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Quantification of anthropogenic impact on groundwater dependent terrestrial ecosystem using geochemical and isotope tools combined with 3-D flow and transport modeling

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Abstract

A dedicated study was launched in 2010 with the main aim to better understand the functioning of groundwater dependent terrestrial ecosystem (GDTE) located in southern Poland. The GDTE consists of a valuable forest stand (Niepolomice Forest) and associated wetland (Wielkie Bloto fen). A wide range of tools (environmental tracers, geochemistry, geophysics, 3-D flow and transport modeling) was used. The research was conducted along three major directions: (i) quantification of the dynamics of groundwater flow in various parts of the aquifer associated with GDTE, (ii) quantification of the degree of interaction between the GDTE and the aquifer, and (iii) 3-D modeling of groundwater flow in the vicinity of the studied GDTE and quantification of possible impact of enhanced exploitation of the aquifer on the status of GDTE. Environmental tracer data (tritium, stable isotopes of water) strongly suggest that upward leakage of the aquifer contributes significantly to the present water balance of the studied wetland and associated forest. Physico-chemical parameters of water (pH, conductivity, Na / Cl ratio) confirm this notion. Model runs indicate that prolonged groundwater abstraction through the newly-established network of water supply wells, conducted at maximum permitted capacity (ca. 10 000 m^3 d^{-1}), may trigger drastic changes in the ecosystem functioning, eventually leading to its degradation.

1 Introduction

There is a growing awareness among policy makers, legislators, water resources managers and researchers of the important environmental and socio-economic functions of Groundwater Dependent Ecosystems (GDE) reflected, among others, in the environmental legislation of the European Union (Kløve et al., 2011b; EC, 2000, 2006). Human needs and GDE appear as the two conflicting groundwater uses (Wachniew et al., 2014) which need to be managed in an integrated, multidisciplinary manner (Kløve et al., 2011b). Groundwater exploitation, climatic and land-use changes, pollution as

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well as other pressures on groundwater quantity and quality affect functions of GDE, yet the relationships between groundwater systems and the performance of dependent ecosystems are not fully understood (Kløve et al., 2011a, b).

The great diversity of GDEs stems from space- and time-variable availability of groundwater to ecosystem organisms. Various classifications of the GDEs (Hatton and Evans, 1998; Sinclair Knight Merz, 2001; Boulton, 2005; Pettit et al., 2007; Dresel et al., 2010; Kløve et al., 2011a; EC, 2011) reflect this diversity. The basic division includes the terrestrial (GDTE; e.g. wet forests, riparian zones, wetlands) and aquatic (GDAE; e.g. springs, lakes, rivers with hyporheic zones and lagoons) groundwater dependent ecosystems. The extreme examples of these two classes are communities that depend on the capillary fringe and the communities composed of the floating or submerged vegetation (Pettit et al., 2007). Wetlands constitute a specific category of GDEs as they are sometimes considered to belong to the aquatic GDEs (EC, 2003) or to form a separate class (Boulton, 2005; Bertrand et al., 2012).

Sustainable management of GDEs requires that their vulnerability to anthropogenic impacts is assessed (Wachniew et al., 2014). A conceptualization of GDE vulnerability must include understanding of two factors: the degree of ecosystem reliance on groundwater (Hatton and Evans, 1998) and groundwater availability to the ecosystem (Sinclair Knight Merz, 2001). Consequently, a substantial component of conceptual models, on which vulnerability assessments are based (EC, 2010) is related to the identification of the origin and pathways and quantification of groundwater fluxes to GDEs.

The presented study was aimed at comprehensive investigation of groundwater dependence of a terrestrial ecosystem (GDTE) consisting of valuable forest stand and associated wetlands. In contrast to many other cases where wetlands primarily depend on shallow groundwater resources, the central hypothesis of the presented work was that the studied GDTE relies also to a significant extent on groundwater originating from deeper aquifer layers. Thus, on the one hand, the work was focusing on identification of flowpaths and water ages of the deeper aquifer in the area of the investigated

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GDTE. On the other hand, its connectivity with the shallow Quaternary aquifer was probed using various methods and tools available. An important additional objective of the presented work was quantification of the risk to the studied GDTE associated with operation of nearby cluster of water-supply wells exploiting deeper aquifer layers.

The following tools were applied to address the problems outlined above: (i) environmental tracers (stable isotopes of water – ^{2}H and ^{18}O; tritium (^{3}H) and isotopes of carbon (^{14}C, ^{13}C)), (ii) physico-chemical parameters of groundwater and surface water supplemented by hydrometric measurements, (iii) geophysical prospecting (GPR (Ground Penetrating Radar) method and DC (Direct Current) resistivity sounding), (iv) Geoprobe® technology enabling vertical stratification of environmental tracers and water chemistry within the Quaternary cover of the studied aquifer to be quantified, (v) geochemical modeling (PHREEQC and NETPATH), and (vi) 3-D flow and transport modeling.

The presented study focusing on the interaction between the Bogucice Sands aquifer and the associated GDTE is a follow-up of the earlier work concerned mostly with the dynamics and geochemical evolution of groundwater in this aquifer (Zuber et al., 2005; Witczak et al., 2008; Dulinski et al., 2013).

2 The study area

The Bogucice Sands aquifer and the associated GDTE are located in the south of Poland (Fig. 1), in the vicinity of Krakow agglomeration. The aquifer covers the area of ca. 200 km^2 and belongs to the category of major groundwater basins (MGWB) in Poland (Kleczkowski et al., 1990). Climate of the study area has an intermediate character between oceanic and continental, with the mean annual temperature of 8.2 °C and annual precipitation rate fluctuating around 700 mm. The mean annual evapotranspiration is equal 480 mm and the runoff reaches 245 mm. The recharge of groundwater is in the order of 8–28 % of annual precipitation. Urban areas and villages cover approximately 20 % of the aquifer surface. The remaining part is mainly agriculture (60 %) and forestry (20 %). In the eastern part of the aquifer forests and wetlands dominate (80 % of area).

The Bogucice Sands aquifer (MGWB 451) is located on the border of the Carpathian Foredeep Basin and belongs to the Upper Badenian. It is underlined by impermeable clays and claystones of the Chodenice Beds (Porebski and Oszczypko, 1999). To the north, the aquifer is progressively covered by mudstones and claystones with thin sandstone interbeds. Paleoflow directional indicators suggest proximity to deltaic shoreline. In the south, near the deltaic mouth, there are outcrops of Bogucice Sands, covered only by thin Quaternary sediments (sands, loesses and locally boulder clays). To the north, the aquifer is deeper and confined by marine mudstones and claystones. The mean total thickness of the aquifer is approximately 100 m, with two water-bearing horizons (cf. Fig. 1).

The mineralogy of the aquifer material is highly heterogeneous and consists of quartz, calcite, dolomite, K-feldspar, plagioclase, muscovite, biotite, glaukonite, organic matter, Fe-feldspar and carbonate cement. Typical carbonate contents are 3–10 % in sands and 25–30 % in sandstones. They are represented by cements and calcareous debris of marine fauna. Minor components are represented by Al_2O_3, Fe_2O_3, CaO, MgO, MnO, Na_2O, K_2O and P_2O_5, whereas the main trace components comprise Sr, Ba, Zn, Mo, Co, Ni, V and Rb (Porebski and Oszczypko, 1999).

The hydrogeology of the aquifer can be considered in three areas: (i) the recharge area related to the outcrops of Bogucice Sands in the south, (ii) the central confined area generally with artesian water, and (iii) the northern discharge area in the Vistula River valley. Groundwater movement takes place from the outcrops in the south, in the direction of the Vistula River valley where the aquifer is drained by upward seepage through semi-permeable clayey formations of Neogene Grabowiec Beds. In pre-exploitation era, artesian water existed on entire confined area. Intensive exploitation decreased the water table in some areas causing downward seepage. The upper, shallow aquifer located in Quaternary sediments is related to the drainage system of Vistula River and its tributaries. Unsaturated zone consists mainly of sands and loess of

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variable thickness, from a fraction of meter in wetland areas to approximately 30 m in the recharge area of the deeper aquifer layers.

The principal economic role of the aquifer is to provide potable water for public and private users. Estimated disposable resources of the MGWB 451 are 40 000 $m^3 d^{-1}$ with typical well capacities of 4–200 $m^3 h^{-1}$ (Kleczkowski et al., 1990; Witczak et al., 2008). Hospitals and food processing plants also exploit some wells. Yield of the aquifer is insufficient to meet all present and emerging needs and, as a consequence, licensing conflicts arise between water supply companies and industry on the amount of water available for safe exploitation.

The recharge area of the deeper aquifer and the shallow phreatic aquifer associated with the Quaternary cover is vulnerable to diffuse sources of pollution from industrial emissions (big metallurgical plant in the north-west and numerous local enterprises). Point sources of pollution may also exist due to disposal of urban and rural wastes, including landfills and farm sources. There is also some evidence of contamination from a linear source of pollution (contaminated river draining large municipal landfill located close to the southern border of the aquifer).

Eastern part of the Quaternary aquifer is occupied by the Niepolomice Forest. This is relatively large (ca. 110 km^2) forest complex. This relict of once vast forests occupying southern Poland is protected as a Natura 2000 Special Protection Area "Puszcza Niepołomicka" (PLB120002) which supports bird populations of European importance. Additionally, a fen in the western part of the forest comprises a separate Natura 2000 area (Torfowisko Wielkie Błoto, PLH120080), a significant habitat of endangered butterfly species associated with wet meadows (Fig. 2). The Niepolomice Forest contains also several nature reserves and the European bison breeding centre and has important recreational value as the largest forest complex in the vicinity of Krakow agglomeration.

