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A model of brackish groundwater formation in the Nemunas River valley, Lithuania

Algirdas Zuzevičius,

Jonas Mažeika,

Valentinas Baltrūnas

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Patterns of the formation subsurface brackish water in the Nemunas River valley were investigated in the environs of Birštonas town (Middle Lithuania) as a typical case. A model comprising seven aquifers and the aquicludes confining them over an area of 80 km^2 was developed using MODFLOW and FEFLOW software. In order to justify its boundary and the initial conditions and to select the parameters, preliminary studies were performed including an analysis of the Pleistocene succession, the layout of palaeoincisions filled with deposits of different age and lithological composition as well as the investigations of carbon and oxygen isotopes (^{14}C, ^{13}C, ^{18}O), tritium (^{3}H) and helium (^{3}He + ^{4}He) in the groundwater.

The modeling data showed that the brackish water in the Birštonas area is formed by a brine discharge from deep aquifers in the zone of tectonic faults and palaeoincisions. The bulk discharge of the brackish water into the unconfined aquifer and the Nemunas channel takes place in a zone approximately 5 km long and 4 km wide, which almost coincides with an incision of the pre-Quaternary surface. The average rate of the groundwater discharge per 1 km of the channel is about 850 m^3/day. The discharge of a solute (in terms of solids dissolved in groundwater) into the Nemunas River channel corresponding to an approximately twenty-kilometer-long river sector in Birštonas' environs is about 36.5 t/day (1.8 t/day per 1 km of the channel).

Key words: brackish groundwater, modeling, stable and radioactive isotopes, river valley, Lithuania

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Algirdas Zuzevičius, Jonas Mažeika, Valentinas Baltrūnas. Institute of Geology and Geography, T. Ševčenkos 13, LT-03223 Vilnius, Lithuania. E-mail: info@geo.lt, zuzevicius @geo.lt

INTRODUCTION

Brackish groundwater springs are known in the middle part of the Nemunas River valley which is about 200 km long (from the upper reaches at the Belarusian–Lithuanian border in the south up to the right tributary Strėva in the north) and where such health resorts as Druskininkai and Birštonas have been established. According to the data of 1950, the discharge of separate visible springs in Birštonas ranged within 4–150 m^3/day, in total 180–230 m^3/day. At the beginning of the 20th century, the discharge of one of the "old" springs "Viktorija" reached 20 000 buckets, i. e. about 250 m^3/day (Bagdonas, 1923; Kaveckis, 1929; Шонта, 1981; Шонта, 1987; Кондратас, Вайтекунас, 1990). The groundwater discharge into the Nemunas channel could be even greater. There are known several sub-aqueous springs: one in the environs of the Ucieka village, which becomes viewable in the channel during low water periods, many flooded small springs in the area surrounding the Druskelė brackish water spring, and the "old" Birštonas' springs flooded by the pond of Kaunas hydroelectric power plant. The concentration of total dissolved solids (TDS) in the discharged water is 1–9 g/l.

This part of the Nemunas valley is situated in the north-western slope of the Belarusian–Masurian crystalline massif dissected by tectonic faults (Lietuvos…, 2003). Most of the faults cross the sedimentary cover to the Triassic rocks inclusive. The Phanerozoic succession reduces towards the massif (from 700 m in Birštonas' environs to 350–400 m in the surroundings of Druskininkai), loses its stratigraphic completeness, and the clay fraction is reduced as well. The geological–tectonic structure and hydrogeological conditions of Birštonas' environs are further complicated by deep palaeoincisions filled with different sediments (clay, silt, sand, gravel and till) (Figs. 1 and 2). Therefore, in spite of the thick layers of impermeable Triassic clay, Permian anhydrite and Silurian–Ordovician carbonaceous rocks, small (1–2 to 10–50 km^2) dome-like zones of brackish groundwater reaching the phreatic aquifer occur in the intersections of tectonic faults and recent relief depressions (first of all, in the valleys of the largest rivers). The Nemunas River valley, due to its direction from the crystalline massif towards the Baltic syneclise, plays the main role in the deep aquifers brine discharge and may serve as a natural source of integrated hydrogeological information on the Phanerozoic sequence in a large area.

The highest salinity of brine at the bottom of the Phanerozoic succession as a potential source of dissolved solids ranges from 45–55 g/l (Triassic and Proterozoic aquifers

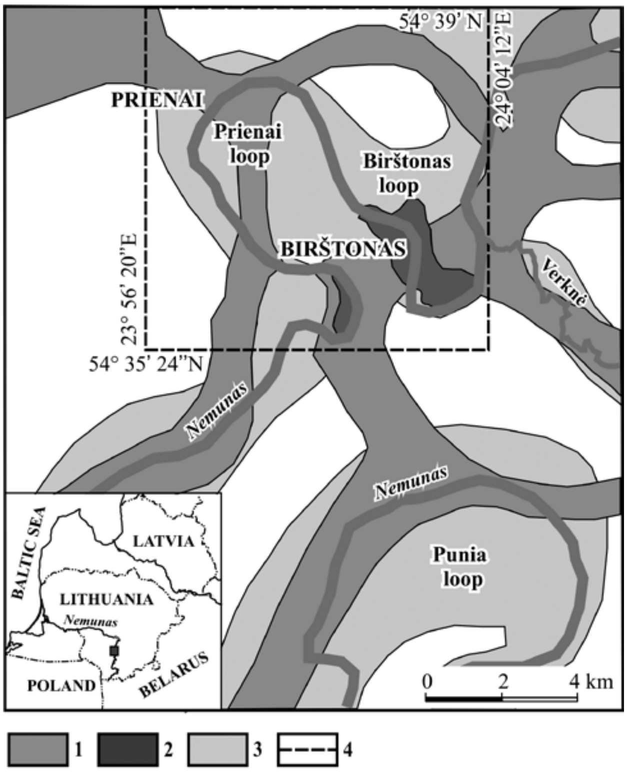

Fig. 1. Location of Birštonas brackish groundwater field and the scheme of palaeoincisions in the region of the great Nemunas loops: *1* – sub-Quaternary palaeoincisions (Šliaupa, 2004), *2* – the deepest incisions in the top of Žemaitija–Medininkai till complex, *3* – recent valleys of the Nemunas and Verknė, 4 – boundaries of the model domain (54°35′2″N – 23°56′20″E; 54°39′N – 24°04′12″E)

1 pav. Birštono mineralinio požeminio vandens telkinio padėtis ir paleoįrėžių Didžiųjų Nemuno kilpų regione schema: *1* – pokvarteriniai įrėžiai (Šliaupa, 2004), *2* – giliausi įrėžiai Žemaitijos-Medininkų morenų komplekso kraige, *3* – dabartiniai Nemuno ir Verknės slėniai, *4* – modeliuoto ploto ribos (54°35′24″ N – 23°56′20″ E; 54° 39′ N – 24°04′12″ E)

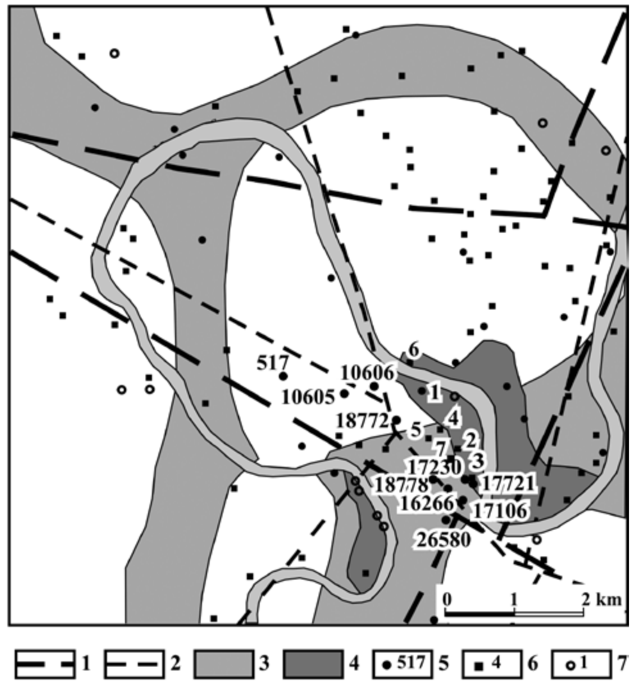

Fig. 2. Geological setting of the Birštonas brackish groundwater field: Tectonic faults*: *1* – in the crystalline basement, *2* – reaching the Triassic layers; palaeoincisions: *3* – in the pre-Quaternary surface, *4* – in the top of Žemaitija–Medininkai till complex; information source: *5* – well, *6* – dug well, *7* – spring (groundwater objects sampled in 2006 are supplied with identification numbers)
*After R. Apirubytė, unpublished data (1974)

