

**The groundwater dynamics in the southern part of the Baltic Artesian Basin  
during the Late Pleistocene**

*Algirdas Zuzevičius*

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**Abstract** The reconstruction of hydrogeological conditions during the Late Pleistocene and Holocene has been performed for the southern part of the Baltic Artesian Basin (BAB) situated on the slope of the Belarusian–Masurian crystalline basement. The reconstruction was accomplished modelling the freezing-and-thawing of the subsurface and migration of unfrozen water under the permafrost, which covered the whole 250-270 m thick fresh water zone before the Nemunas (Late Weichselian) glacier advance (22 000-23 000 BP). Due to anomalous high gradients (0.003-0.004) caused by glacier loading (in the north) and draining periglacial lake (in the south), the unfrozen mineralised water could fill a 10-35 km wide strip in the lower beds of the sedimentary cover at the BAB's southern margin. This can explain the current small thickness of the fresh water zone, as well as the older age of water in deeper beds and water mineralisation in the southern part of the BAB as compared to the northern part of the basin, which is in a similar geological setting.

**Keywords** Late Pleistocene, permafrost modelling, glacier, groundwater dynamics, Baltic Artesian Basin, Lithuania.

*Algirdas Zuzevičius [zuzevicius@geo.lt], Institute of Geology and Geography, T. Ševčenkos 13, Vilnius 03223, Lithuania. Manuscript submitted 15 November 2009; accepted 22 April 2010.*

## INTRODUCTION

The southern and northern parts of the Baltic Artesian Basin (BAB) situated on the north-western slope of the Belarusian-Masurian Antecline and southern slope of the Baltic Shield (respectively) are similar in their geostructural position and geological setting, as well as in their Late Glacial history (Gaigalas 2001; Kalm 2006) (Fig. 1).

The thickness of the sedimentary cover in the northern part of the BAB is growing southwards from the Baltic Shield: from 250 m (southern coast of the Gulf of Finland) to 450 m in the central part of Estonia. Only fresh groundwater discharging into the Gulf is observed in this area. According to the oxygen isotope  $^{18}\text{O}$  concentrations ( $\delta^{18}\text{O}$  ranging from -18 to -21.5‰ SMOW), even the deepest lying Vendian, Cambrian and Ordovician rocks isolated from above by thick regional aquitards contain fresh water that had been

formed here rather recently during the Pleistocene cold period (Vaikmäe *et al.* 2001; Mokrik, Mažeika 2002) (profile I-I on Fig. 2).

The southern part of the BAB situated on the slope of the Belarusian-Masurian Antecline, where the crystalline basement is descending towards the Baltic Syncline from 200 m (Paversekiai, Druskininkai) to 700 m (Birštonas) and even 900 m (Kaunas) below the sea level. Respectively, the thickness of the sedimentary cover grows from 350-400 to 800 and 1000 m. Number of aquifers, thickness of aquitards and clay content in terrigenous formations also increase in this direction (see profile II-II on Fig. 2).

Fresh groundwater zone thickness in the recharge areas of the BAB is usually about 250-300 m, whereas in the southern part of the basin and even in the area close to the top of the Belarusian-Masurian Antecline, which is the current recharge area of the basin, that is lower (to 200 m). Oxygen isotope composition

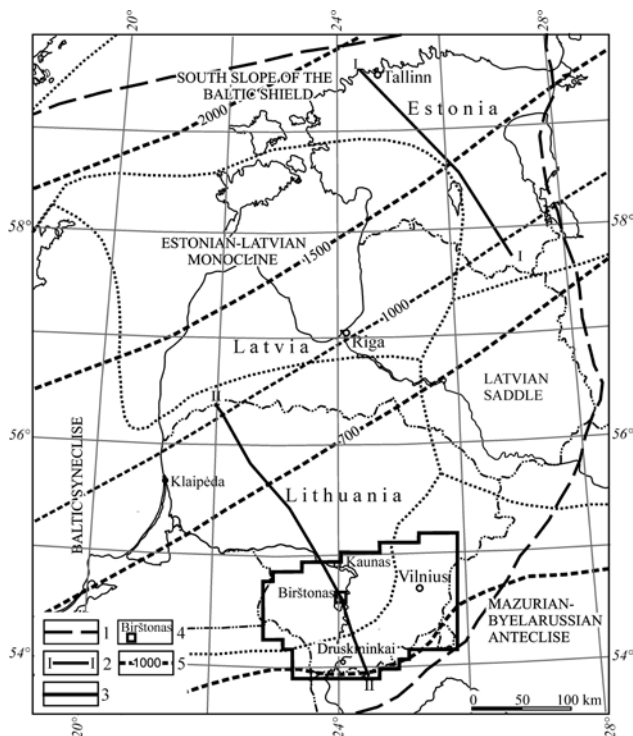


Fig. 1. A tectonic scheme of the Baltic Artesian Basin (BAB) (after Suveizdis 2003): 1—boundary of the artesian basin; 2—direction of the hydrogeological sections; boundary of the modelled area; 3- in southern part of BAB; 4-in the environs of Birštonas; 5—glacier isopachs during LGM.

