

## Conceptual model of groundwater quality for the monitoring and management of the Voronka groundwater body, Estonia

Andres Marandi<sup>a</sup>, Enn Karro<sup>b</sup>, Valle Raidla<sup>a</sup> and Rein Vaikmäe<sup>a</sup>

<sup>a</sup> Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; Andres.Marandi@gi.ee

<sup>b</sup> Department of Geology, Institute of Ecology and Earth Sciences, University of Tartu, Ravila 14A, 50411 Tartu, Estonia

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**Abstract.** A fundamental knowledge of processes that control groundwater composition is required for informed management of water quality. The Voronka groundwater body in northeastern Estonia represents a good example of a complicated, overexploited groundwater system where conceptual understanding of baseline quality and governing hydrogeochemical processes can support sustainable aquifer management. A conceptual understanding or conceptual model is a simplified representation or a working understanding of the real hydrogeological system and its processes. The baseline chemical composition of the Voronka groundwater body was formed during the last glaciations, when glacial meltwater intruded into water-bearing rocks. Two main processes that can change Voronka groundwater body quality at the present day are: (1) seawater intrusion and (2) water exchange between buried valleys and formation's groundwater. Future monitoring and management should focus on changes in the natural composition of groundwater caused by abstraction. The  $\text{HCO}_3^-/\text{Cl}^-$  value is the best parameter to describe the fluctuations in natural background chemistry in the Voronka groundwater body and to assess significant trends induced by abstraction. In case of the discovered trends, a suite of isotope methods, especially  $^{14}\text{C}$ ,  $^3\text{H}$ ,  $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ , can be used to detect whether the intrusion of seawater or exchange of water with buried valleys is taking place.

**Key words:** conceptual model, groundwater management, groundwater monitoring, stable isotopes, hydrochemistry, Estonia.

### INTRODUCTION

Solutes within groundwater contain wide ranges of trace and major elements. Therefore, a fundamental knowledge of processes that control groundwater composition is required for informed management of water quality (Hem 1985). The subject of groundwater chemistry in relation to water quality prediction is complicated. Interaction between groundwater and rock can significantly modify solute concentrations during transport.

The Cambrian–Vendian Aquifer System (CVAS) is the most utilized groundwater system in North Estonia. Several previous studies have addressed the origin of waters within the CVAS (Punning et al. 1987; Vaikmäe & Vallner 1989; Yezhova et al. 1996; Mokrik 1997; Vaikmäe et al. 2001; Marandi et al. 2004; Raidla 2010). The results of the monitoring studies, which commenced in the 1950s, show that intensive consumption of groundwater has modified the chemical composition of CVAS groundwater (EGS 1998). If a confined, artesian, groundwater system is pumped, the water is initially taken from aquifer storage as a result of expansion and compaction of rock material induced by water pressure (Theis 1940; Meinzer 1945). During compaction, the water captured by silt and clay layers and by the surrounding water-

bearing rocks can be squeezed out and will flow to pumping wells (Meinzer 1945). The water added from clayey sediments is chemically distinct from the water generally flowing in the aquifer and can change the quality of water discharged by wells. Therefore, it is important to know the origin of groundwater and the processes that affect the chemistry within it in order to predict future changes to groundwater quality. Such processes may have been influential in controlling changes in the CVAS in Estonia.