2 pav. Tektoninė Birštono mineralinio požeminio vandens telkinio padėtis: tektoniniai lūžiai*: *1* – kristalinio pamato, *2* – kertantys triaso uolienas; paleoįrėžiai: *3* – pokvarteriniai, *4* – Žemaitijos-Medininkų morenų komplekso kraige; faktinės informacijos objektai: *5* – gręžiniai, *6* – kastiniai šuliniai, *7* – šaltiniai. (Nurodyti tik 2006 m. tirtų objektų identifikaciniai numeriai)
*Nepublikuoti R. Apirubytės duomenys (1974)

in the Druskininkai environs and the Upper Permian aquifer in the Birštonas environs) to 100–110 g/l (the Cambrian aquifer in Birštonas' environs).

The last glaciation, deglaciation and post-glacial (Holocene) time may be regarded as typical Quaternary climatic cycles. Rock and water freezing (presumptive depth about 200 m) and thawing due to the upward thermal flux, and the glacier movement and melting essentially changed the flow structure, dynamics and chemical composition of the groundwater.

The present groundwater dynamics, chemical composition and thermal regime of the subsurface developed during permafrost degradation (renewal of water flow and solute transport in the upper aquifers, the rising temperature of water and rocks, head redistribution under conditions of the reducing glacier pressure, etc.) and in the post-glacial (Holocene) time under the influence of new natural (climate, surface topography and hydrography) and anthropogenic (hydrotechnical constructions, groundwater exploitation, etc.) driving forces. It makes the reconstruction of these processes quite complicated.

The typical case of the Birštonas area was selected as a model domain representing the formation pattern of brackish groundwater in the Nemunas River valley and its geological role in the Holocene. A relatively rich database concerning this area allows a reliable calibration of the model.

The analysis of the Quaternary succession, the specification of the palaeoincisions and the investigations of carbon, oxygen, hydrogen isotopes and helium concentrations in the groundwater of the Birštonas environs served as a basis for the model scheme and for the determination of specific features of groundwater flow patterns and formation time.

Hydrogeological setting. The Nemunas is a tributary of the Baltic Sea. Its channel is more than 900 km long, its basin area is about 98 thousand km^2 and the annual run-off is about 21 km^3 (665 m^3/s) (approximately 11.5 km^3 or 365 m^3/s in the Birštonas reaches). Having filled the pond of Kaunas hydroelectric power plant in 1959, the long-term Nemunas water level in the Birštonas environs rose from 39 to 43–44 m above sea level. The width of the channel in the Birštonas area after river damming is about 200 m and the depth is 5–6 m.

The Birštonas health resort is located in the central part of a seventy-kilometer-long sector of the Nemunas channel that starts an upstream from Punia, ends a downstream from the Verknė stream mouth and includes as many as four large loops (Punia, Balbieriškis, Prienai and Birštonas). The width of the valley with terraces ranges from 1.5 to 5 km and the depth reaches 45–80 m (Fig. 1). An analysis of drilling cores and the data on geophysical logging of boreholes shows that these environs are located in a regional fault zone of the crystalline basement, extending from south to north and transacted by another perpendicular fault zone. The block structure of the crystalline basement predetermined the specific features of the structure of the sedimentary cover. The neotectonically active and uplifting anticlinal structure between Nemajūnai and Birštonas largely predetermined the formation of the Nemunas loops during the recession of the last glacier (Baltrūnas et al., 2005).

A comparison of the sub-Quaternary surface map of the territory with the structural maps of the regional (marker) Middle Pleistocene (Žemaitija and Medininkai) till complex and Upper Pleistocene (Varduva–Grūda and Grūda–Baltija) intertill glaciofluvial deposits has shown that the Nemunas valley near Birštonas is characterized by a recurrence (heritage) of palaeoincisions of different age (Šliaupa, 2004). The palaeoincisions are filled mostly with Quaternary sand and gravel formations.

Phreatic (unconfined), Quaternary intertill, Upper Cretaceous, Cenomanian–Lower Cretaceous, Upper Permian (Naujoji Akmenė Formation), Triassic 1 (Tauragė Formation) and Triassic 2 (Nemunas Formation) (both in the Upper Triassic rocks) and Cambrian aquifers were distinguished in the Phanerozoic sequence 700 m in total thickness in the Birštonas environs (Fig. 3). The aquifers and aquicludes in the upper part of the section are very uneven in thickness because they are transected by buried valleys of different depths filled with formations of variable lithological composition. Therefore, the Upper Cretaceous and Quaternary groundwater bodies comprise a joint aquifer. The continuity of the deeper impermeable layers is interrupted by tectonic faults.

METHODS

An original method was used for the reconstruction of the network of palaeoincisions including buried valleys (Baltrūnas, 1995; 1997a). This method is based on the following principles: 1) each genetic type of the Quaternary deposits may be geomorphologically generalized (principle of actualism), 2) the negative forms of a palaeorelief (like of a recent relief) are joined into open erosive systems (principle of erosive systems) and 3) sedimentation and relief formation often depend on geological and tectonic structures and their development in the neotectonic stage (morpho-structural principle). Archival material of large-scale geological mapping and data on prospective boreholes and geophysical logging were employed for the reconstruction. Data and generalizations of resent scientific researches were also used (Baltrūnas, 1995).

The sites for the groundwater isotope studies were selected taking into consideration the physicochemical properties and origin (stable, radioactive or artificial) of the isotopes (hydrogen, carbon and oxygen), their distribution patterns in the hydrosphere and the possibilities of analytical determination. The samples were taken following the unified techniques and procedures (Kadūnas, 1999; Mook, 2000).

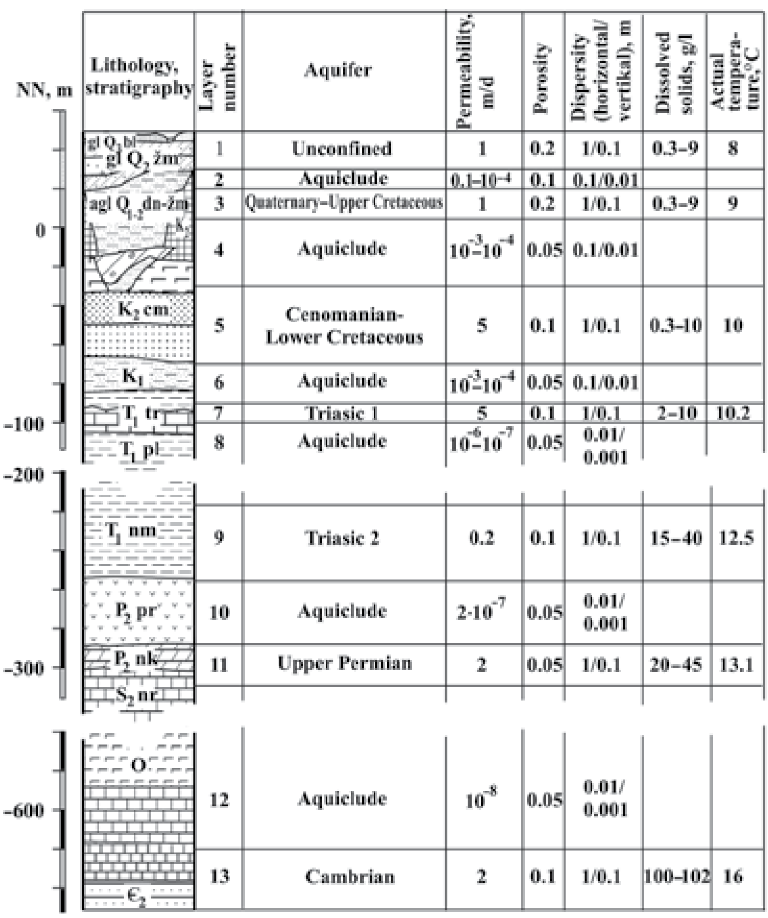

Fig. 3. Phanerozoic succession in Birštonas (well 18772), its schematization for modeling, main parameters and indices (average values)

