

Thesis of doctoral (PhD) dissertation

**CHARACTERIZATION AND EVALUATION OF
EXCESS WATER FORMATION PROCESSES
IN THE BÉKÉS-CSANÁD LOESS PLATEAU**

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“Water can be a blessing or a shock.
A lot depends on how we treat it.”
Hanusz, 1895

1. BACKGROUND AND OBJECTIVES OF THE THESIS

Global climate change and its effects have become increasingly apparent in the last hundred years, with well-perceived consequences in the Carpathian Basin as well (more frequent extreme hydrological events, excess water inundations and water scarcity within a year). In the lowland areas of Hungary, due to morphological, agrometeorological and hydrogeological, as well as pedological conditions, as a directly natural phenomenon, spatial inundations (excess water, groundwater uprush) and water shortages causing droughts regularly occur in temporarily. Damage to both phenomena sometimes means an unacceptable risk. A very significant part of Hungary's approximately 45,000 km² lowland area, around 60%, is significantly endangered by excess waters (*Pálfai, 2004*). According to expert estimates, the damage caused by excess waters can reach more than ten billion HUF / year (*Pálfai, 2006; Somlyódy, 2011*). The study of the multifactorial phenomenon resulting from environmental and anthropogenic processes is a priority area of Hungarian (agricultural) water management. The accumulated professional knowledge is significant, and the technological development of the last 15-20 years has opened a new chapter in the description of excess water. Nevertheless, mapping of excess water hazards and risks is a major scientific challenge. Especially if, in addition to the current known processes, we also take into account possible water management and land use interventions, as well as the effects of environmental trends (climate change). Therefore, an essential condition for water management and agricultural planning is excess water hazard mapping, which enables the planning of interventions related to regional active and passive excess water management and the specification of the excess water protection strategy (*Tamás, 2013*). Following the zoning system established in excess water hazarded areas, the current forms of cultivation and utilization that are better adapted to the excess water regime can be replaced by the current ones.

My investigations into the cause and effect relationships of excess water hazard and the rationalization of land use were carried out in the area of the Békés-Csanád Loess Plateau, which adequately represents the natural and anthropogenic effects determining the formation of excess water inundation.

The general objective of my research is to determine the excess water hazard in areas endangered by excess water inundations based on an established zoning system. In this way, it would enable the regional development of cultivation and utilization forms that are better adapted to the areas affected by excess water, laying the foundations for sustainable regional water management. My main scientific goals are:

1. Exploration of the causal and effect relationships of the influential factors determining excess water hazard; determination of the weight of the influential factors.
2. The role of groundwater uprush (in Hungarian "Földárja" as "Earth flooding") in the development of excess water inundations.
3. Determining the excess water hazard of the Békés-Csanád Loess Plateau based on the main influential factors.
4. Identification of land use alternatives as a function of excess water hazard reduction.

2. MATERIAL AND METHODS

2.1. Characterization of the Békés-Csanád Loess Plateau

The study area was the Békés-Csanád Loess Plateau (**Figure 1**) taking into account the micro-region classification (*Marosi and Somogyi, 1990*).

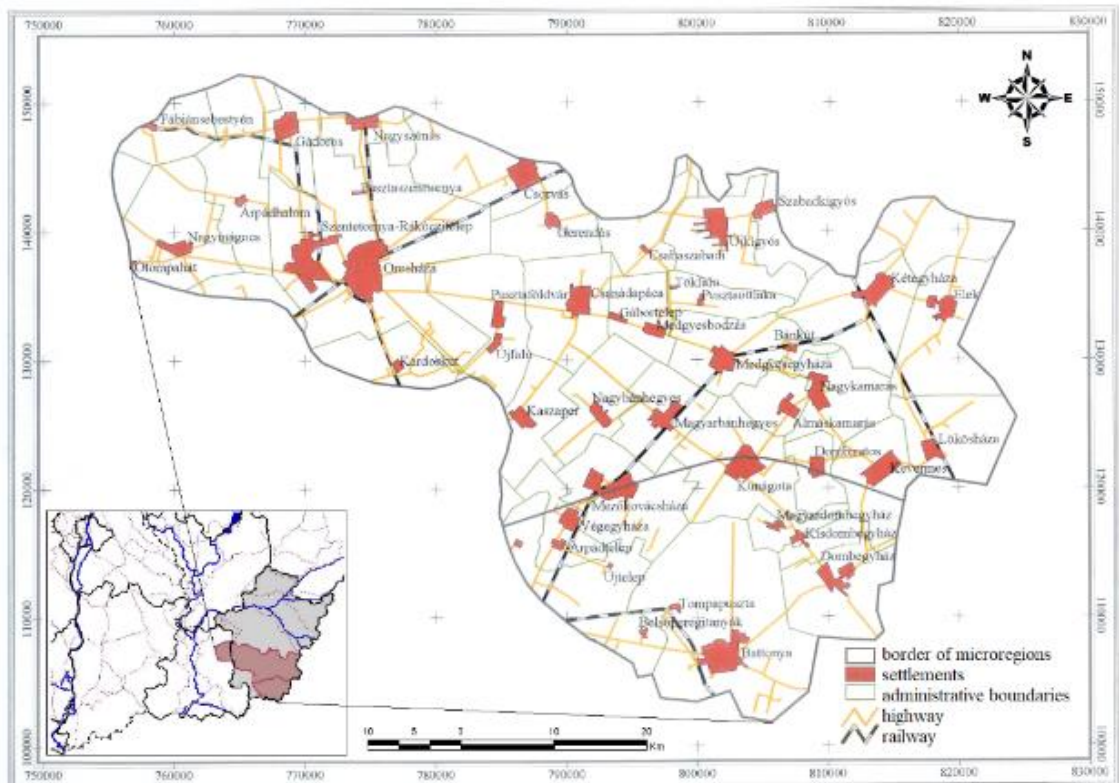


Figure 1. Map of Békés-Csanád Loess Plateau

According to its location, it covers almost a third (1700 km²) between the Körös and Maros rivers in the south-east part of the Great Hungarian Plain. It can divide into two parts, the Békés and the Csanád Plateau (*Marosi and Somogyi, 1990*). The Csanád Plateau is a low-relief, low-probability flood risk, lowland featured plain (400 km²), which slopes slightly in a south-southwest direction. The southern part of the highest central part of the Maros River Alluvial Fan. The Békés Plateau is a slightly more subdivided surface with a west-northwest slope (1300 km²). It gives the central and northern masses of the Maros River Alluvial Fan. The typically lowland featured landscape is divided and made more diverse by dead riverbeds (palaeo-channels). Very different geological processes took part in the formation of this part of the Great Hungarian Plain. During the Pleistocene, almost all of rivers of the Great Hungarian Plain affected the area (*Sümeghy, 1944; Andó, 2002*). “The soil conditions of the micro-region, which is mainly used for agriculture, are determined by the location of loess sediments and groundwater near the surface” (*Bozán et al., 2008*). The mechanical composition of soils are clay with medium water management properties. Due to groundwater, which basically contains a lot of dissolved salts, salt accumulation is very common at different levels of subsoil. Compacted layers (disk-pan, plough-pan) can form in the soils, which limit the deep infiltration of groundwater. The climate of the Békés-Csanád Loess Plateau is most strongly characterized by the continental climate influence (*Andó, 1974*), which means a warm, moderately dry climate to the east direction. On the plateau, there is also a fundamentally east-west orientation in precipitation distribution and temperature. Annual rainfall of 550-620 mm, many hours of sunshine (2000 hours/year) and high evaporation result in a basically water-deficient micro-region where the aridity index varies from 1.13 to 1.26 in an east-west direction. From the point of view of water flow (palaeo-channels), the very diverse grain composition of the alluvial fan series built by the former rivers is also reflected in the appearance of soil and aquiferic waters (*Rónai, 1985*). Precipitation in the recharge zone (foothill of the Carpathians) has a direct effect on the pressure conditions in the plateau waters. Due to the frequent and large area of watertight sediment layers, high pressures can develop in the aquiferic waters in some places. This particular hydrological phenomenon is referred to as a groundwater uprush (in Hungarian “Földárja” as “Earth flood”), which means inundations from groundwater even in dry periods. Lateral movement of aquifers with a lot of dissolved matter is slow.

