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Hydrodynamic and hydrochemical conditions in the Wda and Mątawa River catchments (NW Poland)

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The paper focuses on the problem of groundwater "ages" in the Pleistocene aquifers of the Wda and Mątawa River catchments. Groundwater residence time in the rocky environment of sandur areas was estimated with two methods i.e.: numerical modelling along the two lines of cross-sections and an isotope method (^{18}O, ^{2}H, ^{3}H) for 6 samples. Chemical parameters (TDS, Cl) confirm the general trends of enriching water mineralization along the flow path in the sandur aquifer, as well as during infiltration towards the deeper aquifers.

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Key words: sandur aquifer, water "age", groundwater chemistry, numerical modelling.

INTRODUCTION

The Wda and Mątawa River catchments are located in the young glacial areas of the Pomeranian Lakeland. Most of the area is covered by widespread sandurs developed during the accumulation of sands carried to the Noteć-Warta proglacial stream valley by marginal waters during the Weischelian glaciations. The subject of this research focuses on groundwaters of the sandur aquifer and the first inter-morainic aquifer from the surface. The objective of the work is to establish the interaction between hydrodynamic and hydrochemical fields in the studied area. The time needed to leak water through unsaturated zone was estimated to realize the task. The groundwater residence time was evaluated next, and the diversity of the selected chemical indicators in waters from sandur aquifer in the hydrodynamic system for the selected fragments of the Wda and Mątawa River catchments was established.

This study is based on the results of the field and laboratory research, as well as on information obtained from the database of the *Hydrogeological map of Poland* at the scale of 1:50 000.

The presented results are derived largely from the PhD thesis completed under the supervision of prof. dr hab. A. Sadurski (Kachnic, 2004).

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RESEARCH AREA

Over 54% of researched Wda and Mątawa River catchments parts are covered by forests (Trampler *et al*., 1990). The other remarkable feature is young, glacial topography of the terrain. Numerous lakes occur in the area. Industry is poorly developed in this region.

Detailed studies were carried out in five parts of the Wda and Mątawa River catchments, which are least affected by anthropogenic changes and have significant forest coverage of 67–94%. These are: the upper Wda catchment (from the springs of the Wda River to the bridge in Papiernia county), the Trzebiocha River (from the outflow from Żółnowo Lake to its mouth), the Brzezianek River (without Święta Struga), the upper Mątawa River (to the outflow from Radodzierz Lake) and the Sinowa Struga River catchment area (Fig. 1).

