Hydrogeochemistry and vulnerability of groundwater in the moraine upland aquifers of the Gdańsk region (Northern Poland)

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The focus of this study was on determination and comparison of natural and current hydrogeochemical features of the groundwater, in order to evaluate changes of water quality and to identify the origin of these changes. Both natural processes and anthropogenic stress affect the chemical composition of groundwater were recognised. In both aquifer groups groundwater chemical composition demonstrates some similarities and is formed by the same kinds of natural processes, which are taking place already in the upper zones of the shallow aquifers, where groundwater is saturated with respect to most of carbonate and clay minerals, as well as minerals containing Fe^{2+} ions. During seepage into deeper aquifers, water is being enriched with Fe^{2+} and Mn^{2+} ions and in some places with SO_4^{2-} and Mg^{2+} as well. The types and intensity of human activities, as well as the vulnerability of aquifers to contamination, were concluded to play an important role in generating the observed changes in the chemical characteristics of the groundwater. They effect on changes of hydrogeochemical background values (e.g. TDS, N-compounds), the current increase of maximum concentrations of N-compounds, chlorides, sulphates, magnesium and TDS (total dissolved solids).

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INTRODUCTION

This study was focused on one of the largest moraine uplands located in the Gdańsk region. This area, the so-called Kashubian Lakeland, plays an important hydrogeological role in the whole region due to the characteristic conditions of groundwater circulation. Existing aquifers are in hydraulic connection typical of the regional groundwater system. The moraine upland of the Kashubian Lakeland is the recharge area for this system, where the groundwater's regional hydrodynamic and hydrogeochemical regimes are determined.

A number of hydrogeochemical and isotopic methods were used to determine the origin of commonly extracted groundwater in the moraine upland of the Kashubian Lakeland, as well as relevant processes affecting and sometimes deteriorating this composition.

Apart from natural processes controlling groundwater chemistry, its composition and quality in many places is increasingly influenced by anthropogenic pollution. Therefore,

an important scientific and practical issue aimed at improving groundwater quality, is to determine and verify the dominant processes and factors that control the chemical composition of groundwater. The hydrogeochemical characteristics of the Kashubian Lakeland are presented and compared with other hydogeologically similar regions in Poland.

RESEARCH AREA

The upland investigated is located in Northern Poland, in the neighborhood of the Gdańsk conurbation (Fig. 1). It is represented by ground moraine with altitudes varying from 120 to 240 m a.s.l. In several locations alluvial plains occur, as well as end-moraine hills, with a maximum altitude of 328.6 m a.s.l. (the Wieżyca hill in the Wzgórza Szymbarskie range). The moraine upland of the Kashubian Lakeland descends in all directions: to 150 m a.s.l. in southern and western parts forming the Starogardzkie and Bytowskie Lakeland; to 60 m a.s.l. in the north, where it is delimited by the Reda–Łeba proglacial stream
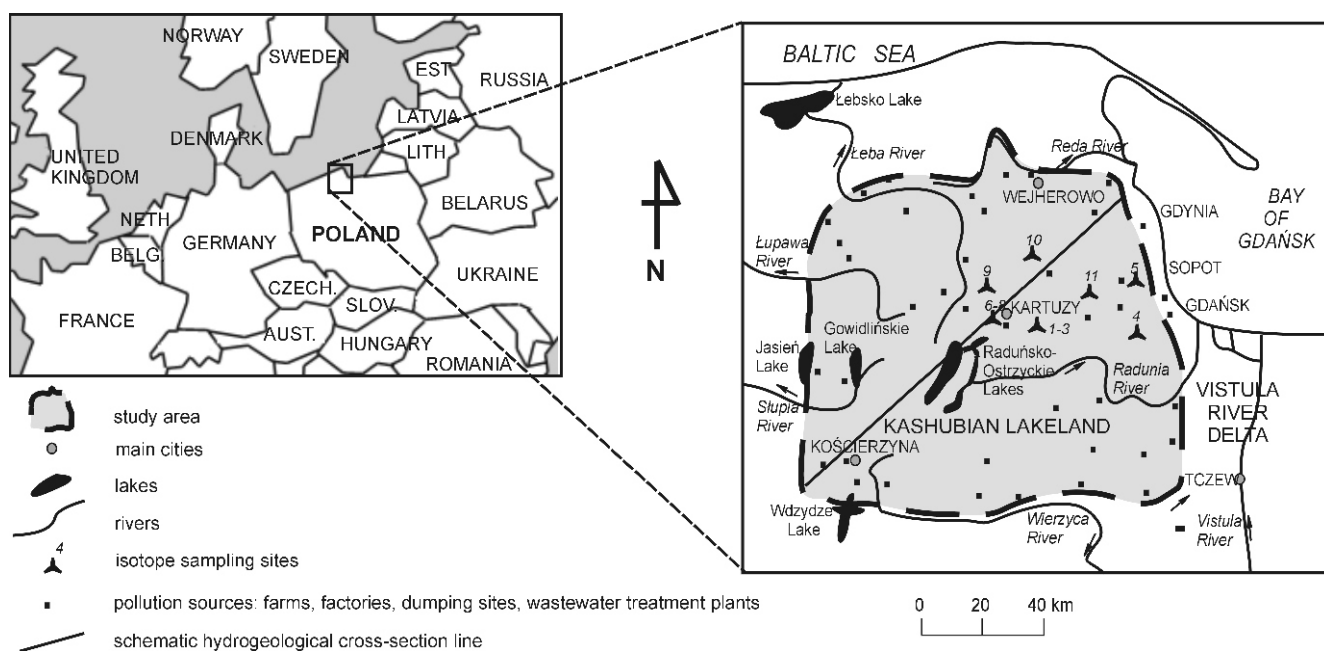
Fig. 1. Localization and map of the research area

