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Methodology for mapping shallow groundwater quality in urbanized areas: A case study from Lithuania

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Abstract Cities have a negative impact on the quality of shallow groundwater. Many of Lithuania's urban residents drink water from dug wells. Moreover, polluted shallow groundwater contaminates deeper aquifers of fresh drinking water. Therefore, this situation should be controlled and managed, as far as possible. In order to evaluate the quality of shallow groundwater in an urban area and to create an optimal monitoring system, an original methodology for groundwater mapping has been proposed. It resembles the GIS (geographical information system) technologies. The set of maps, laid one over another, consists of the following: (1) urbanization map, (2) geological–hydrogeological map, (3) groundwater chemistry map, (4) resulting groundwater chemistry factorial analysis map, and (5) pollution and pollutant transport map. The data obtained from studies on dug and geotechnical wells have been used for compilation of the maps. The system for shallow groundwater monitoring in the city with an area of 70 sq km and a population of 140,000 is proposed to consist of about 30 monitoring wells and several dug wells.

Key words Urbanization impact · Groundwater quality · Mapping procedure

Introduction

Shallow groundwater quality in cities almost always is poor for two reasons: (1) water table aquifers are vulnerable to pollution, and (2) a city is a source of concentrated pollution of various origins. In Lithuania, a rather large part of the population consumes water for drinking from dug wells despite its poor quality (Mikalauskas 1976). Pollution from water table aquifers often spreads to deeper drinking water aquifers if they are not protected from pollution or when they are intensively developed (Klimas 1994).

We know about the poor quality of the upper aquifers in cities from control studies on a rather small scale done with dug well water by the Hygiene Centres. However, this information is not sufficient for assessment of the scale of shallow groundwater pollution, for determination of reasons and sources, and for recommendations of protective measures. During the last several years, data on groundwater quality in dug wells has accumulated. However, the question arises whether it is possible to use the analyses of water sampled at different times for assessment of shallow groundwater chemistry in a city.

There is also another information source for this study in Lithuanian cities: wells drilled for geotechnical engineering data necessary for various construction work. Even in small Lithuanian towns, there are hundreds or even thousands of such wells. Many of them provide water chemistry data. However, the data were collected at very different time periods, as was already mentioned for dug wells. Moreover, it is not clear if data from both dug and geotechnical engineering wells could be used together. There is an opinion that dug wells are polluted but not water table aquifers. Another barrier to using such hydrochemical information from different sources is that groundwater quality data are not complete, analyses often are done for different purposes, and thus, they are difficult to compare.

We tried to obtain answers to these and other questions by carrying out investigations in three Lithuanian towns of different sizes. The results analyzed in the present paper are from one of them—Shiauliai.

The geographical information system (GIS) has been used for a long time to map shallow groundwater quality in urbanized areas (Goodchild and others 1993). Lithuanians are trying to apply it. Therefore, we are still using our own methodology, which is similar to GIS (Klimas 1993; Gregorauskas and others 1994).

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Description of the area

Shiauliai is the fourth largest town in Lithuanian with a population of 140,000 and is situated in the northwestern part of Lithuania (Fig. 1). Its area is about 70 sq km. The town is a rather large industrial center of leather, electronics and, during the Soviet time, military industries with the adjacent Zokniai airport—one of the largest military airfields in Europe. From a topographical point of view, the town is located on the northeastern slopes of the Zhemaitija watershed hills (Basalykas 1958). Moreover, the town itself is a watershed, since its southern part is in the catchment area of the Dubysa River flowing to Nemunas, whereas the northern part is in the catchments of the Venta and Mūsha rivers flowing northwards to Latvia (see Fig. 1).