Depth to water table in the study area is generally shallow, with wetlands and marshes occurring in several parts of the Niepolomice Forest. The dependence of Niepolomice Forest stands on groundwater is enhanced by low available water capacity

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and low capillary rise of the soils supporting the forest (Łajczak, 1997; Chełmicki et al., 2003). Depth to water table was used as a basis for defining an index quantifying dependency of the Niepolomice Forest on groundwater. Three classes of the GDTE susceptibility to changes of water table were proposed: (i) class A – very strongly dependent (depth of water table ranging from 0.0–0.5 m), (ii) class B – strongly dependent (0.5–2.0 m), and (iii) class C – weakly dependent (> 2.0 m). Forest stands growing on areas where depth to water table exceeds 2 m utilize mostly soil moisture and are weakly dependent on groundwater level fluctuations. Forest stands on areas with shallower water table are more susceptible to changes in groundwater level, regardless of their direction. It should be noted that groundwater conditions in the Niepolomice Forest have been affected by land improvement carried out mostly after the Second World War and by forest management (Łajczak, 1997; Lipka, 1989; Lipka et al., 2006).

The presented study was focused on the western part of Niepolomice Forest, where Wielkie Bloto fen is located (Fig. 2). Due to artesian conditions prevailing in the area and relatively thin clay layer separating Neogene aquifer layers from the shallow Quaternary aquifer, the question arises whether upward seepage of the deeper groundwater may significantly contribute to the water balance of the investigated GDTE. In July 2009 a cluster of six new water-supply wells (Wola Batorska wellfield) exploiting deeper aquifer layers has been set up close to the northern border of Niepolomice Forest (wells Nos. 44–49 in Fig. 2) and there is a growing concern that ongoing exploitation of this new wellfield may lead to lowering of water table in the western part of Niepolomice Forest area and, as a consequence, trigger drastic changes of this valuable groundwater dependent ecosystem (Fig. 3).

In order to quantify the dynamics of groundwater flow in the Bogucice Sands aquifer underlying the western part of Niepolomice Forest and the Wielkie Bloto fen, physicochemical parameters and concentrations of environmental tracers (stable isotopes of water, tritium, radiocarbon) were measured in wells located in the study area. Also, the Dluga Woda stream draining the area of Wielkie Bloto fen (Fig. 2) was monitored over the period of two years (flow rates, stable isotopes and tritium content, chemistry). To detect potential diffusive upward discharge of deeper groundwater, Geoprobe® sampling of water from different levels of the shallow phreatic aquifer was performed (cf. Fig. 2). Geoprobe® survey was supplemented by geophysical measurements (GPR, DC resistivity) aimed at delineating the position of peat layers and claystone layers underlying the area of Wielkie Bloto fen. Dedicated modeling runs of the existing 3-D flow and transport model of the Bogucice Sands aquifer were also made to investigate the possible impact of the newly established wellfield on groundwater flow regime and evolution of hydraulic heads in the study area.

3 Materials and methods

Tritium (^{3}H) and radiocarbon (^{14}C) concentrations in the analyzed groundwater samples (water and total dissolved inorganic carbon pool, respectively) were measured at the AGH University of Science and Technology in Krakow by electrolytic enrichment followed by liquid scintillation spectrometry for tritium, and benzene synthesis followed by liquid scintillation spectrometry for ^{14}C. Tritium concentrations are reported in tritium units (T.U.). (1 T.U. corresponds to the ratio ^{3}H/^{1}H equal 10^{-18}). Radiocarbon content is reported in percent of modern carbon (pMC), following recommendations of Stuiver and Polach (1977) and Mook and van der Plicht (1999). Stable isotope composition of water (δ^{18}O, δ^2H) and TDIC pool (δ^{13}C) was determined in the same laboratory by dual-inlet isotope-ratio mass spectrometry and reported on V-SMOW and V-PDB scales (Coplen, 1996). Typical uncertainties of ^{3}H, ^{14}C, δ^{18}O, δ^2H and δ^{13}C analyses were in the order of 0.5 T.U., 0.7 pMC, 0.1, 1 and 0.1 ‰, respectively. Dissolved carbonates in the analyzed groundwater samples were precipitated in the field from ca. 60 L of water following the established procedures (Florkowski at al., 1975; Clark and Fritz, 1997).

Chemical composition of groundwater samples collected in the recharge area was modeled using PHREEQC (Version 2.18) geochemical code (Parkhurst and Appelo, 1999). Piston-flow radiocarbon ages of groundwater in the confined part of the studied system were calculated for using NETHPATH code (Fontes et al., 1979; Plummer et al., 1994).

Geoprobe® direct push device (Model 420M) was used to perform vertical profiling of the Quaternary cover in the area of Wielkie Bloto, combined with sampling of water at different depths (cf. Fig. 2). Water samples were collected at GP1, GP3 and GP4 sites. Site GP2 did not yield enough water for sampling. In addition, soil cores were collected at GP1, GP2 and GP3 sites. PCV tubes were installed in GP1, GP2 and GP3 for subsequent observations of water table.

Field procedures for hydrochemical sampling were similar to those described by Salminen et al. (2005). Unfiltered water was collected in 500 mL polyethylene bottles for major ion analysis. Filtered water was acidified using HNO_3 to $pH < 2$ and collected to new hardened polyethylene 100 mL bottles for major, minor and trace components. For pH and Eh field determinations, two laboratory calibrated instruments were used. They were immerged in the pumped water until equilibrium was reached and minimal difference between both instruments was recorded. Then, mean value of both readings was taken as accepted value. Alkalinity was measured in the field by titration method. Inductively-coupled plasma mass spectrometry (ICP-MS) and other routine methods were used for determinations of chemical composition of water samples collected during the study (water-supply wells, Dluga Woda stream, Geoprobe® samples). Isotope and chemical data were also obtained for the Anna spring (No. 52 in Fig. 2) located in the forest, east of the Wielkie Bloto fen. In fact, existence of this spring is linked to badly liquidated well drilled in 1970s for geophysical prospecting. It was tapping the Neogene strata of the Bogucice sands aquifer. Active flow of the Anna spring indicates that artesian conditions are still prevailing in the Wielkie Bloto area.

Samples for chemical and isotope analyses of the Dluga Woda stream were collected at gauge station G (Fig. 2) over the two-year period, from August 2011 till August 2013, in roughly monthly intervals. The purpose of this monitoring activity was the identification and quantification of the expected contribution of the upward seepage from the Bogucice Sands aquifer to the total discharge of the Dluga Woda stream

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draining the Wielkie Bloto area. Initially, both the stages and flow rates of the Dluga Woda were recorded. They provided the basis for constructing the rating curve of the stream. Subsequently, pressure transducer was installed for continuous stream-level monitoring, starting from June 2012. Discharge hydrograph of the Dluga Woda stream was then generated for entire observation period.

In order to detect hydraulic response of the aquifer to operation of new pumping wells located in Wola Batorska, systematic observations of hydraulic head in well No. 32, situated ca. 1 km north of the Wola Batorska wellfield were performed. Initially, the depth of water table was measured manually using sounding device. Starting from 4 July 2012, automatic recording of the position of water table using pressure transducer was performed. Well No. 32 maintained artesian conditions prior to establishing the cluster of the new water-supply wells.

The MODFLOW-2000 code for groundwater flow simulation (Harbaugh et al., 2000) as well as MT3DMS code (Zengh and Wang, 1999) for modeling mass transport, both incorporated in the Visual MODFLOW 2011.1 Pro (Schlumberger Water Services, 2011) were used to construct a numerical model of the Bogucice Sands aquifer. The finite-difference grid for the flow and transport calculations consisted of 5 layers with 27 225 rectangular cells (250 m × 250 m, 72 rows and 129 columns). The longitudinal dispersivity (α_L) was assumed to be 50 m. Although the selected size of computational cells did not satisfy the criterion $\Delta x < 2\alpha_L$ required for avoiding the numerical dispersion (Kinzelbach, 1986), its influence was reduced by applying the total-variation-diminishing method (TVD – Zheng and Wang, 1999; Hill and Tiedeman, 2007). The MODFLOW River Package was used to simulate the exchange of water between the aquifer and the surface water with head-dependent seepage interaction. The agreement between calculated and observed heads was satisfactory. Hydraulic heads were maintained in subsequent calibrations of the transport model with the aid of tracer data (Zuber et al., 2005; Witczak et al., 2008). In this process the hydraulic conductivity and the aquifer thickness were modified, without changing the transmissivity. The changes of aquifer thickness were constrained by available geological information on the extent

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of water-bearing horizons. Three water-bearing layers were distinguished in the model: the shallow Quaternary aquifer and two Neogene aquifers. To investigate possible impact of the newly-established Wola Batorska wellfield on groundwater flow regime in the study area, transient flow simulations were performed with quarterly changes of well discharge during the period July 2009–September 2013.

Surface DC resistivity sounding surveys were used as a reconnaissance tool to assess the depth and thickness of clay and claystone layers underlying the shallow aquifer in the area of Wielkie Bloto fen (Fig. 2) and controlling the upward seepage of water from the Bogucice Sands aquifer. The Vertical Electrical Sounding (VES) surveys with the Schlumberger array (Koefoed, 1979) were applied at 11 locations. Quantitative interpretation of the apparent resistivity as a function of electrode spacing (VES curve) was performed with the aid of RESIS and IPI2WIN software (Mościcki, 2005; Bobachev, 2010).