valley; and to 60–80 m a.s.l. in the east, where it descends sharply towards the coast and the Vistula River Delta region.

Main rivers form the hydrographic system: Reda, Słupia, Łeba, Łupawa, Radunia and Wierzyca, which are the local groundwater drainage zones. Lakes are another important hydrographic element in this area. The most important are postglacial, deep lakes, which are also the local drainage zones; they include the Raduńsko-Ostrzyckie, Gowidlińskie, Jasień and Wdzydze lakes.

PREVIOUS INVESTIGATIONS

Hydrogeological investigations in the Gdańsk region have been carried out since the beginning of the XXth century as a result of increasing water demand by the intensively developing Gdańsk conurbation. After World War II, the most important works included hydrogeological survey maps of Poland (scale 1:300 000) developed in 1950–1960. Further extensive studies carried out by Pazdro, Kozerski and Sadurski comprised determination of regional hydrogeological conditions of the Gdańsk artesian basin as well as the quality, resources and groundwater protection issues of the Gdańsk moraine upland, the catchments areas of the Radunia, Kłodawa and Wierzyca rivers and the Baltic sea.

Since the 1980's studies have been carried out by researchers from the Gdańsk University of Technology, initially on genesis of groundwater from the chalk water-bearing unit, including anomalies of fluorine, hydrogen sulphide and ammonium contents, and defining the hydrogeochemical background values of groundwater. The investigations were further expanded into the hydrogeology and hydrogeochemistry of the lakeland regions in Northern Poland. They resulted in a detailed description of the hydrogeochemical background of

Quaternary groundwater, including a prognosis of its changes (among works by Kozerski, 1986, 1988; Kozerski *et al.*, 1987, 1990; Pruszkowska, 2001, 2004). Isotopic studies were conducted mainly by Dowgiałło and Sadurski (1988), Zuber *et al.* (1990) and Sołtyk (2004).

METHODOLOGY APPLIED IN THE PRESENT STUDY

The original research results were obtained between 1997 and 2004 during 28 field campaigns, when more than 1380 working wells were sampled. In addition to the groundwater table level, the measurements included: temperature, electrical conductivity, pH, redox potential and total dissolved solids content (TDS). These parameters were measured during the fieldwork using, respectively, pH-meter (*pH 330/SET-1*) and a conductometer (*Elmetron IP67*). Groundwater samples were taken, processed and transported according to standard procedures (protocols), and analyzed for standard physical-chemical properties, as well as for major and minor ions, at the Chemical Laboratory of the Polish Geological Institute (PIG) in Warsaw. For further interpretation only those chemical analyses were considered for which the analytical errors did not exceed ±5% (Table 1).

Hydrogeochemical background levels were determined according to the methodology described by Macioszczyk (1976, 1987), using statistic distributions of the frequency of observed concentrations of analyzed parameters. The histogram method was applied, followed by the method of cumulative curves (as a control). Background levels were determined for two time intervals:

— based on analyses made during test-pumping of new wells — these were assumed to represent the natural chemical composition of groundwater,

T a b l e 1

Chemical composition of groundwater in the moraine upland of the Kashubian Lakeland