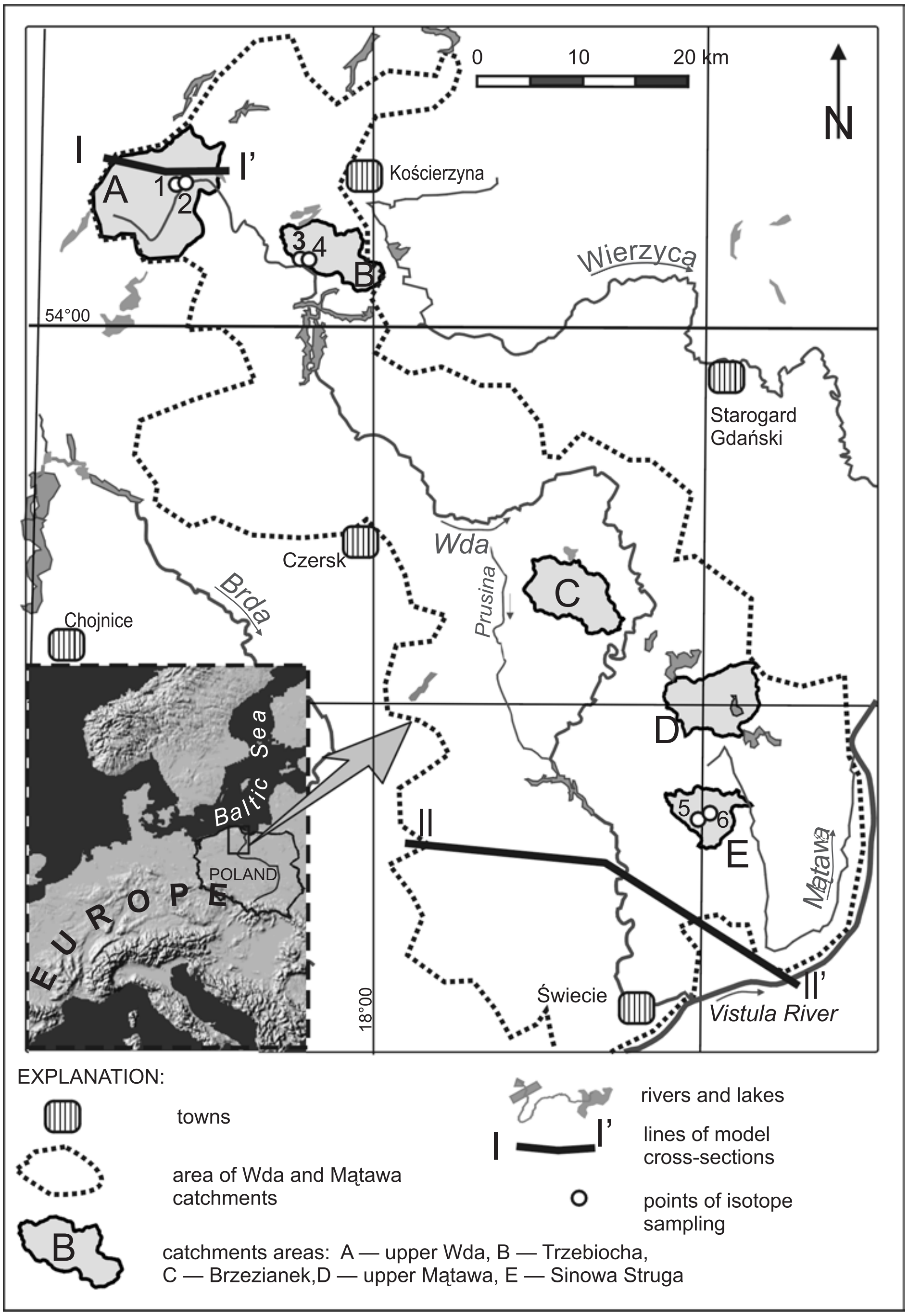

Fig. 1. Location of the studied area

PAST RESEARCH

The past research in the selected areas was focussed on general characteristics of hydrogeological conditions of the region and on determination of a hydrochemical background (Bojarski, 1978; Michalska, 1986; Przewłócka, 1988; Pruszkowska, 1999; Bojarski and Sadurski, 2000).

The aim of the research was to recognize hydrogeological structures and to delineate the areas that can be the recharge zones for the groundwaters.

There are no past studies of circulation of the groundwaters and modelling of groundwater chemistry.

The area of the Wda and Mątawa catchments includes parts of 4 sheets of the 1:200 000 *Hydrogeological map of Poland* and 19 sheets of the 1:50 000 *Hydrogeological map of Poland*.

SCOPE AND METHODS OF THIS STUDY

The general assessment of the Pleistocene aquifers groundwater chemistry was based on archive analysis, mainly from the database of the 1:50 000 *Hydrogeological map of Poland*.

Ninety five samples were taken from the sandur aquifer, from the places with undisturbed localities, in order to prepare reliable characteristics of the groundwaters. Most of the samples was taken from the springs and effluent seepages; forty samples were taken from drillings, usually less than 5 m in depth.

Total dissolved solids content, calculated from the conductivity and chlorides concentration in groundwater, was chosen as the indicators of water chemistry.

Groundwater sampling points were located far from the countryside buildings. Such location is important in sampling of sandur aquifer, because the majority of waters from farms wells is contaminated with nitrogen compounds (Górski, 1989; Kachnic, 2001)

The groundwater residence time was evaluated by two methods: by ratios of ^{18}O, ^{2}H and ^{3}H isotopes and by using hydrodynamic modelling with PM Modflow program.

HYDROGEOLOGICAL CONDITIONS

The Pleistocene water-bearing horizon contains subsurface (sandur) aquifer and inter-morainic aquifers. Subsurface aquifer is made of sands and gravels deposits of the Weischelian glaciations — the Wda and Mątawa sandurs, and the alluvial