Ground Penetrating Radar (GPR) method (Daniels, 2004) was applied to assess the thickness of peat layers in the area of Wielkie Bloto fen. This method has been successfully used in the past to delineate location of peat layers in various environments (e.g. Warner et al., 1990; Slater and Reeve, 2002; Plado et al., 2011). Short electromagnetic pulse generated by transmitting antenna of georadar propagate in the shallow subsurface and reflects back from the geological strata which differ in relative dielectric permittivity (ε_r). Peat layers are characterized by very high ε_r values (60–75) while sandy layers show ε_r values in the order of 10–15, depending on actual water content. The GPR surveys were performed with ProEx System (MALA Geoscience), using offset configuration with co-polarized 250 MHz centre frequency shielded antenna. Seven separate GPR profiles with the total length of approximately 1400 m were obtained (cf. Fig. 2).

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4 Results and discussion

The results of comprehensive investigations carried out during the period 2010–2013 in the study area are presented in the following sections. They comprise the results of georadar and geoelectric survey of the area of Wielkie Bloto fen leading to new insights with respect to structure and extension of the Quaternary cover; environmental tracer and water chemistry data leading to quantification of timescales of groundwater flow in the deeper aquifer underlying Niepolomice Forest and Wielkie Bloto fen; the data quantifying isotope and chemical stratification in the shallow aquifer in the area of Wielkie Bloto fen; the assessment of water balance of the Dluga Woda watershed and the results of 3-D numerical modeling of groundwater movement in the deeper aquifer and its modification due to continued abstraction of groundwater through the Wola Batorska wellfield.

4.1 Delineation of the Quaternary cover in the area of Wielkie Bloto fen

Interpretation of the apparent resistivity obtained from VES surveys was performed for eleven sections located near GP1, GP3 and GP4 sites. The interpreted values of resistivity (ρ_{int}) obtained on the basis of VES curves are presented in Fig. 4 in the form of depth profiles of ρ_{int} along 11 studied sections (S01–S11, Fig. 2). The selection of VES curves was aided by additional measurements performed in the vicinity of GP2 site which allowed to select fixed resistivity value (21 Ωm) representing clay layers in the profile. It is worth to note that the clay layer (blue) seen in the upper panel of Fig. 4 is very thin in some places (less than ca. 1 m), with possible discontinuities facilitating hydraulic contact of deeper aquifer layers with the shallow Quaternary aquifer. The interpreted resistivity of the strata lying above the clay layer roughly corresponds to sand with high water content. The uppermost layer is characterized by distinctly higher resistivity which can be linked to the presence of peat (see discussion below).

The total length of GPR profiles obtained in the area of Wielkie Błoto exceeded 1400 m. Here we discuss only one echogram representing the distance of

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approximately 200 m (profile P1 in Fig. 2). Field results of GPR survey were subject of dedicated data processing aimed at improving the signal-to-noise ratio and phase correlation. This processing included equalization of the average level of the signal to zero, time-variable amplification, filtering in time domain and filtering in frequency domain, surface averaging and others. Based on the data available for the soil core collected at GP1 site, electromagnetic wave velocity in peat was set at $v = 3.6\,\mathrm{cm\,ns^{-1}}$. This value was then used to construct the depth scale of the echogram presented in the lower panel of Fig. 4. Peat layer located between ca. 0.4 and 1.2 m can be distinguished. The boundary located at approximately 0.4 m depth can be linked to degradated peat (moorsh), also visible in the vertical cross-section shown in the lower panel of Fig. 2. Due to high attenuation of the signal, the border between sands and clays seen in the apparent resistivity profile presented in the upper panel of Fig. 4 could not be identified.

4.2 Geochemical evolution and age of groundwater in the Bogucice Sands aquifer

Table 1 summarizes environmental tracer data obtained for water samples collected in the production wells of the Bogucice Sands aquifer and during Geoprobe® survey of the Quaternary cover in the area of Wielkie Bloto fen. The corresponding physico-chemical parameters are summarized in Table 2.

Deuterium and oxygen-18 isotope composition of water in the production wells located the study area and tapping the Bogucice Sands aquifer is shown in Fig. 5a in δ^2H–δ^{18}O space, against the background of global and local meteoric water lines and the mean isotopic composition of modern recharge. As seen in Fig. 5a, all wells located in the eastern part the recharge area (Szarów wellfield, wells Nos. 11, 12, 22, 23, 24) cluster around the mean isotopic composition of modern recharge. All of them contain tritium, testifying recent origin of groundwater in this area. Radiocarbon content was measured in two wells (Nos. 11, 12) and shows values around 64 pMC. Stable isotope composition of water in well No. 42, located ca. 1 km north of the Szarów wellfield also belongs to this cluster of points in Fig. 5a. This water is devoid of tritium and reveals

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reduced radiocarbon concentration (ca. 48 pMC) pointing to its pre-bomb (Holocene) age.

Stable isotope composition of water in wells belonging to the newly established well-field in Wola Batorska reveals systematic shift towards more negative δ^2H and δ^{18}O values, clearly indicating recharge in colder climate (Rozanski, 1985; Zuber et al., 2004). This groundwater does not contain tritium and reveals low radiocarbon content, in the order of few pMC, also suggesting glacial age of this water (see discussion below). In well No. 32, located ca. 1 km north of the Wola Batorska wellfield, the radiocarbon content of TDIC reservoir drops below the detection limit ($<$ 0.7 pMC) suggesting significant increase in groundwater age, while maintaining characteristic stable-isotope signature of this water indicating recharge in cold climate (Fig. 5). In contrast, stable isotope composition of water in well No. 16, located ca. 2 km south-west of Wola Batorska wellfield (cf. Fig. 2) reveals higher radiocarbon content (32.1 pMC), lack of tritium and stable isotope composition of water suggesting its Holocene origin. The same concerns Anna spring (No. 52) located in the forest, east to Wielkie Bloto fen.

Waters in the recharge zone of the investigated part of Bogucice Sands aquifer (wells Nos. 11, 12, 22, 23, 24) reveal almost neutral, uniform pH values between 7.00 and 7.13 and are dominated by HCO_3^-, Ca^{2+}, and Mg^{2+} ions (Table 2). They show average TDIC content around 7.2 mmol L^{-1}. Saturation indices with respect to calcite are close to zero indicating full development of carbonate mineralization. The partial pressure of CO_2 controlling the observed carbonate chemistry calculated from the available chemical data, varies between 0.018 and 0.032 atm. These waters contain elevated concentrations of sulphate ions, most probably originating from industrial pollution of regional atmosphere during the second half of the XX century.

Waters exploited by the Wola Batorska wellfield (wells Nos. 44–49) are dominated by HCO_3^-, Na^+ and Cl^- ions. The TDIC content is reduced by ca. 0.3 mmol L^{-1} when compared to waters from the recharge area. The Ca^{2+} and Mg^{2+} content is also reduced, while significantly higher Na^+ concentrations are recoded (Table 2). These

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waters reveal elevated pH values (8.07–8.82) and are supersaturated with respect to both calcite and dolomite.

The observed patterns of geochemical evolution of groundwater in the studied part of the Bogucice Sands aquifer reflect its marine origin. Gradual freshening of the aquifer continuing since the Miocene involves ion exchange processes between the solution and the aquifer matrix. Waters dominated by Ca^{2+} and Mg^{2+} ions, while penetrating the aquifer, exchange those ions in favor of Na^{+} ions which are released to the solution. Presence of this process is supported by Fig. 6 which shows the relationship between deficit of Ca^{2+} and Mg^{2+} ions with respect to the sum of HCO_3^{-} and SO_4^{2-} ions and the excess of Na^{+} and K^{+} ions over the Cl^{-} ions. The data points in Fig. 6 cluster along charge equilibrium line confirming that chemical evolution of groundwaters in the investigated part of Bogucice Sands aquifer is dominated by cation exchange processes.

Inverse modeling of radiocarbon ages of groundwater in wells Nos. 16, 32, 42, 44, 46, 49 and 52 was performed using NETPATH code. First, input solution representing recharge area in the investigated part of Bogucice Sands aquifer was calculated. The calculations were based on chemical and isotope data available for wells Nos. 11, 12, 22, 23 and 24. Equal contribution of waters from those wells to the final solution was assumed. Carbon isotope parameters of the input solution were calculated as the mean values of respective parameters in individual waters contributing to the final solution, weighted by the size of carbonate reservoirs (TDIC). The calculated input carbon isotope values characterizing TDIC reservoir in the solution were $\delta^{13}C = -13.4$ ‰, $^{14}C = 64.1$ pMC. The solution determined by this way was then used as the initial solution in inverse calculations using NETPATH code. Parameters used in the calculations (constraints and phases) and the resulting radiocarbon ages are presented in Table 3. The calculated radiocarbon ages vary from ca. 2 ka for water in well No. 42 located close to the recharge area of the aquifer, up to the age in excess of ca. 36 ka for well No. 32 located in most distant, northern part of the aquifer. Radiocarbon ages of three wells representing Wola Batorska wellfield (Nos. 44, 46 and 49) reveal radiocarbon ages between 25 and 34 ka, confirming glacial origin of water in this wellfield, already apparent from the stable isotope data presented in Fig. 5. The Anna spring and well No. 16 reveal Holocene groundwater ages.

