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# Late Pleistocene and Holocene groundwater flow history in the Baltic Artesian Basin: a synthesis of numerical models and hydrogeochemical data

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**Abstract.** We review our current understanding of groundwater flow history in the northern part of the Baltic Artesian Basin (BAB) from the end of the Late Pleistocene to current conditions based on the hydrogeological studies carried out in 2012–2020 by the Department of Geology, Tallinn University of Technology and its partners. Hydrogeochemical data and various numerical models are combined in order to understand the link between glaciations and groundwater flow. The results of our earlier research and published literature on groundwater flow history in the BAB are also taken into account. The reconstruction of groundwater flow history is based on the database of the isotopic, chemical and dissolved gas composition of groundwater. The database contains data on 1155 groundwater samples collected during 1974–2017. We find that groundwater in the BAB is controlled by the mixing of three distinct water masses: interglacial/modern meteoric water ($\delta^{18}O \approx -11‰$), glacial meltwater ($\delta^{18}O \leq -18‰$) and an older syngenetic end-member ($\delta^{18}O \geq -4.5‰$). The numerical modelling has suggested that the preservation of meltwater in the northern part of the BAB is controlled by confining layers and the proximity to the outcrop areas of aquifers. Aquifers containing groundwater of glacial origin are in a transient state with respect to modern topographically-driven groundwater flow conditions. The most important topics for future research that can address gaps in our current knowledge are also reviewed.

**Key words:** Baltic Artesian Basin, groundwater flow, environmental tracers, numerical modelling, palaeohydrology.

## INTRODUCTION

Pleistocene glaciations had a strong impact on groundwater flow dynamics in a wide variety of geological environments in both the glaciated and non-glaciated parts of the world. This is exemplified by the hypothesis that in some regions recharge waters which formed in different climatic conditions in the past accounted for the observed chemical and isotopic composition of groundwater (e.g. Clayton et al. 1966). In glaciated regions, it was assumed that subglacial recharge could have penetrated to significant depths in both moderately permeable sedimentary aquifers (Siegel & Mandle 1984) and crystalline environments (Clark et al. 2000). Glacial meltwater is characterized by low $\delta^{18}O$ and $\delta^{2}H$ values and low concentrations of total dissolved solids (TDT; Clark et al. 2000). These characteristics have been used as the primary indicators for identifying groundwater of glacial origin. Vaikmäe et al. (2001a) have proposed that the presence of exceptionally large amounts of excess air can be used as an indicator for glacial meltwater recharge. Excess air in groundwater is usually formed by the dissolution of entrapped air bubbles in a transition between the unsaturated and saturated zones under an increased hydrostatic pressure and/or due to capillary pressure (Kipfer et al. 2002; Aeschbach-Hertig & Solomon 2013). The amount and fractionation of excess air (i.e. its elemental and isotopic deviation from atmospheric air) strongly depend on the hydrostatic pressure acting on the trapped gas bubbles, which, in turn, depends on recharge dynamics and climatic conditions (Aeschbach-Hertig & Solomon 2013). In glacial ice, air is entrapped as small bubbles, which can produce very high amounts of excess air (at least for the low-solubility noble gases Ne and Ar) in subglacial meltwater. Subglacial water originating from both the basal melting of ice and drainage of surface meltwater might recharge under high pressure, due to glacial overburden, which can lead to the formation of large amounts of dissolved excess air in the subglacially recharged water (Christner et al. 2012; Grundl et al. 2013).

Groundwater modelling studies in recent decades have supported the hypothesis of subglacial recharge and highlighted the potentially large impact that continental ice sheets have had during the Quaternary glacial periods on groundwater flow systems in North America and Europe (e.g. Boulton et al. 1995, 1996; Piotrowski 1997; Van Weert et al. 1997; Person et al. 2003, 2007; Ma et al. 2004; McIntosh & Walter 2005, 2006; Carlson et al. 2007; Moeller et al. 2007; Lemieux & Sudicky 2010; Neuzil 2012). The basic tenet of these models is that the basal melting of warm-based ice sheets occurred at high excess fluid pressure with hydraulic heads up to 90% of ice thickness. Modelling has shown that these heads drive large-scale groundwater flow systems and that extensive recharge of aquifers with meltwater from these ice sheets must have occurred. The models of Van Weert et al. (1997), for example, suggest that the volume of meltwater that recharged the area of the Baltic Sea, northern Poland, northern Germany, Denmark and the eastern North Sea during one of the periods of ice coverage by the Fennoscandian Ice Sheet alone is equivalent to the groundwater volume present in that area up to several hundreds of metres deep. Even larger volumes of fresh water are associated with the Laurentide Ice Sheet in North America (McIntosh & Walter 2006; Person et al. 2007). In some locations, it is also suggested that the continental ice sheet load may have reversed the direction of groundwater flow and that the current flow patterns still reflect the gradual recovery from the ice sheet load rather than steady state conditions (Grasby et al. 2000; Boulton et al. 2001; Person et al. 2007; Lemieux et al. 2008). Obviously, these pristine, ice sheet-derived groundwaters are in disequilibrium with the current climatic and hydrologic surface conditions and are therefore the key example of palaeowaters that are extremely vulnerable to human interference. The knowledge of the distribution, origin and current dynamics of these waters is of key importance for guaranteeing sustainable groundwater development in areas where this type of groundwater is present (Edmunds 2001; Kooi & Groen 2003).