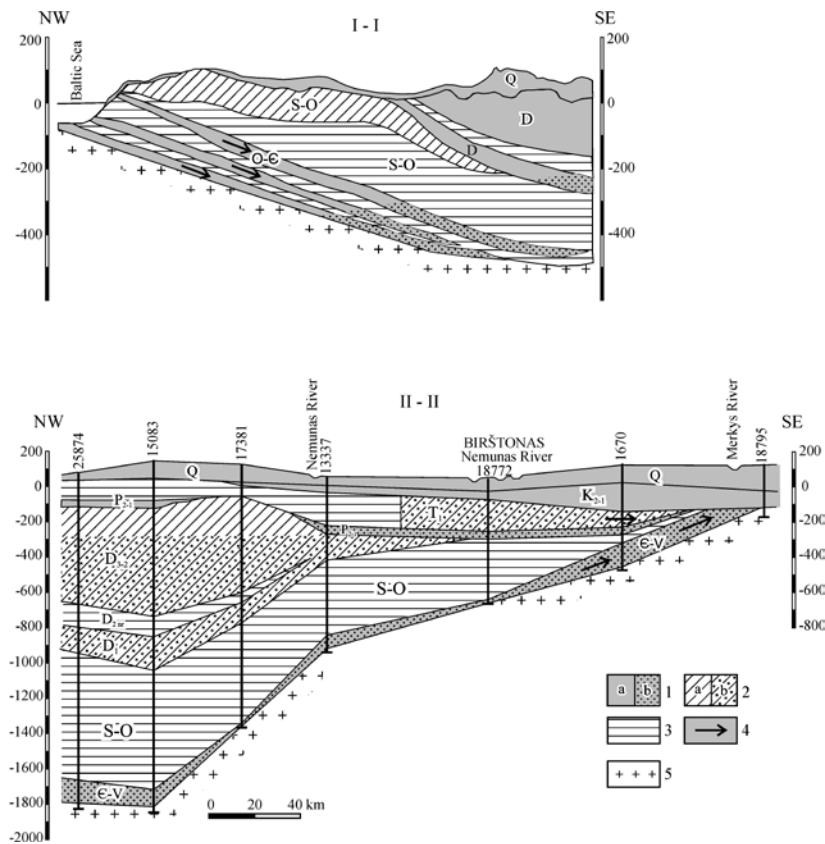


Fig. 2. Hydrogeological sections of the Baltic Artesian Basin (BAB): I-I—across BAB's northern part, II-II—across BAB's southern part: 1—aquifer with fresh (a) and mineralised (b) water; 2—sporadically water-bearing bed with fresh (a) and mineralised (b) water; 3—aquitard; 4—presumptive direction of groundwater flow during the Pleistocene glaciations. The age of sediments is marked by capital letters in accordance with an International Stratigraphic Chart.

indicates that the fresh groundwater had mainly been formed here in Post-Glacial time (Holocene) ( $\delta^{18}\text{O}$  ranging from -11.5 to -8.8 ‰ SMOW, and very slightly differing from the average for the meteoric water, that is -10.4). This is confirmed by the radiocarbon dating showing the fresh groundwater age usually being less than 10 000 years (Mokrik, Mažeika 2002; Mokrik 2003; Zuzevičius *et al.* 2007). Nevertheless, the brackish metamorphosed groundwater or even brine occurs here, differently to that in the northern part of the BAB, just under the active groundwater flow zone. So, 45-55 g/l groundwater occurs already at 200 m depths in the Triassic and older deposits close to the top part of the Antecline in Druskininkai environs, where the crystalline basement lies at about 200 m below the sea level. Analogous mineralised water in the significantly deeper basin's part in the zone of discharge in Birštonas area occurs deeper—in the Upper Permian rocks lying at about 350 m depths.

The piezometric surface of mineralised water in the Upper Permian and Cambrian-Vendian aquifers (recalculated for fresh water density) is close to or even higher than that of the shallow groundwater. Therefore, mineralised water domes reaching the unconfined aquifer are formed in the active groundwater flow zone in the areas where tectonic faults and/or buried post-Quaternary incisions coincide with the current relief depressions. Most of them are observed in the valley of the Nemunas River that is the largest in the region. Natural mineral water sources favoured the formation of large spa resorts of Druskininkai and Birštonas.

As a positive tectonic structure the Belarusian-Masurian Antecline has remained from the Devonian (Zuzevičius 2005). Therefore, here, at the southern margin of the BAB, there were no conditions favourable for the co-sedimental groundwater to remain (Mokrik 2003). During the last Merkinė (Eemian) Interglacial, which lasted from 30 000 to 50 000 years after different literature sources (Grigelis, Kadūnas 1994; Gaigalas 2001), the southern margin of the BAB at the Belarusian-Masurian Antecline slope was the groundwater recharge zone. The brine also could not survive under such conditions at present location near the Antecline as long as the beginning of the Last Glacial. Presumably, here it was replaced by infiltrated fresh water. The current gradients in the lower aquifers of the sedimentary cover are very low or even undetectable. Analogous hydrodynamic situation is typical for nearly all Holocene. Discharge of salt water

or brine in the sources of the Nemunas River valley was not higher than now. For instance, the discharge of the Cambrian brine (about 100 g/l) in Birštonas area makes only about 50 m<sup>3</sup>/d, while that of the Upper Permian (35-50 g/l) is about 200 m<sup>3</sup>/d (Kaveckis 1929; Kondratas, Vaitiekūnas 1990; Zuzevicius *et al.* 2007). However, the mineral water field situated near Druskininkai is notable for salt water (45-55 g/l) discharge from the Triassic aquifer in the area of approx. 4 km<sup>2</sup>. Total debit is about 150 m<sup>3</sup>/d. Discharge flow rate of other known mineral water sources are still lower. The calculations showed that the shift caused by such intensity discharge in mineralised water contour in deep aquifers during the all Holocene (about 10 000 years), going towards the south-eastern margin of the Artesian Basin, was less than 1 km. Undoubtedly, all the rocks in the lower part of the sedimentary cover occurring close to the Belarusian-Masurian Antecline at the 10–30 km wide southern margin of the Basin could be filled with mineral water only under the favourable hydrodynamic conditions, which could be formed due to changes in groundwater dynamics caused by the glacier's loading. During the Last Glacial Maximum (LGM), the increased groundwater pressure (head) in the unfrozen lower part of the sedimentary cover in the distance of 80-100 km from the glacier's margin could reach 300-450 m. At the same time, the gradient and flow rate of unfrozen groundwater into the periglacial lake situated on the southern margin of the Artesian Basin could grow significantly.

Therefore, we can see that, in spite of plain relief and similarity in geological setting and development of the northern and southern parts of the BAB, the aquifers in the lower part of the sedimentary cover contain water of very different origin. It could not be formed either in preglacial or under recent hydrodynamic conditions. Namely, fresh groundwater occurs in all 350-400 m thick sedimentary cover in the area of the current discharge (the northern part of the BAB), while the current recharge area (southern part of the BAB) is notable for a shallow occurrence of highly mineralised water or brine. A real factor to form such a hydrochemical situation could be only the groundwater dynamics affected by the freezing of the subsurface and the load of glaciers during the Pleistocene. The interaction of glaciers and the subsurface during the Pleistocene was the important factor in formation of groundwater and hydrogeodynamical processes (Bekele *et al.* 2003; Person *et al.* 2003; Zuzevičius 2003; Grasby, Chen 2005). However, a better reasoned reconstruction is possible only for the last stage—Late Pleistocene—groundwater formation conditions. The role of glaciations, when a non-typical oxygen isotope composition is formed in fresh groundwater of the northern part of BAB, is given, and its possible mechanism is described by many researchers (Boulton, Caban 1995; Boulton *et al.* 1995, 2001; Vaikmäe *et al.* 2001; Mokrik, Mažeika 2002).

The goal of our investigation was to assess if the Last Glaciation could cause the low thickness of fresh

groundwater zone and numerous sites of current discharge of mineral water at the land surface at the southern margin of the BAB. The assessment has been made by modelling the changes in hydrodynamic conditions during the Late Pleistocene time. The temperature and freeze-and-thaw, regime in the subsurface, which affected the formation of groundwater during the Late Glacial, was modelled on the base of the sedimentary cover in the area of Birštonas environs. The potential changes in the values of the runoff and flow direction in unfrozen aquifers on the southern margin of the Baltic Artesian Basin were assessed in the Kaunas–Druskininkai segment of the Belarusian-Masurian Antecline slope.