2.2 Methods used in geostatistical examinations

Spatially continuous phenomena (precipitation, temperature, and groundwater) are determined by interpolation procedures based on point monitoring measurements – based on the principle of Tobler's similarity with spatial continuous estimating surfaces (Tobler, 1970). As a prerequisite for this, I performed statistical homogeneity and independence analysis. The homogeneity or uniformity of the data set has fundamentally determined further analysis, as a data set can be considered uniform if its parts can be described by a distribution function of the same type and parameter. The Kolmogorov-Smirnov test ($SZD \geq 5$) was used to determine uniformity. In order to compare the different well data sets, I normalized them because, during the uniformity analysis, I inferred from the comparison of the empirical distribution functions the closeness of the relationship between the groundwater levels of the wells. In view of the specificity of the groundwater flow (groundwater uprush), I performed the descriptive statistical characterization for all wells, with which I obtained numerical values for the expected value, standard deviation, mode, median, peaks and skewness. Since our data set followed a skew distribution, I chose Pearson's 3-parameter theoretical distribution function, which shows the best fit.

2.3. Methodology of excess water hazard mapping, determination of the value of independent factors

The developed and applied excess water hazard spatial decision support model was implemented in ESRI ArcGIS software environment, EOVS projection system. Based on my investigations aimed at clarifying the relationship between excess water hazard and influential factors, I performed a hazard mapping model based on the regression relationship of 6 independent and 1 dependent factor.

Development of the hydro-meteorological factor (HUMI): From the precipitation and air temperature data (OVF, VIZIG, OMSZ), which decisively determine the hydro-meteorological conditions, a single factor, so-called Humidity Index (HUMI) was developed, which takes into account the winter semester precipitation with more weight than the summer semester, and thus expresses the hydro-meteorological conditions of excess water formation better than the simple summarized values. It is clear that excess water hazard is proportional to the humidity index, i.e., the higher the value of the index, the higher the hazard. The HUMI calculation procedure is as follows:

$$HUMI = \left(\frac{P^*}{PET} \right)^{0,5} \text{ where, } P^* = \text{weighted precipitation; } PET = \text{potential evapotranspiration}$$

Development of the relief factor (RELI): Digital Elevation Model (DDM) was used (1:10000) for my investigations. 50x50 meters grid was used for the analysis. The value of the relief energy of each cell was determined, i.e. the height level difference within 100 m² expressed in meters. To construct the RELI, the obtained values with the altitude of the discrete points and the lowest altitude value was corrected: $RELI = (MASL / 82) * RELIEF ENERGY$, where MASL is meters above Baltic Sea level.

Development of the soil factor (SOIL): The water management properties of the soils were characterized by a numerical indicator with the help of Kreybig's soil maps and landscape cultivation maps in the ATK TAKI GIS Laboratory. The Kreybig and Várallyay category systems were also incorporated into the soil factor. The Kreybig saline classes had to be divided to match the Várallyay division.

Development of the geological factor (GEOL): To determine the geological factor, the location and thickness of the near-surface aquitards (MBFSZ database) was taken into account. The water permeability of each formation was determined by *Rónai et al.* (1969). Overall, the depth (0, 0-2, 2-4, 4-10, deeper than 10 meters) of the first aquitard layer from the surface and its thickness (0, 1, 1-2, 2-4, thicker than 4 meters) were examined.

Development of the groundwater factor (GW): Based on the available database (OVF, KÖVIZIG, ATIVIZIG), the reliability of the groundwater resistance values of the typical HGWL (highest groundwater level) with a more detailed examination have been improved. The well data was examined one by one, the annual maximum values were selected, which was used for further analyzes. The higher the value of the groundwater factor, i.e. the deeper the groundwater level, the lower the potential for excess water development. The calculation used was as follows:

$$GW (HGWL_{Avg}) = HGWL_1 (1966-1991) + HGWL_2 (1966-1991) + HGWL_3 (1992-2016) + HGWL_4 (1992-2016) / 4$$

In the final calculation of the raster estimation surface, the topographic spatial correlation with co-kriging was taken into account.

Development of land use factor (LU): Land use categories have been separated and classified according to the importance of their role in excess water formation based on the CORINE CLC50 database. To compile the excess water hazard map, each land use category was characterized with values of 0.1–5 (e.g., saline swamps of 0.1 => highly hazarded).

According to the methodology, the higher the value of the influential factor, the lower the possibility of excess water formation.

2.4. Determination of the frequency of excess water inundations (as a dependent factor)

The integration of the hazard result map was performed based on a multivariate spatial regression analysis in which the independent variables were the selected influencing factors, while the dependent variable was the excess water inundation values determined from the excess water inundation frequency map, in other words the relative frequency of excess water inundations. The frequency was determined according to the following equation:

$$RF = (EW * y) / (\sum n)$$

where, RF = relative frequency; EW = excess water inundation / pixel; y = number of events; n = time interval in years

During the processing, the available excess water inundation maps were merged over a 60-year time interval (OVF, KÖVIZIG, ATIVIZIG).

2.5. Statistical methods for causal and effects relationships, and spatial regression analysis

During the spatial regression analysis, the decision weight of the influencing factors in the development of excess water hazard was examined. There were two main questions: A) how the influencing factors are related to each other, and B) which of the 6 variables examined determines the excess water hazard. The corrected R^2 value, the t-test required to examine the linear relationship, and the correlation matrix of the independent variables were calculated. To assess the independence of each factor, a partial correlation analysis was performed. The Durbin-Watson test was used for the autocorrelation test, while the Kolmogorov-Smirnov test was used for the evaluation of normality. Finally, the independence of the residual values and the independent variables was examined, which also showed a linear function relationship. The aim of the spatial regression analysis was to determine the weight of the influential factors. Based on a multivariate regression analysis, the excess water hazard indicator can be determined, which can be calculated with the resulting regression equation.

2.6. Development and application of the excess water hazard indicator

An excess water hazard indicator was developed to produce the hazard map. To calculate the indicator, multivariate regression analysis were required, for which the excess water inundation map (excess water frequency values) was used directly as a dependent variable. After determining the ratios and weights between the influential

factors, the values of the weighted factors obtained by the regression equation had to be multiplied by the hydro-meteorological factor.

$$EWHI = (c - w*SOIL + w*GEOL - w*LU - w*RELI - w*GW) * a * HUMI$$

where, EWHI = Excess Water Hazard Indicator; c = constant value; w = weighting value; a = proportional factor; SOIL = Soil factor; GEOL = Geological factor; LU = Land use factor; RELI = Relief factor; GW = Groundwater factor; HUMI = Hydro-meteorological factor

Based on the formula, an excess water hazard map of the study area can be prepared. Several classification options can be used to establish hazard categories, of which the Jenks classification method was used (Jenks, 1967).

3. RESULTS

A statistical evaluation of the main hydrological and meteorological factors determining excess water formation and the evaluation of the role of locally different excess water formation (groundwater uprush) were performed. The numerical values of the 6 main factors responsible for the development of excess water inundations were determined and the excess water frequency values were determined. Subsequently, a mathematical-statistical analysis of causal and effects relationships was completed. An excess water hazard indicator was developed based on spatial regression analysis. It can be used to construct an excess water hazard map. The resulted map can be classified (Jenks), spatially differentiated and the land use alternatives can be assigned to it.

3.1. Investigation of locally different excess water formation (groundwater uprush)

In the course of my working hypothesis, I started from the premise that the extent of excess water inundation is not determined by the average values of the water balance elements, but by the random joint effects of the unfavorable, extreme states of the influential factors. Therefore, I statistically evaluated the extreme values. Excess water inundation is a consequence of the accumulation of water related processes, therefore it is not enough to quantify the parameters assigned to each period, but in some cases, it is also necessary to characterize the accumulation periods. I paid special attention to the behavior of groundwater, especially because the centuries-old experience of the Békés-Csanád Loess Plateau suggests that not only precipitation plays a decisive role in excess water formation, but the so-called groundwater uprush phenomenon. That is why, in addition to the statistical estimation of the parameters, I performed a local statistical analysis among the wells. I used descriptive statistics to quantify the general characteristics of groundwater fluctuation. In addition, I characterized the general

groundwater flow, so I examined the fit of different theoretical distribution functions to the empirical distribution.

