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

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Abstract

Groundwater Dependent Ecosystems (GDE) have important functions in all climatic zones as they contribute to biological and landscape diversity and provide important economic and social services. Steadily growing anthropogenic pressure on groundwater resources creates a conflict situation between nature and man which are competing for clean and safe source of water. Such conflicts are particularly noticeably in GDEs located in densely populated regions. 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). It relies mostly on groundwater from the shallow Quaternary aquifer and possibly from the deeper Neogene (Bogucice Sands) aquifer. In July 2009 a cluster of new pumping wells abstracting water from the Neogene aquifer was set up 1 km to the northern border of the fen. A conceptual model of the Wielkie Bloto fen area for the natural, pre-exploitation state and for the envisaged future status resulting from intense abstraction of groundwater through the new wellfield was developed. The main aim of the reported study was to probe the validity of the conceptual model and to quantify the expected anthropogenic impact on the studied GDTE. A wide range of research tools was used. The results obtained through combined geologic, geophysical, geochemical, hydrometric and isotope investigations provide a strong evidence for existence of upward seepage of

groundwater from the deeper Neogene aquifer to the shallow Quaternary aquifer supporting the studied GDTE. Simulations of groundwater flow field in the study area with the aid of 3D flow and transport model developed for Bogucice Sands (Neogene) aquifer and calibrated using environmental tracer data and observations of hydraulic head in three different locations on the study area, allowed to quantify the transient response of the aquifer to operation of the newly-established Wola Batorska wellfield. The model runs reveal presence of the upward groundwater seepage to the shallow Quaternary aquifer in the order of 440 $m^3 d^{-1}$. By the end of the simulation period (2029), with continuous operation of the Wola Batorska wellfield at maximum permissible capacity (ca. 10 000 $m^3 d^{-1}$), the direction of groundwater seepage will change sign (total change in the order of 900 $m^3 d^{-1}$). The water table drawdown in the study area will reach ca. 30 cm. This may have significant adverse effects on functioning of the studied GDTE.

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) as 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, sometimes 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 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, 2014). The great diversity of GDEs stems primarily from space and time variations of groundwater supply to those ecosystems. Various classifications of the GDEs (Hatton and Evans, 1998; Sinclair Knight Merz, 2001; EC, 2003; Boulton, 2005; Pettit et al., 2007; Dresel et al., 2010; Kløve et al., 2011a; EC, 2011; Bertrand et al., 2012) 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, lagoons) groundwater dependent ecosystems.

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: (i) the degree of ecosystem reliance on groundwater (Hatton and Evans, 1998), and (ii) 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 wetland, located in the south of Poland (Fig.1). The central hypothesis of the presented work was that the studied GDTE relies not only on the shallow, unconfined Quaternary aquifer but indirectly also on groundwater originating from deeper confined aquifer, underlying the Quaternary cover and separated from it by an aquitard of variable thickness. Consequently, the presented study was addressing flowpaths and water ages of the deeper aquifer and its connectivity with the shallow Quaternary aquifer. An important additional objective was the quantification of the potential risk to the studied GDTE associated with operation of nearby cluster of water-supply wells exploiting the deeper aquifer. The deeper aquifer is an important source of drinking water for local population, intensely exploited for several decades now.

A suite of tools were applied to address the problems outlined above. Two monitoring wells were drilled in the centre of the studied GDTE to obtain direct information on the vertical extent and geologic structure of the Quaternary cover and the deeper aquifer. The drillings were supplemented by geophysical prospecting. DC resistivity sounding was used to obtain additional information about spatial extent and thickness of the confining layer separating the Quaternary cover and the underlying deeper Neogene aquifer. Ground penetrating radar surveys supplied information about thickness of peat layers in the area of GDTE. Hydrometric measurements, carried out over a two-year period on the Dluga Woda stream draining the area of GDTE and supported by chemical and isotope analyses of stream water, were used to quantify the expected contribution of groundwater seepage from the deeper aquifer to the water balance of the Dluga Woda catchment. The seepage was further characterized by dedicated Geoprobe® sampling of the Quaternary cover enabling vertical stratification of environmental tracers and water chemistry within the Quaternary cover to be assessed. The hydrochemical evolution and age of water in the Neogene (Bogucice Sands) aquifer was characterized using chemical and isotope data (water chemistry, stable isotopes of water (^{2}H and ^{18}O), tritium (^{3}H), isotopes of carbon (^{14}C, ^{13}C)) accompanied by geochemical modeling

(PHREEQC and NETPATH). Finally, the 3D flow and transport model available for the Bogucice Sands aquifer was used to quantify the expected impact of enhanced exploitation of the aquifer on the status of the studied GDTE.

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

2 The study area

The study area is located in the south of Poland, in the vicinity of Krakow agglomeration (Fig. 1). The studied groundwater dependent terrestrial ecosystem consists of valuable forest stand – the Niepolomice Forest, and associated wetland – the Wielkie Bloto fen. The Niepolomice Forest is a relatively large (ca. 110 km^2) lowland 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. The Niepolomice Forest contains also several nature reserves and the European bison breeding center and has important recreational value as the largest forest complex in the vicinity of Krakow agglomeration.

The Wielkie Bloto fen located in the western part of Niepolomice Forest (Fig. 1 and 2) comprises a separate Natura 2000 area (Torfowisko Wielkie Błoto, PLH120080), a significant habitat of endangered butterfly species associated with wet meadows. It contains different types of peat deposits with variable thickness (Fig. 2). Due to drainage works carried out mostly after the Second World War, the uppermost peat layers were drained and converted to arable land (Lipka, 1989; Łajczak, 1997; Lipka et al., 2006). In the recent decades the agriculture usage of Wielkie Bloto was greatly reduced and the studied GDTE is returning nowadays to its natural state.

Climate of the study area has an intermediate character between oceanic and continental, with the mean annual temperature of 8. 2^{o}C. Mean annual precipitation rate amounts to 725 mm whereas the mean actual evapotranspiration in the Niepolomice Forest area reaches 480 mm. The annual mean runoff fluctuates around 245 mm. The regional runoff is related to the drainage system of Vistula River and its tributaries (cf. Fig. 1). The Wielkie Bloto fen area and the adjacent parts of Niepolomice Forest are drained by the Dluga Woda stream with 8.2 km^2 of gauged catchment area (Fig. 2).

Depth to water table in the study area is generally small, 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 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 Niepolomice Forest on groundwater. This dependency relies on rooting depth and the depth to local water table. It also influences typology of forest and type of plant cover associated with GDTE (Schaffers and Sýkora, 2000; Pettit et al., 2007; GENESIS, 2012; Hose et al., 2014). The rooting depth must be smaller than depth to water table. Otherwise water-clogging occurs and roots cannot respire due to excess of water in the soil profile. Three classes of GDTE susceptibility to changes of water table depth were proposed (Fig. 2): (i) class A - very strongly dependent (depth of water table ranging from 0.0 to 0.5 m), (ii) class B - strongly dependent (0.5 to 2.0 m), and (iii) class C - weakly dependent (> 2.0 m). Forest stands growing on areas where depth to water table exceeds 2 meters 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 (Forest Management Manual, 2012).

Groundwater is stored in the study area in the upper, phreatic aquifer associated with Quaternary sediments and in the confined, deeper aquifer composed of Neogene marine sediments (Bogucice Sands). Unsaturated zone consists mainly of sands and loess of variable thickness, from a fraction of meter in wetland areas to approximately 30 meters in the recharge area of the deeper aquifer layers.

The Bogucice Sands (Neogene) 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). It is located on the border of the Carpathian Foredeep Basin and belongs to the Upper Badenian (Middle Miocene). The aquifer (MGWB No. 451) is composed mainly from unconsolidated sands, locally sandstones with carbonate cement. The variable percentage of carbonate cement, up to 30%, affects the hydraulic conductivity of water-bearing horizons. The aquifer 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. The mean thickness of the aquifer is approximately 100 m, with two water-bearing horizons (cf. Fig. 1). 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 (Fig. 1) where the aquifer is drained by upward seepage through semi-permeable aquitard. The recharge of groundwater, related to outcropping lithology, is in the order of 8 to 28 percent of annual precipitation.

The principal economic role of Bogucice Sands aquifer is to provide potable water for public and private users. Estimated safe yield of the aquifer is approximately 40 000 m^3d^{-1}, with typical well capacities of 4 to 200 m^3h^{-1} (Kleczkowski et al., 1990; Witczak et al., 2008; Górka et al., 2010). 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.

In pre-exploitation era, artesian water existed most probably on entire confined area of the aquifer. Intensive exploitation decreased the hydraulic head in some areas causing downward seepage. In the area of Wielkie Bloto fen the aquifer is exploited by Szarów wellfield located in the south (wells Nos. 11, 12, 22-24, 42 - cf. Fig. 1 and 2). In July 2009 a cluster of six new water-supply wells (Wola Batorska wellfield - wells Nos. 44-49 in Fig. 1 and 2) exploiting deeper aquifer layers was set up close to the northern border of Niepolomice Forest. There is a growing concern that intense exploitation of this new wellfield may lead to lowering of hydraulic head in the western part of Niepolomice Forest area.

The available geological information (Porebski and Oszczypko, 1999; Górka et al., 2010), supplemented by the results of previous work on the dynamics and geochemical evolution of groundwater in the Bogucice Sand aquifer (Zuber et al., 2005; Witczak et al., 2008), provided the basis for construction of conceptual model illustrating the interaction between shallow Quaternary aquifer and the deeper Neogene aquifer in the area of studied GDTE and suggesting possible impact of intense exploitation of groundwater by the Wola Batorska wellfield (Fig. 3). Figure 3a presents presumable natural status of this interaction. The Wielkie Bloto fen represents in this model local discharge area for both shallow and deeper aquifer. Artesian conditions in the deeper aquifer combined with relatively thin aquitard layer separating both aquifers, may lead to upward seepage of deeper groundwater, contributing to the water balance of the studied GDTE. The envisaged future status of the shallow/deep aquifer interaction a result of intense exploitation of the Wola Batorska wellfield is presented in Fig. 3b. It is expected that intensive pumping of the deeper aquifer by the wellfield localized close to the northern border of Niepołomice Forest (wells Nos. 44-49 in Fig. 2), exceeding its safe yield, may modify the groundwater flow field in the area of Wielkie Bloto fen in such a way that the upward leakage will be stopped or significantly reduced, thus leading to lowering of water table and endangering environmental water requirements of the studied GDTE.

