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Use of Digitalized Hydrogeological Maps for Evaluation of Salt-Affected Soils of Large Areas

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Soil salinity and sodicity is often related to the presence of shallow groundwater. We evaluated the importance of factors that affect soil salinity and sodicity in one typical salt-affected area, the Carpathian Basin. Five hydrogeological maps were used to demonstrate the occurrence of salt-affected soils in the Great Hungarian Plain. The 1 : 500,000 scale maps showed the depth to groundwater, the concentration of soluble salts in the groundwater, the height of groundwater table above sea level, textural classes of near-surface formations, and the dominant ions in the groundwater. After digitizing the maps, a database was created, and the association between variables was quantified by the uncertainty coefficient. The largest statistical association with the occurrence of salt-affected soils was found for the height of groundwater above sea level, the dominant ions of groundwater, and the textural class of subsurface layers. The hydrogeological maps showed close interrelationships of these factors, therefore no single factor, but a combination of factors, were responsible for the occurrence of salt-affected soil types. Regarding the most frequent categories of hydrogeological variables in which the salt-affected soils occurred, two groups were distinguished: the noncalcareous solonetzes and related soils (26.7% of the Plain) were most frequently associated with clay and the groundwater is dominated by Na^+ and HCO_3^- with a height above sea level at 80–90 m. The sodic solonchak and calcareous meadow solonetzes cover only 1.5% of the Plain, and these are most frequently associated with sand, where Ca^{2+} and HCO_3^- was

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dominant in the groundwater. However this group did not adhere to one specific zone of groundwater level, and also showed territorial segregation.

Keywords soil formation, hydrogeological survey, Hungary, cross-tabulation, statistical association, Geographical Information System, GIS

Due to the complexity of the processes of soil formation, it is difficult to set up deterministic relationships between soil-forming factors and soil properties. However, possible statistical relationships may exist between soil properties and soil-forming factors. Such relationships would be useful in the spatial prediction of soil types and soil properties. For example if the major factors that affect the formation of salt-affected soils (SASs) are quantified, then the risk of management practices which may result in salinization can be more reliably predicted.

Through digitizing soil maps and soil-forming factors, it may be possible to create a database which lists the occurrences of categories required for map delineation. The quantitative relationships between digitized maps require methods suitable for the analysis of categorical variables.

Based on published maps, our objective was to describe the distribution of the main hydrogeological factors related to the formation of SASs on the Great Hungarian Plain. The SASs of Hungary were formed under the influence of shallow groundwater, and that is characteristic for alluvial basins worldwide. Paralleling the work of Daineko and Fridland (1972), we calculated statistical associations based on the cross-tabulation between soil-forming factors. The association was interpreted employing existing theories on the formation of SASs. A subsequent article (Tóth et al., 2001) describes the probability of predicting the occurrence of SASs.

Materials and Methods

The Base Maps

A map of salt-affected Hungarian soils was published by Szabolcs (1974) (Figure 1). Soil categories of this map (Table 1) are correlated with other classification systems. Most of the categories are compatible with those of Kellog (1934), McClelland and colleagues (1959) and Bui and others (1998).

About one-third of the territory of the Great Hungarian Plain (46–48.5°N and 19–22.5°E) is affected by salinity/sodicity, mainly by solonetz-forming processes, one-third has potential SAS, and one-third is not threatened by salinity/sodicity. Potential SASs were distinguished from other soils as those which are not affected at present, but which could become considerably saline or sodic as a consequence of irrigation (Szabolcs 1974). The territorial segregation of some types of SASs is evident. The soil types Nos, 2–6 of Table 1 are concentrated mostly in the Danube-Tisza Interfluve, the Nos, 7–10 are more typical in the Tisza Plain. Except for the grouping of calcareous SASs (No 4 and 6) with the solonchaks, Table 1 lists the types of SASs roughly in decreasing salt concentration.

In the study region, the elevation of typical salt-affected areas above sea level is 80–90 m, climate is temperate continental with mean annual temperature of 10°C, (_ 2° in January, 21° in July), average annual precipitation is 527 mm (the rainiest month is June with 71 mm, the least rainy is January with 30 mm), mean annual pan evaporation is 900 mm.

The methodology of hydrogeological mapping (Figures 2–6) was formulated by Rónai (1975). Shallow borings, totaling 12422 were completed inside the Plain between 1964 and 1985. Boring depth was 10 m, or to the first solid/gravely layer. Soil and underground samples were collected from each stratigraphically distinguished layer. The depth of the groundwater table was determined with 0.5 m