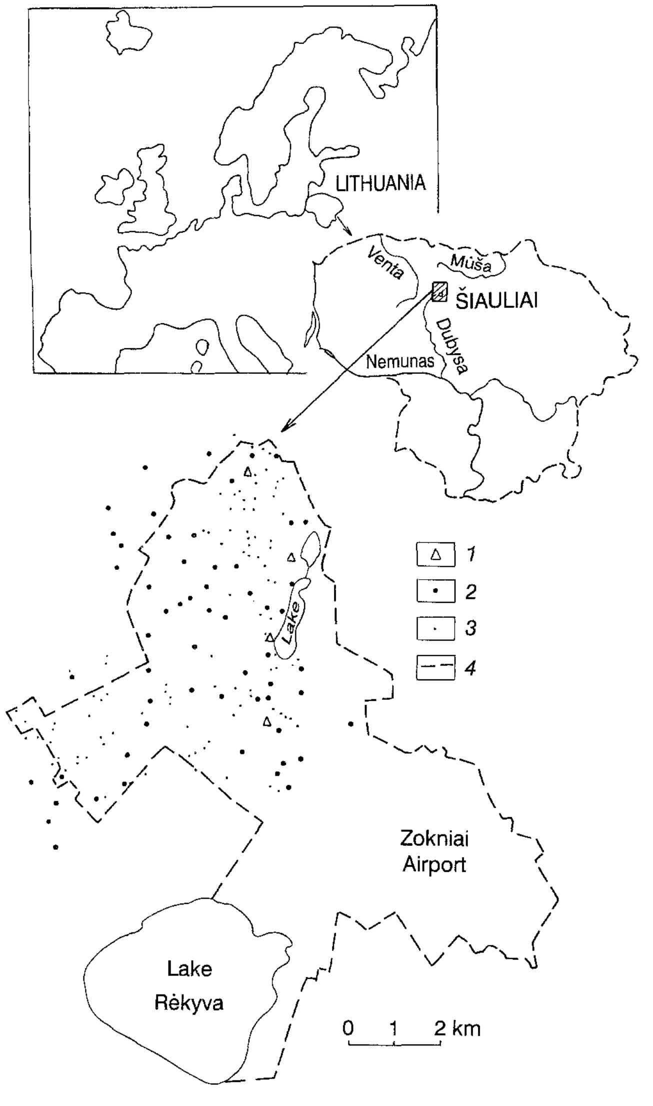

Fig. 1 Location scheme and sampling sites: 1—monitoring wells, 2—dug wells, 3—geotechnical wells, 4—city boundaries

Methodology

Studies of urban impact on groundwater quality in Lithuania started a rather long time ago (Mikalauskas 1976). However, only recently did we begin searching for the best methodology (Klimas 1993; Klimas and others 1993; Alminas and others 1993; Klimas and Shleinius 1994). The essence of our methodology is shown in Fig 2. Three basic maps of urbanized areas are compiled: (1) a map of urbanization; (2) a geological–hydrogeological map of shallow groundwater; and (3) a map of groundwater chemistry in shallow aquifers. The scale of the maps is 1:5000 or 1:10,000.

In the urbanization map, according to data obtained from municipal and environmental departments, three areas are singled out: industrial, residential, and green areas. They are further divided into smaller zones. According to their degree of impact, industries are grouped under three types: (1) heavy polluting industries—wastewater and solid wastes in large quantities, substances that are very dangerous for groundwater are applied during production process, and disposed of afterwards; (2) moderately polluting industries; and (3) those with little impact —where practically no impact is detected. Residential areas are also divided into three categories: (1) modern multistorey buildings with water supply, sewerage, and central heating systems; (2) areas of individual houses, usually without the above systems; and (3) village and small

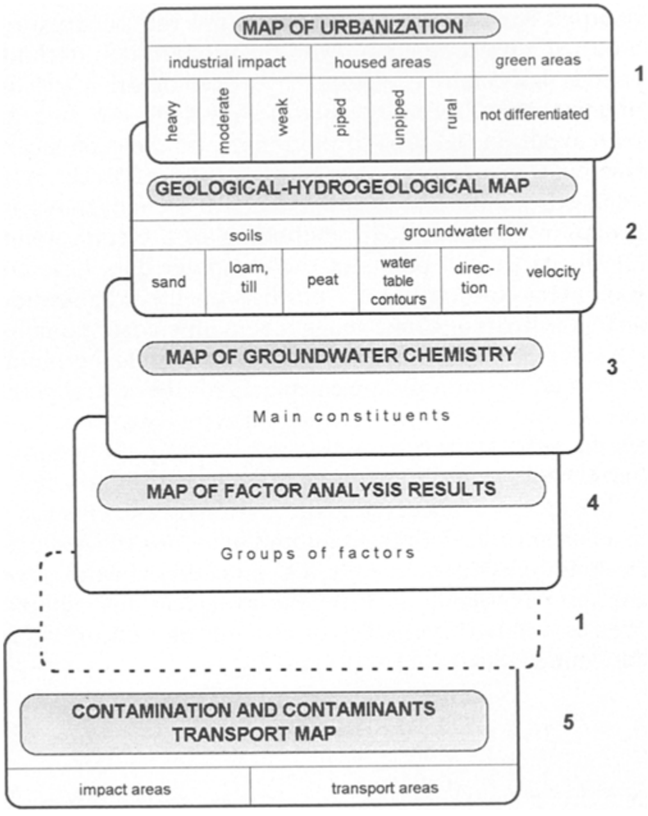

Fig. 2 Mapping procedure

settlement areas included into the territory of the town. Green areas are mapped without further detailing.

The geological–hydrogeological characterization of the urban area is done on the basis of available maps and information accumulated in various reports and data bases, as well as geotechnical and dug-well data. This map shows not only the lithology of water-bearing rocks, but also elements of shallow groundwater flow, i.e., lines of equal hydraulic potential, flow direction, and gradient.

Hydrochemical assessment of shallow groundwater is done on the basis of analyses of water sampled in 1993–1994 from 89 dug wells and those performed during the period of 1957–1992 for 185 geotechnical wells (see Fig. 1). Moreover, data from several monitoring wells have been used. The necessity to use such varied data is due to the fact that there are usually no dug wells in the industrial areas and no drilled wells in the residential areas.

There are some arguments supporting this methodology. First, statistical treatment of water chemistry in the samples from the above-mentioned dug and geotechnical wells and comparison with Fischer criterion has shown that there is no significant difference between these two data groups. Second, the hydrochemistry maps compiled in 1953–1974 for some shallow aquifers do not differ significantly from the present ones (Mikalauskas 1976). Third, such maps were compiled first on dug well data only (Malishauskas 1993; Damashevichius 1994); after they were supplemented with drilled well data, the maps changed only insignificantly.

