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ORIGINAL PAPER

Health risk assessment maps for arsenic groundwater content: application of national geochemical databases

Stanislav Rapant · Katarína Krčmová

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Abstract This investigation assesses the feasibility of calculating and visualizing health risk estimates from exposure to groundwater contaminated with arsenic (As) using data from national geochemical databases. The potential health risk associated with As-contaminated groundwater was assessed based on an elaboration of existing geochemical data in accordance with accepted methodological procedures established for human health risk assessment (U.S. Environmental Protection Agency methodology). A screening analysis approach was used for estimating the contribution of As to the total chronic health risk from exposure to groundwater contaminated with potentially toxic elements, including As, Ba, Cd, Cu, Hg, Pb, Sb, Se and Zn, and the results indicate that As contributes significantly (>50%) to this total health chronic riskin about 10% of Slovak territory. Based on the calculation of the potential risk level by exposure modelling, increased chronic as well as carcinogenic risk levels (medium to high) were documented in approximately 0.2 and 11% of the total Slovak area, respectively. The areas characterized by high health risk levels are mainly those geogenically contaminated. High and very high carcinogenic risk was determined in 34 of 79 districts and in 528 of 2924 municipalities.

S. Rapant (✉)
Geological Survey of Slovak Republic, Mlynská dolina 1, 817 04 Bratislava, Slovakia
e-mail: rapant@gssr.sk

K. Krčmová
Department of Geochemistry, Faculty of Natural Sciences, Comenius University, Mlynská dolina, 842 15 Bratislava, Slovakia

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Introduction

Groundwater contamination by inorganic and organic compounds of natural or anthropogenic origin represents a serious global environmental problem since groundwater is used as a significant drinking water source worldwide. The identification and characterization of associated human health risks are important problems that need to be addressed by environmental and medical geochemistry. Current knowledge of element and compound toxicity enables a descriptive (qualitative) risk assessment based on the identification of adverse effects (chronic, carcinogenic) and the quantitative assessment of risk level (calculation and map presentation of health risk).

Arsenic (As) represents one of the most potentially toxic inorganic contaminants of groundwater worldwide (Bundschuh et al., 2004; Focazio, Welch, Watkins, Helsel, & Hom, 1999; Lin, Tang & Bian, 2002; Smith, Lingas & Rahman, 2000), including Slovakia (Khun, Jurkovič & Urminská, 2000; Rapant & Kordik, 2003). The chronic and carcinogenic manifestations of ingesting As-contaminated groundwater for drinking purposes are of great concern to many researchers and health care workers, and international epidemiological, geochemical and medical-geochemical studies have focused on the problems associated with As-contaminated groundwater (e.g., Ahmed et al., 2004; Cabrera & Gómez, 2003; Fletcher et al., 2003; Guo & Tseng, 2000; Tollestrup et al., 2005; Van Geen et al., 2002). The main aim of these studies has been the qualitative/quantitative health risk assessment related to increased levels of As in the environment in order to implement the appropriate mechanisms for minimalizing these levels. The results of such studies may lead to the future reassessment of the currently valid drinking water limit value for arsenic, which has been established at 0.01 mg l^{-1} in most countries. According to the World Health Organisation (WHO), this concentration corresponds to the estimated excess lifetime skin cancer risk of 6×10^{-4} (six cases per 10,000 population; WHO, 1993). One of the major remaining uncertainties is related to the nonthreshold approach in carcinogenic risk assessment for As. Future results may determine whether or not there will be a reduction in the permitted level of As in drinking water, which would would have direct bearing on the future availability of some of the water sources currently used for drinking purposes. As such, risk assessment studies of As-contaminated drinking water have important consequences worldwide.

The present study is designed as a model evaluation of the potential health risk from As-contaminated groundwater in the Slovak Republic based on existing geochemical data in accordance with currently valid methodological principles and procedures of health risk assessment. The aim of the study was to acquire basic information on health risk levels related to the chronic as well as carcinogenic effects of As with a view to identifying potential risk sites for future detailed medical-geochemical study.

Materials

The health risk assessment for groundwater As in Slovakia reported here is based on a national geochemical data set which was assembled during the compilation of the *Geochemical Atlas of Slovak Republic, Part I: Groundwater* (Rapant, Vrana & Bodiš, 1996). This complex geochemical database consists of a total number of 16,359 groundwater samples taken from the first aquifer in Slovakia, including springs (8857), drillholes (1537), adits (51), wells (5716) and drainages (198), at a sampling density of one sample per 3 km^2. The samples were collected between May and October in each of the years in the period spanning 1991–1994, at medium groundwater levels and under stable climatic conditions. For the trace element analysis, water samples were filtered through a 0.45-μm pore-size membrane filter and chemically stabilized (HCl). Total As contents were analysed by the hydride generation-atomic absorption spectrometry method [HG-AAS; SpectrAA with GTA (graphite tube atomizer), Varian, Palo Alto, Calif.], with the detection limit set to 0.001 mg l^{-1}. The reliability interval for the analytical results, determined at tenfold the amount of the detection limit, corresponds to ±0.0005 mg l^{-1}.