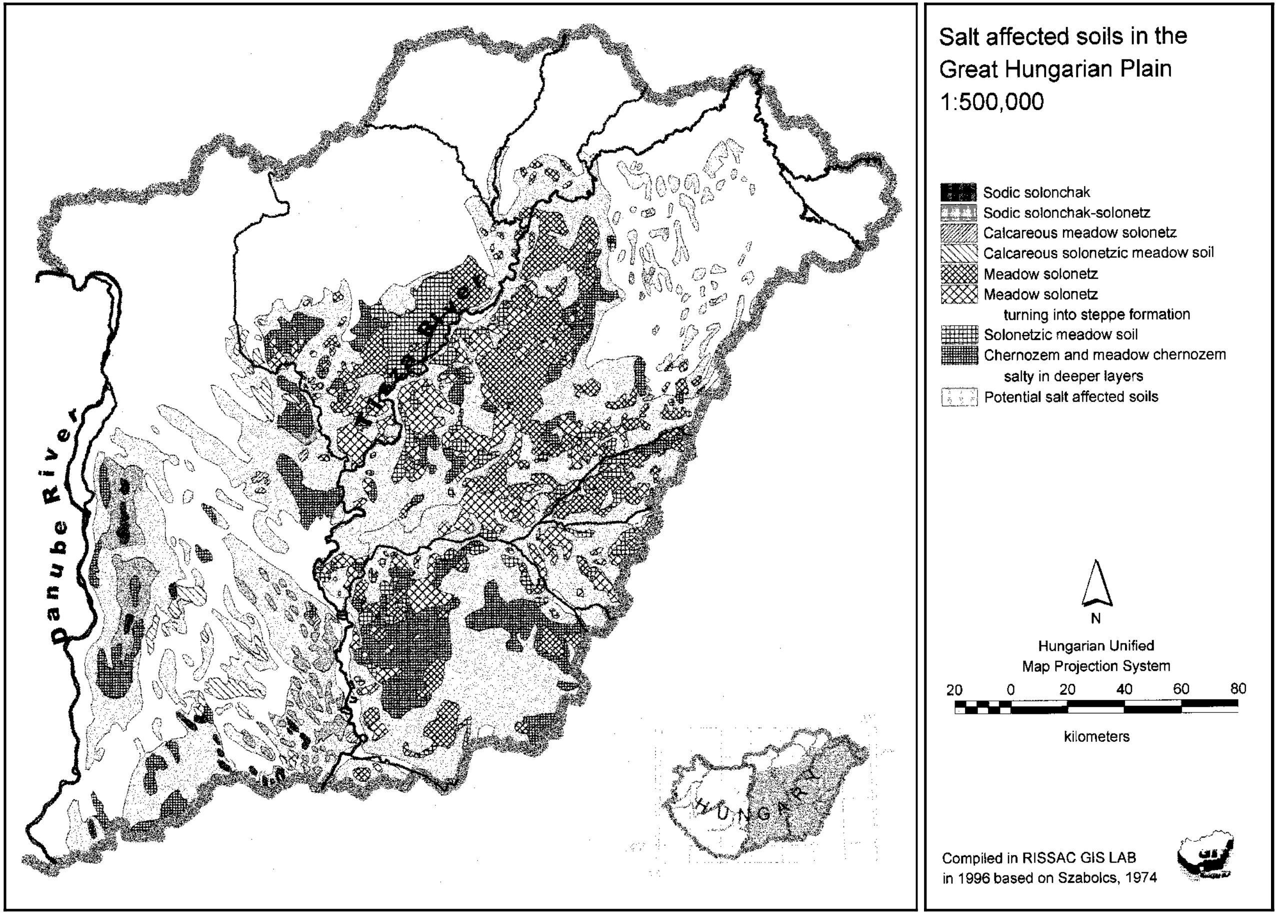

FIGURE 1 Salt affected soils in the Great Hungarian Plain.

TABLE 1 The area covered by the categories of the map "Salt-affected soils of Hungary" inside the Great Hungarian Plain

Soil type (No. of soil type on map)	Area km^2	Area % of all	Number of delineations	%	Mean size km^2	Std Dev km^2
Sodic solonchak (No. 2)	200.9	0.4	17	4.0	11.8	8.7
Sodic solonchak-solonetz (No. 3)	1135.5	2.5	51	11.9	22.3	56.0
Calcareous meadow solonetz (No. 4)	61.7	0.1	7	1.6	8.8	3.7
Calcareous solonetzic meadow soil (No. 6)	462.4	1.0	19	4.4	24.3	26.2
Meadow solonetz (No. 7)	3451.7	7.5	71	16.6	48.6	27.4
Meadow solonetz turning into steppe formation (No. 8)	2503.5	5.4	67	15.6	37.4	63.2
Solonetzic meadow soil (No. 9)	1585.5	3.4	57	13.3	27.8	86.0
Chernozem and meadow chernozem salty in deeper layers (No. 10)	3552.4	7.7	45	10.5	78.9	36.1
Potential salt-affected soils (No. 11)	16827.6	36.6	83	19.3	202.7	63.2
Non salt-affected soils (No. 12)	16185.9	35.2	12	2.8	1348.8	2744.7
Total	45967.1	100.0	429	100.0		

precision. Elevation of the boring point was read from 1 : 25,000 scale topographic maps. In the beginning, cations in the groundwater samples were determined by complexometry and flame photometry, later with atomic adsorption spectrophotometry and inductively coupled plasma spectrophotometry. Anions were titrated, except for sulfate, which was measured gravimetrically (the various methods used for analyzing cations and anions are described by Lukács and Rédly 1988). Particle size distribution of soil and ground samples was measured by sieving particles greater than 0.06 mm, and by sedimentation and pipetting for smaller particles (Methodological Publications 1973).

The five agrogeological maps used were described by Kuti and others (1999). The map of "Textural classes of near-surface geological formations" (Figure 2.) shows the stratification of the soil and underground materials in the 10 m deep boreholes. The acronyms in Table 2 show the continuous sequences of 2 m thick layers, where G stands for gravel (> 2 mm), S for sand (0.06–2 mm), I for silt (0.002–0.06 mm), and C for clay, (< 0.002 mm), so SCGGG for code 27 (which was used on the map as shown by Figure 2) indicates that this category has sand from the surface down to 2 m depth, under that 2 m clay, under that gravel down to 10 m.

If there was one anion or cation that constituted more than 50% of the total equivalent anion or cation concentration, respectively (Figure 3 and Table 3), only that anion or cation was mentioned. If two anions or cations constituted 25–50% of the total equivalent anion or cation concentration, respectively, but the ion first mentioned had larger percentage, there were two ions mentioned. If three anions or cations each constituted 25–50% of the total equivalent anion or cation concentration, respectively, and the HCO_3^- or Ca^{2+} ion was the dominant, three ions were mentioned. The acronyms in Table 3 are chemical symbols, except for bi (HCO_3^-) and su (SO_4^{2-}). The legends of the remaining three hydrogeological maps, "Total soluble salt concentration of groundwater" (Figure 4), "Depth to groundwater" (Figure 5) and "Groundwater level above sea level" (Figure 6) are self-explanatory.