The maps of shallow groundwater quality variables are compiled from computer data bases, drawing lines of equal concentrations (isocones), and the isocones are adjusted after comparison with the urbanization (technogenous load) and geological–hydrogeological maps. In practice, the procedure is as follows: (1) the isocone map is put on the urbanization map and the geological–hydrogeological map, then the position of isocones is adjusted, taking into account the real technogenous or geological–hydrogeological situation at a certain point; (2) all the treated points in the computer data base are grouped according to their position on the urbanization and lithohydrodynamic maps, i.e., points corresponding the same combinations are grouped, and shallow groundwater quality variables are calculated for the central point (before this procedure extreme and erroneous values are eliminated); (3) these data are used to fill up the "empty" plots, where no hydrochemical information is available.

In order to connect the shallow groundwater chemistry in an urban area with the economic activities and geological conditions quantitatively, a hydrochemical data factor analysis has been done. First, the coefficient of a summarized anomaly of variables of groundwater chemistry is determined (Schwartzew 1987):

$$A_n = \sum_{i=1}^{n} (K_i) - (n - 1) \tag{1}$$

$$K_i = C_i/C_0 \tag{2}$$

where A_n is an anomaly coefficient, C_i is a concentration of the ith variable, C_0 is a background values, K is a concentration coefficient, n is a number of variables. Equation 1 applies only when the value of the concentration coefficient exceeds 1, i.e. $C_i > C_0$.

The anomalies singled out in such a way are compared with the first map of urbanization (see Fig. 2). The plumes that coincided with a certain urbanization type are named the areas of impact or pollution, and the plumes found beyond these limits are named as the pollution transport areas. The quality of shallow groundwater in the urbanized area mapped according to the above methodology enables one to organize optimal and hydrogeological motivated monitoring of water table aquifers in the town.

Results

The methodology proposed above has already been tried in practice in three Lithuanian cities differing in size, degree of urbanization (especially industrialization), and geological–hydrogeological conditions. The results obtained are similar. Therefore, we present here the mapping results of shallow groundwater quality for the town of Shiauliai.

Urbanization map

Industry in Shiauliai is concentrated in the northern and southern districts (Fig. 3). The northern district contains mainly food industries, whereas the southern one is comprised of electronics and metal processing. A specific industrial object situated in the Zokniai airfield in the eastern part of the town is not discussed here.

The industrial districts, as mentioned, are grouped into highly, moderately, and low polluting zones. The first zone has large leather processing factories and old sewage treatment plants with mud storage sites. The second zone embraces mainly food processing enterprises, railway and military units, as well as transport enterprises. The third zone has electronics and metal processing companies and various storehouses causing less pollution. It should be emphasized that the companies in the latter category are low polluters only in terms of groundwater, not the entire environment. For instance, soil in enterprises dealing with metal processing and electronics is greatly polluted with heavy metals.

The division of residential districts into two zones—with water supply and sewerage facilities and without such systems—has been done applying maps of municipal networks of water supply, sewerage, and heating. The urbanization map shows (Fig. 3) that all these pipelines occupy mainly the central, oldest part of the city and a newly built southwestern residential area. The city center is surrounded by a rather large area with individual houses, usually without municipal facilities. A majority of the population in this zone uses water from dug wells (see Fig. 1). There are also some villages, homesteads, and small settle-

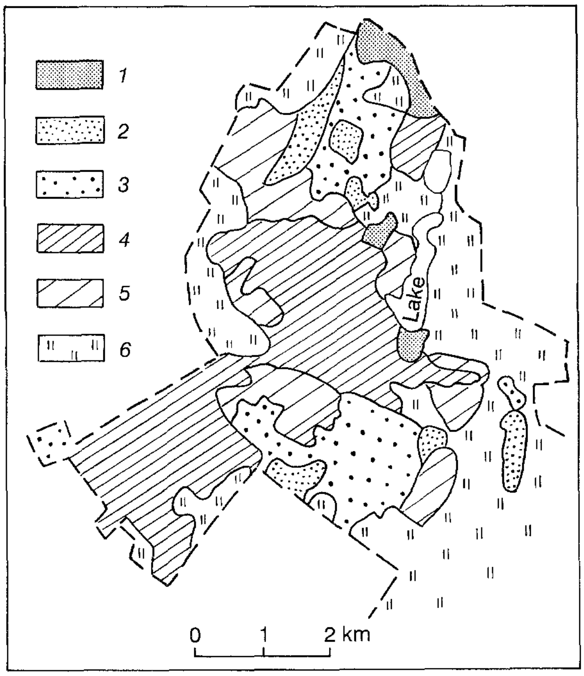

Fig. 3 Map of urbanization: *1–3* areas of industrial impact (*1* heavy, *2* moderate, *3* weak), *4* residential areas (*4* with pipelines, *5* without pipelines), *6* green areas

ments included in the city territory. Moreover, green zones —parks and meadows—occupy rather large areas in the city.

Geological–hydrogeological map

The distribution of shallow groundwater resources in the upper part of the geological section in Shiauliai and its environs depends greatly on how the Zhemaitija Upland was formed during the Late Pleistocene and Postpleistocene (Fig. 4). Only scarce groundwater resources are found in the hilly ridge area and at its northeastern slope, where the northern part of Shiauliai is located. However, the retreating glacier caused formation of a large meltwater lake at the site of the present Lake Rekyva and its boggy environs. The excess water of the periglacial lake flowed southwestwards along several streams that eroded the land surface with valleys. The bottom of the Rekyva limnoglacial basin is covered mainly with sand; at present most of it is bog. Sand deposits in the northern part of this basin (or southern part of Shiauliai) contain rather large amounts of shallow groundwater.