The concentration of As in Slovakian groundwater ranges from 0.0005 up to 4.9 mg l^{-1}, with an average value corresponding to 0.0019 mg l^{-1} (Rapant et al., 1996; Fig. 1). Of the 16,359 samples analysed, more than 76% (12,485 samples) were below the detection limit of standard analytical methods for As determination. For the purpose of statistical data elaboration and the subsequent map construction, values below the analytical detection limit (0.001 mg l^{-1}) were conventionally replaced by those of half of the detection limit (0.0005 mg l^{-1}).

In terms of the origin of the As, two basic types of areas with documented As-contaminated groundwater can be distinguished in Slovakia:

- geogenically contaminated areas with naturally high As contents in the range of 0.0X–0.X mg l^{-1} (mostly in a form of surface anomalies);
- areas influenced by anthropogenic activities, characterized with sporadic appearances of

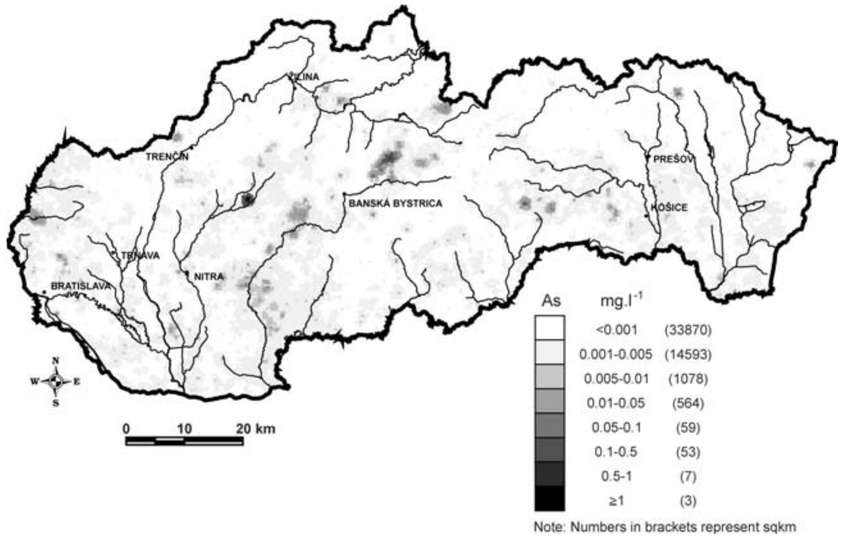


Fig. 1 Map showing arsenic (As) levels in groundwater in Slovakia

increased As levels, usually not exceeding 0.0X mg l^{-1} (predominantly point anomalies).

It can generally be stated that geogenic As anomalies in the groundwaters of Slovakia are, in terms of As concentrations in the groundwater (>0.05 mg l^{-1}) and spatial distribution, more significant than anthropogenically influenced ones.

Methods

For the purposes of calculating and assessing the potential health risks from potentially toxic element contamination of groundwater in Slovakia – in this case, primarily As – methodological procedures of risk analysis defined by U.S. Environmental Protection Agency (U.S. EPA, 1989) were used. Subsequently acquired results were transformed into a map form by applying standard methods of data interpolation used for geochemical and environmental map construction (Rapant & Kordík, 2003; Rapant, Vrana & Čurlík, 2004).

A screening procedure was performed in order to identify the significance of the contaminant in a particular medium – in this case, As in groundwater. The calculation of the health risk from groundwater As was derived using the RISC Workbench software, ver. 4.01 (Spence & Walden, 2001). Calculated health risk levels were classified in accordance with the U.S. EPA approach (1999). Software programmes, including Surfer (Win32), ver. 6.01 and Map Info Professional, ver. 4.1 were used for visualizing the results.

Screening procedure

The screening procedure was used to identify the most significant chemicals associated with the contamination (U.S. EPA, 1989) that were also the most likely to contribute significantly to the health risk. This procedure is based on the evaluation of two of the most important factors contributing to potential effects of chemicals – analytical concentration and toxicity:

$$R_r = \frac{C_{ij} \times T_{ij}}{\sum_{i=1}^{n} C_{ij} \times T_{ij}}$$

where R_r is risk rate of the chemical $_i$ in medium$_j$ on total risk (–), C_{ij} is (the highest) concentration of the chemical $_i$ in medium $_j$ (mg l^{-1}), T_{ij} is toxicity value for a chemical $_i$ in medium $_j$: chronic effects – 1/reference dose [(1/RfD), mg/kg-day]/carcinogenic effects – cancer slope factor [CSF, $(\text{mg/kg-day})^{-1}$]

The screening procedure is performed separately for chronic effects of chemicals, for which toxicity is characterized with a RfD and for carcinogenic effects for which toxicity value is expressed by a cancer slope factor.