3 Materials and methods

A suite of different methods was applied to address two major questions posed by the conceptual model presented in Fig. 3, i.e. the existence of upward seepage of groundwater from the deeper Neogene aquifer to the shallow Quaternary aquifer and its role in the water balance of Wielkie Bloto fen, and quantification of the expected impact of intense exploitation of deeper aquifer by the Wola Batorska wellfield on groundwater flow in the study area, in particular on the postulated upward seepage of groundwater. Four major areas of investigation were open: (i) verifying the available information on the vertical extent and geologic structure of the shallow Quaternary aquifer and the deeper Neogene aquifer in the area of the studied GDTE through direct (drillings) and indirect (geophysical prospecting) observations, (ii) assessing, through hydrometric observations, the water balance of the Dluga Woda stream draining the area of Wielkie Bloto fen, (iii) extensive sampling of surface water and groundwater in the study area for chemical and isotope analyses, aimed at quantifying the dynamics of water flow and tracing the postulated upward seepage of groundwater, and (iv) modeling of expected changes in groundwater flow in the study area, in response to intense pumping by the Wola Batorska wellfield.

The 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. Water samples were collected at GP1, GP3 and GP4 sites (Fig. 2). Site GP2 did not yield enough water for sampling. In addition, soil cores were collected at GP1, GP2 and GP3 sites (Fig. 4). The Geoprobe® profiling verified the position of the aquitard separating the shallow and deep aquifer in the study area. PVC screened pipes with a 2.5 inch outside diameter were installed in GP1, GP2 and GP3 for subsequent observations of water table.

In July 2014, two monitoring wells were drilled in the centre of the Wielkie Bloto fen (cf. Fig. 2). The well No. 54N reached the depth 97.5 m penetrating the Quaternary cover a reaching the deeper Neogene aquifer (cf. Fig. 1 and 4). The second well (No. 54Q) was drilled till the depth of 8 m. Both wells were screened (cf. Table 1) and water samples were collected for chemical and isotope analyses. Also, measurements of hydraulic heads in both Quaternary and Neogene aquifers were made.

Geoprobe® profiling and direct drillings were supplemented by geophysical prospecting. Surface DC resistivity sounding surveys were used as a reconnaissance tool to assess the depth and thickness of clay and claystone layers separating the shallow aquifer from the deeper aquifer in the area of Wielkie Bloto fen. The Vertical Electrical Sounding (VES) surveys with the Schlumberger array (Koefoed, 1979) were applied at 11 locations, linked to the locations of Geoprobe® profiling (Fig. 2). 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), defined as the ratio of the measured dielectric permittivity to the dielectric permittivity of vacuum. 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).

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 (see Fig. 2). Initially, the depth of water table was measured manually using water level meter. Starting from July 4, 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.

Network for collecting water samples for chemical and isotope analyses is shown in Fig. 2. 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 (exploratory boreholes, water-supply wells, Dluga Woda stream, Geoprobe® samples). Samples of water for isotope analyses were collected using established protocols. Isotope and chemical data were also obtained for the ‘Anna Spring’ (No. 52 in Fig. 2). Groundwater appearance at this side is linked to badly sealed borehole drilled in 1970s for seismic prospecting.

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 (cf. Tab. 4). The purpose of this monitoring activity was the identification and quantification of the expected contribution of the upward seepage from the Bogucice Sands (Neogene) aquifer to the total discharge of the Dluga Woda stream 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.

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 ($\delta^{18}O$, $\delta^{2}H$) and TDIC pool ($\delta^{13}C$) 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, $\delta^{18}O$, $\delta^{2}H$ and $\delta^{13}C$ 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 liters of water following the established procedures (Florkowski et 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).

The existing 3D numerical model of the Bogucice Sands aquifer was employed to investigate the impact of Wola Batorska wellfield on groundwater flow in the area of Wielkie Bloto fen. The MODFLOW-2000 code for simulation of flow (Harbaugh et al., 2000) and 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. The finite-difference grid consisted of 5 layers with 27 225 rectangular cells (250x250 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 in individual grid cells, without changing adopted transmissivity values. The changes of aquifer thickness were constrained by available geological information. Three water-bearing layers were distinguished in the model: one layer in the shallow Quaternary aquifer and two layers in the deeper Neogene aquifer. Transient flow simulation were performed by the model, with quarterly pumping rates of Wola Batorska wellfield during the period July 2009 – September 2013 and with maximum permitted capacity of 10 080 $m^3 d^{-1}$, starting from the end of 2014 and continuing till the end of 2029.

4 Results and discussion

4.1 Delineation of vertical structure of the Quaternary cover and the Neogene aquifer in the area of Wielkie Bloto fen

The geological structure of the Neogene (Bogucice Sands) aquifer in the area of Wielkie Bloto fen, emerging from the results of Geoprobe® profiling and exploratory drillings, is shown in Fig. 4. At site GP1 and GP3 unconsolidated sands reach the thickness of 5.5. and 5 m, respectively. Below this depth, mudstones and claystones start to appear, making deeper penetration of Geoprobe® not possible. At both locations thin layer of peat at ca. 50-70 cm was identified. Water table was located at the same depth. At GP2 site peat was absent and mudstone layer begun already at 1.8 m depth.

Interpretation of the apparent resistivity profiles 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 monitoring wells drilled in July 2014 confirmed the results obtained from VES profiling. Simplified geological profile of well No. 54N shown in Fig. 4 revealed that thickness of the aquitard separating the shallow Quaternary aquifer and the deeper Neogene aquifer is rather small. Three mudstone layers were identified in the profile. Thickness of the largest layer does not exceed one meter and occurs at the depth of 9 m.

The total length of the GPR profiles obtained in the area of Wielkie Błoto exceeded 1400 m. Here only one echogram representing the distance of approximately 200 m (profile P1 in Fig. 2) is discussed. Based on the data available for the soil core collected at GP1 site, electromagnetic wave velocity in peat was set at v = 3.6 cm $nsec^{-1}$. 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 degraded mineralized peat soil, 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 Neogene aquifer

Table 1 summarizes environmental tracer data obtained for water samples collected in the production wells of the Bogucice Sands (Neogene) 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 in the study area and tapping the Bogucice Sands (Neogene) aquifer is shown in Fig. 5a in δ^2H - $\delta^{18}O$ 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 of 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, in the range of radiocarbon concentrations measured in other wells located in the recharge area of the Bogucice Sands aquifer (cf. Fig. 1). Reduced concentrations of radiocarbon in recharge waters containing tritium result from geochemical evolution of TDIC reservoir in these waters (see e.g. Dulinski et al., 2013). 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 Figure 5a. This water is devoid of tritium and reveals reduced radiocarbon concentration (ca. 48 pMC) pointing to its pre-bomb (Holocene) age. The same concerns newly-drilled monitoring well tapping the Neogene aquifer (No. 54N). Its radiocarbon content (30 pMC) reflect gradual aging of water along the flow lines starting in the recharge area (Szarów wellfield). Well No. 54Q tapping the Quaternary aquifer shows significant concentration of tritium and reduced radiocarbon content, in agreement with expectations. Stable isotope composition of waters collected during Geoprobe® survey from different levels of the Quaternary cover scatter along the Local Meteoric Water Line reflecting seasonal variations of δ^2H and δ^{18}O in local precipitation (see section 4.4).

Stable isotope composition of water in wells belonging to the newly established wellfield 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 age of groundwater, 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 the Bogucice Sands (Neogene) 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., in agreement with partial pressures of soil CO_2 observed close to the study area (Dulinski et al., 2013). 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 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 (Neogene) 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 groundwater in the investigated part of Bogucice Sands aquifer is dominated by cation exchange processes. This conclusion is supported by Piper diagram shown in Figure 7.

Inverse modeling of radiocarbon ages of groundwater in wells Nos. 16, 32, 42, 44, 46, 49, 52 and 54N was performed using NETPATH code. First, input solution representing recharge area in the investigated part of Bogucice Sands (Neogene) 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 summarized 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. Well No. 54N, the ‘Anna Spring’ (No. 52) and well No. 16 reveal mid-Holocene groundwater ages.

It is apparent from the above discussion that groundwater which eventually penetrates the confining layer and reaches the shallow Quaternary aquifer in the area of Wielkie Bloto fen should have distinct chemical and isotopic characteristics. 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 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 Quaternary 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 deeper Neogene 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 Table 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 $\delta^{2}H$ and $\delta^{18}O$ in the upper portions of the profiles stems from strong seasonality of $\delta^{2}H$ and $\delta^{18}O$ 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. 8. A distinct reduction of tritium content with depth, accompanied by increase of pH, conductivity and concentration of major ions (Cl and Na) is apparent. 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 deeper, confined Neogene aquifer indeed takes place in the area of Wielkie Bloto (Fig. 8). The chemical data of Geoprobe® water samples are also plotted in

Fig. 6 and 7. They are consistent with geochemical evolution of groundwater in the Neogene (Bogucice Sands) aquifer, discussed in the previous section.

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) were 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 deeper, confined aquifer to the shallow aquifer, in the total discharge of the Dluga Woda stream. The results are summarized in Table 4. Chemical data for the Dluga Woda stream are shown also on Piper diagram (Fig. 7).

Figure 9 shows temporal variations of $\delta^{18}O$ 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. 9a that strong seasonality of $\delta^{18}O$ in precipitation survives during transport through the watershed and is visible in the Dluga Woda $\delta^{18}O$ record. However, the amplitude of seasonal changes of $\delta^{18}O$ 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:

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

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) $\delta^{18}O$ curves are inserted in the equation (1) the resulting mean transit time of water through the catchment of Dluga Woda stream, relatively to the river section used for sampling water, is 3.2 months.