It is apparent from the above discussion that groundwater which eventually penetrates the confining layer of the Bogucice Sand aquifer and reaches the shallow Quaternary aquifer in the area of Wielkie Bloto fen should have distinct chemical and isotopic characteristic. In particular, is should be characterized by reduced Ca^{2+} and Mg^{2+} and elevated Na^{+} contents when compared to young groundwater present in the Quaternary cover. It should also have elevated pH values (around 8). This water does not contain tritium and is most probably of Holocene age. Holocene age of this water implies that its stable isotope signature will be non-distinguishable from the mean isotopic composition of present-day precipitation in the area.

4.3 Isotope and chemical stratification of shallow aquifer in the area of Wielkie Bloto fen

To investigate isotopic and chemical stratification of groundwater in the shallow Quaternary aquifer underlying Wielkie Bloto fen, and to detect eventual contribution coming from the Bogucice Sands aquifer, a dedicated sampling campaign using Geoprobe® device has been carried out in October 2011. Isotope and chemical data obtained for water samples collected during this campaign are summarized in Tables 1 and 2, respectively.

As seen in Fig. 5b and Table 1, stable isotope composition of Geoprobe® water samples varies significantly with depth and location. The deepest points cluster around mean isotopic composition of local precipitation suggesting that the observed variability of δ^2H and δ^{18}O in the upper portions of the profiles stems from strong seasonality of δ^2H and δ^{18}O signal in local precipitation, surviving in the upper part of the Quaternary cover and converging towards the mean isotopic signature of the local precipitation at the bottom of this cover. Vertical profiles of tritium content and selected chemical parameters are summarized in Fig. 7. A distinct reduction of tritium content with depth, accompanied by increase of pH, conductivity and concentration of major ions (Cl and Na)

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is apparent. The chemical data of Geoprobe® water samples are also plotted in Fig. 6. They are consistent with geochemical evolution of groundwater in the Bogucice Sands aquifer, discussed in the previous section. Only one data point (GP1-C), which represents the deepest level reached by the Geoprobe® device in the Quaternary aquifer (4.6 m), deviates significantly from the trend represented by charge equilibrium line in Fig. 6. It should be noted that there were serious difficulties in obtaining this particular water sample and the chemical analyses might not be fully representative in this case.

The observed increase of pH, conductivity and concentration of major ions (Cl and Na) with depth in the shallow Quaternary aquifer, accompanied by reduction tritium content, strongly suggest that upward seepage of groundwater from Bogucice Sands aquifer indeed takes place in the area of Wielkie Bloto.

4.4 Water balance of the Dluga Woda catchment

The catchment of Dluga Woda stream comprises Wielkie Bloto fen and adjacent parts of the Niepolomice Forest (cf. Fig. 2). Physico-chemical parameters of the stream water (flow rate, temperature, pH, major ions, stable isotopes of water and tritium content) have been monitored on monthly basis over the two-year period (August 2011–August 2013) with the main aim to detect and quantify the possible contribution of groundwater seeping from the Bogucice Sands aquifer to the shallow aquifer in the total discharge of the Dluga Woda stream. The results are summarized in Table 4.

Figure 8 shows temporal variations of δ^{18}O and tritium content in the Dluga Woda stream presented against the background of seasonal variability of those parameters in local monthly precipitation. It is apparent from Fig. 8a that strong seasonality of δ^{18}O in precipitation survives during transport through the watershed and is visible in the Dluga Woda δ^{18}O record. However, the amplitude of the seasonal changes of δ^{18}O is significantly reduced: from approximately 5 ‰ seen in precipitation to ca. 1.5 ‰ in the stream water. Maloszewski et al. (1983) have shown that the mean transit time of purely sinusoidal isotope input signal through a hydrological system characterized by an exponential distribution of transit times can be expressed by the following equation:

$$\mathrm{MTT} = \frac{1}{2\pi}\sqrt{\left(\frac{A_{\mathrm{IN}}}{A_{\mathrm{OUT}}}\right)^2 - 1} \tag{1}$$

where MTT is the mean transit time of water (in years), A_{IN} and A_{OUT} are the amplitudes of input and output isotope signals. The assumption about exponential distribution of transit times of water seems to be adequate to describe transport of precipitation input through a watershed. If the observed amplitudes of the input (precipitation) and output (stream) δ^{18}O curves are inserted in the Eq. (1) the resulting mean transit time of water through the catchment of Dluga Woda stream is 3.2 months.

Figure 8b shows the tritium content in local precipitation and in the Dluga Woda stream during the observation period. Weighted mean tritium content in precipitation (9.8 T.U.) appears to be significantly higher than that of the Dluga Woda stream water (6.9 T.U.). Assuming that the total discharge of Dluga Woda is composed of fast (MTT = 3.2 months) and slow component devoid of tritium, the contribution of this old component can be easily assessed from first-order calculations based on tritium balance and is equal ca. 30 %. A more appropriate approach based on lumped-parameter modeling (Maloszewski and Zuber, 1996) of tritium transport through the watershed of Dluga Woda stream confirms this rough assessment. The insert of Fig. 8b shows the results of lumped-parameter modeling of tritium record in the Dluga Woda stream using the following prescribed parameters: (i) the mean transit time of water in the catchment equal 3.2 months, (ii) exponential distribution of transit times, and (iii) the contribution of tritium-free component in the Dluga Woda discharge equal to zero and 30 %, respectively ($\beta = 0.0$ and 0.3 in the insert figure). It is obvious that the assumption of 30 % contribution of tritium-free component to the total discharge of Dluga Woda stream fits the experimental data much better than the case neglecting this component. In addition, it should be noted that the difference between the weighted mean δ^{18}O in precipitation for the period January 2011–December 2013 (−8.61 ‰) and the mean

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^{18}O content of the Dluga Woda stream (−8.84 ‰) can be easily reconciled if 30 % contribution of the old component ($\delta^{18}O$ = −9.55 ‰, represented by the Anna spring) in the total discharge is taken into account.

Hydrograph of the Dluga Woda stream constructed for the period July 2012–June 2013 is shown in Fig. 9. It reveals large variability of the flow rate. The measured values varied from ca. 1.5 $L\,s^{-1}$ (31 August 2012) to 180 $L\,s^{-1}$ (8 June 2013) (cf. Table 4) while the corresponding values derived from the rating curve were equal 0.8 $L\,s^{-1}$ (26 August 2012) and over 250 $L\,s^{-1}$ (26 June 2013). Persisting low flows during August and September 2012 resulted from lower than normal precipitation in the preceding months; during the period September 2011–August 2012 they reached only 300 mm, to be compared with long-term annual mean equal approximately 700 mm.

The hydrograph shown in Fig. 9 allows quantitative assessment of the Dluga Woda baseflow. It was derived as the mean monthly low flow (MMLF) according to Wundt (1953). The MMLF value for the period July 2012–June 2013 was equal 46 $L\,s^{-1}$ (Fig. 9).

Large fluctuations of Dluga Woda discharge rates are linked with substantial variability of the physico-chemical parameters of the stream water (cf. Table 4 and Fig. 10). The relationships between SEC, pH, Na content, Na/Cl molar ratio and the discharge rate of Dluga Woda shown in Fig. 10 clearly indicate that for the flow rates lower than ca. 14 $L\,s^{-1}$ the physico-chemical parameters of water attain distinct values (SEC > 600 $\mu S\,cm^{-1}$; pH > 7.8; Na > 30 $mg\,L^{-1}$, Na/Cl ratio higher than 1.3) not observed for higher flow rates. In addition, these low flow rates were accompanied by low tritium contents in the stream water. High pH values and high Na/Cl molar ratios in groundwater are typical for gradual freshening of sediments deposited in marine environment (Appelo and Postma, 2005). This strongly suggest that discharge of Dluga Woda stream is dominated at very low flow rates (ca. < 14 $L\,s^{-1}$) by waters seeping through clayey sediments separating Neogene water-bearing layers of the Bogucice Sands aquifer from the Quaternary shallow phreatic aquifer. It is worth to note that the flow rate in the order of 14 $L\,s^{-1}$ constitutes approximately 30 % of the MMLF value

46 L s^{-1}, remarkably close to the percentage contribution of the tritium-free component in the total discharge derived from tritium data.

4.5 3-D flow and transport modeling of groundwater flow in the area of Wielkie Bloto fen

The 3-D flow and transport model of entire Bogucice Sands aquifer was calibrated with the aid of environmental tracer data (Zuber et al., 2005; Witczak et al., 2008). In the framework of the presented study this model was used to simulate the response of regional flow field to groundwater abstraction by the newly-established Wola Batorska wellfield.

Figure 11 summarizes the measurements of the position of hydraulic head in well No. 32 located 1075 m north of the center of Wola Batorska wellfield (cf. Fig. 2). Hydraulic head in this well has changed radically after groundwater abstraction was initiated in July 2009. Initially slightly artesian, it has stabilized around 14 m below the surface after four years of the operation of the new wellfield. Figure 11 shows also changes of the hydraulic head in well No. 32 simulated with the aid of 3-D flow model forced by quarterly mean pumping rates of the entire wellfield. The agreement between modeled and observed evolution of hydraulic head is satisfactory, particularly in the second part of the observation period. Complex, multi-layered structure of the modeled aquifer is probably the reason of significant deviations between measured and simulated heads during the initial stages of the operation of Wola Batorska wellfield.

