Geological Quarterly, 2022, 66: 9
DOI: http://dx.doi.org/10.7306/gq.1641

# Hydrogeohazards in post-mining areas – the phenomenon of uncontrolled groundwater outflows in wetlands

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Potrykus, D., Lidzbarski, M., Tarnawska, E., 2022. Hydrogeohazards in post-mining areas – the phenomenon of uncontrolled groundwater outflows in wetlands. Geological Quarterly, 66: 9, doi: 10.7306/gq.1641

Associate Editor: Tetyana Solovey

Aquifers formed in the wetland area around the closed lacustrine chalk mine at Mierzyno (northern Poland) are distinguished by a specific groundwater flow system, the main component of which is lateral flow and ascent seepage from the deep aquifer to the ground surface. In investigating the origin of the uncontrolled groundwater outflows and the phenomenon of progressing spring pools, field and laboratory work, as well as model studies of groundwater flow, allowed assessment of damage to the soil and aqueous environment. These occurred due to defective reclamation of post-mining areas, as a result of which the natural hydrodynamic balance in the groundwater was disturbed. Artesian pressure in the deep aquifer caused layer interruption at the boundary of the lacustrine chalk deposit. In consequence, strong uncontrolled outflow of groundwater occurred, and the accompanying spring pools are changing their position as a result of headward erosion. So far, the amount of washed-out carbonate sediment exceeds 5,600 m$^3$.

Key words: groundwater, spring pools, lacustrine chalk, post-mining areas, wetlands.

## INTRODUCTION

During opencast mining of natural resources, the natural environment is most often degraded. The resulting damage can largely be repaired at the stage of reclamation of the post-mining area, but improperly planned and carried out reclamation may cause additional damage. Undesirable hydrogeological phenomena and irreversible changes in the natural environment, often catastrophic in nature, may occur (Karmakar and Das, 1991; Kachnic and Krawiec, 2008; Zhao et al., 2018, Jurys et al., 2018). This has been the case in the post-mining areas of lacustrine chalk, gyttja and peat in the Mierzyno region (northern Poland). The waterlogged mine workings have been transformed into fish breeding ponds. However, the hydrogeological conditions were not analysed effectively, and the specificity of the groundwater circulation system and the possible associated hydrogeohazards were not taken into account during the "reclamation". As a result, several years after the cessation of mining activities, there were strong groundwater outflows and dynamically developing depressions and sinkholes near the inactive mine. Surface waters became degraded with suspended material washed out from organic and mineral sediments, which significantly limited the possibility of their economic use.

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Received: December 6, 2021; accepted: March 7, 2022; first published online: April 11, 2022

The groundwater flow system of wetland areas can be complex and affected by natural as well as anthropogenic processes (van Loon et al., 2009a, b; Grygoruk et al., 2011; Anibas et al., 2012; Gruszczyński and Krogulec, 2012; Krogulec and Zabłocki, 2015; Low et al., 2018). Wetlands are often situated in lowlands areas, where artesian springs are formed. The location and volume of artesian spring discharge is controlled by a combination of topographic, geological and hydrogeological conditions (Martinez-Santos et al., 2014). In terms of performance, artesian discharge of groundwater is usually considerable and shows little or no seasonal fluctuation (Carter et al., 2001).

The presence of natural groundwater outflows in areas of lacustrine chalk and gyttia deposits is a well-known phenomenon (Jurys, 2005; Johansen et al., 2014; Schumann et al., 2017). This may result from natural environmental conditions of the mineral deposits and specific hydrogeological processes, or be triggered by the exploitation of the deposit. However, it is rare for the effects of mining activities to become apparent only several years after the end of mining. Therefore, due to the considerable lapse of time since the closure of the Mierzyno mine, it was difficult to link the resulting hazards with the mining activities or reclamation treatments. With this in mind, the main goal of the research undertaken was to explain the origin of the changes and the mechanism of damage to the soil and water environment. On this basis, it is possible to forecast future changes and plan appropriate remedial measures.