Figure 9b shows the tritium content in local precipitation and in the Dluga Woda stream during the observation period. The weighted mean tritium concentration in precipitation (9.8 TU) appears to be significantly higher than that of the Dluga Woda stream water (6.9 TU). Assuming that the total discharge of Dluga Woda is composed of fast (*MTT* ca. 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 approximately 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. 9b 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 containing tritium 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 zero and 30 %, respectively (β = 0.0 and 0.3 in the insert figure, where β is the fraction of tritium-free component in the total flow of the stream). It is obvious that the assumption of 30 % contribution of tritium-free component in the total discharge of Dluga Woda stream fits the experimental data much better than the case neglecting this component. The contribution of tritium-free component also explains the difference between weighted mean δ^{18}O in precipitation for the period January 2011 - December 2013 (-8.61‰) and the mean ^{18}O content of the Dluga Woda stream (-8.84‰) seen in Fig. 9a. Mass-balance calculations based on δ^{18}O data yield the contribution of the old component in the order of 20 %, assuming that its ^{18}O content is represented by arithmetic mean of δ^{18}O values available for 'Anna Spring' and wells Nos. 16, 42 and 54Q, all characterized by Holocene ages of groundwater.

Hydrograph of the Dluga Woda stream constructed for the period July 2012 - July 2014 is shown in Fig. 10. It reveals large variability of the flow rate. The measured values varied from ca. 1.5 L s^{-1} (August 31, 2012) to 180 L s^{-1} (June 8, 2013) (cf. Table 4), while the corresponding values derived from the rating curve were equal 0.8 L s^{-1} (August 26, 2012) and over 250 L s^{-1} (June 26, 2013). Persisting low flows during August and September 2012 and 2013 resulted from lower than normal precipitation in the preceding months.

The hydrograph presented in Fig. 10 allows quantitative assessment of the Dluga Woda baseflow. It was derived as the mean monthly annual low flow (MMALF) according to Wundt (1953). 'Low flow' defines the lowest flow during the given month. MMALF reflects the discharge of the aquifer and may represent the annual baseflow in the river catchment. The MMALF value for the period July 2012 - July 2014 was equal 40 L s^{-1}. For the Dluga Woda catchment, with surface area of 8.2 km^2, this flow rate corresponds to annual baseflow equal 154 mm (ca. 21% of annual precipitation rate).

Large fluctuations of Dluga Woda discharge rates are accompanied by substantial variability of the physico-chemical parameters of the stream water (cf. Table 4 and Fig. 11). The relationships between SEC, pH, Na content, Na/Cl molar ratio and the discharge rate of Dluga Woda shown in Fig. 11 clearly indicate that for the flow rates lower than ca. 14 L s^{-1} the physico-chemical parameters of water attain distinct values (SEC > 600µS cm^{-1}; pH > 7.8; Na > 30mg L^{-1}, Na/Cl ratio higher than 1.3) not observed for higher flow rates. In addition, these low flow rates are 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 at very low flow rates (ca. < 14 L s^{-1}) carries significant contribution of waters seeping through clayey sediments separating water-bearing layers of the Neogene 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 MMALF value of 40 L s^{-1}, remarkably close to percentage contribution of the tritium-free component in the total discharge of Dluga Woda derived from tritium data.

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

The 3D flow and transport model of entire Bogucice Sands (Neogene) 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 12 summarizes the measurements of the position of hydraulic head in well No. 32 located 1075 meters 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 meters below the surface after four years of the operation of the new wellfield. Figure 12 also shows the changes of hydraulic head in well No. 32 simulated with the aid of 3D 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.

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):

$$T^* = \frac{S_S \cdot L_C^2}{K} \quad (2)$$

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 (Neogene) 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 Figure 12, 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.

The assessment of the impact of groundwater abstraction by the Wola Batorska wellfield to hydraulic head changes in well No. 32 allowed to calibrate the initially steady-state flow model to transient conditions during the first four years of wellfield operation. Further, such calibrated transient model allowed to assess the expected lowering of the hydraulic heads in the Wielkie Bloto fen area and to quantify changes of the upward seepage of groundwater from the deeper Neogene confined aquifer to the shallow Quaternary aquifer and the Dluga Woda stream draining the Wielkie Bloto area. Figure 13 shows the expected changes of hydraulic head in Quaternary and Neogene aquifers with respect to the observation wells (54Q and 54N, respectively), simulated in the center of the Wielkie Bloto fen. The simulation takes into account both the actual discharge of the Wola Batorska wellfield (2009-2014) and the prognosis of maximum allowed pumping rate (10 080 $m^3\ d^{-1}$) for the next 15 years, from the end of 2014 till the end of 2029.

Lowering of the simulated hydraulic head in both aquifers was generally confirmed by the observations in two monitoring wells (54Q and 54N), starting from July 2014. The difference between simulated and observed heads are in the order of 30 cm. The monitoring of hydraulic heads in both aquifers in the years to come will provide the basis for refinement of modeling results.

According to model output, the expected shortage of groundwater flow to the fen and the Dluga Woda stream depends strongly on adopted scenarios of expected pumping rates. Before initialization of groundwater exploitation by the Wola Batorska wellfield, the simulated upward seepage from deeper confined aquifer to shallow Quaternary aquifer was in the order of 441 $m^3 d^{-1}$. For scenario with maximum permitted pumping capacity of the Wola Batorska wellfield (10 080 $m^3 d^{-1}$) maintained from the end of 2014 till 2029, this upward seepage will reverse to downward flow of approximately 465 $m^3 d^{-1}$ by the end of the simulation period. This means that the overall change will reach 906 $m^3 d^{-1}$ (10.5 $L s^{-1}$) in Dluga Woda outflow. It should be noted that simulations were run for mean yearly conditions. During low flow conditions occurring in the summer months (c.f. Fig. 10) such drop of Dluga Woda discharge may lead to temporal disappearance of stream flow. By the end of the simulation period, the expected drop of water table in the center of Wielkie Błoto fen (c.f. Fig. 2) will be approximately 30 cm (from 192.31 to 192.00 m a.s.l.) (see Fig. 13). It may change difference for wetland area. The climatic changes envisaged till the end of 2029 were not considered in the simulation runs.

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 deeper Neogene aquifer. Although the hydraulic head dropped by about 1.5 m (from 194.33 to 192.88 m a.s.l.) since beginning of pumping in July 2009 till July 2014 when monitoring wells Nos. 54Q and 54N were drilled, the artesian conditions in the deeper confined aquifer are still maintained (Fig. 13). This will, however, change in future when more intense abstraction of groundwater will take place. As shown in Fig. 13, the simulated hydraulic heads of both aquifers will be equal approximately 310 days (0.85 years) after beginning of the exploitation of Wola Batorska wellfield with the maximum permitted capacity of 10 080 $m^3 d^{-1}$. At the end of the simulation period (end of 2029) the hydraulic head in the deeper aquifer will be about 0.6 m lower than in the shallow aquifer.

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 combined with 3D flow and transport modelling 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 deeper Neogene 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 3D 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^3d^{-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 groundwater samples collected in the study area.

Site/Well No.	Depth[a] (m)	$\delta^{2}H$ (‰)	$\delta^{18}O$ (‰)	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
Well No. 54 Q	2.0-6.0	-70.5	-9.90	8.7	5.8	-16.8	56.0
Well No. 54N	22.5-85.5	-71.4	-10.11	9.5	<0.3	-12.7	30.0

[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 sealed borehole drilled in 1970s for seismic prospecting (cf. Fig. 1,2).

n.m. - not measured

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

Site/Well No.	Temp. (°C)	pH	SEC (µS 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	278	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
Well No. 54Q	12.6	6.5	706	81.6	16.0	48.7	8.09	207	51.2	141
Well No. 54N	12.5	7.4	1576	15.7	16.3	276	9.56	424	244	26.0

n.m. – not measured

Table 3. Radiocarbon piston-flow ages of groundwater in the confined zone of the investigated part of the Neogene 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,	calcite, dolomite,
32	-10.6	-10.6	<0.7	>36	K, Na, S, Cl	CO_2 gas, halite,
42[b]	-12.2	-12.2	48.5	2		sylvite, gypsum,
44	-10.2	-10.2	2.9	25		exchange, CH_2O,
46	-10.5	-10.7	0.8	34		Mg/Na exchange
49	-9.3	-9.3	2.2	26		
52	-12.8	-12.9	36.9	6		
54N[c]	-12.7	-12.7	30.0	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.

[c] Carbon isotope and chemical analyses of water sample collected in July 2014 were used for NETPATH inverse calculations and determination of radiocarbon ages.