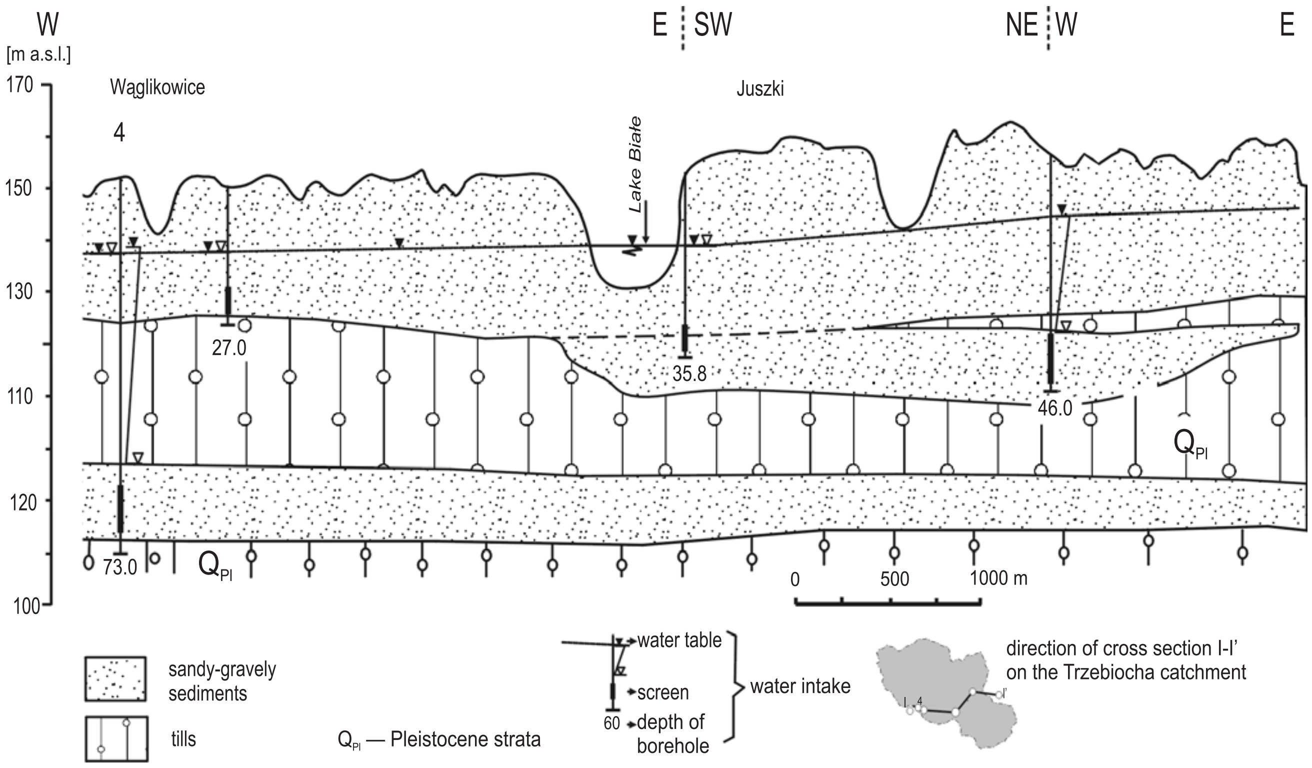

Fig. 2. Hydrogeological cross-section through the Trzebiocha catchment

deposits of their valleys. Alluvial deposits of the Vistula are present in the mouths of the Wda and Mątawa.

The deeper Pleistocene aquifers are mostly composed of clastic deposits of the Warta and Weichsel glaciations. The Pleistocene sequence contains from 1 to 4 aquifers, but commonly recognized and documented are only the two most shallow aquifers. The aquifers are separated by tills or clayey-silty layers (Fig. 2). Erosional forms occuring in the vicinity of lakes and proglacial stream valleys result in a hydraulic contact between the aquifers (Michalska and Michalski, 1980; Grdeń and Nikadon, 1998) and are responsible for the zones of increased aquifer thickness.

The sandur aquifer is widespread in the Wda and Mątawa catchments. The sandur is locally separated by till outcrops.

The groundwater table of the aquifer occurs at relatively shallow depths, from 0.5 to 20 m. The more shallow values are typical for the areas close to rivers and lakes with average depth of 5 m. The thickness of water-bearing sandur layers ranges from 2 to 50 m.

The position of aquifers in the northern part of the research area is shown in Figure 2. The Wda sandur narrows towards the south, and there are moraine plateaux on the surface. In that part of the area layers located under tills are of determining significance for water collection.

CIRCULATION SYSTEMS AND GROUNDWATER RESIDENCE TIME

The characteristic features of the groundwater circulation in the Pomeranian Lakeland include good water storage properties of deposits and large capability of water infiltration on the surface and underground.

The Wda and Mątawa River young glacial catchments are covered by a large variety of glacial forms gradually declining towards the south. There is 200 metres difference in topographic height between the northern and the southern-east part of the area. It causes intensive drainage of groundwaters by Vistula River.

Main recharge zones in the Wda and Mątawa River catchments are watershed areas and the majority of outwash plain surface. The regional drainage base for the Pleistocene aquifers is the Vistula valley.

The relationship between groundwater flow systems in deep layers and topography of the terrain, and the size of large rivers catchments were discussed by Toth (1963, 1978), Freeze and Witherspoon (1967), Macioszczyk (1980), Szymanko (1980) and Sadurski (1991).

The surface recharge of sandur aquifer is related to infiltration of rainfalls, which is facilitated by permeable sandur deposits and by existing numerous topographic depressions without outflow.

The deeper aquifers are recharged indirectly from the sandur aquifer by waters leaching through poorly permeable layers*. The exchange of waters between the sandur and the deeper aqui-

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* Model research were performed for the upper Wierzyca and the upper Wda catchments (to the gauge in Błędno). The results presented in Frączek and Kobyliński (unpubl.) — "Regionalne zasoby wód podziemnych z utworów czwartorzędowych na obszarze zlewni górnej Wierzycy i górnej Wdy, woj. gdańskie", part II, proved that 99% of the Pleistocene aquifer waters came from rainfalls infiltration. The rest (1%) comes from the side flow. About 61% is drained through surface waters, and the side outflow is 31%. About 8% of the total quantity of groundwater is being exploited.

fers also take place in erosional forms in glacial tills separating these aquifers (channels, proglacial stream valleys). These channels usually intersect several aquifers, for example Wdzydze Lake channel (Michalska and Michalski, 1980).

The general direction of the groundwater flow is towards the Wda mouth to the Vistula valley, which is the region drainage base. The Neogen aquifers are also drained by the Vistula (Sadurski, 1989; Chmielowska, 1997; Zambrzycka, 2002). Groundwater table stabilization of this aquifer is similar or below that in the younger aquifers, but there is a lack of detailed identification of flow directions in this aquifer.

CONCEPTUAL MODEL OF WATER CIRCULATION

The conceptual model of water circulation contains essential information concerning the arrangement of the aquifers and layers separating them, hydrogeological conditions (layers with confined or unconfined water table), hydrologic data (coefficient of permeability of rivers beds deposits) and technical-exploitation factors (construction, yields of wells).