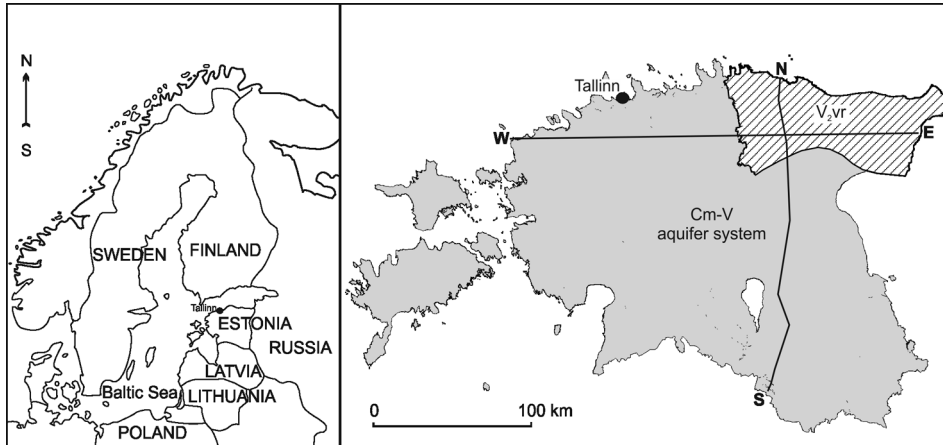
One of the primary and key steps within implementation of the European Water Framework Directive (WFD) is the analysis of characteristics of groundwater bodies, review of the environmental impact of human activity and economic analysis of water use. All that is achievable only if there exists a conceptual understanding of what happens in a groundwater body and what causes the impact. A conceptual understanding or conceptual model is a simplified representation or a working understanding of the real hydrogeological system and its processes (Scheidleder et al. 2008).

The current study presents a conceptual understanding of the formation of groundwater composition in the Voronka groundwater body (V<sub>2</sub>vr), which is a part of the CVAS in the northeastern area, but was

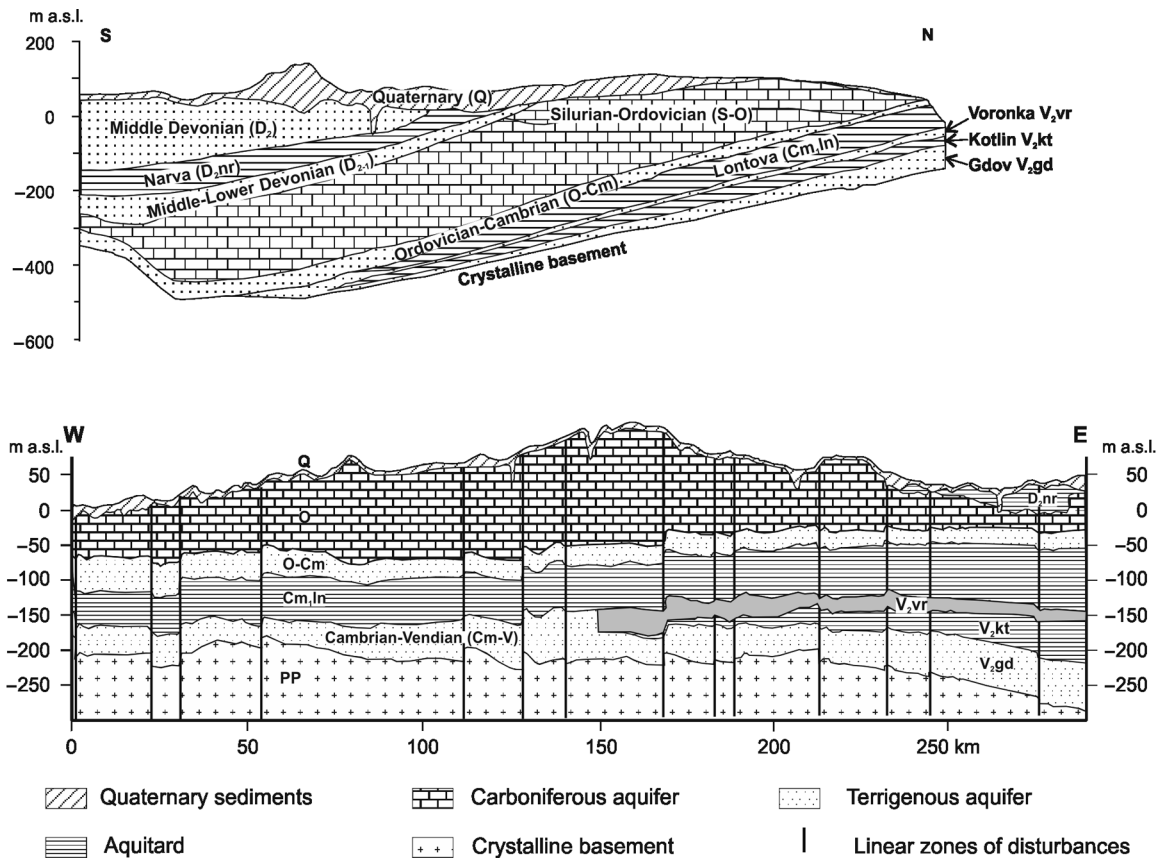
delineated as a separate groundwater body for management purposes. The conceptual model presented below includes examples showing the original composition of  $V_{2vr}$  and also the changes taking place because of intensive groundwater abstraction.