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 (µS cm^{-1})	pH	Cl (mg L^{-1})	Na (mg L^{-1})
16 Jul 2011	38.5	n.m.	n.m.	n.m.	562	7.75	25.1	17.2
29 Aug 2011	10.1	-62.7	-8.70	5.9	559	7.86	33.2	31.9
25 Sep 2011	1.0	n.m.	n.m.	n.m.	635	7.94	44.1	33.1
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 012	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 Nov2012	42.2	-63.8	-9.01	5.4	573	7.75	30.1	20.5
29 Dec 2012	89.4	-76.2	-9.39	7.0	567	7.48	33.6	17.2
06 Mar 2013	128.3	-70.2	-9.97	5.7	501	7.44	31.2	n.m.
20 Apr 2013	71.3	-71.7	-10.01	6.2	505	7.69	24.2	17.0
08 Jun 2013	180.7	-67.6	-9.62	8.6	356	7.02	13.5	15.4
06 Jul 2013	49	-68.0	-9.20	6.1	495	7.62	26.3	18.8
09 Aug 2013	1.2	-63.0	-8.26	5.6	692	8.00	51.7	44.3

n.m. - not measured

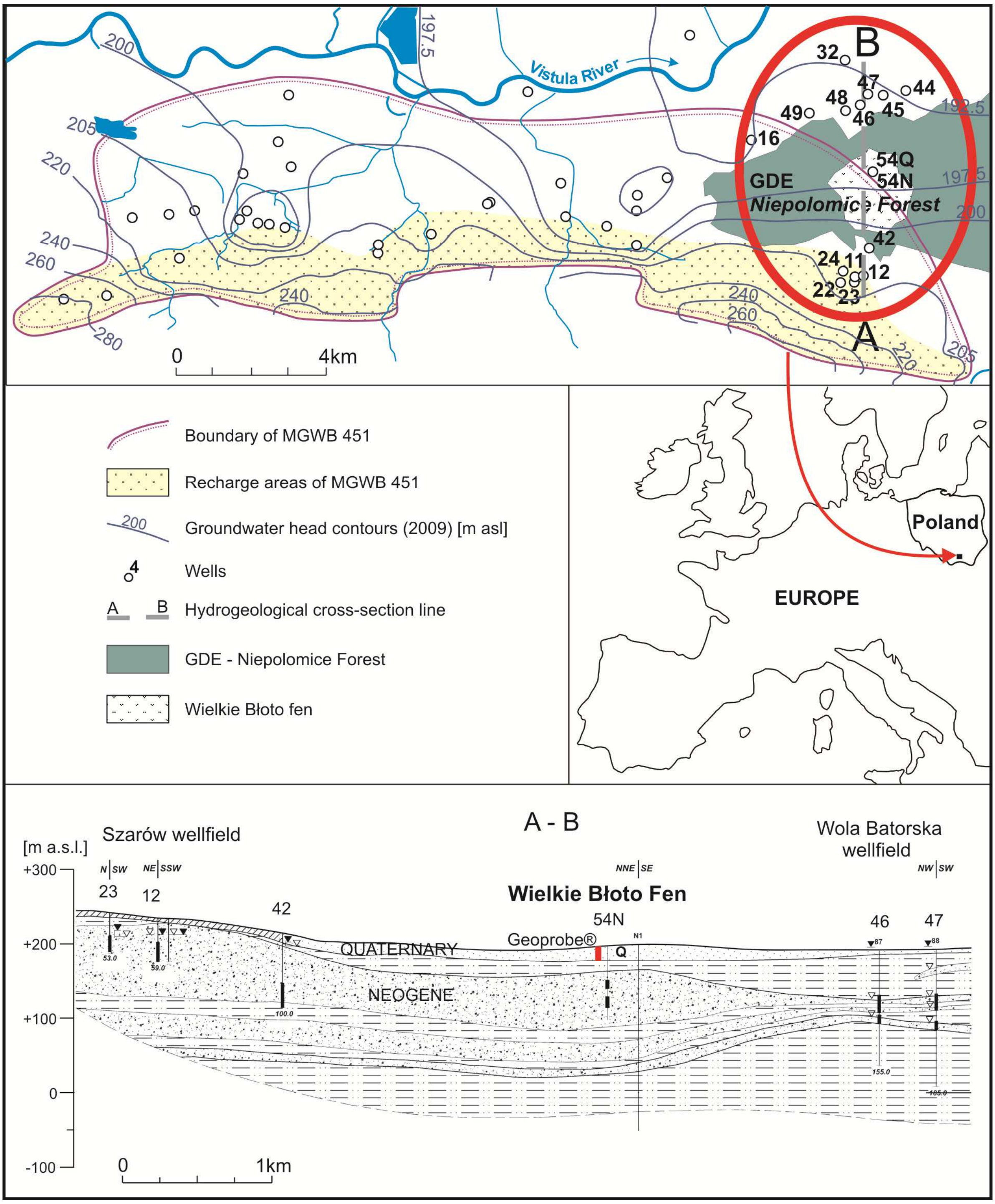

Figure 1. Hydrogeological map and cross-section of the Bogucice Sands (Neogene) aquifer (Major Ground Water Basin – MGWB 451). The study area is marked by red oval. Open circles mark the position of pumping wells. Cross-section according to Górka et al. (2010).

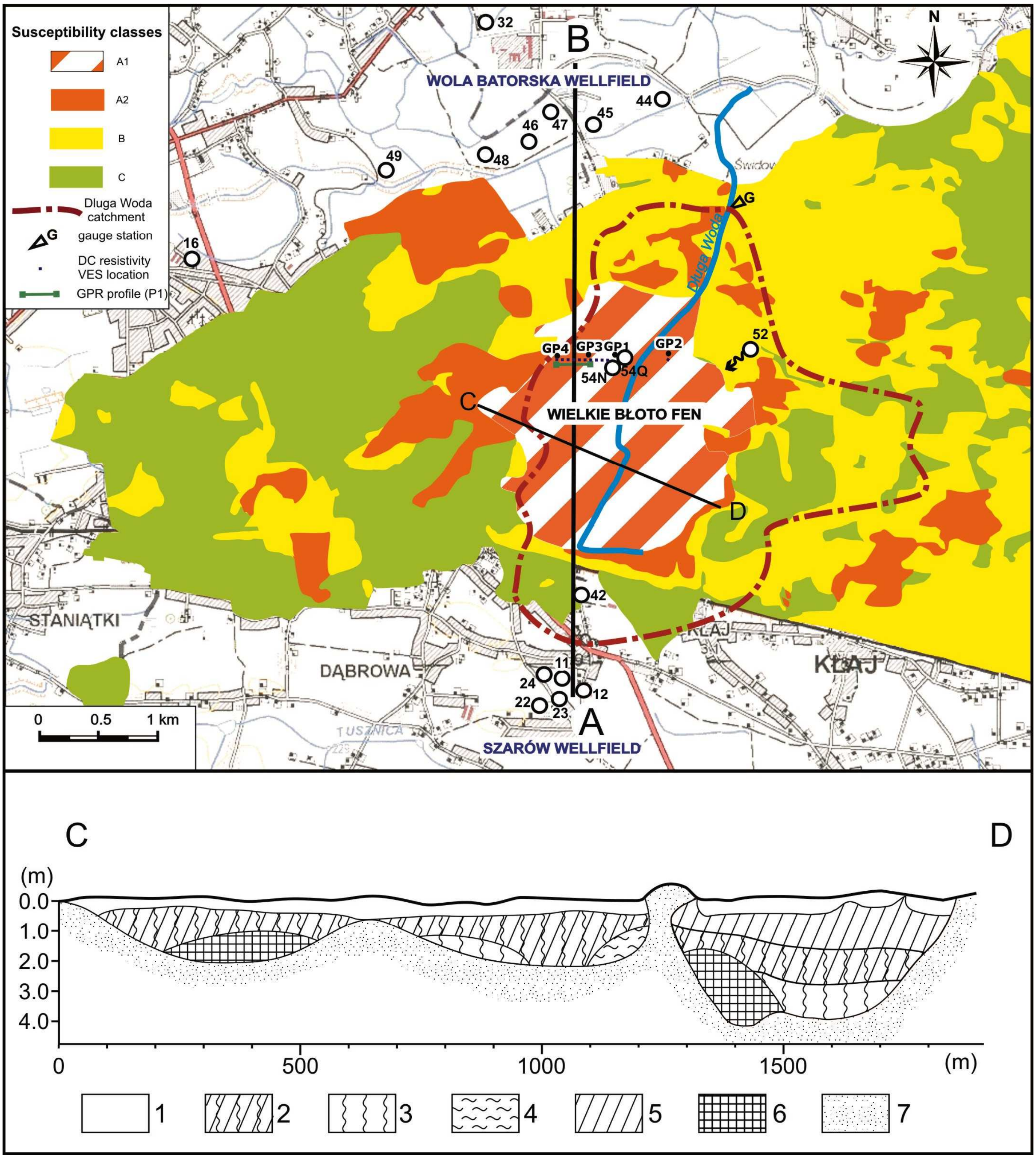

Figure 2. Upper panel - map of the study area showing western part of Niepolomice Forest and Wielkie Bloto fen. GDTE susceptibility classes based on the depth to water table: A - very strongly dependent (0.0 to 0.5 m): A1 – wetland ecosystem, A2 - forest ecosystem; B - strongly dependent (0.5 to 2.0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