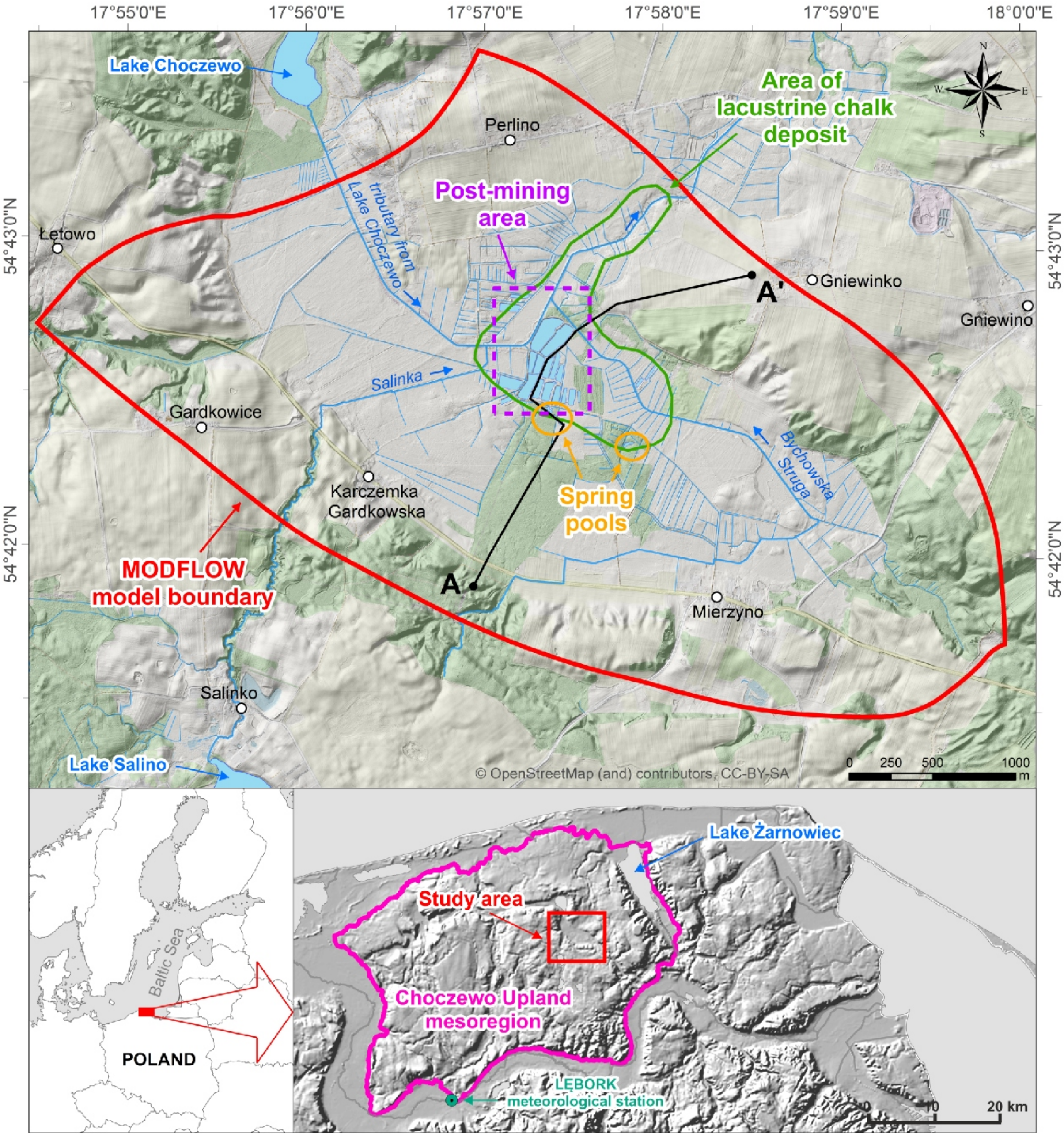


**Fig. 1. Location of the study area**

## STUDY AREA

The study covered an area located near the inactive mine of lacustrine chalk, gyttja and peat at Mierzyno (Fig. 1), within the Choczewo Upland mesoregion (Solon et al., 2018). The average annual precipitation, determined on the basis of measurements carried out in the period 1951-2020 at the Lębork meteorological station is 703 mm and the average annual temperature is 8.0°C. Weather data were obtained from Institute of Meteorology and Water Management – National Research Institute database.

The research area comprises mainly wetlands, distinguished by a well-developed hydrographic network consisting of drainage ditches, canals, rivers and water reservoirs. The main drainage watercourse here is the Bychowska Struga, which flows across the northern part of the study area, towards Lake Żarnowiec. It is also connected by smaller watercourses with Lake Salino and Lake Choczewo. The average water discharge (SSQ) in the Bychowka Struga drainage basin is 7.8 l/s/km$^2$, and the approximate value of groundwater runoff ($SQ_{gr}$) is up to 5.9 l/s/km$^2$ (Lidzbarski, 2000). This indicates a large contribution of groundwater runoff to the total runoff, of ~75%. The Bychowska Struga stream is fed by water characterised by increased turbidity, through a network of drainage ditches from numerous spring areas in the southern part of the post-mining area. The breeding ponds located in the post-mining pits also have an indirect contact with the Bychowska Struga. The water table in these ponds occurs at an elevation of ~42.2 m a.s.l. However, significant changes in its position were noticed during successive field inspections due to meteorological conditions, affecting the volume of water inflow, as well as the hydrological practice of pond management.

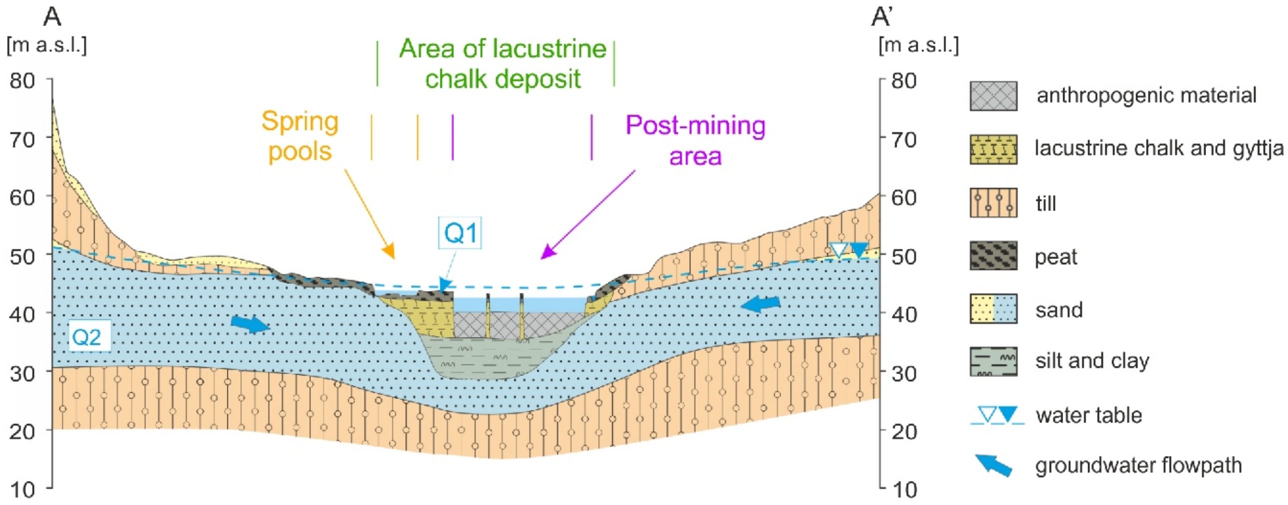


**Fig. 2. Hydrogeological cross-section A–A'**

Q1 – local aquifer, Q2 – regional aquifer; for the cross-section line location see Figure 1

The main elements of the study area relief are uplands, meltwater valleys, and subglacial channels, which developed during the Pomeranian phase of the Main Stadial of the North Polish Glaciation (Skompski, 1982). The major part of the research area has been finally shaped in the Holocene, when swamp and lacustrine deposition took place in an extensive melt-out depression. The lake basin area, ~5.0 km long and 0.5–1.5 km wide, is almost flat and descends to the north, following the course of the Bychowska Struga valley. The elevations in the research area vary around 43.0 m a.s.l. Significant relief variations, reaching ~50.0 m, can be observed only on a regional scale between the valley and upland areas.

## HYDROGEOLOGICAL CONDITIONS

The occurrence and hydrodynamics of groundwater in the study area are diverse and result from the complex geological history of this region. This area is a local groundwater drainage base, which plays an important role in draining the adjacent uplands. In the study area, two aquifers have been identified, which locally remain in hydraulic connection (Fig. 2).