3 pav. Geologinis fanerozojaus pjūvis Birštone (pagal 18772 gręžinį), jo schematizavimas modeliavimui ir vidutinės pagrindinių parametrų reikšmės

Table 1. **List of groundwater samples taken from Birštonas area in 2006**
1 lentelė. **Požeminio vandens mėginių, paimtų 2006 m. Birštono apylinkėse, sąrašas**

No	Sampling site and its description*	Aquifer (index)	Depth, m	Elements (isotopes)				
				^{3}H	He**	Carbon		$\delta^{18}O$
						$\delta^{13}C$	^{14}C	
1.	Spring, bottom of skiing hill	Unconfined (Qg)	0	+	+	+		
2.	D. well, Vaižganto 10	Unconfined (Qg)	6.4	+	+			
3.	D. well, Birutės 10	Unconfined (Qg)	4.7	+	+			
4.	D. well, Pušyno 29	Unconfined (Qg)	7.0	+	+			
5.	D. well, Jaunimo 21	Unconfined (Qg)	3.8	+	+			
6.	D. well, Žvėrinčiaus 2	Unconfined (Qg)	n/m***		+			
7.	D. well, Dariaus ir Girėno 20	Unconfined (Qg)	6.3		+			
8.	Well 17721 (Versmė)	Quaternary (Qsp)	18		+	+	+	+
9.	Well 10606	Quaternary (Qsp)	28	+	+	+	+	+
10.	Well 26580 (Aldona)	Quaternary (Qsp)	46	+	+	+	+	+
11.	Well 517 (Akvilė)	Quaternary (Qsp)	53	+	+	+	+	+
12.	Well 16266 (Vytautas-7)	Quaternary (Qsp)	60		+		+	+
13.	Well 10605	Upper Cretaceous (K_2)	64	+	+	+	+	+
14.	Well 17106 (Vytautas-2)	Cenomanian–Upper Cretaceous (K_{2cm}–K_1)	125		+	+	+	+
15.	Well 17230 (Vaidilutė)	Triassic 2 (Nemunas) ($T_{1\,nm}$)	306	+	+	+	+	
16.	Well 18778	Triassic 2 (Nemunas) ($T_{1\,nm}$)	315	+	+	+	+	+
17.	Well 18772	Cambrian (Є)	715		+			

* D. well – a shallow dug well with concrete blockhouse; well – drilled exploitation or monitoring well. **Sum of ^{4}He and ^{3}He. ***No measurement.

The location of the groundwater objects investigated in April–October 2006 is shown in Fig. 2, and their short description and the list of the samples are given in Table 1.

The ratio of stable isotopes and the concentrations of radioactive isotopes in the groundwater taken from dug wells, drilled wells and springs were analysed using different nuclear techniques.

Carbon-14 (^{14}C) content in groundwater samples was measured as described in (Gupta and Polach, 1985; Arslanov, 1985). For the synthesis of benzene from groundwater carbonates (or dissolved inorganic carbon, DIC) a conventional method was applied. The ^{14}C specific activity of benzene was measured by liquid scintillation spectrometry (LSA TRICARB 3170TR/SL) at the Radioisotope Research Laboratory of the Institute of Geology and Geography (Vilnius). The main performance parameters of the spectrometric system for ^{14}C in benzene form with 3 ml Teflon vials were as follows: background count rate 0.41 ± 0.04 CPM, counting efficiency 71.3 ± 0.8%. The results were presented as specific activity (per cent of modern carbon: 1 pmC = 2.27 Bq/kg C) (Stuiver and Polach, 1977). The uncertainty of the results was reported at 1 sigma-level.

The volumetric activity of tritium (^{3}H), a radioactive isotope of hydrogen in the water samples was also determined by liquid scintillation spectrometry (LSA TRICARB 3170TR/SL) at the Radioisotope Research Laboratory of the Institute of Geology and Geography (Vilnius). The beta decay counting of ^{3}H was run for the scintillation cocktail with 12 ml of OptiPhase "TriSafe" and 8 ml of water electrolytically enriched or not with ^{3}H. The main performance parameters of the spectrometric system for ^{3}H with 20 ml plastic vials were as follows: background count rate 1.01 ± 0.08 CPM, counting efficiency 22.0 ± 0.4%.

The delta values of carbon isotopes of the groundwater carbonates ($\delta^{13}C$) and of oxygen isotopes in the groundwater ($\delta^{18}O$) were determined using gas source isotope ratio mass spectrometry. The analysis of the carbon isotopes in CO_2 samples prepared from the water carbonates was performed at the Institute of Geochemistry and Geophysics of Belarusian National Academy of Sciences with an MI-1201 mass-spectrometer.

The analysis of the oxygen isotopes in the water was performed at the Laboratory of Isotope Palaeoclimatology of the Institute of Geology, Technical University of Tallinn. Samples of gas carriers CO_2 in the isotopic equilibrium with chemically reduced oxygen from water samples were analysed. The analysis was performed employing a Finnigan-MAT Delta-E mass-spectrometer. The accuracy of both stable isotope techniques was better than ±0.1‰. The results in δ-values were expressed as the permil (‰) difference from the international standards: SMOW for ^{18}O in water and PDB for ^{13}C in carbonates.

The concentration of helium (the sum of isotopes ^3He and ^4He) in water (per cent of helium in gases dissolved in water) was measured at the Radioisotope Research Laboratory of the Institute of Geology and Geography (Vilnius) with the aid of an INGEM-1 indicator, which operates by the principle of magnetic discharge.

The following software was used for the modeling of the groundwater flow, solute and heat transport: MODFLOW (a three-dimensional groundwater flow analysis using finite differences), MT3D (a three-dimensional transport of reacting or decaying chemical elements) and Groundwater Vistas 4.0 basic package, FEFLOW (fluid flow, solute and heat transport analysis using finite elements) (licensee – Institute of Geology and Geography).

The three-dimensional groundwater flow (MODFLOW software) may be described by a partial–differential equation (1):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t};\quad(1)$$

where:
K_{xx}, K_{yy} and K_{zz} are the values of hydraulic conductivity along x, y and z coordinate axes, Lt^{-1};
h is the potentiometric head (L);
W is a volumetric flux per unit volume and represents water sources and / or sinks (t^{-1});
S_s is the specific storage of the porous material (L^{-1});
t is time (t).

The solute transport within groundwater (MT3D software) is described by equations of partial derivatives (2):

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}D_{ij}\frac{\partial C}{\partial x_j}-\frac{\partial}{\partial x_i}v_iC+/-\frac{q_s}{n_0C_s}+\sum_{k=1}^{k=N}R_k\;;\quad(2)$$

where:
C is the concentration of the total dissolved solids (in this study), (ML^{-3});
x_i is the distance along the respective Cartesian coordinate axis, (L);
D_{ij} is the hydrodynamic dispersion coefficient, (L^2t^{-1});
v_i is the seepage (infiltration) or linear pore water velocity, (Lt^{-1});
q_s is the volumetric flux of water per unit volume of the aquifer representing sources (positive) and sinks (negative), (t^{-1});
n_o is the porosity of the porous medium (dimensionless);
C_s is the concentration of the sources or sinks, (ML^{-3});
ΣR_k is the chemical reaction term, $ML^{-3}t^{-1}$.

