Salinity and sodicity hazard in water flow processes in the soil

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ABSTRACT

This paper presents the results of the distribution of salinity characteristics (electrical conductivity and sodium adsorption ratio) of groundwater, and based on the results, it reports the evaluation of the salinity and sodicity hazards in the fluctuation processes of shallow mineralised groundwater, or in the processes if such groundwater is used for irrigation. The issue was studied for the soil-water environment in the south-east of the Danube Lowlands for the period 1991 to 1994. The measured data and data taken from archives were processed in the form of graphical attachments (appendixes, supplements, graphical documentation) – maps, by means of the kriging interpolation method. Groundwater in the area in question is classified as highly mineralised with a high hazard of salinisation of the subsurface soil environment. The average annual values of the electrical conductivity of groundwater ranged from 600 to 2100 µS/cm in the examined period. The sodium adsorption ratio values ranged from 1.7 to 22.0 and indicate low, medium to high sodium salinisation of the environment due to groundwater. The distribution of electrical conductivity and sodium adsorption ratio on the regional scale can serve as a reference basis for the evaluation of changes in the groundwater salinity after 1994.

Keywords: groundwater; electrical conductivity; sodium adsorption ratio; salinity hazard; sodicity hazard; Danube Lowlands

The results of the monitoring of saline soil development prove that the main source of salts in soil is the salinity of shallow groundwater. In areas with an evaporation water regime of the soil, such as the south-east Danube Lowlands or the Eastern Slovak Plain, dissolved salts are transported from a groundwater level to the soil profile by means of vertical flow. Moreover, using such groundwater for irrigation also leads to the accumulation of salts in the soil profile. In both processes groundwater is drawn by evapotranspiration, and soluble salts coagulate on the surface of soil particles and sodium ions are adsorbed into the soil colloidal system. The water motion processes are determined by hydro-physical characteristics and hydraulic parameters of the porous subsurface environment and by water flow from and to the groundwater level. These processes result in the emergence and expansion of saline and alkali soils.

Many problems that have emerged in the irrigation management have also ensued from the chemical composition of irrigation water. The use of various types of water for irrigation and the ability to predict problems that may arise in the course of their use, invoked the need to create a water quality classification system that should be completely different from the systems used for geochemical, industrial, recreational, sanitary and other purposes.

The suitability of water depends on how it can be used under specific conditions. These conditions include the tolerance of crops to salts (Burger and Čelková 2001), various physical and chemical properties of soil, management of irrigation methods, and climatic conditions in the given region. The criteria for the evaluation of water properties for irrigation must include all the aforementioned factors. The problem is so complex and complicated that, so far, no universal and generally valid scheme for the classification of irrigation water quality has been developed.

Definition of characteristics relating to water salinity

The total water mineralization is defined as the sum of mass concentrations of solid inorganic substances dissolved in water, electrolytes (cations and anions) and non-electrolytes.

The term salinity relates to the total concentration of the main dissolved inorganic ions, i.e. Na^+, Ca^{2+}, Mg^{2+}, K^+, HCO_3^-, SO_4^{2-} and Cl^- in groundwater, channel waters and drainage waters. The particular concentrations of these cations and anions can be expressed by means of chemical equivalents ($mmol_c/l$) or on a mass basis (mg/l). The total concentration of salts (i.e. the salinity) is then expressed as the sum of the individual cations and anions in $mmol_c/l$, or in mg/l.

For reasons of analytical simplification the real salinity indicator is the electrical conductivity of water (EC) expressed in dS/m, or in mS/m or µS/cm. Electrical conductivity is always expressed at a standard temperature of 25°C in order to allow for the comparison of electrical conductivity in various climatic conditions.