The long time series of groundwater levels provided an opportunity to determine the monthly maximum and minimum frequency of groundwater recurrence per month. Typically, the frequency of recurrence of the maximum and minimum groundwater levels measured in high-water wells in the summer and winter months, respectively, follows the most probable and essentially sinusoidal periodicity in addition to long-term trends. In the case of wells with deeper groundwater levels – where the annual distribution of maxima and minima is much more balanced, the fluctuation of groundwater levels decreases logarithmically with depth – we can least expect the formation of excess water inundations in these areas.

One of the geo-hydrological features of the Békés-Csanád Loess Plateau is that the alluvial mass spread by the ancient Maros River has a loose structure. As a consequence, the groundwater, through this formation with good water permeability, is associated with precipitation falling on the foothill of the mountains. As a result, the rise of the groundwater level in the foothills, spreads as a pressure wave (*Bogárdi, 1952*) and can cause groundwater uprush, especially where the uppermost aquitard is missing.

Taking into account all these special conditions, I evaluated in which areas the local weather shows a difference and where the “Earth flood” phenomenon prevails.

I performed the descriptive statistical characterization for each well to obtain numerical values for expected value, standard deviation, mode, median, peaks, and skewness. I hypothesized that if the groundwater movement observed in each well is characterized by the same statistical value, then the given statistics can be considered as a general feature of the whole area. In addition, I also hypothesized that for all sites where the same theoretical distribution functions can be fitted to the empirical distributions, the groundwater flow can be considered to have the same structural features. As a first step, I used standardized values to determine the vertex of the distribution functions, which expresses whether the image of the function is peak or flat relative to the normal distribution. In wells where the peak is negative, the standard deviation is extremely large. If this includes even high groundwater levels, it can be assumed that the change in groundwater levels in such areas strongly depends on the amount of local precipitation (486 Dombegyház, 472 Kaszaper, 483 Kunágota, 430 Medgyesbodzás, 413 Orosháza).

Based on the skewness analysis, we can infer the “use” of the wells, more specifically the possible external disturbances in their environment. In the case where the skewness

has a positive sign (467 Kardoskút, 485 Nagykamarás), the distribution function is skewed to the right compared to the normal distribution, so the water level fluctuation (standard deviation) of the well is distorted towards higher values (deeper groundwater level). In case of negative skew, the distribution function shifts to the left (411 Fábíansebestyén, 433 Újkígyós). In this context, I examined the multi-year, monthly linear trends characteristic of wells. As a general conclusion, wells where the skewness of the empirical distribution function has a negative sign and the associated linear trend is increasing, it is likely that a positive water inflow (e.g. 411 Fábíansebestyén) around the well, otherwise water abstraction (e.g. 436 Szabadkígyós). Based on all this, we cannot say convincingly that the fluctuations in the resting water level of the wells are “only” natural, which is further complicated by the fact that the vast majority of wells are located within a city, which fundamentally determines the behavior of the well. In the case of wells with positive skew, the function flattens towards large values and cuts towards small values. From this, I concluded that the groundwater level has an extreme lower limit. The deeper the groundwater level, the more evaporation decreases. In our case, the increase in recharge from aquiferic water is balanced by the evaporation loss of groundwater. Where I received a positive skew, a significant part of the wells are within the settlement, but as with all wells, some groundwater use can be assumed (especially in summer), so in addition to human effects, aquiferic water can play a balancing or stabilizing role (*Orlóci, 1991*).

For wells with negative skew, the function flattens toward small values and cuts toward large values. There is a level of groundwater near the ground level where, due to some factor, the possibility of groundwater rising becomes limited. The reason for this can be noted in the fact that the groundwater reservoir becomes open in a horizontal way and at groundwater levels exceeding the mode, an increasing degree of horizontal leakage develops. If, during periods of high groundwater levels, the deeper sinks in the area are inundated with water, we will find those sinks that will drain the groundwater and prevent its further rise, i.e. the groundwater uprush phenomenon will appear.

Based on the above, we can see that the groundwater flow follows some skewed distribution. If groundwater level fluctuations were primarily a function of local weather, the distribution would probably be regular. Methodologically, this hypothesis had the advantage that instead of extra- and interpolation of discrete statistics, it would be expedient to construct the distribution of basic parameters.

3.2. Quantification and mapping of influential factors

Value of hydro-meteorological factor: Based on my results, the northwestern part of the Békés-Csanád Loess Plateau is less humid than the southeastern part (**Figure 2a**). I used data from 13 stations to calculate HUMI values. 10% possibility of occurrence of HUMI ranges from 0.71 to 1.31.

Value of relief factor: Using the digital terrain model (50x50 m grid) I determined the relief energy value of each cell (0-5 relative scale value). The spatial extension is illustrated in **Figure 2b**. The smaller the value of the factor, the greater its role in the formation of excess water.

Value of soil factor: According to the previously presented methodology, by correlating the Kreybig, Várallyay and landscape cultivation maps, it was possible to give the water-carrying capacity of the soils. The value of the soil factor is the average and estimated soil water conductivity in the fifth column of **Table 1**. The map is shown in **Figure 2c**.

Table 1. Relationship between the categories of Kreybig's soil map and Landscape cultivation maps and Várallyay's soil-water management category

Várallyay's 9 soil-water management categories, by soil physics	Infiltration rate, IR (mm/hour)	Corresponding with Landscape category	Specified soil water conductivity, mm/hour	Average and estimated soil water conductivity value Soil factor (cm/hour)
1. sand s.	500	(1.,3.) limestone, sand without humus s.	40-60	5
1. sand s.	500	(2.,4.) limestone, humus sand	20-40	3
2. sandy loam s.	325	-	-	(2.3-3) 2.6
3. loam s.	125	(5.) excellent loam and silt s.	15-30	2.3
3. loam s.	125	(6.) high quality loam and clay s.	-	1.5
4. clay loam s.	85	-	-	(1-1.5) 1.3
5. clay s.	60	(7.) very strong texture s., lime-demanding s., loam and clay s.	5-15	1
6. slightly saline, pseudogleys s.	30	(10.) slightly saline s., suitable for agriculture	-	1.1
6. slightly saline, pseudogleys s.	30	(11.) slightly saline s., unsuitable for agriculture	-	5
7. strongly saline s.	10	(12.) strongly saline s.	-	1
8. peats, mull s.	0	(9.) peats and mull s.	-	-
9. shallow topsoil	-1	(8.) shallow topsoil	-	-

Value of geology factor: The probability of occurrence of excess water inundations may be increased or decreased by the position and/or thickness of the uppermost aquitard. I compiled the map of the geology factor (**Figure 2d**) using the values reported in **Table 2**, in the same pixel size as the other factors.

Table 2. Value of the geology factor based on the position and thickness of the uppermost aquitard

Thickness	Depths				
	Aquitard on the surface	<2 m	2-4 m	4-10 m	>10 m
<1 m	0.2	1.8	3.6	4.8	5
1-2 m	0.1	1.5	2.7	4.2	5
2-4 m	0.1	0.9	1.8	3.4	5
>4 m	0.1	0.3	1.1	3.0	5

Value of groundwater factor: During the examination of groundwater wells (25 pc.) I came to the conclusion that I delimit the maximum groundwater level averages relevant to the formation of excess water based on the HGWL (highest groundwater level) averages, which also expresses the value of the groundwater factor in meters (**Table 3**). Spatial interpolation was performed by co-kriging (**Figure 2e**). Based on my results, it can be stated that the areas affected by the phenomenon of groundwater uprush (Maros River Alluvial Fan) appear on the groundwater factor map.

Table 3. The values of groundwater factor (sample)

Number	Well	MASL	HGWL ₁ 1961-1991	HGWL ₂ 1961-1991	HGWL ₃ 1992-2016	HGWL ₄ 1992-2016	HGWL _{Avg} GW factor
480/2337	Battonya	102.29	1.76	1.90	1.92	1.95	1.88
426/2314	Csanádapáca	94.48	2.14	2.19	3.18	3.20	2.67
422/2808	Csorvás	92.18	1.87	1.91	1.76	1.76	1.82
424/2810	Csorvás	89.43	0.44	0.52	1.72	1.94	1.15
486/2345	Dombegyház	102.02	0.82	0.87	1.06	1.08	0.96
...