The following potentially toxic elements and significant groundwater contaminants in Slovakia were included in the risk rate calculation: As, Ba, Cd, Cu, Hg, Pb, Sb, Se and Zn. Given the lack of data on carcinogenic effects of the majority of these elements, it was only possible to assessed the rate of ''total'' chronic risk of each through a concentration–toxicity screen. An overview of reference doses characterizing the toxicity of the chemicals analysed in terms of their adverse chronic effects is introduced in Table 1 (according to Spence & Walden, 2001; RAIS – Risk Assessment Information System: www.risk.lsd.ornl.gov).

The results of the screening procedure performance were subsequently recalculated to percentage rates for the evaluated contaminants on the total risk of groundwater contamination, and, based on this, an approximation of ''relative'' chronic risk for As in the groundwater of Slovakia was determined. This approach makes it possible to identify and spatially visualize those sites of concern in which adverse chronic effects of As on the resident population can be expected.

Health risk level calculation

Health risk assessment is generally based on a quantification of risk level in relation to two types of adverse effects: chronic (noncarcinogenic) and carcinogenic. Characterization of the chronic risk level consists of threshold effects (tolerance chemical level) and is based on the presumption of manifestation of adverse chronic effects until the threshold (the so-called RfD, which represents the lifetime daily exposure level tolerated by a human organism) is exceeded. The characterization of carcinogenic risk level consists of a concept of nonthreshold effects – that is, no dose is safe and risk-free and each level of exposure can generate a carcinogenic response (U.S. EPA, 1989).

The level of health risk was calculated using software developed in accordance with the U.S. EPA approach (1989) – RISC Workbench. It is based on the assumption of the long-term ingestion of groundwaters contaminated with As and used for drinking purposes by the adult population. Health risk from increased concentrations of As in the groundwater was assessed in relation to its chronic as well as carcinogenic effects, based on the evaluation of average daily dose estimates and defined toxicity values for As (U.S. EPA, 1998) according to the following relationships.

The chronic risk level was calculated as:

$$HQ = \frac{ADD}{RfD}$$

where HQ is the hazard quotient (–), ADD is the average daily dose (mg/kg-day), RfD is the reference dose (mg/kg-day); for As, this is 0.0003 mg/kg-day).

The carcinogenic risk level was calculated as:

$$CR = ADD \times CSF$$

where CR is the cancer risk (–), ADD is the average daily dose (mg/kg-day), CSF is the cancer slope factor (mg/kg-day^{-1}); for As, this is (1.5 mg/kg-day)$^{-1}$

As input data, conventionally accepted exposure parameters were chosen for ADD estimation according to the equation

$$ADD = \frac{C \times IR \times ED \times EF}{BW \times AT}$$

where ADD is the average daily dose (mg/kg-day), *C* is the concentration of As in the groundwater (mg l^{-1}), IR is the ingestion rate (l day^{-1}; considered here to be 2l day^{-1}), ED is the exposure duration (in years; considered here to be 70 years), EF is the exposure frequency (day year^{-1}; considered here to be 365 days year^{-1}), BW is the body weight (kg; considered here to be 70 kg), AT is the averaging time = average

Table 1 Overview of reference doses (RfD) estimated for selected potentially toxic elements

Chemical	As	Ba	Cd	Cu	Hg	Pb	Sb	Se	Zn
Oral reference dose (mg/kg-day)	0.0003	0.07	0.0005	0.037	0.0003	0.0036	0.0004	0.005	0.3

lifetime [in days; considered here to be 25,550 days (70 years)].

Health risk level assessment

Health risk level was classified in accordance with the U.S. EPA approach (1999). Evaluative scales used for chronic and carcinogenic risk level classification are reviewed in Tables 2 and 3, respectively.

Construction of the health risk map

The results of this study are presented as a visualization of the spatial data and the graphic interpretation of these data in a map form. The maps of health risk from As groundwater contamination were compiled as follows. Chronic and carcinogenic risk levels were calculated for each groundwater sample based on the analytically determined As concentration. These data were subsequently used for health risk map construction for the whole Slovak territory in a form of pixel maps. The pixel maps were compiled by modelling – which included data averaging and smoothing – based on the inverse distance interpolation gridding method. A basic grid cell of the pixel map represents a square (pixel) with a 1-mm side corresponding to 1000 m (area equal to 1 sq. km). The risk level was computed for each grid cell health by calculating the weighted average, based on the inverse distance from the cell centre to the nearest 15 samples and through subsequent data smoothing. A smoothing factor of 1 and a power function of 2 were reflected in the calculation, which did not include an anisotropism.

