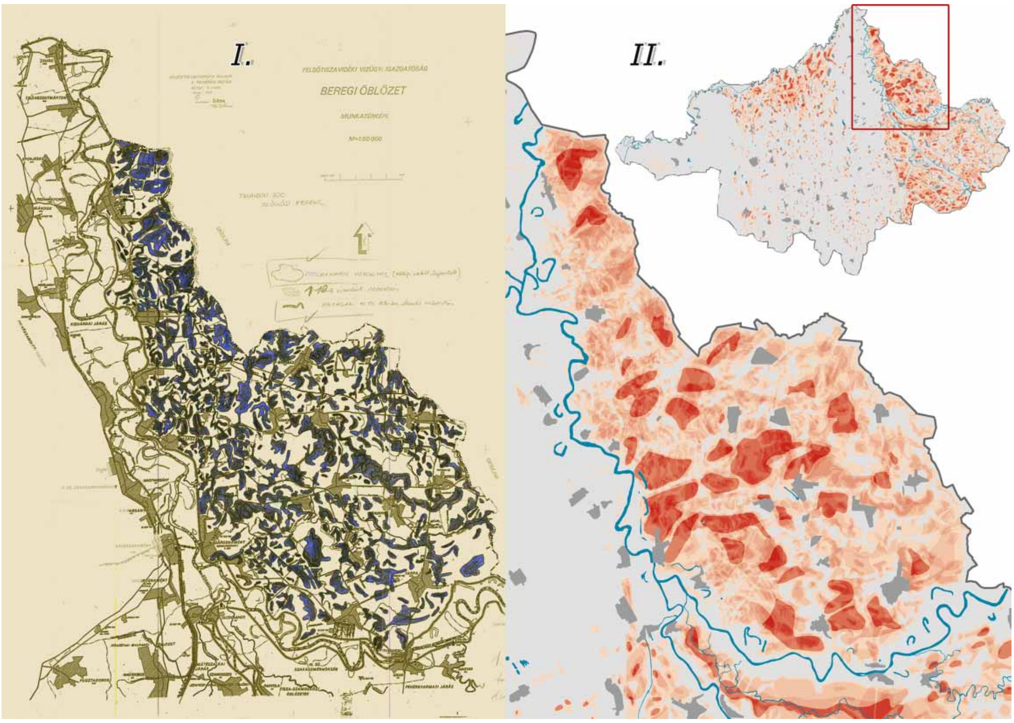

Figure 4. A hand-drawn inundation map (I.) and the corresponding part of the integrated reference map displaying the relative frequency of inland excess water events (II.).

components (PCs) were used in the further procedures. Since PCs are orthogonal and independent, they satisfy the requirements of the MLRA and decrease multicollinearity. The PCs were used as explanatory variables and the inundation data as response variable in MLRA, applying stepwise selection at the 0.05 significance level. The coefficient of determination varied between 0.15% and 0.25% in the course of the 100 runs. The best performing case was selected for further processing.

MLRA only partly explains the spatial variability (pattern) of the distribution of inland excess water. On the other hand, taking the role of environmental factors by the linear model into account, it eliminates the trend. Kriging of the MLRA residuals (Figure 5) provides the stochastic component. Kriging requires knowledge of the spatial auto-correlation, estimated by the semivariogram of the variable to be spatially predicted, which in our case is the MLRA residual. An exponential semivariogram model was fitted to the experimental semivariogram (range = 10,623 metres, sill = 24.5 and nugget = 17.2), which was then applied to calculate the kriging weights in the spatial interpolation. Superposing the regression and interpolation results provided the overall RK prediction of the inundation hazard.

3. Conclusions

The result of the applied regression kriging process is a map which spatially predicts inundation frequency. Nevertheless we are careful to present this explicit numeric value in its raw form. As the reference inundation dataset is not comprehensive and also rather short – as opposed to the hundred-year baseline generally used in Hungarian hydrological practice – the resultant numbers

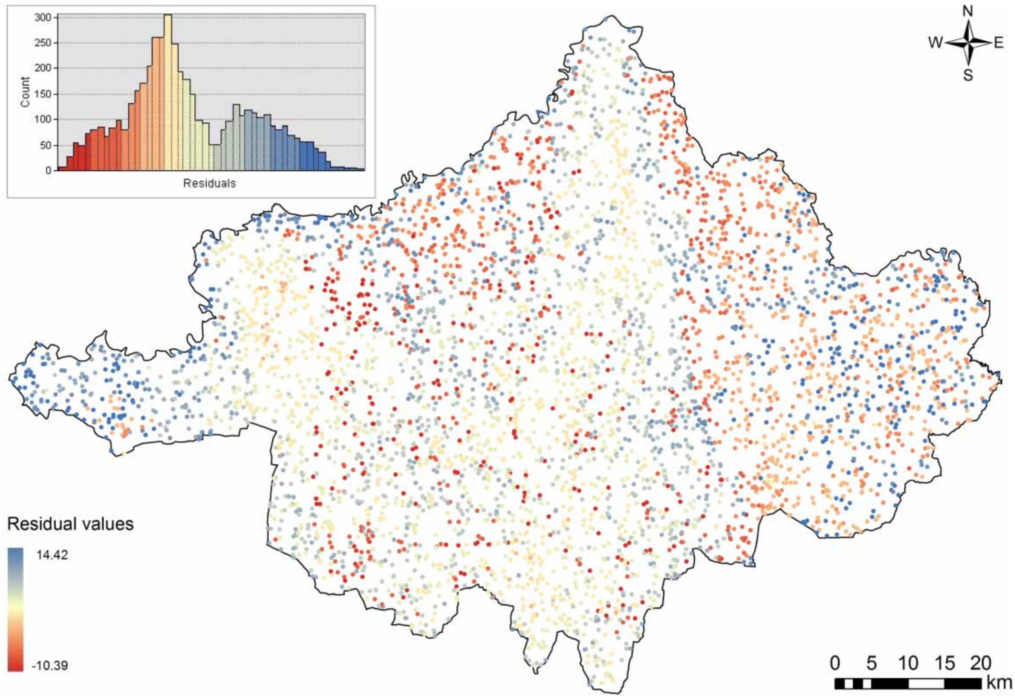

Figure 5. Histogram and spatial distribution of the MLRA residuals.

indicate the potential frequency. Consequently, the result was interpreted as a proxy of the inundation hazard, expressed by an interval scale indicator.

The final risk map can be used in spatial planning, as it is valuable in numerous land-related activities (land use and agricultural planning, water management procedures, water-oriented cultivation systems, wetland restoration, etc.).

The presented method, which is an improved version of CEWHI1, could be further refined:

- The application of regression kriging together with the applied multiple, virtual sampling allows the consideration of multiple data layers for each affecting factor. In addition to relief, the role of other environmental factors could also be represented more thoroughly at the data level.
- As Earth observation services are becoming more and more affordable, improved reference data series on the spatial distribution of inland excess water events could be incorporated.
- The environmental correlation expressed by multiple linear regression could be substituted by further, knowledge based, data mining methods for improving the modelling of the complex relationship between inundation and its affecting factors. The first planned step is the substitution of MLRA with Regression Tree Analysis to generalize the linear model between inland excess water events and the explanatory environmental variables.

Software

Preprocessing and derivation of ancillary environmental variables was carried out using Esri ArcGIS 10.x. Hand-drawn inundation maps were digitized in Esri ArcView 3.1. Terrain-based morphometric features were derived and regression kriging carried out using SAGA2.1. The Main Map was compiled in Esri ArcMap 10.2.

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