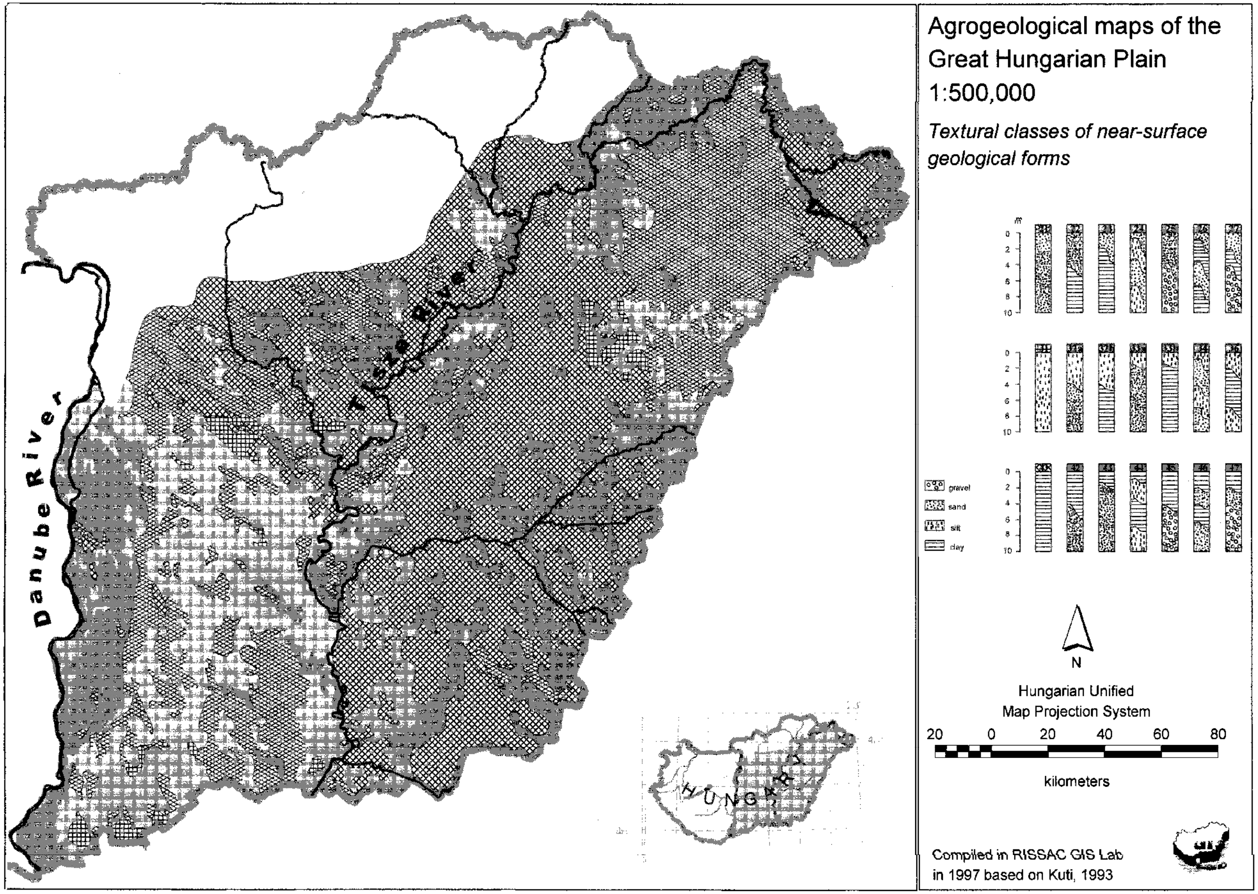

FIGURE 2 Textural classes of near surface geological formations.

TABLE 2 Crosstable of the map of SASs with the hydrogeological maps: depth to groundwater, textural classes and groundwater above sea level

	Depth to groundwater (m)					Textural classes of near-surface geological formations (sequences and original map codes)																		Groundwater level above sea level (m)													
Categories of the map of SAS	< 1	1–2	2–4	4–8	> 8	SSSSS(21)	SSCCC(22)	SCCCC(23)	SISSI(24)	SSGGG(25)	SCSCC(26)	SCGGG(27)	IIIII(31)	IISSS(32)7	ISSSS(33)	ISIIS(34)	ICCCI(36)	CCCCC(41)	CCSSS(42)	CSSS(43)	CICII(44)	CCGGG(45)	CSCSS(46)	< 80	80–85	85–90	90–95	95–100	100–105	105–110	110–115	115–120	120–130	130–140	140–150	150–160	> 160
No. 2 Sodic solonchak	X	x	x	.		X	X		X				X	.				.			X	X			.	x	X	X	x	x	x	.	X	X			
No. 3 Sodic solonchak-solonetz	X	X	x	.	.	x	x	x	.	x		x	.	.	X	x		.	x	.	X	X	x	x	x	x	X	.	.	.	.	x	.	.	.	x	
No. 4 Calcareous meadow solonetz	X		x			X		X	X						X			.						X	.	x	.	.	X	X	x						
No. 6 Calcareous solonetzic m. soil	X	X	x	.		X	X	.	X					x				.	.	x						.	.	X	X	X	X	X	x				
No. 7 Meadow solonetz		x	x	x	.	.		.		.	.		.	x	.			x	x	x	.		X	x	x	X	x	.	.	.	.	.	.				
No. 8 Meadow sol. turning into steppe f.		x	x	x	x	.	.	X			x		.	x	.		X	x	x	X	.		X	X	X	X	.	.	.		.	.	.				
No. 9 Solonetzic meadow soil		X	x	x	.	.	.	X			.			x	.	.		X	.	X	.		X	x	X	X	x	x	.	.	.						
No. 10 Chernozem and m. c. salty	.	x	x	x	.	.	x	.	.	.	X	x	X	X	x	x	X	x	X	x	X	.	x	.	X	X	x	x	.	.	.	X	.	.			
No. 11 Potential salt-affected soil	x	x	x	x	.	x	x	x	x	x	X	.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	X	x	x	.	x	
No. 12 Non salt-affected soil	x	x	x	x	X	x	X	x	X	x	x	x	x	.	x	x		x	x	x	x	x	.	x	.	.	x	x	x	X	X	X	X	X	X	X	X
Column total %	1.2	15.8	61.1	17.8	4.2	12	5.8	0.8	5.3	1.2	0.3	0.3	1.7	3.7	2.1	2.4	0.2	45.2	4.9	6.4	2.8	2.2	2.6	3.7	18.6	19	14.9	8.6	5.9	5.8	5.2	4.6	6.3	4.6	2.3	0.5	0.02

Inside cells X, x or . indicate whether the percent area of the relevant delineations is substantially larger near to or smaller compared to the average column total percent (±50%) of the same map category, respectively.

In sequences of textural classes G, S, I, and C means 2 m thick gravely, sandy, silty, clayey layers, respectively.

The five letter sequences of textural classes of 2 m thick layers starts from surface 0–2 m layer and ends at 8–10 m layer.