## METHODS

The present work includes the analysis of the information available on the geological setting of the southern part of the Baltic Artesian Basin, its paleogeographical and hydrogeological conditions and data generalisation for modelling purposes, as well as the modelling assessment of the freeze and unfreeze regime of the subsurface and migration of groundwater and chemical substances during the Late Pleistocene. The changes in groundwater formation conditions in Pleistocene and partly the current outcomes were determined by climate-caused freezing (or unfreezing) of the subsurface and the glacier's load. To assess the permafrost depth and related changes in groundwater flow structure, the necessary data on the paleogeographical Late Pleistocene conditions and subsurface setup and characteristics of rocks and fluids filling them in the southern part of the BAB were taken from the literature sources. The material published by numerous Quaternary researchers was used to make the palaeoenvironmental characterisation. The data on Late Pleistocene climate and the time and duration of geological phenomena taken from literary sources, due to different reasons (theoretical assumptions, method errors, and geographical position of the objects studied, etc.), were found to disagree. The errors of organic matter and rock dating are, as a rule, proportional to their formation age and ranges from hundreds to 25 thousand years. Due to a relatively small duration, the absolute error of Late Pleistocene samples dating is significantly lower. The numerical references to the age of climatic or geological phenomena, as based on different authors' data, were assessed taking into account the above conditions and the geographical position of the study target. The palaeoenvironmental data (situation of land surface, temperature of air or surface water bodies, glacier thickness, their variation) necessary for the reconstruction of the Late Pleistocene hydrogeological conditions was generalised according to indices determined by the up-to-date and most reliable methods. To perform the analysis of regional geological setup and hydrogeological conditions, the

material generalised in published works (Kondratas, Ignatavičius 1969; Grigelis, Kadūnas 1994; Zuzevičius 2005) has been used. Moreover, the parameters selected during previous modelling attempts (Diliūnas, Zuzevičius 1997; Zuzevičius *et al.* 2004, 2007) have been used to assess the subsurface freezing and groundwater flow in the region.

To solve the problems of mass and heat transport, the FEFLOW software based on finite element method was used; the mathematical base and assumptions applied are given in software methodological recommendations (Diersch 2002, 2004). It was directly applied for assessment of mass transport in the unfrozen rocks of the Phanerozoic lower beds during the Late Pleistocene glaciation.

The Pleistocene climate variation-caused changes in physical state of groundwater from liquid to solid (ice) and vice versa bring additional complications into modelling of the subsurface processes, since (1) during the conversion of 0°C water into ice and during the opposite process (conversion of 0°C ice into water), due to latent heat capacity, much energy (333 kJ/kg, under atmospheric pressure conditions) is consumed with the temperature almost not changing; (2) the frozen beds play the role of aquitards, their volume changes or (when volume remains constant) the freezing layer can give off water of almost 0.1 pore volume with related overpressure of the unfrozen water; and (3) thermal parameters are varying due to different physical properties of water and ice.

The parameters given in the Table 1 satisfy the conditions of the equation (1):

$$\alpha = \frac{\lambda}{\rho c}, \quad (1)$$

where  $\alpha$  is thermal diffusivity,  $10^{-6} \text{ m}^2\text{s}^{-1}$ ,  $\lambda$  is thermal conductivity,  $\text{Jm}^{-1}\text{s}^{-1}\text{K}^{-1}$ ,  $\rho$  is density,  $\text{kg m}^{-3}$ ,  $c$  – specific heat capacity,  $\text{J kg}^{-1}\text{K}^{-1}$ .

Since the FEFLOW software is not elaborated to forecast saturated rock freezing and unfreezing, it was used to assess the qualitative rate and scale of this process by applying additional assumptions on the changes in parameters due to variations of water physical state and the role of latent heat capacity in backward process of water–ice conversion. The variation of thermal parameters in the saturated rock layer and consumption of latent heat during the conversion of water into ice (and vice versa) depends on a content of water (porosity) in the layer. The typical parameters of sedimentary rocks, fluids (water) and ice are given in Table 1.

Table 1. Typical thermal properties of sedimentary rocks, water and ice (Maksimov 1967; Clark 1969; Diersch 2004).

Substance	Thermal conductivity ( $\lambda$ ), $\text{Jm}^{-1}\text{s}^{-1}\text{K}^{-1}$	Volumetric heat capacity ( $\rho c$ ), $10^6 \text{ Jm}^{-3}\text{K}^{-1}$	Thermal diffusivity ( $\alpha$ ), $10^{-6} \text{ m}^2\text{s}^{-1}$
Rocks (solid)	2–3	2.52	0.8–1.2
Water	0.65	4.186	0.16
Ice	2.25	2.05	1.2

Total thermal conductivity of the layer ( $\lambda$ ) depends on the sum of conductivities of solid part of rock (index  $s$ ), water present in its pores (index  $f$ ) or ice (index  $i$ ) proportional to their mass (2):

$$\lambda = +\lambda^f + \lambda^s = n_0\lambda^f + (1 - n_0)\lambda^s \text{ (unfrozen layer),}$$

$$\lambda = \lambda^i + \lambda^s = n_0\lambda^i + (1 - n_0)\lambda^s \text{ (frozen layer), (2)}$$

where  $n_0$  is porosity of saturated rocks.

Table 2. Thermal properties of unfrozen (a) and frozen (b) layers\*.

Porosity	Thermal conductivity, $\text{Jm}^{-1}\text{s}^{-1}\text{K}^{-1}$			Volumetric heat capacity, $10^6\text{Jm}^{-3}\text{K}^{-1}$			Thermal diffusivity, $10^{-6} \text{ m}^2\text{s}^{-1}$		
	a	b	a/b	a	b	a/b	a	b	a/b
0	2.5	2.5	1	2.52	2.52	1	1	1	1
0.01	2.48	2.50	0.99	2.54	2.50	1.02	0.98	1	0.98
0.05	2.41	2.49	0.97	2.60	2.47	1.05	0.95	1.01	0.94
0.1	2.32	2.48	0.94	2.69	2.45	1.10	0.86	1.02	0.84
0.2	2.13	2.47	0.86	2.89	2.39	1.21	0.74	1.03	0.72
0.5	1.58	2.43	0.65	3.35	2.23	1.50	0.47	1.09	0.43

\*Porosity cases untypical for the region are shaded

Conversion of groundwater into ice changes also the total thermal conductivity of the layers, as well as the volumetric heat capacity and thermal diffusivity. The maximum possible range of their changes from monolithic (non-porous) to karstified parts of the layers under the average solid, water and ice parameters are given in Table 2.