The ratio of transmissivity to specific storage is a measure of the ability to transmit differences in hydraulic heads by groundwater systems (Alley et al., 2002; Sophocleous, 2012). The response of confined aquifers to changes in groundwater abstraction rates is relatively fast. Characteristic timescale of this response can be assessed using approximate expression proposed by Alley et al. (2002):

$$T^* = \frac{S_S \cdot L_c^2}{K} \tag{2}$$

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where T^* is the hydraulic response time for the basin (in days), S_S is specific storage (m^{-1}), L_c is characteristic length (m) of the basin, and K is hydraulic conductivity ($m\,d^{-1}$). The response time of horizontal flow in the Bogucice Sands aquifer between the Wola Batorska wellfield and the observation well (No. 32) was assessed using Eq. (2). With specific storage $S_S = 2.5 \times 10^{-5}\,m^{-1}$, derived from fitting of the measurement data shown in Fig. 11, the characteristic length L_O equal 1075 m and the hydraulic conductivity K set at $0.8\,m\,d^{-1}$, the first-order assessment of the hydraulic response time of Bogucice Sands aquifer in the vicinity of Wola Batorska wellfield, leads to the T^* value equal to approximately 36 days.

In reality, the response time of the multi-layer flow system modeled below the Wielkie Bloto fen is far more complex. The impact of groundwater abstraction by the Wola Batorska wellfield, with the current mean pumping rate of ca. $3800\,m^3\,d^{-1}$ is already seen in the flow field of the deepest model layer but is still negligible in the upper parts of the aquifer. Presence of artesian flow in the Anna spring confirms this notion. This will, however, change in future when more intense abstraction of groundwater will take place. This future impact is illustrated in Fig. 12 which shows the simulated flow field of the aquifer beneath the Wielkie Bloto fen for the present abstraction rates (ca. $3800\,m^3\,d^{-1}$) and for the envisaged exploitation of the Wola Batorska wellfield with the maximum permitted capacity ($10\,080\,m^3\,d^{-1}$).

5 Conclusions

Steadily growing anthropogenic pressure on groundwater resources, both with respect to their quality and quantity, creates a conflict situation between nature and man which are competing for clean and safe source of water. It is often forgotten that groundwater dependent ecosystems have important functions in all climatic zones as they contribute to biological and landscape diversity and provide important economic and social services. The presented study has demonstrated that isotope and geochemical tools

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combined with 3-D flow and transport modeling may help to answer important questions related to functioning of groundwater dependent ecosystems and their interaction with the associated aquifers.

In the context of the presented study environmental tracers appeared to be particularly useful in quantifying timescales of groundwater flow through various parts of the Bogucice Sands aquifer, including its Quaternary cover. Environmental tracer data (tritium, stable isotopes of water) and physico-chemical parameters of groundwater and surface water in the study area, provide a strong collective evidence for upward seepage of groundwater from the Bogucice Sands aquifer to the shallow Quaternary aquifer supporting the studied GDTE (Niepolomice forest and Wielkie Bloto fen).

Simulations of groundwater flow field with the aid of 3-D flow and transport model developed for the studied aquifer and calibrated using environmental tracer data, strongly suggest that prolonged groundwater abstraction through the newly-established cluster of water-supply wells at maximum permitted capacity (ca. 10 000 $m^3 d^{-1}$) represents significant risk to the studied GDTE. It may lead to reorganization of groundwater flow field in the study area and significant drop of water table, leading to degradation of this valuable groundwater dependent ecosystem in the near future.

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Table 1. Environmental tracer data for water samples collected in the study area.

Site/Well No.	Depth[a] (m)	δ^2H (‰)	δ^{18}O (‰)	d-excess (‰)	Tritium (T.U.)	$\delta^{13}C_{TDIC}$ (‰)	$^{14}C_{TDIC}$ (pMC)
Szarów:							
Well No. 11	49.5–60.1	−70.3	−9.75	7.7	9.0	−14.1	64.6
Well No. 12	44.5–63.6	−70.1	−9.93	9.3	1.1	−12.8	63.6
Well No. 22	48.0–60.0	−69.4	−9.81	9.1	16.1	n.m.	n.m.
Well No. 23	33.0–50.0	−68.5	−9.84	10.2	0.7	n.m.	n.m.
Well No. 24	45.9–58.4	−72.1	−10.03	8.1	15.2	n.m.	n.m.
Well No. 42	70.0–95.0	−69.2	−9.68	8.2	< 0.3	−12.2	48.5
Wola Batorska:[b]							
Well No. 44	98.0–144.0	−75.7	−10.19	5.8	< 0.3	−10.2	3.2
Well No. 45	75.0–149.0	−78.3	−10.67	7.1	< 0.3	n.m.	n.m.
Well No. 46	63.0–131.0	−79.9	−10.86	7.0	< 0.3	−10.4	1.3
Well No. 47	69.0–132.0	−79.2	−10.89	7.9	< 0.3	n.m.	n.m.
Well No. 48	79.0–131.0	−80.2	−10.83	6.4	< 0.3	n.m.	n.m.
Well No. 49	72.0–146.0	−78.2	−10.71	7.5	< 0.3	−9.1	3.0
Well No. 16	107.5–143.1	−69.7	−10.03	10.5	< 0.3	−13.3	32.1
Well No. 32	90.9–102.0	−76.8	−10.93	10.6	< 0.3	−10.6	< 0.7
Wielkie Bloto area:							
GP1-A	1.6	−70.8	−10.07	9.8	8.1	n.m.	n.m.
GP1-B	2.8	−68.2	−9.65	9.0	5.4	n.m.	n.m.
GP1-C	4.6	−71.0	−10.10	9.8	0.9	n.m.	n.m.
GP3-A	1.6	−61.9	−8.83	8.7	10.1	n.m	n.m.
GP3-B	3.1	−69.3	−9.86	9.6	1.4	n.m.	n.m.
GP4-A	1.6	−64.4	−9.09	8.3	6.5	n.m.	n.m.
GP4-B	4.0	−69.6	−9.67	7.8	2.1	−14.3	57.2[c]
Anna-spring (No. 52)[d]	~ 30	−67.6	−9.55	8.8	< 0.3	−12.9	36.9

[a] Screen position in the production wells; maximum depth for Geoprobe® sampling.
[b] Isotope data reported for wells Nos 44, 46 and 49 are arithmetic averages of the results obtained in three consecutive sampling campaigns carried out in June 2010, July 2012 and October 2013.
[c] Analyzed using AMS technique.
[d] Badly liquidated well drilled in 1970s located in the forest ca. 300 m east of Wielkie Bloto fen.
n.m. Not measured.

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Table 2. Physico-chemical parameters of water samples collected in the study area.

Site/Well No.	Temp. (°C)	pH	SEC ($\mu S\,cm^{-1}$)	Ca ($mg\,L^{-1}$)	Mg ($mg\,L^{-1}$)	Na ($mg\,L^{-1}$)	K ($mg\,L^{-1}$)	HCO_3 ($mg\,L^{-1}$)	Cl ($mg\,L^{-1}$)	SO_4 ($mg\,L^{-1}$)
Szarów:										
Well No. 11	11.5	7.1	733	116	16.5	10.1	1.27	384	23.3	41.1
Well No. 12	11.5	7.1	646	107	15.8	6.91	1.19	394	7.38	21.8
Well No. 22	11.0	7.0	607	105	17.1	7.54	1.42	410	8.82	19.2
Well No. 23	11.5	7.5	906	138	17.4	20.5	1.51	340	45.1	87.3
Well No. 24	11.0	7.1	542	96.8	15.6	6.53	1.59	306	20.4	57.3
Well No. 42	11.6	7.1	n.m.	117	18.4	25.7	1.49	350	15.5	77.2
Wola Batorska:										
Well No. 44	12.7	8.7	745	6.28	1.71	170	2.67	395	28.2	< 3.0
Well No. 45	12.4	8.1	780	19.2	5.13	160	4.69	448	51.0	< 3.0
Well No. 46	13.2	8.3	768	16.5	3.48	153	3.27	388	49.7	< 3.0
Well No. 47	14.1	8.1	824	23.6	4.98	174	3.70	436	60.4	< 3.0
Well No. 48	16.8	8.1	855	16.9	3.68	178	4.43	468	28.5	8.10
Well No. 49	12.5	8.7	1152	10.3	2.67	250	4.12	429	79.8	21.0
Well No. 16	13.0	7.4	1313	80.4	16.6	160	7.28	413	200.0	19.2
Well No. 32	12.0	8.3	717	5.62	1.68	139	5.84	324	65.3	0.59
Wielkie Bloto area:										
GP1-A	11.2	6.0	352	50.0	3.72	11.7	2.21	76.3	13.9	81.1
GP1-B	11.8	7.1	899	78.4	14.7	65.8	5.44	276	57.5	112.0
GP1-C	12.3	7.6	960	46.9	13.8	123	7.92	431	119.0	68.0
GP3-A	12.3	7.2	549	97.3	9.36	8.90	2.20	221	25.9	66.9
GP3-B	15.3	8.2	1150	48.4	17.9	163	7.88	398	121.0	44.2
GP4-A	11.8	6.6	568	99.8	10.6	9.46	1.85	298	21.1	39.2
GP4-B	11.6	8.8	1054	136	32.7	51.9	8.49	473	43.3	129.0
Anna-spring (No. 52)	9.0	7.7	390	40.2	8.72	31.9	6.17	288	5.74	< 3.0

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Table 3. Radiocarbon piston-flow ages of groundwater in the confined zone of the investigated part of Bogucice Sands aquifer, calculated using NETPATH code.