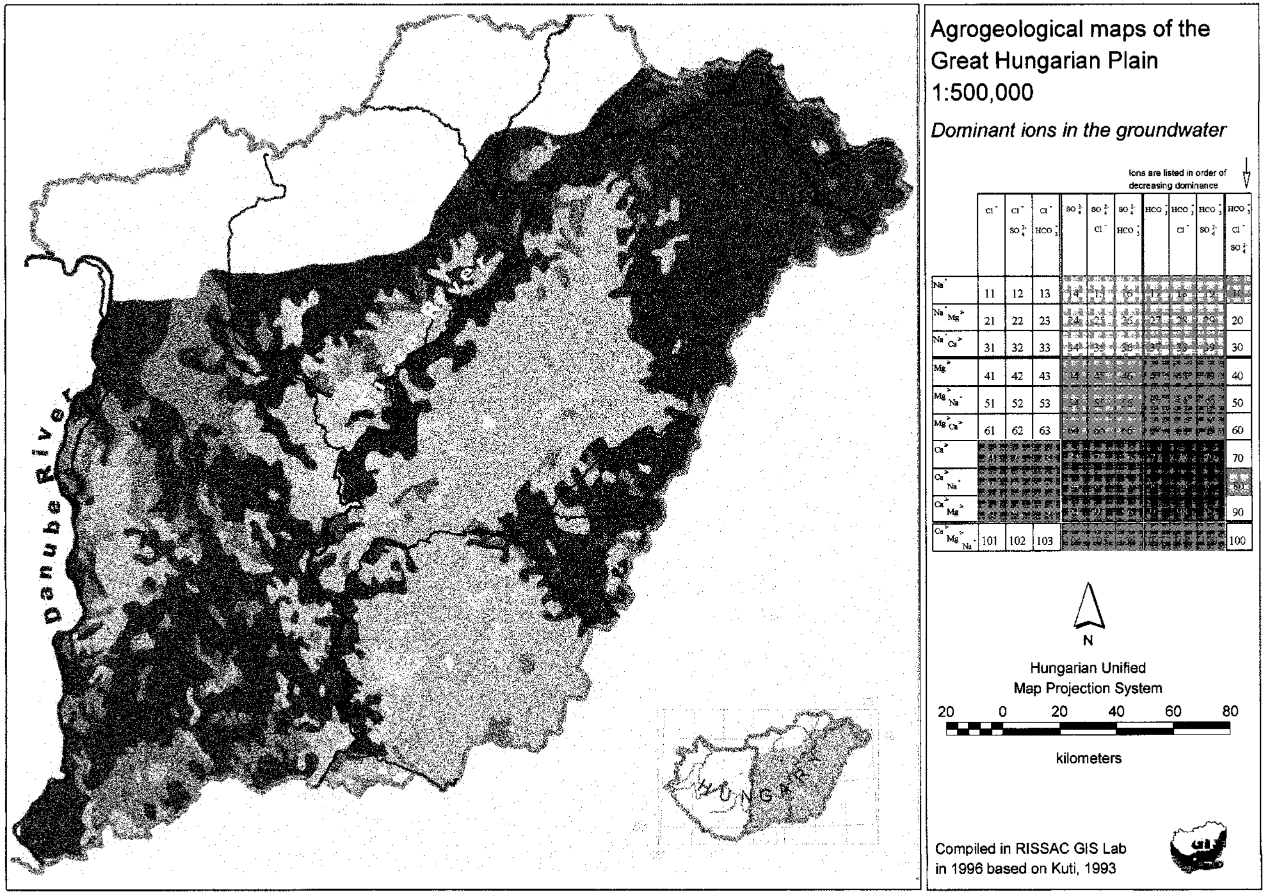

FIGURE 3 Dominant ions in the groundwater.

TABLE 3 Crosstable of the map of SASs with the hydrogeological maps: total soluble salt concentration and dominant ions

	Total soluble salt concentration of groundwater (g/l)					Dominant ions in the groundwater (dominant ions and map codes)																													
Categories of the map of SASs	< 0.5	0.5–1	1–5	5–10	> 10	Na biClsu(10)	Na Cl(11)	Na su(14)	Na subi(16)	Na bi(17)	Na bsiu(19)	NaMg su(24)	NaMg bi(27)	NaMg bisu(29)	NaCa bi(37)	NaCa biCl(38)	Mg su(44)	Mg bi(47)	Mg subi(46)	MgNa su(54)	MgCa subi(66)	MgCa bi(67)	Ca Cl(71)	Ca Clsu(72)	Ca su(74)	Ca subi(76)	Ca bi(77)	Ca bisu(79)	CaNa biClsu(80)	CaNa bi(87)	CaMg bi(97)	CaMgNa su(104)	CaMgNa bi(107)	CaMgNa biCl(108)	
No. 2 Sodic solonchak		x	x	x							x									X								x							
No. 3 Sodic solonchak-solonetz		.	x	x	.						X									x		X	x			.		x			.	.		.	
No. 4 Calcareous meadow solonetz			x	x	X				X		x																	x				X			
No. 6 Calcareous solonetzic m. soil		x	x	x							.									X								x				x		x	
No. 7 Meadow solonetz		.	x	x	X	X	X		.		X		X	X			X			.	X					.		.			X	.	X	X	x
No. 8 Meadow sol. turning into steppe f.		.	.	x	X	X	.	x	X		X		X							.	.					.		x			.	.	X	x	
No. 9 Solonetzic meadow soil			.	x	x	x	x		.		X		X							.						x		x				.	X	X	
No. 10 Chernozem and m. c. salty		.	x	x	X	x	X		X	X	X		X	.						x	X		.					.			x	x		x	
No. 11 Potential salt-affected soil		x	x	x	x	x	x	X	x	x	x	x	x	x	X	X	x			x	x		x	X		x		x		X	.	x	x	x	X
No. 12 Non slat-affected soil		X	X	x	.				.		.			x	x			X	X	x			X		X	X	X	X	X		X	x	x	.	x
Column total %		1.8	39.6	54.8	3.8	0.1	0.4	0.1	2.9	0.1	33	0.1	0.4	0.3	0.1	0.03	0.05	0.1	0.04	5.3	0.1	0.1	2	0.02	0.02	1.1	0.03	49.3	0.02	0.03	0.5	1.3	0.2	1.3	0.2

Inside cells X, x or . indicate whether the percent area of the relevant delineations is substantially larger, near to or smaller compared to the average column total percent (±50%) of the same mapcategory, respectively.

Dominant cations and chloride are shown by chemical symbols, bicarbonate and sulfate are indicated by bi and su, respectively.