Typical porosity of sedimentary rocks in the southern part of the BAB is 0.01-0.2. Conversion of water into ice in the case of the highest porosity (0.2) can change (increase) the total thermal conductivity to 15% and decrease the volumetric heat capacity of the layer by 20%. In this case, thermal diffusivity of the most porous frozen layers is by 1.35 times higher than

that of the unfrozen layer. Namely, the heat quantity necessary to make the same size of temperature change in the case of frozen layer is lower than that of the unfrozen layer by 1.35 times. Since the major part of the profile is notable for lower open porosity (0.05-0.1), the difference for a whole freezing thickness is several times smaller. The role of latent heat in the process of freezing-thawing of the saturated layer is best shown by the amount of heat ( $q$ ) that is necessary to unfreeze the frozen layer ( $q_1$ ), to convert the ice into water ( $q_2$  – latent heat of water) and to rise the temperature of the unfrozen layer ( $q_3$ ); it can be assessed according to the following equations (3):

$$q = q_1 + q_2 + q_3 = ((\rho^i c^i n_0 + \rho^s c^s (1 - n_0))\Delta T^- + L\rho^i n_0 + ((\rho^f c^f n_0 + \rho^s c^s (1 - n_0))\Delta T^+ \quad (3)$$

In the equation (3):  $\rho^s c^s$ ,  $\rho^f c^f$ ,  $\rho^i c^i$  are volumetric heat capacities of solid, water and ice,  $Jm^{-3}K^{-1}$ ,  $\Delta T^-$  and  $\Delta T^+$  show the change of temperature of the frozen layer to the ice thawing temperature (conventionally  $0^\circ C$ ) and the rise of the temperature of the unfrozen layer,  $L$  is latent heat. Real water-ice conversion and consumption of latent heat occurs within the temperature

interval from  $-1$  to  $+1^\circ C$  (Mottaghy, Rath 2006). The relative heat amount for separate processes necessary to rise the temperature of a  $1 m^3$  saturated layer as calculated according to the equation (3) for the parameters given in Table 1 are shown in Table 3. It is assumed that volumes of pores and layer do not change during the conversion of ice into water.

Table 3. Amount of heat consumed to change the temperature of saturated layers.

Porosity*	Amount of heat, $10^6 Jm^{-3}$ (% of total)			
	Total ( $q$ )	Including		
		$q_1$	$q_2$	$q_3$
Temperature interval from -1 to +1°C				
0	5.04	2.52 (50)	0	2,52 (50)
0.01	8.39	2.52 (30)	3.34 (39.8)	2.54(30.2)
0.05	2.78	2.5 (11.4)	16.68 (76.6)	2.6 (12)
0.1	38.52	2.47 (6.4)	33.36 (86.6)	2.69 (7)
0.2	72	2.43 (3.3)	66.72 (92.7)	2.85 (4)
0.5	172.42	2.28 (1.3)	166.8 (96.8)	3.4 (1.9)
Temperature interval from -5 to +5°C				
0	25,2	12.6 (50)	0	12,6 (50)
0.01	28.64	12.6 (44)	3.34 (11.7)	12.7 (44.3)
0.05	42.18	12.5 (29.6)	16.68 (39.5)	13 (30.9)
0.1	59.16	12.35 (20.9)	33.36 (56.4)	13.45 (22.7)
0.2	93.12	12.15 (13.4)	66.72 (71.6)	14.25 (15.3)
0.5	194.9	11.4 (5.8)	166.8 (85.6)	16.7 (8.6)
Temperature interval from -10 to +10°C				
0	50.4	25.2 (50)	0	25,2 (50)
0.01	53.94	25.2 (46.7)	3.34 (6.2)	25.4 (47.1)
0.05	67.68	25 (36.8)	16.68 (24.6)	26 (38.4)
0.1	84.96	24.7 (29.1)	33.36 (39.3)	26.9 (31.6)
0.2	120.6	24.3 (20.1)	66.72 (55.3)	28.5 (23.6)
0.5	222.95	22.75 (10.2)	166.8 (74.8)	33.4 (15)

\*Porosity cases untypical for the region are shaded.

Latent heat used to convert pore water from the liquid to the solid or vice versa makes obvious impact on freezing/unfreezing rate. Therefore, due to rather high porosity of the rocks in the BAB, the reconstruction of Late Pleistocene permafrost depth and development and degradation rate requires that the latent heat of groundwater was taken into account. Thus, two techniques were used: (1) adding the latent heat of a layer (in case of freezing) or taking it out (a case of unfreezing) during the time when the temperature varies in the interval from  $-1$  to  $+1\text{C}^\circ$  (heat transfer rate in terms of FEFLOW software) (Diersch 2004); and (2) replacing the heat capacity of a layer for the same temperature range by a changed (higher) apparent specific heat capacity value proportional to the amount of the latent heat (Mottaghy, Rath 2006). Both methods in the case of sequence consisting of many layers require modelling by means of approximation, and analogous result is obtained in both cases.

The calculations showed that the latent heat depending on porosity and thickness of layers in the southern part of the BAB make longer their freezing (unfreezing) duration by 20-100 years, and the total duration of all freezing 200-250 m thick beds grows by 400-500 years. Final temperature and the depth of permafrost, due to long duration of the processes studied, do not differ practically. Since the Late Pleistocene climatic periods are significantly longer, the lagging of freezing–unfreezing moments does not virtually affect the duration of different water state in a layer with typical

groundwater regime conditions. The indicated errors of the modelling can be considered as permissible for the paleohydrogeological reconstructions, since the information about the process-controlling characteristics (air temperature, glacier thickness, etc.) and their chronology are of similar accuracy.

The assessment of subsurface heat regime in Late Pleistocene was chosen to be done in Birštonas environs, where mathematical modelling of another purpose had been performed (Zuzevičius *et al.* 2007). The filtration and migration parameters of layers chosen during the calibration of the above model were used as the initial ones. Mass transport in the beds occurring below the permafrost zone in the southern part of the BAB was modelled taking into account the pressure caused by glacier loading and conditions of groundwater discharge on the slope of the Belarusian-Masurian Antecline.

#### PALEOENVIRONMENTAL AND HYDROGEOLOGICAL SETTING

According to the chronostratigraphical scheme applied in Lithuania, Late Pleistocene includes Merkinė (Eemian) Interglacial (120 000-70 000 BP) and Nemunas (Weichselian) Glacial (70 000-10 000 BP), i.e., it covers the whole climatic cycle typical of Pleistocene. The generalized chronology of Late Pleistocene climate phenomena in Lithuanian area is given in Table 4.

Table 4. Generalized chronology of Late Pleistocene climate variations and glaciations in the area of Lithuania (Gaigalas, Satkūnas 1994; Kondratienė 1996; Marks 2002; Ber 2006).