Health risk level maps for the administrative units of Slovakia were compiled based on a calculation of chronic and carcinogenic risks from an average As concentration for each district/municipality. This was acquired by averaging As levels calculated for each pixel within the borders of the respective districts and municipalities using pixel maps of the distribution of As in the groundwater in Slovakia compiled in the same way as described above.

Table 2 Scale for chronic risk level assessment

Risk level	ADD/RfD[a]	Chronic risk
1	≤1	No risk
2	>1 ≤ 5	Low
3	>5 ≤ 10	Medium
4	>10	High

[a] ADD, (Average daily dose mg/kg-day); RfD, reference dose (mg/kg-day)

Table 3 Scale for carcinogenic risk level assessment

Risk level	Calculated cases of neoplasm occurrence	Carcinogenic risk
1	<1 per 1,000,000 inhabitants	Very low
2	>1 per 1,000,000 inhabitants <1 per 100,000 inhabitants	Low
3	>1 per 100,000 inhabitants <1 per 10,000 inhabitants	Medium
4	>1 per 10,000 inhabitants <1 per 1,000 inhabitants	High
5	>1 per 1,000 inhabitants	Very high

Results

Screening procedure

Results of the screening procedure are presented in Fig. 2. Based on the map visualization, it appears that approximately 10% of the Slovak territory is characterized by groundwater containing As at a concentration where it contributes more than 50% to the total chronic risk from groundwater contaminated by potentially toxic elements. The results suggest that As is a significant groundwater contaminant in several areas in Slovakia (see Fig. 2) and can pose a potential health risk for resident population based on the presumption of their use of the groundwater for drinking purposes.

In some areas of potential risk more detailed medical-geochemical investigations have already been carried out – for example, Spišsko-Gemerské rudohorie Mountains (Rapant, Cicmanová, Dietzová, & Khun, 2003) and the Žiarska basin (Khun et al., 2000) – or are ongoing projects (Horná Nitra region, basin of the river Hron). The results of these studies to date indicate a causal association between the exposure of the inhabitants to the groundwater As and the negative impact on their health, based on analyses of external (As content in drinking water) and internal exposure (As content in biological materials).

Health risk level calculation and map construction

Results of the health risk calculations are shown in map form in Fig. 3. A review of health risk levels from As-contaminated groundwater for the respective districts of Slovakia (79), both chronic and carcinogenic, is presented in Table 4. Calculated data on risk levels for all municipalities of Slovakia (2924) are also available.

Based on their graphic visualization it can be concluded that only a negligible part of the entire Slovak territory is characterized by a medium (0.1% of area) and high (0.1% of area) risk of chronic disease occurrence in association with As groundwater contamination. In terms of administrative units, medium to high chronic risk levels were documented in four of the 79 Slovak districts (Table 4) and in 18 of the 2924 Slovak municipalities. Approximately 1% of the Slovak area is characterized by the presence of a low level chronic risk. Chronic risk from groundwater As was determined mainly in areas of significant geogenic contamination, characterized with the occurrence of ore mineralization and deposits (Nízke Tatry Mts., Spišsko-Gemerské rudohorie Mts., Malé Karpaty Mts.) but also in areas contaminated by anthropogenic sources (Horná Nitra region). High chronic risk level was documented in several municipalities of the following districts: Brezno (Jasenie, Dolná Lehota and others), Prievidza (Zemianske Kostoľany, Bystričany and others) and Partizánske (Veľké Kršteňany, Malé Kršteňany).

Based on carcinogenic risk assessment, the results indicate that approximately 11% of the Slovak territory is characterized by high to very high risk of carcinogenic occurrence (Fig. 4). The areas potentially at greater risk are similar to those with chronic risk occurrence, including sites with significant natural as well as anthropogenic increased As groundwater concentrations. Estimated carcinogenic risk corresponds to more than one case of neoplasm occurrence per 1000 inhabitants in each area. Increased carcinogenic risk levels (high, very high risk) were documented in 34 districts and 528 municipalities, with the very high risk of carcinogenic occurrence category (more than one case per 1000 inhabitants) found in predominantly naturally contaminated regions of central and eastern Slovakia (mainly districts Brezno, Banská Bystrica, Rožňava, Gelnica). High carcinogenic risk (more than one case per 10,000) was found mainly in anthropogenically contaminated regions, in the areas of lowlands and intermountain basins (districts Nové Zámky, Levice, Žiar nad Hronom, Partizánske, Prievidza and Nitra).