The adverse effect of irrigation water quality on the physical properties of soil is associated with the accu-

Supported by the Grant Agency of Slovak Academy of Sciences VEGA Project No. 2/3049/23.

mulation of sodium ion on the soil exchange complex which imparts instability to the soil aggregates and whose disruption is followed by dispersion of clay particles resulting in clogging of soil pores. The adsorption of sodium by the soil is expressed by the sodium adsorption ratio (SAR) of the solution. This ratio is used as an indicator of sodicity hazard and is defined by the following equation:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}} \qquad (1)$$

where: Na^{+}, Ca^{2+} and Mg^{2+} are concentrations of the individual ions expressed in mg/l

Salinity hazard

It is necessary to express the total concentration of dissolved salts in irrigation waters in terms of the electrical conductivity of water for diagnostic and classification purposes. Based on electrical conductivity, waters are classified into four classes according to Richards (1954). The boundary values between the individual classes are 250, 750 and 2250 μS/cm. These limit values were determined on the basis of the relationship between the electrical conductivity of waters and the electrical conductivity of saturated soil extracts.

Low-salinity water (EC < 250 μS/cm) can be used for irrigation of most crops on most soils with little probability that soil salinity will develop.

Medium-salinity water (250 < EC < 750 μS/cm) can be used if the soil is washed with a moderate amount of water. In most cases crops with a moderate salt tolerance can grow without applying special methods of salinity regulation.

High-salinity water (750 < EC < 2250 μS/cm) cannot be used on soils with restricted drainage. Special management of salinity regulation and choice of crops with good salt tolerance are required even for soils with adequate drainage.

Very high-salinity water (EC > 2250 μS/cm) is not suitable for irrigation under ordinary conditions, but it can be used under very special circumstances. The soils must be permeable, drainage must be adequate, water must be applied in excessive amounts in order to ensure high soil leaching to be able to grow crops that are very salt tolerant.

Sodicity hazard

The sodicity hazard is determined by absolute and relative cation concentrations. If the content of sodium is high, the sodicity hazard is high and vice versa. If calcium and magnesium are dominant, the hazard is low. The introduction of water quality classes with regard to the sodicity hazard is even more complicated than with regard to the salinity. The classification of irrigation water with respect to SAR is mainly based on the effect of exchangeable sodium on the physical condition of the soil. Sodium sensitive crops can be damaged due to the accumulation of sodium in plant tissues.

Low sodium water (SAR = 0–10) can be used for irrigation on almost all soils with low risk of the emergence of harmful levels of exchangeable sodium. However, sodium sensitive crops can accumulate harmful concentrations of sodium.

Medium sodium water (SAR = 10–18) represents an obvious sodium hazard in fine textured soils having high cation-exchange capacity, especially in the case of low soil leaching if gypsum is not present. Such water can be used in coarse-grained soils or in organic soils with good permeability.

High sodium water (SAR = 18–26) can produce a harmful amount of exchangeable sodium, and will therefore require special soil management – good drainage, high soil leaching, and the addition of organic substances.

Very high sodium water (SAR > 26) is generally unsuitable for irrigation purposes.

The values of sodium adsorption ratio and groundwater electrical conductivity are the main criteria that characterise the degree of soil salinisation and alkalisation hazards in the processes of fluctuation of the shallow mineralised groundwater, or in flow regime processes if such groundwater is used for irrigation.

The objective of the present paper was to obtain groundwater salinity characteristics and to use them to determine the salinity and sodicity hazard within the aforementioned processes in the subsurface soil environment of the south-east part of the Danube Lowlands from 1991 to 1994. The regional distribution of the EC and SAR values can serve as a reference basis for the evaluation of changes in the groundwater salinity after 1994.

MATERIAL AND METHODS

The territory of interest is the south-east part of the Danube Lowlands and is delineated by the occurrence of saline soils usually in combination with Chernozems and a shallow level of mineralised groundwater (Čerwenka 1970, Kováčová 2001).

In order to describe the general hydrogeochemical situation, the territory of interest is divided into the following hydrogeological regions and structures in compliance with the *Hydrogeological Regionalisation of the Slovak Republic* (1984):

– Region: the Quaternary of the Danube Lowlands – Ray Island, lower Váh River and the confluence of the Váh and Nitra Rivers;
structure: Danube Lowlands Quaternary

– Region: the Quaternary of the Danube River – Komárno – Štúrovo area;
structure: Quaternary of the Danube River fluvial plain

To process the groundwater salinity characteristics, data and knowledge from the monitoring and research projects of the Hydrology and Hydraulics Institute, Slovak Academy of Sciences in Bratislava, as well as from other archive and database sources mentioned below were used.