Geological time	Interstadial and Stadial		Interphasial and Phasial	Age, kyr BP	
LATE PLEISTOCENE	NEMUNAS (WEICHSELIAN) GLACIAL	Žiemgala Stadial	Upper Dryas Phasial Allerod Phasial Middle Dryas Phasial Bölling Interphasial	10-12.8	
			North Lithuanian Phasial	12.8-13.5	
		Baltija Stadial	Linkuva Interphasial Middle Lithuanian Phasial	13.5-14.5	
			Šušvė Interphasial South Lithuanian Phasial	14.5-15.9	
			Punia Interphasial East Lithuanian Phasial	15.9-16.5	
		Pavytė Interstadial			16.5-22
		Grūda Stadial	Žiogeliai Phasial Krikštonys Interphasial Puvočiai Phasial		
		Rokai Megastadial	Biržai Megainterphasial Bičiai Metaphasial Rokai Megainterphasial	22-55	
		Varduva Stadial		55-70	
		MERKINĖ (Eemian) Interstadial			

The last glaciation of the Pleistocene in Lithuanian area lasted about 10 000 years. The maximum thickness of ice in the northwestern part of the area was about 1000 m, whereas it was lower than 500 m in south Lithuania coinciding with the southern part of the Baltic Artesian Basin. The thickness of glacial deposits increases going from southeast northwestwards, but it caused no serious impact on the relief formed before. Their thickness in the environs of Druskininkai and Kaunas (Rokai) is about 7 and 34 m, correspondingly (Gaigalas 2001).

During the Merkinė Interglacial, the glaciofluvial and glaciolacustrine plains prevailed in the south Lithuanian area occupying the southern part of the BAB, while at the beginning of the Holocene, moraine hills and plateaus dominated here. The environs of Birštonas, as it is now, belonged to the glaciolacustrine plain, where the relief was similar to the current one (Melešytė 2001; Baltrūnas 2001). There are no reliable data about the river network of that time period.

The Nemunas (Weichselian) Glacial, especially its end, is notable for large temperature variations with repetitive retreats and smaller advances of ice-sheet margin that during its maximum reached the Belarusian Grodno area. Therefore, the periglacial lakes, water of which was flowing southwards, were also retreating northwards and covered a major part of the area freed of ice in different time (Iljin, Mander 1972; Baltrūnas 2001; Marks 2002). The shift of surface water runoff direction from southward to north-westward and formation of the recent Nemunas River valley could start only 13–14 thousand years ago (from the Middle Lithuanian Phasial). The areas situated in the direction of advances and retreats of the Late Pleistocene glacier underwent almost analogous development of palaeoenvironmental conditions. Thus, the southern margin of the BAB experienced the following processes: (1) climate becoming colder and permafrost is forming (Varduva Stadial and Rokai Megastadial),

(2) glacier advancing, ice thickness growing, partial degradation of permafrost possible, and formation of periglacial lakes (Grūda Stadial), (3) gradual retreat of a glacier and periglacial lakes north-westwards (Baltija Stadial); and (4) development of recent surface and groundwater formation conditions (Fig. 3).

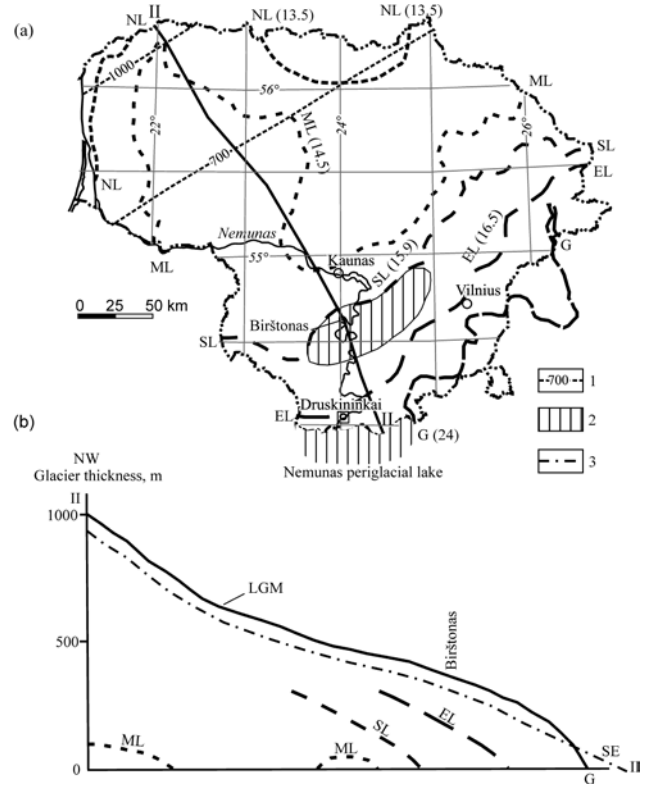


Fig. 3. Limits of last glacier advances in Lithuanian area and their age (kyr BP) according to A. Gaigalas, J. Satkūnas (1994), and V. Baltrūnas (2001) data on the scheme (a) and the section (b): G–Grūda Stadial, EL–East-Lithuanian Phase of Baltija Stadial, SL–South-Lithuanian Phasial, ML–Middle-Lithuanian Phasial, and NL–North-Lithuanian Phasial; 1–isopachs of glacier during LGM; 2–periglacial water body; 3–piezometric surface of groundwater.

Table 5. Chronology of paleoenvironmental conditions and climatic phenomena during the Late Pleistocene in the environs of Birštonas applied for modelling.

Characteristics	Period									
	Varduva–Rokai		Grūda–Baltija			South Lithuanian	Žiemgala			Holocene
Age, kyr BP	70-65	65-23	23-22	22-16.5	16.5-15.9	15.9-14.5	14.5-11.5	11.5-10.9	10.9-10	10-0
Surface type	Land		Glacier			Periglacial lake	Land			
Ice thickness, m	0	0	0-500	500	500-0	0	0	0	0	0
Average annual air temperature, °C	0– -10	-10	-10– -15	-15	-15– -10	+2	-5	-5–0	0–+6	+6
Duration, kyr	5	42	1	5.5	0.6	1.4	3.0	0.6	0.9	10.0

The environs of Birštonas, which due to their geological awareness were chosen to model the freezing of the subsurface, lie at about 80–100 km from the line of the maximum southward spreading of the last glacier. Taking into account the rate of glacier's advance and retreat ranging in 0.1-0.2 km per year (Khodakov 1978; Kalm 2006), the glaciation of this area began approx. 23 000 years ago and lasted about 7 000. The generalised for modelling chronology of changes in palaeoenvironmental conditions of Birštonas environs is given in Table 5.