### DELINEATION OF GROUNDWATER BODIES

The  $V_{2vr}$  groundwater body forms the upper part of the CVAS in northeastern Estonia (Figs 1, 2). The CVAS is distributed throughout Estonia, except the uplift area of



**Fig. 1.** Schematic map of the study area showing the location of the  $V_{2vr}$  groundwater body ( $V_{2vr}$ ) and the lines of hydrogeological cross sections.



**Fig. 2.** Hydrogeological cross sections (SN and WE) of the Cambrian–Vendian aquifer system (CVAS) in northern Estonia. Lines of cross sections shown in Fig. 1. The investigated part of the CVAS is marked with grey colour on the WE cross section.

the crystalline basement in South Estonia. There is an obvious difference between cross sections of the CVAS in eastern and western parts of Estonia. In the eastern part, clays of the Kotlin Formation divide the CVAS into two separate aquifers, the upper Voronka aquifer and the lower Gdov aquifer (Fig. 2). The Voronka and Gdov aquifers in the eastern part and the joint CVAS in the western part are treated as separate groundwater bodies, respectively,  $V_{2vr}$ ,  $V_{2gd}$  and  $Cm-V$  (Fig. 2). The groundwater bodies were identified primarily on the basis of hydrogeological characteristics, the amount of water abstraction as well as administrative and water management considerations (ME 2005). Thus, the  $V_{2vr}$  forms only the upper part of the CVAS in northeastern Estonia.

## GEOLOGY AND HYDROGEOLOGY

The water-bearing rocks of  $V_{2vr}$  consist of variable siliciclastic rocks of the Voronka Formation of the Ediacara System, which represents a single upwards coarsening cycle from argillaceous rocks to well-sorted sandstones. The deposits of the lower part of the Voronka Formation are derived from the weathered zone of sedimentary rocks and consist of alternating multicoloured clays and siltstones with interlayers and lenses of light-coloured sandstones, the proportion of which increases upwards in the section. Most of the detrital grains are subrounded quartz with a small quantity of feldspars (up to 10%) and micas (mainly muscovite). In the clay fraction, kaolinite slightly prevails over illite. The upper part of the Voronka Formation has been formed by redeposition of older sediments and consists of light weakly cemented fine- to medium-grained quartzose sandstones with a few thin interlayers of multicoloured clayey siltstones (Mens & Pirrus 1997a). The siliciclastic rocks of the Voronka Formation have hydraulic conductivity of 0.6 to 12.5 m day<sup>-1</sup> and the aquifer transmissivity varies from 100 to 150 m<sup>2</sup> day<sup>-1</sup> (Perens & Vallner 1997).