Well No.	Measured $\delta^{13}C_{TDIC}$ (‰V-PDB)	Computed $\delta^{13}C_{TDIC}$ (‰V-PDB)	Measured ^{14}C content [a] (pMC)	^{14}C age (ka)	Constraints	Phases
16	−13.3	−12.9	32.2	5	C, Ca, Mg, K, Na, S, Cl	calcite, dolomite, CO_2 gas, halite, sylvite, gypsum, exchange, CH_2O, Mg/Na exchange
32	−10.6	−10.6	< 0.7	> 36		
42[b]	−12.2	−12.2	48.5	2		
44	−10.2	−10.2	2.9	25		
46	−10.5	−10.7	0.8	34		
49	−9.3	−9.3	2.2	26		
52	12.8	−12.9	36.9	6		

[a] Carbon isotope and chemical analyses of water samples in collected in wells Nos. 44, 46 and 49 in June 2010 were used for NETPATH inverse calculations and determination of radiocarbon ages.
[b] Isotope exchange between solid carbonates and water solution to reconcile the computed $\delta^{13}C$ of TDIC with observed value (0.2–0.3 mmol L^{-1} of exchanged carbon) was required only for well No. 42.

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Table 4. Physico-chemical parameters of Dluga Woda stream monitored on monthly basis during the period: August 2011–August 2013.

Date	Flow rate ($L\,s^{-1}$)	δ^2H (‰)	$\delta^{18}O$ (‰)	Tritium content (T.U.)	SEC ($\mu S\,cm^{-1}$)	pH	Cl ($mg\,L^{-1}$)	Na ($mg\,L^{-1}$)
29 Aug 2011	10.1	−62.7	−8.70	5.9	559	7.86	33.2	31.9
29 Oct 2011	12.4	−62.5	−8.81	9.1	628	7.87	46.5	41.8
29 Nov 2011	36.7	−65.9	−9.17	7.7	599	7.75	34.8	18.1
30 Dec 2011	46.7	−61.9	−9.21	7.6	548	7.72	25.2	17.1
28 Jan 2012	23.1	−68.4	−9.76	9.0	628	7.23	35.0	17.8
29 Feb 2012	167	−68.7	−9.78	7.8	456	6.84	24.9	11.5
31 Mar 2012	97.5	−65.8	−9.12	8.2	506	7.41	46.3	16.7
30 Apr 2012	37.3	−64.7	−8.57	6.2	560	7.59	31.9	19.4
30 May 2012	5.0	−62.7	−8.17	4.0	681	7.79	50.6	31.7
22 Jun 2012	14.2	−55.5	−7.72	8.1	556	7.76	41.5	35.1
30 Jul 2012	73.1	−46.7	−6.92	9.4	460	7.57	23.8	12.2
31 Aug 2012	1.5	−56.7	−7.48	5.0	768	8.27	54.0	18.1
28 Sep 2012	3.4	−55.5	−7.54	5.4	736	8.12	53.4	44.9
30 Oct 2012	79.3	−65.9	−9.27	6.3	566	7.62	33.0	15.2
29 Nov 2012	42.2	−63.8	−9.01	5.4	573	7.75	30.1	n.m.
29 Dec 2012	89.4	−76.2	−9.39	7.0	567	7.48	33.6	17.2
6 Mar 2013	128.3	−70.2	−9.97	5.7	501	7.44	31.2	n.m.
24 Apr 2013	71.3	−71.7	−10.01	6.2	505	7.69	24.2	17.0
8 Jun 2013	180.7	−67.6	−9.62	8.6	356	7.02	13.5	15.4
6 Jul 2013	49	−68.0	−9.20	6.1	495	7.62	26.3	18.8
9 Aug 2013	1.2	−63.0	−8.26	5.6	692	8.00	51.7	44.3

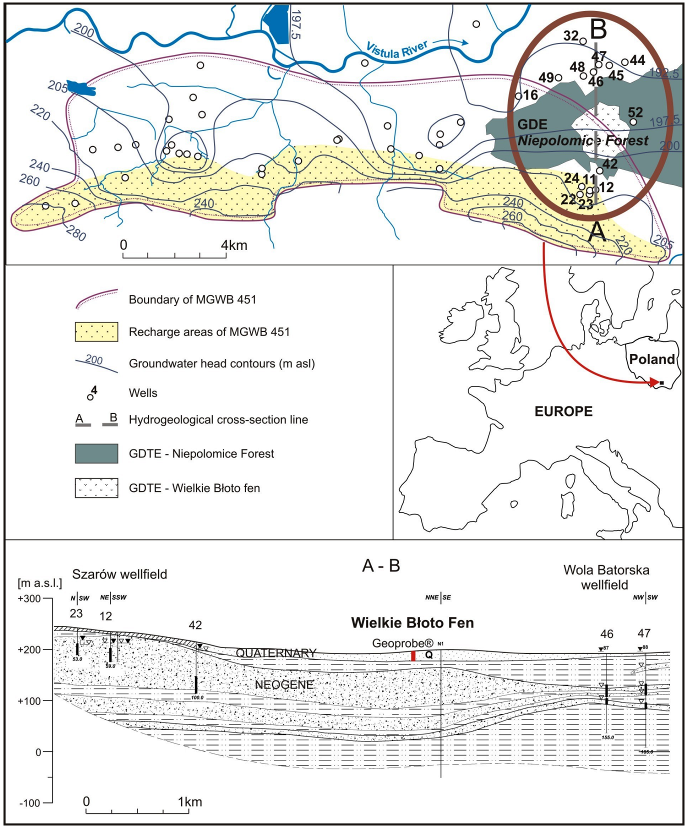

Figure 1. Hydrogeological map and cross-section of the Bogucice Sands aquifer (Major Ground Water Basin – MGWB 451). The study area is marked by brown oval. Open circles mark the position of pumping wells. Cross-section according to Górka et al. (2010).

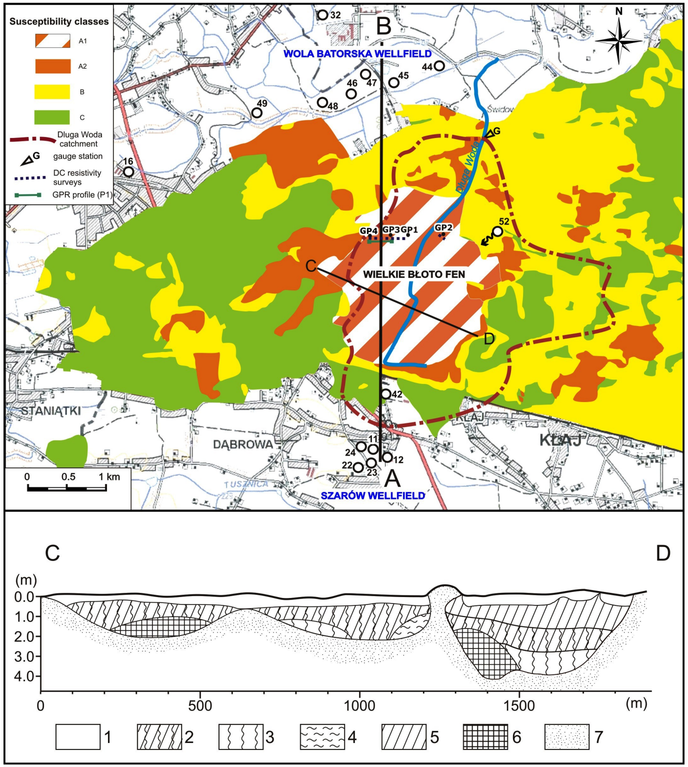

Figure 2. Upper panel – map of the study area showing western part of Niepolomice Forest and Wielkie Bloto fen. GDTE susceptibility classes based on the depth to water table: A – very strongly dependent (0.0–0.5 m): A1 – wetland ecosystem, A2 – forest ecosystem; B – strongly dependent (0.5–2.0 m) forest ecosystem; C – weakly dependent (> 2.0 m) forest ecosystem. Lower panel – cross-section through Wielkie Bloto fen according Lipka (1989). 1 – moorsh, 2 – tall sedge-reed peat, 3 – reed peat, 4 – *Sphagnum* peat, 5 – tall sedge peat, 6 – gyttja, 7 – sand.

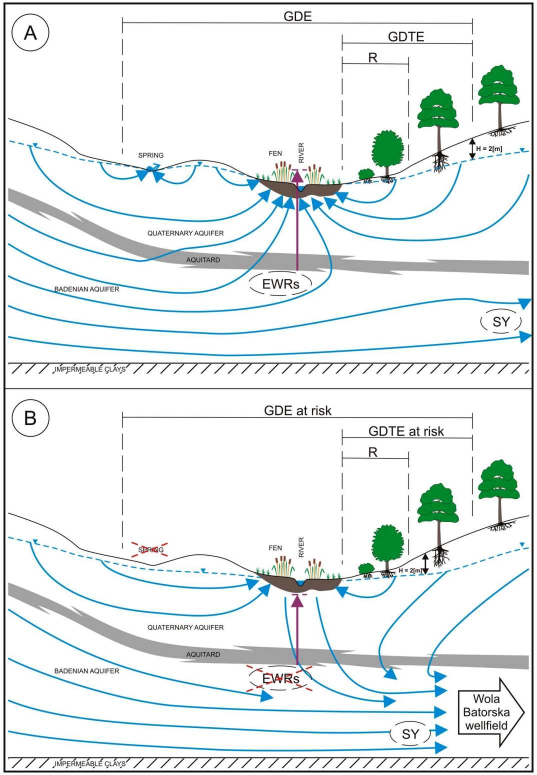

Figure 3. Conceptual model of the Wielkie Błoto fen. **(A)** – natural state; **(B)** – envisaged future status as a result of intense exploitation of the Wola Batorska wellfield. GDE – Groundwater Dependent Ecosystem; GDTE – Groundwater Dependent Terrestrial Ecosystem, R – riparian forest, EWRs – Environmental Water Requirements, SY – Safe Yield of the aquifer exploited by the Wola Batorska wellfield.