The geological–hydrogeological map shows the groundwater level in the dug and drilled wells (see Fig. 4). The highest water level in the Shiauliai environs is Lake Rekyva and the bogs surrounding it. Shallow groundwater flows in all directions from it and crosses the town in a general northward direction. On its way, the flow is distributed to different catchments of small rivers flowing northeast and northwest. Lake Rekyva is also drained by several smaller lakes.

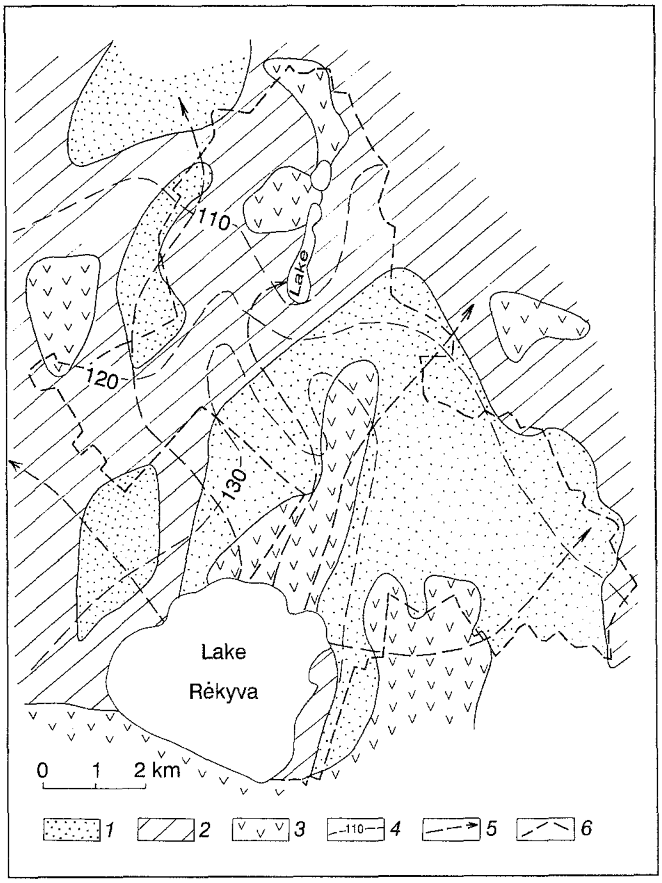

Fig. 4 Geological–hydrogeological map: *1* sand, *2* sandy loam or loam, *3* peat, *4* groundwater table contours, masl, *5* groundwater flow direction, *6* city boundaries

Shallow groundwater quality

In order to describe the shallow groundwater chemistry, the above-mentioned computer data base was used. First, a statistical analysis of the hydrochemical data stored in it was done (Table 1). All the data available about shallow groundwater chemistry in Shiauliai was grouped according to the methodological principles described above, i.e., they are grouped according to lithology of water-bearing rocks, character of urbanization, and intensity of economic activity in the area.

The data given in Table 1 confirm that shallow groundwater in Shiauliai is hard and rich in nitrates; its total mineralization is rather high, and it contains sulfates and chlorides in significant quantities. The quality of shallow groundwater is lowest in the lodgement moraines and bogged formations.

The urbanization impact is maximal in the industrial districts, but nitrates usually are found in suburbs (villages), whereas organics (permanganate oxidation), sodium, and potassium related to household wastes are most often found in residential areas.

Furthermore, a picture of groundwater quality is detailed for different combinations of water-bearing rocks

Table 1 Some variables of shallow groundwater chemistry in Shiauliai (arithmetic averages, mg l^{-1})[a]