The Voronka groundwater body lies between confining clay layers: clays of the Lontova Formation (Lontova aquitard) above and clays of the Kotlin Formation (Kotlin aquitard) below (Fig. 2). The Lontova Formation is represented by greenish-grey and variegated argillaceous rocks with interbeds of coarse- to fine-grained sandstone in the lowermost and fine-grained sandstones in the uppermost part (Mens & Pirrus 1997b). The dominant components of the Kotlin Formation are thinly laminated grey claystones with intercalated light-coloured, very fine-grained sandstones or siltstones, or both. The lamination is complicated by the occurrence of dark-brown films of organic matter (Mens & Pirrus 1997b). The thickness

of clays of the Lontova Formation varies from 60 to 90 m and increases eastwards, whereas the maximum thickness of clays of the Kotlin Formation occurs in eastern part (50 m), pinching out on the western border of  $V_{2vr}$  (Fig. 2).

In places, erosional processes in pre-Quaternary time, during interglacial and in late- and postglacial times have formed erosional valleys, cutting through the Lontova aquitard (Tavast 1997; Vaher et al. 2010). These ancient buried valleys are filled with Quaternary sediments, mostly till, but marine, glaciofluvial and glaciolacustrine sediments are also present. The valleys are oriented from northwest to southeast, thus being approximately perpendicular to the North Estonian coastline. Based on the data of  $\delta^{18}O$  and radiocarbon analyses, Vaikmäe et al. (2001) have shown that in the places where groundwater is intensively abstracted modern water infiltrates into the Cambrian–Vendian aquifer system along these valleys.

## BASELINE COMPOSITION

As shown by previous studies, the natural composition of waters within the CVAS formed during the last glaciations when the glacial meltwater intruded into the aquifer system (Vaikmäe et al. 2001; Raidla et al. 2009). The direction of groundwater flow during the intrusion was from northwest to southeast. Water exchange was more intensive in western Estonia, where the CVAS is covered by sediments of Cambrian age with a relatively low clay content. Water exchange was less intensive in eastern Estonia, where the underlying sediments are thicker and have a relatively higher content of clay. Additionally, Kotlin clays divide the CVAS into two groundwater bodies (Voronka and Gdov) in eastern Estonia. This could explain the formation of different water type zones in the CVAS (Marandi 2007).

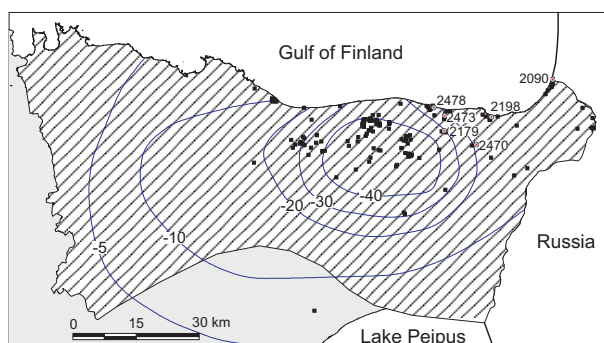
As a result, most of groundwater in  $V_{2vr}$  represents  $HCO_3-Cl-Ca-Na$  or  $Cl-HCO_3-Ca-Na$  type of ‘fresh baseline’ water of glacial origin, recharged during the last glaciations (Marandi 2007). The water has a distinct isotope composition of  $\delta^{18}O$ , the values of which range between  $-18.4\text{‰}$  and  $-21.3\text{‰}$  and a low radiocarbon concentration (1.4–4.3 pmc), indicating the formation of the water under cold climatic conditions and of glacial age (Vaikmäe et al. 2001).

The eastern part of  $V_{2vr}$  contains groundwaters with a higher content of bicarbonate and chloride. The  $Cl-HCO_3-Na$  groundwater type can be interpreted as a mixture of glacial meltwater with older brine water (Marandi 2007), or as a result of dissolution of evaporate minerals (Raidla 2010).