In equations 1 and 2, L, M and t represent the length, mass and time measuring units used by the computational system.

FEFLOW is designed for the modeling of groundwater flow, solute and heat transport in a layered three-dimensional system as coupled or separate phenomena (Diersch, 2002). It is based on the physical conservation principles for mass, chemical species, linear momentum and energy in a transient and three-dimensional numerical analysis. For three-dimensional (3D) and two-dimensional (2D) processes, vertical and axisymmetric, respectively, the representative model general equation is as follows (i, j = 1, 2, 3):

$$S_s\frac{\partial h}{\partial t}+\frac{\partial q_i^f}{\partial x_j}=Q_x+Q_{EB}(C,T)\;;\quad(3)$$

where:
q_i^f is the Darcy velocity vector of fluid;
Q_x is the source / sink function of fluid; in this particular case, the function of pumping in and out ($x = p$ – fluid, $x = c$ – solute mass, $x = T$ – heat);
Q_{EB} is the extended Boussinesq approximation describing the chemical and thermal processes;
T is temperature.

The processes described by equations 1, 2 and 3 in the nature are usually non-linear and take place in a heterogeneous environment under transient boundary conditions and sometimes with variable parameters. As these equations cannot be solved analytically, they are solved numerically by the methods of finite differences (MODFLOW) or finite elements (FEFLOW). The numerical solutions are justified for certain assumptions using mathematical procedures which are itemized in methodical recommendations by the authors of the computer codes (McDonald, Harbaugh, 2000; Diersh, 2002, 2004; Zheng., Papadopulos, 1990).

The Birštonas area model domain comprises all the seven Phanerozoic aquifers (unconfined, joint Quaternary–Upper Cretaceous, Cenomanian–Lower Cretaceous, Triassic 1 (Tauragė), Trassic 2 (Nemunas), Upper Permian and Cambrian) and the separating impermeable layers. The model domain in the area covers the Prienai Loop of the Nemunas River (about 80 km^2), where Birštonas is located (Figs. 2 and 3). The set boundary conditions for the model domain were the following: the upper boundary – an unconfined aquifer recharged by infiltration; the recharge (Q) and concentration of total dissolved solids (TDS) in water (C) were steady (Q, C = const – 2nd type boundary condition) and the temperature of water (T) was also steady (T = const – 1st type boundary condition). The streams and the surface water bodies (the Nemunas and Druskupis rivers, ponds) are set as groundwater drains with a defined water level (H) and temperature (T) = $f(t)$ (1st type boundary conditions). The natural springs and artesian wells are set as drains with a constant hydraulic head (3rd type boundary condition – $Q = f(\Delta H)$).

The lower boundary of the model is represented by the hydraulic head, the concentration of TDS and the temperature of the Cambrian aquifer that remain steady (H, C, T = const – 1st type boundary condition) due to the great depth and good isolation from other aquifers. Exploitation wells of groundwater fields are set as 2nd type boundary condition ($Q = f(t)$).

The site-specific parameters for MODFLOW and MT3D (groundwater flow and mass transport modeling) were calibrated employing the Groundwater Vistas tools.

A statistical comparison of the groundwater levels drawn by the calibrated model with the groundwater levels from the observation data (51 measurements) gave quality indices of the mathematical model: residual mean 0.13, residual standard deviation 4.8 and the standard deviation and range ratio 0.046. Similar results were obtained by comparing the calibrated model results and TDS for the observation wells. The input data on TDS also covered 51 measurements.

In order to obtain comparable results, the same set of parameters was used for the solute and heat transport evolution reconstruction in the Holocene by the FEFLOW code.

The analysis of the heat transport by the FEFLOW code was based on the previous assessments of permafrost formation and degradation and the data on the environmental changes at the end of the glaciation and in the Holocene (Zuzevičius, 2003; Kabailienė, 2006). During the last glaciation, the depth of permafrost in the Birštonas area could have been 150–200 m, i. e. embraced the Quaternary, Cretaceous, Jurassic and the Upper Triassic (Tauragė Formation) rocks. The temperature and concentration of TDS in the groundwater that occurred after permafrost thawing and rock permeability renewal at the end of the glaciation were taken as initial conditions for the reconstruction of the present-day subsurface conditions (hydraulic head, temperature and TDS). It is assumed that after the renewal of the permeability, Quaternary, Cretaceous and Lower Triassic rocks of the Tauragė Formation (Triassic aquifer1) contained fresh water with a concentration of TDS of 0.3 g/l and temperature +1 °C, whereas the TDS and T values for the deepest Cambrian aquifer were the same as today.

RESULTS

Palaeoincisions. At the beginning of the Quaternary (before glaciations) and during the inter-glacials (Turgeliai, Butėnai, Snaigupėlė (?) and Merkinė), the formation of palaeoincisions was induced by an erosion of the former hydrographic network, the most distinct phases of which were related to the variations of erosion basis (sea and world ocean) (Šliaupa, 2004; Baltrūnas, 1995). A strong deepening of comparatively shallow river valleys started at the beginning of the glaciations with a recurring considerable subsidence (by 100–200 m) of the sea level (Baltrūnas, 1997b). The following events of palaeoincision formation can be distinguished: palaeofluvial erosion → pre-glacial deepening by erosion → glacial exaration → post-glacial fluvioglacial erosion → erosion of recent rivers. These events under favourable geological and palaeogeographical conditions might have turned into the formation stages. The most numerous are palaeoincisions filled with glacial, glaciofluvial and glaciolacustrine sediments of one or a few events. Palaeovalleys of different geological age in the Birštonas environs are incised into pre-Quaternary rocks or into Quaternary till (Žemaitija and Medininkai) complexes.

Isotope data. Isotope (^{3}H, ^{14}C and δ^{13}C, δ^{18}O and ^{3}H + ^{4}He) data for the wells and springs are presented in Tables 2 and 3.

Groundwater oxygen isotope composition for the Birštonas area changes from −10.7 to −9.4‰ and does not differ significantly from the isotope patterns of the Lithuanian unconfined groundwater (Rozanski et al., 1993; Mažeika et al., 1999). Enriched δ^{18}O values (well 18778) are typical of the groundwater which has a certain leakage from deeper aquifers. Depleted δ^{18}O values (well 10606) are characteristic of groundwater containing water portions of a colder climate. These δ^{18}O values are somewhat more depleted than δ^{18}O of recent atmospheric precipitation whose average δ^{18}O in Lithuania equals to about −10.4‰. Generally, the δ^{18}O value of the groundwater differs but little from the modern atmospheric precipitation. This indicates the most active groundwater recharge in the post-glacial. In the presence of some portions of the glacial water with a more depleted δ^{18}O value and of the leakage from deeper aquifers with a less depleted δ^{18}O value in mixing conditions they compensate for each other and the oxygen isotope composition becomes

Table 2. **Stable isotope and radiocarbon data (δ^{13}C, δ^{18}O, ^{14}C) for the wells in Birštonas area**

2 lentelė. **Stabilių izotopų (δ^{13}C, δ^{18}O) ir radioaktyvios anglies (^{14}C) tyrimo Birštono apylinkių požeminiame vandenyje rezultatai**

Sampling site and its description	Aquifer (index)	DIC				Water
		^{14}C				
		Specific activity, pmC	Apparent (not corrected) age, years (BP)	Standard error (±1σ), years or pmC	δ^{13}C, ‰ PDB	δ^{18}O, ‰ SMOW
Spring, bottom of skiing hill	Qg	–	–	–	–	– 10.1
D. well, Vaižganto 10	Qg	109.0	uncertain	0.6	−18.9	–
D. well, Birutės 10	Qg	98.5	115	40	−10.2	–
D. well, Pušyno 29	Qg	87.9	1040	110	−10.1	–
D. well I, Jaunimo 21	Qg	80.3	1760	60	−12.2	–
Well 10606	Qsp	89.3	910	50	−10.1	– 10.7
Well 26580 (Aldona)	Qsp	–	–	–	–	– 10.5
Well 517 (Akvilė)	Qsp	60.9	3980	100	−12.2	– 10.6
Well 17721 (Versmė)	Qsp	42.0	6970	100	−8.2	
Well 10605	K2	23.4	11 680	100	−11.2	– 10.4
Well 17106 (Vytautas-2)	K_2–K_{1cm}	26.9	10 530	100	−9.0	– 10.4
Well 17230 (Vaidilutė)	$T_{1\ nm}$	Beyond limits of method			−19.1	– 10.3
Well 18778	$T_{1\ nm}$				–	– 9.4

Note: standard determination error for δ^{13}C and δ^{18}O ±0.1‰.