The model assumes existence of main, regional circulation system in Pleistocene aquifer, which is outlined by the Wda catchment watershed. The main drainage base is the Wda River while in the southern part of the area the influence of the Vistula drainage is significant. Groundwater is recharged by rainfall infiltration.

To calculate the depth of water circulation in the system and evaluate the time of water exchange, simplified hydrodynamic models were prepared in the two cross-sections of the Wda River. The first cross-section (I-I') runs across the upper Wda catchment (Fig. 1) near Osława Dąbrowa–Skwierawy townships . The second cross-section (II-II') is located in the south part of the Wda catchment (Fig. 1), near the Wierzchucin, Stępiska, Lniano, Sierosław, Wery, Krąplewice, Laskowice, Taszewo and Sartowice villages.

Construction of these two models is based on the two-dimentional finite-differences method.

It was assumed that two to three aquifers, separated by unpermeable horizons exist in a vertical profile.

Constant head-boundary conditions were assumed (H = const, on watersheds and in rivers valleys), and the hydraulic height H value was established there. These values were established on the basis of water level in the boreholes on watersheds and from the topographic map with respect to the height of the water level in the valleys of the Mukrz, Wda and Vistula.

The cross-section running in the southern part of the Wda catchment (II-II') is about 45 km in length. It runs across the moraine plateau and continues to the Vistula valley near Sartowice. The topographic denivelation between moraine plateaux and Vistula valley reaches 100 m.

The Pleistocene and the Neogen aquifers were modeled. They are separated from each other by a thick layer (about 60 m) of poorly permeable deposits.

The analysis of existing data, including hydroizohypses maps (from *Hydrogeological map of Poland*) and geological cross-sections, shows clear drainage of the Vistula in this part of catchment and the drainage of deeply incised (over 30 m) Wda valley. It applies to both, the Pleistocene and Neogene aquifers.

At the marginal zone of the Vistula valley the Pleistocene aquifer disappears.

NUMERICAL MODEL OF WATER CIRCULATION

"Processing MODFLOW" program of Chiang and Kinzelbach (2000) was used for numerical modeling of water circulation. In this program the solution of differential equation of groundwater flow in a two-dimensional porous medium was made by the method of finite differences. The algorithm (see below) is based on numerical, approximated solution of the system of the equations of a flow balance that results from a general differential equation that describes the motion of groundwaters in the three-dimensional space of a porous medium.

$$\frac{\partial}{\partial x} = \left(k_x b \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial z} \left(k_z b \frac{\partial H}{\partial z} \right) = W$$

where: k_x, k_z — coefficient of permeability in the direction of x and z axes of the assumed reference system [LT^{-1}], b — elementary width of cross-section, x, z — coordinates of assumed reference system, H — hydraulic height, W — recharge or discharge.

The "Processing MODFLOW" program is useful for modelling the steady and non-steady flow of groundwaters, that take place in rocky complexes containing aquifers. The program gives also possibility to monitor the paths of motion of hypothetical particles of water on the base of generated hydrodynamic net (the module PM PATH).

The discussed cross-sections were discretised by a rectangle grid of a diversified distance step Δx and Δz. Widths of rectangle sides ranges from 500 to 600 m and the heights range from 5 to 13 m. For the cross-section through the northern part of catchment the matrix consisted of 26 columns and 30 rows (Fig. 3), and for the second cross-section of 61 columns and 14 rows.

The coefficient of horizontal permeability k_x for the model, was established on the base of pump testing results for water intakes located in the research area. Pleczyński (1983) described the coefficient of horizontal permeability k_x for the deposits of low permeability as ranging from 10^{-6} to 10^{-4} [m/s]. The effective porosity of rocks n_e was assumed basing on the literature data (Kovács, 1981; Dąbrowski, 1982).

The cross-section in the northern part of the research area (Fig. 3) runs through the upper Wda River catchment from west to south-east and its length is 13.5 km. The denivelation of this area is about 40 m. The altitude is lowest in the Wda valley (155 m a.s.l.) and reaches its maximum of 193 m a.s.l. in the western watershed area.

The groundwater table of the first aquifer occurs at the height of 153 m a.s.l. in the Wda valley and at the 162 m a.s.l. in the watershed area.

The calculations results for I-I' cross-section are shown on Figure 3. Equipotential lines and flow paths that start in the recharge zones are marked. The time of circulation in shallow