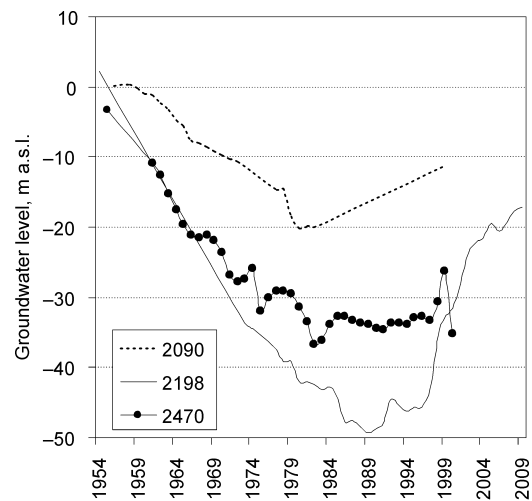
## PRESSURES ON GROUNDWATER QUANTITY AND QUALITY

According to Article 5 report of the Water Framework Directive (ME 2005), groundwater abstraction for public water supply and industry, seawater intrusion, and upconing of saline groundwater are the most important pressures for the Voronka groundwater body. A large cone of depression has formed because of intensive use of groundwater from  $V_2vr$  in northeastern Estonia (Fig. 3; Vallner 2003). Overpumping the aquifer constitutes a potential anthropogenic disturbance of the natural chemical balance in groundwater. The intruded saline water may irreversibly change the development of groundwater resources, whether it is seawater encroaching into effectively exploited aquifers in coastal areas or older saline groundwater upconing in response to pumping of an overlying layer of fresh water. Coastal groundwater aquifers are particularly threatened by salt-water intrusion from both sources (Custodio 2002). Thus, the most serious consequence of groundwater overexploitation of the Cambrian–Vendian aquifer system in northeastern Estonia is the formation of regional depressions in potentiometric levels and the increase in the total dissolved solids (TDS) content and concentration of major ions in groundwater. Northward regional groundwater flow has been replaced with a radial flow towards the centre of the piezometric depression located 20 km to the south from the coast. As a result, lateral groundwater flows induce the seawater intrusion to groundwater intakes. Therefore, the pumping-induced groundwater deterioration may locally restrict the use of groundwater as a source of drinking water supply.

The rate of groundwater extraction increased steadily during the 1950s–1980s in northeastern Estonia due to rapid industrialization and urbanization. The potentiometric surface of the Voronka groundwater body had



**Fig. 3.** Location of  $V_2vr$  monitoring wells for background data (solid squares) and for detailed studies (grey points marked with the well number). Solid lines (m) represent the maximum of the regional cone of depression in 1995 according to Perens & Vallner (1997).



**Fig. 4.** Changes in groundwater levels in the Voronka groundwater body according to state groundwater monitoring data.

lowered 20–50 m by 1990 due to intensive water abstraction (Fig. 4). A decrease in groundwater extraction started in the 1990s with the decline in industrial and agricultural production and more sustainable use of groundwater. During the last 15 years the potentiometric surface of groundwater has steadily recovered.

The  $V_2vr$  groundwater body is confined by an up to 70 m thick Cambrian clay layer that protects it from modern infiltration and pollution. However, in places the clay layer is cut through by buried valleys filled with glacial sediments from recent glaciations. Under natural conditions, the valleys would act as discharge channels for  $V_2vr$ , but the developed cone of depression has reversed the process, causing fresh water to intrude into  $V_2vr$  instead.

Based on the previous discussion, two main processes can change  $V_2vr$  groundwater quality because of changes in flow direction: (1) seawater intrusion and (2) water exchange between  $V_2vr$  and buried valleys.

## DATA AND METHODOLOGY

The groundwater monitoring in eastern Estonia has long history. Many of the wells with long-term monitoring data were drilled in the 1950s. Water chemistry, fluctuations of groundwater levels and changes in water abstraction rates have been monitored. Most of the water sampling and groundwater level measurements were performed by the Geological Survey of Estonia.

Groundwater monitoring data collected between 1954 and 2009 from 154 wells were used as background data. Additionally 5 groundwater production wells (Nos 2179, 2198, 2470, 2473 and 2478) were used for detailed

studies. The wells for data processing were selected according to the following criteria: (1) assurance of a good spatial representation, (2) data available from the whole monitoring period and (3) existence of water chemistry, water level and pumping rate data, or at least two of these, from the same well. The location of monitoring wells is given in Fig. 3.