The Belarusian-Masurian Antecline was formed during the Devonian. The older than Cretaceous sedimentary beds in the Baltic Syneclise successively wedge out on the northern slope of the Antecline (see Fig. 3). Total thickness of the sedimentary cover decreases towards the Antecline from 700-800 m in the environs of Birštonas to 350-400 m in Druskininkai area. Its stratigraphic completeness and number of aquifers also decreases.

The hydrogeological structure in the environs of Birštonas contains the following distinguished water-bearing beds: unconfined, Quaternary, Upper Cretaceous, Cenomanian–Lower Cretaceous, Tauragė and Nemunas (latter both in the Lower Triassic rocks), Upper Permian (Naujoji Akmenė Formation) and Cambrian-Vendian aquifers. Druskininkai environs being closer to the Antecline include Quaternary, Upper Cretaceous, Triassic and Proterozoic crystalline rock aquifers. The aquifers and aquitards in the upper part of the section vary in thickness, and they are intersected by buried valleys (incisions) of various depth filled with deposits of different lithology. The uniformity of the deeper occurring beds is broken by tectonic faults. The generalised filtration–migration parameters of the hydrogeological units in the southern part of the BAB as well as temperature are given in Table 6 according to the setting of the Birštonas environs.

Table 6. Characteristics of current hydrogeological conditions in the environs of Birštonas.

Aquifer, aquitard	Depth of bottom, m	Conductivity, m/d	Porosity	Temperature, °C	TDS*, g/l	Piezometric level, m a. s. l.
1		2	3	4	5	6
1. Unconfined	5-20	1	0.2	8	0.3 - 9	45 - 70
2. Aquitard	30	0.1 - 10 <sup>-4</sup>	0.1	8		
3. Quaternary-Upper Cretaceous	40	1	0.2	9	0.3 - 15	48 - 70
4. Aquitard	80	10 <sup>-3</sup> - 10 <sup>-4</sup>	0.05	9.5		
5. Cenomanian-Lower Cretaceous	110	5	0.1	10	0.3 - 15	50 - 60
6. Aquitard	130	10 <sup>-3</sup> - 10 <sup>-4</sup>	0.05	10		
7. Tauragė (Triassic 1)	150	5	0.1	10.2	10 - 15	50 - 65
8. Aquitard	230	10 <sup>-6</sup> - 10 <sup>-7</sup>	0.05	11.5		
9. Nemunas (Triassic 2)	270	0.2	0.1	12.5	15 - 25	65 - 75
10. Aquitard	310	2 · 10 <sup>-7</sup>	0.05	12.8		
11. Upper Permian	350	2	0.05	13.1	25 - 30	70 - 85
12. Aquitard	670	10 <sup>-8</sup>	0.05	14.5		
13. Cambrian-Vendian	690	0.1-2	0.1	16	100 - 110	145 - 155

\*TDS-concentration of total dissolved solids in groundwater.

The geological setting of the region during Late Pleistocene was almost analogous to the present day one, since the deposits formed during it make up only a part of the current unconfined aquifer. A rather thin glacier had no serious effect on the properties (including filtration ones) of the earlier formed Quaternary and deeper occurring beds in the region. Therefore, the filtration of unfrozen water and heat transport were modelled in the beds indicated in Table 6, under the conditions of varying temperature. It is assumed that the temperature of the Cambrian–Vendian beds occur-

ring at about 700 m depths does not vary due to climate impact. As the bed temperature falls to –2°C, the filtration ceases, and the glacier being formed becomes the additional model aquitard with heat conditions typical of ice. During the maximum of the last glaciation in the southern area of the BAB, the glacier ice thickness ranged from 100 m (in Grodno environs) to 500-600 m (in Kaunas environs). Respectively, the increase in groundwater pressure in the unfrozen Cambrian-Vendian and Triassic deposits of the Nemunas Formation beds caused by glacier's static loading could reach from 90 to 450-540 m.



The periglacial lake that was moving after the retreating glacier northwestwards and thawing the permafrost could play the role of discharge area of unfrozen groundwater occurring under the glacier. However, due to increase in impermeable Triassic clay in direction of the Baltic Syncline, the conditions favourable for discharge existed only into the Nemunas periglacial lake situated at the top of the Belarusian-Masurian Antecline (south of Druskininkai) (Iljin, Mander 1972). The water level altitudes of the lake that lay here approximately 22 000-16 500 years ago were about 150 m.

So, the unfrozen Cambrian-Vendian and Triassic (Nemunas) aquifers occurring in the lower part of the sedimentary cover now attributed to the zone of slow flow appeared to get into an untypical hydrodynamic medium. Due to the glacier loading-caused increase in pressure and proximity of drainage area (periglacial lake), untypical high 0.003-0.004 gradients and conditions, favourable for intensive migration of brine from the central part of the basin to its southern margin, were formed. Similar altitudes of land surface remained after the lake was drained, however, due to formation of repetitive permafrost and degradation of glacier, the discharge of water from deep aquifers had to interrupt.

The hydrogeological parameters of the sedimentary beds consisting of terrigenous and calcareous rocks in the southern part of the BAB are close to those given in Table 6. Thermal properties of all the sedimentary rocks are also similar. Therefore, average parameters for rocks, fluids (groundwater) and ice are assumed for the modelling (see Table 1).

## RESULTS

The conditions of groundwater formation during the Late Pleistocene had been caused by the changes in climate and ice sheet-caused changes in hydrogeological setup of the subsurface and its hydrodynamics. Modelling assessment of the formation of the permafrost has been performed for the case of the geological setting of the Birštonas environs. During the Merkinė Interglacial, the palaeoenvironmental conditions of Lithuanian area were close to the present day ones. Therefore, as an initial condition, the current temperature distribution in the subsurface is applied for modelling that covers the period from the Varduva cooling 70 000 years ago.

Temperature variations in the aquifers of the Birštonas environs during Late Pleistocene are shown in Fig. 4, and numerical values of temperature and hydrogeological setting are given in Table 7. It is assumed that the filtration in the Triassic (Nemunas) aquifer, due to high mineralisation of water, ceases below  $-2^{\circ}\text{C}$ .

The analysis of the palaeoenvironmental conditions and thermal regime of the subsurface enables to make the following conclusions about the development of the hydrogeological conditions in the southern part of the Baltic Artesian Basin during the Late Pleistocene.