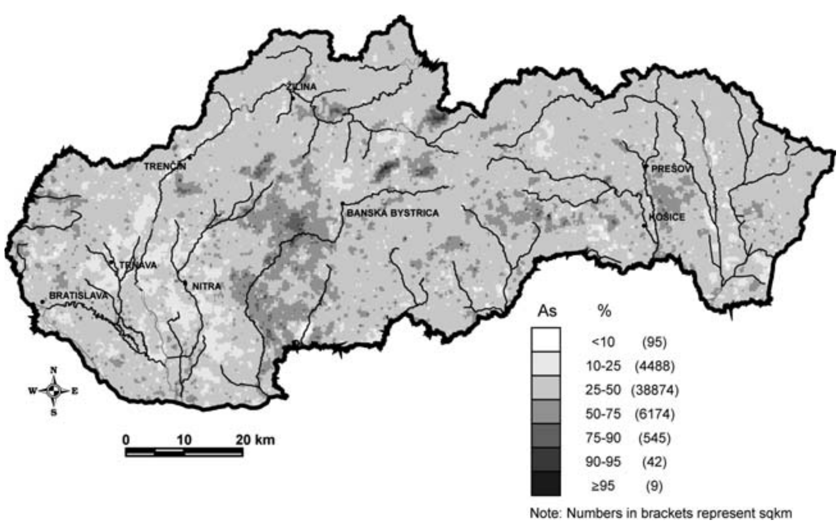


Fig. 2 The percentage contribution of As to the total chronic risk from Slovakian groundwater contaminated by As, Ba, Cd, Cu, Hg, Pb, Sb, Se, and Zn

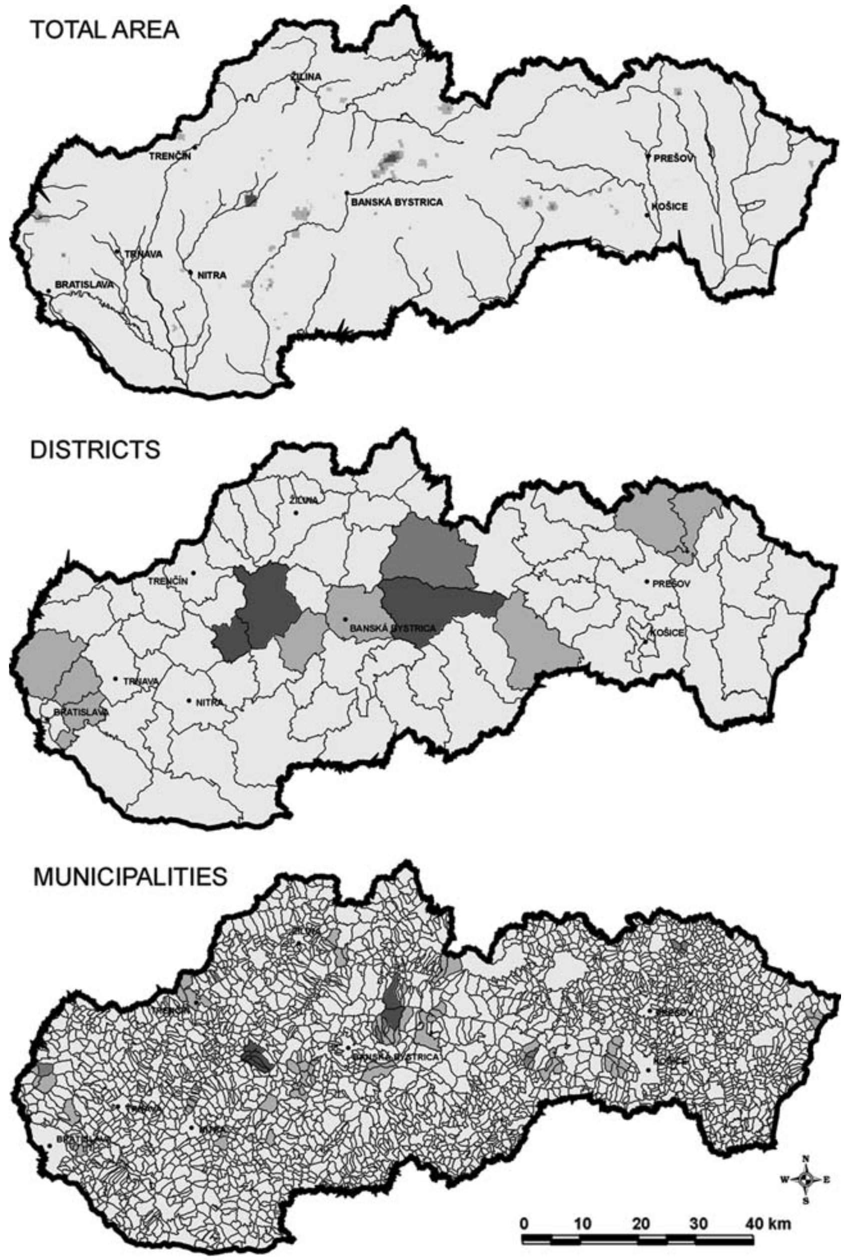


Fig. 3 Maps illustrating the risk levels of chronic disease occurrence in association with As-contaminated groundwater in Slovakia