Our previous work on the Cambrian–Vendian aquifer system (CVAS), an important source of public water supply in northern Estonia, has provided compelling evidence that the aquifer has been strongly impacted by glaciations and recharged by glacial meltwater. The evidence can be summarized as follows: the groundwater has the lightest known oxygen isotopic composition in Europe ($\delta^{18}O$ values as low as –23‰; Raidla et al. 2019a), unexpectedly high gas concentrations, absence of $^{3}H$ and a low radiocarbon concentration (Vaikmäe et al. 2001a; Raidla et al. 2012; Vallner & Porman 2016; Pärn et al. 2019; Vallner et al. 2020). Our first noble gas analyses suggest that palaeorecharge took place at temperatures around the freezing point (Vaikmäe et al. 2001a). However, Weissbach (2014) showed that the high excess air amount in the northern part of the CVAS complicated the fitting routine of determining the noble gas temperatures. So, the noble gas composition of sampled wells does not allow determination of recharge temperature and an appropriate model to describe the data set has not been found yet. The analyses of the gas composition in groundwater samples also showed a rather high concentration of biogenic methane (Vaikmäe et al. 2001a; Raidla et al. 2019a). McIntosh et al. (2012) have shown that shallow biogenic methane in the Illinois Basin (USA) was stimulated by subglacial recharge. Taking the current understanding of groundwater ages in the northern part of the Baltic Artesian Basin (BAB) into account and considering the isotope data and the results of the noble gas analyses, it is likely that palaeorecharge of the CVAS occurred mainly during the last glaciation (Vaikmäe et al. 2001a; Raidla et al. 2009, 2012; Pärn et al. 2016, 2019; Vallner et al. 2020). If these groundwater resources originate from the last glaciation, an insight into their distribution and current dynamics which are important for sustainable groundwater development can only be gained through a detailed analysis of the groundwater flow history in the basin.

In this paper, we present a review of our current understanding of groundwater flow history in the BAB from the end of the Late Pleistocene to current conditions.

The review is based on the hydrogeological studies carried out in 2012–2020 by the Department of Geology, Tallinn University of Technology and its partners but the results of our earlier research and published literature on groundwater flow history in the BAB are also taken into account. More specifically, we show that the geochemical signatures characterizing glacial palaeogroundwater of the CVAS can be found in other aquifer systems in Estonia. We also explain how we have used geochemical tracers to infer groundwater ages and groundwater origin in the BAB. Finally, we integrate our geochemical understanding with modelling studies which have tested the subglacial recharge hypothesis in the BAB.

## STUDY AREA

Hydrogeologically, the BAB is a complex multilayered system of aquifers and aquitards (Mokrik 1997). The BAB covers the territories of Estonia, Latvia, Lithuania and parts of Russia, Poland and Belarus (Fig. 1). The thickness of the sedimentary cover reaches 5000 m in its south-western part, while the crystalline basement crops out in the northern margin of the BAB (Virbulis et al. 2013). The sedimentary formation consists of Ediacaran to Devonian siliciclastic and carbonate rocks in the northern part of the basin. In the south, these strata are overlain by Mesozoic and Cenozoic rocks. Generally, the geological formations dip in the southern direction and the sedimentary cover is less than 100 m in northern Estonia.

In the northeastern area of the BAB, where Ediacaran sandstones and clays are present, the system can be separated into two parts, with the deeper part known as the CVAS (Ediacaran) and the shallower one known as the Ordovician–Cambrian (O–Cm) aquifer system. Both aquifer systems are used as a source of drinking water in northern Estonia. The CVAS directly overlies the crystalline basement in most of the BAB (see Fig. 1C, D) and