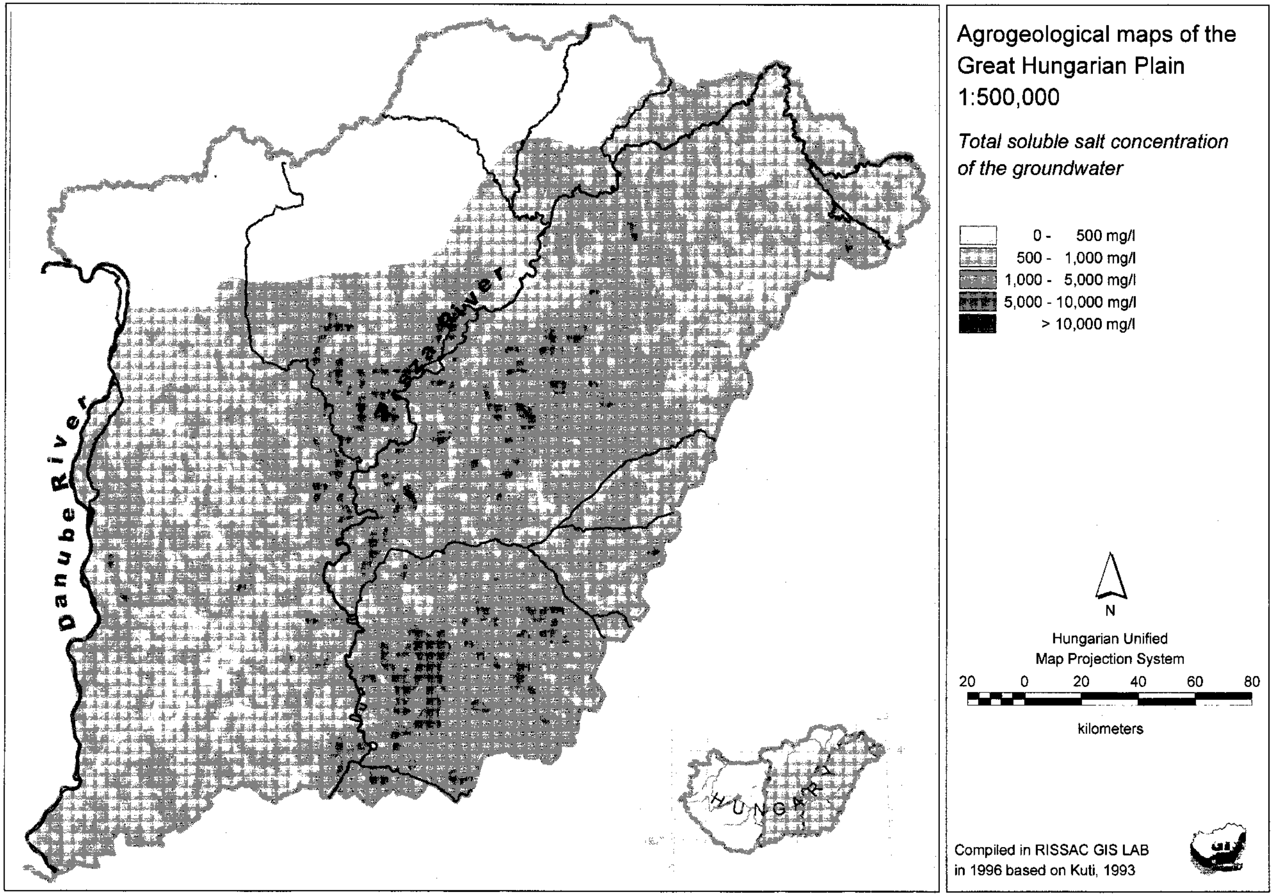

FIGURE 4 Total soluble salt concentration of the groundwater.

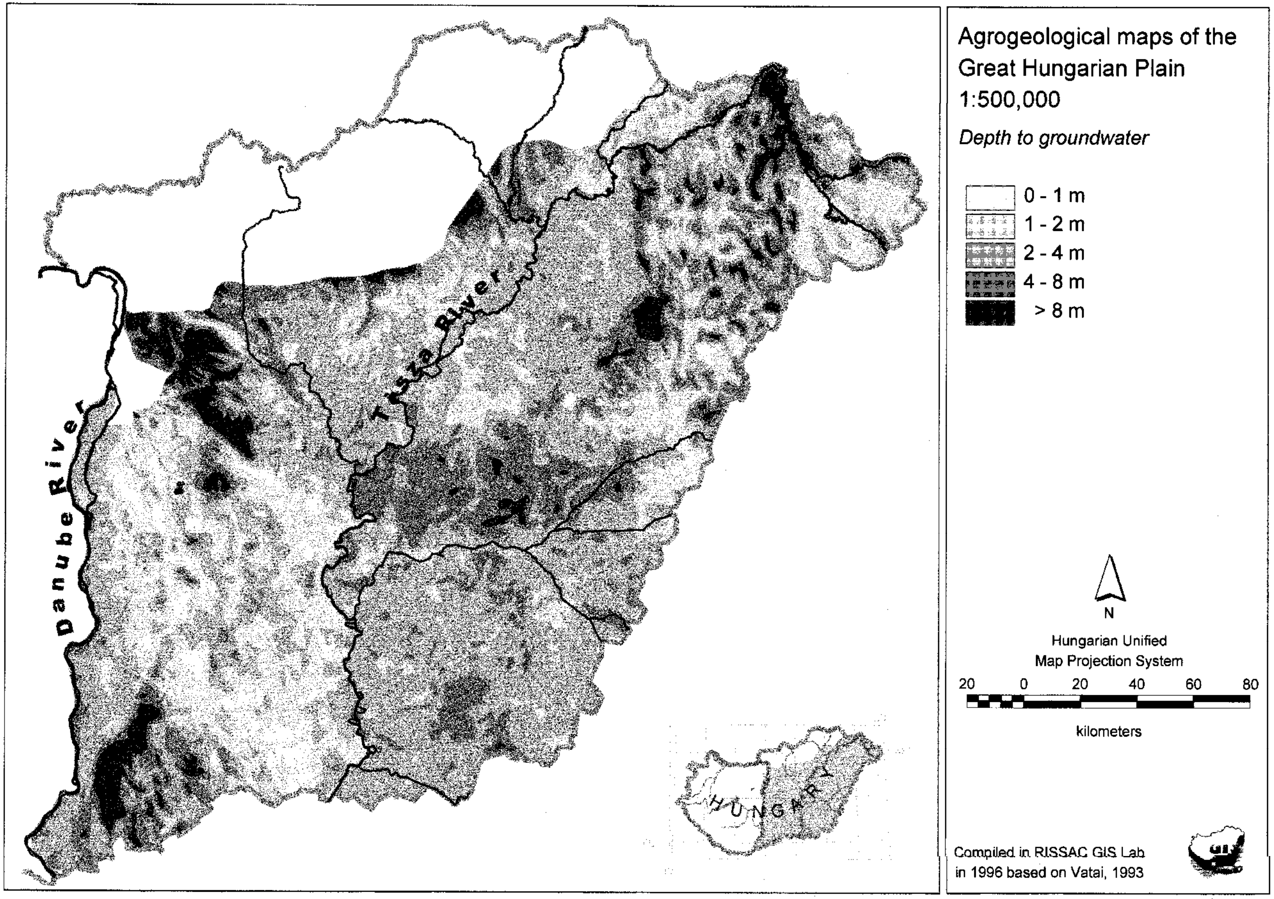

FIGURE 5 Depth to groundwater.