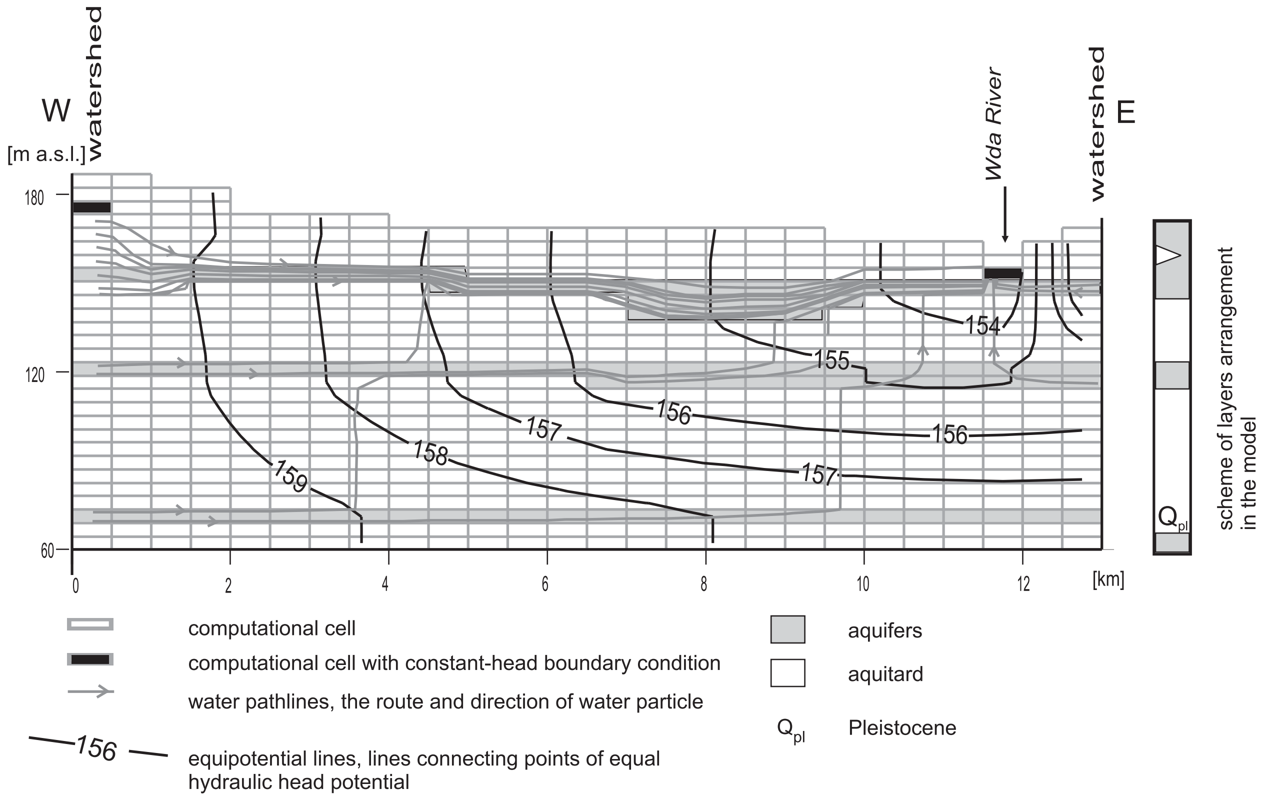

Fig. 3. Groundwater flow model in the I-I' cross-section

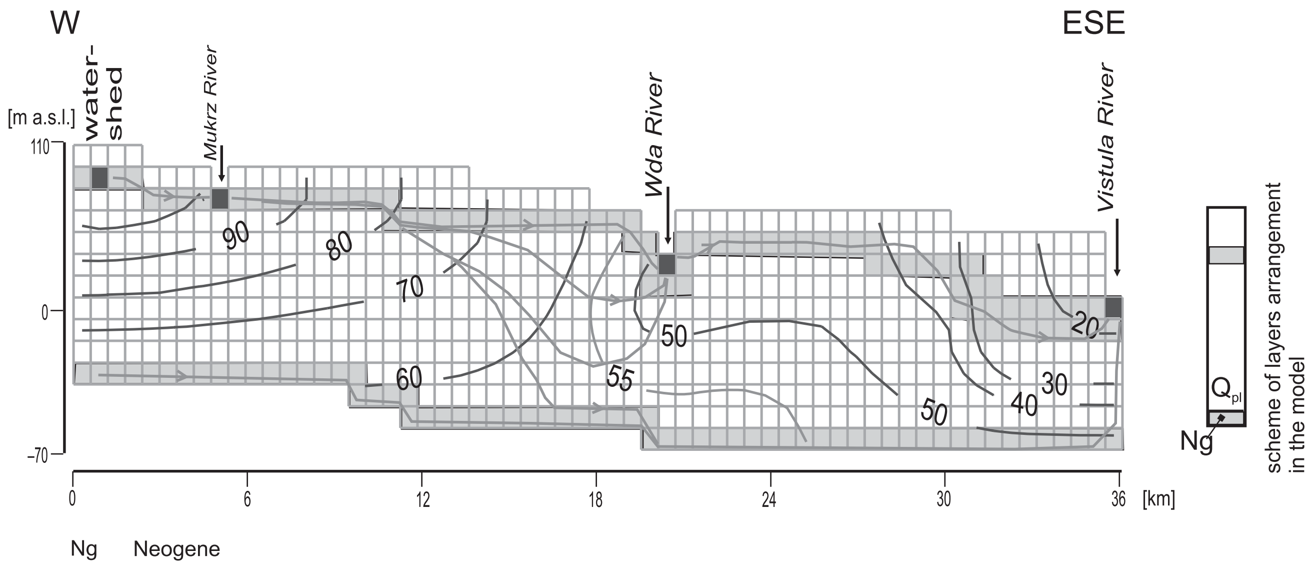

Fig. 4. Groundwater flow model in the II-II' cross-section

For explanations see Figure 3

aquifers is about 10 times shorter than in the deep aquifers. The time of water circulation amounts to 80 years in a subsurface (sandur) aquifer and the first aquifer under tills. In deeper Pleistocene aquifers, occurring at a depths of 60 to 100 m, the cycle takes about 1000 years.