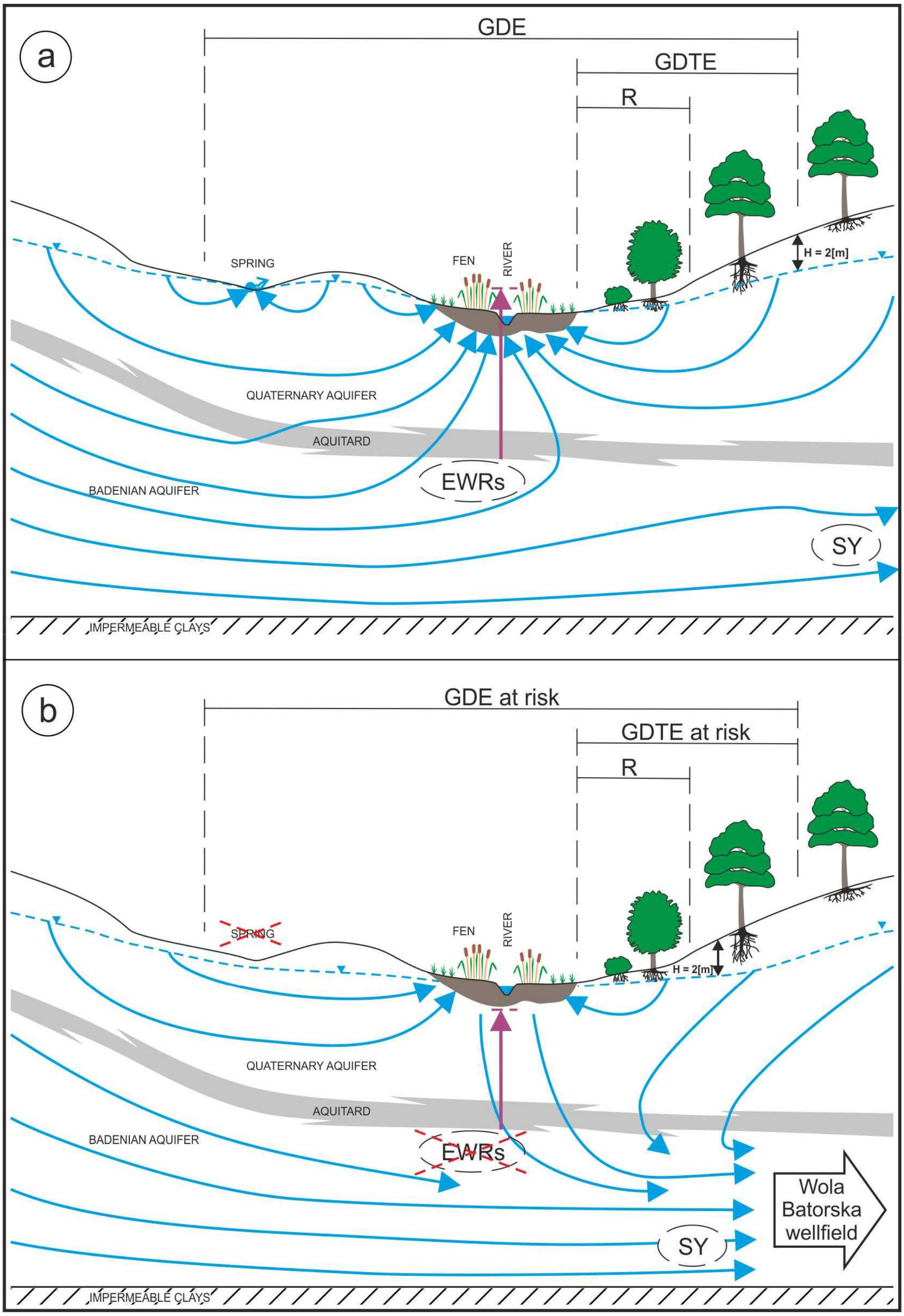

Figure 3. Conceptual model of the Wielkie Bloto fen. **(a)** - natural state; **(b)** - envisaged future status as a result of intense exploitation of the Wola Batorska wellfield. GDE - Groundwater Dependent Ecosystem; GDTE - Groundwater Dependent Terrestrial Ecosystem, R – riparian forest, EWRs - Environmental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

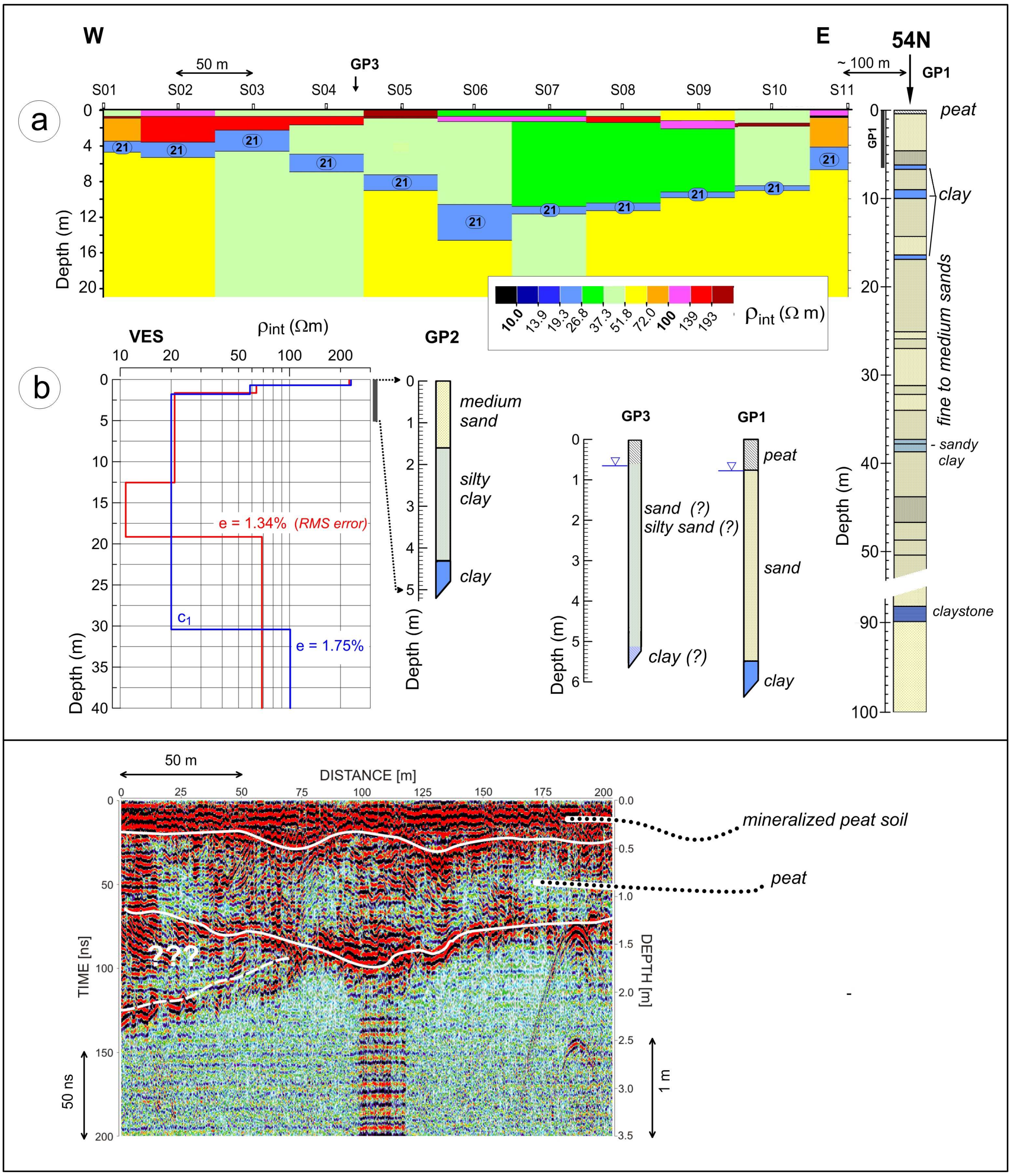

Figure 4. Upper panel - the results of Vertical Electrical Sounding (VES). **(a)** 1-D interpreted resistivity section (S01-S11). Clay layer marked in blue. **(b)** two variants of interpreted resistivity vertical profile based on VES sounding in the vicinity of GP 2 site. C1 corresponds to fixed resistivity of clay equal 21 Ohmm. Shown are also geological logs of Geoprobe® soil cores at GP1, GP2 and GP3 and the borehole drilled in the centre of the Wielkie Bloto fen (54N). Lower panel - GPR echogram along P1 profile shown in Fig. 2 (see text for details).

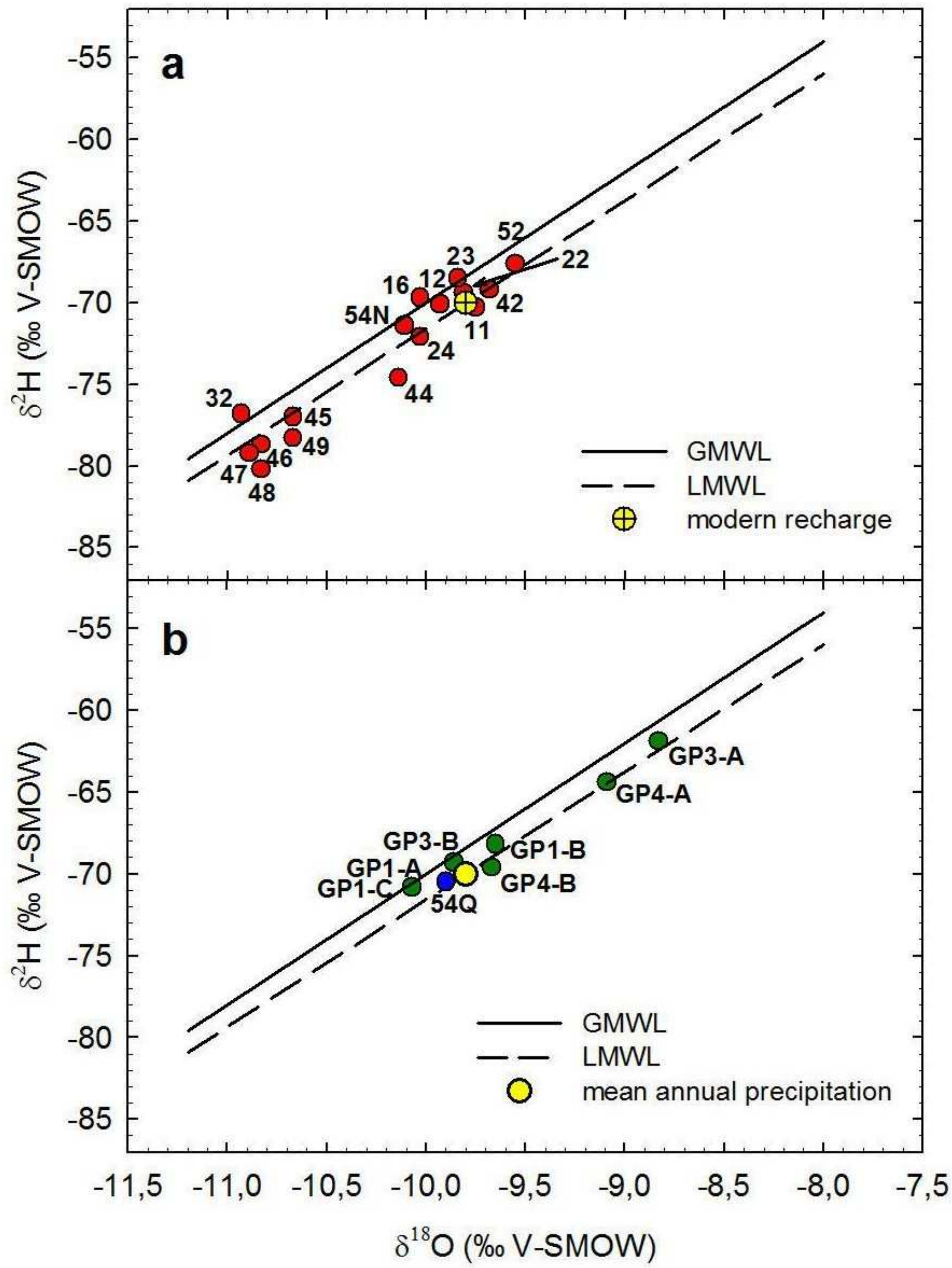

Figure 5. (a) δ^{2}H-δ^{18}O relationship for groundwater samples representing the Neogene aquifer, collected in the study area. Shown is also mean isotopic composition of modern recharge of the aquifer. GMWL - Global Meteoric Water Line: LMWL - Local Meteoric Water Line (monthly precipitation at Krakow station, ca. 15 km north-west of the study area, collected during the period 1975 - 2013). **(b)** δ^{2}H-δ^{18}O relationship for groundwater samples representing shallow Quaternary aquifer underlying the Wielkie Bloto fen (cf. Fig. 1,2 and Table 1).