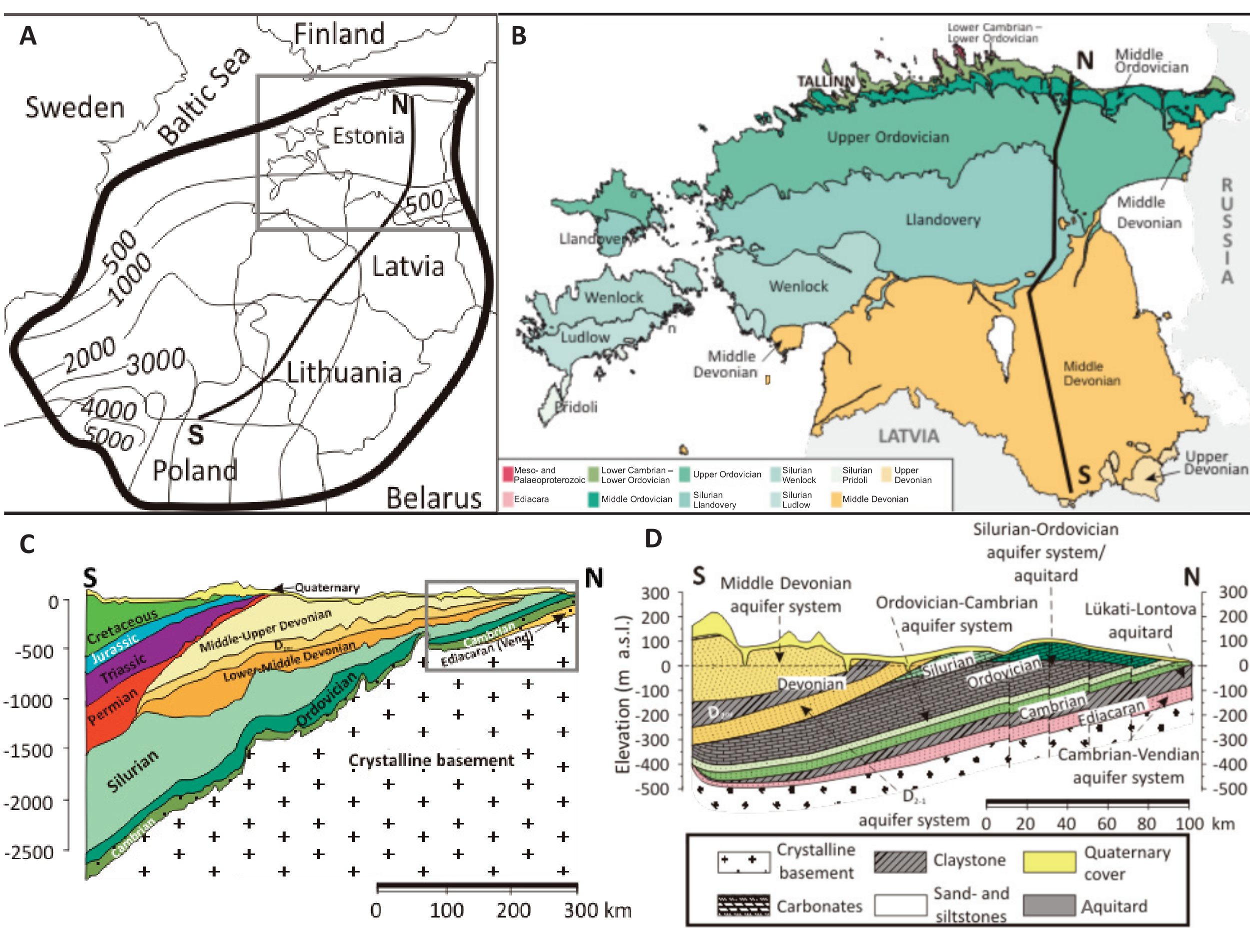


**Fig. 1. A**, the location and boundaries of the Baltic Artesian Basin (BAB); modified from Juodkazis (1980) and Virbulis et al. (2013). Contour lines mark the depth of the crystalline basement in metres below sea level. The geological cross-section of the BAB along the line N–S is shown in **C** and **D**. Abbreviations: $D_{2-1}$ aquifer system – Lower–Middle Devonian aquifer system, $D_{2nr}$ – Narva regional aquitard, Q – Quaternary. **B**, the close-up (rectangle in C) depicting the geological and hydrogeological setting in the northern part of the BAB (Estonia). Modified from Pärn (2018).

consists mainly of sand- and siltstones with dolomitic cement (Raidla et al. 2006). The CVAS varies in thickness from several hundred metres near the Danish–Polish Basin to 200 m at the northern and southern fringes and to approximately 50 m in the central part, the average being 80–100 m (Poprawa et al. 1999; Lukševičs et al. 2012). The CVAS is covered by limestones and dolomites with a variable clay content which host the Silurian–Ordovician (S–O) aquifer system in the northern part of the BAB, while the sequence turns into a regional aquitard as its depth from the ground increases (Fig. 1B). This sequence reaches a thickness of over 1 km in the deeper areas of the BAB, while pinching out in the southeast and north (Poprawa et al. 1999; Lukševičs et al. 2012). The Ordovician and Silurian sedimentary rocks have been considerably faulted, especially along the Liepāja–Pskov fault zone in the central part of the BAB (Brangulis & Kanevs 2002; Tuuling & Põldsaar 2021). Faults are an important factor for aquifer connectivity, as they may block the water flow or act as vertical aquifers, connecting otherwise disconnected aquifers (Virbulis et al. 2013). The present-day hydraulic heads indicate a recharge of the CVAS in the southeastern margin of the BAB, with a regional groundwater flow direction towards the north-west, where it discharges into the Baltic Sea (Virbulis et al. 2013).

Groundwaters in the shallow northern part of the basin are fresh (TDS <1 g $L^{-1}$). Water with higher salinity is present in the Lower–Middle Devonian ($D_{2-1}$), O–Cm and the Cm–V aquifer systems with maximum values of 4.6, 14 and 17 g $L^{-1}$, respectively (Vingisaar 1978). The chemical composition of these waters varies from Ca–Na–$SO_4$–Cl to Na–Cl type (Karise 1997). These waters have formed via complex geochemical evolution that has been influenced by the dilution with fresh water of both recent meteoric and glacial origin (Raidla et al. 2009). The influence of glacial recharge is manifested in the $\delta^{18}O$ values of –18‰ to –23‰ and –11.5‰ to –22.5‰ in the northern parts of the Cm–V and O–Cm aquifer systems, respectively (Raidla et al. 2009; Pärn et al. 2016; Vallner et al. 2020). At the same time, the annual weighted mean $\delta^{18}O$ value in modern precipitation in Estonia varies between –10.2‰ and –10.7‰ (Punning et al. 1987; IAEA/WMO 2020). Thus, a strong deviation in the isotopic composition is seen between these waters and modern precipitation, which is an important characteristic of glacial palaeowater. Gradual zoning from north to south in the chemical composition and salinity can be observed in aquifer systems of the BAB. The salinity is mostly above 100 g $L^{-1}$ and can exceed 180 g $L^{-1}$ with the dominant Na–Cl and Na–Ca–Cl water types in the southern and deeper parts of the BAB (Kalvāns 2012). Brines with a salinity of 110 g $L^{-1}$ have been reported from the Cambrian aquifer system (CAS) in Riga, Latvia (Babre et al. 2016) and 158 g $L^{-1}$ in Klaipeda, Lithuania (Gerber et al. 2017). Oil and natural gas are found in the deeper southern parts of the O–Cm aquifer system (Kalvāns 2012). The stable isotope composition of brines in the deeper parts of the BAB becomes more positive relative to modern precipitation but remains depleted relative to the modern seawater values of ~0‰ for $\delta^{18}O$ (Craig 1961). Mokrik et al. (2009) report $\delta^{18}O$ values from –4.5‰ to –9.9‰ from the Lower–Middle Devonian ($D_{2-1}$) aquifer system in Lithuania. The corresponding values in the CAS are –4.6‰ in Latvia and –5‰ in Lithuania (Gerber et al. 2017).

The chemical evolution and groundwater age of glacial palaeowaters in the CVAS have been studied by Raidla et al. (2009, 2012, 2014). Raidla et al. (2009) found that the water in the northeastern part of the CAS is a mixture of three end-members: recent meteoric water ($\delta^{18}O$ value of –11.5‰), fresh glacial meltwater with a very light isotopic composition (down to –23‰ in $\delta^{18}O$ values) and brine with a heavy isotopic composition ($\delta^{18}O \geq -4.5$‰).