| Hydrogeochemical parameters | Deeper aquifers group | | Shallow aquifers group | | Polish drinking water standards (2002) |
| | Natural | Actual | Natural | Actual | |
	concentrations/ hydrogeochemical background	concentrations /hydrogeochemical background	concentrations /hydrogeochemical background	concentrations /hydrogeochemical background	
total hardness [mval/dm^3]	1.9–8.5/2.6–5.4	1.5–10/2.0–5.4	1.2–8.8/2.6–5.4	1.6–8.2/2.0–5.4	–
total alkalinity [mval/dm^3]	0.8–5.5/2.4–5.5	0.4–7.1/1.6–5.5	0.25–7.6/2.9–5	0.7–8.4/1.6–5.8	–
pH	6.8–8.2/7.5–8.0	6.5–8.2/6.9–7.9	6.8–8.2/7.5–8.0	6.7–8.2/6.9–7.8	6.5–9.5
Eh [mV]	–	–50–340/–	–	100–350/–	–
TDS (total dissolved solids) [mg/dm^3]	168–688/190–340	94–580/110–400	172–624/200–350	90–923/110–450	–
color [mgPt/dm^3]	3–40/–	2–20/–	1–190/–	3–250/–	15
oxygen consumption [mgO$_2$/dm^3]	0.7–25/1.3–3	0.5–4.4/0.5–2.9	0.1–28/0.9–3	0.5–15/1–2	–
HCO^{3-} [mgHCO^3/dm^3]	32–170/–	24–285/–	97–521/ –	40–277/–	–
Cl$^-$ [mgCl/dm^3]	2–55/5–15	0.2–100/0–20	0.1–151/5–22	0.1–185/0–23	250
SO$_4^{2-}$ [mgSO$_4$/dm^3]	5.8–81/17–50	0.1–58/10–42	3.8–134/20–42	4.7–187/8–42	250
Ca^{2+} [mgCa/dm^3]	28–160/35–90	19.4–185/30–90	8–194/50–100	14.3–197/25–105	–
Mg^{2+} [mgMg/dm^3]	1.2–22/4–16	0.1–28.2/0–16	1.2–48/2–19	0.1–69/0–18	50
Na$^+$ [mgNa/dm^3]	1.8–15.7/–	2.1–16.0/–	1.8–25.0/–	2.9–48.8/–	200
K$^+$ [mgK/dm^3]	0.1–5.5/–	0.6–6.0/–	0.1–12.7/–	0.6–18.4/–	–
Fe tot. [mgFe/dm^3]	0.01–8/0.2–0.7	0.01–7.8/0–1.3	0.02–8/0.1–0.5	0.01–7.7/0–0.9	0.2
Mn^{2+} [mgMn/dm^3]	0.01–1.5/0–0.19	0.001–2.5/0–0.19	0.003–1.8/0–0.15	0.001–0.7/0–0.15	0.05
NH$_4^+$ [mgNH$_4$/dm^3]	0.001–2/0–0.13	0.004–3.2/0–0.28	0.002–4/0–0.12	0.015–2.7/0–0.35	0.5
NO$_3^-$ [mgNO$_3$/dm^3]	0.001–2.9/0.009–0.15	0.001–10.6/0.04–0.5	0.001–4/0.01–0.1	0.001–30/0.01–1.2	50
NO$_2^-$ [mgNO$_2$/dm^3]	0.001–0.4/0–0.02	0.001–3.4/0–0.05	0.001–1/0–0.01	0.001–0.35/0–0.05	0.1
Zn^{2+} [mgZn/dm^3]	–	0.005–0.85 /–	–	0.005–2.48/–	3
Sr^{2+} [mgSr/dm^3]	–	0.056–0.75/–	–	0.01–0.61/–	–
F$^-$ [mgF/dm^3]	0.05–0.75 /–	0.1–1/–	0.05–0.8/–	0.1–1/–	1.5

— based on analyses made within 1990–2005 in long-term operating wells, or in wells after renovation, that were assumed to present changes of groundwater chemical composition.

In order to determinate geochemical processes, as well as the origin and changes in groundwater chemical composition, a variety of hydrogeochemical modelling software is available, including *PHREEQCI2* (Parkhurst and Appelo, 2002). This software was used for hydrogeochemical calculations in this

study. Based on detailed groundwater analyses including physical parameters, ionic composition and redox conditions, saturation indexes (SI) were calculated of the main groundwater components in relation to aquifer minerals (Table 2).

Apart from interactions at the water-rock interface, another source of components dissolved in groundwater may be the infiltration the meteoric water. To evaluate the contribution of compounds of the meteoric origin, two parameters:

Saturation indexes (SI) of groundwater solution

Minerals	Shallow aquifers group		Deeper aquifers group		SI balance range $\pm$
	minimum value	maximum value	minimum value	maximum value	
Albite	−3.7	−2.5	−6.3	−1.7	1.0
Anorthite	−6.7	−4.2	−6.8	−2.7	1.0
$Al(OH)_3 \cdot nH_2O$	−2	−1.9	−2.4	−1.2	1.6
$SiO_2 \cdot nH_2O$	−0.9	−0.4	−2.2	−0.5	0.1
Quartz	0.4	0.6	−0.7	0.8	0.2
Muscovite	4.9	8.3	4.0	7.9	0.8
Chlorites	−17	−7.1	−9.2	0.5	3.7
Illite	−1.6	1.0	−3.4	1.0	2.1
Kaolinite	0.7	3.2	−0.5	2.5	1.9
Apatite (F)	−2.8	3.7	1.5	5.5	0.1
Calcite	−1.7	0.2	−0.5	0.7	0.4
Dolomite	−3.8	−0.5	−1.3	0.2	0.8
Siderite	−1.7	0.2	−1.7	0.4	0.8
Goethite	4.5	6.9	5.1	6.2	0.2
Hematite	14	17.6	15.1	17.2	0.1

r[Cl/(Cl+HCO₃)] and r[Na/(Na+Ca)], were used as suggested by Appelo and Postma (1993).

Two types of isotopes, stable and radioactive, may be helpful in evaluating groundwater residence time. Stable isotopes, such as ^2H (deuterium), ^{13}C, ^{16}O and ^{18}O, indicate the environmental conditions at the time of recharge. Radioactive isotopes, the concentrations of which may change seasonally or annually, such as ^3H (tritium), ^{14}C and ^{36}Cl, allow evaluation of the time elapsed since water infiltration took place (Clark and Fritz, 1997; Dowgiałło and Nowicki, 1999). Interpreting the results, the presence of tritium in groundwater may indicate good conditions of water circulation, direct contact with the surface as well as (up to 50 years) infiltration times from surface to groundwater. Tritium, then can be considered as a good indicator of anthropogenicpressure because it was artificially introduced to the environment during nuclear explosions in the 1950's.