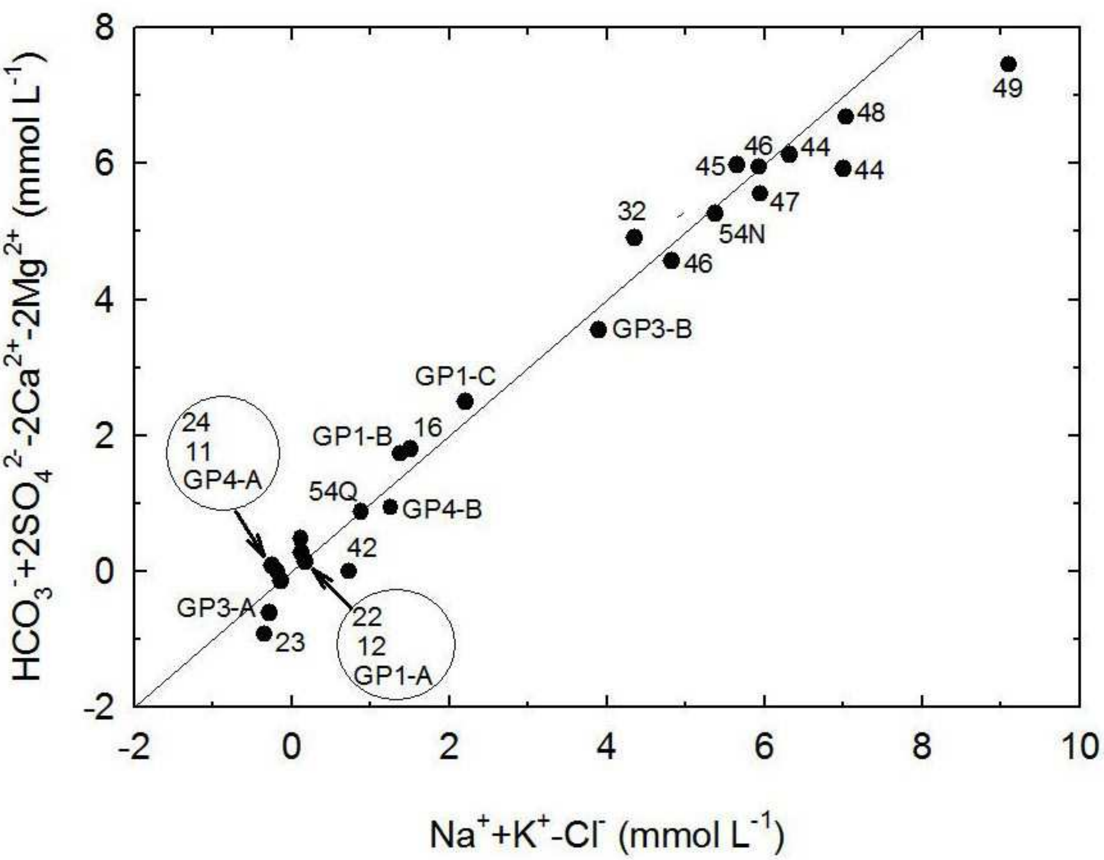

Figure 6. The relationship between deficit of Ca^{2+} and Mg^{2+} ions with respect to the sum of HCO_3^- and SO_4^{2-} ions and the excess of Na^+ and K^+ ions over the Cl^- ions in groundwater samples representing the part of the Neogene aquifer located in the study area and the shallow Quaternary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

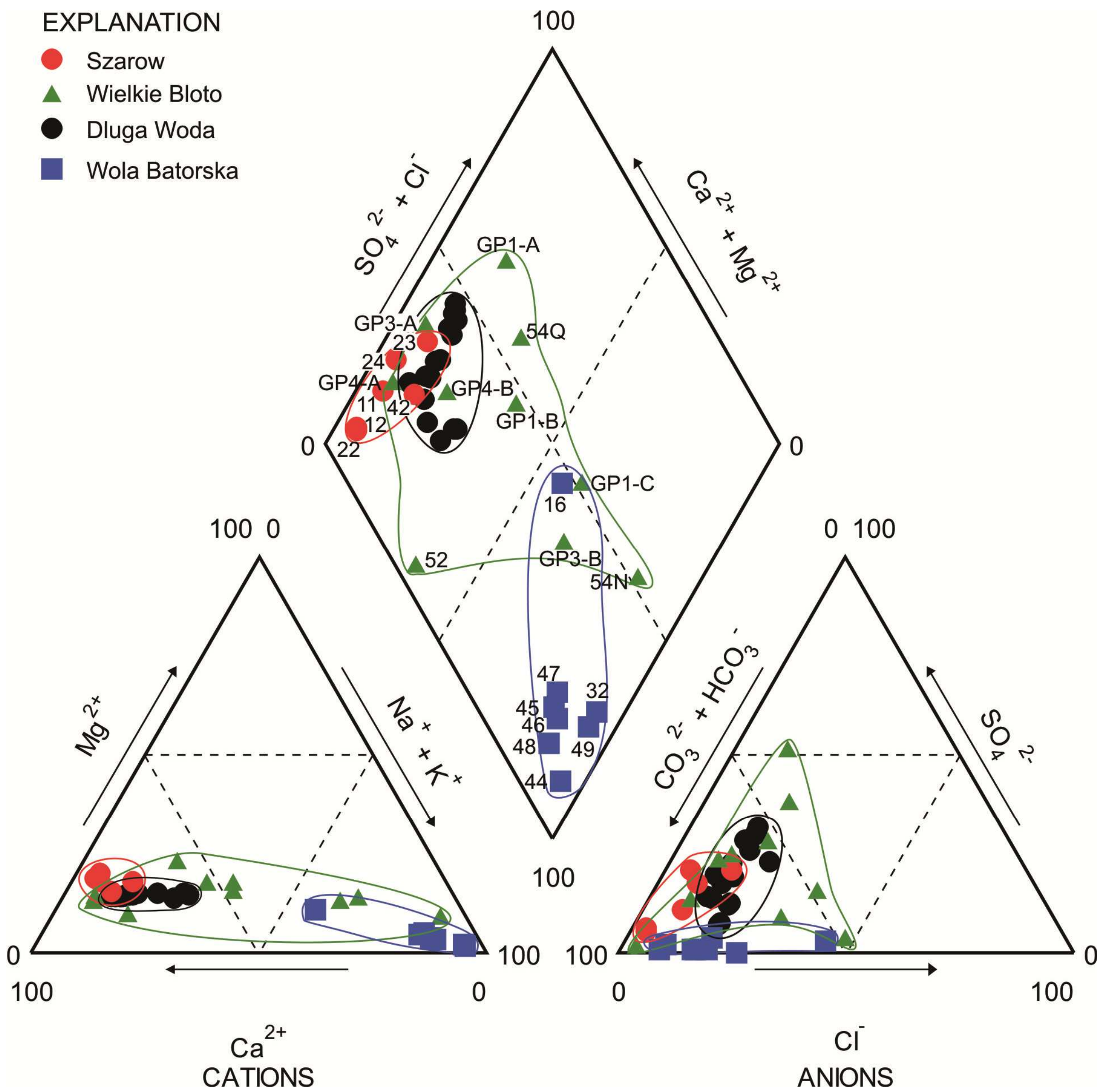

Figure 7. Piper diagram representing chemistry in water samples collected in the study area.

