Final Author Comments.

Anonymous Referee #1

We very much appreciate thorough review of the manuscript done by Referee #1. His insightful and comprehensive comments helped us to make numerous changes in the way how our data are interpreted, presented and discussed. The manuscript is in much better shape now. We followed large majority of the reviewer's comments and suggestions when preparing the revised version of the manuscript. In some points, however, we do maintain our views and opinions. Detailed comments addressing all questions/comments of Referee #1 are listed below.

<u>1. General comments:</u>

1.1. 3D Flow and Transport Modelling: this is the main drawback of your paper. The use of a 3D flow model is important because the paper must provide some quantitative evaluation of the long term impact to GDE (the forest and the fen) due to pumping. The only way to provide this is by a flow and transport model but: - You must dedicate more text to describe how you have implemented and calibrated the model - You must show the results of the possible impact not only showing, in a purely qualitative way, the comparison between two contour maps but estimating the expected shortage of groundwater fluxes to the fen or the expected lowering of the water table. - Your on site investigation, through direct push drillings and sampling and by the geochemical approach, has provided you the needed data to calibrate and properly design the model but you have to use the model in a quantitative way answering the following questions: - - how much is the shortage of groundwater seepage to the fen and to the river, depending of different scenarios of expected pumping rate? - How much is the lowering of water table and the effects against the forest, depending of different scenarios of expected pumping rate? In the chapter dedicated to the model you simply talk about a generic time of piezometric delay but it is a purely qualitative chapter. But you must be quantitative in forecasting scenarios; applied hydrogeology must provide quantitative estimates. You write in the conclusions "strongly suggest that prolonged groundwater abstraction through the newly-established cluster of water-supply wells at maximum permitted capacity (ca. 10 000m^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" and in the abstract "may trigger drastic changes in the ecosystem functioning, eventually leading to its degradation" but: how much is the risk? How much is the water table drop? How intense are these changes?

We appreciate this comment . As in the meantime (July 2014) two new boreholes were drilled in the center of Wielkie Bloto fen (cf. Fig. 2 of the revised manuscript) and hydraulic heads were measured in both the shallow Quaternary aquifer and the deeper Neogene aquifer, it was possible to make additional model runs to determine the response of the system to operation of newly-established Wola Batorska wellfield, including the chosen scenario of future exploitation, and compare them with the measurements. These new model runs allowed us to be more quantitative in defining the risk to the investigated GDW associated with exploitation of Neogene aquifer (see Fig. 13 and revised text).

1.2. In the conceptual model of the site you can rely on direct drillings and geological logs or on geophysics. You begin the description of your geologic conceptual model with geophysics. It's an error: geophysics is an indirect investigation tool and can accomplish and integrate the geological direct investigations but not be the starting point. So improve the description of your conceptual model starting from geological logs and drillings. You performed direct push at shallow depth. You should have direct geological information.

We accept the criticism. Appropriate parts of the text have been thoroughly revised. New information coming from boreholes drilled in the center of Wielkie Bloto fen in July 2014 was added in the revised version.

1.3. …particularly in the introduction, the text is too much long and boring in some parts, it seems more the introduction of a master thesis. Some parts could be integrated in material and methods, some parts could be strongly reduced, some parts should be skipped (the less useful for the investigation; see the specific notes)

The Introduction has been thoroughly modified, following suggestions of the reviewer.

1.4. About vertical fluxes between the confined aquifer and the fen, have you head profile data showing how hydraulic head changes along the vertical in order to demonstrate upward seepage of groundwater from Bogucice Sands aquifer toward Wielkie Bloto?. Was you able to measure head? Comment upon that.

Availability of two new boreholes drilled in the center of Wielkie Bloto enabled measurements of hydraulic heads both in the upper Quaternary aquifer as well as in the lower Neogene aquifer. They are discussed in the revised text and shown in Fig. 13

1.5. A Piper diagram should be useful to map the hydrochemical facies in a more quantitative way.

The Piper diagram was added as a separate, new figure. It confirms the hydrochemical evolution of the analysed waters already apparent from Fig. 6 of the old version of the manuscript.

2. Specific comments:

THE STUDY AREA.

2.1. Comment upon the fact that the runoff value is higher than the difference between total precipitation and actual evapotranspiration. Express the data in a more precise way. Is evapotranspiration actual, I presume?

It should read "725 mm" instead of "...around 700 mm". The text has been modified accordingly.

2.2. The range 8-28% of coefficient of infiltration is related to outcropping lithology? Comment upon it.

Yes. Additional explanation was added in the revised version.

2.3. Comment and describe the degree of consolidation or looseness of sands (any cementation? Grain-size?), parameters important from hydrogeologic standpoint. You talk of sands but also of sandstones. Clarify better. They are sands or sandstones?

The aquifer matrix consists mainly of unconsolidated sands, locally sandstones with carbonate cement. The text has been modified accordingly.

2.4. What do you mean as "disposable resources" in hydrogeological terms? A safe yield? A maximum sustainable pumping rate? A recharge rate? Explain better and also make reference to the references and the evaluation method.

The proper expression should be "safe yield". The text has been modified accordingly
The safe yield value, originated from Kleczkowski et al. (1990), was evaluated according to Polish low taking into account recharge rate, sustainable pumping rate and environmental water requirements. That value was confirmed by Górka et al. (2010).

2.5. Is there a relationship between the vegetative assemblage and the depth to water table? Where depth to water table is higher than 2 m the typology of the forest is different from areas with shallower water table? If yes describe shortly in which sense.

Although detailed discussion of the relationship between plant assemblages and the depth of water table in the study area is beyond the scope of this work, we provided in the revised text some additional information about the typology of the forest and the water table position, following appropriate Manual worked out for forest managers

MATERIAL AND METHODS.
2.6. Change the order of description, starting with the field tools, the sampling tools and finally the analytical methods, in a logical order.

Agreed. The section "Materials and methods" has been extended and modified according to the suggestions of both reviewers.

2.7. The description of the modelling is too much detailed for a chapter dedicated to material and methods and too much simplicistic and low understandable for a chapter dedicated to the model description. If the modelling is important for your research dedicate a chapter to it, otherwise skip it. In the material and method it is enough to describe the code. Moreover the description is confusing, mixing together flow, transport, calibration, in a messy way

We maintain our opinion that the description of modelling in "Material and methods" is of adequate extent. Modeling is one of several tools used to assess the extent of groundwater dependence of terrestrial ecosystem studied. Nevertheless, we modified the text following the suggestions of the reviewer. Also, section 4.5 has been largely extended and Figure 12 was replaced by new figure summarizing the results of additional model runs (Fig. 13).

RESULTS AND DISCUSSION.

2.8. Skip completely the paragraph of introduction. It's redundant. You can integrate the informations about the goal of the various investigations in the material and method section.

Done.

2.9. Delineation of Quaternary cover It's strange to begin with indirect surveys (geophysics) that can accomplish and integrated direct data but cannot be the foundation of the conceptual model. Shallow geoelectrics has a high degree of inaccuracy in represent the structure and stratigraphy of subsoil and this is more true in your case for the very low expected thickness of clay layer and the noise that different sources (water content, grain size, organic content, air content) can provide to determination of resistivity. It's very strange to begin the conceptual model with geophysics and not with direct data.

The situation has changed because direct information about lithology and stratigraphy of the Quaternary cover, as well as underlying Neogene aquifer, became available thanks to new boreholes drilled in the center of Wielkie Bloto in July 2014. The chapter was revised accordingly, by putting in front geological information.

2.10. What about the importance of GPR? Simply to define the position of the bottom of moorsh? How this is important for your study?

The GPR surveys were carried out basically to define the position of degraded peat layers. Mineralization of peat is one of the processes which can be triggered by water table lowering.

2.11. The delineation of Quaternary cover should be completely rewritten,. Begin it starting from direct data (boreholes) and then, eventually, integrate it with geophysics. You cannot base your conceptual model simply upon geophysics

See comment to point No. 9.

2.12. Geochemical evolution A Piper diagram should be useful to map the hydrochemical facies in a more quantitative way.

Agreed. The Piper diagram was added in the revised version.

2.13. Water balance of the Dluga Woda catchment Explain why the MTT of 3.2 months is not affected by the contribution of 30% of slow recharge water (presumably with a different input signal of delta ^{18}O; see sentence at the end of 9688), whereas you see this contribution in the tritium Clarify how the flow rate measurement were taken in relationship to rainfall. Independently or not during rainfall event?

Good point. Note that tritium is in this case a far more sensitive indicator of the presence of additional component than the heavy stable isotopes are. We mix one component which has ca. 10 TU with other component which has zero tritium. This is why, with 30 % contribution of the tritium free component, the two horizontal lines in Fig. 9b are so far away. In case of stable isotopes, the difference is not that big. The expected ^{18}O isotope composition of tritium-free component is in the order of -9.8‰ (average of groundwater in the study area which is of Holocene age), to be compared with -8.61‰ of the 'recent' component (weighted mean $\delta^{18}O$ of local precipitation). The apparent difference between weighted mean $\delta^{18}O$ 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, corresponds to ca. 20% contribution of the 'old' component. The text has been modified accordingly.

2.14. Explain better, in a short statement, how Wundt (a very old method!) determines the base flow. The term "low flow" sounds not good, also because in some months it is not so low. If the "low flow" is, as I presume, the base flow component of total runoff (coming from the discharge of the aquifer), I think, independently of Wundt, that base flow is a better term. MMBF, at the end, will be the mean monthly base flow. It's more correct from a hydrogeologic standpoint.

The fact the Wundt method is an old one, does not compromise its value. The method is based on measurements of the daily flow rates. To obtain more precise assessment of the Dluga Woda baseflow, a 2-year (instead of 1-year) hydrograph was analyzed in the revised version of manuscript. Additional explanation of Wundt method was included in the revised text. The term "low flow" is used by hydrologists to define lowest flow during the given month or year. The monthly mean annual low flow (MMALF) reflects the discharge of the aquifer and may represent the annual baseflow in the river catchment.

TABLES AND FIGURES
Table 1: badly sealed well (not "liquidated")

Done.

Table 4: put the meaning of n.m. in the legend

Done. "n.m." signifies "not measured".

Fig.1: indicate the time of reference or date for the head measures

Done.

Fig.2: some of the terms in the legend are poorly understandable for not very specialistic experts (gyttia, moorsh) define it in more hydrogeologically meaningful terms and more widely known for wetland experts: poorly decayed peat, acrotelm, catotelm, for example, or other terms

The term 'moorsh' is used in German and Polish peat soil classification. As too specialized, the term has been changed to 'mineralized peat soil'. Gyttja has no appropriate synonim but is a widely used term by paleoclimatologists and paleohydrologists.

The position of 11 VES soundings should be better rendered in the legend; if one dot is a VES, in the legend you have to maintain only one dot.

Done.

Fig.4: the resistivity numbers in the upper panel are too much little. In the legend the second point is b and not c.