TDS	TH	PO	Cl^-	SO_4^{2-}	HCO_3^-	NO_3^-	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	*n*	Lithology	Urbanization	Economic activities
Shallow groundwater chemistry in different soils															
867	11.7	4.2	112	161	527	55	157	50	44	18	0.9	167	1		
763	10.5	6.2	111	117	501	38	141	42	46	30	1.3	47	2		
857	13.6	2.4	189	241	539	54	172	62	33	11	0.1	48	3		
Shallow groundwater chemistry in urbanized areas															
908	12.0	4.9	192	222	542	38	160	56	34	22	1.2	91		A	
829	11.8	5.1	86	145	517	51	157	48	45	23	1.1	129		B	
722	10.6	2.9	81	88	505	57	147	38	43	15	0.1	19		C	
1050	12.2	n.d.	126	130	517	n.d.	153	55	n.d.	n.d.	n.d.	23		D	
Shallow groundwater chemistry (soils + urbanization)															
918	11.7	6.2	145	188	541	52	159	53	57	47	1.5	70	1	A	
868	11.8	4.4	83	149	517	55	156	48	43	16	0.9	77	1	B	
717	10.5	2.9	83	86	493	57	144	38	45	15	0.1	15	1	C	
1050	13.8	n.d	191	191	610	n.d.	179	60	n.d.	n.d.	n.d.	5	1	D	
613	9.0	3.1	209	125	429	22	127	33	21	7	0.2	8	2	A	
797	10.9	7.4	91	118	515	40	145	45	56	40	1.6	33	2	B	
713	10.8	3.8	61	108	528	52	162	35	23	10	0.2	3	2	C	
n.d.	9.7	n.d.	96	98	512	n.d.	124	43	n.d.	n.d.	n.d.	3	2	D	
1406	15.9	n.d.	436	475	622	47	190	84	n.d.	n.d.	n.d.	13	3	A	
625	13.3	2.5	91	176	521	54	178	53	27	7	0.1	19	3	B	
828	11.0	1.8	101	58	610	72	150	43	68	31	0.0	1	3	C	
n.d.	12.1	n.d.	111	113	484	n.d.	151	56	n.d.	n.d.	n.d.	15	3	D	
Shallow groundwater chemistry (soils + urbanization + economic activities)															
n.d.	15.2	n.d.	129	98	930	n.d.	95	128	n.d.	n.d.	n.d.	2	1	A	a
888	13.1	n.d	52	108	549	n.d.	100	56	n.d.	n.d.	1.0	6	1	A	b
924	11.4	6.2	157	200	528	52	168	51	57	47	1.5	62	1	A	c
924	11.8	4.7	72	143	517	70	158	49	50	15	1.4	52	1	B	a
769	11.6	3.8	107	161	518	29	153	48	32	18	0.2	25	1	B	b
698	11.1	3.0	53	100	512	49	157	28	34	8	0.1	3	1	C	a
722	10.3	2.8	91	83	488	59	141	40	48	17	0.1	12	1	C	b
1050	13.8	n.d.	191	191	610	n.d.	179	60	n.d.	n.d.	n.d.	5	1	D	—
n.d.	13.0	n.d.	88	139	494	n.d.	180	49	n.d.	n.d.	n.d.	1	2	A	a
1016	10.6	0.8	405	196	530	24	160	32	19	2	0.0	4	2	A	b
412	6.4	3.6	42	50	312	22	81	29	21	9	0.2	3	2	A	c
864	11.5	1.8	75	131	568	45	143	53	58	13	2.2	15	2	B	a
759	10.5	8.4	104	108	473	39	146	38	56	45	1.3	18	2	B	b
713	10.8	3.8	61	108	528	52	162	35	23	10	0.2	3	2	C	b
n.d.	9.7	n.d.	96	98	512	n.d.	124	43	n.d.	n.d.	n.d.	3	2	D	—
n.d.	7.8	n.d.	122	119	616	n.d.	105	31	n.d.	n.d.	n.d.	2	3	A	a
2751	19.2	n.d.	628	722	671	n.d.	219	109	n.d.	n.d.	n.d.	8	3	A	b
734	12.7	n.d.	134	52	492	n.d.	167	53	n.d.	n.d.	n.d.	3	3	A	c
784	15.9	1.4	99	263	575	53	215	63	23	1	0.1	10	3	B	a
562	10.1	2.7	81	69	456	54	133	42	28	8	0.1	9	3	B	b
828	10.0	1.8	101	58	610	72	150	43	68	31	0.0	1	3	C	b
n.d.	12.1	n.d.	111	113	484	n.d.	151	56	n.d.	n.d.	n.d.	15	3	D	—

[a] TDS = total dissolved solids; TH = total hardness (meq/l); PO = permanganate oxidation (mg O_2 l^{-1}); *n* = number of samples; n.d. = not detected; Lithology (1—till, loam; 2—sand; 3—peat); Urbanization and impact (A—industrial areas, a—heavy impact, b—moderate impact, c—weak impact; B—residential areas, including a—with pipelines; b—without pipelines; C—rural; D—green areas, not differentiated)

and degrees of urbanization. It then can be concluded that, for example, sulfate and chloride concentrations in the groundwater of the industrial districts are always higher in the soils of any composition. Thus, they are undoubtedly related to the character of urbanization in the town, and in contrast, nitrates in the suburban zones are always higher in any soils.

Finally, more detailed divisions of economic activities give such a variegated picture of shallow groundwater chemistry that it is impossible to relate it to a certain degree of urbanization or water-bearing rock character by applying such a simple statistical analytical method. Nevertheless, the regularities detected remain in some combinations of lithology and urbanization categories. For instance, shallow groundwater in different soils of the residential areas with municipal facilities contains more nitrates or ammonium and hydrocarbonates, thus showing obvious pollution with household wastewater.