Raidla et al. (2012) used $^{14}C$ to date the meltwater intrusion to 14–27 ka ago, which is coeval with the advance and maximum extent of the Weichselian glaciation in the area (Kalm 2012). In addition, the isotopic composition of methane in the Cm–V aquifer system indicates that the annual air temperature when the methane formed was about –2 to –8 °C (Raidla et al. 2019a). It supports the understanding that Pleistocene ice sheets advanced over areas where terrestrial vegetation had been only recently active and the infiltration of glacial meltwater happened mainly during the phase of ice sheet advance.

Similar ages have been reported from Lithuania, where water in the overlying Middle–Upper Devonian aquifer system was also $^{14}C$-dated to a few thousand years to 27 ka ago (Mokrik et al. 2009). Much higher groundwater ages on the order of a hundred thousand to several million years are expected for the deep formation waters (brines) in the southern part of the BAB. The hypothesis on the deep formation origin waters in the BAB was proposed by Mokrik (1997). He suggested that meteoric waters replaced the original connate seawater within the Cambrian sedimentary rocks during the Middle–Late Cambrian uplift of the BAB area and the seawater again intruded the sediments during the Ordovician to Devonian, when the basin was considerably subducted.

## MATERIAL AND METHODS

Over the years a database of the isotopic, chemical and dissolved gas composition of groundwater in Estonia, Latvia and Lithuania (now published as Vaikmäe et al.

2020) has been used to study the geochemical evolution of groundwater in the aquifers of the BAB. The database contains data on 1155 groundwater samples collected from both private, water supply and observation wells during the period of 1974–2017. The data describe the chemical (major ions, minor ions, trace elements, alkalinity), isotopic (stable isotope ratios of $\delta^{2}H_{water, CH4}$, $\delta^{18}O_{water, SO4}$, $\delta^{13}C_{DIC, CH4, CO2}$, $\delta^{34}S_{SO4}$; activities of $^{226}Ra$, $^{228}Ra$; $^{14}C$ and $^{3}H$) and dissolved gas (noble gas concentrations of He, Ne, Ar, Kr, Xe; the ratios of $^{3}He/^{4}He$, $^{36}Ar/^{40}Ar$, $^{81}Kr/^{85}Kr$; $CO_2$ and $CH_4$ concentrations) composition of groundwater.

The results of the studies on the origin, geochemical evolution and age of groundwater in the aquifer systems of the northern BAB have been published in recent decades in a number of papers and dissertations (Mokrik 1997; Vaikmäe et al. 2001a, 2001b, 2008; Karro et al. 2004; Marandi 2007; Raidla et al. 2009, 2012, 2014, 2016, 2019a, 2019b; Raidla 2010; Pärn et al. 2016, 2018, 2019; Gerber et al. 2017; Suursoo et al. 2017; Pärn 2018; Vallner et al. 2020). However, several recent studies on the palaeowaters in the BAB have employed other methodologies besides geochemistry and $^{14}C$ dating, which have been traditionally used for that purpose. To determine groundwater ages and uncover the flow dynamics of the system on the one million-year timescale, Gerber et al. (2017) measured $^{81}Kr$ and noble gases in the deepest aquifer system of the BAB. Jiang et al. (2012) determined the isotope ratios $^{81}Kr/Kr$ and $^{85}Kr/Kr$ using the ATTA-3 instrument in the Laboratory for Radiokrypton Dating, Argonne National Laboratory. The origin and formation of methane in groundwater of glacial origin from the CVAS in the northern part of the BAB was studied using isotope analyses of methane ($\delta^{13}C_{CH4}$ and $\delta^{2}H_{CH4}$; Raidla et al. 2019a). Finally, numerical models have been developed to assess palaeo-recharge under the Fennoscandian ice sheet and its impact on regional groundwater flow (Sterckx et al. 2017, 2018; Vallner et al. 2020).

## RESULTS AND DISCUSSION

The regional groundwater flow reversal that occurred during the glaciations is the most important characteristic for understanding the distribution of water types together with geochemical and dissolved gas signatures in the northern part of the BAB (Jõeleht 1998; Vaikmäe et al. 2001a, 2008; Raidla et al. 2009; Zuzevičius 2010; Saks et al. 2012; Pärn et al. 2018). On the basis of hydrogeochemical studies (Vaikmäe et al. 2008; Raidla et al. 2009; Pärn et al. 2018), noble gas studies (Vaikmäe et al. 2001b) and hydrodynamic modelling (Saks et al. 2012), it can be suggested that the intrusion of glacial meltwater occurred most likely in the outcrop area in the northern margin of the basin. Saks et al. (2012) assume that one glacial cycle is insufficient to flush the entire system, or even to drive the waters of glacial origin very far from the basin margin due to the large size of the BAB. However, over several glacial cycles, multiple reversals of the flow direction have probably taken place, which have enabled the glacial meltwater to move more than 100 km into the southern deeper parts of aquifers (Sterckx et al. 2018; Vallner et al. 2020).

It does not mean that the deeper aquifers further to the south were not altogether influenced by periodic flow reversals caused by advancing ice sheets. Gerber et al. (2017) developed a simple conceptual model of groundwater flow over several glacial cycles for the deepest aquifer system, the CVAS. The model assumes that the Ordovician–Silurian (O–S) aquiclude is impermeable, isolating the CVAS completely except in the recharge and discharge zones in the southeast and the Baltic Sea. Conceptually, throughout the glacial cycle, four stages of glacial overburden and groundwater flow patterns can be distinguished (Fig. 2). Stage 1 (interglacial) represents the present-day situation with recharge in the southeast and discharge in the northwest of the BAB. Stage 2 prevailed at the beginning and the end of glaciation, when the present-day discharge area in the north was covered by ice, but large parts of the BAB were still ice free. Stage 3 was reached when these areas were also covered by ice. At this point, the aquifer system discharged to the present-day recharge area, whereas recharge took place below the glacier. During stage 4, the whole of the BAB was covered by ice and groundwater flow was driven by the hydrostatic pressure at the ice sheet base, which followed the ice sheet topography. Stage 4 was probably not reached during the last glaciation (Weichselian), but such conditions were possible during the previous Saalian glaciation (Guobyte & Satkunas 2011). During deglaciation, the stages were passed through in reverse order.