Figure 4 has been corrected.

Fig.8: on the x axis (time) put in evidence the months of the year to better appreciate the seasonality. Explain in the legend the meaning of the small graph inside the lower diagram, there is non explanation of that (characters perhaps are too much little).

Done

Fig.11: I guess that the symbol to the right top is ground surface. Put in evidence this attribution

Done

TECHNICAL CORRECTIONS
r.8: 9674 provided better than supplemented r.11: 9674 to be assessed better than quantified

Done

r.14: 9674 Bogucice sand aquifer should be introduced before at r.28 of page 9673

Done

r.4: 9675 Badenian: which period? Miocene? specify

Done

r.17-19: 9675 I suggest to skip these unuseful oxides and traces elements if they do not affect meaningfully the discussion and conclusion of the paper

Done

r.25: 9675 aquitard is better than semi-permeable

Done

r.27: 9675 hydraulic head or piezometric surface (not water table).

Done

r.27: 9675 go to a new row after seepage.

Done

r.11: 9676 do not use the term "diffuse", related to agricultural and not industrial sources.

Related paragraph was omitted in the revised section

r.11: 9677 which kind of land improvement?.

Done. This expression was replaced by "drainage works" .

r.21: 9677 not water table, the wells pump put groundwater from deep aquifer

Done. Water head has been used.

r.1: 9678 upward leakage (or flow) is a better term (respect to diffusion)

Done. We use 'upward seepage' throughout the text

r.3: 9678 integrated better than supplemented

Done

r.6: 9678 which code was used?

The type of code and all relevant details are described in Materials and Methods section (r.13 9680).

MATERIALS AND METHODS
r.7: 9679 PVC. Describe the depth and filter position and also diameter of the tubes; open stand-pipes is a better term than tubes

Done

r.22: 9679
badly liquidated? What does it mean? Use a better term, more clear. It's not clear if the spring is natural or not. Perhaps it's not a spring but it is a flowing not properly sealed artesian well.

The notation 'Anna Spring' (in quotes) was used in the revised text to indicate that this is not natural spring. Information about geophysical prospecting conducted in the area in 1970s as well as chemistry and isotopic composition of water from this 'spring' strongly suggest that this is fact not properly sealed artesian well tapping the Neogene aquifer. Additional explanation has been added in the revised manuscript.

r.9: 9680 Phreatimeter

The term "water level meter" was used in the revised version.

r.18: 9680 You talk about rectangular cell but they are square in plain section

"Rectangular cell" is one of options of the grid selection in the Visual MODFLOW. Note that squares are a sub-set of rectangle family of figures.

r.20: 9681 Any measuring unit?

This is a relative quantity. Appropriate explanation was added in the revised text *r.1-5: 9683 skip these unuseful information*

Done

r.20: 9683 in the study area

Done

r.26: 9683 "and shows values around 64 pMC" (comment upon this value, what does it imply?)

Additional explanation was included in the revised text.

r.22: 9684 comment upon the value and the significance of these value of partial pressures of carbon dioxide

Included in the revised text.

r.6: 9687 which kind of difficulties? Describe better and in which sense they could bias the results

The phrase was deleted. Inspection of the results of chemical analyses revealed that there was a typing mistake in Table 2 .

r.26: 9687 Maloszewski et al. is missing in the references

This reference was added to the list of references

r.9: 9688 specify "relatively to the river section used for sampling water"

Done.

r.23: 9688 explain a bit the insert graph in fig.8b and the meaning of parameters

Done.

r.7: 9691 a K of 1E-5 m/s seems to me very low for an important sandy aquifer like yours. Are you sure about this value? Comment upon it

K value of 1E-5 m/s is correct. It was estimated on the basis of the pumping tests.

Anonymous Referee #2

We appreciate the comments of Referee #2. They helped us to improve the manuscript. Detailed responses addressing all points raised by the reviewer are listed below.

1. General comments

1.1. Description and pertinence of the tools should be stated in the introduction – authors should make a link with the context of the study area. Some of these aspects are included – but not in the introduction

We agree. The Introduction has been thoroughly modified accordingly.

1.2. In most parts of the ms, authors used qualitative estimate instead giving number. I believe that quantitative estimate will be more appropriate to estimate impact.

We accept this criticism (cf. reply to Referee #1). The text has been extended and quantitative aspects of the discussion were strengthen.

1.3. Sampling network should be developed in section materials and methods

We agree. The section Materials and methods has been thoroughly modified and extended. New data were added in the revised version of the manuscript.

1.4. In page 5 first paragraph, authors should give the scientific basis for depth classification – is this classification related to depth of the root zone or not.

Agreed. The required information was provided in the revised version of the manuscript

1.5. Comments on model result are not well developed

We accept the criticism, expressed also by Referee #1. The modeling section was thoroughly revised and extended. Quantitative estimate of the expected impact was included in the revised manuscript.

1.6. One striking point is the lack of discussion taking into account the isotopic, hydrochemistry and model result in term of flow exchange and contribution and validate them with the system functioning and stream flow with regard the new pumping stress

Additional sections addressing this issue were added in the revised manuscript (see revised section 4.5).

1.7. Abstract does not reflect main findings of the ms

Abstract has been modified accordingly.

2. Specific comments

2.1. A lot of style and grammatical errors – may be some revisions for the writing will help

Although Referee # 1 was of somewhat contrasting opinion (see page C4013 of his comments, line 5 from the top), we will nevertheless try to improve the writing.

2.2. References in text should be in date order

Done.

2.3. Page 7 last paragraph of conceptual model should be in this part – however, I propose to authors to add a section related to hydrodynamic in section "results" where conceptual model should be described

As adequate conceptual model is the starting point of any investigation, we think that its description fits better to the section "Study area" than to "Results and discussion" were we make reference to it and discuss whether any changes in the model are needed in light of the results obtained.

2.4. First paragraph and sentence in page 9 is too long.

This sentence has been removed and the discussion was extended by adding a new paragraph presenting the stratigraphy and lithology of the aquifer in the area of Wielkie Bloto fen obtained from drilling performed in July 2014 (see revised text).

Editor Initial Decision: Reconsider after major revisions (17 Dec 2014) by Christine Stumpp

Authors' response:

Two reviewers thoroughly evaluated the manuscript. The main points raised were 1) missing quantitative interpretation of modeling results, 2) restructuring of some sections in the introduction, material & methods and in the results chapter, 3) more specific information about the modeling approach, 4) more specific interpretation about environmental tracer data.

The authors responded to all the raised concerns. It was mentioned that corrections will be implemented into the text. Sometimes, too little information was provided what these new facts in the revised version will be. E.g., the authors have not responded to the question whether evaporation is actual evaporation or not. However, I am convinced that comments like this will be considered in the revised manuscript.

The evaporation is actual evaporation and this term was added to the text.

When restructuring the introduction, the authors should keep in mind the very first comment given by the editor, i.e. not stick too much to the case study, but keep it more general because there are lots of things we can learn also for other sites with similar issues.

In the revised introduction general comments on conflict situations between GDEs and human needs are given.

Second, the authors answered that more information and figures are included into the manuscript. Certainly, the referees were asking for more information and more detailed discussion; however, the manuscript should not be too long in the end. It should be carefully considered to provide some of the Figures or Tables as supplement.

The revised text size is nearly the same as before. More information were added to the manuscript but at the same time some sections were strongly reduced. Only one new figure (Piper diagram) was added to the manuscript.

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

A.J. Zurek[1], S. Witczak[1], M. Dulinski[2], P. Wachniew[2], K. Rozanski[2], J. Kania[1], A. Postawa[1], J. Karczewski[1], and W.J. Moscicki[1]

[1] AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, Krakow, Poland

[2] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

Correspondence to: A.J. Zurek (zurek@agh.edu.pl)

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 noticeable 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. ~~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) 3D 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. 10000 $m^3 d^{-1}$), may trigger drastic changes in the ecosystem functioning, eventually leading to its degradation.~~ 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 space- and time-variable availability of groundwater to ecosystem organisms. 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. 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: (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). 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 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 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.

~~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) 3D flow and transport modeling.~~

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 ~~this~~ 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 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^{o}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 to 28 percent 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 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 land improvement 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 evapotranspiration 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). 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).

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 aquifer (MGWB 451) is located on the border of the Carpathian Foredeep Basin and belongs to the Upper Badenian.

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. 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 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. 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 variable thickness, from a fraction of meter in wetland areas to approximately 30 meters in the recharge area of the

~~deeper aquifer layers.~~ The recharge of groundwater, related to outcropping lithology, is in the order of 8 to 28 percent of annual precipitation.

~~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 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.

~~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 Niepolomicka" (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 Bloto, 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.~~

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 3D 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.

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 (~~cf.~~ 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. ~~PCV tubes~~ 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. ~~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, 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 ~~sounding device~~ 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' ~~Anna spring~~ (No. 52 in Fig. 2). Groundwater appearance at this side is linked to badly sealed borehole drilled in 1970s for seismic prospecting. ~~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 (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 ~~groundwater flow~~ 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 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 (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 on the extent of water-bearing horizons. Three water-bearing layers were distinguished in the model: one layer in the shallow Quaternary aquifer and two layers in the deeper Neogene aquifer the shallow Quaternary aquifer and two Neogene aquifers.. 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. 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.

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 3D 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~~

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 ~~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 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 ~~we discuss~~ only one echogram representing the distance of approximately 200 m (profile P1 in Fig. 2) is discussed. ~~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 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 ~~degradated peat (moorsh)~~ 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 ~~Bogucice Sands~~ 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 - 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 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' ~~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 ~~presented~~ 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' ~~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 ~~of the Bogucice Sand aquifer~~ 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 ~~Bogucice Sands~~ 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. ~~7~~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 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~~ 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 ~~Bogucice Sands~~ 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 ~~8~~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. ~~8~~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 ~~8~~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. ~~8~~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 ~~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 $\delta^{18}O$ in precipitation for the period January 2011 – December 2013 (-8.61‰) and the mean ^{18}O content of the Dluga Woda stream (-8.84‰) 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.~~ The contribution of tritium-free component also explains the difference between weighted mean $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 – ~~June 2013~~ July 2014 is shown in Fig. ~~9~~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~~; 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~~ presented in Fig. ~~9~~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 – ~~June 2013~~ July 2014 was equal ~~46~~ 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 ~~linked with~~ accompanied by substantial variability of the physico-chemical parameters of the stream water (cf. Table 4 and Fig. ~~10~~11). The relationships between SEC, pH, Na content, Na/Cl molar ratio and the discharge rate of Dluga Woda shown in Fig. ~~10~~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}) by waters seeping through clayey sediments separating Neogene water-bearing layers of the Bogucice Sands aquifer 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 4640 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 1112 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 1112 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. 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):

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

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 ~~11~~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.