The monitoring locations were chosen to the east of Ray Island, on the left side of the lower Váh River and in the Danube River fluvial plain between Komárno and Štúrovo. Field measurements and groundwater sampling were carried out in these locations from 1990 to 1992.

The concentration of salting ions was determined in groundwater samples. This concerns the following anions: hydrogen carbonates, sulphates, chlorides, nitrates and the following cations: calcium, magnesium, sodium, potassium. The pH-value and the EC were measured and the SAR values calculated.

The water reaction, temperature, conductivity and the total amount of dissolved substances were determined directly under field conditions using a portable pH meter and an LF-191 conductometer manufactured by WTW.

All the other chemical indicators were determined in the laboratory with pMX 3000 pH/ION meter – universal standard ionometer. The calcium and magnesium cations were determined by the AAS method in the adsorption run of the device.

Further knowledge and data on the groundwater hydrochemistry in the given territory resulted from a compilation of data acquired in the course of a hydrogeological survey of groundwater resources that was carried out within a geological survey mainly by the company IGHP Žilina. The observations of the Slovak Hydrometeorological Institute in Bratislava are another significant source of information. Groundwater quality monitoring, which has been systematically performed by this Institute since 1982, is a source of regionally significant hydrogeochemical knowledge and also includes data on changes of groundwater quality in time. Further information was obtained by monitoring of the salty soil development performed by the Soil Science and Conservation Research Institute in Bratislava with the partial monitoring system *Soil*, and by geochemical mapping of groundwater in Slovakia, which was one of the most significant tasks of the work in the *Geochemical Atlas of Slovakia* from 1991 to 1995. The Atlas gives a picture of the chemical composition of groundwater of the first aquifer in Slovakia for the period from 1991 to 1994 (Rapant et al. 1996).

The measured data and data taken from archives were processed in the form of graphical attachments – maps applying the kriging interpolation method using the *Field Interpolator* of PMWIN software (Wen-Hsing Chiang and Kinzelbach 1998) and SURFER (Golden Software, Inc. 2001) software. The theory is not emphasised in this description because it is described in numerous sources of literature.

RESULTS AND DISCUSSION

Region: Danube Lowlands Quaternary – Ray Island, lower Váh River and the confluence of the Váh and Nitra Rivers

The groundwater levels drop towards the Small Danube and Váh River in the middle of the Danube Lowlands. The groundwater level depth usually ranges from 0.5 to 2 m, and is only deeper in localised areas. The groundwater of the territory of interest is quite similar as far as the abundance of the individual components is concerned, especially Ca^{2+}, Mg^{2+} and HCO_3^-, which signifies that the bulk of the groundwater can be characterised as specifically calcium-bicarbonate waters with increased magnesium content. In addition to the aforementioned components, other components are also instrumental in the formation of the chemistry of this type of water in the following sequence: $SO_4^{2-} > Na^+ + K^+ > Cl^- > NO_3^-$. With respect to the considerable fluctuation of the sulphate, alkaline and chloride ions, in addition to the aforementioned types of waters, there are also bicarbonate waters with an increased sulphate, chloride, or alkali content. Only in exceptional cases does the nitrate component show a considerable fluctuation exceeding the amount of the sulphate and chloride components. The concentration of alkalis is also considerably variable in some places whose values exceed those of Ca^{2+}, Mg^{2+}. Such waters can be characterised as bicarbonate-alkaline waters with an increased amount of calcium or magnesium.

The salinity hazard (Figure 1c) in the groundwater level fluctuation processes or use of groundwater for irrigation purposes is medium in the western section of the southern part of the area of interest, which is small in terms of area, with EC up to 750 μS/cm (minimum value 683 μS/cm). In the rest of the area the salinity hazard is classified as high with EC values of up to 1848 μS/cm.