New age determinations with $^{81}Kr$, $^{4}He$ and $^{40}Ar$ analyses of samples from deep wells over the BAB area (Fig. 3) indicate that the residence time of the brine component in the deeper central and southern parts of the BAB is more than 1–5 Ma (Gerber et al. 2017). The combination of the chemical and stable isotope composition of the brine noble gas concentrations and dating results favour evaporative enrichment of seawater, implying a pre-Quaternary origin of the brine (Pärn et al. 2016; Gerber et al. 2017).

Tracer ages of interglacial water and glacial meltwater in southern Estonia are on the order of several hundred thousand years. These ages support the previously stated hypothesis that this part of the BAB has been influenced by several reversals of the flow direction as a result of the expansion and retreat of ice sheets in the area.

Using a method proposed by Rousseau-Gueutin et al. (2013), the time needed for the CVAS to reach a near-

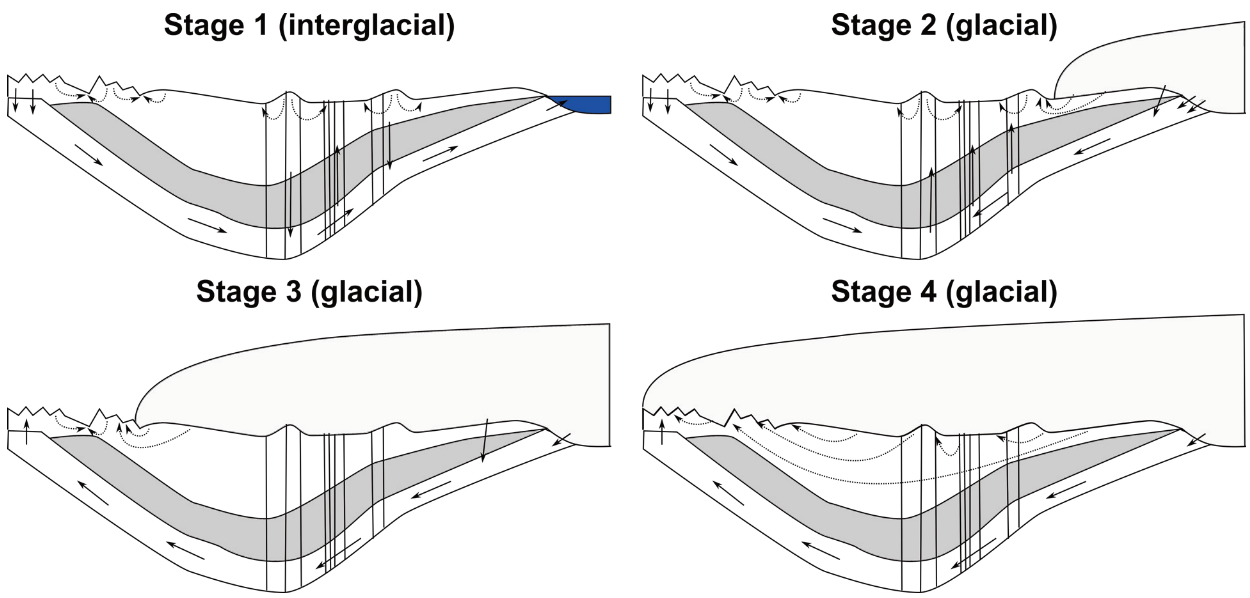


**Fig. 2.** Presumed flow patterns in interglacial and glacial periods, controlled by the expansion and retreat of the ice sheet. In the shallow aquifers (dashed arrows) and the Liepaja–Pskov fault zone, flow is mainly driven by topography during interglacial periods (Stage 1). During glacial periods (Stages 2–4), it is assumed that the fault zone has negligible influence on water flows and flow is mainly driven by ice sheet topography (Gerber et al. 2017). From Gerber et al. (2017).