~~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 $m^3 day^{-1}$ 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 $m^3 day^{-1}$) and for the envisaged exploitation of the Wola Batorska wellfield with the maximum permitted capacity (10080 $m^3\ d^{-1}$).~~

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.

Acknowledgements. The study was supported by the GENESIS project funded by the European Commission 7FP (project contract 226536) and by statutory funds of the AGH University of Science and Technology (projects no. 11.11.220.01 and 11.11.140.026).

References

Alley, W.M., Healy, R.W., LaBaugh, J.W., and Reilly, T.E.: Flow and storage in groundwater systems, Science, 296, 1985-1990, 2002.

Appelo, C.A.J., and Postma, D.: Geochemistry, Groundwater and Pollution, 2nd Edn., A.A. Balkema Publishers, Amsterdam, 2005.

Bertrand, G., Goldscheider, N., Gobat, J.-M. and Hunkeler, D.: Review: From multi-scale conceptualization to a classification system for inland groundwater-dependent ecosystems, Hydrogeol. J., 20, 5–25, 2012.

Bobachev, A.: Resistivity Sounding Interpretation – IPI2Win, Moscow State University, 2010.

Boulton, A.J.: Chances and challenges in the conservation of groundwaters and their dependent ecosystems, Aquat. Conserv., 15, 319–323, 2005.

Chełmicki W., Ciszewski S. and Żelazny M.: Reconstructing groundwater level fluctuations in the 20th century in the forested catchment of Drwinka (Niepołomice Forest, S. Poland), in: Interdisciplinary Approaches in Small Catchment Hydrology: Monitoring and Research, Proc. of the 9th ERB Conference, Demanovska dolina, Slovakia, 25-28 September 2002, IHP Technical Documents in Hydrology, 67, edited by: Holko, L., Miklanek, P., UNESCO, Paris, 203-208, 2003.

Clark, I.D. and Fritz, P.: Environmental Isotopes in Hydrogeology. Lewis Publishers, NY,1997.

Coplen, T.: New guidelines for reporting stable hydrogen, carbon and oxygen isotope-ratio data. Geochim. Cosmochim. Ac., 60, 3359-3360, 1996.

Daniels, D.J.: Ground Penetrating Radar, 2nd Edn., The Institution of Electrical Engineers, London, United Kingdom, 2004.

Dresel, P.E., Clark, R., Cheng, X., Reid, M., Terry, A., Fawcett, J. and Cochrane, D.: Mapping Terrestrial Groundwater Dependent Ecosystems: Method Development and Example Output, Department of Primary Industries, Melbourne, Victoria, 66 pp, 2010.

Dulinski, M., Rozanski, K., Kuc, T., Gorczyca, Z., Kania, J. and Kapusta, M.: Evolution of radiocarbon in a sandy aquifer across large temporal and spatial scales: case study from southern Poland, Radiocarbon, 55, 905-919, 2013.

EC: Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy, OJ L 327, 22 December 2000, Office for Official Publications of the European Communities, Luxembourg, 2000.

EC: Common Implementation Strategy for the Water Framework Directive (2000/60/EC). The role of wetlands in the Water Framework Directive, Guidance document No. 12, Office for Official Publications of the European Communities, Luxembourg, 2003.

EC: Directive 2006/118/EC of the European Parliament and of the Council on the protection of groundwater against pollution and deterioration, OJ L 372, 27 December 2006, Office for Official Publications of the European Communities, Luxembourg, 2006.

EC: Common Implementation Strategy for the Water Framework Directive. Guidance on Risk Assessment and the Use of Conceptual Models for Groundwater, Guidance document No. 26, Office for Official Publications of the European Communities, Luxembourg, 2010.

EC: Common Implementation Strategy for the Water Framework Directive. Technical Report on Groundwater Dependent Ecosystems, Technical Report 6, Office for Official Publications of the European Communities, Luxembourg, 2011.

Florkowski, T., Grabczak, J., Kuc, T. and Rozanski, K.: Determination of radiocarbon in water by gas or liquid scintillation counting, Nukleonika, 20, 1053-1062, 1975.

Fontes, J.C. and Garnier, J.M.: Determination of the initial ^{14}C activity of total dissolved carbon: a review of existing models and a new approach, Water Resour. Res., 15, 399-413, 1979.

Forest Management Manual, The State Forests National Forest Holding, Warsaw, Poland, 2012 (in Polish).

GENESIS: Deliverable 4.3: New indicators for assessing GDE vulnerability, www.thegenesisproject.eu, 2012.

Górka, J., Reczek, D., Gontarz, Ż. and Szklarz, K.: Annex to the Project Documenting Disposable Reserves of Groundwater and Delineating Protection Zones of Bogucice Sands Aquifer (GZWP 451), SEGI-AT Sp. z o.o., Warszawa, Poland, 2010 (in Polish).

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G.: MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, Reston, Virginia, 2000.

Hatton, T. and Evans, R.: Dependence of Ecosystems on Groundwater and its Significance to Australia, LWRRDC Occasional Paper No 12/98, Canberra, Australia, 1998.

Hill, M.C. and Tiedeman, C.R.: Effective Groundwater Model Calibration With Analysis of Data, Sensitivities, Predictions, and Uncertainty, John Wiley and Sons Inc., Hoboken, NJ, 2007.

Hose, G.C., Bailey, J., Stumpp, C. and Fryirs, K.: Groundwater depth and topography correlate with vegetation structure of an upland peat swamp, Budderoo Plateau, NSW, Australia, Ecohydrol., 7, 1392-1402, 2014.

Kinzelbach, W.: Groundwater Modeling: An Introduction with Sample Programs in BASIC. Elsevier Science Publishers B.V., Amsterdam, The Netherlands, 1986.

Kleczkowski, A.S. (ed.): The Map of the Critical Protection Areas (CPA) of the Major Groundwater Basins (MGWB) in Poland, Institute of Hydrogeology and Engineering Geology, Academy of Mining and Metallurgy, Krakow, 1990.

Kløve, B., Ala-aho, P., Bertrand, G., Boukalova, Z., Ertürk, A., Goldscheider, N., Ilmonen, J., Karakaya, N., Kupfersberger, H., Kværner, J., Lundberg, A., Mileusnic´, M., Moszczynska, A., Muotka, T., Preda, E., Rossi, P., Siergieiev, D., Šimek, J., Wachniew, P. and Widerlund, A.: Groundwater dependent ecosystems: Part I – Hydroecology, threats and status of ecosystems. Environ. Sci. Pollut. R., 14, 770–781, 2011a.

Kløve, B., Ala-aho, P., Allan, A., Bertrand, G., Druzynska, E., Ertürk, A., Goldscheider, N., Henry, S., Karakaya, N., Karjalainen, T.P., Koundouri, P., Kværner, J., Lundberg, A. Muotka, T., Preda, E., Pulido Velázquez, M. and Schipper, P.: Groundwater dependent ecosystems: Part II – ecosystem services and management under risk of climate change and land-use management, Environ. Sci. Pollut. R., 14, 782–793, 2011b.

Kløve, B., Ala-Aho, P., Bertrand, G., Gurdak, J.J., Kupfersberger, H., Kværner, J., Muotka T., Mykrä, H., Preda, E., Rossi, P., Bertacchi Uvo, C., Velasco, E., Pulido-Velazquez, M.: Climate change impacts on groundwater and dependent ecosystems, J. Hydrol., 518, 250-266, 2014.

Koefoed, O.: Geosounding Principles, 1. Resistivity Sounding Measurements, Elsevier, Amsterdam Oxford New York, 1979.

Lipka, K.: The Wielkie Błoto Peat Bog in the Niepołomice Forest Near Szarów. Przewodnik LX Zjazdu PTG, Kraków, 143-146, 1989 (in Polish).

Lipka, K., Zając, E. and Zarzycki, J.: Course of plant succession in the post-harvest and post-fire areas of the Wielkie Bloto fen in the Niepolomice Primeveal Forest, Acta Agrophysica 7, 433-438, 2006.

Łajczak, A.: Geomorphological and hydrographic characterization of the „Royal Fern" nature reserve in the Niepolomice Forest, Ochrona Przyrody, 54, 81-90, 1997 (in Polish).

Małoszewski, P., Rauert, W., Stichler, W. and Herrmann, A.: Application of flow models in an Alpine catchment area using tritium and deuterium data, J. Hydrol., 66, 319-330, 1983.

Maloszewski, P. and Zuber, A.: Lumped parameter models for the interpretation of environmental tracer data, in: Manual on Mathematical Models in Isotope Hydrogeology, IAEA-TECDOC-910, International Atomic Energy Agency, Vienna, 9-58, 1996.

Mościcki, J.: Characterization of near-surface sediments based on DC resistivity soundings in the Starunia area, fore-Carpathian region. in: Ukraine. Polish and Ukrainian Geological Studies (2004-2005) at Starunia – the Area of Discoveries of Woolly Rhinoceroses, Polish Geological Institute and Society of Research on Environmental Changes "Geosphere", Warszawa-Kraków, 103-114, 2005.

Mook, W.G. and van der Plicht, J.: Reporting ^{14}C activities and concentrations, Radiocarbon, 41, 227-239, 1999.

Parkhurst, D.L. and Appelo, C.A.J.: User's Guide to PHREEQC (Version 2) – A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations, USGS, Water-Resources Investigations Report 99-4259, Reston, Virginia, 1999.

Pettit, N.E., Edwards, T., Boyd, T.C. and Froend, R.H.: Ecological Water Requirement (Interim) Framework Development. A conceptual framework for the maintenance of groundwater dependent ecosystems using state and transition modelling, Centre for Ecosystem Management report 2007-14, ECU Joondalup, Australia, 2007.

Plado, J., Sibul, I., Mustasaar, M. and Jõeleht, A.: Ground-penetrating radar study of the Rahivere peat bog, eastern Estonia, Est. J. Earth Sci., 60, 31-42, 2011.

Plummer, L.N., Prestemon, E.C., and Parkhurst, D.L.: An Interactive Code (NETPATH) for Modeling NET Geochemical Reactions Along a Flow PATH, Version 2.0, Water-Resources Investigations Report 94-4169, USGS, Reston, Virginia, 1994.

Porebski, S. and Oszczypko, N.: Lithofacies and origin of the Bogucice Sands (Upper Badenian), Carpathian Foredeep, Proceedings of Polish Geological Institute, CLXVIII, 57–82, 1999 (in Polish).

Rozanski, K.: Deuterium and oxygen-18 in European groundwaters - link to atmospheric circulation in the past. Chem. Geol., 52, 349-363, 1985.

Salminen, R. (Ed.): Geochemical Atlas of Europe. Part 1. Background Information, Methodology and Maps, Geological Survey of Finland. Espoo, 2005.

Schaffers, A.P. and Sýkora, K.V.: Reliability of Ellenberg indicator values for moisture, nitrogen and soil reaction: a comparison with field measurements, J. Veg. Sci., 11, 225-244, 2000.