Groundwater origins and ages were determined in this study by using isotope analyses of oxygen ($\delta^{18}O$), hydrogen (δ^2H), carbon ($\delta^{14}C$) and tritium (δ^3H). The analyses were performed at the Institute of Nuclear Physics and Technique in Kraków.

HYDROGEOLOGICAL CONDITIONS

The Quaternary multi-aquifer formations comprise the main groundwater reservoir present in the area. The hydrogeological conditions are represented on a schematic hydrogeological cross-section (Fig. 2).

In relation to the hydrogeological conditions two main aquifer groups were distinguished. They differ from each other not only in the depth of the groundwater table, but also in the thickness and lithology of the overlying layers, and in conse-

quence, in the degree of isolation from surface influences and vulnerability to anthropogenicpressure. Based on these conditions, the boundary between both aquifer groups was estimated at a depth of approximately 30 m below the surface (Pruszkowska, 2001, 2004).

The shallow aquifers occur only locally and are composed of sandy sediments of alluvial plains, of river and lake valleys, and sandy interbed in the moraine deposits of the Vistula Glaciation (Qp_4) (Fig. 2). They have direct contacts with surface waters are directly recharged by meteoric water, and they are poorly isolated from the surface. The groundwater of these aquifers is thus under direct threat of anthropogenic contamination.

The deeper aquifers occur regionally in inter-moraine Quaternary deposits, partially Qp_4 (Vistula Glaciation), Qp_3 (Odra Glaciation) and Qp_2 (San Glaciation), isolated from the surface (Fig. 2). They are recharged laterally or by indirect seepage from the overlying layers. Locally, they are hydraulically connected with the shallow aquifers and also with Tertiary aquifers (Pruszkowska, 2001, 2004).

RESULTS OF INVESTIGATIONS AND DISCUSSION

HYDROGEOCHEMICAL CONDITIONS

Regional-scale groundwater hydrogeochemical characterization was done for both shallow and deeper aquifer groups. Special attention was paid to hydraulic connections between aquifers, ways of recharge, types of human activities on the land surface and possibilities of contaminant migration from the surface. The natural background of the groundwater chemical composition in both aquifer groups was found to be very
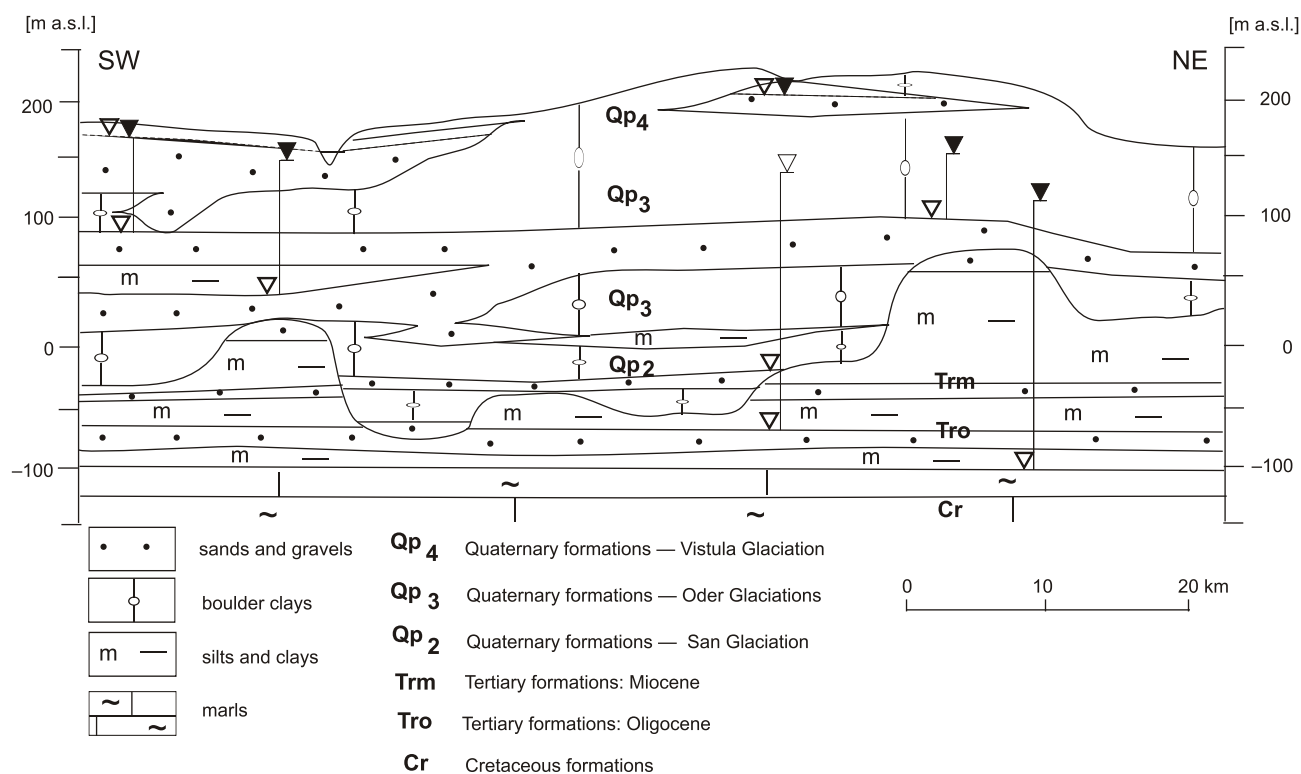
Fig. 2. The schematic hydrogeological cross-section for the moraine upland of the Kashubian Lakeland (Pruszkowska, 2004)