An extensive depression in the near-surface zone is filled with Holocene deposits. These are mainly carbonate deposits of lacustrine chalk and gyttja (calcareous and organic type) (Gawlikowska et al., 2009; Seifert, 2017), overlying silt and clay. These sediments were formed as a result of calcium carbonate precipitation by physicochemical and biological processes taking place in the lake that existed in this area in the past. The deposits of lacustrine chalk and gyttja range in thickness from 0.4 to 9.4 m, but not all boreholes have penetrated the full thickness (Matuszewski, 1997, 2000, 2002, 2007, 2009). The valley surface is covered with peat ranging from 0.5 to 3.4 m thick. Below are Pleistocene deposits of fluvioglacial sand and till (Fig. 2).

The first, shallow water table aquifer (Q1) occurs on a local scale and is not usable (Sierżęga et al., 2006). It is represented by Holocene peats that overlie lacustrine chalk and gyttja or tills and sands in the marginal zone of the valley. The water table is unconfined and occurs at an elevation slightly greater than 42.0 m a.s.l., i.e. at a depth of 0.4 to 1.1 m b.g.l. in the central part.

Aquifer Q1 is recharged predominantly by both rainwater infiltration and ascending percolation from the deeper-lying Pleistocene aquifer. Drainage takes place mainly through a dense network of drainage ditches and major watercourses (Bychowska Struga, Salinka and a tributary from Lake Choczewo), and post-mining ponds (Fig. 1).

The second aquifer (Q2) is the usable aquifer, shows a continuous distribution (regional scale), and occurs at greater depths (Lidzbarski, 2000). It is an intermoraine aquifer represented by sandy deposits that vary in grain size. In the valley area, it lies directly beneath either a lacustrine deposits or a peat bed, while in the upland area it occurs beneath tills. The base of the aquifer is located at an elevation of ~30.0 m a.s.l., and it descends and thickens towards the north; its thickness ranges from 20 to 40 m. In the area of the greatest accumulation of lacustrine deposits (central part of the area), its thickness is up to 10 m. In the upland area, its water table is unconfined and is located at an elevation of ~50 m a.s.l. In the valley, the water table is artesian in nature and stabilises up to 2.0 m a.g.l., i.e. ~45.0 m a.s.l. These conditions result from the sealing properties of lacustrine chalk and gyttja, the permeability of which decreases with a decrease in porosity and an increase in pore water pressure (Dobak and Wyrwicki, 2000).

Groundwater flow takes place from the moraine uplands towards the valley area and farther to the valley of Lake Żarnowiec, which is the regional groundwater drainage base in this area. The intermoraine aquifer is recharged predominantly by lateral inflow from the upland areas, water percolation from Aquifer Q1, and rainwater infiltration from the ground outside the area of Aquifer Q1. Groundwater drainage is associated mainly with surface watercourses in the Bychowska Struga valley and with numerous uncontrolled groundwater outflows. Due to the difficult access to the spring pools and the risk of landslides, it was impossible to measure the water flow rate. The measurements were made at a greater distance and the total discharge rate of the springs was estimated at 15–25 l/s.

## CHARACTERISTICS OF THE DEPOSIT MINING

Lacustrine chalk, gyttja and peat were probably mined in this region from the early 1930s, as shown by a small excavation in the eastern part of the post-mining area (Fig. 3). The first geological surveys to determine the prospective area for the lacustrine chalk deposit were carried out in 1986 (Olszewski, 1988). The lacustrine chalk resources were estimated then at 2.5 million tonnes in an area of ~90 ha between the localities of