The sodicity hazard (Figure 2c) is classified as low in a major part of the territory, with SAR ranging from 2 to 10. In the area approximately delineated by a line connecting V. Kosihy, Okoličná, Čalovec and the Váh and Danube Rivers, the sodicity hazard increases to medium (SAR ranging from 10 to 18) to the limit of high sodicity hazard (SAR = 18) which is to be found around the area delineated by a line connecting Zlatná na Ostrove, Okoličná and Čalovec.

Territory east of the Váh River to the borders of the region – left side of the Váh River

Most of the water saturated group of strata in the given territory is constituted of Levant sediments. The Quaternary is 10–30 m deep and the boundary between the Quaternary and the Levant is unclear. In the area closest to the town of Komárno its depth is less than 10 m.

Based on the results of physico-chemical analyses that were carried out on samples taken from a large number of drilled wells it can be concluded that waters from the

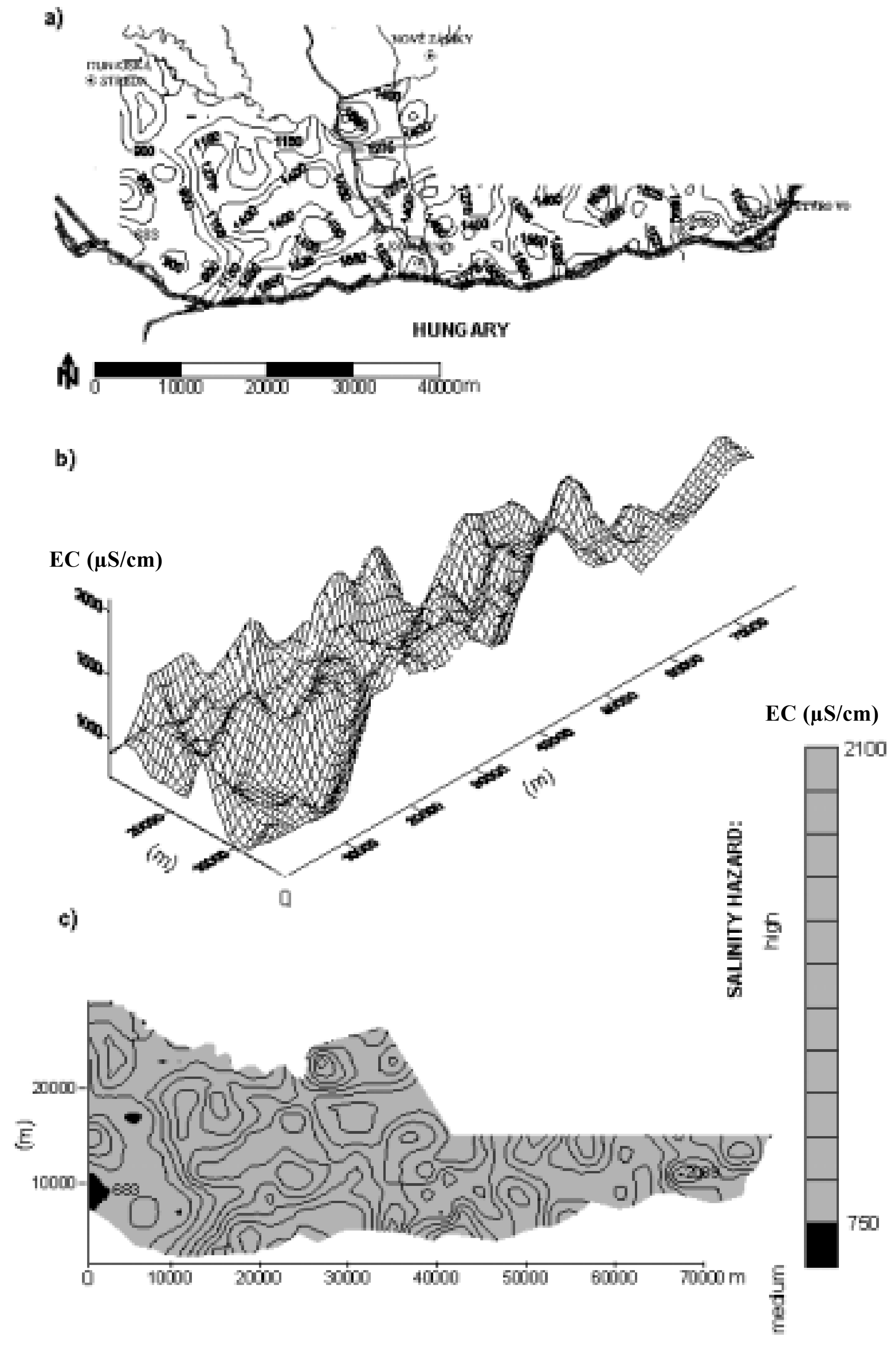

Figure 1. Distribution of electrical conductivity (EC) values (µS/cm) of groundwater in the first aquifer of the south-east Danube Lowlands
a) location of the position and EC isolines
b) 3-D depiction of the EC values
c) salinity hazard in the groundwater level fluctuation processes or in the use of groundwater for irrigation purposes

probes situated especially in the north of the area are weakly alkaline, while the results of water southwards range from weakly acidic through neutral to weakly alkaline. The total hardness of these waters is mostly caused by weakly acidic calcium and magnesium carbonates, while the increase in the permanent hardness is caused by the sulphate content.

The waters can be enriched with mineral salts, which is proved by a relatively high concentration of Ca^{2+}, Mg^{2+}, HCO_3^- ions. Thus from the hydrochemical aspect the