similar. Moreover, in both aquifer groups oxidizing and transient redox were observed, the Eh ranging between 100–350 mV, and only locally shifting towards slightly reducing capacities (Eh = 26–100 mV).

The most important and characteristic hydrogeochemical properties of the groundwater are discussed below, and the concentrations analyzed are shown in Table 1.

The shallow aquifers group: the mineralization of the groundwater represented by total dissolved solids (TDS) ranges up to 923 mg/dm^3, and the total hardness to 8.2 mval/dm^3 (Table 1). The concentrations of manganese and iron ions up to 0.7 mgMn/dm^3 and 7.7 mgFe/dm^3, thus exceeding the Polish standard values for potable water (Rozp. M.Z., 2002, see Table 1). Moreover, the maximum concentrations of all ions determined (Cl$^-$, SO$_4^{2-}$, Ca^{2+}, Mn^{2+}), N-compounds and TDS exceed the ranges of the natural hydrogeochemical background values typical of the area considered. Finally, an increase in maximum concentrations has recently been observed of Cl$^-$, SO$_4^{2-}$, Mn^{2+}, NO$_3^-$ ions and TDS.

The deeper aquifers group: the mineralization of groundwater represented by total dissolved solids (TDS) ranges up to 580 mg/dm^3, and high concentrations of Mn^{2+} (2.5 mgMn/dm^3) and Fe^{2+} ions (7.8 mgFe/dm^3) were observed, which are also above the Polish standard values (Rozp. M.Z., 2002; Table 1). The maximum concentrations of Cl$^-$, SO$_4^{2-}$ and N-compounds are significantly higher than the hydrogeochemical background values. As in the shallow aquifers group, within the last 15 years an increase in maximum concentrations of N-compounds and Cl$^-$ has been observed. However, with the exception of NO$_3^-$, NH$_4^+$ and TDS, the hydrogeochemical background values have not yet been exceeded.

Hydrogeochemical background levels were determined for chosen representative parameters in both aquifer groups and similar ranges of natural and current hydrogeochemical background values can be observed (Table 1).

The chemical composition of the shallow and deeper aquifers groups are shown in Figure 3, in the form of a Piper diagram. The similar positions of points representing the chemical compositions of groundwater of both aquifer groups suggests a similar origin for groundwater components. Both aquifer groups show relatively uniform cationic compositions. By contrast, their anionic compositions are not uniform as indicated by the dispersion of points. This may also indicate the enrichment of groundwater with Cl$^-$ and SO$_4^{2-}$ ions.

Moreover, the chemical composition of groundwater in both aquifer groups is typical of Pleistocene groundwater, with high concentrations of Fe^{2+} and Mn^{2+} ions, often exceeding the Polish standards for drinking water (Rozp. M.Z., 2002). These high concentrations are distributed rather uniformly throughout the research area, and show an increasing trend as the depth increases. Besides, the ranges of natural and current hydrogeochemical background values are very similar for both aquifer groups. These facts indicate a geological origin for the high concentrations of Fe^{2+} and Mn^{2+} ions, as has also been reported for other late Pleistocene deposits in Poland (Płochniewski, 1973; Ratajczak and Witczak, 1983).