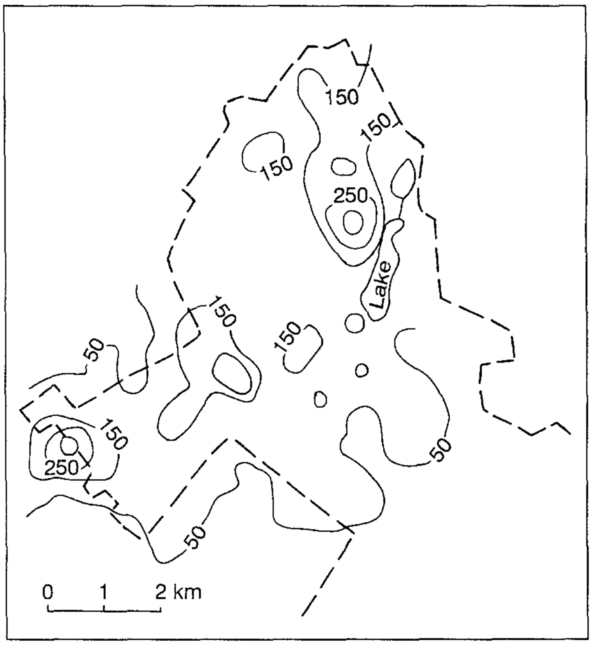

Fig. 5 Sulfates in shallow groundwater, isocones in milligrams per liter

Since pollution variables of different origin are often the same, their origin can be evaluated from their distribution in a given area. Therefore, these regularities are analyzed by a method of mapping certain groundwater chemistry variables in the town territory. For this purpose, groundwater quality variables were taken from the data base and, applying the kriging method, lines of equal concentrations —isocones—were drawn. An example is presented in Fig. 5, where a scheme of sulfate distribution in shallow groundwater is given. Analysis of this and all other component schemes enables one to make two important methodological conclusions: (1) groundwater quality in the city is rather stable (consistently poor), and (2) hence, in order to reveal it, hydrochemical data obtained at different time periods can be used. It was found that shallow groundwater of poor quality in Shiauliai occurred according to nitrates in almost half the city and according to total hardness in almost the entire city. Moreover, total dissolved mineral matter (evaporated residue, total dissolved solids), sulfates and chlorides are obviously higher in the industrial districts, or more exactly, in the streams of outflowing groundwater.

The very high total hardness of water in Shiauliai, as in other towns, is caused by certain geochemical processes occurring in the polluted underground. These processes are oxidation of organics and reduction of nitrates (Klimas and Paukshtys 1993; Klimas 1994).

Organics of various origins as a constituent part of wastewater (especially of municipal sewerage) are the most important indicator of shallow groundwater pollution in the city. However, due to the rather good connection of shallow groundwater with the atmosphere, high amounts of organics are not accumulated in it. Approximate evaluations show just a slight increase in permanganate oxidation of this groundwater. The content of organics in shallow groundwater having enough oxygen decreases due to the following biochemical reaction (Matthes and others 1992):

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \qquad (3)$$

Furthermore, under the interaction of carbon dioxide with calcium and magnesium ions, the cations of alkaline metals, and the anions of hydrocarbonates are accumulated. Thus water hardness increases (Matthes and others 1992):

$$CO_2 + CaCO_3 + H_2O \rightleftharpoons H_2CO_3 + CaCO_3 \rightleftharpoons Ca^{2+} + 2HCO_3^- \qquad (4)$$

The increase in nitrate content at the city margins is detected in Shiauliai. This increase can be seen in Table 1 (urbanization A, B, C in the second fragment). Such a regularity can be easily explained not by lower pollution in the city, but by nitrate reduction in densely built residential areas, as well as in the areas laid with asphalt over the phreatic groundwater reservoir. In such places, there are low amounts of oxygen in the shallow groundwater (Eq. 3); therefore oxygen for oxidation of organics is taken first from nitrates (Apello and Postma 1993).

$$4NO_3^- + 5CH_2O \rightarrow 2N_2 + 4HCO_3^- + CO_2 + H_2O \qquad (5)$$

We can see that this process is the cause not only of nitrate reduction, but also of the increase in shallow groundwater hardness.

In order to relate more closely the processes of shallow groundwater chemistry formation and transformation in the city with the specific economic activities and geological conditions, factor analysis for all the hydrochemistry data accumulated has been done repeatedly since 1993. Values of conventional background variables of groundwater chemistry were taken from the studies done in 1963 (Mikalauskas 1976). They are given in Table 2. Table 2 shows that, over three decades, sulfates and unoxidized

Table 2 Characteristics of shallow groundwater in Shiauliai

Characteristic	Conventional background concentration C_0, 1963	Average concentration C_i, 1993	K
Dry residue (mg/l)	590	847	1.4
Total hardness (meq/l)	10	11.8	1.2
Permanganate oxidation (mg O_2/l)	1.3	4.2	3.2
Ca^{2+} (mg/l)	136	156	1.1
Mg^{2+} (mg/l)	32	51	1.6
NH_4^+ (mg/l)	1.4	0.65	0.5
Cl^- (mg/l)	75	91	1.2
SO_4^{2-} (mg/l)	31	168	5.4
HCO_3^- (mg/l)	482	525	1.1
NO_3^- (mg/l)	27	42	1.5

Table 3 Results of factor analysis applied to shallow groundwater chemistry data

Variable	Factor 1	 2	 3	 4
Dry residue	0.893	0.224	−0.099	0.145
Total hardness	0.861	−0.101	−0.153	0.366
Ca^{2+}	0.859	−0.086	−0.247	−0.123
Cl^-	0.764	−0.056	0.370	0.087
SO_4^{2-}	0.638	0.343	−0.033	−0.135
Permanganate oxidation	0.167	0.872	−0.005	0.034
NH_4^+	−0.001	0.685	0.114	−0.019
HCO_3^-	0.523	0.085	−0.667	0.282
NO_2^-	−0.065	0.203	0.660	0.111
NO_3^-	0.400	−0.448	0.525	0.290
Mg^{2+}	0.059	−0.009	0.081	0.964