Risk level	ADD/RfD	Chronic risk	% of area	No. of districts	No. of municipalities
1	≤1	no risk	98.7	67	2828
2	>1≤5	low	1.1	8	78
3	>5≤10	medium	0.1	1	9
4	>10	high	0.1	3	9

The remaining Slovak territory (approximately 89%) is comprised in a linked category of very low to medium carcinogenic risk levels. We found the detection limit for groundwater As used within a compilation of the *Geochemical Atlas of Slovakia* (0.001 mg l^{-1}) to be inadequate for the assessment of health risk at lower levels of As. For the distinction of carcinogenic risk levels from

Table 4 Health risk[a] from As-contaminated groundwater in Slovakia according to district

District	C_{As}	HQ	CHRL	ELCR	CRL	District	C_{As}	HQ	CHRL	ELCR	CRL
Bánovce n. Bebrav.	0.0022	2.10E-01	1	9.43E-05	1–3	Nové M. n. Váhom	0.0019	1.81E-01	1	8.14E-05	1–3
Banská Bystrica	0.0377	3.59E+00	2	1.62E-03	5	Nové Zámky	0.0040	3.81E-01	1	1.71E-04	4
Banská Štiavnica	0.0026	2.48E-01	1	1.11E-04	4	Partizánske	0.7576	7.22E+01	4	3.25E-02	5
Bardejov	0.0490	4.67E+00	2	8.57E-05	5	Pezinok	0.0152	1.45E+00	2	6.51E-04	4
Bratislava I	0.0013	1.24E-01	1	5.57E-05	1–3	Piešťany	0.0011	1.05E-01	1	4.71E-05	1–3
Bratislava II	0.0016	1.52E-01	1	6.86E-05	1–3	Poltár	0.0021	2.00E-01	1	9.00E-05	1–3
Bratislava III	0.0036	3.43E-01	1	1.54E-04	4	Poprad	0.0015	1.43E-01	1	6.43E-05	1–3
Bratislava IV	0.0019	1.81E-01	1	8.14E-05	1–3	Považ. Bystrica	0.0006	5.71E-02	1	2.57E-05	1–3
Bratislava V	0.0012	1.14E-01	1	5.14E-05	1–3	Prešov	0.0022	2.10E-01	1	9.43E-05	1–3
Brezno	0.1798	1.71E+01	4	7.71E-03	5	Prievidza	1.6680	1.61E+02	4	7.23E-02	5
Bytča	0.0006	5.71E-02	1	2.57E-05	1–3	Púchov	0.0005	4.76E-02	1	2.14E-05	1–3
Čadca	0.0006	5.71E-02	1	2.57E-05	1–3	Revúca	0.0010	9.52E-02	1	4.29E-05	1–3
Detva	0.0024	2.29E-01	1	1.03E-04	4	Rimavská Sobota	0.0018	1.71E-01	1	7.71E-05	1–3
Dolný Kubín	0.0023	2.19E-01	1	9.86E-05	1–3	Rožňava	0.0397	3.78E+00	2	1.70E-03	5
Dunajská Streda	0.0021	2.00E-01	1	9.00E-05	1–3	Ružomberok	0.0023	2.19E-01	1	9.86E-05	1–3
Galanta	0.0039	3.71E-01	1	1.67E-04	4	Sabinov	0.0008	7.62E-02	1	3.43E-05	1–3
Gelnica	0.0056	5.33E-01	1	2.40E-04	4	Senec	0.0109	1.04E+00	2	4.67E-04	4
Hlohovec	0.0009	8.57E-02	1	3.86E-05	1–3	Senica	0.0029	2.76E-01	1	1.24E-04	4
Humenné	0.0007	6.67E-02	1	3.00E-05	1–3	Skalica	0.0020	1.90E-01	1	8.57E-05	1–3
Ilava	0.0006	5.71E-02	1	2.57E-05	1–3	Sniná	0.0098	9.33E-01	1	4.20E-04	4
Kežmarok	0.0006	5.71E-02	1	2.57E-05	1–3	Sobrance	0.0016	1.52E-01	1	6.86E-05	1–3
Komárno	0.0021	2.00E-01	1	9.00E-05	1–3	Spišská Nová Ves	0.0019	1.81E-01	1	8.14E-05	1–3
Košice I	0.0016	1.52E-01	1	6.86E-05	1–3	Stará Ľubovňa	0.0007	6.67E-02	1	3.00E-05	1–3
Košice II	0.0026	2.48E-01	1	1.11E-04	4	Stropkov	0.0006	5.71E-02	1	2.57E-05	1–3
Košice III	0.0009	8.57E-02	1	3.86E-05	1–3	Svidník	0.0274	2.61E+00	2	4.29E-05	5
Košice IV	0.0030	2.86E-01	1	1.29E-04	4	Šaľa	0.0039	3.71E-01	1	1.67E-04	4
Košice - okolie	0.0043	4.10E-01	1	1.84E-04	4	Topoľčany	0.0032	3.05E-01	1	1.37E-04	4
Krupina	0.0022	2.10E-01	1	9.43E-05	1–3	Trebišov	0.0029	2.76E-01	1	1.24E-04	4
Kysucké N. Mesto	0.0011	1.05E-01	1	4.71E-05	1–3	Trenčín	0.0096	9.14E-01	1	4.11E-04	4
Levice	0.0085	8.10E-01	1	3.64E-04	4	Trnava	0.0011	1.05E-01	1	4.71E-05	1–3
Levoča	0.0010	9.52E-02	1	4.29E-05	1–3	Turčianske Teplice	0.0019	1.81E-01	1	8.14E-05	1–3
Liptovský Mikuláš	0.0535	5.10E+00	3	9.44E-05	5	Tvrdošín	0.0007	6.67E-02	1	3.00E-05	1–3
Lučenec	0.0020	1.90E-01	1	8.57E-05	1–3	Veľký Krtíš	0.0020	1.90E-01	1	8.57E-05	1–3
Malacky	0.0266	2.53E+00	2	1.14E-03	5	Vranov n. Topľou	0.0011	1.05E-01	1	4.71E-05	1–3
Martin	0.0070	6.67E-01	1	3.00E-04	4	Zlaté Moravce	0.0055	5.24E-01	1	2.36E-04	4
Medzilaborce	0.0005	4.76E-02	1	2.14E-05	1–3	Zvolen	0.0065	6.19E-01	1	2.79E-04	4
Michalovce	0.0016	1.52E-01	1	6.86E-05	1–3	Žarnovica	0.0069	6.57E-01	1	2.96E-04	4
Myjava	0.0007	6.67E-02	1	3.00E-05	1–3	Žiar n. Hronom	0.0175	1.67E+00	2	7.50E-04	4
Námestovo	0.0006	5.71E-02	1	2.57E-05	1–3	Žilina	0.0049	4.67E-01	1	2.10E-04	4
Nitra	0.0076	7.24E-01	1	3.26E-04	4						