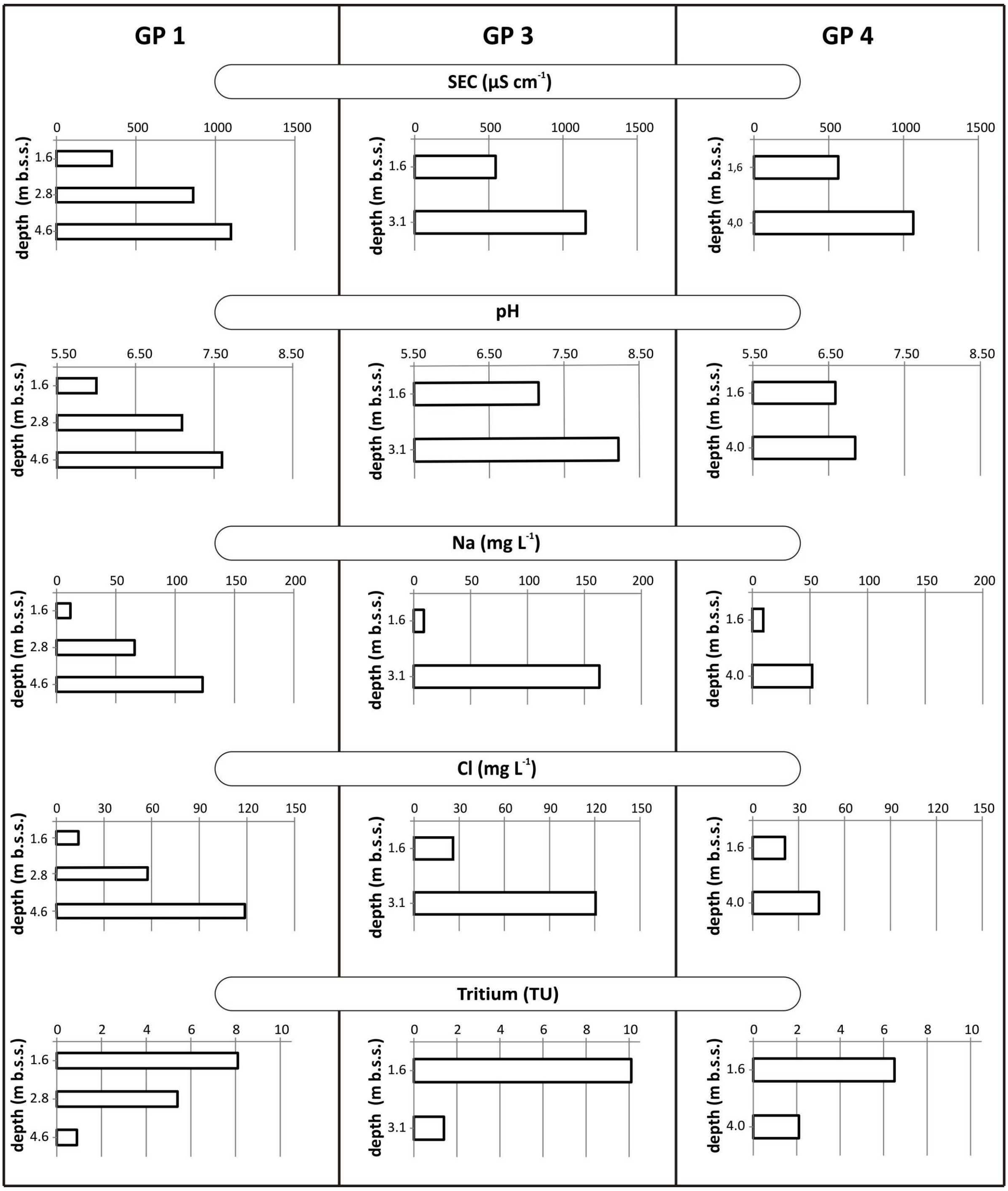

Figure 8. Depth stratification of pH, conductivity, Cl, Na and tritium content in the shallow Quaternary aquifer underlying the Wielkie Bloto fen and adjacent parts of the Niepolomice Forest. Water samples were collected with the aid of Geoprobe® device. Location of sampling sites (GP1, GP3, GP4) is shown in Fig. 2.

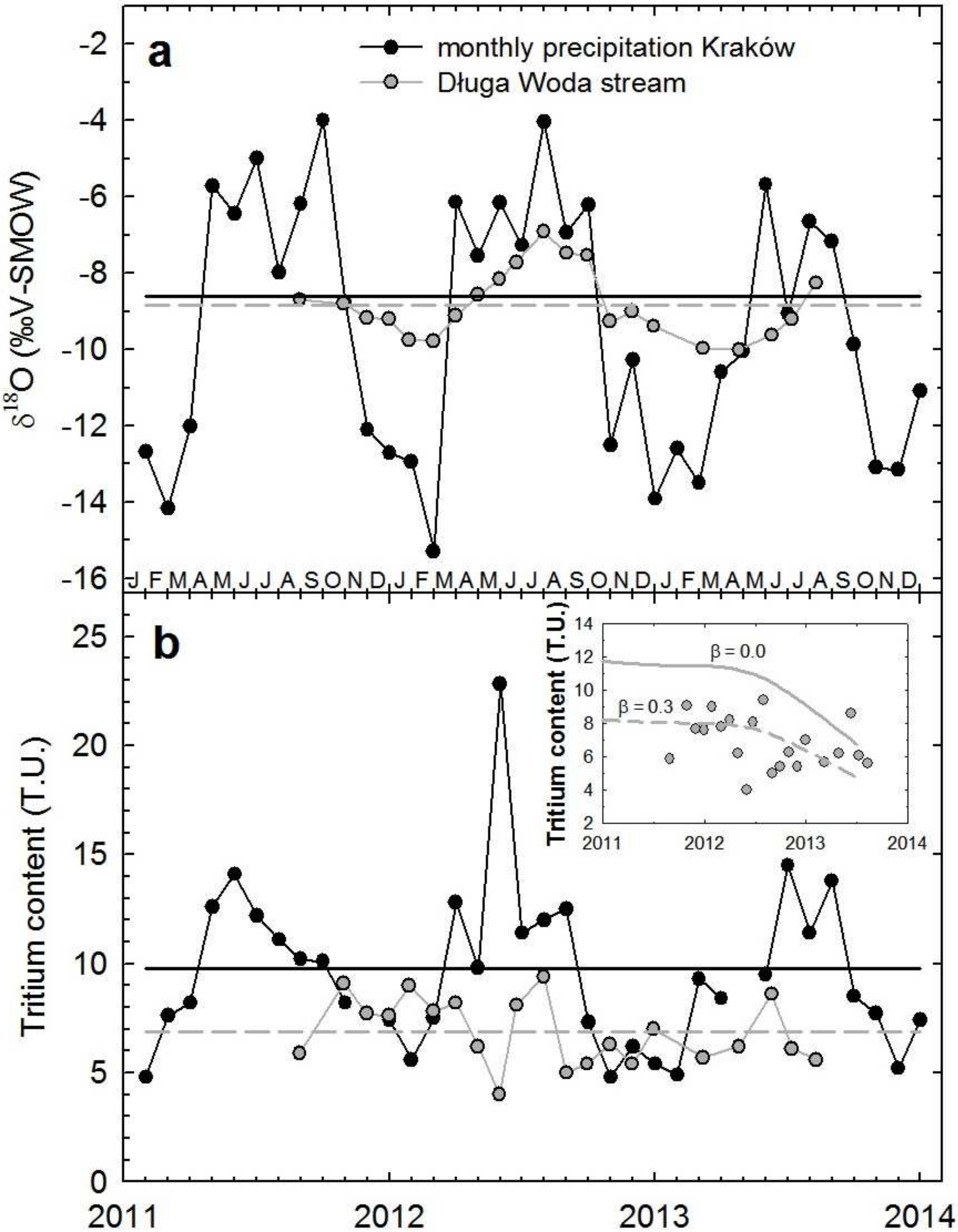

Figure 9. Seasonal variations of $\delta^{18}O$ **(a)** and tritium content **(b)** in the Dluga Woda stream during the period 2011-2013. The insert in Fig. 9b shows the comparison of modeled and measured tritium concentrations in the Dluga Woda stream. β is the fraction of tritium-free component in the total flow of the stream (see text for details).

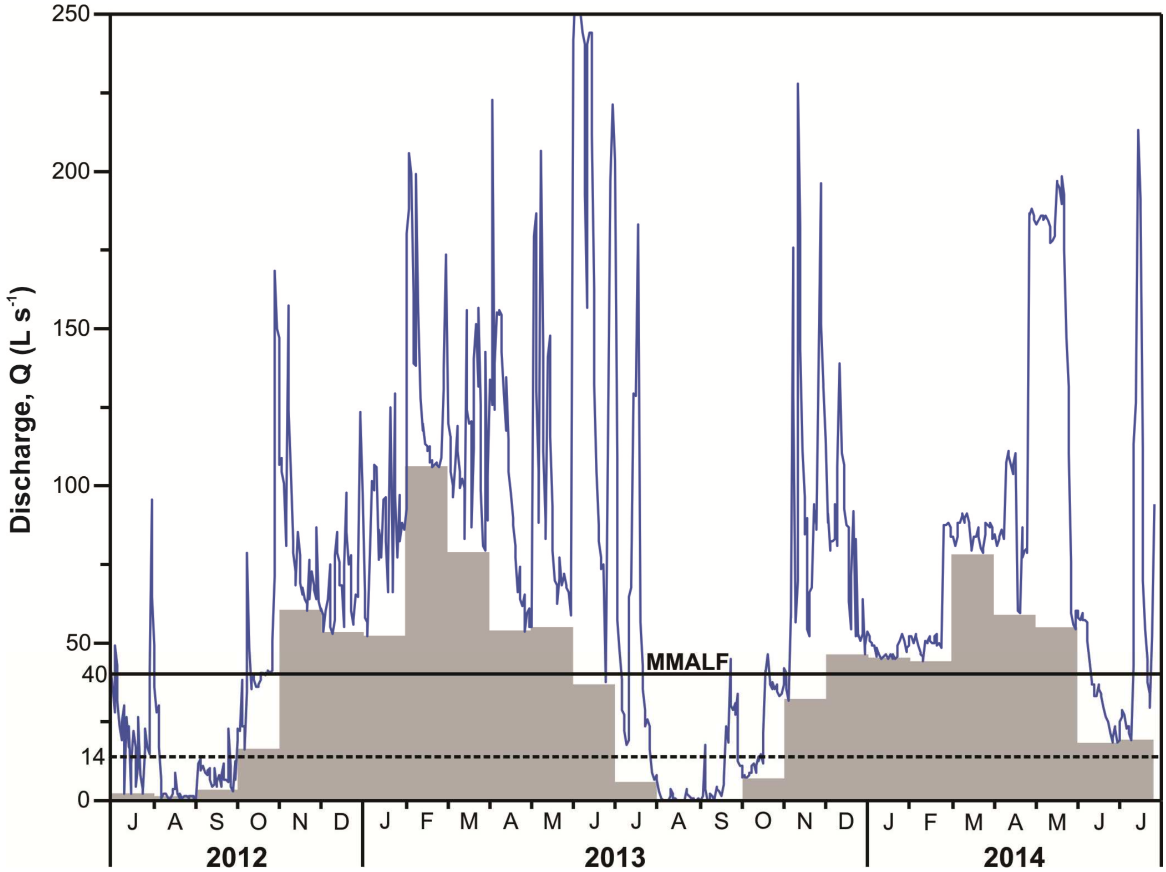

Figure 10. Hydrograph of Dluga Woda stream. Grey histogram reflects monthly low flows for the period July 2012-June 2014. The mean monthly annually low flow (MMALF) equal 40 $L\ s^{-1}$ corresponds to the baseflow of the stream. The characteristic discharge rate of 14 $L\ s^{-1}$ (cf. Fig. 11) is marked by dashed line (see text).