The results of simulation of the simplified scheme of hydrogeological conditions in II-II' cross-section is shown in Figure 4. The conducted calculations indicate the major influence of the regional Vistula drainage on the groundwater circulation system. The Wda River drainage is evident in the Pleistocene aquifer. The Mukrz River that flows through the western part of the area over poorly permeable deposits is not a drainage base for the aquifers (Fig. 4).

It is possible that its local influence could be shown by more detailed study.

ISOTOPE COMPOSITION OF WATERS FROM THE PLEISTOCENE AQUIFERS

One of the methods of evaluating groundwater residence time and vulnerability of the groundwater to antropopressure is the tritium method (among others Zuber, 1991; Felter and Nowicki, 1997; Dowgiałło and Nowicki, 1999). This method gives the opportunity to state if the analysed waters infiltrated before or after the period of nuclear tests (1950s). The lack of tritium in the analysed waters means that their infiltration took place before the period of nuclear tests, and that we deal with waters of low vulnerability (ibidem).

Stable isotopes (oxygen ^{18}O and deuterium) analysis and tritium concentrations in groundwater were determined to evaluate the groundwater residence time and the vulnerability of groundwater for antropopressure.

Three springs and three water intakes that exploit waters from the first aquifer under tills were sampled (Table 1). The location of samples is shown on Figure 1. Each out of six sample points are located in close vicinity to each other, and come from the sandur and inter-morainic aquifer. The sampling was carried out during a low water level, after hydrologic drought in 2003. This provided an opportunity to sample water from the basic flow, without a considerable inflow from recent rainfalls.

Table 1

Results of isotope researches of groundwater of sandur and inter-morainic aquifer as of June 11th, 2003

No.	Sampled point	Depth of screen [m]	δ^{18}O [‰] V-SMOW	δ^{2}H [‰] V-SMOW	Tritium [T. U.]
1	Skwierawy water-supply intake	50.3–60.4	–9.98	–70.0	0.3±0.3
2	Skwierawy spring	0	–10.01	–70.2	11.5±0.6
3	Wąglikowice spring	0	–9.05	–64.8	10.2±0.5
4	Wąglikowice water-supply intake	59.1–69	–9.83	–69.9	7.6±0.4
5	Kotówka spring	0	–9.95	–72.2	5.0±0.4
6	Kotówka Forestry	25.3–29.3	–9.97	–71.6	21.7±1.0

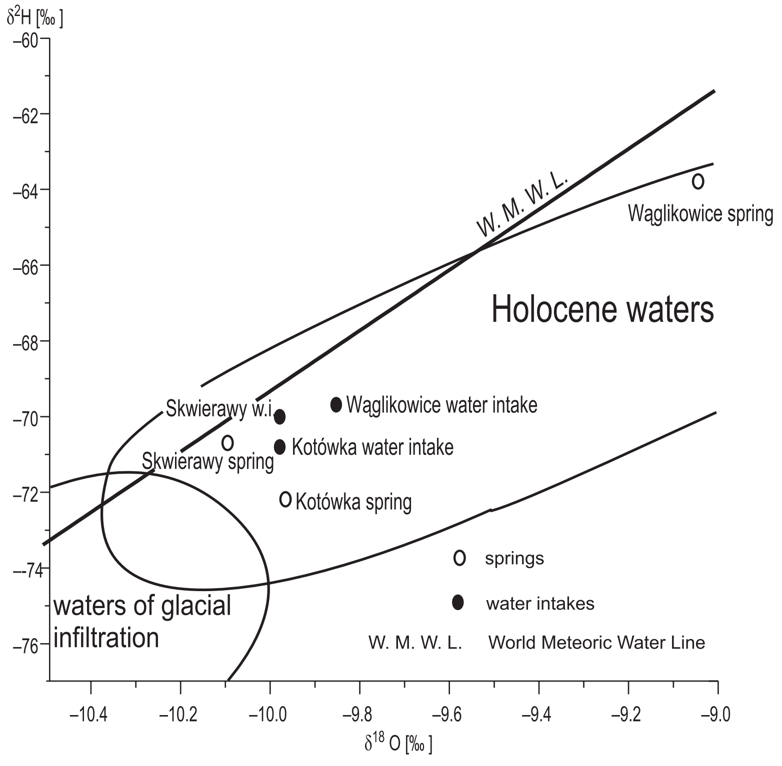

Fig. 5. Relationship δ^{18}O – δ^{2}H for waters from the sampled Pleistocene aquifers according to Grabczak and Zuber (1983) classification

In all but one sample from the water supply intake in Skwierawy tritium concentration ranged from 5 to 21.7 T.U. Lack of tritium in the water intake in Skwierawy (Table 1) shows that the water infiltrated before 1953. The contribution of tritium from rainfalls (Felter and Nowicki, 1997; Dowgiałło and Nowicki, 1999) makes it possible to evaluate the time of water inflow to the intake in Kotówka Forestry. It ranges from 20 to 40 years. The other waters contain from 5 to 11 T.U. Such a concentration is close to the natural level before nuclear tests period, which was about 2 T.U. The tritium concentration in the water of several T.U. occurs also in the waters of present infiltration. The results of determination ^{18}O and deuterium indicate the present infiltration (Fig. 5).