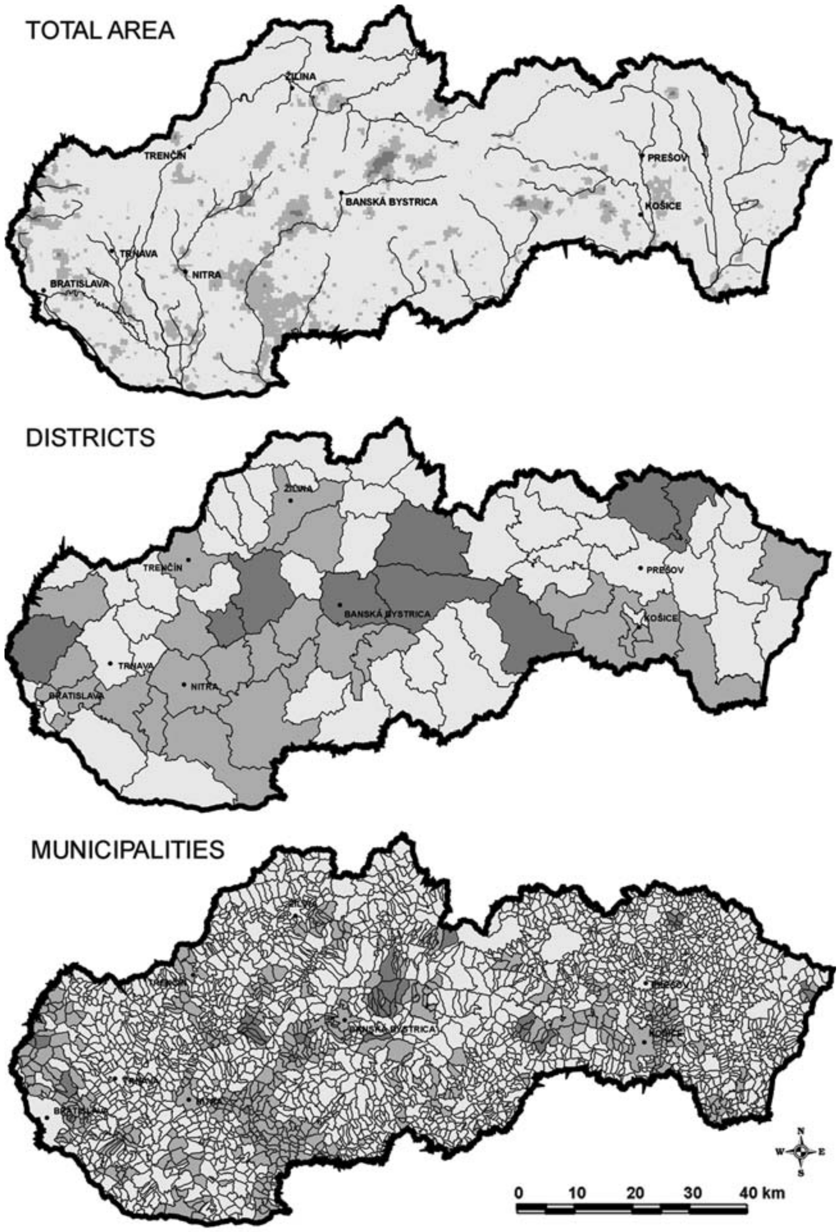
[a] C_{As}, Average As concentration (in mg l^{-1}); HQ, hazard quotient; CHRL, chronic risk level; ELCR, excess lifetime cancer risk; CRL, carcinogenic risk level