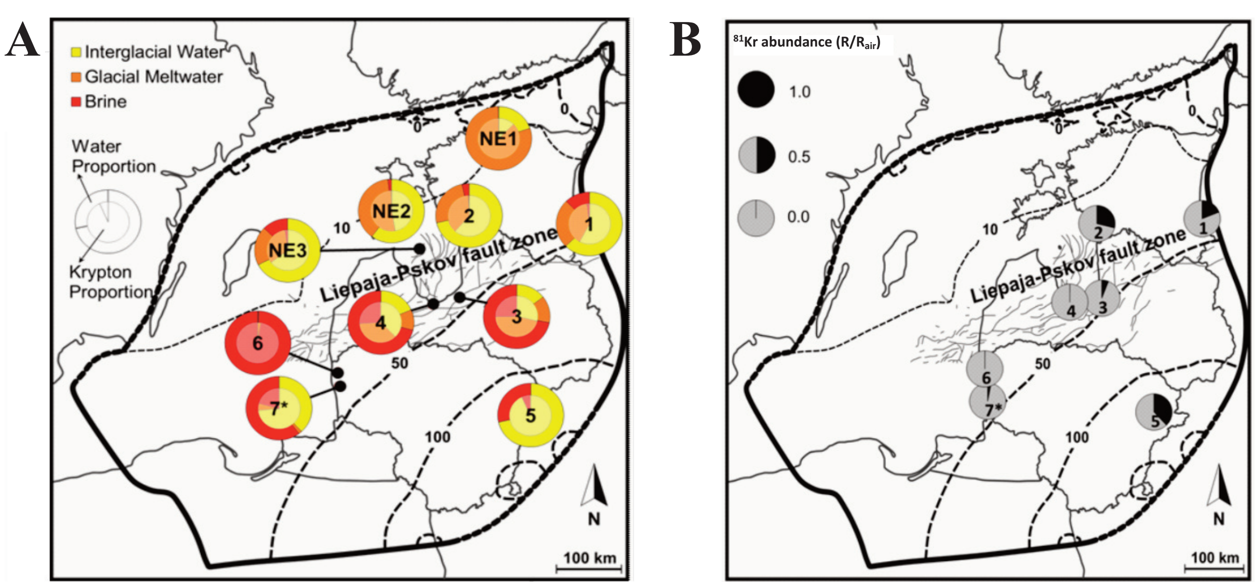


**Fig. 3. A**, spatial distribution of the proportions of the three end-members in the deep groundwater of the Cambrian aquifer system (CAS) and the corresponding proportions of Kr. Present-day hydraulic heads (dashed lines, in metres above sea level) in the CAS are according to Virbulis et al. (2013). Also shown are results for selected samples from northern Estonia (NE1–NE3, data from Raidla et al. 2009). **B**, the spatial pattern of contamination-corrected $^{81}$Kr abundances. Dashed black lines are isobars of the present-day piezometric head (m a.s l.) in the Cambrian–Vendian aquifer system (CVAS) modelled by Virbulis et al. (2013). From Gerber et al. (2017).

steady state following a large hydraulic perturbation can be estimated (Gerber et al. 2017). The calculations suggest that a relaxation time of ~50 ka is needed for the CVAS to reach a near-steady state after the glaciation. Thus, this aquifer system is still recovering from the last glaciation and taking into account the cyclic flow direction reversals that occurred during previous glacial cycles, the aquifer system has probably been in a transient state over most of the last 1 Ma period (Gerber et al. 2017).

It has been shown that in the northern part of the BAB, the spatial and vertical distribution of glacial palaeowater in shallower aquifer systems overlying the CVAS is wider than previously thought (Pärn et al. 2016, 2018, 2019; Pärn 2018). The occurrence of glacial palaeogroundwater is especially wide in the O–Cm aquifer system with fresh groundwater in the northeastern part of this aquifer system having $\delta^{18}O$ values as low as –22.4‰ (Pärn et al. 2016; Fig. 4).

Several reports from the Geological Survey of Estonia (Savitskaja et al. 1995, 1996 1997) and available hydrogeochemical data (Vaikmäe et al. 2020) show that even more shallow Silurian–Ordovician (S–O) and Lower–Middle Devonian ($D_{2–1}$) aquifer systems contain palaeogroundwater with $\delta^{18}O$ values as low as about –20‰. In

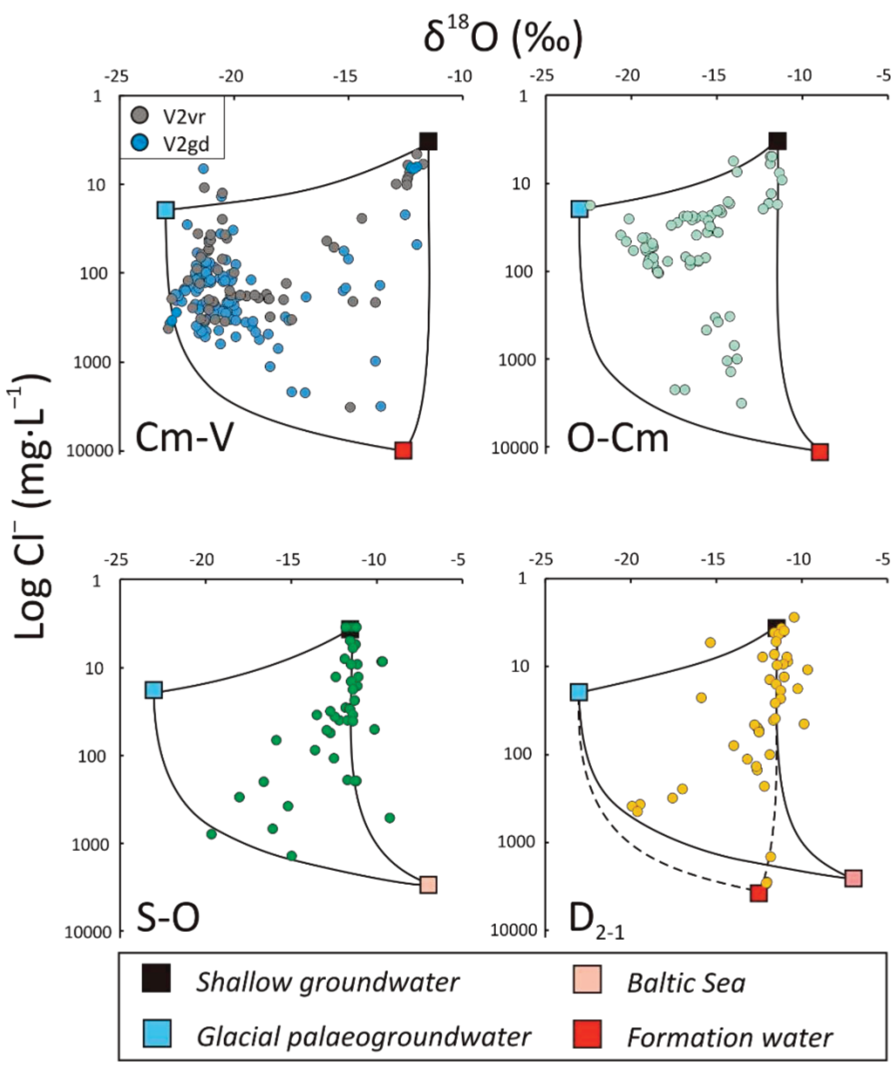


**Fig. 4.** Mixing relationships in the Baltic Artesian Basin (BAB) depicted using conservative tracers $\delta^{18}O$ and chloride for several aquifer systems in the northern part of the BAB. The end-member values for $\delta^{18}O$ and chloride are the following: shallow groundwater (–11.7‰, 4 mg $L^{-1}$), glacial palaeogroundwater (–23‰, 20 mg $L^{-1}$), the Baltic Sea (–7.0‰, 3735 mg $L^{-1}$), formation water (Cm–V: –12.6‰, 9800 mg $L^{-1}$; O–Cm: –9‰, 11 438 mg $L^{-1}$; $D_{2–1}$: –12.5‰, 3740 mg $L^{-1}$). Abbreviations: Cm–V – Cambrian–Vendian aquifer system (equivalent of the CVAS in the northern part of the BAB), V2vr – Voronka aquifer, V2gd – Gdov aquifer; O–Cm – Ordovician–Cambrian aquifer system; S–O – Silurian–Ordovician aquifer system; $D_{2–1}$ – Lower–Middle Devonian aquifer system. From Pärn (2018).

these shallow aquifer systems such waters occur mainly in western and southwestern Estonia (Pärn 2018). The exact origin and geochemical evolution of these waters is the subject of further studies.