Table 3. **Tritium (^{3}H) and helium ($^{3}He + ^{4}He$) data for the wells in Birštonas area**
3 lentelė. **Tričio (^{3}H) ir helio ($^{3}He + ^{4}He$) tyrimo Birštono apylinkių požeminiame vandenyje rezultatai**

Sampling site and its description	Aquifer, index	^{3}H			$^{3}He + ^{4}He$, $\times 10^{-5}$ ml/l
		Volumetric activity in water		Standard error, ±TU (1σ)	
		TU	Bq/l		
Spring, bottom of skiing hill	Qg	14	1.7	4	5.2
D. well, Vaižganto 10	Qg	9	1.1	3	11
D. well, Birutės 10	Qg	8	0.9	3	16
D. well, Pušyno 29	Qg	10	1.2	3	13
D. well, Jaunimo 21	Qg	4.2	0.5	3	18
D. well, Žvėrinčiaus 2	Qg	–	–	–	54
D. well, Dariaus ir Girėno 20	Qg	–	–	–	5.2
Well 17721 (Versmė)	Qsp	–	–	–	12
Well 10606	Qsp	20	2.4	2	5.2
Well 26580 (Aldona)	Qsp	< 0.3	< 0.036	0.3	77
Well 517 (Akvilė)	Qsp	0.6	> 0.071	0.3	77
Well 16266 (Vytautas-7)	Qsp	–	–	–	5.2
Well 10605	K_2	< 2	< 0.24	2*	240
Well 17106 (Vytautas-2)	K_2–K_{1cm}	–	–	–	1965
Well 17230 (Vaidilutė)	$T_{1\,nm}$	–	–	–	8900
Well 18778	$T_{1\,nm}$	< 0.3	0.0	0.3	26
Well 18772	Є	–	–	–	2694

* Detection limit (2–3 TU) when measured without enrichment.

Table 4. **Corrected radiocarbon age of groundwater for the wells in Birštonas area**
4 lentelė. **Koreguotas Birštono apylinkių požeminio vandens amžius (pagal radioaktyviąją anglį)**

Sampling site and its description	Aquifer (index)	$\delta^{13}C$, ‰ PDB	^{14}C activity, pmC	Age, years	
				Case 1	Case 2
D. well, Vaižganto 10	Qg	–18.9	109.0	Modern*	1200
D. well, Birutės 10	Qg	–10.2	98.5	Modern*	Modern*
D. well, Pušyno 29	Qg	–10.1	87.9	Modern*	Modern*
D. well, Jaunimo 21	Qg	–12.2	80.3	Modern*	110
Well 10606	Qsp	–10.1	89.3	Modern*	Modern*
Well 517 (Akvilė)	Qsp	–12.2	60.9	1100	2400
Well 17721 (Versmė)	Qsp	–8.2	42.0	700	2000
Well 10605	K_2	–11.2	23.4	8300	9600
Well 17106 (Vytautas-2)	K_2–K_{1cm}	–9.0	26.9	5300	6600
Well 17230 (Vaidilutė)	$T_{1\,nm}$	– 19.1	–	–	–

* Undefined age.

very close to the modern atmospheric precipitation. In these cases, the groundwater origin should be identified by other isotope proxies (helium, $\delta^{13}C$, ^{14}C) and hydrochemical information (Fig. 5).

^{14}C may not behave as a conservative tracer in groundwater as it is a constituent of the DIC compounds undergoing hydrochemical reactions with the rock matrix of the aquifer. Therefore, the initial (apparent) radiocarbon age and the corrected age may be different (Tables 2 and 4).

In the geochemical equilibrium between CO_2 and carbonate or close to it, the $\delta^{13}C$ values for DIC of the groundwater should approach from –12 to –13‰. Sometimes the geochemical behaviour of DIC and $\delta^{13}C$ variations in groundwater are more complicated. Among the modifying factors there may be a dissolution of the carbonate minerals (enriched $\delta^{13}C$ values) and the organic matter destruction (depleted $\delta^{13}C$ values) (Clark and Fritz, 1997). Therefore, the radiocarbon age of the groundwater could not be estimated because of the complicated geochemical patterns and has an indefinite value.

Extreme $\delta^{13}C$ values (enriched or depleted) of DIC in the groundwater of the Birštonas area were observed in some cases (for example, for well 17721 $\delta^{13}C$ = –8.2‰ PDB, for well 17230 $\delta^{13}C$ = –19.1‰ PDB) (Table 2). Mostly depleted $\delta^{13}C$ values (D. well, Vaižganto 10; well 17230) imply an excess of biogenic CO_2 in the groundwater. Mostly enriched $\delta^{13}C$ values (well 17721) show a more intensive dissolution of carbonates (whose $\delta^{13}C$ value is close to 0‰).

The uncorrected age of the radiocarbon could be considered only relatively: the lower the ^{14}C specific activity, presumably the older is the water (Table 2).

There are various models to estimate the corrected radiocarbon age by applying the concentrations of bicarbonate and CO_2 or the isotopic composition of carbon including isotopic fractionation and mixing (Mook, 2000).

For the correction of the age, $\delta^{13}C$ measured in the groundwater and additional carbon isotope parameters ($\delta^{13}C$ of dissolved soil CO_2: in the first case $\delta^{13}C = -17.5$ ‰, formula 4, in the second −15.0‰ PDB, formula 5) selected from similar geochemical systems (Ферронский, Поляков, 1983) were used. The corrected groundwater age was determined by the following formulae (Ферронский, Поляков, 1983):

$$t_{age} = 8267 \ln\left(-\frac{5.7 \cdot \delta^{13}C_{meas}}{^{14}C_{meas}}\right) \tag{4}$$

and

$$t_{age} = 8267 \ln\left(-\frac{6.7 \cdot \delta^{13}C_{meas}}{^{14}C_{meas}}\right), \tag{5}$$

where $^{14}C_{meas}$ and $\delta^{13}C_{meas}$ are the ^{14}C and $\delta^{13}C$ values measured in the groudwater.

We assume that the first case (formula 4) is more relevant to our study. In this case, the groundwater age in the wells varies from modern to 8300 years. The age of the unconfined groundwater is modern (Table 4). This was also proven by tritium data. However, the tritium data also show water age differences in the dug wells. The groundwater from the Cretaceous aquifers is the oldest – 5300–8300 years. The age of the groundwater from confined Quaternary aquifers is 700–1100 years (Table 4).

Generally it is assumed that the main reason for helium ($^3He + {}^4H$) anomalies in groundwater is a dissolved helium transport from deeper Earth structures by convection. Many studies (Ферронский, Поляков, 1983) have shown that higher helium concentrations are characteristic of permeable tectonic fault zones. In these zones, through the rocks of crystalline basement, helium is transported from the deeper part of the lithosphere. In the water of crystalline basement of South Lithuania (well 10171), helium concentration reached 16550×10^{-5} ml/l (measurements were performed 14 June 1996).