Value of land use factor: To compile the excess water hazard map, I characterized each land use category with the values in **Table 4**, which I chose to fit the values of the other factors. The lower the excess water hazard, the higher the value of the land use factor (**Figure 2f**).

Table 4. Values of the land use factor by land use categories (sample)

Land use category	Land use factor
1. Artificial areas	0.6-1.0
2. Agricultural areas	
2.1. Arable lands	0.3-1.0
2.2. Permanent crops	2.5
2.3. Pastures	0.6
2.4. Heterogeneous agriculture	0.5-2.0
3. Forrest and Natural vegetation	
3.1. Forrest	1.0-5.0
3.2. Other natural vegetation	0.6-3.0
3.3. Without vegetation or open spaces	0.3-0.6
4. Wetlands	0.1
5. Water bodies	0.1

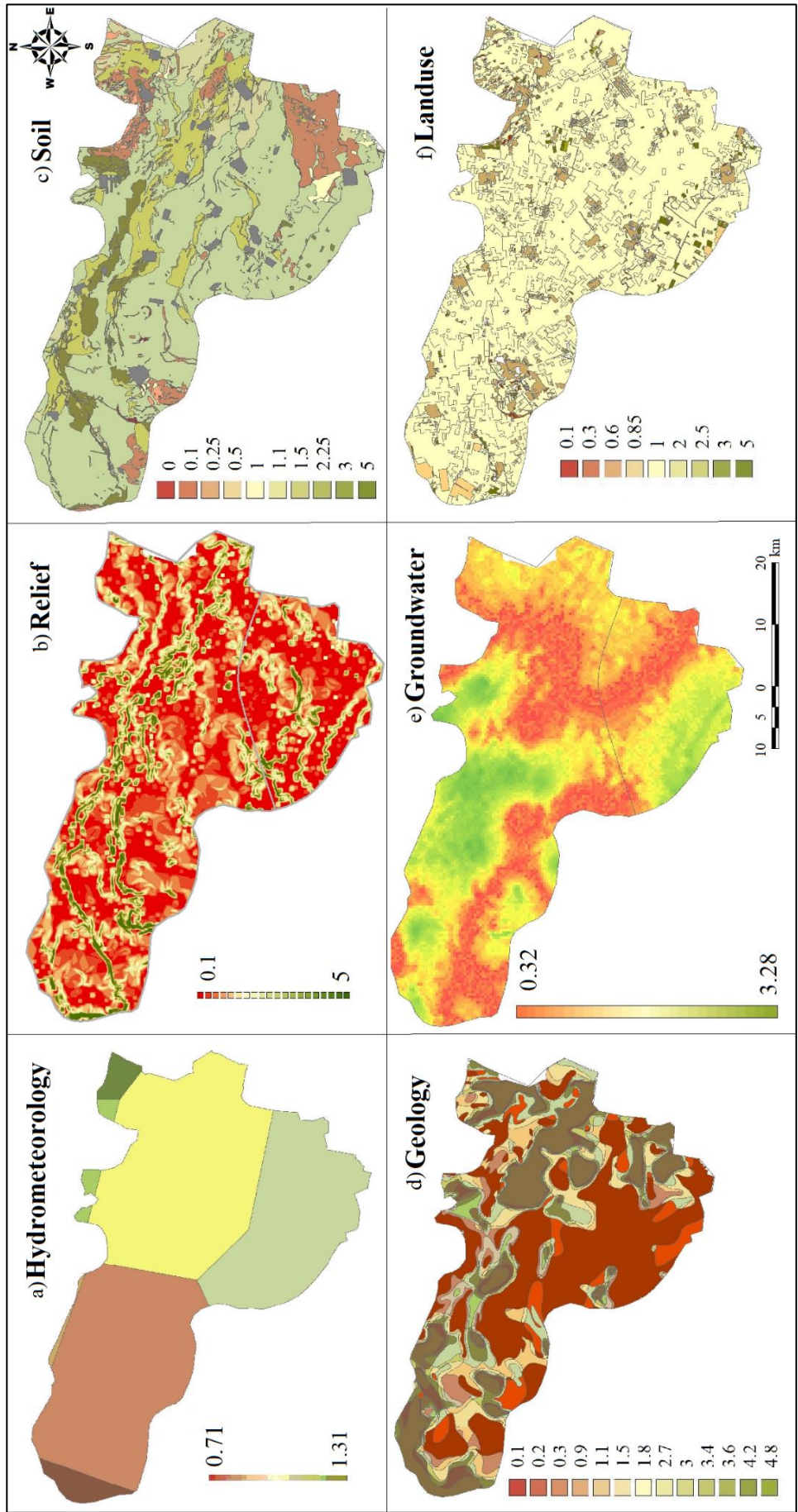


Figure 2. Maps of influential factors

3.3. Value and spatial distribution of inland water inundations

The spatial distribution of the frequency values summarized in **Figure 3**, taking into account the inundations that occurred in different years. The strength of the color scale of the frequency values adequately characterizes the hazard of excess water inundations in the study area.

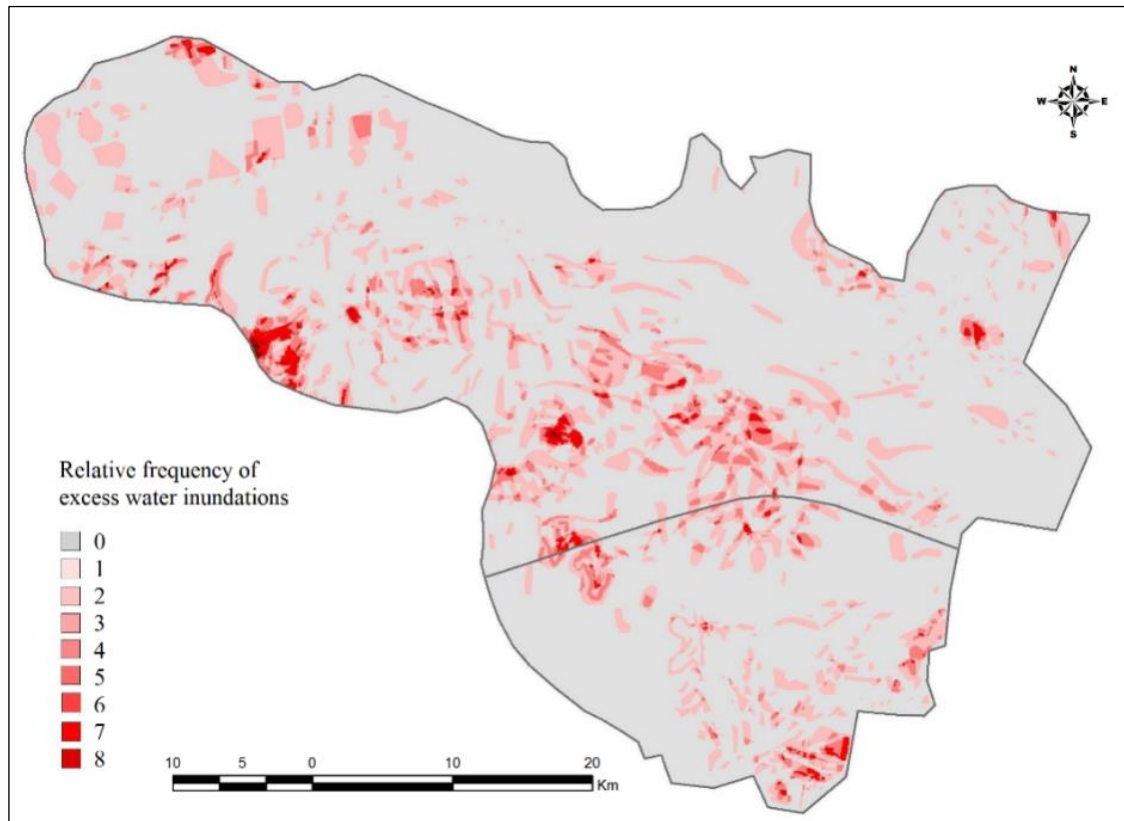


Figure 3. Map of relative frequency of excess water inundations

3.4. Results of the cause and effects relationships of excess water formation

In the course of my research, I was looking for the answer to which of the six variables examined and to what extent excess water inundation is determined. Analysis of the linear correlation showed a loose positive relationship (R-value: 0.336) between the independent factors and the dependent factor. Based on my results detailed in the dissertation, all factors have a positive effect on the formation of excess water. The analysis confirmed that the effect of the factors on the formation of excess water is significant, but it can also be assumed that the influential factors are only partially independent of each other. Subsequently, I performed the partial correlation analysis (**Table 5**) to exclude the effect of each factor. Based on the partial correlation coefficients, the soil factor with the greatest spatial variability determines the spatial behavior of the excess water model the most, followed by land use, topography, groundwater, geology, and finally hydro-meteorology factor.