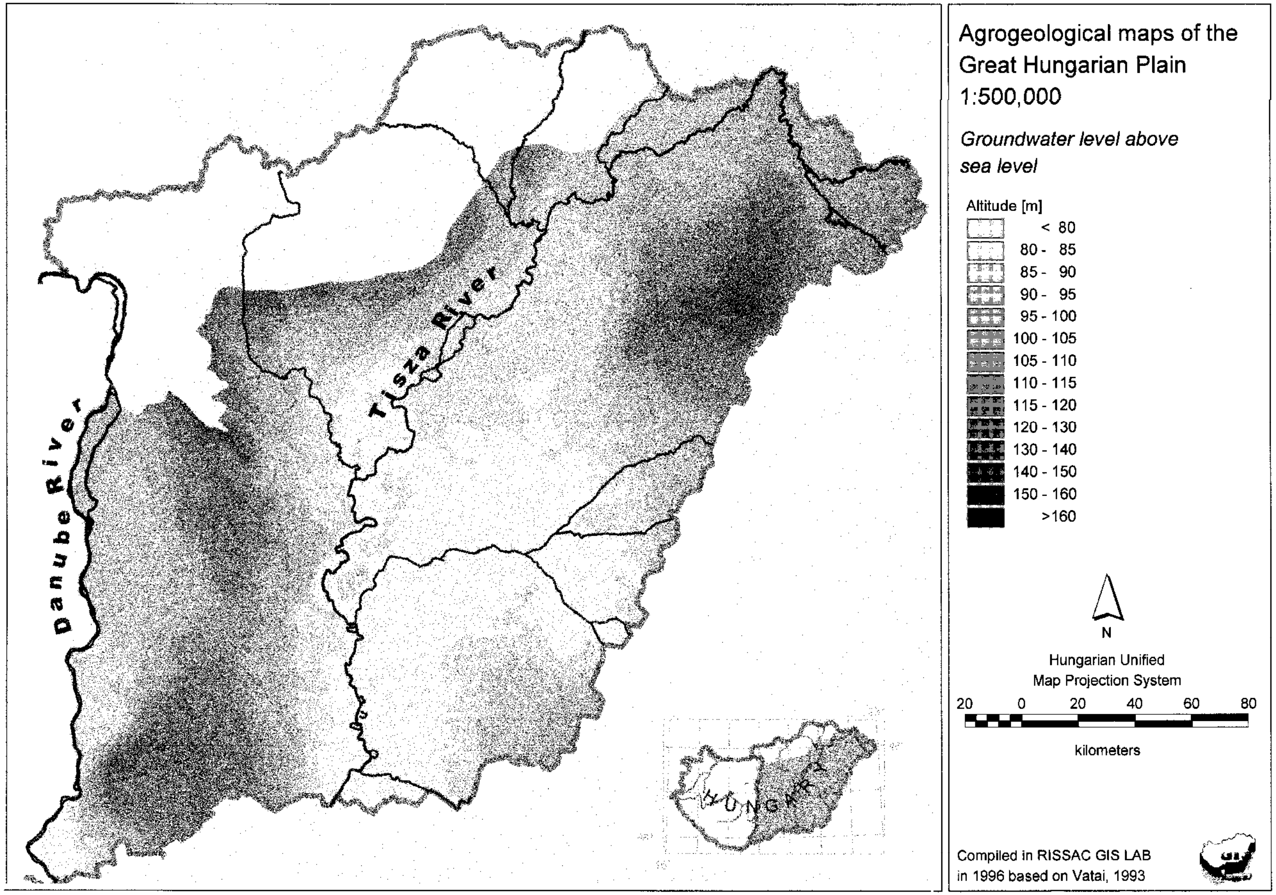

FIGURE 6 Groundwater above sea level.

Processing Cartographic Data by Using Geographical Information System (GIS)

The digital maps were intersected. Feature attributes from all coverages were joined. That is, each delineation of the resulting map was characterized by six attributes as opposed to the single attributes of the original maps.

In the course of overlaying the maps, sliver (that is small and/or elongated) delineations emerged. The areal distribution of delineations showed a sharp peak at 0.14 km^2, and this limit was set as the threshold value under which delineations were eliminated from the statistical analyses.

From a mathematical or statistical point of view, units of the resultant map are elements of a multidimensional space factor. Statistical behavior of the 16601 units in this six dimensional factor space was then studied.

Statistics Applied

Tests were based on the cross-tabulation of the data, using the type of SAS as the dependent variable (Figure 1), and the hydrogeological variables (Figures 2 to 6) as independent variables. Since the number of delineations does not necessarily reflect the extent of the given type of salt affected soil, for this study weights (area of each delineation) were assigned to the raw values.

We intended to calculate a quantified measure of statistical association between the type of SAS and the hydrogeological variables (categorical variables of the original maps). Based on an informational theory approach, a common method for the measurement of associations between two nominal variables is to calculate the asymmetric uncertainty coefficient, showing the relative reduction of uncertainty on one variable when the other variable is known.

The asymmetric uncertainty coefficient, $U_{j\backslash i}$ of Table 5 was calculated as:

$$U_{j\backslash i} = (U_j + U_i - U_{ij})/(U_j),$$

where

$$U_{ij} = -\sum_i \sum_j (a_{ij}/N) \log(a_{ij}/N),$$

$$U_j = -\sum_j (c_j/N) \log(c_j/N),$$

$$U_i = -\sum_i (r_i/N) \log(r_i/N),$$

$a_{ij}; i = 1, \ldots, F;\ j = 1, \ldots, G$ are frequency values in the $F \times G$ crosstable (F and G are the total number of categories of independent and dependent variables, respectively), subscript $_j$ denotes the dependent variable, and $_i$ denotes the independent variable, and $r_i = \sum_j a_{ij}$ and $c_j = \sum_i a_{ij}$, total row and column counts, and

$$N = \sum_i \sum_j a_{ij}, \text{ total sample size.}$$

$U_{j\backslash i}$ values range between 0 and 1. A value of 0 means that the independent variable does not contribute to the prediction. A value of 1 means the independent variable perfectly specifies the categories of the predicted variable. An advantage of using uncertainty coefficients is their solid formulation, since they show the reduction in entropy of the dependent variable (as introduced into information theory by Shannon 1948) when the independent variable is known.