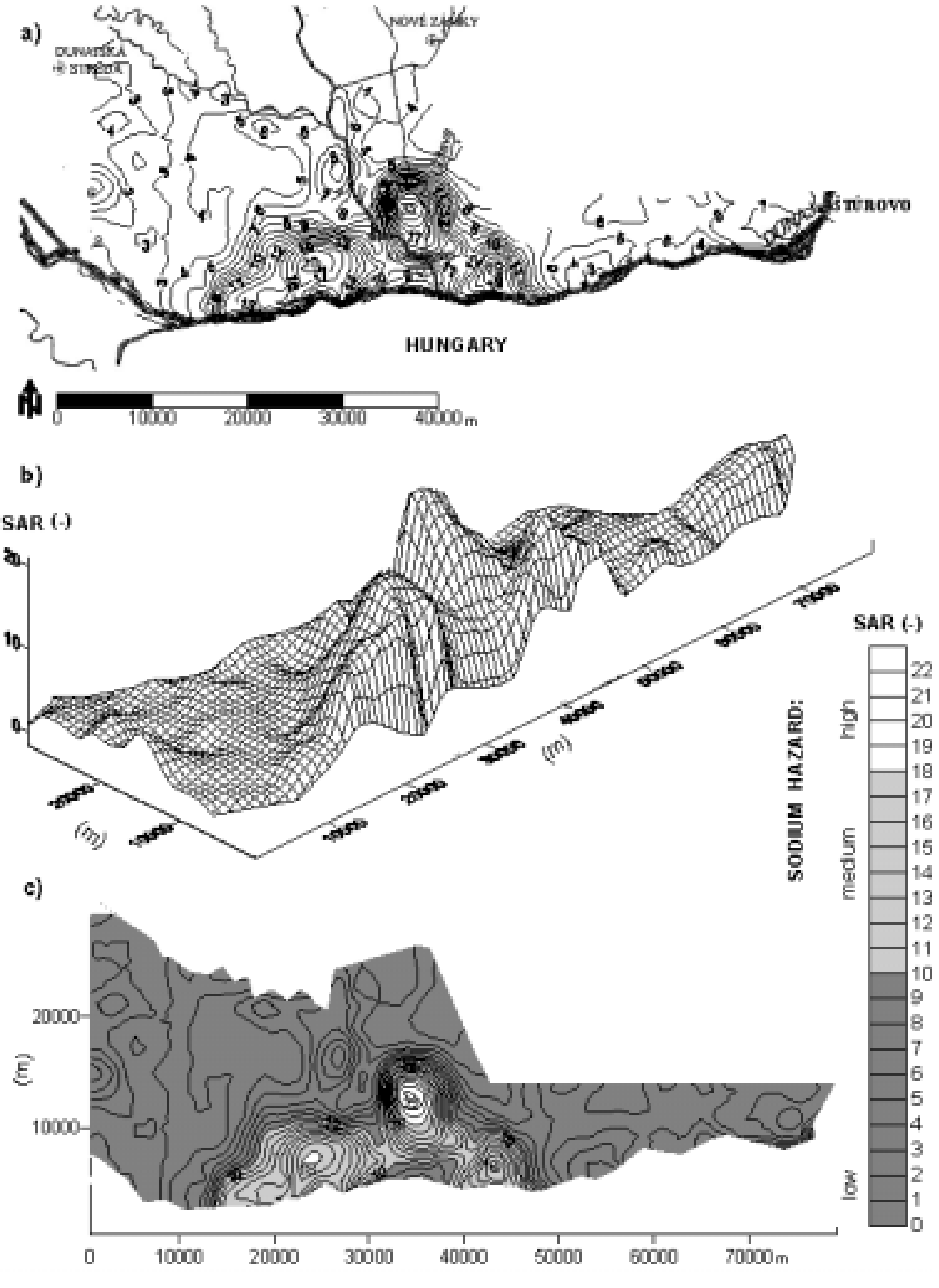

Figure 2. Distribution of the sodium adsorption ratio (SAR) values (–) of groundwater in the first aquifer of the south-east Danube Lowlands
a) location of the position and SAR isolines
b) 3-D depiction of the SAR values
c) sodicity hazard in the groundwater level fluctuation processes or in the use of groundwater for irrigation purposes

waters are classified as calcium-bicarbonate waters containing Mg^{2+} and SO_4^{2-}. In addition to the considerably unstable concentration of the sulphate component, chlorides and nitrates fluctuate as well.

The salinity hazard (Figure 1c) in the whole area is high with EC values ranging from 1046 to 2019 µS/cm. The sodicity hazard (Figure 2c) ranges from low values (SAR = 4–5) to high values that reach the maximum values in the whole area of interest (SAR = 22) south of the confluence of the Nitra and Žitava Rivers.

Region: Danube River Quaternary – Komárno – Štúrovo area

The Danube River fluvial plain is built of the Danube River deposits, whose depth irregularly ranges from 5 to 12 m, with the most frequent depths being between 6 m and 9 m. Gravels and sands covered by alluvial clays prevail in the group of strata. The gravel sand filling the Danube River fluvial plain bottom in this section belongs to the Würm. The cover of sandy loams is Holocene.

The fluvial deposits are strongly water saturated almost in the entire vertical profile. On the one hand, the groundwater level in these deposits is mainly affected by the surface flow of the Danube River and on the other hand, by water running off the adjacent Riss terrace and precipitation.