Schlumberger Water Services: Visual MODFLOW 2011.1 User's Manual; For Professional Applications in Three-Dimensional Groundwater Flow and Contaminant Transport Modeling, Schlumberger Water Services, Kitchener, Ontario, Canada, 2011.

Sinclair Knight Merz Pty Ltd: Environmental Water Requirements of Groundwater Dependent Ecosystems, Environmental Flows Initiative Technical Report Number 2, Commonwealth of Australia, Canberra, 2001.

Slater, L.D. and Reeve, A.: Investigating peat stratigraphy and hydrology using integrated electrical geophysics, Geophysics, 67, 365-378, 2002.

Sophocleous, M.: On understanding and predicting groundwater response time, Ground Water, 50, 528–540, 2012.

Stuiver, M. and Polach, H.: Discussion: reporting of 14C data. Radiocarbon, 22, 355-363, 1977.

Wachniew, P., Witczak, S., Postawa, A., Kania, J., Żurek, A., Różański, K. and Duliński, M.: Groundwater dependent ecosystems and man: conflicting groundwater uses, Geol. Q., 58 (4), ~~doi: 10.7306/gq.1168, in press~~, 595-706, 2014.

Warner, B.G., Nobes, D.C. and Theimer, B.D.: An application of ground penetrating radar to peat stratigraphy of Ellice Swamp, southwestern Ontario, Can. J. Earth Sci., 27, 932-938, 1990.

Witczak, S., Zuber, A., Kmiecik, E., Kania, J., Szczepańska, J. and Różański, K.: Tracer based study of the Badenian Bogucice Sands aquifer, Poland, in: Natural Groundwater Quality, edited by: Edmunds, W.M. and Shand, P., Blackwell Publishing, Malden, MA, USA, 335-352, 2008.

Wundt, W.: Gewässerkunde, Springer-Verlag, Berlin Göttingen Heidelberg, 1953.

Zheng, C. and Wang, P. P.: MT3DMS, a Modular Three-Dimensional Multi-Species Transport Model for Simulations of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems, Documentation and User's Guide, US Army Engineer Research and Development Center Contact Report SERDP-99-1, Vicksburg, MS, 1999.

Zuber, A., Weise, S.M., Motyka, J., Osenbrück, K. and Rozanski, K.: Age and flow patter of groundwater in a Jurassic limestone aquifer and related Tertiary sands derived from combined isotope, noble gas and chemical data, J. Hydrol., 286, 87-112, 2004.

Zuber, A., Witczak, S., Rozanski, K., Sliwka, I., Opoka, M., Mochalski, P., Kuc, T., Karlikowska, J., Kania, J., Jackowicz-Korczynski, M. and Dulinski, M.: Groundwater dating with ^{3}H and SF_6 in relation to mixing pattern, transport modelling and hydrochemistry, Hydrol. Process., 19, 2247–2275, 2005.

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	~~431~~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 Bogucice Sands the Neogene aquifer, calculated using NETPATH code.

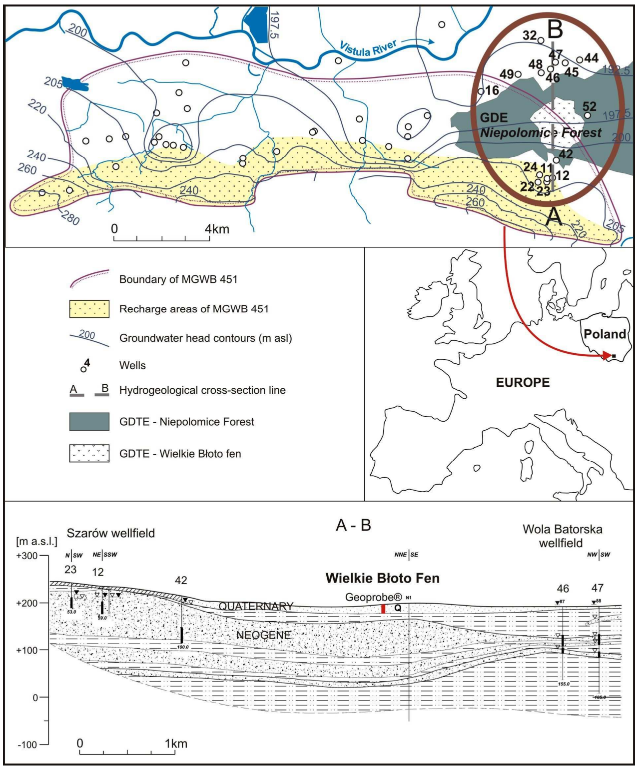
Well No.	Measured $\delta^{13}C_{TDIC}$ (‰V-PDB)	Computed $\delta^{13}C_{TDIC}$ (‰V-PDB)	Measured ^{14}C content [a] (pMC)	^{14}C age (ka)	Constraints	Phases
16	-13.3	-12.9	32.2	5	C, Ca, Mg, K, Na, S, Cl	calcite, dolomite, CO_2 gas, halite, sylvite, gypsum, exchange, CH_2O, Mg/Na exchange
32	-10.6	-10.6	<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		
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 (‰)	δ^{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



corrected:

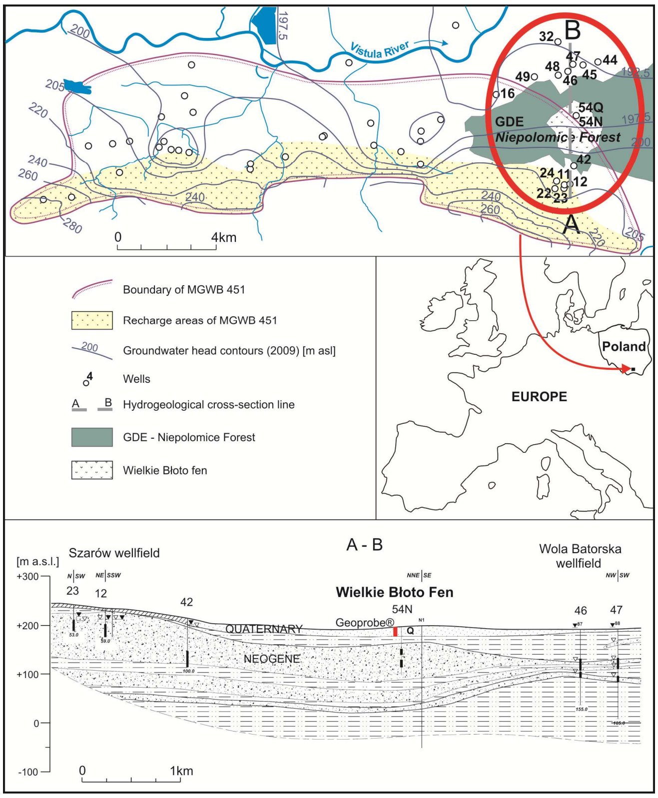
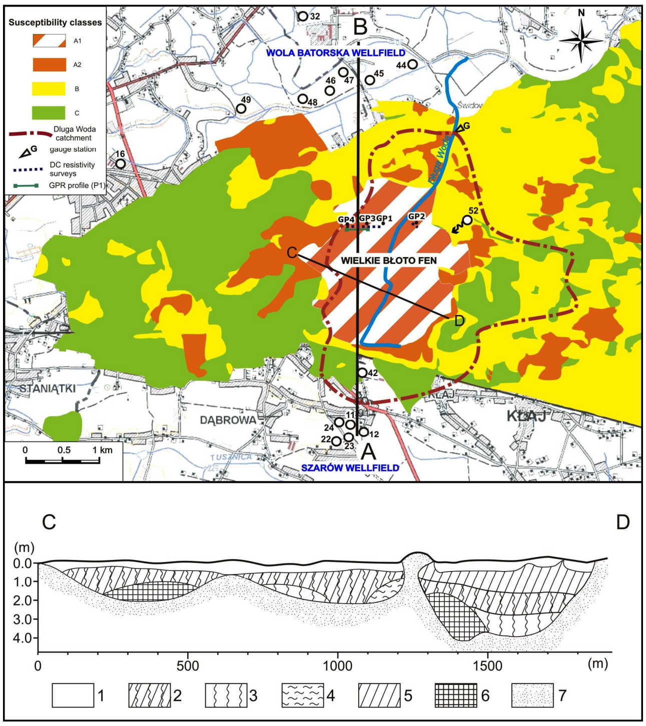


Figure 1. Hydrogeological map and cross-section of the Bogucice Sands (Neogene) aquifer (Major Ground Water Basin – MGWB 451). The study area is marked by ~~brown~~ red oval. Open circles mark the position of pumping wells. Cross-section according to Górka et al. (2010).



corrected:

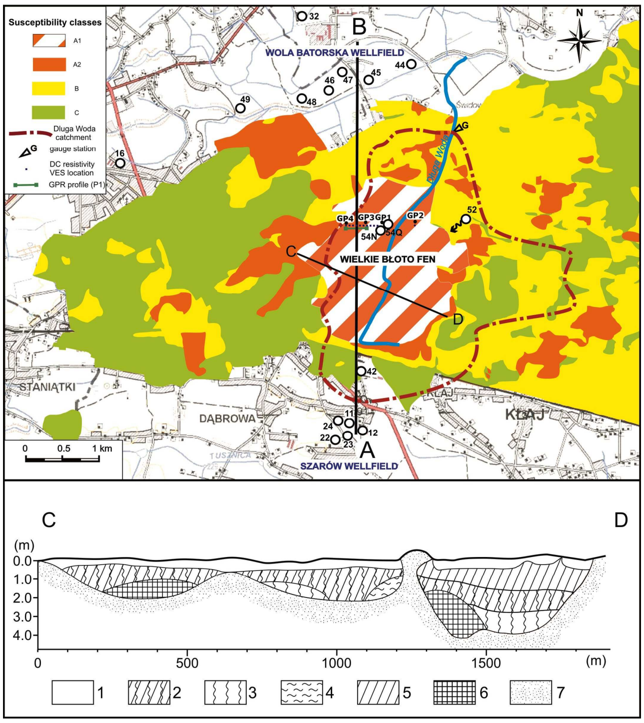


Figure 2. Upper panel - map of the study area showing western part of Niepolomice Forest and Wielkie Bloto fen. GDTE susceptibility classes based on the depth to water table: A - very strongly dependent (0.0 to 0.5 m): A1 – wetland ecosystem, A2 - forest ecosystem; B - strongly dependent (0.5 to 2.0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