In the Birštonas environs, helium concentrations at the same depth increase towards the groundwater discharge zone. For example, rather high concentrations of helium were found in the central part of the brackish groundwater zone (Table 3), while helium concentrations in the Cenomanian–Lower Cretaceous aquifer ($2156 \cdot 10^{-5}$ ml/l, well 17106) are very close to its concentrations in the deeper Cambrian aquifer ($2694 \cdot 10^{-5}$ ml/l, well 18772). This allows assuming that the well to the Cambrian aquifer is more distant from the tectonic fault, through which helium from the crystalline basement is transported to Phanerozoic aquifers. This statement is supported by the $\delta^{18}O$ value of the groundwater from the Late Triassic aquifer (Nemunas Formation) (well 18778). This well is in the centre of a brackish water zone with an enriched $\delta^{18}O$ value (−9.4‰), indicating brine influence from a deeper zone (Table 2).

The results of tritium and helium measurements and the corrected radiocarbon age of the groundwater are presented in Tables 3 and 4. The plot $\delta^{13}C$ versus ^{14}C and the depth distribution of isotopes are shown in Figs. 4 and 5.

Zone I in Fig. 4 represents the data for which ^{14}C age estimates are acceptable; zone II represents the data for modern or close-to-modern groundwater; zone III represents the groundwater recharged in the "nuclear epoch" after 1950 (normally tritium-bearing groundwater).

Contemporary groundwater and solute circulation. The data on the dynamics and hydrochemistry of the groundwater in Birštonas' environs have been investigated for more than 50 years by geological mapping at different scales and groundwater prospecting for fresh and mineral water supply. Meantime surface water regime changes occurred due to the construction of the Nemunas dam, the operation of ponds in the Druskupis stream valley and groundwater exploitation.

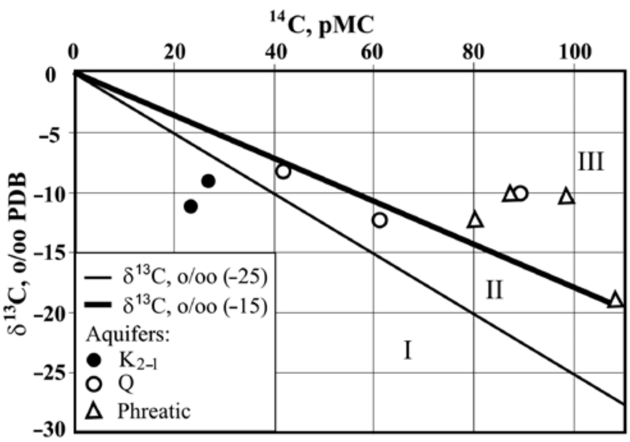

Fig. 4. Plot $\delta^{13}C$ versus ^{14}C for Birštonas area groundwater

4 pav. $\delta^{13}C$ priklausomybė nuo ^{14}C Birštono apylinkių požeminiame vandenyje

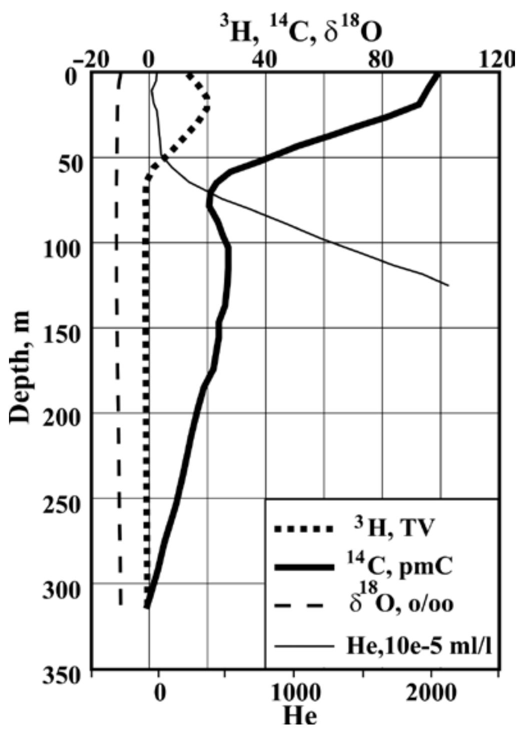

Fig. 5. Depth distribution of tritium (^3H), helium ($^3He + {}^4He$), oxygen ($\delta^{18}O$) and radiocarbon (^{14}C) in Birštonas area groundwater

5 pav. Vertikalus tričio (^3H), helio ($^3He + {}^4He$), deguonies ($\delta^{18}O$) ir radioaktyviosios anglies (^{14}C) pasiskirstymas Birštono apylinkių požeminiame vandenyje

Table 5. **Groundwater flow and solute transport quantities for Birštonas model domain**
5 lentelė. **Požeminio vandens ir medžiagų apykaita Birštono apylinkėse (modeliavimo duomenys)**

Aquifer	Constituents (origin) of groundwater	Groundwater budget (inflow–outflow), thou m³/day	Discharge of solute, kg/day Average TDS, g/l
1	2	3	4
Unconfined	Top: *including: – infiltration* *– river* Bottom Lateral	20320–26800 20320–0 0 –26800 15300–13100 7930–3650	36470 / 1.36
	Total:	43550–43550	
Quaternary–Upper Cretaceous	Top Bottom	13100–15300 12430–10230	33650 / 2.2
	Total:	25530–25530	
Cenomanian–Lower Cretaceous	Top Bottom Lateral	10230–12430 1990–720 4100–3170	32770 / 2.6
	Total:	16320–16320	
Triassic 1 (Tauragė)	Top Bottom	720–1990 1270–0	31120 / 15.6
	Total:	1990–1990	
Triassic 2 (Nemunas)	Top Bottom Lateral Withdrawal	0–1270 230–30 1160–0 0–90	30900 / 24.3 2400 / 27.0
	Total:	1390–1390	
Upper Permian	Top Bottom Lateral	0–230 43–0 187–0	10150 / 44.1
	Total:	230–230	
Cambrian	Top Capacity	0–43 43–0	4300 / 100.0
	Total:	43–43	

Based on available data, the modern distribution of hydraulic heads and TDS in the groundwater of the upper part of the Phanerozoic succession is typical of a groundwater discharge zone. The strong draining impact of the Nemunas' valley reaches the Triassic aquifers. This impact is negligible for the deeper Upper Permian and Cambrian aquifers (water levels, respectively, about 80 and 130 m above sea level, TDS concentration 45 and 100 g/l).

The simulated groundwater flow constituents in Birštonas' environs are shown in Table 5.

The average infiltration recharge in the model domain is about 250 m^3/day/km^2 (about 90 mm/a). The lower part of the Phanerozoic succession (Triassic and deeper aquifers) accounts for 5% of the total groundwater flow.

The hydraulic conductivity of the aquifers in Birštonas' environs is relatively low, and ranges within 0.1–5 m/day.

Moreover, due to the tortuosity of the channel in the loop segment (a twenty-kilometer-long segment of the valley at the level of high terraces includes about 70 km of the river channel) and the plain relief, the hydraulic gradients and the lateral inflow to the channel are small. The modeled twenty-kilometer-long channel segment (Prienai loop) including the Birštonas brackish groundwater field is almost perpendicular to the extension of the valley (Fig. 1). Therefore, the total groundwater discharge in the Nemunas' channel here ranges from 500 to 1500 m^3/day/km and is considerably less than in the channel upstream from Alytus, where the channel length unit covers almost the same length of a discharge-forming valley, and the permeability of the rocks is better (Zuzevičius et al., 2004). Therefore, the relatively larger portion of water from the deeper aquifers in the total groundwater discharge to the Nemunas' channel is also one of the factors forming the Birštonas brackish groundwater zone.