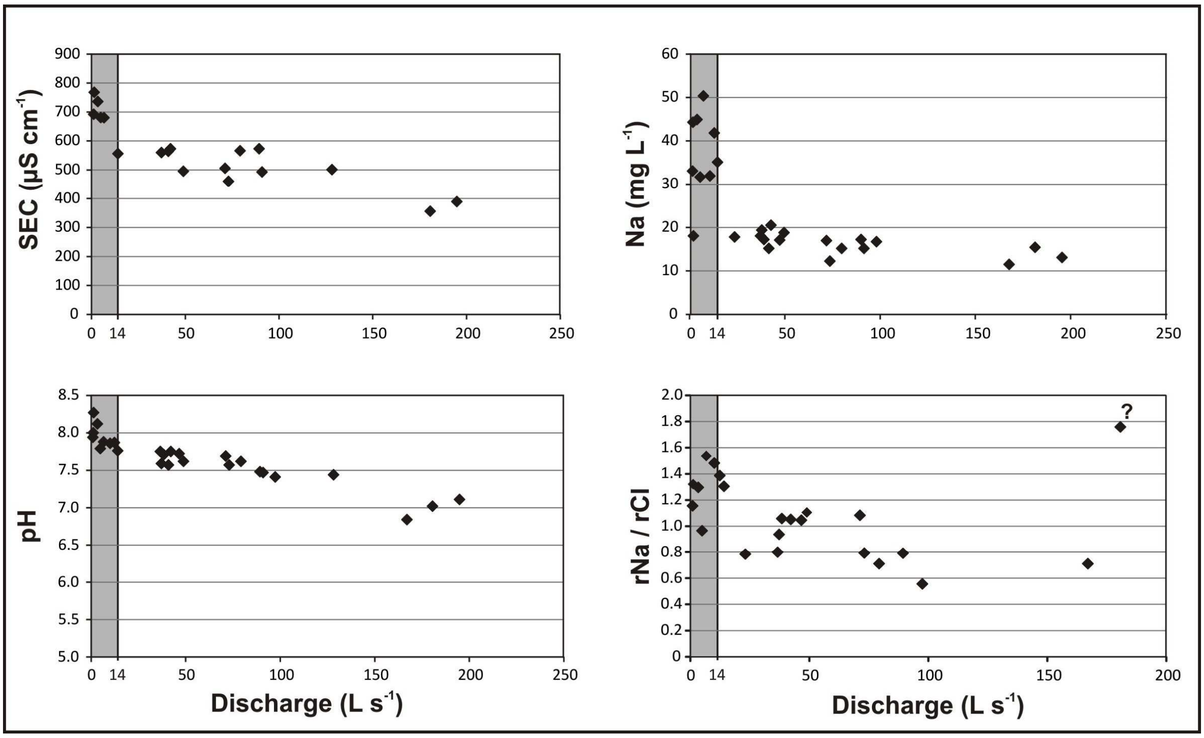

Figure 11. Electrical conductivity, pH, Na content and Na/Cl molar ratio in the Dluga Woda stream observed at monthly intervals during the period July 2012 - June 2013, as a function of stream discharge rate measured at gauge station G (cf. Fig. 2).

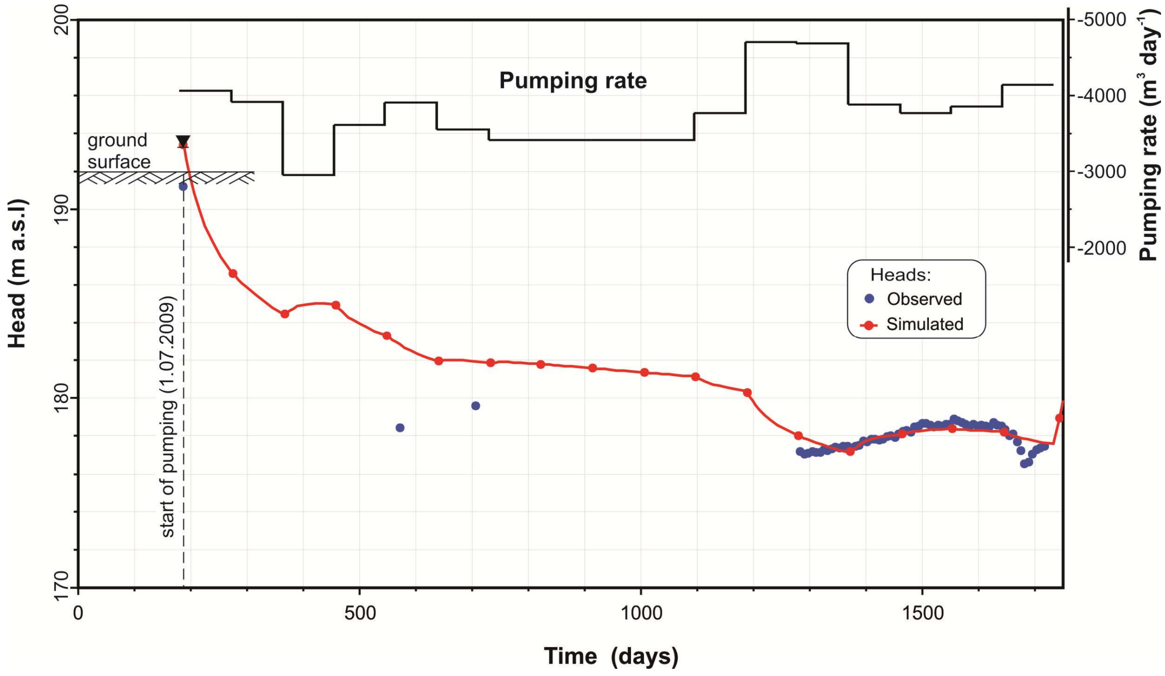

Figure 12. Changes of the hydraulic head in well No. 32 (cf. Fig. 2) after initialization of the operation of Wola Batorska wellfield in July 2009.

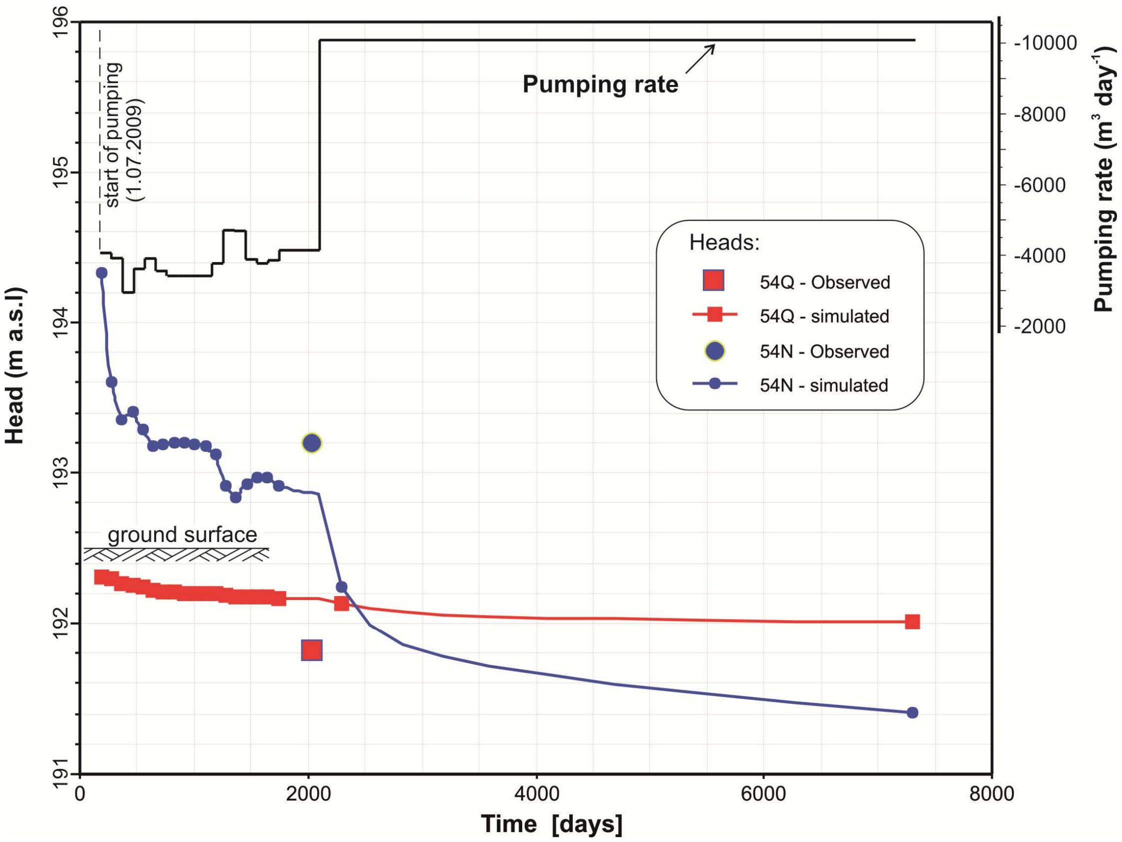

Figure 13. Changes of hydraulic heads in the shallow Quaternary and deeper Neogene aquifers in observation wells (54Q and 54N, respectively, cf. Fig. 2) simulated in the center of the Wielkie Bloto fen. Pumping rate of Wola Batorska wellfield from the start in July 2009 till October 2014 was simulated as actual abstraction. Later part of the diagram shows future levels of groundwater abstraction with maximum permitted capacity (10 080 m^3 d^{-1}).