Iža – Žitavská Tôňarea

Waters in this area are neutral to weakly alkali. Most of the waters contain dissolved mineral salts in a range of 430 to 600 mg/l. As for the total composition of the prevailing cations, calcium and magnesium are mostly present at an approximately 1:1 ratio. Most of the waters in this area are classified as calcium-bicarbonate waters with a higher magnesium content, or magnesium-calcium-bicarbonate waters, and in some cases, especially in the vicinity of Patince village, even as sodium-magnesium-calcium-bicarbonate waters, which could demonstrate the effect of waters from the lower Pannonian subground.

The salinity hazard (Figure 1c) is high here with EC values ranging from 1333 to 1929 μS/cm. In the Patince area the sodicity hazard is medium with SAR values ranging from 10 to 18. In the rest of the territory the sodicity hazard is low with SAR values ranging from 3 to 7 (Figure 2c).

Kravany – Obid area

The analysed waters from this area exhibited neutral to weakly alkaline results. When evaluating their qualitative properties, considerable differences in the degree of mineralisation can be observed. There are waters containing 360 to 1200 mg/l of dissolved substances here. As for cations, calcium and magnesium prevail at a ratio of approximately 2:1 in most of the waters, however they are at a 1:1 ratio in some waters. As for the total classification of groundwater, it can be concluded that these are hard to very hard waters. The prevailing types of water are especially calcium-bicarbonate waters with a higher magnesium content which also show a higher sulphate content in most cases.