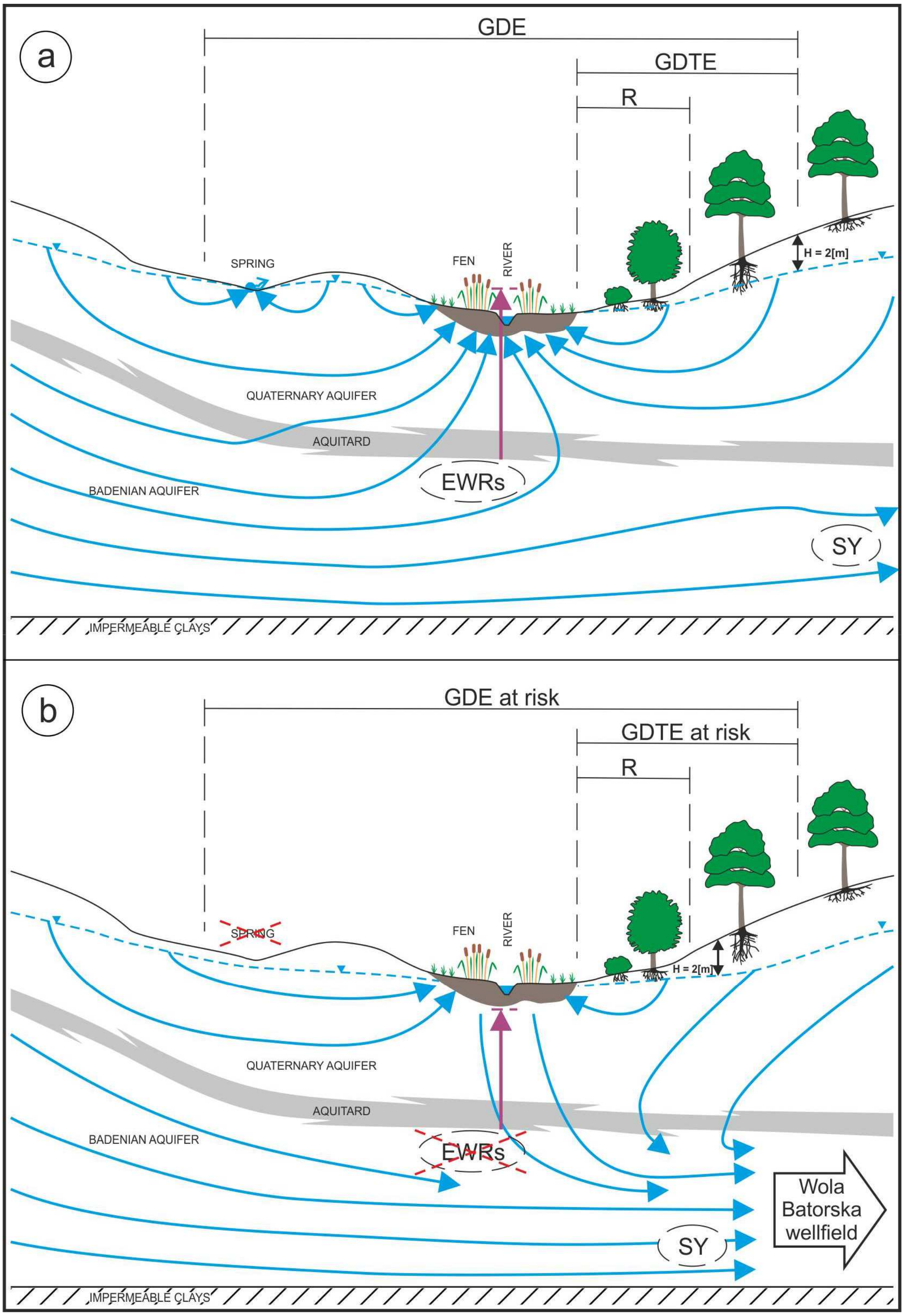
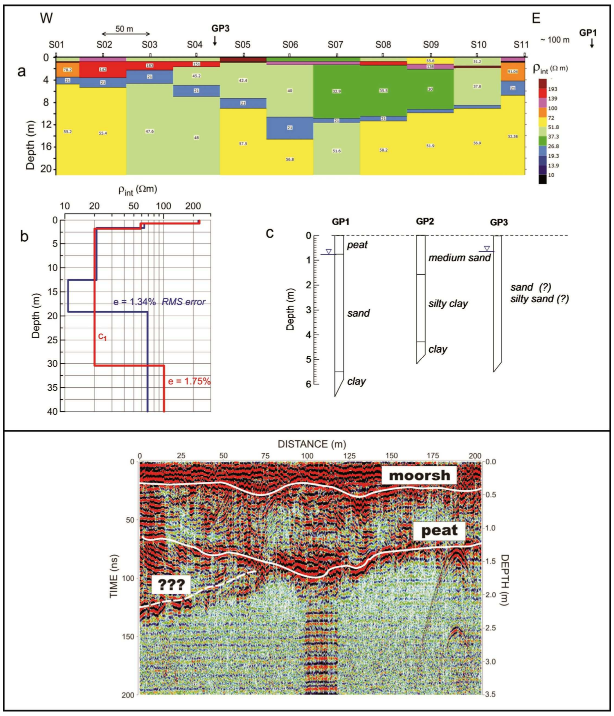


Figure 3. Conceptual model of the Wielkie Bloto fen. **(a)** - natural state; **(b)** - envisaged future status as a result of intense exploitation of the Wola Batorska wellfield. GDE - Groundwater Dependent Ecosystem; GDTE - Groundwater Dependent Terrestrial Ecosystem, R – riparian forest, EWRs - Environmental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



corrected:

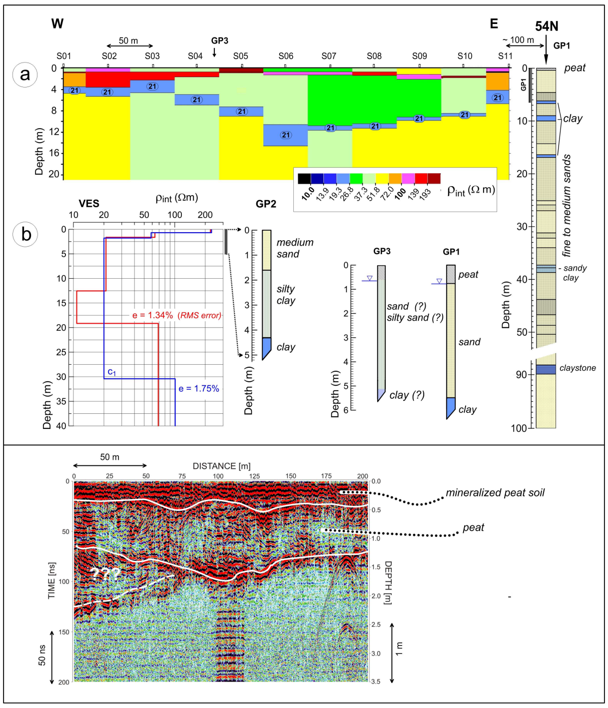
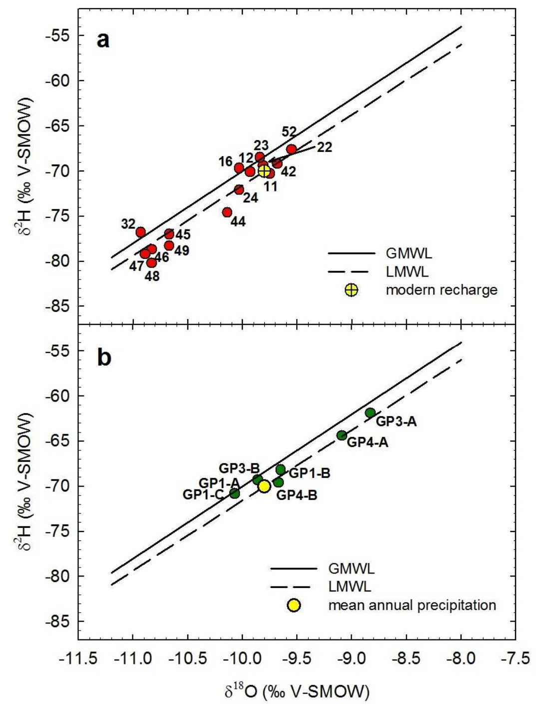


Figure 4. Upper panel - the results of Vertical Electrical Sounding (VES). **(a)** 1-D interpreted resistivity section (S01-S11). Clay layer marked in blue. **(b)** two variants of interpreted resistivity vertical profile based on VES sounding in the vicinity of GP 2 site. C1 corresponds to fixed resistivity of clay equal 21 Ohmm. ~~**(c)** structure of Geoprobe® soil cores at GP1, GP2 and GP3 sites.~~ 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).



corrected:

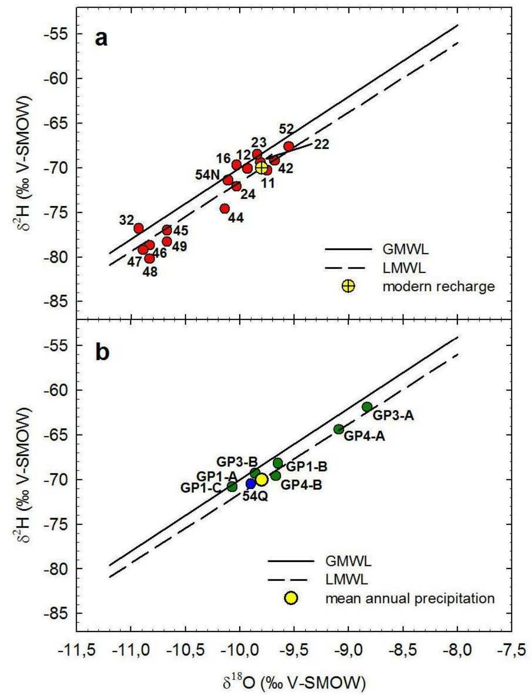
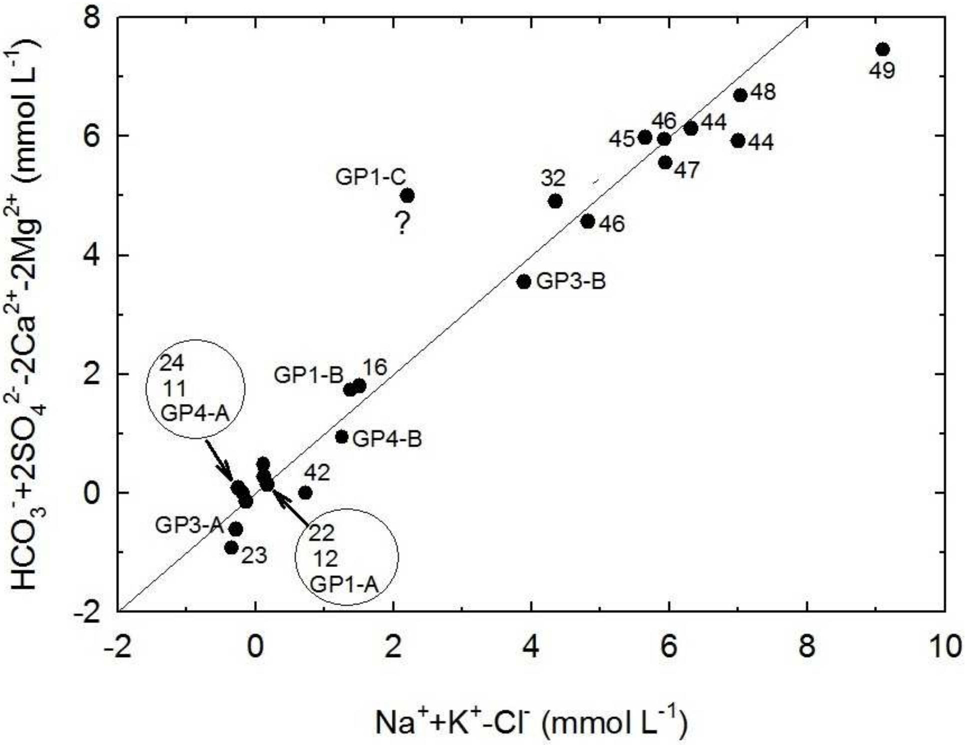