Results and Discussion

Tables 2 and 3 show the crosstables calculated between the types of SASs and the hydrogeological variables. SAS types are listed as in the map (Figure 1). Column variables are the categories (original codes of Figure 1, and acronyms are also shown) of the hydrogeological maps. Tables 2 and 3 show the relative occurrence of the categories of the hydrogeological maps (column) inside the particular soil type (row) compared to the overall coverage of the same category (column total). For this purpose we calculated the ratio of two percent values. In the ratio, the numerator is the percent area of the given hydrogeological category (column) in the whole area covered by the given soil type (row). The denominator of the ratio is the overall percent area of the given category (column) of hydrogeological maps inside the Great Hungarian Plain, which is shown in the last line of Tables 2 and 3 as "Column total %." Where this ratio was more than 1.5, a capital X is shown inside the cell and that showed that the occurrence of the particular soil type (row) was at least 50% more abundant in the given category (column) than the average occurrence of the category (column). Where it was less than 0.5, indicating less abundant occurrence, a dot is used. Where these ratios were between 0.5 and 1.5 showing occurrences of the given category inside the soil type close to average occurrences of the same category, an x is used. Empty cells showed nonexisting combinations of map categories. Table 4 shows the category of the respective maps in which the soil types had the largest occurrence.

TABLE 4 The most frequent categories of hydrogeological variables and their percent area compared to the overall extent of the particular soil type

Soil No.\Hydrogeology	Texture sequence	Ions in gw	Salts conc. $g\ L^{-1}$	Depth to gw m	Groundwater ASL m
No. 2 Sodic solonchak	SSSSS	Ca bi	1–5	2–4	90–95
	43%	58%	60%	62%	26%
No. 3 Sodic solonchak–solonetz	CCGGG	Na bi	1–5	2–4	90–95
	25%	60%	65%	55%	53%
No. 4 Calcareous meadow solonetz	SISSI	Ca bi	1–5	2–4	< 80
	36%	45%	66%	83%	26%
No. 6 Calcareous solonetzic meadow soil	SSSSS	Ca bi	0.5–1	2–4	100–105
	52%	70%	57%	57%	31%
No. 7 Meadow solonetz	CCCCC	Na bi	1–5	2–4	85–90
	66%	65%	70%	71%	52%
No. 8 Meadow sol.turning into steppe f.	CCCCC	Na bi	1–5	2–4	80–85
	67%	61%	75%	63%	48%
No. 9 Solonetzic meadow soil	CCCCC	Na bi	1–5	2–4	85–90
	69%	52%	76%	61%	40%
No. 10 Chernozem with saline subsoil	CCCCC	Na bi	1–5	2–4	80–85
	43%	62%	65%	74%	32%
No. 11 Potentially salt-affected soil	CCCCC	Ca bi	1–5	2–4	80–85
	40%	41%	61%	66%	23%
No. 12 Non salt-affected soil	CCCCC	Ca bi	0.5–1	2–4	120–130
	45%	78%	61%	50%	12%

In sequences of textural classes G, S, I and C means 2 m thick gravely, sandy, silty, clayey layers, respectively. The five letter sequences of textural classes of 2 m thick layers starts from surface 0–2 m layer and ends at 8–10 m layer. Dominant cations and chloride are shown by chemical symbols, bicarbonate and sulfate are indicated by bi and su, respectively. ASL: above sea level; gw: groundwater.

TABLE 5 Matrix of statistical associations between the maps studied (n = 16601)

Uncertainty coefficient values (and the Student's t values and their significance in parentheses)

Variable (map)	Textural classes	Dominant ions	Salt conc.	Depth to gw	Groundwater ASL
Salt–affected soil type	0.08 (61, 0.00)	0.13 (80, 0.00)	0.05 (44, 0.00)	0.03 (32, 0.00)	0.16 (93, 0.00)
Textural classes		0.07 (60, 0.00)	0.02 (34, 0.00)	0.02 (33, 0.00)	0.10 (77, 0.00)
Dominant ions			0.10 (61, 0.00)	0.02 (27, 0.00)	0.16 (84, 0.00)
Salt concentration				0.01 (16, 0.00)	0.11 (49, 0.00)
Depth to groundwater					0.084 (49, 0.00)

Textural Classes of Near-Surface Geology

According to Gardner (1960), intermediate textural classes and downward fining of the soil solum promotes capillary rise from the groundwater, and in Hungary 'Sigmond (1927) prognosticated larger salinity with downward fining due to zero leaching. In contrast to the previously cited theories, this present study shows that categories with downward fining were small and not extended, and did not show a larger cover of SASs than other sequences.

The association between SAS type and the textural classes of near-surface geological formations (Table 5) was large (0.08), and the differences in texture of most solonchaks and solonetzes are defined in Table 2. It is worthy to note that the solonchaks, and calcareous SASs (Nos, 3 and 4) are closely associated with sandy particle size and most of these are found in the Danube-Tisza Interfluve on coarse sediments. Solonchak-solonetzes occur on sandy, silty and surface clayey sequences. For the development of the columnar/prismatic natric (B_t) horizon of solonetzes, the major SAS type of Hungary, it is a prerequisite that a defined amount of fine material be present in the parent material. On half of the area of the Great Hungarian Plain covered by SASs, solonetzes and solonetzic soils can be found inside the Tisza valley and is linked to clayey categories, (CCCCC, CSSSS, and CSCSS).

Except for soil types Nos. 3–4, all soils showed the largest occurrence in either the CCCCC or SSSSS category (Table 4). Sodic solonchak-solonetzes occurred most frequently on fine layers deposited on Danube gravel (CCGGG).

Dominant Ions in the Groundwater

Eugster and Jones (1979) and Timpson and Richardson (1986) showed that, during transport processes with increasing concentration, sodium tends to dominate groundwater composition. In Hungary, Endrédy (1941) proposed a model for the Carpathian basin-scale salt accumulation, in which the original source of soluble salts is the weathering of rhyolitic volcanic tuffs of the peripheral mountains around the Great Hungarian Plain. Rainwater washes the salts into the groundwater, which flows towards the deepest points of the Plain, and, due to the solubility relations, Na^+ is concentrated.