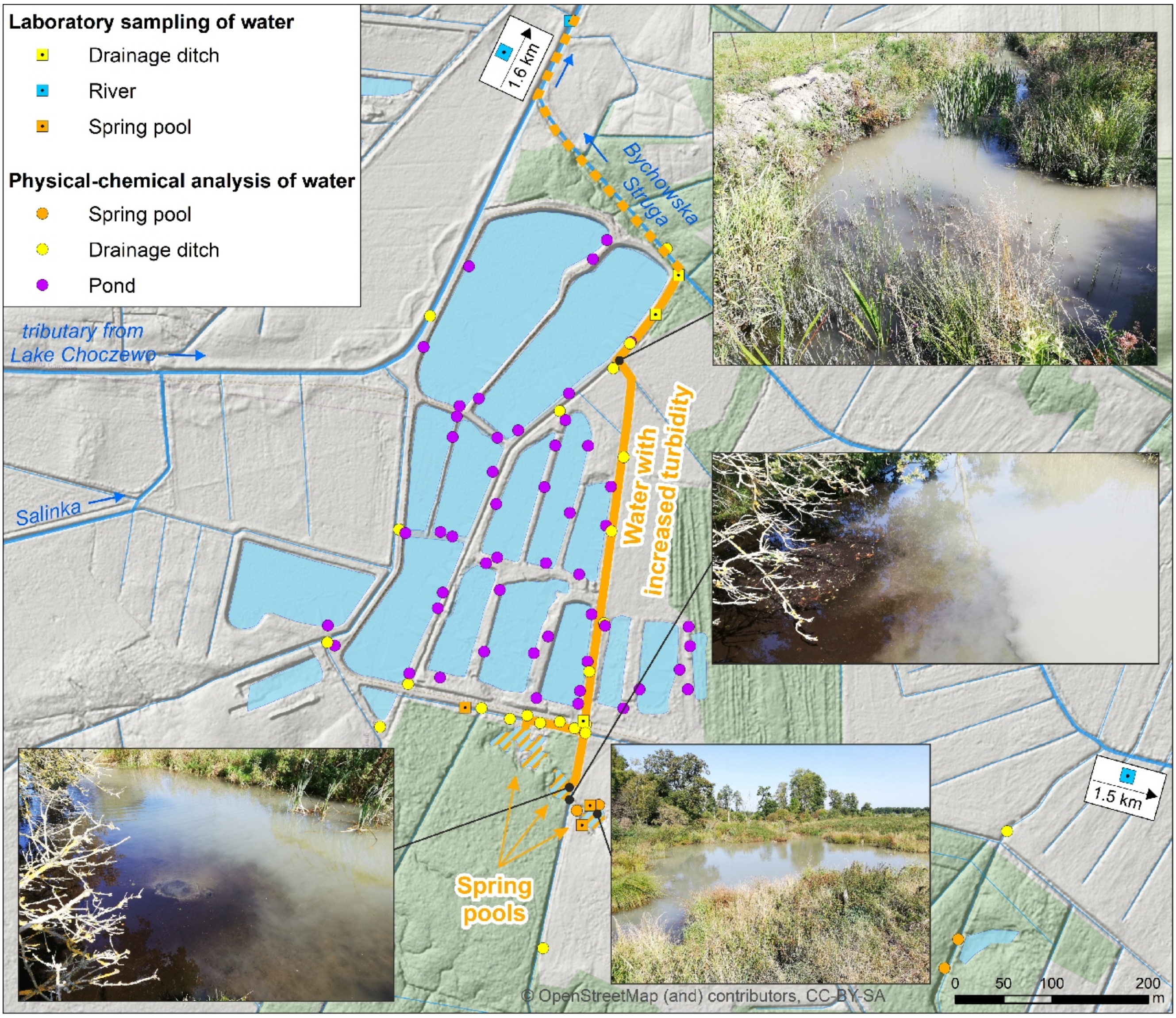


**Fig. 3. Location of sites of hydrochemical measurements and of flow of high-turbidity water from the spring pool area towards the Bychowska Struga**

Łętowo, Perlino and Mierzyno (Fig. 1). Documents show that the main extraction work was carried out in this area in 1998–2005. An output of 259,300 tonnes was recorded over this time. During the mining, the excess water from excavations was drained with the use of gravity channels connected with streams. Drainage pumps were not used. However, there is no complete information on the volume of drainage or on the total extraction of the resources, which means that the actual amount of raw material mined from the deposit may be greater.

The mining resulted in significant changes to the condition of the environment and ecosystems. After the mining activities in the area of former grasslands and meadows were abandoned, deep water-flooded pits were formed, with an average depth of 6.0 m. Unfortunately, there is no knowledge about the condition of the mining area after the extraction was stopped. However, after the mining activities, the primary state of the ponds changed. The treatments applied included constructing culverts and dykes dividing larger reservoirs, making the reservoirs shallower, sealing the bottom, damming or lowering the water table level in the ponds, and changing the water flow direction in surface watercourses. Over time, some of the reservoirs were transformed into open fish breeding ponds, separated by a dyke. During the first years after the end of mining, there was also a natural process of shallowing of the workings due to runoff pressure and suffosion (Jurys, 2005). The current depth of the reservoirs is ~2.0 m.

Troublesome changes in the soil and aqueous environment appeared only a few years after extraction finished (Fig. 3). In 2005, the first automatic, uncontrolled groundwater outflow was observed at the southern boundary of the post-mining area, damaging the slope of the excavation. The progressive dynamics of this process resulted in the expansion of ground subsidence towards the southeast. In 2008, large spring pools formed in the area of nearby forests and meadows, from which groundwater of increased turbidity flowed out. This process intensified in 2018–2019, when the spring pools increased in area significantly, and the flowing water washed away the lacustrine chalk and gyttja sediments that had polluted the Bychowska Struga.

## MATERIAL AND METHODS

The environmental conditions and processes were analysed on the basis of mapping, geological documentation of the deposit, legacy boreholes of the Central Hydrogeological Data Bank and Central Geological Database, a Digital Terrain Model, archived chemical analyses of water, and published literature. The collected archival data were the basis for planning detailed hydrogeological field, laboratory and modelling research.

### HYDROCHEMICAL MEASUREMENTS

Field studies were carried out during four sessions from August 3 to November 13, 2019. Basic measurements of physical and chemical properties of water (temperature, pH, electrical conductivity – EC) were performed using portable devices with specialised sensors (Slandi SC300, Slandi SP300, Hanna HI98194). Nine samples of surface water were also collected for detailed laboratory tests. These were taken from pre-selected sites on the inflow and outflow paths from the mining area (Fig. 3). The scope of laboratory analysis included major ions ($HCO_3^-$, $SO_4^{2-}$, $Cl^-$, $Ca^{2+}$, $Mg^{2+}$, $Na^+$, $K^+$), turbidity, total dissolved solids (TDS) and total suspended solids (TSS). Laboratory tests were carried out at the chemical laboratory of the Polish Geological Institute – National Research Institute.

### GROUNDWATER FLOW MODEL

The modeling work was carried out for an area of ~13 km$^2$ (Fig. 1) using the *MODFLOW-2005* computational code (Harbaugh, 2005) and *GMS 8.3* software (Groundwater Modeling System). The *MODFLOW-2005* software enables numerical calculations using the finite difference method to solve the governing equation of groundwater flow:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

where: $K_{xx}$, $K_{yy}$, $K_{zz}$ – values of hydraulic conductivity along the x, y and z axes ($LT^{-1}$); *h* – total head (L); *W* – sources and sinks of water ($LT^{-1}$); $S_s$ – specific storage ($L^{-1}$); *t* – time (T)

Simulations of steady state were performed and the aim was to determine the hydrodynamic conditions for three scenarios representing the state of the study area at various developmental stages:

- variant I – mid-extraction state (no spring pools);
- variant II – post-extraction state, after shallowing of the reservoirs (no spring pools);
- variant III – current state (presence of spring pools).

A groundwater flow model was constructed based on the hydrogeological cross-sections, borehole logs, geological documentation of the deposit, and information from hydrogeological and geological maps at the scale of 1:50,000, Choczewo sheet (Skompski, 1982; Lidzbarski, 2000; Sierżęga et al., 2006). The terrain surface was mapped on the basis of a digital elevation model obtained using LIDAR data supplied by the Polish Head Office of Geodesy and Cartography. Hydraulic conductivity values for the individual layers are based on both results of pumping tests in local groundwater intakes and published data (Döll and Schneider, 1994; Marciniak et al., 1999; Dobak and Wyrwicki, 2000; Kellner, 2007). The set values of the hydraulic conductivity were as follows: for the first layer of the model 1.00 $10^{-5}$ m/s, for the second layer 1.11 $10^{-8}$ - 1.39 $10^{-6}$ m/s, and for the third layer 2.64 $10^{-4}$ m/s.