Figure 5. (a) δ^2H-$\delta^{18}O$ relationship for groundwater samples representing the Neogene aquifer, collected in the study area. Shown is also mean isotopic composition of modern recharge of the aquifer. GMWL - Global Meteoric Water Line: LMWL - Local Meteoric Water Line (monthly precipitation at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



corrected:

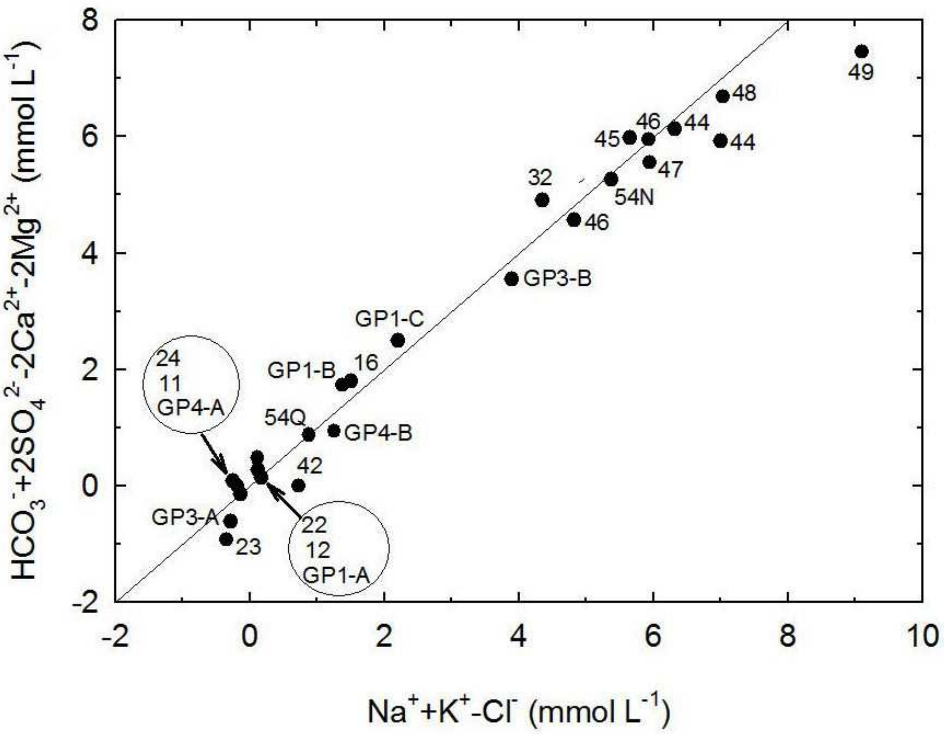


Figure 6. The relationship between deficit of Ca^{2+} and Mg^{2+} ions with respect to the sum of HCO_3^- and SO_4^{2-} ions and the excess of Na^+ and K^+ ions over the Cl^- ions in groundwater samples representing the part of the Neogene aquifer located in the study area and the shallow Quaternary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

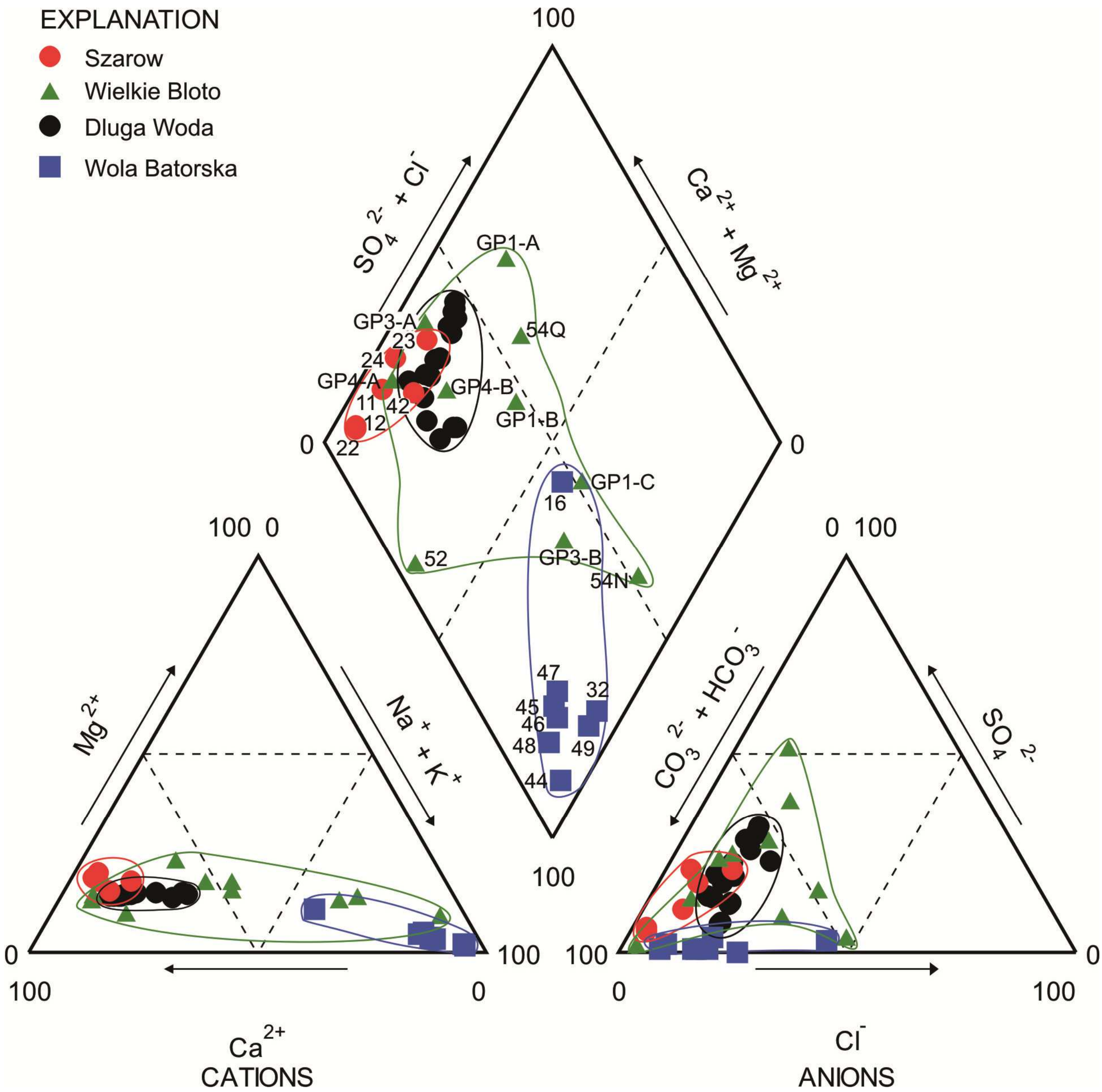


Figure 7. Piper diagram representing chemistry in water samples collected in the study area.

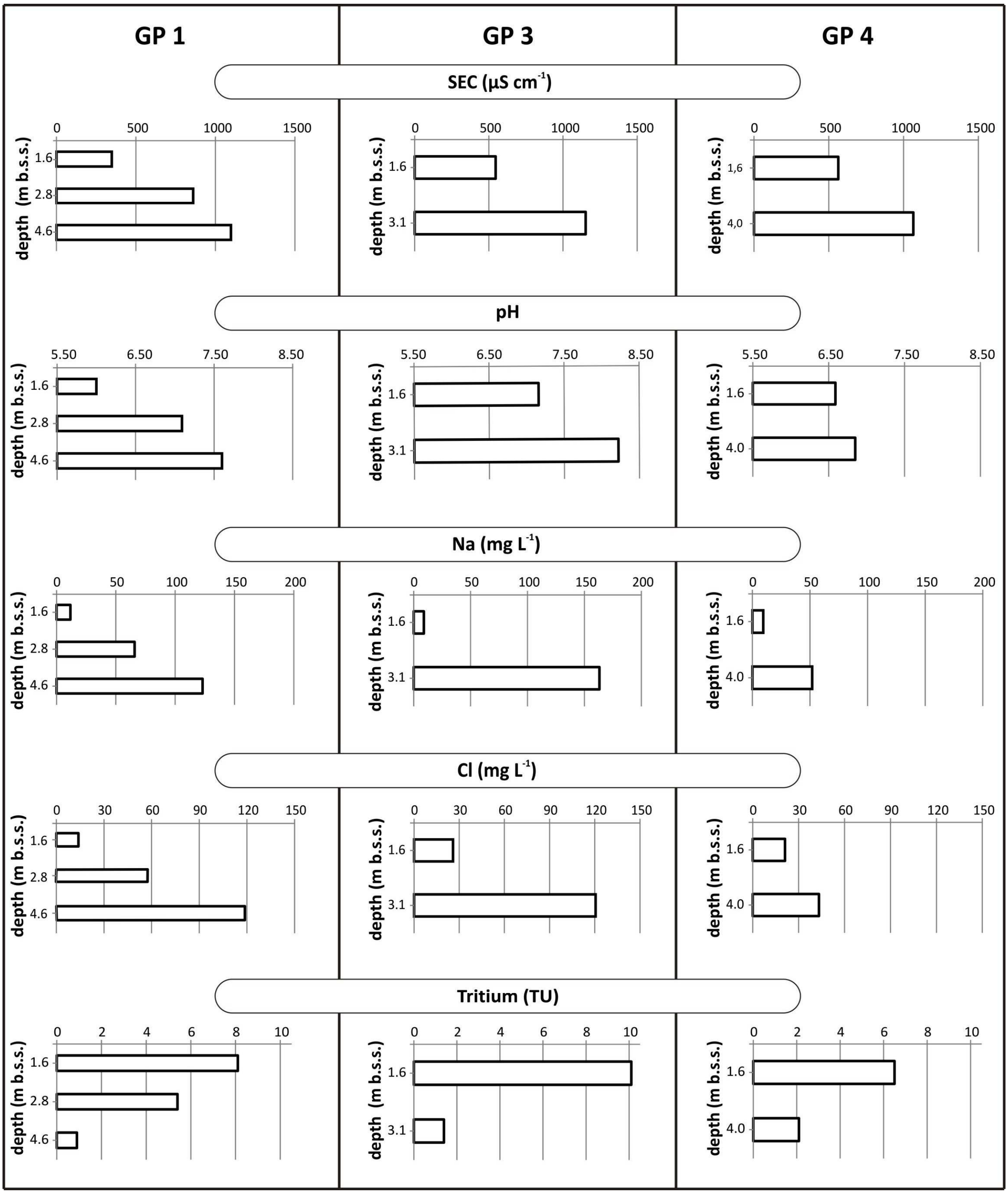
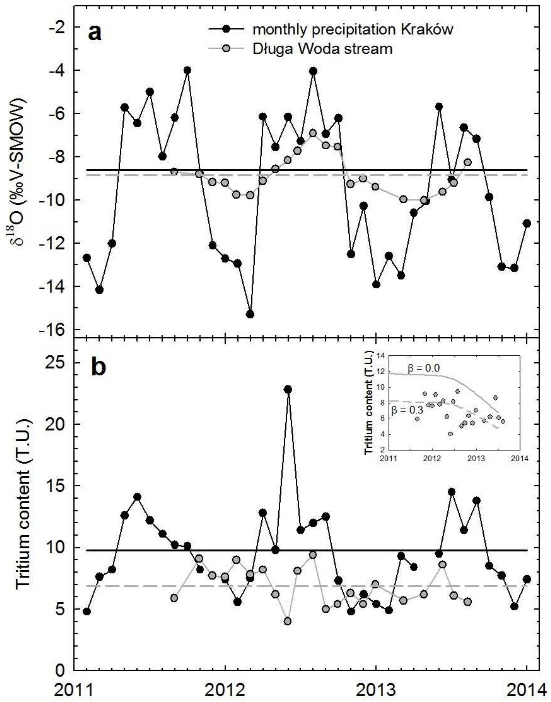