The water abstraction and level data have a different measuring interval, therefore only annual averages are used for interpretation. No aggregation is performed for water quality data and the results of single analyses are used for interpretation.

Simple mixing of two end members was used to assess the magnitude of possible seawater content in  $V_{2vr}$  abstraction well 2198. The chemical composition of water from well 2470 was used as representative for  $V_{2vr}$  groundwater chemistry. This water was mixed with different ratios of seawater. The result of the mixing was compared with the chemical composition of the water from well 2198.

Isotope analyses were conducted in the Department of Isotope-Palaeoclimatology of the Institute of Geology at Tallinn University of Technology. The conventional equilibration technique was used to prepare water samples for oxygen isotope ( $\delta^{18}O$ ) analyses (Epstein & Mayeda

1953). All measurements were carried out with Finnigan MAT Delta E isotope ratio mass spectrometry and data are expressed in  $\delta$  ‰ notation relative to the international water standard VSMOW with standard errors  $\leq 0.1$ ‰. For radiocarbon measurements large volume water samples (200–300 L) were taken. The pH of carbon isotope samples was set to  $pH > 12$  by adding the required amount of concentrated carbon dioxide-free NaOH solution. Analytical grade  $BaCl_2$  in excess of expected alkalinity was added to precipitate  $HCO_3^-$  in the form of  $BaCO_3$ . Radiocarbon activities in groundwater were measured with a two detector liquid scintillation  $\beta$ -spectrometer. The  $^{14}C$  results are reported as percentage of the modern carbon standard (pmc).

### NATURAL BACKGROUND COMPOSITION OF $V_{2vr}$

A Piper plot illustrating the chemical composition of  $V_{2vr}$  is presented in Fig. 5. It includes all analyses used in the current study which vary spatially as well as in time. Although groundwater samples have a wide range of chemical types from  $HCO_3$ –Cl–Ca–Na to Cl– $HCO_3$ –Na,Ca, most of the samples taken from  $V_{2vr}$  have the