During the **Merkinė Interglacial** that ended 70 000 years ago by the Varduva Stadial cooling, the climatic and hydrogeological conditions in the region, as well as the relief were close to the present day ones. Due to

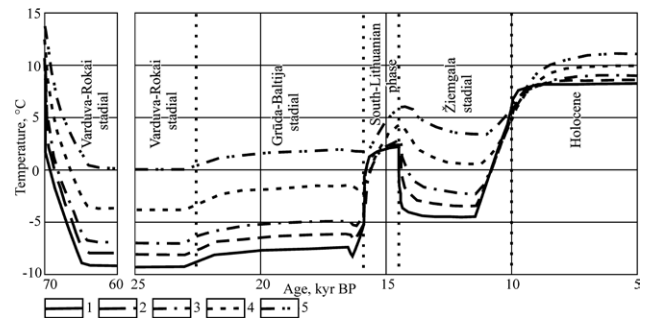


Fig. 4. Temperature variations in the aquifers of the Birštonas environs during the Late Pleistocene (model reconstruction): 1–Upper Cretaceous; 2–Cenomanian–Lower Cretaceous; 3–Lower Triassic Tauragė Formation; 4–Lower Triassic Nemunas Formation; 5–Upper Permian.

higher values of air temperature and precipitation, as well as long duration of the Interglacial (about 50 000 years), the zone of fresh groundwater had to be thicker than today. At the same time, the contact between fresh and mineralised groundwater in the lower part of the Phanerozoic was shifted along the Antecline slope towards the Baltic Syncline.

**The Varduva-Rokai** climatic cooling with short warmer breaks lasted more than 40 000 years. Already after 5 000–7 000 years the fresh water zone due to freezing began to be replaced by about 250 m thick aquitard.

With glacier advancing and ice thickness reaching 300–500 m (**Grūda–Baltija Stadial**), the frozen rocks were unfreezing from below due to the geothermal flow. However, due to small thickness of the ice and low isolating effect, the degradation of the permafrost from below was very weak and had not changed the hydrostratigraphy formed during the climatic cooling (see Table 7).

After the periglacial lake is formed, as the Late Pleistocene reconstruction of the thermal regime of the subsurface in the environs of Birštonas indicates, the permafrost under it disappears in 400-600 years. This confirms the assumption that the Nemunas periglacial lake lying south of the maximum glacier spreading line was a discharge zone for the unfrozen aquifers in the southern part of the BAB during the major time of its existence 22 000-16 500 years ago. Due to glacier-caused pressure increase and proximity of the discharge zone—the periglacial lake—in the lower aquifers of the sedimentary cover, especially favourable hydrodynamic conditions formed for migration of mineralised water towards the margin of the BAB: flow gradients rose to 0.003-0.004, and the actual flow rate of water and mass transport ranged in 0.01-0.05 m/d or about 3-20 m/a. The modelling showed that the shift of mineralised water and brine contours in the Cambrian-Vendian and the Triassic aquifer replacing it on the slope of the Belarusian-Masurian Antecline during the last glaciation could reach from 10 to 30-35 km (Fig. 5). Southeast of Vilnius, mineralised water migration towards the BAB margin, due to of thick porous Vendian sandstone beds, covered significantly smaller distances.

Table 7. Changes of temperature and hydrogeological structure of section during Late Pleistocene in the environs of Birštonas (model reconstruction)\*.

Current aquifer	Depth of bottom, m	Temperature of section at different points of Late Pleistocene (kyr BP), °C									
		Varduva–Rokai			Grūda–Baltija		South Lithuania		Žiemgala		Holo-cene
		68	65	23	18	15.9	15	14.5	12	10.9	0
Unconfined	20	-3.9	-10	-10	-8.3	-5.2	2	2	-5	0	8
Quaternary–Upper Cretaceous	40	-2.9	-8.9	-9.2	-7.5	-5.2	1.9	2.2	-4.5	-0.3	8.2
Cenomanian–Lower Cretaceous	110	-1.6	-7.5	-8.1	-6.2	-4.8	1.9	2.5	-3.5	-0.6	8.5
Tauragė (Triassic 1)	150	-0.4	-6.1	-6.9	-4.9	-4.2	2.0	3.0	-2.3	-0.3	8.9
Nemunas (Triassic 2)	270	2.7	-2.6	-3.8	-1.5	-1.6	2.8	4.2	1.1	1.3	9.9
Upper Permian	350	5.9	1.4	0.1	1.3	1.8	4.3	6.9	3.5	3.6	11.0
Cambrian–Vendian	690	16	16	16	16	16	16	16	16	16	16

\*The periods when aquifers turn into aquitards are shaded.

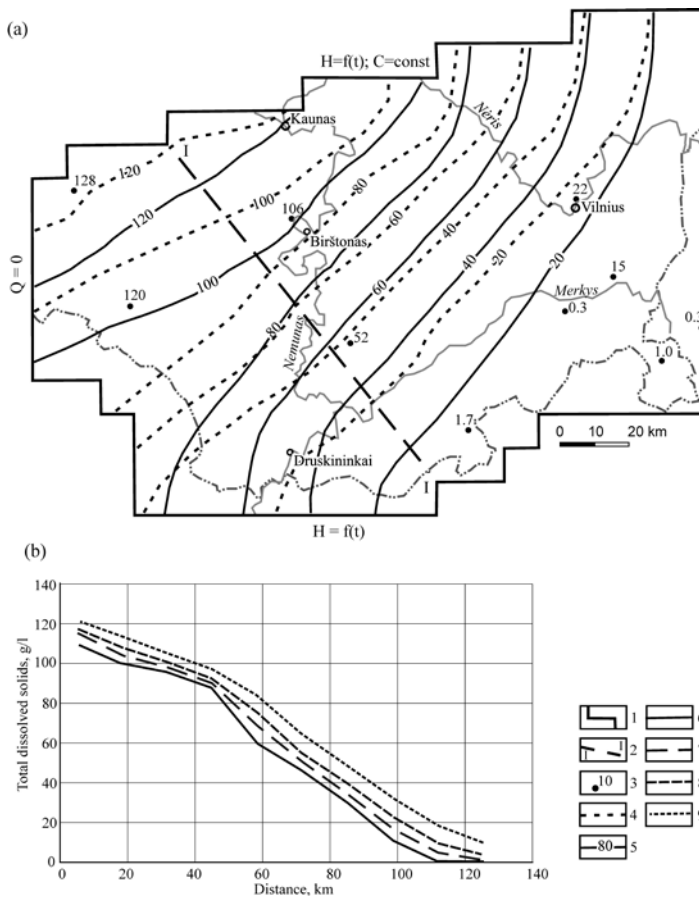


Fig. 5. A scheme of groundwater mineralisation in the unfrozen aquifers during the last glaciation (a) and its formation in time due to glacier's loading and periglacial lake interaction (b) (model reconstruction): 1—limits of the modelled fragment and their role; 2—a trend of diagrams defining the mineralisation variations; 3—current mineralisation of groundwater in the wells, g/l; *groundwater mineralisation isolines*: 4—before the last glaciation, 5—at the end of the last glaciation; *water mineralisation on section*: 6—before the last glaciation (approx. 22 000 BP), 7—1 000 years after the discharge beginning, 8—2 000 years after the discharge beginning, 9—at the end of the last glaciation.