The simulated most intensive groundwater discharge takes place in a five-kilometer-long channel segment of the Nemunas upstream from the former mouth of the Druskupis stream and in a three-kilometer-long segment on the opposite side of the Prienai loop. This zone almost repeats the direction of the pre-Quaternary relief incision (Fig. 6). Half of the solute load (about 18500 kg/day) presented in the model domain is discharged in the first sector. The average groundwater discharge rate per 1 km of the channel equals to about 850 m^3/day, and the average concentration of TDS in the discharged groundwater is about 4.4 g/l.

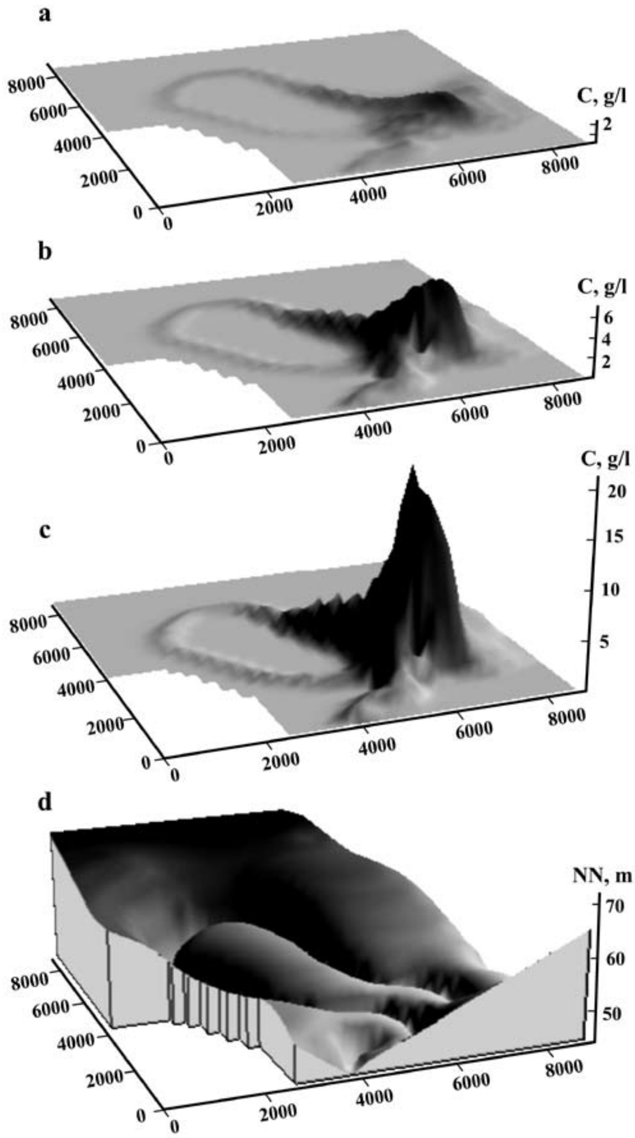

Fig. 6. Simulated concentration of TDS in unconfined aquifer and groundwater discharged into the river channel 400 (*a*), 1000 (*b*) and 10 000 (*c*) years after permafrost degradation; (*d*) – contemporary groundwater level

6 pav. Modelinė gruntinio horizonto ir į upės vagą išsikraunančio požeminio vandens mineralizacija praėjus 400 (*a*), 1000 (*b*) ir 10000 (*c*) metų po įšalo sunykimo; (*d*) – absoliutus dabartinis gruntinio horizonto vandens lygis

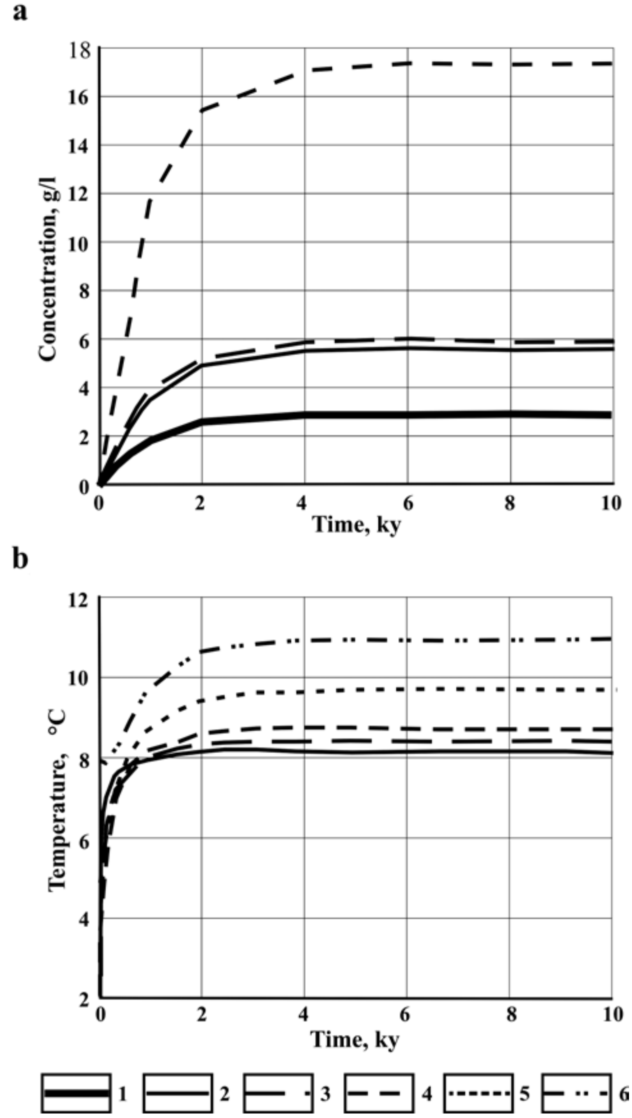

Fig. 7. Reconstructed time series of TDS in groundwater (*a*) and temperature (*b*) in the field centre in the post-glacial. Aquifers: *1* – unconfined (phreatic), *2* – Quaternary–Upper Cretaceous, *3* – Cenomanian–Lower Cretaceous, *4* – Triassic 1 (Tauragė), *5* – Triassic 2 (Nemunas), *6* – Upper Permian

7 pav. Požeminio vandens mineralizacijos (*a*) ir temperatūros (*b*) kitimas telkinio centre poledynmečiu (modeliavimo duomenys). Vandeningieji horizontai: *1* – gruntinis, *2* – kvartero–viršutinės kreidos, *3* – cenomanio–apatinės kreidos, *4* – triaso 1 (Tauragės), *5* – triaso 2 (Nemuno), *6* – viršutinio permo

In the central part of the field (in the area of the "old" flooded springs), the groundwater discharge rate is lower (about 350 m^3/day/km), but the concentration of TDS is higher (average 5.5 g/l and maximal in channel bottom 11–15 g/l). These simulated values cannot be proved *in situ* but are consistent with the ones observed on the banks and are reliable because the observed maximal concentration of TDS in the water of visible springs is 9 g/l.

Brackish water dome formation in the Holocene. The velocity of the solute and heat transport in the subsurface are substantially lower than the predetermining variations of groundwater dynamics. The post-glacial evolution of the groundwater TDS and the temperature for the Birštonas model domain was based on the mentioned assumptions of the permafrost degradation and groundwater flow and solute transport renewal: the upper aquifers (down to Triassic aquifer 1 inclusive) contain fresh (average TDS concentration 0.3 g/l) and cold (average temperature +1 °C) water; the TDS concentration for the lower Phanerozoic aquifers equals the recent value (initial condition), and the TDS concentration and the temperature for the shallow groundwater and the Cambrian aquifer equal the recent values (the upper and the lower boundary conditions of the model).

Simulated time histories of the TDS and temperature after the permafrost degradation in the upper aquifers are shown in Fig. 7.