The calculated saturation indexes (SI) of water with respect to common aquifer minerals for both aquifer groups were also very similar (Table 2). It was found that groundwaters are not saturated with regard to: albite, anorthite, dolomite, chlorites and siderite, and that, consequently the dissolution of these
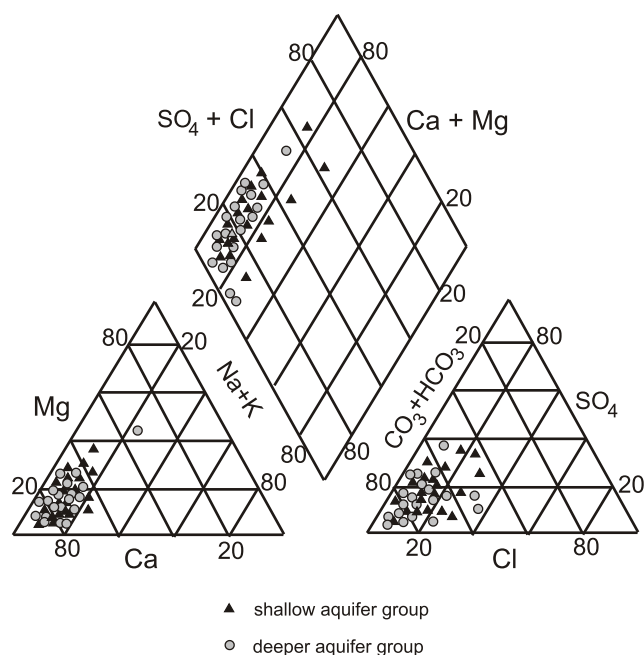
Fig. 3. The chemical composition of groundwater within shallow and deeper aquifer groups
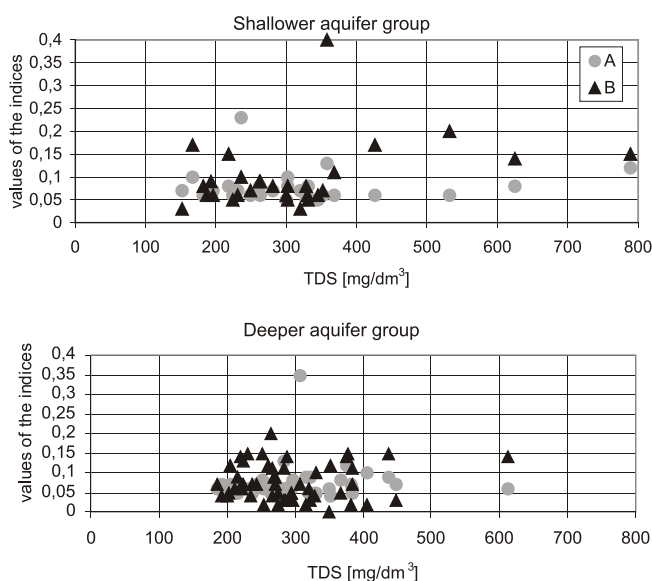

Fig. 4. Values of A = r[Na/(Na+Ca)] and B = r[Cl/(Cl+HCO₃)] parameters *vs*. TDS (total dissolved solids) for both aquifer groups

minerals may lead to enrichments of groundwater with Ca^{2+}, Mg^{2+}, Na^+ and Fe^{2+} ions.

It seems that the chemical composition of groundwater occurring in both groups is determined already in the upper parts of the shallow aquifers group. In this zone groundwater is being saturated with respect to most of the siliceous, carbonate and clay minerals, as well as with respect to minerals containing ferrous ions. Moreover, ice-barrier sediments as clays and silts are rich in organic matter and minerals containing ferrous

and manganese ions (Grabowska-Olszewska and Sergiejew, 1977). During subsequent seepage through these deposits to deeper units the groundwater may additionally be enriched in SO_4^{2-}, Mg^{2+}, Fe^{2+} and Mn^{2+} ions.

Apart from products of interactions at the water-rock interface, other compounds that are present in groundwater may originate from recharging meteoric waters. Following the suggestion of Appelo and Postma (1993), the contribution of compounds of meteoric origin was determined using r[Cl/(Cl+HCO₃)] and r[Na/(Na+Ca)] ratios. The distribution of values of these parameters in groundwater of both aquifer groups is generally similar (Fig. 4). A decrease of the maximum values with increasing depths, observed within the shallow group, may suggest that compounds of meteoric origin play an important role in the chemical composition of the shallow groundwater.

ISOTOPE STUDY

The contribution of components of meteoric origin in groundwater is also supported by the results of isotope study (Table 3). Concentrations of stable isotopes of oxygen ($\delta^{18}O \approx -10‰$) and deuterium ($\delta^2H \approx -71‰$) in relation to VSMOW (Vienna Standard Mean Ocean Water) and WMWL (World Meteoric Water Line), suggest that all waters considered were recharged during the Holocene Epoch (Zuber *et al*., 1990; Nowicki, 1999; Sołtyk, 2004). The values of stable isotopes ($\delta^{18}O$ and δ^2H) given in Table 3 indicate the seasonal effects of temperature influence, and they are typical for a warm climate or summer intervals. Moreover, recharge took place at different times. Early Holocene recharge as well as late Holocene "contemporary" recharge took place. Late Holocene infiltration is confirmed by increased concentrations of tritium (δ^3H), up 3 to 100 T.U., which were found both in shallow and deeper aquifer groups. This may indicate that infiltration took place during or after nuclear test, i.e. not earlier than 50–60 years ago (Sołtyk, 2004). Such infiltration is observed in shallow aquifer group at several sites (Dzierżążno, Kartuzy, Szemudzka Huta). Locally, increased concentrations of tritium are also observed in the deeper aquifer group (Dzierżążno and Kartuzy) suggesting good flow and recharge conditions.

In the case of Dzierżążno, concentrations of tritium and ^{14}C in two investigated wells indicate "young" waters that might have infiltrated within the time of nuclear tests in 1960. Moreover, values of $\delta^{18}O$ and δ^2H are specific for infiltration in summer periods. However, these values do not indicate good circulation conditions of groundwater in this area, but stagnation within the groundwater system. Hydrogeological conditions may favour stagnation, because both shallow and deeper aquifers are not continuous and are in hydraulic contact with one another. In addition, both analyzed wells are in the close vicinity of the Radunia River, where any flooding could result in groundwater recharge with water of such isotopic composition. However, as the isotopic analyses mode were based on single measurements, they should be repeated for more detailed and unambiguous determination of the genesis of groundwater isotopic composition in the Dzierżążno region.