### DISCRETIZATION

Transformation of the conceptual model into a three-dimensional discrete model was performed using a rectangular grid. The rectangular grid generated consists of 3 layers, 441 rows and 640 columns. The total number of cells was 846,720, of which 311,747 remain active. The spacing in the horizontal direction was uniform for all layers and equal to 10 m. The 3 layers were defined as follows: (I) first aquifer occurring locally, mainly in peat (Q1), (II) low-permeability deposits (till, lacustrine chalk, gyttja), (III) inter-moraine aquifer in fluvioglacial sand (Q2; Fig. 2).

### BOUNDARY CONDITIONS

The boundaries of the area covered by the model research were defined using the assumed boundary conditions. The type I boundary condition (H = const) was adopted only for the third layer of the model, at its south-western border. The hydraulic head elevation was derived from a hydrogeological map. The type II boundary condition (Q = const) with the assumption of no water flow was adopted for the first layer of the model at the boundary of the aquifer occurrence, with the exception of two sections in the vicinity of a tributary from Lake Choczewo and from the Bychowska Struga. For the third layer of the model, this condition was set at the northeastern and northwestern edges of the model on the delineated course of a neutral flow path. The type II boundary condition was also taken into account as the set value of recharge from the terrain surface within the entire study area. The type III boundary condition [Q = f (H)] was set as external and internal. For the first layer of the model, this condition was set on two sections in the region of the tributary from Lake Choczewo and the Bychowska Struga. It was defined at these places by using the GHB-type package that allows figuring out the amount of lateral inflow/outflow to/from the model, taking into account the constant value of the groundwater table elevation at its edge. On the other hand, the internal type III boundary condition was set for watercourses (river), canals and drainage ditches (drain), as well as water reservoirs (GHB).

### IDENTIFICATION

During model identification, calibration was performed predominantly on the values of hydraulic conductivity of the layers determined in the model, as well as on the parameters of bottom sediments of surface waters. Due to a small number of observation points (6) within the modelled area, the water flow measurements in surface watercourses and the pattern of hydraulic head contour lines in the hydrogeological map were also used to verify the results obtained (Lidzbarski, 2000). Flow velocity in watercourses was measured using an OTT MF pro hydrometric mill.

There was good agreement of the hydraulic head level measured in the field with the results of model calculations (mean error 0.25 m, mean absolute error 0.63 m, standard error 0.70 m). And, the amount of water outflow from the breeding ponds (28.8 m m$^3$/h) and through the spring pools (82.8 m$^3$/h), determined in the field, is comparable with the values obtained on the basis of simulations: 27.1 m$^3$/h (breeding ponds) and 70.3 m$^3$/h (spring pools). The model has thus been constructed adequately to the existing data and it enables making of the assumed variant simulations.

# RESULTS

## HYDROCHEMICAL MEASUREMENTS

Field measurements of the basic physical and chemical properties of water in the post-mining area were carried out at 78 points located within drainage ditches, ponds, and spring pools (Fig. 3). The pond water has an average temperature of 20.6°C, the pH is 8.28, and the EC is 391 µS/cm. In turn, the average water temperature in drainage ditches is much lower - 11.7°C, the pH is 7.98, and the PEW is 392 µS/cm. The water parameters measured in the spring pools are as follows: average temperature 13.6°C, pH ~7.89, EC 388 µS/cm. The determinations of the basic physical and chemical parameters of water show the dependence of the spatial distribution of their values. The lowest water temperatures were recorded in the ditches located in the spring pool area (9.0°C), which increase to the north on moving away from the outflows studied. The highest temperatures (23.0°C) were found in a pond in the northern part of the post-mining area. The pH values in the study area are distributed similarly. The lowest values of this parameter (7.70) were also recorded in the vicinity of spring pools, ditches and ponds located in the southern part of the post-mining area, at the bottom of which there are visible signs of groundwater outflows. The pH values increase on moving away from these places towards the north and west, where a value of 8.62 was recorded in the ponds. The spatial orientation of the values measured is not so clear in case of the EC parameter. Its highest values (574 µS/cm) were recorded in the ponds located in the eastern part of the study area, which formed likely due to exploitation of the deposit in the 1930s (Table 1).

Within all the samples collected, the anions concentrations ranged from 196 to 224 mg$HCO_3$/l for bicarbonate, from 35.0 to 37.0 mg$SO_4$/l for sulphate and from 7.9 to 15.2 mgCl/l for chloride. The cation concentrations of calcium, magnesium, sodium and potassium were in the range of 63.8–77.2 mgCa/l, 6.4–8.4 mgMg/l, 5.2–6.0 mgNa/l and 0.9–1.4 mgK/l, respectively. The water sampled is of $HCO_3$-Ca type. The results for the major chemical components do not show any significant differences between the water samples. They do not exceed the values typical of natural waters (Macioszczyk and Dobrzyński, 2007) and of the hydrogeochemical natural background specified for the region (Lidzbarski, 2000).The waters from the spring pool area were characterised by slightly higher mineralisation (TDS = 372 mg/l) than the waters collected in other places (TDS from 321 to 350 mg/l), which could be associated with the occurrence of groundwater outflows.

The impact of waters flowing out of the springs studied on surface waters is best determined by the measured values of turbidity and total suspended solids. Water turbidity is caused by dispersed colloidal particles and suspensions, which include clay-silt particles, iron hydroxides, carbonates, insoluble organic compounds, higher microorganisms, etc. (Witczak et al., 2013). The highest turbidity was measured near the springs analysed (407.0 NTU), and the lowest in the Bychowska Struga (~1.6 km from the post-mining area) near the locality of Perlino (21.5 NTU). In a drainage ditch on the tributary to the Bychowska Struga, the water turbidity was 317.0 NTU. The concentrations of TSS at these sites were 383 mg/dm$^3$, 13 mg/dm$^3$ and 396 mg/dm$^3$, respectively.

The specified chemical composition of the waters sampled does not show typical or similar values of individual parameters characteristic of the waters of Holocene carbonate deposits (lacustrine chalk and gyttja), which are conspicuous in their high mineralisation level (>1 g/l), high concentrations of calcium (263.5–709.9 mgCa/l) and sulphates (500.0–2,131.9 mg$SO_4$/l), and pH<7 (Żurek-Pysz, 1989; Wyrwicki, 2003). The low variability and relatively low values of individual parameters of the study area waters result mainly from the short time of water circulation in the aquifer analysed, largely due to the intensified drainage of groundwater and the mixing of outflowing groundwater and surface water.