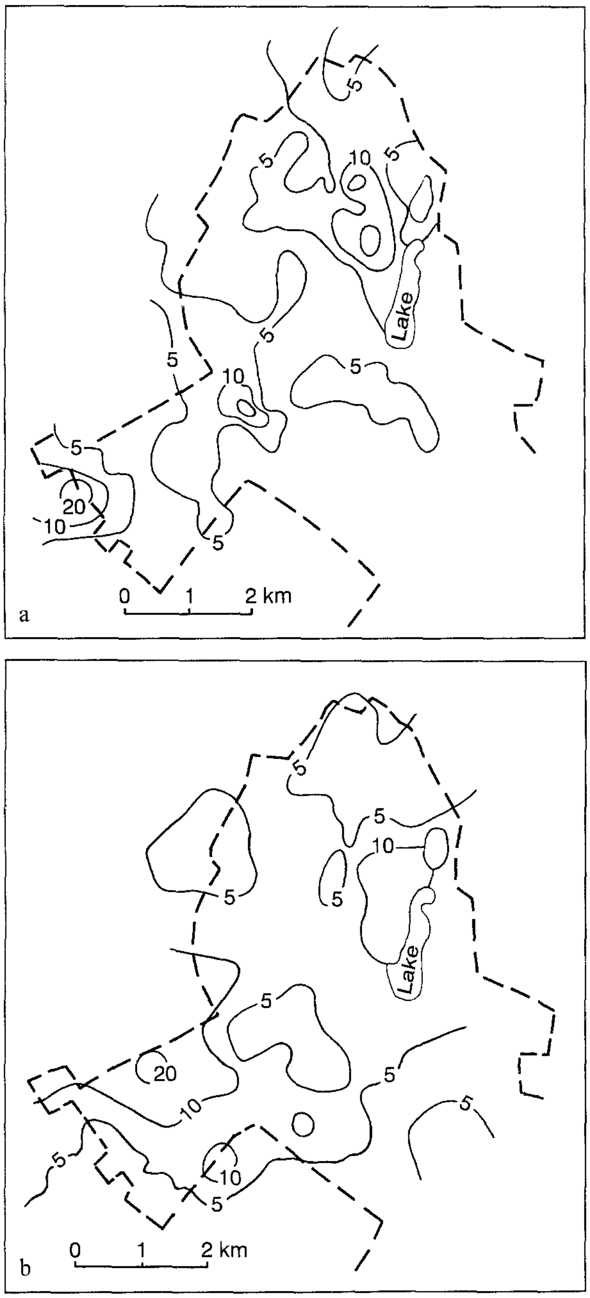

Fig. 6a,b Isolines of anomalies in groundwater chemistry drawn according to factor analysis data: **a** factors I + IV (TDS + TH + Ca^{2+} + SO_4^{2-} + Mg^{2+}), **b** factors II + III (PO + NH_4^+ + HCO_3^- + NO_3^-)

organics (permanganate oxidation) increased. When discussing Table 1, we have already mentioned that sulfates are raised in the industrial areas, whereas the latter are determined in the areas polluted with household wastewater. However, only factor analysis of all groundwater chemistry variables enables us to reveal the interrelationships among urbanization and the variables. The results of factor analysis are given in Table 3.

At first glance, Table 3 shows that variables such as total mineralization (dry residue), total hardness, SO_4^-, Cl^-, and Ca^{2+} are closely positively related for the first group of factors; according to the data from Table 1, they can be related to industrial city zones. The correlation of this factor with the components grouped by factors 2 and 3—permanganate oxidation, NH_4^+, HCO_3^-, NO_2^-, and NO_3^-—is in fact negative. Therefore, all the variables mentioned are typical of a household pollution impact on groundwater. The interrelationships between the variables of factors 2 and 3 are somewhat weaker than for those of factor 1. Moreover, correlation of HCO_3^- with NO_2^- and NO_3^- is negative, as it should be according to the equation of nitrate reduction (Eq. 5). For the same reason, the NO_3^- correlation is negative with the variables of factor 2 (PO, NH_4^-). It is a bit more difficult to explain distinguishing Mg^{2+} into a separate factor that is very weakly positively correlated with factors 1 and 3 and negatively correlated with factor 2. Since Mg^{2+} geochemistry does not differ from Ca^{2+} geochemistry, for further analysis, factor 4 is combined with factor 1 into one factor—that of industrial pollution (Fig. 6a). Close genetic and formal links allow joining factors 2 and 3 into one group, that of household pollution variables (Fig. 6b).

Isolines in Fig. 6 show the values of the coefficient of summarized anomalies of variables A_n (see Eqs. 1 and 2) and highlight three industrial plumes (factors I + IV) and two household plumes (factors II + III) of groundwater pollution. It is important to note that these anomalies, especially industrial ones, if compared to the urbanization map (see Fig. 3), are "shifted" along the groundwater flow direction and are a bit out of the limits of the direct impact area. These shifts are clearly seen in the areas contoured by isoline 5 of coefficient A_n (see Fig. 6). Therefore, further schemes of summarized anomaly coefficients (Fig. 6) coincide with the urbanization map (Fig. 3). The anomalies that coincide with corresponding zones of economic activity make up the impact areas of a certain activity, whereas those beyond the zone make up pollutant migration areas (Fig. 7).