Figure ~~7~~8. Depth stratification of pH, conductivity, Cl, Na and tritium content in the shallow Quaternary aquifer underlying the Wielkie Bloto fen and adjacent parts of the Niepolomice Forest. Water samples were collected with the aid of Geoprobe® device. Location of sampling sites (GP1, GP3, GP4) is shown in Fig. 2.



corrected:

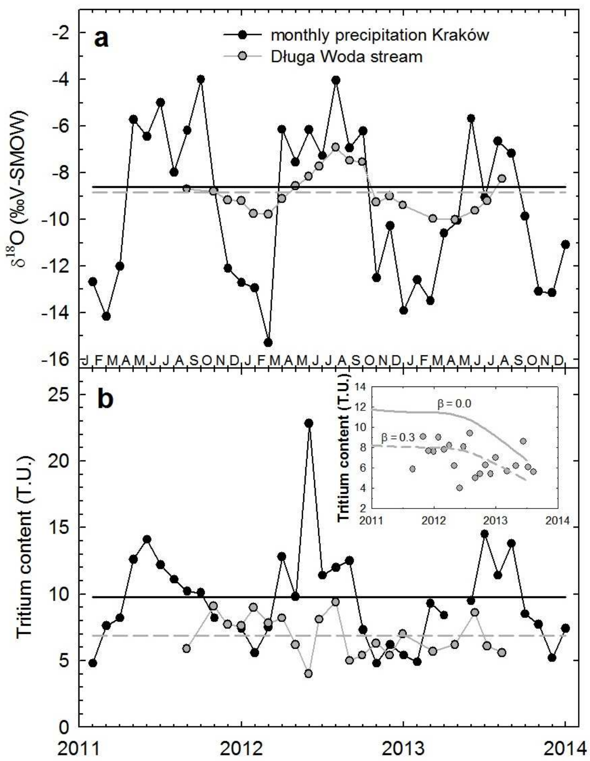
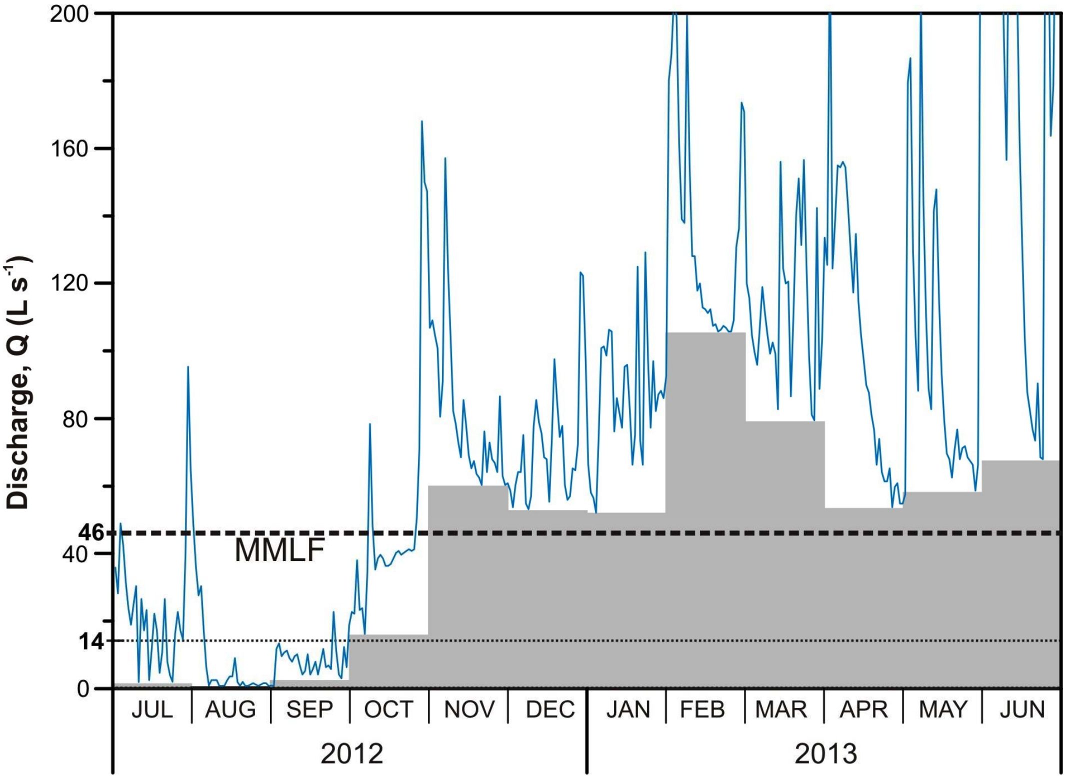


Figure ~~8~~9. Seasonal variations of $\delta^{18}O$ **(a)** and tritium content **(b)** in the Dluga Woda stream during the period 2011-2013. The insert in Fig. 9b shows the comparison of modeled and measured tritium concentrations in the Dluga Woda stream. β is the fraction of tritium-free component in the total flow of the stream (see text for details).



corrected:

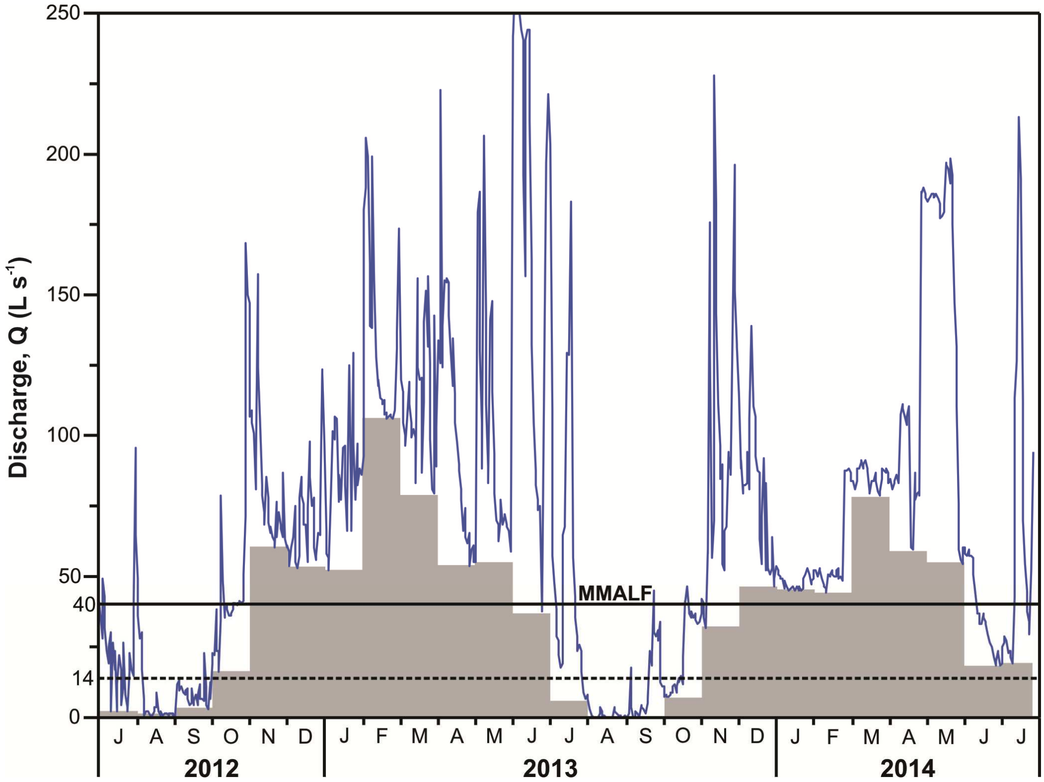


Figure 910. Hydrograph of Dluga Woda stream. Grey histogram reflects monthly low flows for the period July 2012 - June 2013 June 2014. The mean monthly annually low flow (MMALF) equal 4640 L s^{-1} corresponds to the baseflow of the stream. The characteristic discharge rate of 14 L s^{-1} (cf. Fig. 1011) is marked by dotted dashed line (see text).