## GROUNDWATER FLOW MODEL

To identify the origin of groundwater outflow activation and to estimate the volume of water flowing out from spring pools, a numerical groundwater flow model has been developed.

On the basis of the modelling studies, it has been determined that the groundwater resources in the study area (current state) are shaped as a result of lateral inflow of waters from the southwest (72.3%), precipitation infiltration (25.7%), and infiltration of surface waters (2.0%). Groundwater runoff from the aquifer system is mainly due to drainage by surface waters (99.9%) that include breeding ponds (5.3%), spring pools (12.6%), drainage ditches and canals (58.4%), rivers (21.6%) and other water bodies (2.0%). Lateral outflow plays a minor role in the total water outflow from the study area (0.1%). The contribution of Aquifer Q1 to the formation of groundwater resources within the study area boundaries is small and amounts to ~10%.

The elevation of hydraulic head in Aquifer Q2 at the south-western boundary of the study area is calculated at ~51.5 m a.s.l., descending towards the valley to 45.0 m a.s.l. (Fig. 4). The variant simulations show considerable differences in its balance, which must be linked with the state of the study area at its different developmental stages. The recharge rate of groundwater in Aquifer Q2 during the three periods discussed

Table 1

**Results of field determinations of basic physical and chemical properties of the water**

| Parameter | Determination site | Number of determinations | Range | Average |
|---|---|---|---|---|
| Temperature [°C] | ponds | 51 | 18.6–23.0 | 20.6 |
| | ditches | 23 | 9.0–17.4 | 11.7 |
| | spring pools | 4 | 10.7–17.9 | 13.6 |
| pH [-] | ponds | 51 | 7.84–8.62 | 8.28 |
| | ditches | 23 | 7.70–8.14 | 7.98 |
| | spring pools | 4 | 7.86–7.98 | 7.89 |
| EC [µS/cm] | ponds | 51 | 338–574 | 391 |
| | ditches | 23 | 367–463 | 392 |
| | spring pools | 4 | 378–399 | 388 |

Table 2

**The groundwater flow balance for Aquifer Q2**

| Balance component | | Variant I [m$^3$/h] | Variant II [m$^3$/h] | Variant III [m$^3$/h] |
|---|---|---|---|---|
| Inflow | Rainwater infiltration | 73.68 | 73.19 | 74.01 |
| | Surface water infiltration | 6.96 | 6.86 | 7.00 |
| | Descending flow from Aquifer Q1 | 25.99 | 25.35 | 25.58 |
| | Lateral inflow | 404.89 | 394.64 | 407.63 |
| | Total inflow | 511.52 | 500.04 | 514.22 |
| Outflow | Ascending flow to Aquifer Q1 | 169.59 | 192.39 | 172.82 |
| | Drainage: | (341.57) | (307.30) | (341.04) |
| | • through breeding ponds | 101.29 | 41.60 | 27.09 |
| | • through spring pools | 0.00 | 0.00 | 70.34 |
| | • other | 240.28 | 265.70 | 243.61 |
| | Lateral outflow | 0.35 | 0.36 | 0.35 |
| | Total outflow | 511.51 | 500.05 | 514.21 |

did not show any significant changes. The values of precipitation infiltration were in the range of 73.19–74.01 m$^3$/h, the surface water infiltration was 6.86–7.00 m$^3$/h, the descending flow from Aquifer Q1 was 25.35–25.99 m$^3$/h, and the lateral inflow was 394.64–407.63 m$^3$/h (Table 2).

There are clear differences in the proportion of individual components of water drainage of the aquifer Q2 between the three variants considered. During the exploitation of the deposit (Variant I), the excavations that were formed at that time drained a significant amount of groundwater from Aquifer Q2 (~101.29 m$^3$/h). The amount of surface waters was 240.28 m$^3$/h and the ascending flow rate to Aquifer Q1 was 169.59 m$^3$/h. After the exploitation was abandoned (Variant II), the drainage base was largely blocked due to the shallowing of the reservoirs and their transformation into fish breeding ponds, reducing the groundwater runoff through the breeding ponds by more than a half (41.60 m$^3$/h). As a result, groundwater runoff from Aquifer Q2 increased due to both drainage through the remaining surface waters (265.70 m$^3$/h) and the ascending flow to Aquifer Q1 (192.39 m$^3$/h). It has been calculated that the breeding ponds