Table 5. Casual and effect relationships of influential factors

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	,900	,060		15,053	,000					
	talaj	-,360	,011	-,336	-32,604	,000	-,308	-,306	-,302	,809	1,237
	foldtan	,033	,005	,071	6,415	,000	-,056	,063	,059	,706	1,417
	landuse	-,025	,015	-,016	-1,665	,096	-,058	-,016	-,015	,935	1,069
	relief	-,017	,004	-,042	-4,201	,000	-,081	-,041	-,039	,851	1,175
	meteo	,625	,056	,110	11,072	,000	,039	,108	,103	,876	1,141
	talajvíz	-,017	,002	-,071	-7,089	,000	-,071	-,070	-,066	,847	1,181

a. Dependent Variable: elontes

In the autocorrelation analysis, I examined the relationship of the data set with itself, using the Durbin-Watson test, which is characterized by a very high uncertain range. In the present case, the value was 0.730, so we can say that my result is between 0.5 and 1.5 in the uncertain range. During the examination of the error terms, I also examined whether they were normally distributed or not, which I checked with the Kolmogorov-Smirnov test, based on which the residual is not normally distributed, so this condition was not confirmed. All this can usually be explained by the fact that the variances of the groups differ greatly from each other, which is caused by the outliers within the groups. The explanation can be found in the spatial variance of the data series (the spatial variance of the hydrometeorological factor is low, than the soil factor is high) and in the methodology of determining the factor values, which in connection with the interpretation of the excess water phenomenon (e.g. the more characteristic the high groundwater level, the greater the potential for excess water formation). Overall, the extent of excess water is not determined by the average values of the water balance elements, but by the random coincidence of the unfavorable, extreme conditions of the influencing factors.

The aim of the studies performed was to prove the relationship between the influential factors and the excess water inundations (values of the relative frequency of excess water inundations). I proved this statistically, but in the last stage of the analysis it was also proved that not all the conditions were met for the relationships to be / can be described clearly in linear regression. Based on the results, in the course of further research, methods other than the linear function relationship must be developed.

3.5. Determination and mapping of Complex Excess Water Hazard Index (CEWHI)

During this analysis, I examined the weight of the influential factors involved in the formation of excess water inundations. For this, I used bivariate and multivariate regression analysis, where the “dependent” variable was the values of the excess water frequency in each case. All independent factors are negatively related to excess water

inundations, so the higher the value of the factor, the smaller its impact on excess water hazard.

In the bivariate relationship analysis, it became certain that the relief factor shows the closest relationship, which can be easily explained given that the accumulated excess waters appear in the deeper ranges of the terrain. There is a weaker relationship between geology, land use, groundwater, and the soil factor. However, according to the results of the multivariate regression analysis, the soil factor is the one that has the best effect on the formation of excess water inundations, as the value of the partial correlation coefficient (-0.306) and its absolute value are the highest. This is followed by groundwater, topography, land use, and geological factor (**Table 6**).

Table 6. Values of the partial correlation coefficient and the standardized coefficient

	Constant	SOIL	GEOL	LU	RELI	GW
Partial correlation coefficient		-0.306	0.063	-0.016	-0.041	-0.070
Unstandardized coefficient (B)	0.900	-0.360	0.033	-0.025	-0.017	-0.017

Based on the multivariate regression analysis, the Excess Water Hazard Index (EWHI) can be calculated using the following regression equation:

$$\text{EWHI} = 0.9 - 0.360 \cdot \text{SOIL} + 0.033 \cdot \text{GEOL} - 0.025 \cdot \text{LU} - 0.017 \cdot \text{RELI} - 0.017 \cdot \text{GW}$$

The correlation coefficients and the variables in the regression equation indicate the weight of each variable practically equally (unstandardized coefficient, B), because their value limits, and thus their average values, cover essentially the same range. The value of the multiple correlation coefficient characterizing the closeness of the multivariate relationship is $R = 0.336$, which can be considered acceptable during hydrological statistical analysis.

3.6. Development of the Complex Excess Water Hazard Index (CEWHI)

After determining the ratios and weights between the factors, we multiplied the EWHI by the hydro-meteorological factor, obtaining the **Complex Excess Water Hazard Index (CEWHI)**. Based on the values of CHEWI, the Complex Excess Water Hazard Map of the Békés-Csanád Loess Plateau can be compiled in a pixel size of 50x50 meters (**Figure 4**).

$$\text{CEWHI} = (0.9 - 0.360 \cdot \text{SOIL} + 0.033 \cdot \text{GEOL} - 0.025 \cdot \text{LU} - 0.017 \cdot \text{RELI} - 0.017 \cdot \text{GW}) \cdot 5 \cdot \text{HUMI}$$

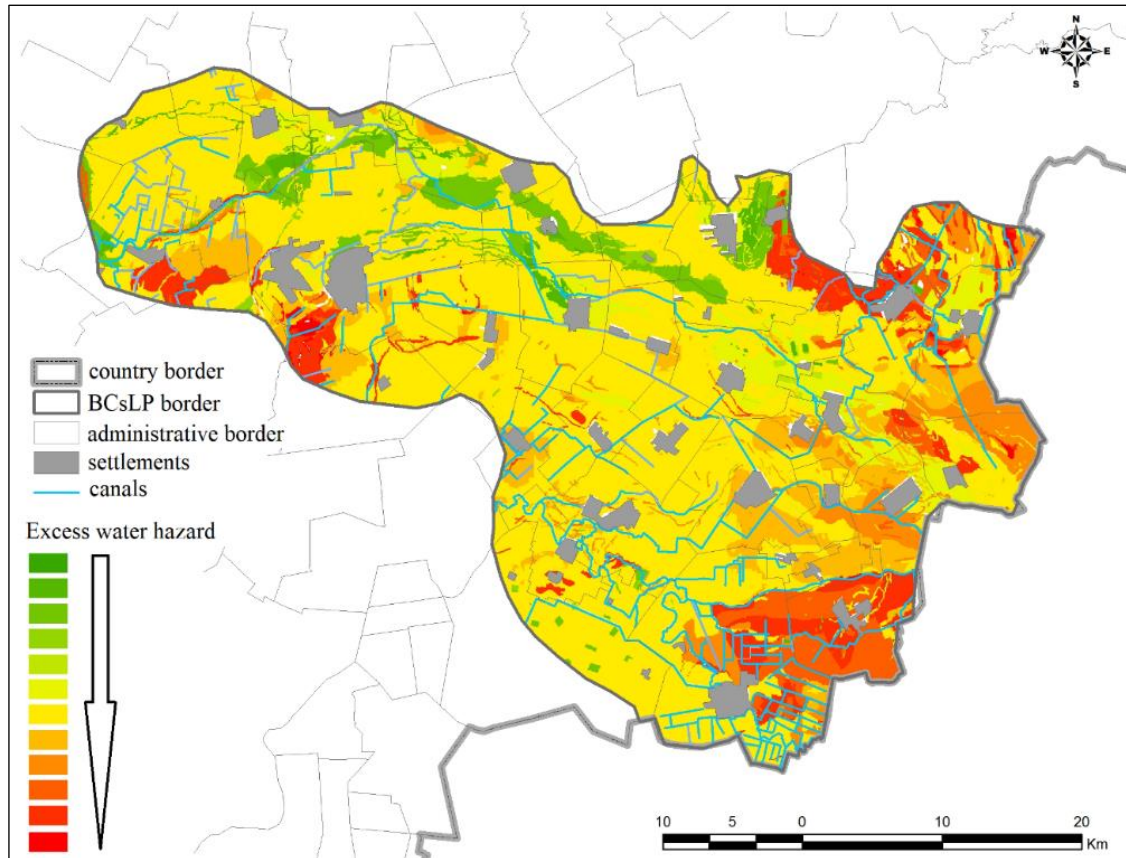


Figure 4. Excess Water Hazard map of the Békés-Csanád Loess Plateau

The colors indicate the degree of excess water hazard. In the not hazarded areas (mostly green and yellow), the value of KBM is low, orange towards reddish is moderately, while deep red areas are classified as very highly hazarded.