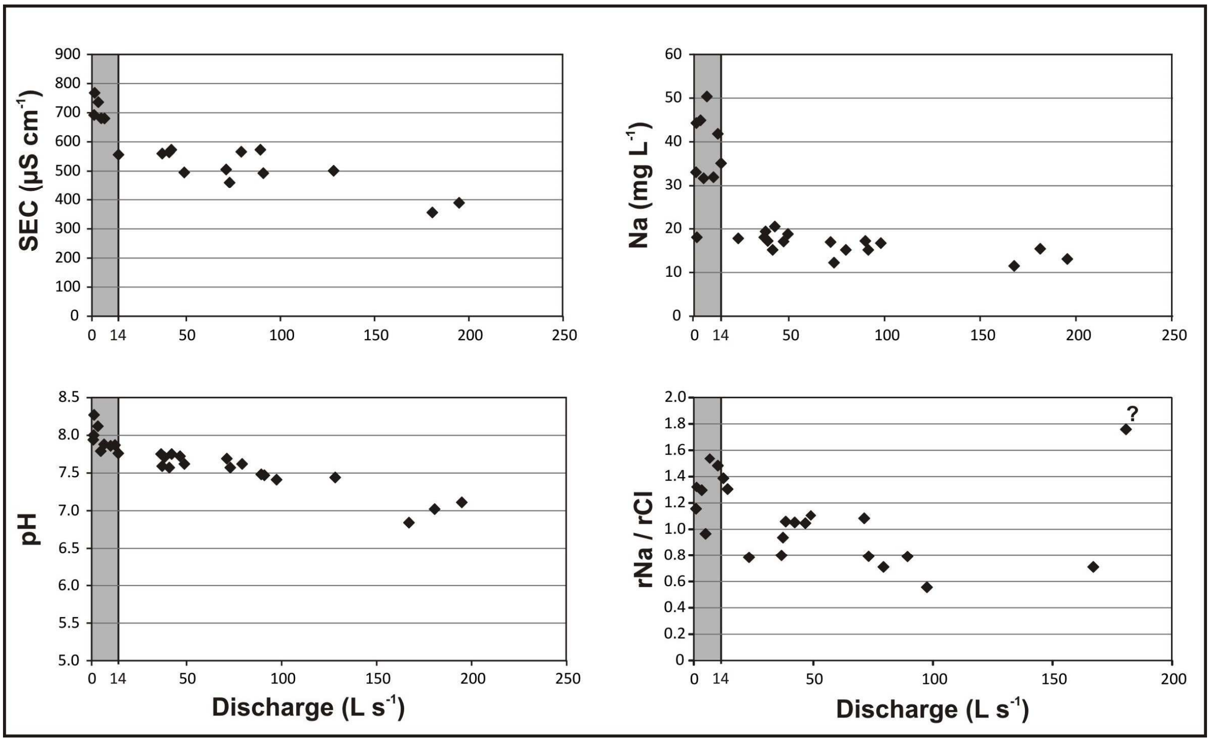
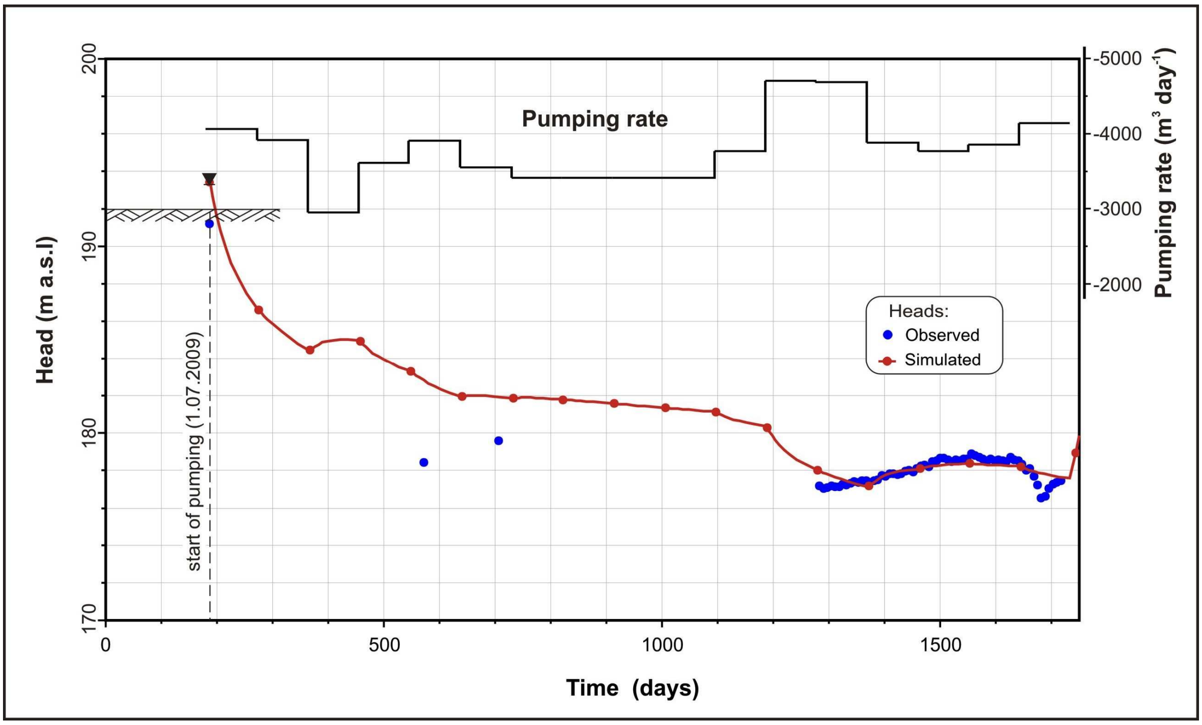


Figure ~~10~~11. Electrical conductivity, pH, Na content and Na/Cl molar ratio in the Dluga Woda stream observed at monthly intervals during the period July 2012 - June 2013, as a function of stream discharge rate measured at gauge station G (cf. Fig. 2).



corrected:

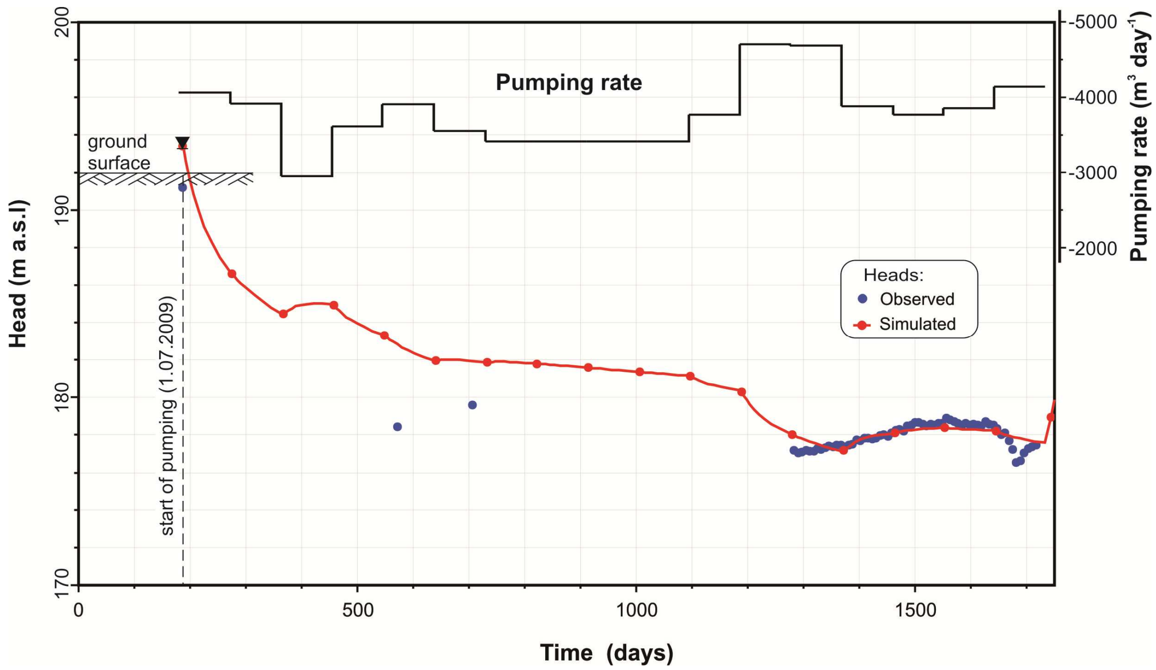
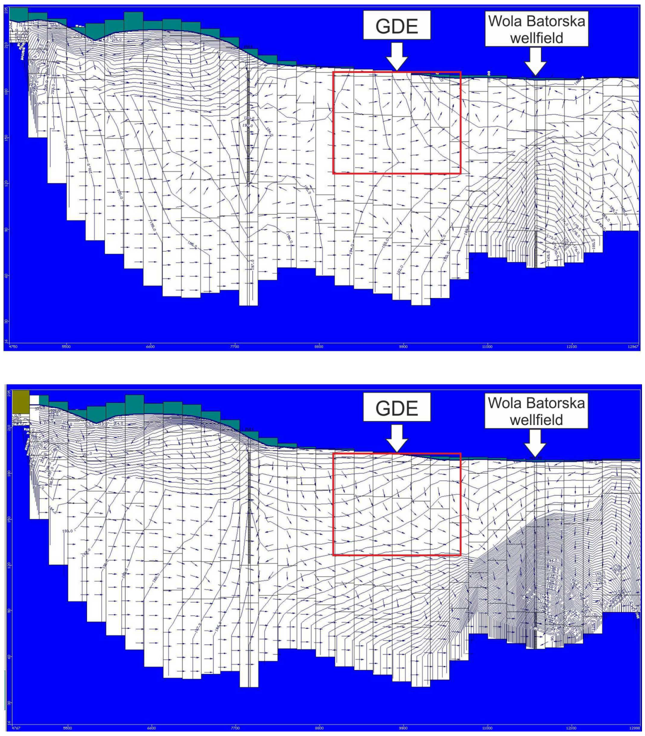


Figure ~~11~~12. Changes of the hydraulic head in well No. 32 (cf. Fig. 2) after initialization of the operation of Wola Batorska wellfield in July 2009.



replaced:

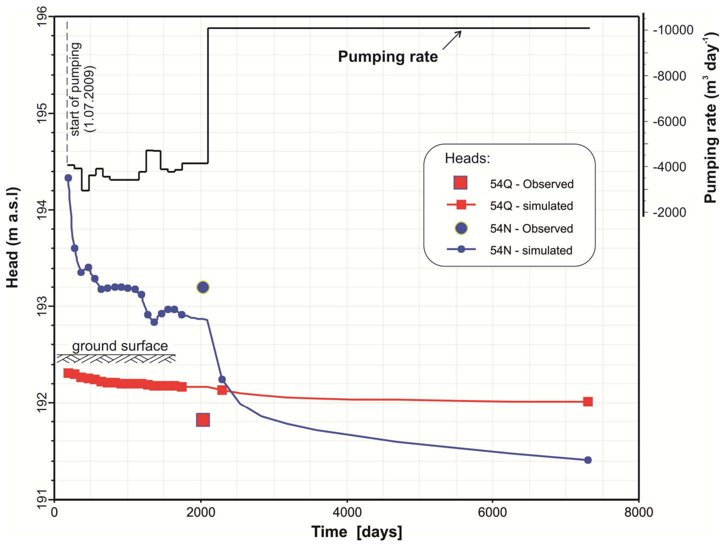


Figure ~~12~~13. ~~Simulated flow field in the Bogucice Sands aquifer (cross-section as in Fig.1). Upper panel: steady-state flow field for present levels of groundwater abstraction through Wola Batorska wellfield (ca. 3800 m^{3}d^{-1}). Lower panel: steady-state flow field for envisaged future levels of groundwater abstraction with maximum permitted capacity (10 080 m^{3}d^{-1}).~~ 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}).