After the ice sheet retreat and the climate chilling of **Žiemgala (Zemgale) Stadial**, about 150 m thick permafrost was formed in the place of the Nemunas periglacial lake for about 1 500-2 000 years (Iljin, Mander 1972). Due to this reason as well as due to the disappearance of glacier and its load, the migration of water and mass transport towards the BAB margins discontinued. As the glacier and the periglacial lake were retreating farther northwestwards, there were no analogous conditions formed for migration of mineralised groundwater also because of large thickness of isolating aquitards.

Water filtration (recharge) in all the sedimentary beds of the southern part of the BAB recovered after the degradation of the permafrost 11 000-12 000 years ago. The groundwater in the thawed beds was represented by fresh pore ice melt water. The recent hydrochemical situation of groundwater was formed over a span of 3 000-5 000 years. The piezometric surface of the lower aquifers is almost horizontal and close to or higher than that of the fresh groundwater. Therefore, the hydrogeochemical situation formed during the Glacial remains up to now. The brine that filled the lower aquifers during the glaciation at the southern margins of the BAB now is the recharge source for current mineralised groundwater domes in relief depressions and intersections of tectonic faults reaching the shallow (unconfined) aquifer in the southern part of BAB.

## DISCUSSION

The interaction of glaciers and the subsurface during the Pleistocene was and is the important factor of current groundwater formation and hydrogeological processes. The best-known fresh groundwater resources formed due to glaciations occur in the aquifers of the Atlantic Ocean shelf at

the North America (Person *et al.* 2003), as well as the fresh groundwater lying deeply in the Alberta Basin in Western Canada (Bekele *et al.* 2003).

The Baltic Artesian Basin (BAB) that is limited in its northern and southern parts by crystalline basement elevations had also been affected by the Pleistocene glaciations. Fresh groundwater of Ice Age in the northern part of the BAB is observed in the lower part of the sedimentary cover occurring rather deeply (to 400 m). While the aquifers occurring at a similar depths in the southern part of the BAB on the northern slope of the Belarusian-Masurian Antecline are filled with significantly older mineralised water or even brine. The difference might be caused by the circumstances described below. The last (Weichselian) glacier in the northern part of the BAB was about 2 km thick, or 2–5 times thicker than that in the southern part, and existed by 2 000–3 000 years longer. The rocks and groundwater of low mineralisation at its bottom could be repeatedly unfrozen for a longer period (so-called thawed-bed bottom of ice-sheet) (Kleman, Glasser 2007). Moreover, the greatly pressed melt water also occurred under the glacier. All this formed the necessary (although insufficient) conditions for injection of this under-glacier fresh water into the subsurface (Vaikmäe *et al.* 2001; Mokrik, Mažeika 2002).

The groundwater formation conditions in the southern part of the BAB during the last glaciation had not been studied before. We shall describe them in a more detailed approach. Advances and retreats of the Last Glacier of the Late Pleistocene in Lithuanian area lasted about 10 000 years. Therefore, the sites situated along the glacier flow lines, in different time, experienced almost analogous evolution of palaeoenvironmental conditions and freezing of the subsurface. The evolution of these conditions in the southern part of the Lithuanian area coinciding with the southern margin of the BAB was as follows: (1) long and warm Merkinė Interglacial with conditions similar to the present day ones (approx. 120 000–70 000 BP), (2) climate cooling and formation of permafrost in the subsurface (Varduva-Rokai period 70 000–22 000 BP), (3) glacier's advance, ice getting thicker (thinner at the end of the period) and partial geothermal degradation of the permafrost (Grūda-Baltija period 22000–16000 BP), (4) formation of periglacial lakes with degradation of permafrost under them, and gradual retreat of the glacier (starting from the Grūda Stadial approx. 22000 BP), (5) repeated formation of subsurface permafrost of a smaller scale after the periglacial lakes were drained, and (6) final degradation of the permafrost, development of the present day river network and recent conditions for groundwater formation.

The most intensive formation of the permafrost took place during the climate cooling before the glacier's advance. Ice thickness at the end of the Rokai Stadial could reach 250–270 m. The hydrogeological consequences: (1) approx. 250 m thick aquitard was formed in the upper part of the section; (2) no fresh groundwater zone is defined in the region. As the glacier has advanced and ice thickness has reached 300–500 m

(Grūda-Baltija Stadial), the permafrost in the rocks is slightly degrading from below due to geothermal heat, but the regional hydrostratigraphical situation formed earlier persists. The glacier lies on the rocks of the frozen fresh groundwater zone. Its thickness and pressure in the unfrozen mineralised groundwater increases northwards from the BAB margin. A basic change in hydrodynamic situation takes place at the BAB margin, when the permafrost is finally degraded under the Nemunas periglacial lake. The draining lake and glacier loading increase the gradients of unfrozen mineralised water for several times (to 0.003–0.004) if compared to those before the glaciation and the present-day ones. The apparent distance of mass transport to the southern part of the BAB during the last glaciation is 10–35 km. After glacier's retreat and draining of the periglacial lake and renewal of permafrost, the discharge of unfrozen groundwater into the BAB margin discontinues.

Due to the current discharge of mineralised water at the sites where tectonic faults coincide with the relief depressions, mineral water fields are forming in the zone of active flow, but its intensity is low. The discharge is compensated from the storage of lower beds of the sedimentary cover and does not change the hydrochemical situation formed during the glaciation. That is, now the Triassic and older rocks notable for very slow flow of groundwater at the southern margins of the BAB (e.g., environs of Druskininkai) contain mineralised water and brine that remained from the last glaciation.

After the permafrost degraded in the subsurface and when the present-day relief was being formed, water filtration renewed in the all thawed aquifers. A tendency in water level, discharge debits and groundwater chemistry approaching the current state is observed. The duration of stabilisation of active zone processes as assessed by modelling under the current conditions of Birštonas environs is about 5 000 years and covers the first half of the Holocene.

## CONCLUSIONS

The groundwater occurring in the lower beds of the sedimentary cover at the southern margins of the Baltic Artesian Basin (BAB) was formed during the last glaciation. Due to anomalous high gradients caused by the glacier ice loading and the periglacial lake 22 000–16 500 years ago, the unfrozen mineralised water migrated to the periphery of the Basin and filled a 10–35 km wide strip in the lower beds of the sedimentary cover. Such hydrochemical situation remained unchanged during the Post-Glacial time also due to stable very slow water flow. Such peculiarities in groundwater formation during the Late Pleistocene can explain the small thickness of current fresh water zone, the older age of water in deeper aquifers and the mineralisation of water in the BAB's southern part if compared to those in its northern part notable for a similar geological setting.

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