The areas of loess plateau are more hazarded, where the remnants of the once large loess steppe grasslands and the solonetz saline soils are located. Highly hazarded areas are the saline patches of the Kígyósi-puszta, the Csanádi-puszta, the loess meadows of Tompapuszta and Kardoskút. In the area of the Maros River alluvial cone on the eastern border of the loess plateau, there is a significant risk due to the groundwater uprush. The areas to the south of Orosháza are one of the main area of the groundwater uprush phenomenon. The ground waters of this area are in contact with the hydraulically pressurized waters of the alluvial cone and the replenishment zone.

3.7. Categorization / classification of influential factor maps and the complex excess water hazard map

I classified the influential factor maps and the final map using the Jenks method. It is important to note that the influential factor maps can also be interpreted as hazard maps,

as the numerical values of the influential factors relevant to the formation of excess water inundations determine the level of hazard. With this solution, the spatial extent can also be quantified.

Hydro-meteorological factor: After categorization, it can be seen (**Table 7, Figure 5a**) that the degree of hazard decreases in the east-west direction, which is explained by the proximity of the foothill area (recharge area).

Table 7. Territorial classification of the hydro-meteorological factor by hazard categories

Classification of hydro-meteorological factor	Level of hazard	Territorial coverage (hectare)	Territorial coverage (%)
1.220 – 1.310	Extreme	43 167	26.6
1.165 – 1.219	Highly	63 714	39.2
1.131 – 1.164	Mainly	23 466	14.5
1.104 – 1.130	Moderately	15 448	9.5
1.084 – 1.103	Not hazarded	16 571	10.2

Relief factor: After the Jenks classification (**Table 8**), it can be seen from **Figure 5b** that the hazard of lowland featured areas with low relief energy is very significant. In the case of mainly agricultural and grassland areas, only the valleys of the canals following the former riverbeds are exceptions.

Table 8. Territorial classification of the relief factor by hazard categories

Classification of relief factor	Level of hazard	Territorial coverage (hectare)	Territorial coverage (%)
0 – 1	Extremely	51 712	43.8
1 – 2	Highly	37 011	31.3
2 – 3	Mainly	24 668	20.9
3 – 4	Moderately	3 700	3.1
4 – 5	Not hazarded	981	0.9

Soil factor: The hazard due to soil reasons is the highest (**Table 9, Figure 5c**), where the remains of the former large loess steppe grasslands and the Solonetz saline grasslands are located (Kígyósi-puszta, Csanádi-puszta, loess grasslands of Tompapuszta, sodic soils of Kardoskút).

Table 9. Territorial classification of the soil factor by hazard categories

Classification of soil factor	Level of hazard	Territorial coverage (hectare)	Territorial coverage (%)
0 – 0.5	Extremely	21 268	12.8
0.5 – 1.1	Highly	2 682	1.6
1.1 – 1.5	Mainly	11 340	6.8
1.5 – 3	Moderately	119 906	72.2
3 – 5	Not hazarded	10 785	6.6

Geological factor: **Table 10** and **Figure 5d** illustrate well that in areas where significant thickness of alluvial loess or alluvial sediments (sand) with good water permeability has accumulated, they are not hazarded (20%). In areas that were

permanently covered with water and a finer sediment fraction was deposited, the hazard due to geological reasons is very high (48.1%).

Table 10. Territorial classification of the geology factor by hazard categories

Classification of geology factor	Level of hazard	Territorial coverage (hectare)	Territorial coverage (%)
0 – 0.3	Extremely	78 052	48.1
0.3 – 1.1	Highly	12 837	7.9
1.1 – 1.8	Mainly	24 497	15.1
1.8 – 3.6	Moderately	14 450	8.9
3.6 – 5	Not hazarded	32 453	20.0

Groundwater factor: After the Jenks classification (**Table 11**), **Figure 5e** illustrates well that the hazarded area in the Maros River Alluvial Fan (eastern boundary of the loess ridge) is significant due to the nature of groundwater. The areas to the south of Orosháza are one of the main location of the groundwater uprush phenomenon. The groundwater and aquifers of this area are in contact with the pressurized waters of the alluvial fan and the recharge zone.

Table 11. Territorial classification of the groundwater factor by hazard categories

Classification of groundwater factor	Level of hazard	Territorial coverage (hectare)	Territorial coverage (%)
0.40 – 0.83	Extremely	19 699	12.3
0.84 – 1.26	Highly	32 582	19.9
1.27 – 1.70	Mainly	52 237	32.2
1.71 – 2.14	Moderately	43 777	27.0
2.15 – 5.00	Not hazarded	14 036	8.6

Land use factor: Based on **Table 12** and **Figure 5f**, it is obvious that the loess plateau is more of a moderately hazarded category in terms of land use – which can be further reduced by coordinating agrotechnical interventions and agricultural water management – as the area is the scene of agricultural production apart from one or two forest patches and forest associations.

Table 12. Territorial classification of the land use factor by hazard categories

Classification of land use factor	Level of hazard	Territorial coverage (hectare)	Territorial coverage (%)
0 – 0.3	Extremely	1 669	1.0
0.3 – 0.6	Highly	6 514	4.0
0.6 – 1	Mainly	151 512	93.3
1 – 3	Moderately	290	0.2
3 – 5	Not hazarded	2 344	1.5