Furthermore, the hydrogeochemical composition of groundwater in many aquifers of the northern BAB suggests that the influence of modern topographically driven flow is limited to the shallow aquifers of the area. For example, both the $^{14}C$ model ages and redox zonation in the O–Cm aquifer system suggest that glacial palaeogroundwater under the modern recharge area (Pandivere Upland) has a long residence time which can be explained by the prevalence of groundwater flow patterns established under the influence of continental ice sheets in the Pleistocene (Pärn et al. 2018, 2019). These new results from the northern BAB suggest that the zone where active exchange with modern infiltration takes place and renewable groundwater is formed does not reach as deep as has been shown in previous studies. In the northern BAB, glacial palaeogroundwater can be found at depths as shallow as 30 m (Pärn 2018). Such a wide distribution of glacial palaeogroundwater in Estonian bedrock makes it a special location in the world and a unique one in Europe (Pärn 2018).

More generally, the dating of glacial palaeogroundwater in the O–Cm aquifer system allowed identification of groundwater originating from three different climatic periods: the Holocene (0–10 ka BP); the Last Glacial Maximum (LGM, ~10–22 ka BP) and the pre-LGM period (>22 ka BP) (Pärn et al. 2019). This indicates that under natural conditions, a significant time is needed for the deeper aquifer systems in the northern BAB to gain hydrochemical and isotopic equilibrium with groundwater originating from modern recharge in agreement with the results of Gerber et al. (2017) for the deeper parts of the BAB.

Pärn (2018) has proposed diagnostic threshold values below –14‰ for the $\delta^{18}O$ and below –102‰ for the $\delta^{2}H$ isotopic composition of groundwater to differentiate between waters with an important glacial palaeowater component and groundwater originating from modern recharge. The dating of palaeowater with age tracers ($^{3}H$, $^{14}C$ and $^{4}He$) in the northern BAB has shown that waters with such an isotopic composition are at least ≥10 ka old (Raidla et al. 2012; Pärn et al. 2019).

The hypotheses on the formation of glacial palaeogroundwater proposed in the hydrogeochemical studies discussed above have been tested in modelling studies (Sterckx et al. 2018; Vallner et al. 2020). Sterckx et al. (2018) used the parameter space exploration of subglacial recharge conditions to tackle the uncertainty in the timing and duration of the glaciation in the northern BAB as well as in the isotopic composition of meltwater. The modelling results show that subglacial recharge under the Scandinavian ice sheet can explain the distribution of $\delta^{18}O$ in the northern BAB as originally suggested by Vaikmäe et al. (2001a). The simulations provide a good fit between the observed and computed values of $\delta^{18}O$, in particular those considering several uncertainties regarding the exact recharge conditions during the formation of glacial palaeowater (such as the upper estimates of subglacial recharge, the values for maximum subglacial hydraulic heads, the duration of subglacial recharge).

In the simulations, infiltration happened below the ice sheet, through the outcrop area of the aquifers, in the northwestern part of the BAB. Shallow aquifers were entirely recharged by meltwater, but were completely replaced by modern meteoric water, following the retreat of the Scandinavian ice sheet. Today, those aquifers only exhibit local evidence of diluted glacial meltwater, probably close to local outcrop areas under local aquitards. Conversely, confined aquifers were not entirely recharged by meltwater, but some meltwater was preserved after the retreat of the ice sheet. Accordingly, meltwater is found today in northern Estonia close to the outcrop area of the Cm–V and O–Cm aquifer systems (the analogues of the CVAS in the northern part of the BAB). In this respect, confining layers are crucial for understanding the preservation of glacial meltwater after the retreat of the Fennoscandian ice sheet but the presence of the Baltic Sea may also be important. The study indicated that large volumes of glacial meltwater could be preserved under the Baltic Sea, even in shallow aquifers. This could explain why glacial meltwater is found in the Narva aquitard and the $D_{2-1}$ aquifer system on Ruhnu and Kihnu islands and not on the mainland (Sterckx et al. 2018).

Similar conclusions were reached in the modelling study by Vallner et al. (2020) conducted in the northern part of the BAB (i.e. Estonian Artesian Basin). According to their hydrodynamic simulations, which modelled the transport of $^{18}O$ isotopes, the discharge of relict groundwater into the depressions of the Baltic Sea and the Gulf of Finland ceased at the beginning of the last glaciation in the Late Pleistocene. The glacial meltwater recharged transversally into the uppermost layers and laterally into deeper ones, thus reversing the regional groundwater flow. By the end of the glaciation, the maximum extent of glacial meltwater in deep layers almost reached the southern border of Estonia. During deglaciation and evolution of the Baltic Sea, modern meteoric water intruded into the upper layers filled earlier with glacial meltwater. Once again, deep groundwater began to move towards the Baltic Sea and the Gulf of Finland relict groundwater, basinal brine, glacial meltwater and modern meteoric water mixed in various proportions due to drastic changes in the hydrodynamic situation.

While these results help us to better understand the palaeogroundwater dynamics and origin in the BAB, they also call for further studies. Among these studies four major topics can be identified as stated in Sterckx et al. (2018) and Pärn (2018).