Results of isotope study for the shallow and deeper aquifer groups

Sampling number	Sampling point aquifers group	$\delta^{18}O$ [‰]	δ^2H [‰]	δ^3H [T.U.]	$\delta^{13}C$ [‰]	^{14}C [pmc]
1	Dzierżążno shallow	−6.6	−51	105.5	−11.3	76.5
2	Dzierżążno deeper	−9.8	−68	3.7	−12.0	46.5
3	Dzierżążno deeper	−7.6	−57	0.0	−11.1	54.0
4	Gdańsk–Kokoszki deeper	−10.7	−72	0.0	−11.2	35.8
5	Gdańsk–Osowa deeper	−10.3	−71	0.0	−11.9	42.5
6	Kartuzy shallow	−9.8	−68	6.8	−11.3	47.3
7	Kartuzy deeper	−9.9	−67	0.6	−11.3	45.3
8	Kartuzy deeper	−10.0	−68	0.0	−	−
9	Pomieczyńska Huta shallow	−10.2	−69	0.0	−10.4	34.1
10	Szemudzka Huta shallow	−10.3	−72	24.8	−11.4	40.5
11	Warzno deeper	−10.4	−71	0.0	−12.2	39.0

THE EFFECTS OF ANTHROPOGENICPRESSURE

Due to the lack of natural isolation of shallow aquifers and good groundwater flow conditions, there is risk of local groundwater contamination from the surface. This has already been observed in shallow and most vulnerable aquifers, and is directly associated with the presence of anthropogenic contamination sources, such as: farms, landfills and dumping grounds, wastewater treatment plants and factories, especially distilleries and dairies. The contamination is currently manifested by high concentrations of TDS, Cl^-, SO_4^{2-}, NO_3^-, NH_4^+ ions in shallow aquifers. An example of such contamination is shown in Figure 5.

Besides this, anthropogenicpressure effects are also indicated by:

— increases in concentration of TDS and Cl^-, SO_4^{2-} ions and N-compounds during the last 15 years;
— changed hydrogeochemical background values in the case of TDS and N-compounds (Table 1).

Following the suggestion of Macioszczyk (1987) and Górski (2001) both of these are considered typical indices of anthropogenic stress on the chemical composition of groundwater. A clear correlation was observed between the local appearance of contaminants in groundwater and their surface sources.
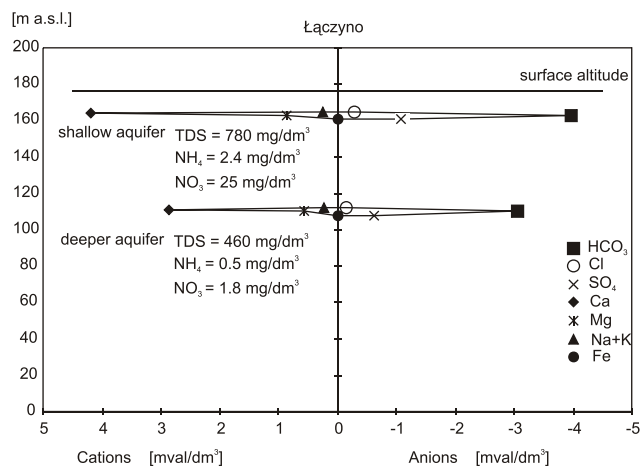
COMPARISON OF GROUNDWATER CHEMICAL COMPOSITION IN THE KASHUBIAN LAKELAND WITH THAT OF OTHER MORAINE DEPOSITS IN POLAND

The chemical characterization of groundwater in the Kashubian Lakeland is comparable to that in other hydrogeologically similar regions in Poland. The hydrogeochemical background values are within the same range as found in other Polish aquifers as described by Witczak and Adamczyk (1995; Table 4). It can also be noticed that these background values differ only to a very small degree from the ranges found by various authors for groundwater from other Quaternary deposits in the moraine uplands of Northern Poland (Macioszczyk, 1987, 1991; Kozerski and Wojtkiewicz, 1990; Witczak and Adamczyk, 1995; Janica, 2001; Macioszczyk and Dobrzyński, 2002). The greatest difference concerns SO_4^{2-}, the background values in groundwater of the Kashubian Lakeland

Fig. 5. Chemical groundwater composition in shallow and deeper aquifer groups as a result of anthropogenicpressure

T a b l e 4

Hydrogeochemical background values in groundwater of the Quaternary deposits of moraine uplands in selected regions of Northern Poland