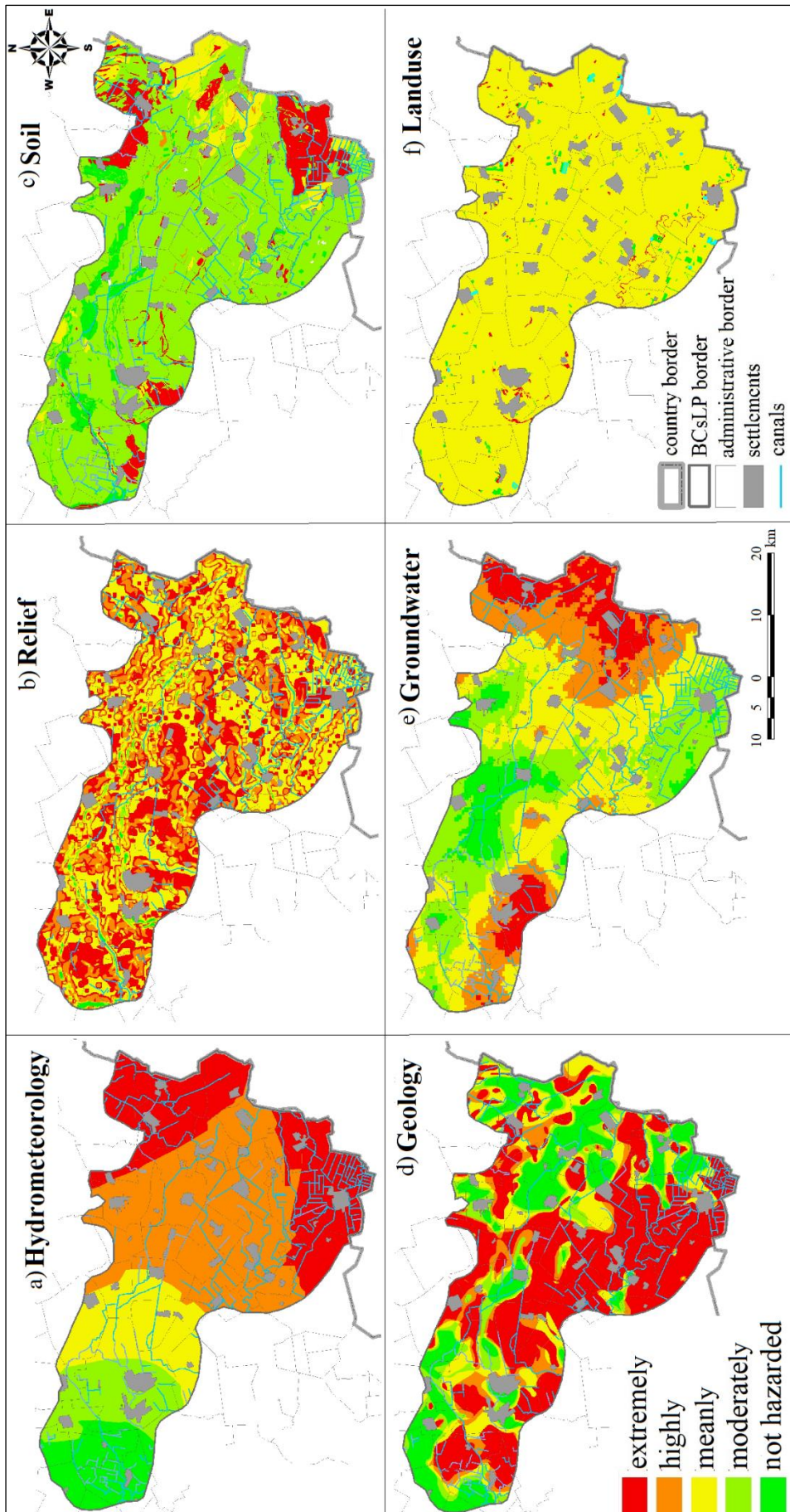


Figure 5. Classification of influential factor maps

3.8. Territorial separation of the result map compiled on the basis of CEWHI according to hazard categories

The distribution and spatial extent of the areas classified by the Jenks method based on CEWHI (Figure 6) are shown in Table 13.

Table 13. Hazard categories and territorial coverage of the result map compiled on the basis of CEWHI

Classification of CEWHI	Level of hazard	Territorial coverage (hectare)	Territorial coverage (%)
0 – 1	Extremely	19 641	12.4
1 – 2	Highly	114 898	72.5
2 – 3	Mainly	12 824	8.1
3 – 4	Moderately	8 681	5.5
4 – 5	Not hazarded	2 351	1.5

The data in Table 14 show that the loess plateau is highly hazarded by excess water. In the compiled result map the effects of all the influential factors were taken into account. The areas hazarded by excess water are well separated, based on which extremely and highly hazarded areas on 85% of the Békés-Csanád Loess Plateau can be found.

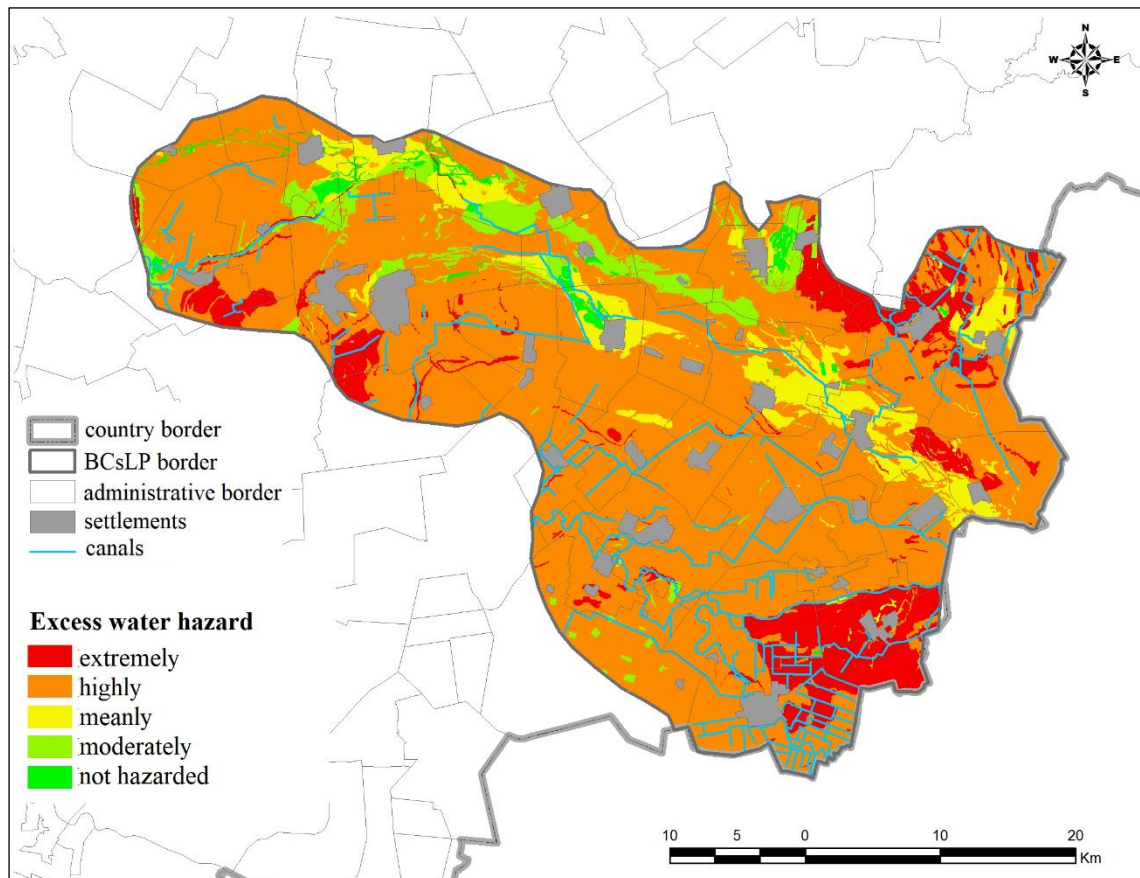


Figure 6. Classified excess water hazard by Jenks method

3.9. Land use options based on the CEWHI map

I separated the spatial coverage according to the individual hazard categories, so the land use alternatives can be assigned to the not, moderately, mainly, highly, extremely hazarded categories.

In the areas of the Békés-Csanád Loess Plateau that are extremely and highly hazarded by excess water (19 641 and 114 898 hectares), it is practical to consider the rationalization of agricultural production. High risk must be taken into account when designing cultivation technologies. The relatively large territorial extent of the highly hazarded category can be explained by the fact that the influential factors that can be considered constant at the time (soil, relief, geology) create the conditions for the formation of excess water. This does not mean that excess water inundations can occur in these areas every year, but the conditions are given. Based on this, the land user (farmer) is vulnerable to the so-called “year effect” (*Tamás and Bozán, 2009; Nagy and Nagy, 2018*), which is of course taken into account during the planning of crop production. When and where the excess water inundations can occur in a given year primarily the hydro-meteorological factors will determine. Based on such considerations, it is strongly recommended to change the cultivation system of some extremely hazarded areas. In areas that extremely hazarded by excess water, forestry (*Tóth, 2000*) and reed management (*Ruttkay et al., 1964*) can be recommended. In the case of a good aquitard layer, the utilization of fishponds can be considered (*Tasnádi, 1997*), of course keeping in mind the principle of multi-functionality. Rice cultivation on Solonetz meadow soils would be the appropriate solution (*Simonné, 1983*). Finally, conditions for grassland and pasture management could be created (*Petrasovits and Balogh, 1969; Vinczeffy, 1993*).

In areas with mainly hazarded to excess water (12 824 hectares), the application of site-specific cultivation technologies becomes necessary. In this case, the potential of tillage processes, such as deep plowing, deep loosening, mole drainage and, in some cases, the partial pipe drainage (*Thyll et al., 1983; Ligetvári, 1999*), must be taken into account, and the harmful disc-pan and plough-pan must be eliminated (*Salamín, 1966; Petrasovits and Balogh, 1969; Birkás and Gyuricza, 2000; Zsembeli et al., 2015; Blaskó, 2015*). It is advisable to use later sowing varieties and secondary crops. These areas are excellent for growing fodder crops. In addition (due to the less frequent of excess water inundations), it is advisable to encourage the establishment of orchards as well (*Andrásfalvy, 1973*).