Taking into account the above maps of pollution and pollutant migration, the structure of shallow groundwater flow, and the present monitoring network, it was proposed

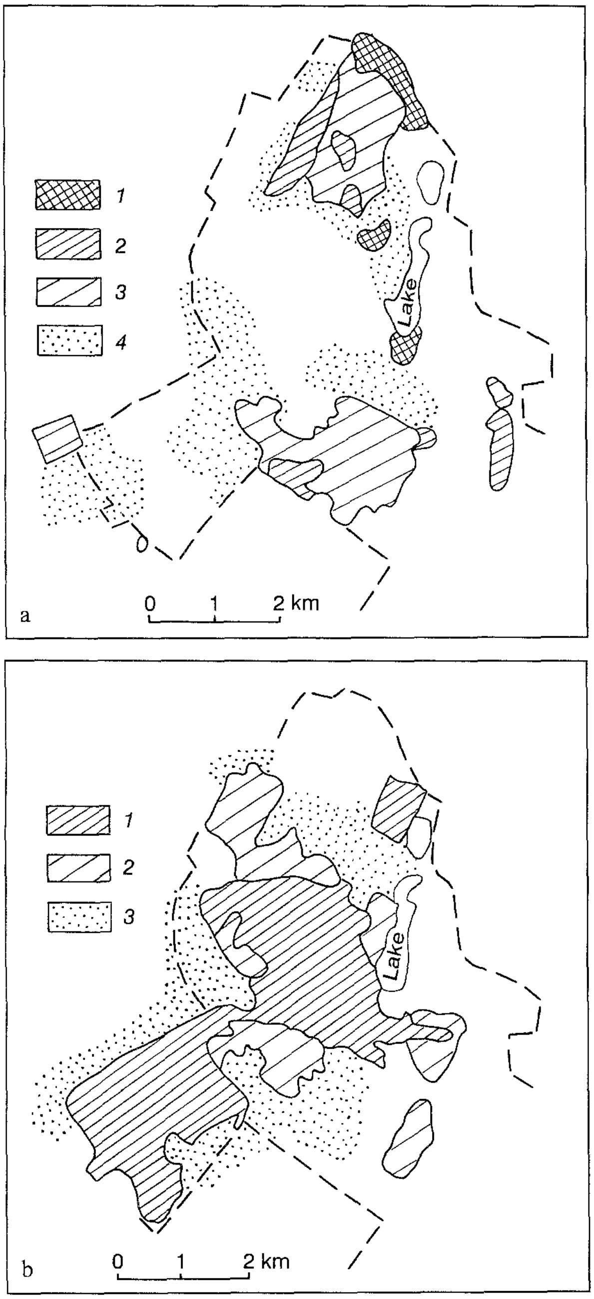

Fig. 7a, b Areas of impact and of pollutant transport: **a** industrial impact (*1* heavy, *2* moderate, *3* weak, *4* pollutant transport areas); **b** residential areas (*1* with pipelines, *2* without pipelines, *3* pollutant transport areas)

to apply a new optimal network to monitor shallow groundwater in the city. Thirty new monitoring wells located in six transects and several dug wells appeared to be enough to accomplish this.

Conclusions

The methodology proposed for mapping shallow groundwater quality in the urbanized areas enables a rather reliable assessment of quality formation and occurrence regularities even using a rather limited number of dug and drilled wells. An argument for this statement relies upon the following facts: Such maps for Shiauliai were first compiled according to 89 data points; later 275 points were used. The differences between groundwater table maps were found to be insignificant, whereas the water quality maps differed by less than 20%.

This methodology has been tried in two other Lithuanian towns—Jonava and Varena—with populations of 30,000 and 8,000. Conditions of shallow groundwater occurrence differ from those in Shiauliai, because Jonava is situated on the Neris River terrace and Varena in the outwash plain left by the last glaciation. Moreover, Jonava's urbanization resembles that of Shiauliai, whereas urbanization of Varena is quite small—there are only several small enterprises of local industry. In spite of the differences mentioned, our methodology enabled us to obtain rather reliable maps of groundwater pollution and pollutant migration for those towns as well.

Maps of Shiauliai have been ordered by the municipality. They are used directly in organizing optimal monitoring of shallow groundwater in the city and equipping a minimal but relevant number of observation points in the area controlled. Since the quality of groundwater in our maps is linked to the type of economic activity and, hence, with pollution in a certain place in the city, not only the city council, but also enterprises polluting groundwater should be involved with monitoring ("polluter pays"). Moreover, the city administration now has a plan for further action to improve groundwater, i.e., gradual elimination of pollution, especially in the places with highly polluted water, if possible.

Distinguishing pollution and pollutant migration zones enables the organization of purposeful and more detailed studies of shallow groundwater quality in the city. First of all they are organized in those residential areas where pollutants migrate from industrial areas and inhabitants still drink water from dug wells. Detailed studies of groundwater quality have already started in the deeper aquifers where four city water intakes extract water. A three-dimensional multilayer water-bearing system model is being worked out in Shiauliai (Gregorauskas and others 1994).

The Shiauliai municipality is starting implementation of GIS technologies in city planning and management. This system will include shallow groundwater mapping methods used and improved by us, as well as application of the results.

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