exposure to low As concentrations, a lower analytical detection limit will be necessary for future studies (at least 0.0001 mg l^{-1}).

Discussion

The assessment of health risks from environmental contamination is generally a very complicated and complex process that is performed by integrating the findings from different fields (epidemiology, medicine, geochemistry and others). Such an assessment is often limited by the availability – of lack thereof – of up-to-date validated scientific knowledge. The main uncertainties within the health risk assessment process comprise the ‘‘reliability’’ of input parameters related to exposure and toxicity assessment (confidence in the

Fig. 4 Maps illustrating the carcinogenic risk levels from As-contaminated groundwater in Slovakia



Risk level	Calculated cases of neoplasm occurrence	Carcinogenic risk	% of area	No. of districts	No. of municipalities
1-3	≤1 per 1000 000 inhabitants <1 per 10 000 inhabitants	very low-medium	89.1	45	2396
4	>1 per 10 000 inhabitants <1 per 1 000 inhabitants	high	10.4	25	487
5	>1 per 1 000 inhabitants	very high	0.5	9	41

reference dose or slope factor). Additionaly, a controversial issue is the nonthreshold approach in the assessment of carcinogenic effects (each concentration >0 represents risk).

The health risk assessment presented here is based on exposure modelling, and the aim was to identify and characterize the upper bound of potential health risk from As-contaminated groundwater in the Slovak republic. Under actual conditions, lower health risk levels would be expected to result from specific exposure of the resident population (water daily ingestion rate, exposure duration, consumption of packaged water and others). As such, these results should be considered to be informative only. They highlight those areas (districts, municipalities) in which future detailed medical-geochemical studies should be conducted in order to test the presumption of the existence of health risk from groundwater As and additional needs of remedial action. The results also help identify those sites where more attention should be paid to the quality of the drinking water – in terms of As levels.

Conclusion

Based on our assessment of health risk from As by means of the screening procedure and risk level calculation for its chronic and carcinogenic effects, we propose the possible existence of potential health risks from As-contaminated groundwater to the resident populations of several areas throughout the Slovak Republic.

Arsenic rate on "total" chronic risk from groundwater contamination by potentially toxic elements exceeds 50% in more than 10% of the Slovak territory. The risk of chronic disease occurrence is generally low. Only 1% of the total area is characterized by low and 0.2% with medium to high noncarcinogenic (chronic) risk levels. However, high to very high risk of carcinogenic occurrence from exposure to groundwater As is documented in11% of the Slovak territory. The areas of greater potential risk were documented at sites with naturally increased groundwater As levels (e.g., the districts Brezno, Banská Bystrica, Rožňava and others) as these had medium to very high chronic as well as carcinogenic risk. The area showing a potentially greater risk due to anthropogenical contamination was the Horná Nitra region (districts Prievidza, Partizánske).

Our assessment of health risk from As-contaminated groundwater in the Slovak Republic, which was based on calculations and map visualization using national geochemical databases, seems to be linked to real threats to humans. Future studies are necessary to determine the magnitude and forms of the exposure. The proposed method of quantification and map visualization of health risks definitely allows the identification and preliminary evaluation of sites at risk in the territory of the Slovak Republic and will be of benefit to directing future complex epidemiological-geochemical research.

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