Firstly, the present-day pattern of groundwater flow in the BAB could be better defined. Steady and unsteady models have been developed using different geological models, hydraulic properties and surface boundary conditions, and all these models were in agreement with field data (Vallner 2003; Virbulis et al. 2013; Vallner & Porman 2016; Vallner et al. 2020 ). Although these models agree upon the overall SE–NW direction of regional flow in the BAB, the delineation and adjustment of hydrogeological units is needed in some places. This issue should be addressed in an extensive uncertainty analysis of groundwater flow in the BAB, to quantify the potential error when one set of hydraulic properties values is used instead of another. Furthermore, computations of groundwater flow in the BAB should account for variable density flow especially in the deeper southern parts of the BAB.

Secondly, most of the studies cited above have been regional in scale. However, many local issues require more detailed attention (e.g. occurrence of glacial palaeogroundwater under Kihnu and Ruhnu islands). For instance, scattered evidence of diluted meltwater in shallow aquifers (S–O and $D_{2-1}$) could be explained by local confining layers. To solve these local issues, more detailed hydrogeochemical studies coupled with modelling should be carried out at the local scale.

Thirdly, mixing processes between brines and fresh water in the deeper BAB demand additional study. Further modelling could be used, including other tracers such as chloride and groundwater ages, but more field data are also needed. Given the scarcity of deep wells in this area, the potential for collecting new field data is limited. Nevertheless, very few groundwater age measurements have been performed so far from the deeper parts of the BAB (Gerber et al. 2017), which leaves room for further isotopic dating studies.

Fourthly, in the light of the isotopic and chemical composition of groundwater in the shallower $D_{2-1}$ and S–O aquifer systems in the northern BAB, it cannot be excluded that glacial palaeogroundwater could be found at even shallower depths in this area (Pärn 2018). These shallow aquifers have been studied to a very limited extent with respect to their isotopic composition and their groundwater age distributions have not been quantified. Thus, it is critical that the quantitative dating of groundwater is also carried out in these aquifer systems to reveal the extent of the active water exchange zone in the northern BAB.

## CONCLUSIONS

With a wide range in groundwater chemical types, isotopic composition and the occurrence of palaeogroundwater originating from the Quaternary ice ages, the BAB is a special groundwater reservoir in the world and a unique one in Europe. The most important recent findings about the BAB can be summarized as follows:

1. Aquifers and aquitards containing glacial palaeogroundwater in the BAB (e.g. the CVAS and the O–Cm aquifer system) area are in a transient state with respect to modern topographically-driven groundwater flow conditions (Pärn et al. 2016, 2019; Gerber et al. 2017; Vallner et al. 2020).
2. In the northern part of the BAB, the zone where active exchange with modern infiltration takes place and renewable groundwater is formed does not reach as deep as previously thought (Pärn 2018). Under natural conditions a significant time is needed for the deeper aquifer systems in the northern BAB to gain hydrochemical and isotopic equilibrium with groundwater originating from modern recharge (Gerber et al. 2017; Pärn et al. 2018, 2019).
3. The chemistry, stable isotopes, noble gas measurements and dating tracers combined with numerical modelling show that the formation of groundwater in the BAB is strongly influenced by the mixing of three distinct water masses: Holocene and Pleistocene interglacial water, glacial meltwater and brine (Raidla et al. 2009; Pärn et al. 2016; Gerber et al. 2017; Pärn 2018; Vallner et al. 2020).
4. The modelling results (Sterckx et al. 2017, 2018; Vallner et al. 2020) show that subglacial recharge under the Scandinavian ice sheet can explain the distribution of $\delta^{18}O$ in the northern BAB and thus the formation of glacial palaeogroundwater in the area.
5. Groundwater dating using $^{81}Kr$, $^{4}He$ and $^{40}Ar$ indicates a residence time of more than 1–5 Ma for the brine component in the southern and central parts of the BAB. The combination of chemical and stable isotope composition of the brine, noble gas concentrations and dating results favours the hypothesis that these brines originate form evaporative enrichment of seawater in the pre-Quaternary (Pärn et al. 2016; Gerber et al. 2017).
6. The isotopic composition of methane in the CAS suggests that it is of biogenic origin and formed before the Last Glacial Maximum (Raidla et al. 2019a). This indicates that Pleistocene ice sheets advanced over areas where terrestrial vegetation had been only recently active.

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## Balti Arteesiabasseini põhjavee geofiltratsiooni ajalugu Hilis-Pleistotseenis ja Holotseenis: hüdrogeokeemilise teabe ja numbrilise modelleerimise süntees

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Viimase kümne aasta jooksul läbiviidud põhjaveeuuringute käigus on oluliselt laiendatud varasemaid teadmisi Balti Arteesiabasseini põhjavete kujunemisest ja mandrijäätumiste mõjust nende geneesile. Artiklis on antud ülevaade Balti Arteesiabasseini põhjaosa põhjavete geofiltratsioonist Hilis-Pleistotseenis ja Holotseenis tänapäevaste teadmiste valguses. Artiklis on keskendutud arteesiabasseini põhjavete dateerimisele ja modelleerimise tulemustele, millega kontrolliti hüpoteese liustikutekkelise põhjavee levikust ja üldistest infiltreerumise mehhanismidest Balti Arteesiabasseini põhja- (Sterckx jt 2018; Vallner jt 2020) ning lõunaosas (Gerber jt 2017). Balti Arteesiabasseini arengut on mõjutanud mitmed järjestikused jääajad, mil bassein kattus täielikult või osaliselt mandriliustikega. Nende sündmuste käigus kujundati ümber tavapärased põhjavee voolusuunad ja hüdrogeokeemilised arengutegurid. Kõige selgemalt on need muutused jälgitavad basseini põhjaosas, Eestis, kus Hilis-Weichseli-aegse liustiku sulaveest pärinevad põhjaveed on praeguseni laialt levinud ja olulised tarbeveeallikad.