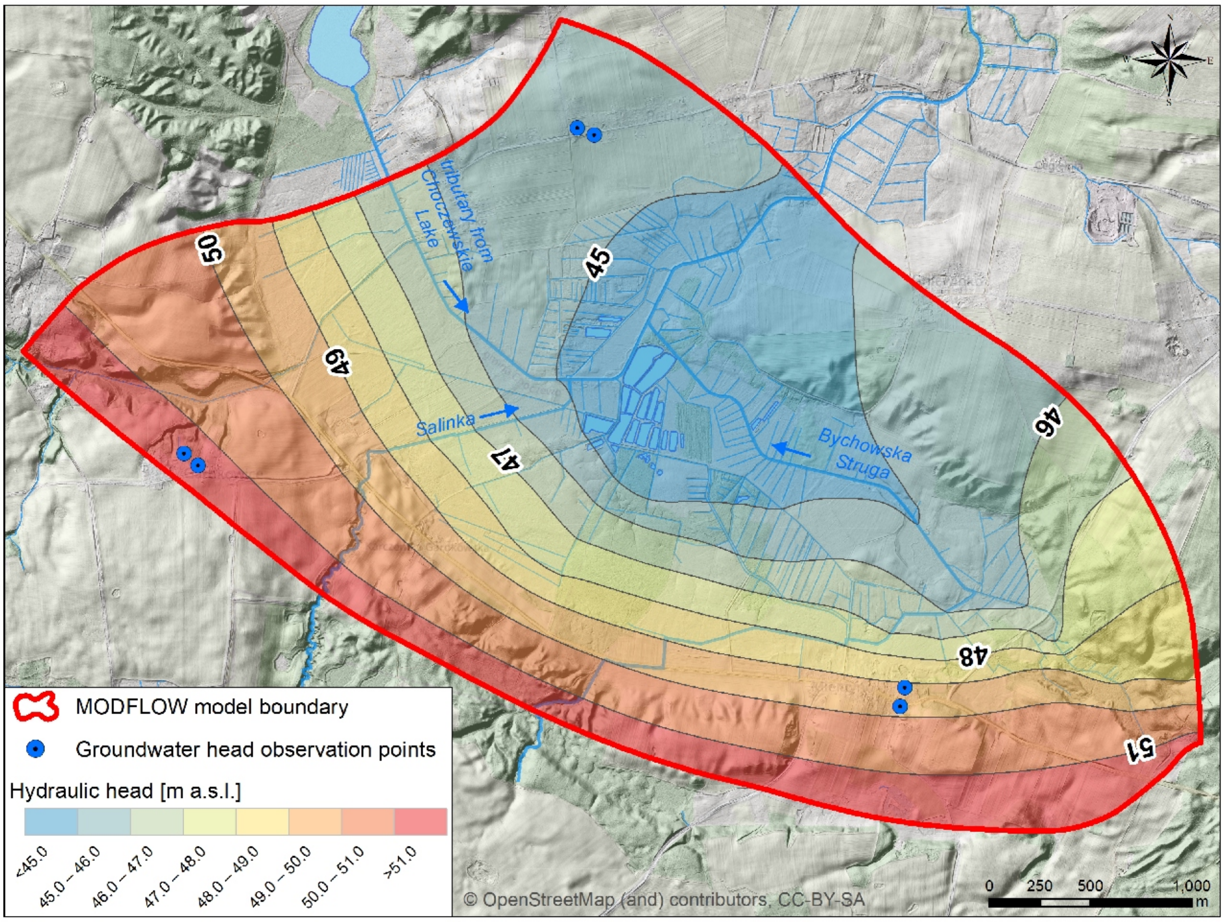


**Fig. 4. Hydraulic head contour lines of Aquifer Q2 for the current state (Variant III)**

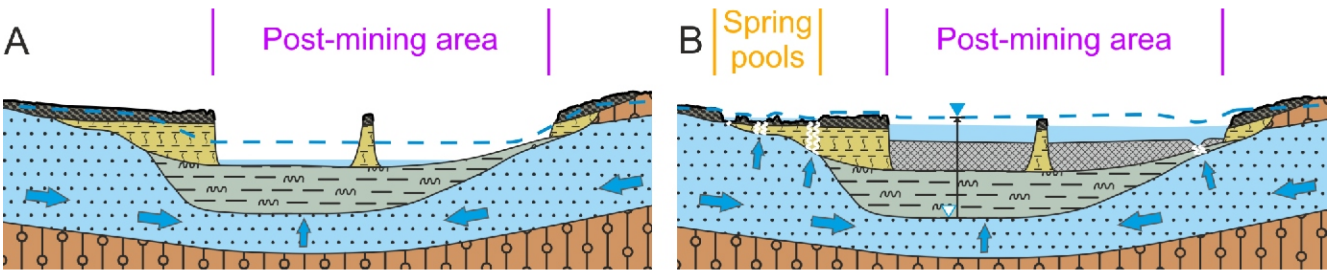


**Fig. 5. Schematic diagram of groundwater flowpaths in the post-mining area (A – during exploitation; B – current state, activation of outflows)**

For explanations see Figure 2

can currently receive ~24.09 $m^3$/h of water, while groundwater flows out of the spring pools that formed at the southern edge of the mine at about 70.34 $m^3$/h. The drainage rate in surface waters decreased to 243.61 $m^3$/h, and the ascending flow from Aquifer Q2 to Q1 is 172.82 $m^3$/h (Table 2).

Due to the incomplete knowledge of hydrogeological conditions and of the geological structure, the results should be treated as approximate values. However, they allowed constraints on changes in this phenomenon.

## DISCUSSION

Lacustrine chalk and gyttja are characterised by high susceptibility to the washing out of fine soil particles by flowing ground water, as well as to the loosening and liquefying of the soil by the pressure acting on soil particles in the direction of water percolation through the soil. This is due to their specific physical and mechanical properties (Rybicki and Żurek-Pysz, 1989) and their mineral composition (Żurek-Pysz, 1989; Dobak and Wyrwicki, 2000; Wyrwicki, 2003).

The nature of the mining and reclamation operations resulted in significant disturbances of the soil and aqueous environment in the area of the former mine, which subsequently resulted in disturbances in the natural hydrodynamic system of groundwater in this area. The changes in groundwater percolation conditions led to hydraulic piping, i.e. soil displacement to form conduits (channels), creating preferred groundwater flow zones. This phenomenon may result from either excessive exploitation of the raw material or improper reclamation operations and materials used to shallow the reservoirs. Presumably, these activities initiated the conditions conducive to the formation of the first spontaneous and uncontrolled outflows of groundwater at the southern edge of the mine area, and then at the edge of the deposit, where the sealing sediments have the smallest thickness. During mining operations, the difference in the water level between the bottom of the excavation and the surroundings exerts runoff pressure on the soil, which reduces its volumetric weight at the bottom (Wiłun, 1976). This state causes the soil to loosen (increase in volume), which in turn translates into an increase in the water flow rate, which, at critical values, causes the soil to liquefy and initiates the suffosion process. Due to the lack of full documentation of the deposit, we cannot rule out that reconnaissance operations carried out in the past, as well as the drilling of exploratory wells and their inappropriate abandonment, also contributed to the activation of the outflows under study.

The successive leaching of the sediment led to the enlargement of pore channels in poorly permeable sediments and to the increase in outflow efficiency, which resulted in the breaking of the dyke to flood the area. In the next phase, soil loosening took place in the opposite direction to the water movement, having a rheological nature of volumetric flow, and the subsequent sinking of the ground surface. The terrain surface and the static groundwater table of the aquifer became intersected, which resulted in a change in the piezometric pressure lines, an increase in hydraulic gradient, and a significant sinking of the terrain around the forming spring pool area. The progressive expansion of the area of outflow sites, accompanied by ongoing headward erosion of the outflowing water, led to a gradual collapse of the terrain towards the southeast and to the development of a spring pool, i.e. a small amphitheatral depression with steep slopes, which has formed around the springs area (Mazurek, 2017). Groundwater outflows can also be observed at the bottom of the breeding ponds and adjacent ditches. Schematic diagrams of groundwater flowpaths within the study area for the mining stage and for the current stage are shown in Figure 5.