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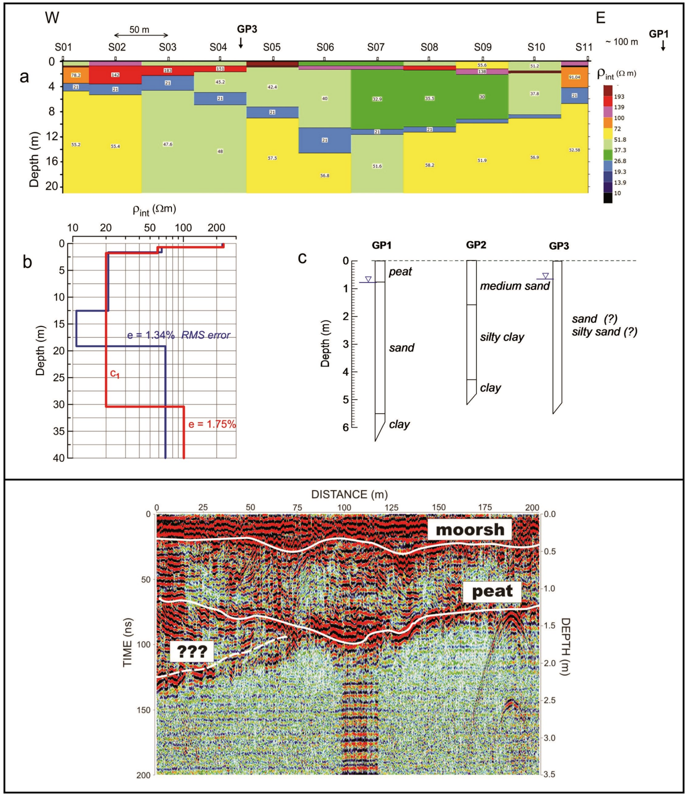

Figure 4. Upper panel – results of Vertical Electrical Sounding (VES). **(a)** 1-D interpreted resistivity section (S01–S11). Clay layer marked in blue. **(c)** two variants of interpreted resistivity vertical profile based on VES sounding in the vicinity of GP 2 site. C1 corresponds to fixed resistivity of clay equal 21 Ohmm. **(c)** Structure of Geoprobe® soil cores at GP1, GP2 and GP3 sites. Lower panel – GPR echogram along P1 profile shown in Fig. 2 (see text for details).

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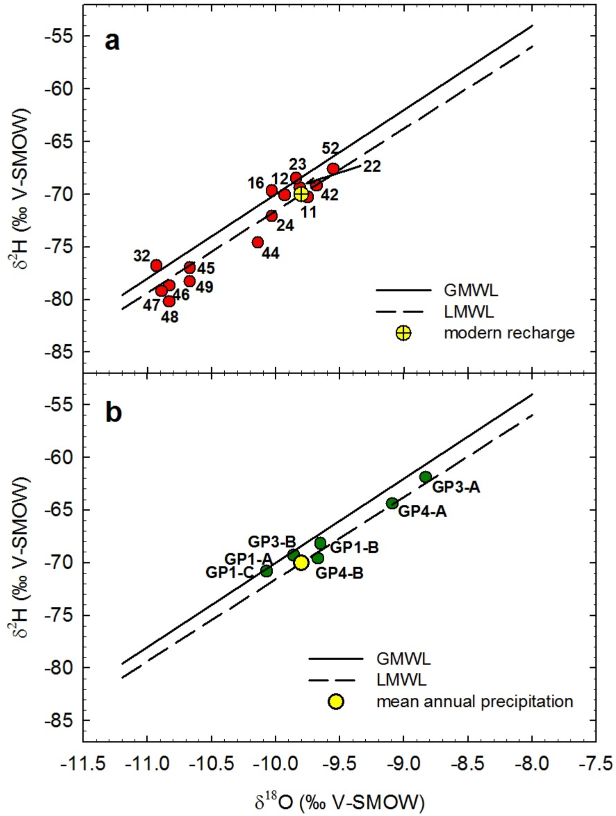

Figure 5. (a) δ^2H–δ^{18}O relationship for groundwater samples representing Bogucice Sands aquifer and collected in the study area. Shown is also mean isotopic composition of modern recharge of the aquifer. GMWL – Global Meteoric Water Line: LMWL – Local Meteoric Water Line (monthly precipitation collected in Krakow, ca. 15 km north-west of the study area collected during the period 1975–2013). **(b)** δ^2H–δ^{18}O relationship for groundwater samples representing the shallow Quaternary aquifer underlying the Wielkie Bloto fen.

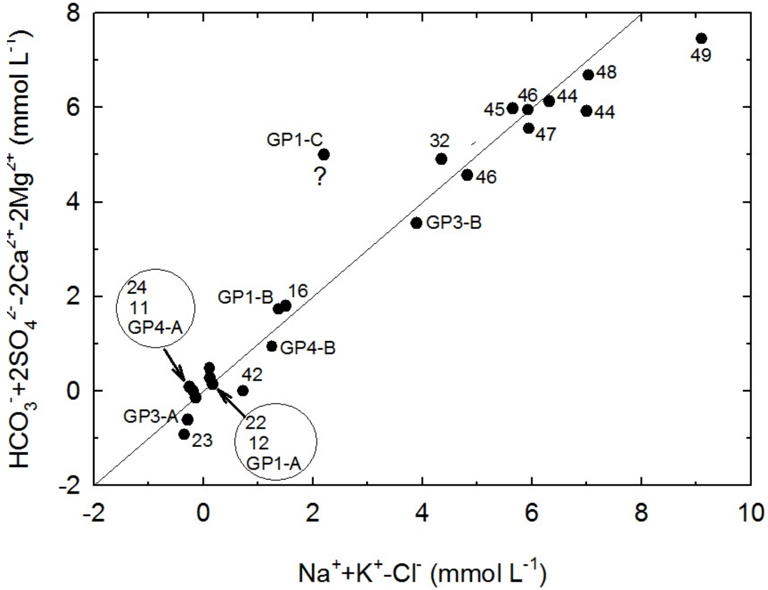

Figure 6. The relationship between deficit of Ca^{2+} and Mg^{2+} ions with respect to the sum of HCO_3^- and SO_4^{2-} ions and the excess of Na^+ and K^+ ions over the Cl^- ions in groundwater samples representing the part of Bogucice Sands aquifer located in the study area and the shallow Quaternary aquifer in the area of Wielkie Bloto fen.

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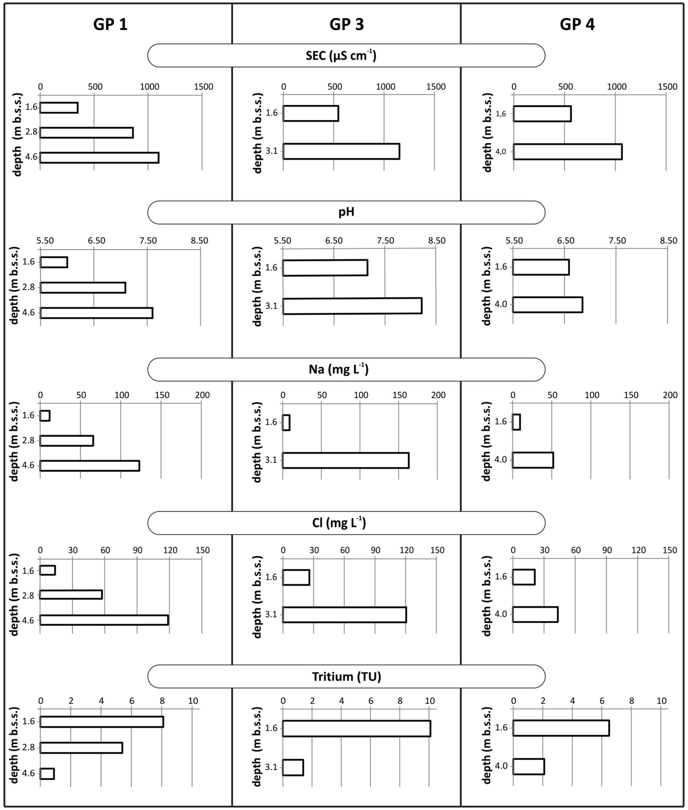

Figure 7. Depth stratification of pH, conductivity, Cl, Na and tritium content in the shallow Quaternary aquifer underlying the Wielkie Bloto fen and adjacent parts of the Niepolomice Forest. Water samples were collected with the aid of Geoprobe® device. Location of sampling sites (GP1, GP3, GP 4) is shown in Fig. 2.