Region	TDS [mg/dm³]	Total hardness [mval/dm³]	Cl⁻ [mg/dm³]	SO₄²⁻ [mg/dm³]	Ca²⁺ [mg/dm³]	Mg²⁺ [mg/dm³]	Na⁺ [mg/dm³]	K⁺ [mg/dm³]	NH₄⁺ [mg/dm³]	NO₂⁻ [mg/dm³]	NO₃⁻ [mg/dm³]	Fe tot. [mg/dm³]	Mn²⁺ [mg/dm³]
Kashubian Lakeland	190–350	2.6–5.4	5–22	17–50	30–100	2–19	–	–	0–0.13	0–0.02	0.009–0.15	0.1–0.7	0–0.19
Elbląska Upland (Kozerski and Wojtkiewicz, 1990)	200–450	3–6.5	3–15	0–25	54–130	8–20	–	–	0–0.77	–	0–0.02	0–4	0–0.4
Warmińska Lowland (Kozerski and Wojtkiewicz, 1990)	–	3–7	5–15	5–33	67–100	–	–	–	0–0.38	–	0–0.02	0–5	0–0.3
Iławskie Lakeland (Kozerski and Wojtkiewicz, 1990)	205–548	3.3–10	3.7–14.8	0–41	61.7–124	0–20	–	–	0–0.62	–	0–0.02	0–5	0–0.5
Suwalskie Lakeland (Macioszczyk, 1987)	200–400 (TS)	1.8–5	2–10	0–10	–	–	–	–	0–0.08	0–0.003	0–0.01	–	–
Ełckie Lakeland (Janica, 2001)	–	3–5	1–10	0–28	–	–	–	–	0–0.51	0–0.002	0–0.1	–	–
Mrągowskie Lakeland (Janica, 2001)	–	3–10	4–12	0–19	–	–	–	–	0–0.45	0–0.001	0–0.05	–	–
Biała River basin (city of Białystok) (Macioszczyk, 1991)	150–400	–	1–20	0–60	40–80	8–20	0–40	0–5	0–0.45	0–0.01	0–0.6	0–2	0–0.012
Groundwater in Poland (Witczak and Adamczyk, 1995; Macioszczyk and Dobrzyński, 2002)	200–500 (TS)	1.9–7.9	2–60	5–60	2–200	0.5–50	1–60	0.5–10	0–0.8	0–0.01	0–1	0.02–5	0.01–0.4

TDS — total dissolved solids; TS — total solids

being higher than the values observed in genetically similar lakelands (e.g. Suwalskie, Mrągowskie, Ełckie), the Elbląska Upland and the Warmińska Lowland (Table 4). On the other hand, for the Kashubian Lakeland the groundwater background values are much lower as regards Fe^{2+} and Mn^{2+} ions.

The concentrations of N-compounds in the Kashubian Lakeland groundwater also differ for the regions given in Table 4. The background values found in groundwater of the Kashubian Lakeland for both NH_4^+ and NO_3^- are lower as compared to the values presented by Witczak and Adamczyk (1995), and Macioszczyk and Dobrzyński (2002). Moreover, the background values of NO_3^- and NO_2^- are higher, and those of NH_4^+ are lower, than those of similar regions of Northern Poland (Table 4).

It is suggested that different ranges of background values, usually lower as compared to those presented by Macioszczyk and Dobrzyński (2002), Witczak and Adamczyk (1995) and other authors, are related to the specific environmental conditions of the Kashubian Lakeland. This is not an industrialized area and the land use for agriculture is also limited as the area is mostly covered with forests.

CONCLUSIONS

Assuming good groundwater flow conditions and hydraulic contacts between aquifers and multi-aquifer successions, the research carried out suggests the following conclusions:

1. The origin of groundwater chemical composition of both aquifer groups in the Kashubian Lakeland indicates that groundwater is taking part in active water exchange and circulation conditions do not change significantly as the depth of groundwater occurrence increases.

2. The residence time of groundwater differs, as in both shallow and deeper aquifers waters of the early Holocene infiltration and "contemporary" (not older than 50–60 years) recharge are present.

3. Groundwater chemical composition shares some similarities and in both aquifer groups is formed by the same kinds of natural processes, which being taking place in the upper zones of shallow aquifers, where groundwater is saturated with respect to most carbonate and clay minerals as well as minerals containing Fe^{2+} ions. During seepage into deeper aquifers, water is enriched in Fe^{2+} and Mn^{2+} ions, and in some places in SO_4^{2-} and Mg^{2+} as well.

4. Natural processes controlling the groundwater chemical composition are reflected by a similarity chemical composition of shallow and deeper groundwater, which is indicated by similar ranges of natural and current hydrogeochemical background values, as well as similar values of a number of physical and chemical features.

5. The chemical composition of groundwater is also affected by anthropogenicpressure, as a result of contamination from various human activities. Fortunately, the effects of contamination of anthropogenic origin have, however, been observed to date only locally, in shallow aquifers that are not isolated.

6. The main effects of anthropogenicpressure include: changes of hydrogeochemical background values (e.g. TDS, N-compounds), the current increase of maximum concentrations of N-compounds, chlorides, sulphates, magnesium and TDS (as compared to background values that were observed 15 years ago), and a clear correlation between the local appearance of contaminants in groundwater and their surface sources.

7. The chemical composition of groundwater from the Kashubian Lakeland is comparable to that of groundwater in hydrogeologically similar regions in Poland.

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