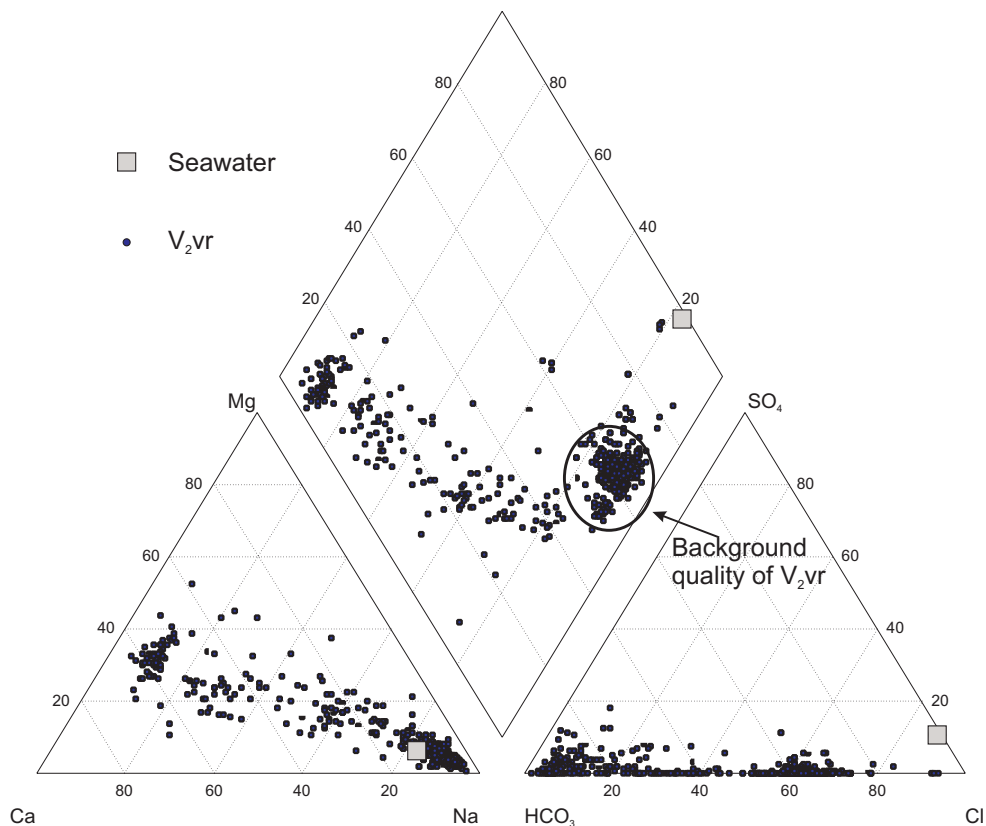


Fig. 5. Piper plot of  $V_{2vr}$  showing the range of all samples and the position of samples with natural background quality in  $V_{2vr}$ .

Cl–HCO<sub>3</sub>–Na–Ca composition as indicated in Fig. 5. These are considered to represent the natural background composition.

Most changes in the background composition result from the mixing of glacial meltwater with older brine water and water–rock interaction during filtration (Marandi 2007; Raidla et al. 2009), which causes spatial and temporal HCO<sub>3</sub><sup>−</sup> and Cl<sup>−</sup> content variation as shown on the right triangle of the Piper plot in Fig. 5. As V<sub>2</sub>vr has mostly reducing conditions, the sulphate ion content is rather low with the mean value of 4 mg L<sup>−1</sup>. Therefore, the value of HCO<sub>3</sub><sup>−</sup>/Cl<sup>−</sup> is the most representative for describing the variations in V<sub>2</sub>vr groundwater chemistry. The HCO<sub>3</sub><sup>−</sup>/Cl<sup>−</sup> value ranges spatially and temporally from 0.9 to 1.3 and the long-term monitoring data from well 2470 are a good example to illustrate the variation in time (Fig. 6).

The high variation in HCO<sub>3</sub><sup>−</sup>/Cl<sup>−</sup> values is a result of oxidation of light, probably organic carbon, and dissolution processes of carbonate minerals (Raidla 2010) during the intrusion of glacial water into V<sub>2</sub>vr (Marandi 2007; Vaikmäe et al. 2008; Raidla 2010). It can also be due to the water leaking from the confining aquitards or from clayey sediments as a result of compaction caused by groundwater abstraction. Dolomite cements are widely distributed in V<sub>2</sub>vr, which lies between clay layers, as the cemented zones are in most cases found at contacts with clay beds of the Cambrian Lontova and the Ediacaran Kotlin age (Raidla et al. 2006). The differences in dissolved HCO<sub>3</sub><sup>−</sup> amounts are probably caused by uneven distribution of dolomite cement and organic material in water-bearing rocks and confining layers.

According to isotope measurements, the δ<sup>18</sup>O value of the background water ranges from −18.4‰ to

−21.3‰, which is typical of cold climate meteoric water (Rozanski et al. 1992). The age measurements show the groundwater residence time from 22 000 to 23 000 radiocarbon years (Raidla 2010).

Therefore, the fluctuation in HCO<sub>3</sub><sup>−</sup>/Cl<sup>−</sup> values without any trend represents the variation in groundwater quality. If any significant temporal trend occurred in the long-term data, the leakage of additional water should be considered and its origin should be studied.