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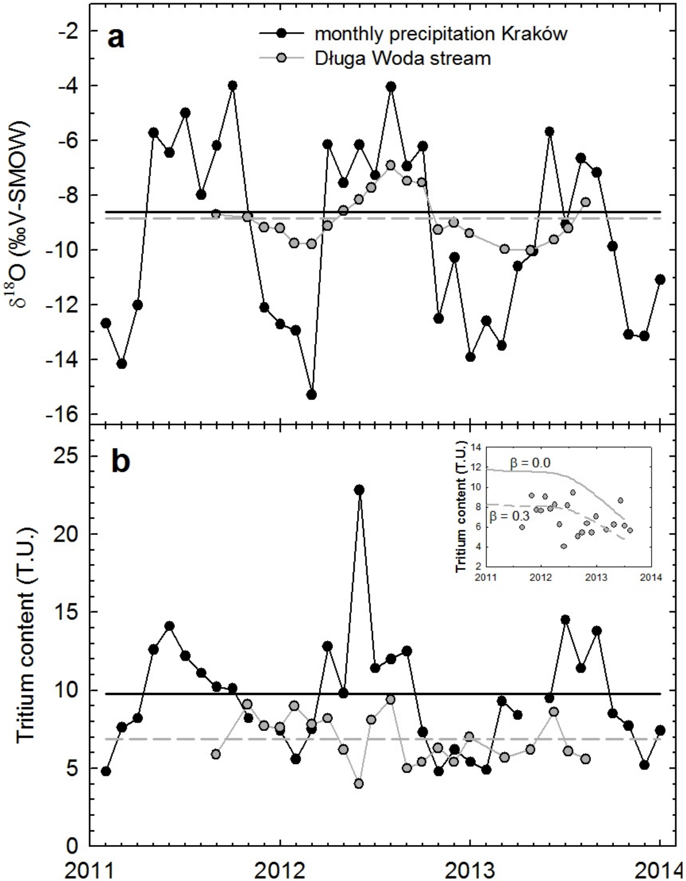

Figure 8. Seasonal variations of $\delta^{18}O$ **(a)** and tritium content **(b)** in the Dluga Woda stream during the period 2011–2013.

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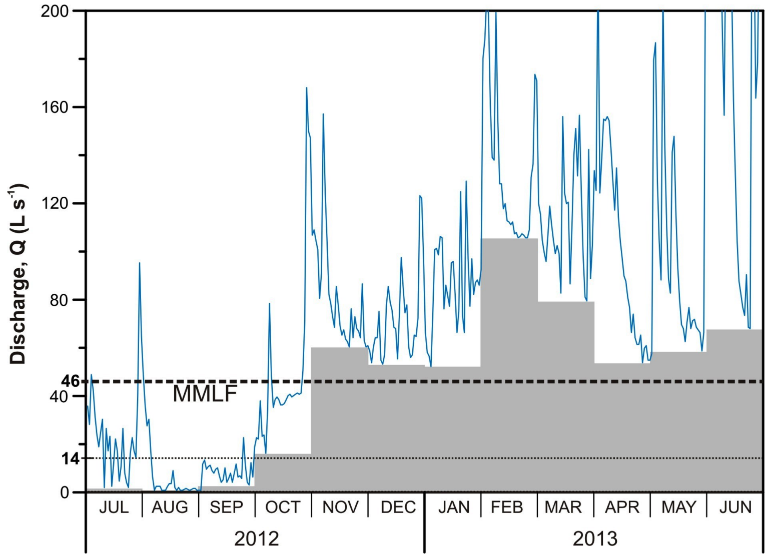

Figure 9. Hydrograph of Dluga Woda stream. Grey histogram reflects monthly low flows for the period July 2012–June 2013. The mean monthly low flow (MMLF) equal 46 $L\,s^{-1}$ corresponds to the baseflow of the stream. The characteristic discharge rate of 14 $L\,s^{-1}$ (cf. Fig. 10) is marked by dotted line (see text).

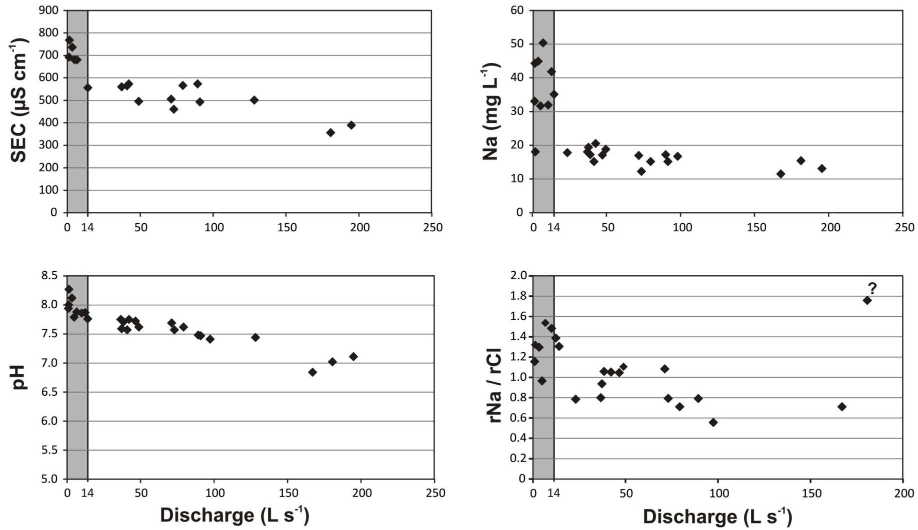

Figure 10. Electrical conductivity, pH, Na content and Na/Cl molar ratio in the Dluga Woda stream observed at monthly intervals during the period July 2012–June 2013, as a function of stream discharge rate measured at gauge station G (cf. Fig. 2).

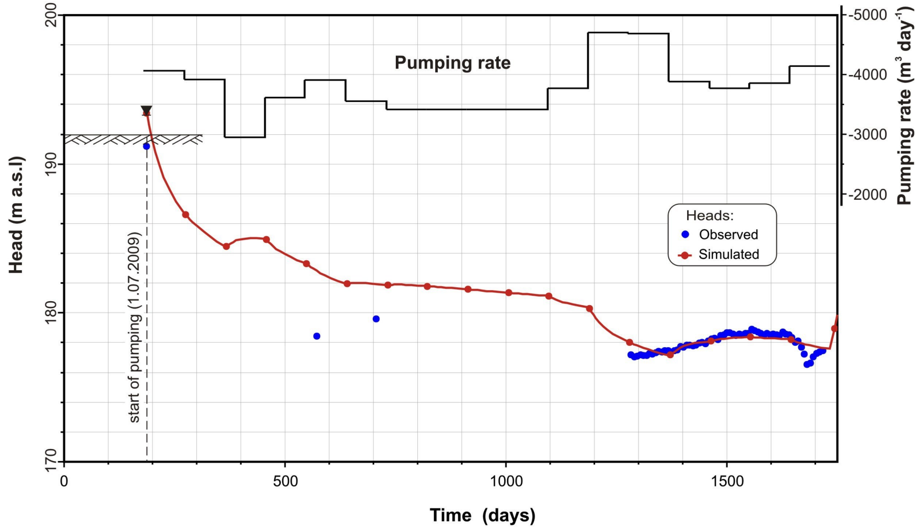

Figure 11. Changes of the hydraulic head in well No. 32 after initialization of the operation of Wola Batorska wellfield in July 2009.

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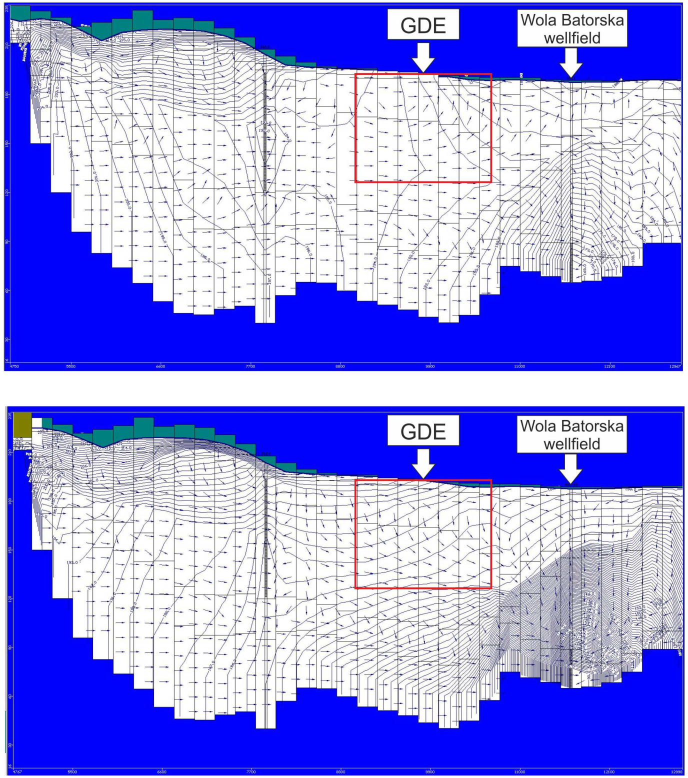

Figure 12. Simulated flow field in the Bogucice Sands aquifer (cross-section as in Fig. 1). Upper panel: steady-state flow field for present levels of groundwater abstraction through Wola Batorska wellfield (ca. 3800 $m^3 d^{-1}$). Lower panel: steady-state flow field for envisaged future levels of groundwater abstraction with maximum permitted capacity (10 080 $m^3 d^{-1}$).