Waters with the lowest residence time were encountered in the spring in Wąglikowice. Their heavier isotope composition (δ^{2}H = –64.8‰ and δ^{18}O = –9.05‰) is probably the result of a seasonal effect, related to the recharging from melting snow. It indicates that the groundwater circulation system of this spring is very shallow. Such interpretation is confirmed by low water temperature (11.5°C) measured in June 2003. In the other two springs water temperatures (Table 2) show fluctuations of 2 degrees (measurement in October 2002 and June 2003), which indicates shallow circulation of these waters.

Waters from the water supply intakes exploiting the aquifer under-tills are derived from a more reducing envi-

Table 2

Results of measurement of selected hydrochemical parameters as of June 11th, 2003 for the points of isotope sampling

No.	Sample point	Temperature [°C]	Eh [mV]	pH [1]	Mineralization [mg/L]
1	Skwierawy water-supply intake	8.8	–143	7.63	227
2	Skwierawy spring	8.3 *10.3*	21 *69*	7.63 *7.23*	193 *164*
3	Wąglikowice spring	11.5	28	7.2	392
4	Wąglikowice water-supply intake	10.0	–159	7.53	257
5	Kotówka spring	9.4 *7.1*	–89 *8*	7.47 *7.29*	223 *219*
6	Kotówka Forestry	9.8	–139	7.78	232

Results of measurement from October 2002 are given in italics

ronment. There are no visible differences in the chemical composition of these waters and waters originating from the sandur aquifer, which may indicate different residence times.

The results show present infiltration of waters both of the sandur aquifer and the under-tills aquifer. This indicates that the waters are vulnerable to antropopressure and the water residence time in the rocky environment is very short. Only in the case of Skwierawy intake, the water "age" is estimated as Holocene, but older than 50 years. The archival hydraulic head data indicate that it is the area of the recharge for a regional water circulation system. The aquifer occurring at the depth of about 50 m is separated from the surface by aquifuge comprising over 20 m thick bed of tills.

Maps of isotope composition of Holocene infiltration waters in Poland (d'Obyrn *et al*., 1997) show general conformity of δ^2H and δ^{18}O values, while deuterium δ^2H for the Wda and Mątawa River catchments varies from –68 to –70‰. Our research results show that the deutherium varies more widely from –64.8 to –72.2‰.

For δ^{18}O d'Obyrn *et al*. (1977) give the value –9.5‰ as the typical for the research area, but the results of our study show greater range between –9.05 and –10.01‰. It proves the diversity of water "ages" in this complex circulation system of Pleistocene multiaquifer formation. The new results provide more accurate data for the research area.

ESTIMATED TIME OF WATER INFILTRATION TOWARDS WATER-BEARING BED

The measure of the protecting role of soil against pollution is the time of the vertical migration of conservative pollution (Witczak and Żurek, 1997). This time can be estimated from water exchange time in the vertical profile, assuming the piston-flow model.

The reserves of the soil water in sandy soils of the northern part of the Wda and Brda River sandurs in the area of Przymuszewo Forestry Management was determined by Prusinkiewicz *et al*. (1981). They distinguished two types of soils: (1) automorphic dry soils, which cover most of the sandur area, and (2) more humid automorphic soils that occur in the terrains located about 1–3 m lower. The humidity of dry soils in one meter deep profile is low and equals 2–4%; for more humid soils it averages 4–8%. In the subsurface soil horizons low wettability and slow infiltration was stated after drought periods. This process is reversible (Prusinkiewicz *et al*., 1981).

The estimated time of water infiltration through unsaturated zone was calculated according to Witczak and Żurek formula (1997):

$$t_a = \frac{m_a \cdot w_o}{I_e}$$

where: t_a — time of water seepage through unsaturated zone [a], m_a — unsaturated zone thickness [m], w_o — average volumetric soil moisture [1], I_e — effective infiltration [m/a].

The thickness of unsaturated zone changes from 0.5 to 20 m, on average equalling about 5 metres. The mean value for a long-term effective infiltration, averaged for the whole area is 0.16 m/a. The results of the calculations of a seepage time for such parameters are given in the Table 3.

For sand horizons that occur below the soil profile, the soil volumetric moisture of 10% was assumed. In such a case the time of a water seepage through 1 metre of sands profile is 0.62 a, for the assumed infiltration value 0.16 m/a.

For the unsaturated zone 5 to 15 m thick, (including 2 metres of soil) the seepage time is 1.6 to 9 years. Shorter seepage times occur close to rivers and waterlogged areas.

Even smaller values of water vertical seepage time through unsaturated zone were obtained using Bindeman's formula modified by Macioszczyk (1999):

$$t_a = \frac{m_a \cdot w_o}{\sqrt[3]{\omega^2 \cdot k'}}$$

where: t_a — time of water seepage through unsaturated zone [d], m_a — thickness of unsaturated zone [m], w_o — soil moisture [1], ω — annual reaching infiltration [m/d], k' — coefficient of vertical permeability of unsaturated zone [m/d].

For the assumed coefficient of vertical permeability of unsaturated zone $k' = 86.4$ (as for sandy gravels) the calculated times is 0.3 to 3.6 year.