The results in this present study support this concept. The association of soil types with the dominant ions in the groundwater (Table 5) was large. In Table 3, the occurrence of solonchaks is substantially more frequent in areas where the groundwater is dominated by Mg^{2+} and HCO_3^- than in areas with other ion dominance. Usually the SASs are found in areas where the dominant cation is Na^+ and the dominant anion is HCO_3^-. Table 4 shows that all soil types have the largest occurrence in either "Na bi" or in the "Ca bi" groundwater type, the first being characteristic for solonetzes and solonchak-solonetz soils.

Total Soluble Salt Concentration of the Groundwater

There is often close proportional relationship between the salinity of groundwater and soil (Henry et al. 1985), since a greater salt concentration in groundwater increases the salt flux towards the soil surface as reported by Endrédy (1941), Darab (1967), Scherf (1935), and 'Sigmond (1927) for Hungarian soils. The data of Table 3 supports these previous findings, since the occurrence of non SASs is larger in areas with a dissolved solid concentration less than 1 g L^{-1} in the groundwater. Table 4 shows that the category of 1–5 g L^{-1} salt concentration is the most frequently encountered for almost each soil type, consequently the uncertainty coefficient of Table 5 is small. Solonetzes, unlike sodic solonchak and sodic solonchak-solonetz soils, have a larger occurrence than average where there are more than 5 g L^{-1} dissolved salts in the groundwater.

Depth to Groundwater

When the saline groundwater is shallow, the probability of salt accumulation increases (Fullerton and Pawluk 1987) due to increased salt fluxes towards the soil surface. In Hungary, there are several soil types which have shallow groundwater, most importantly the meadow and peaty soils, which cover 27% of the plain. In Figure 1 and Table 1 most of these soils are included in the category of potential SASs. It is the reason why the association with the soil types (as shown by the uncertainty coefficient in Table 5) is small. Table 2 shows that the occurrence of non SASs is larger in areas with deep groundwater than in other areas. Solonchak and solonchak-solonetz soils occur above shallower groundwater tables than solonetzes. Meadow solonetzes occur above deeper groundwater tables than solonetzic meadow soils. Table 4 shows that for each soil type the most frequent category was the 2 to 4 m depth, therefore the association was the smallest for this map.

Groundwater Level Above Sea Level (ASL)

SASs are located mostly on lowest positions on alluvial toposequences (McClelland et al. 1959). According to Endrédy (1941) and Kreybig and Endrédy (1935) the occurrence of SASs inside the Great Hungarian Plain is limited to certain zones of specified elevation ASL. These authors reported that elevation has a strong influence on the occurrence of SASs because of the groundwater table, and that the groundwater level (expressed above the sea level) was expected to be a factor strongly associated with the occurrence of SASs.

These concepts are strongly supported by our data. The association with the soil type is the largest (0.16). In Table 2, non SASs occur more frequently in higher groundwater level categories. Most solonchaks occur between a groundwater level of 90–100 m, but some occur between 120 and 140 m. These latter soils are found in the upper Tisza valley above small pockets of shallow saline groundwater. The difference between the elevation of groundwater level of solonchaks and calcareous meadow solonetzes shows that the latter is found lower and close to the Tisza River. The difference between the elevation in the Danube (higher) and Tisza valleys is clearly visible in that the meadow solonetzes (typical for the Tisza valley) occur at a lower groundwater level ASL than the solonchaks. Table 4 shows that the occurrence of meadow solonetzes upstream of the Tisza River (85–90 m height of groundwater ASL) is greater than the downstream occurrences.

Table 4 shows that noncalcareous solonetzes and related soils (Nos. 3, 7, 8, 9, 10) occur most frequently with similar conditions for particle size and dominant ions (clay, Na^+ and HCO_3^- dominant in groundwater 80–90 m ASL). Sodic solonchak and calcareous solonetzes (Nos. 2, 4, 6) are more frequently encountered on sands, where Ca^{2+} is dominant ion in the groundwater. One combination of most frequently encountered categories is shared by two soil types: meadow solonetz and solonetzic meadow soil (Nos. 7 and 9) are closely related and distinguished only by the structural features of A and B horizons.

Association between Hydrogeological Variables

Table 5 shows that the associations, expressed by an uncertainty coefficient between the hydrogeological variables themselves, are not as strong as the association between the SASs types and the hydrogeological variables. This showed that the hydrogeological variables and SASs have multiple interrelationships.

All calculated associations were very significant, due to the large number of delineations. The associations could not be improved with better sampling, since this sampling was comprehensive. The differences between the associations show the degree of relationships.

These results support the importance of not a single factor but a combination of cooperating factors on the formation of SASs. Sand and loess deposited in dunes or as plateaus provide fast leaching, where the groundwater level is deep. In the lower lying areas in the recent floodplains, the groundwater level is shallow, and the fine clayey surface deposits favor salt accumulation. Due to the shallow depth, evaporation from groundwater is greater, and consequently, the salt concentration in groundwater increases. Due to the differences in the solubility of the dissolved salts in the groundwater, Ca and Mg salts tend to precipitate at smaller concentrations, and there is a tendency of dominance by the most soluble Na and sulfate and chloride salts in the more saline groundwaters. These results support the theories of Endrédy (1941), Várallyay (1967), Erdélyi (1979), and Tóth (1984) on the role of basin-wise accumulation and concentration of groundwaters.

Conclusions

The uncertainty coefficient values between the maps are small, but all are statistically significant at $P < 0.0001$ and comparable to those reported earlier (Sorochkin 1977). A possible reason why the uncertainty coefficients are small, is that recent human activity has sunk groundwater levels. This has an additional affect, in that soils are changing in response to the new hydrological events, and solonchaks were converted to solonchak-solonetzes (Tóth and Blaskó 1998). Since the hydrogeological maps studied were compiled for general information and not for the study of soil salinization, an increase in uncertainty coefficients may be expected in the application of other categories to these maps. The separation of new categories inside the categories “2–4 m groundwater depth” and “1–5 g L^{-1} salt concentration in groundwater” is the most promising.

The GIS approach to the evaluation of soil distribution is a powerful means of utilizing large data sets and developing regional perspective of soil distribution and geological factors responsible for the distribution. Additionally, this approach is useful for developing hypothesis of SAS formation and for identifying areas for more detailed pedological and hydrological research. Prediction of the occurrence of SAS is treated in a subsequent paper (Tóth et al. 2002).

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