Table 6. **Solute discharge to the Nemunas River channel for the Birštonas model domain**
6 lentelė. **Mineralinių medžiagų iškrova į Nemuno vagą Birštono apylinkėse (modeliavimo duomenys)**

Groundwater discharge		Solute discharge							
Total, thousand m³/day	Modulus, thousand m³/day/km	Total						Modulus	
		Per day		Per year		In the Holocene (10000 years)		ton/day/km	m³/day/km
		ton	m³	ton	m³	ton	m³		
26.8	1.34	36.5	15.2	$13 \cdot 10^3$	$5.5 \cdot 10^3$	$130 \cdot 10^6$	$55 \cdot 10^3$	1.8	0.76

According to the model, the TDS concentration and the temperature in the upper aquifers should reach the contemporary values in approximately 5 thousand years. During the glacier recession from the territory of Lithuania (12–14 thousand and years ago), the groundwater was already in the liquid state due to the geothermal impact. Therefore, the traces of the last glaciation in the groundwater isotope and hydrochemical pattern could be hardly proven. On the other hand, the groundwater flow renewal due to the permafrost thawing under the thermal impact from below and from above was a long-lasting and complicated process. Thus, the assumption that it has been taking place since the glacier recession requires careful consideration.

The solute discharge with the groundwater into the twenty-kilometer-long segment of the Nemunas' channel for the Birštonas model domain under the contemporary conditions is shown in Table 6.

About 36.5 t/day (13.3 thousand tons per year) of the solute or about 1.8 t/day per 1 km of the channel length are discharged into the Nemunas' channel in the Birštonas environs. For a rough calculation, it can be assumed that during 10 thousand years about 130 million tons of the solute (about 55 million m^3) have been discharged. Almost 85% or 30 t/day (11 thousand tons per year, 110 million tons per 10 thousand years) of the solute discharge come from the deeper aquifers (Triassic and deeper). The deepest Cambrian aquifer accounts for about 10% (4 t/day) of the solute discharge.

CONCLUSIONS

1. Three valleys of different configurations filled with Quaternary sediments of different age and lithological composition were distinguished in the Birštonas environs: a valley transecting the sub-Quaternary surface composed of the Upper Cretaceous rocks to the Triassic (Palanga) Formation, a valley incised into the top of till (Žemaitija and Medininkai) complex (palaeoincisions), and the recent valleys of the Nemunas River and the Verknė stream.
2. Groundwater $\delta^{18}O$ in the Birštonas area changes from −10.7 to −9.4‰ and differs but little from the present atmospheric precipitation (−10.4‰), indicating that the bulk groundwater recharge took place in the post-glacial. This conclusion is supported by ^{14}C and $\delta^{13}C$ data. The age of the groundwater in the wells studied varies from modern to 8300 years. However, the leakage from deeper aquifers is traced by $^3He + {}^4He$, $\delta^{18}O$ and TDS data.
3. The results of the groundwater flow, solute and heat transport modeling for the Phanerozoic system (7 aquifers) in the Birštonas area (80 km^2) are in line with the isotope data and give evidence that in the groundwater chemical and isotope composition there are no traces of the impact of the last glaciation. The brackish groundwater zone is formed by a brine discharge from deep aquifers in the zone of tectonic faults and palaeoincisions. An intensive brackish groundwater discharge into the phreatic (unconfined) aquifer and the Nemunas' channel takes place in a five-kilometer-long and four-kilometer-wide zone, which almost coincides with the sub-Quaternary relief incision.
4. The average groundwater discharge value per 1 km of the channel is about 850 m^3/day, the average concentration of TDS in the discharged groundwater is 4.4 and the maximal concentration is about 15 g/l. About 36.5 t/day (1.8 t/day per 1 km) of the solute are discharged into a twenty-kilometer-long segment of the Nemunas' channel in the Birštonas environs. Based on the assumption that the average solute discharge rate in the whole sector of 200 km is close to the value for the Birštonas environs (about 1.8 t/day/km), the total solute discharge in the Middle Nemunas should be about 360 t/day. During the Holocene (a period of slightly more than 10 thousand years), this value could be more than one billion tons or 0.5 billion m^3 of the dissolved solids lost by the Phanerozoic succession. The greatest amount of the dissolved solids is carried away from the narrower riverside zone. Consequently, the rate of the chemical erosion in this zone is higher and is followed by fissuring and increasing porosity and permeability of rocks. This conclusion is supported by the evolution of the Nemunas valley whose traces are left even in the pre-Quaternary surface. The intensive discharge of the solute almost in the whole Nemunas River valley upstream from the mouth of its right tributary Strėva during the Holocene (about $130 \cdot 10^6$ thousand tons) is one of the most important recent geological processes in the area.

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Algirdas Zuzevičius, Jonas Mažeika, Valentinas Baltrūnas

MINERALINIO POŽEMINIO VANDENS FORMAVIMOSI NEMUNO SLĖNYJE (LIETUVA) MODELIS

Santrauka

Mineralinio požeminio vandens telkinių formavimosi Nemuno slėnyje dėsningumams tirti pasirinktas tipiškas Birštono telkinys. Modelis, apimantis 7 vandeninguosius horizontus ir juos skiriančias vandensparas 80 km^2 plote, kurtas MODFLOW, FEFLOW programinėmis priemonėmis. Siekiant pagrįsti jo ribines, pradines sąlygas ir parametrus, detalizuota pleistoceno nuogulų sandara ir patikslinta skirtingo amžiaus bei įvairios litologijos uolienomis užpildytų paleoįrėžių padėtis, atlikti specializuoti anglies, deguonies, vandenilio izotopų (^{14}C, ^{13}C, ^{18}O, ^{3}H) ir helio požeminiame vandenyje tyrimai.

Modeliavimo duomenimis, Birštono mineralinio požeminio vandens telkinį Nemuno slėnyje formuoja giliai slūgsančių horizontų vandens iškrova tektoninių lūžių ir paleoįrėžių zonoje. Iškrova į gruntinį horizontą ir Nemuno vagą daugiausia vyksta apie 5 km ilgio ir 4 km pločio zonoje, kuri beveik sutampa su pokvarterinio reljefo įrėžiu. Vidutinis požeminio vandens iškrovos debitas viename km vagos čia yra apie 850 m^3/d, vidutinė išsikraunančio požeminio vandens mineralizacija – apie 4,4 g/l. Bendra mineralinių medžiagų iškrova su požeminiu vandeniu į Nemuno upės vagą apie 20 km ilgio ruože Birštono apylinkėse yra apie 36,5 t/d (13,3 tūkst. t per metus), arba beveik apie 1,8 t/d viename km vagos. Izotopų tyrimai ir modeliavimas rodo, kad dabartinė telkinio požeminio vandens cheminė sudėtis ir temperatūrų pasiskirstymas susidarė poledynmečiu (holocene).

Альгирдас Зузевичюс, Йонас Мажейка, Валентинас Балтрунас

МОДЕЛЬ ФОРМИРОВАНИЯ МИНЕРАЛЬНЫХ ПОДЗЕМНЫХ ВОД В ДОЛИНЕ РЕКИ НЯМУНАС, ЛИТОВСКАЯ РЕСПУБЛИКА

Резюме

Закономерности формирования куполов минеральных подземных вод в долине р. Нямунас рассмотрены на примере месторождения Бирштонас. Модель, включающая 7 водоносных и их разделяющие горизонты на площади 80 км^2, реализована MODFLOW, FEFLOW программными средствами. Для обоснования параметров граничных и начальных условий модели проведена детализация структуры и состава плейстоценовых отложений в пределах погребенных долин, определения изотопов углерода, кислорода, водорода (^{14}C, ^{13}C, ^{18}O, ^{3}H), гелия в подземных водах.

Бирштонское месторождение формирует разгрузка вод глубоких горизонтов в грунтовый горизонт и русло реки в пределах зоны (5 на 4 км), почти совпадающей с палеоврезом дочетвертичной поверхности. Суммарная разгрузка минеральных веществ с подземными водами в русло р. Нямунас на 20 км участке в пределах месторождения составляет 36,5 т в сутки при средней минерализации 4,4 г/л. По данным изотопных исследований и моделирования, современный химический состав и распределение температур подземных вод месторождения сформировались в голоцене.