In areas moderately or not hazarded by excess water (8 681 and 2 351 hectares), the use of traditional technologies may be maintained, but due to the specifics of the area, short-term excess water inundations may occur during extreme weather circumstances (e.g. sudden snow melting in early spring). In these areas, producing higher value crops is less risky.

In **Table 14**, I have summarized the utilization alternatives that could consider in relation to the use of excess water hazarded areas.

Table 14. Land use options (*Bozán et al., 2011*)

Utilisation	Characteristics, requirements	Options
Uncultivated land (fallow)	- neglected fallow is harmful; centre of infection: parasites, pests and weeds.	Not recommended, not sustainable.
Field specified agricultural production	- adaptation of early maturity groups; - decreasing of plant population; - increasing of amount of fertilisers and manures; - considered plant protection and weed control.	Corn hybrids (FAO 200-400); Silage maize (lower FAO number). Fodder-crops (millet, Hungarian grass, Sudan-grass, white mustard, green maize). Traditionally produced plants (rice, fibre hemp, sunflower, cabbage, herbs, alfalfa). Fodder sorghum (Sudan-grass, broomcorn). Protein rich fodder-crops (five-finger, hairy vetch, Hungarian vetch, white lupine, yellow lupine, white melilot, alsike clover, berseem clover, Persian clover, red clover, cat's-tail) .
Forestation	- removing of harmful shrubs (<i>Amorpha fruticosa</i>) from floodplains; - plantation of native species in autumn especially on the excess water hazarded areas.	Forestation: white willow, ashen, black walnut, poplars, oak, leaved maple, limes, alders, elms, swamp cypress. Planting of energy useful native trees.
Grassland management	- one of the main characteristics of grassland is the excess water toleration.	Grassland: meadow-foxtail, slough grass, reed canary grass, Yorkshire fog, creeping bentgrass, meadow fescue, purple moor grass, rough-stalked meadow-grass.
Meadow and pasture management, Grazing husbandry	- the temporary excess water inundation can be useful for meadow and pasture, but the long-term inundation cannot be tolerable; - direct manuring; - extensive animal husbandry.	Recommended seed mix: meadow fescue (25%), narrow-leaved meadow grass (40%), creeping bentgrass (20%), white clover (10%), birdsfoot trefoil (5%). Skudde sheep, mangalica pig, Hungarian grey cattle, native poultry species.
Orchards	- native species; - bio-production.	Plum, apple, walnut.
Reed production	- reed production based on the water flowing; nutrient filtering function.	Reed, sedge, bulrush.
Rice production	- high temperature and water demand; good water retention soil.	Multi-functionality (rice and fish).

Medicinal herb production	- it can be produced on temporarily inundated areas.	Anise, menthol mint, licorice, lovage, caraway, fennel.
Water retention and storage	- application of constructed wetlands with filtrating fields (reeds, sedges, bulrushes).	Temporary water reservoir, excess water reservoir, other purposed reservoirs, fish ponds, oxbows, dead river beds.
Fish ponds, multifunctional fish production	- multi-functionality; combined extensive-intensive aquaculture system; pond in pond system; native species.	Multifunctional wetlands.
Tourism and ecotourism	- development of infrastructure (parking places, restaurants, picnic areas, bird watching places, tourist paths, prospects, maps, information desks and signs, tourist guides, publicity etc.).	Oxbows, lakes, arboretums, parks, multifunctional ponds etc.
Hunting management	- supplemental feeding; artificial game protection places.	Big- and small-games.
Nature conservation area	- damage caused by suddenly raising water level; preventing from spreading of invasive species; buffer zones.	National Parks; Protected Landscapes Areas; Nature Conservation Areas; Special Protected Area (SPA); Proposed Sites of Community Interest (pSCI).
Wetland restoration and construction	- biodiversity conservation; landscape management; good quality and quantity of water.	Lakes, ponds, reservoirs, channels, dead river beds, lowland features areas, excess water hazarded areas, etc.

Table 14 illustrates that there are a number of options for the use of excess water hazarded areas. When evaluating the alternatives, it should also be taken into account that there are currently two types of approaches. According to some interpretations, the agricultural use of areas extremely hazarded by excess water should be completely avoided, and nature conservation could take the lead instead. However, it should be noted here that nature conservation interventions also have a significant cost – with special special emphasis on the need for state involvement –, which can only be compensated from the incomes provided by ecological services. In contrast, the other interpretation is a much more complex, integrated, collaborative approach, according to which field-level agricultural developments and interventions need to be coordinated with regional (river basin-level water resources management) and landscape management strategies.

4. NEW SCIENTIFIC RESULTS OF THE DISSERTATION

1. Examining the relationship between excess water hazards and influencing factors with mathematical-statistical methods, I determined the relative scale values (0-5) of the six influential factors of the Békés-Csanád Loess Plateau (soil, geology, relief, land use, groundwater, and hydrometeorology) and the order of priority of the influential factors causing excess water inundations. According to the obtained results, the soil characteristics >>>>> the type of land use >>>> the characteristic of the topography >>> the groundwater movement >> the geological conditions> and the hydro-meteorological conditions are the typical order.
2. I proved that the groundwater uprush phenomenon appears on the Békés-Csanád Loess Plateau. Based on the results, I proved that the Pearson III theoretical distribution function as statistical model is an acceptable approximation of the essential laws for groundwater movements on the Békés-Csanád Loess Plateau.
3. Based on the results of the spatial regression analysis I developed the Complex Excess Water Hazard Index ($CEWHI = (0.9 - 0.360 * SOIL + 0.033 * GEOL - 0.025 * LU - 0.017 * RELI - 0.017 * GW) \times 5 * HUMI$), and I compiled the Complex Excess Water Hazard map of the Békés-Csanád Loess Plateau.
4. I classified the influential factor maps and the CEWHI integrated map using the Jenks method. Based on spatial data, I summarized the territorial distribution of the Békés-Csanád Loess Plateau according to the excess water hazard categories, according to which 1.5% is not, 5.5% is moderately, 8.1% is meanly, 72.5% is highly, while 12.4% can be classified as extremely hazarded by excess water inundation.
5. I determined the utilization possibilities of the excess water hazarded areas of the Békés-Csanád Loess Plateau, which I assigned to the hazard categories in a differentiated way. I marked the main element of the possibilities in the site-specific cultivation technology.

5. APPLICABILITY OF RESULTS IN PRACTICE

1. Digital influential factor maps and the CEWHI map are suitable for comparing areas with different properties and for taking into account the causal and effects relationships of factors in regional and local decision-making processes.
2. My results provide the basis for the development of excess water control systems, especially the development of lower-level canal networks, in order to replace the current state of water management with a target state based on drainage priorities within an excess water control system.
3. The excess water hazard map prepared for the study area and the hazard maps derived based on the influential factors delimit the areas where interventions are needed. It can be stated which factor is most responsible for the formation of excess water in a given area, so it is possible to e.g. also for the direct treatment of the excess water situation formed for soil reasons, e.g. with agrotechnical solutions.
4. In order to rationalize land use, the level of excess water hazard shows in which areas it is worth changing the way of land use, for which I have elaborated specific proposals (e.g. removal of extremely hazarded areas from cultivation; creation of wetlands; creation of reservoirs, etc.).
5. The results will help decision-makers to prepare and implement larger-scale programs (e.g. implementation of EU Water Framework Directive, Climate Adaptation Plan, Land Reclamation Program, etc.) and specific intervention points (e.g. development / reconstruction of water management works, irrigation development, soil loosening, melioration, etc.). I have provided a result that can be used as a methodological background material in making strategic and operational decisions on land use and water management issues.

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7. LIST OF PUBLICATIONS RELATED TO THE DISSERTATION



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List of publications related to the dissertation

Hungarian scientific articles in Hungarian journals (4)

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