After the exploitation of lacustrine chalk ceased, clear hydrodynamic changes in Aquifer Q2 can be observed (Fig. 6A). The greatest changes occurred in the southern part of the excavation that was formed at that time - the groundwater table rose by 2.00 m and was artesian in nature. On the water inflow path, in the area of future spring pools, hydrostatic pressures increased from 0.75 to 1.25 m.

Activation of groundwater outflows resulted in a significant depression of the area around the spring pools (Fig. 6B), where the groundwater table of Aquifer Q2 decreased by ~1.8 m. Based on the calculations performed with the use of GIS tools, the amount of the washed-out sediment (land loss) within the spring pools at the southern edge of the post-mining area is estimated at 5,611 $m^3$. On the other hand, the groundwater table in the area of post-mining excavations is still artesian, although the pressure decreased by 1.0 m in relation to the post-mining period. The shape of the cone of depression that has formed around the spring pools is quite regular and spreads mainly in the direction of groundwater flowpath over an average distance of 500 m, where the depression is ~2.0 m. Hydrodynamic changes of lower values reach much further (up to ~1.0 km). On the other hand, the extent of the cone of depression to the north is highly limited and ranges to the southern dyke of the ponds, which separates them from the forest areas (~180 m).

Regardless of natural factors (e.g., the amount of water recharge to the aquifer, a change in the hydraulic gradient), hydrological measures applied in the post-mining area may also have a significant impact on the further development of the spring pools. These comprise mainly constructing culverts and dykes that divide larger reservoirs, making the reservoirs shallower, interfering with the groundwater table level in ponds by raising or lowering it, and changing local water flow directions in surface watercourses.

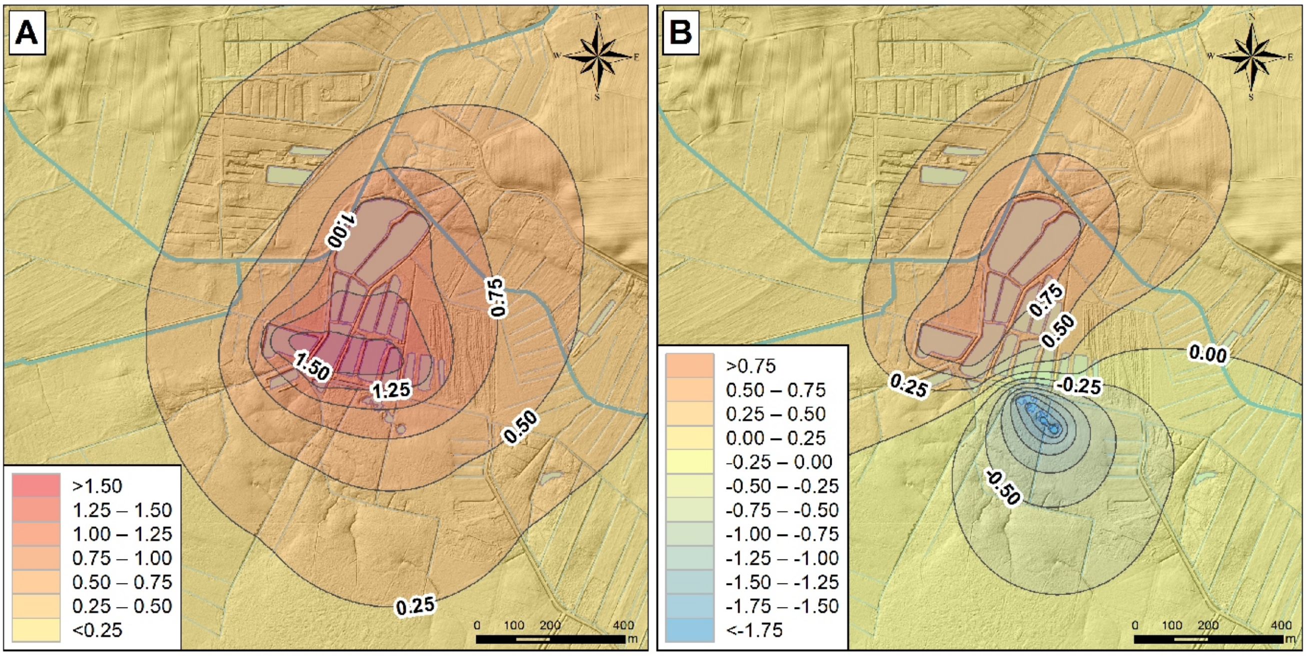


**Fig. 6. The piezometric pressure variation in Q2, from the mining period to the following points in time: A – mining cessation and shallowing of the excavations (Variant II); B – resence of spring pools (Variant III)**

The values are given in metres

## CONCLUSIONS

We have identified a groundwater flow system in a wetland and demonstrated the origin of groundwater outflow activation.

The mining and reclamation operations carried out in the area of an inactive mine of lacustrine chalk at Mierzyno disturbed the natural hydrodynamic groundwater system. In consequence, due to artesian pressure changes in the deep aquifer there were groundwater outflows at the edge of post-mining excavations and the formation of spring pools in the adjacent area. The outflowing groundwater is characterised by increased turbidity, which is believed to be associated with the washing away of silt-clay particles from lacustrine chalk and gyttja. The amount of sediment washed out in the area of the spring pools is ~5,611 $m^3$. However, based on the model simulations, the discharge rate of the springs has been estimated at ~70.34 $m^3$/h.

Hydrological practice applied within the post-mining areas may have a significant impact on the further development of spring pools and the intensity of outflow of water with increased turbidity. Inconsiderable actions, such as backfilling of the spring pools, or filling or decommissioning of the ponds, may bring temporary benefits, but in the further future, they may contribute to an increase in both geodynamic hazards and damage to the natural environment. To improve environmental conditions and inhibit the undesirable effects of uncontrolled groundwater outflows we recommend deepening of the breeding ponds in order to increase the volume of drainage of the deeper aquifer that will allow limiting of spring pools expansion. The phenomenon analysed should be subject to quantitative and chemical hydrogeological and hydrological monitoring. This will allow prediction of unwanted changes in the environment. We also recommend appropriate measures for the purification of water flowing out the post-mining area.

**Acknowledgements**. The authors are grateful to the reviewers for their valuable remarks and suggestions that allowed improvement of the manuscript. This research was funded by the Polish Hydrogeological Survey, in the framework of the task no. 33: *Conducting activities by research team for identify extension of pollution caused by incidental events, accidents or catastrophes.*

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