Table 3

Water seepage time through 1 metre of profile of soils that developed on the sandur sands

w_o [1]	0.02	0.03	0.04	0.06	0.08
t_a [a]	0.12	0.19	0.25	0.38	0.5

Table 4

Statistical parameters of mineralization and chlorides concentrations in the waters of the recharge and discharge zones of the sandur aquifer and inter-morainic aquifers

Conc. [mg/L]	n	geom. mean	Median	Min.	Max.	Perc. 16%	Perc. 84%	Range	Stand. dev.
RECHARGE ZONES									
TDS	32	113.8	108.0	34.9	472.5	61.9	210.9	437.6	103.8
Cl^-	32	2.3	1.6	0.90	14.80	0.9	6.3	13.9	4.0
DISCHARGE ZONES									
TDS	61	254.4	260.8	44	510.7	206.8	328.0	466.7	68.9
Cl^-	61	6.5	6.9	0.9	19.2	5.2	9.8	18.3	3.2
INTER-MORAINIC AQUIFERS									
TDS	105	348.5	325.7	171.5	1079.0	244.6	523.4	907.5	187.6
Cl^-	105	9.6	8.0	2.0	146.2	3.5	27.0	144.2	25.6

n — number of samples

The results of the above calculations (Table 3) confirm high vulnerability of sandur aquifer to pollution, where the time of inflow of the potential pollution toward the aquifer is lower than 10 years. Also the determination of tritium concentration in the sandur aquifer waters indicates that the water residence time is short and does not exceed 50 years.

SELECTED CHEMICAL INDICATORS IN WATER CIRCULATION SYSTEM — TDS, CL

The diversity of chemical components of waters in the studied area results mainly from antropogenic influence and natural changeability associated with water flow in the water-bearing system. The residence time of water in a rocky environment determines the degree of mineralization of these waters.

Large variation of chemical components, related to antropopressure, was minimized by choosing areas for detailed investigations in the forested catchments.

Mineralization (TDS) of waters and chloride concentration were analyzed as indicators of water chemistry. The measurement results for samples from the sandur aquifer were divided into two groups: (1) samples from the recharge areas (watershed zones, hollows without outflow) and, (2) samples from the discharge areas (mainly from springs). Comparison of TDS in both groups and the results of sampling of deeper inter-morainic aquifers (mainly the data from the MhP database) allowed to estimate the natural hydrochemical changeability (Table 4).

In the recharge zones, the mineralization values are significantly lower than in the drainage zones. They average 141 mg/L and usually range 62 to 211 mg/L. These are, hence, ultrafresh or fresh waters. The maximum values of TDS, over 380 mg/L, were recorded in the vicinity of peat bogs. The minimum value in that group (34.9 mg/L) was found in the depression without outflow in the Brzezianek catchment. It represents a typical value for rainfalls mineralization. It also shows that depressions without outflow have poorly mineralized waters, which mainly enrich in chemical elements when they flow in the aquifer.

Within the drainage areas the typical concentration of TDS ranged from 206 to 328 mg/L, and these are usually fresh waters. Sporadically (2 samples), TDS exceeded 400 mg/L, in the areas of organic deposits. Antropogenic influence (agriculture) can not be excluded in these areas.

Mineralization of waters increases in the next stage of flow and leakage towards the deeper aquifers. The increase is almost 100 mg/L in comparison to the mineralization of waters in the drainage areas.

On average, chlorides concentration in the recharge zones is 2.3 mg/L, almost three times lower than in the discharge areas. The maximum values of chlorides in the recharge areas does not exceed 20 mg/L, and is accompanied by the increased values of phosphates (0.4–0.6 mg/L) or sulfates (160 mg/L). They were recorded in the forested areas without visible pollution sources. The maximum value for the drainage areas of 19.2 mg/L was recorded in Sinowa Struga catchment, in the spring located 200 m from the bitumen road.

Slightly higher concentration of chlorides (3 mg/L more than their average concentration in the discharge areas of the sandur aquifer) was detected in waters of the inter-morainic aquifers.

The above results confirm that the TDS content increases along the flow path and that there is a normal hydrogeochemical zoning in the waters studied.

SUMMARY

The groundwaters of the sandur aquifer in the Wda and Mątawa River catchments are strongly susceptible to the pollution from the surface. The estimated time of seepage through the unsaturated zone does not exceed 10 years. The results of the isotope study, confirmed by field measurements and modelling show short water residence time in rocky sequences. The residence time ranges from several weeks to about 80 years for the sandur aquifer and the first inter-morainic aquifer. Longer residence time of about one thousand years characterises waters of aquifers deeper than 100 metres, separated from the surface by low permeability deposits.

The analysis of groundwater mineralization and chlorides concentration in the circulation system show increase of these parameters along water flow from recharge to discharge zones.

The average increase of mineralization is 140 mg/L. It further increases by 100 mg/L during the flow and penetration of groundwater towards the inter-morainic aquifers. Chlorides concentration increases almost three times along the flowpath. The lowest concentration of the dissolved solids was recorded in the depressions without outflow, where the values were similar to those in the rainfall waters.

The investigation results prove a natural connection of hydrodynamic and hydrochemical fields in the Wda and Mątawa River catchments.

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