The salinity hazard (Figure 1c) is high in the whole area with EC values amounting maximally to 2089 μS/cm. The sodicity hazard is low with SAR values ranging from 3 to 7 (Figure 2c).

The distribution of salinity and sodicity characteristics results in the fact that compared to the groundwater of eolian and proluvial sediments, which is typical petrogenic water, the origination of groundwater salinity in the fluvial sediments of hydrogeological regions in the south-east Danube Lowlands exhibits several specific characteristics. Directly infiltrating rainwater is not one of the main sources of the complementation of the chemistry of these waters, but rather surface and slope waters infiltrating into the alluvial deposits which display variable mineralisation in time and space. Furthermore, it is the close hydraulic interrelation and interaction of groundwater in the riparian zones with the surface water courses (Danube, Small Danube, Váh, Nitra, Žitava Rivers, channel network and others) and its alterations in time and space (Šoltézs and Szolgay 1993). The chemical composition of groundwater in the hyporheic and riparian zones of surface water flows in the territory under investigation, and hence their salinity is determined rather by the mixing of waters of various mineralisation and composition than by mineralisation processes taking place in the fluvial gravel sand – water system. Such genetic conditions cause the characteristic spatial variability of mineralisation and salinity of the fluvial plain groundwater. Man also participates in the generation of this variability as a significant factor.

CONCLUSION

Groundwater in the area of interest, in the south-east Danube Lowlands, is classified as highly mineralised water with a high hazard of salinization of the subsurface environment. In the scrutinised period from 1991 to 1994 the average yearly EC concentrations in groundwater ranged from 600 μS/cm up to 2100 μS/cm. SAR values ranged broadly from $1.7 < SAR < 22$ and demonstrated locally a low, medium to high sodicity hazard due to the groundwater.

The plotted maps of the EC (Figure 1a, b) and SAR (Figure 2a, b) distribution as well as the maps of salinity hazard (Figure 1c) and sodicity hazard (Figure 2c) complement appropriately the knowledge of the hydrogeochemical composition of groundwater in the area of interest with respect to salinity in the fluctuation processes of the shallow mineralised groundwater level, or in the regime of processes if such groundwater is used for irrigation, and they can serve as a reference basis when assessing alterations in its development in the period following 1994.

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Received on February 6, 2003

ABSTRAKT

Hazard salinity a sodicity při procesech proudění vody v půdě

Příspěvek prezentuje distribuci charakteristik salinity podzemní vody (elektrická vodivost EC a sodíkový adsorpční poměr SAR) a jejich prostřednictvím stanovený hazard salinity a sodicity při procesech fluktuace hladiny mělké mineralizované podzemní vody, resp. při režimových procesech v případě využívání takovéto podzemní vody na závlahy. Problematika byla řešena pro půdní prostředí jihovýchodní části Podunajské roviny za časové období let 1991 až 1994. Naměřené údaje a převzatá data z archivních zdrojů byly zpracovány do grafických příloh (mapek) interpolační metodou krigingu. Podzemní vody ve sledovaném území patří do skupiny vysoce mineralizovaných vod s vysokou mírou nebezpečí salinizace půdního prostředí. V pokusném období se průměrné roční koncentrace EC podzemních vod pohybovaly v intervalu od 600 μS/cm až do 2100 μS/cm, což svědčí o existenci vysoce salinizované podzemní vody. Hodnoty SAR, které se pohybovaly v širokém rozmezí 1,7 < SAR < 22,0, poukazují na lokálně nízké, střední až vysoké riziko sodíkového zasolení prostředí vlivem podzemních vod. Vytvořené mapky distribuce EC a SAR, jakož i mapky hazardu salinity a sodicity, dovolují vhodně doplnit poznatky o hydrogeochemickém složení podzemních vod sledovaného území a mohou sloužit jako referenční báze při posuzování změn v jejich vývoji v následujících letech.

Klíčová slova: podzemní voda; elektrická vodivost; sodíkový adsorpční poměr; hazard salinity; hazard sodicity; Podunajská rovina

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