## SEAWATER INTRUSION

A serious threat to the quality of V<sub>2</sub>vr, due to changes in the groundwater flow direction, is seawater intrusion. In order to follow the changes in water chemistry (salinization, mixing), good indicators are chloride concentration and the characteristic ion ratios (Richter et al. 1993; Giménez & Morell 1997; Appelo & Postma 1999; Pulido-Leboeuf 2004; Lee & Song 2007). Fresh groundwater is often dominated by Ca<sup>2+</sup> and HCO<sub>3</sub><sup>−</sup> ions, and cation exchangers in groundwater therefore have mostly Ca<sup>2+</sup> adsorbed on solid surfaces (Appelo & Postma 1999). Groundwaters of Na–Cl type generally indicate a strong seawater influence (Pulido-Leboeuf 2004; Lee & Song 2007). Thus, the main diagnostic sign of seawater intrusion into wells on the seaside intake could be the appearance of or increase in elements such as sodium and chlorine.

The major ions constitute the bulk of the mineral matter contributing to TDS in water. Accordingly, Na<sup>+</sup>, Ca<sup>2+</sup> and Cl<sup>−</sup> concentrations in groundwater influenced by seawater intrusion display the same increasing/decreasing trends as TDS. However, when Na<sup>+</sup>- and Cl<sup>−</sup>-rich seawater

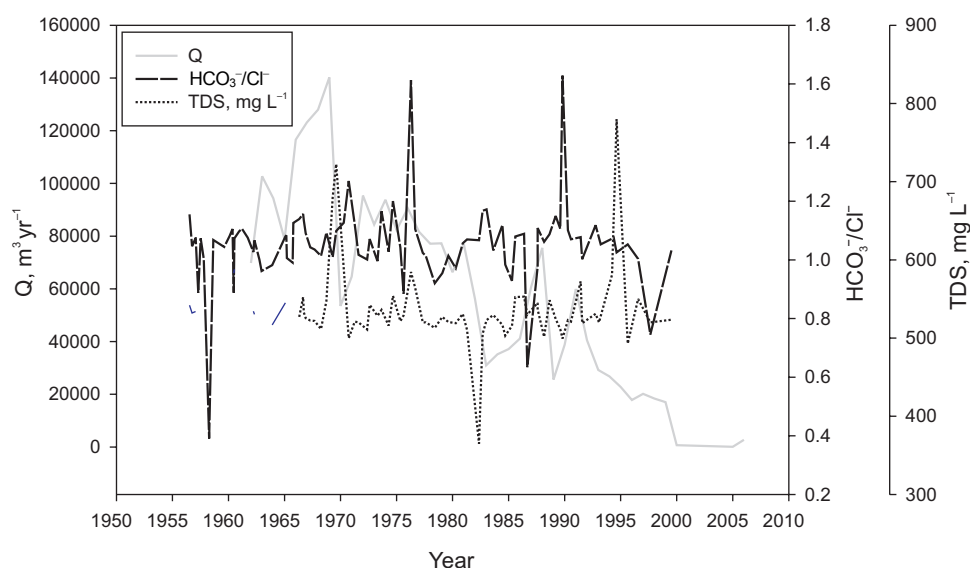


Fig. 6. Fluctuation of the HCO<sub>3</sub><sup>−</sup>/Cl<sup>−</sup> value in groundwater pumped from well 2470.

intrudes into a coastal aquifer, an exchange of cations takes place. Sodium is taken up by the exchanger and  $\text{Ca}^{2+}$  is released. The water quality thus changes from Na–Cl to Ca–Cl type (Appelo & Postma 1999; Petalas & Diamantis 1999) and groundwater is enriched in calcium relative to seawater.

The ion ratios of two drilled wells opening the Voronka groundwater body are presented in Fig. 7. Well 2198 is situated at the coast, well 2470 inland, 8 km to the south from the coastline. The groundwater in both wells is enriched in sodium as well as in calcium relative to seawater and lies above the seawater dilution line (SDL). The distribution of data in case of well 2198 is quite linear, suggesting a mixing trend of saline water with dilute water (Richter et al. 1993; Appelo & Postma 1999). The chloride concentration in well 2470 has been stable around  $200 \text{ mg L}^{-1}$  during the monitoring period of over several decades. The well at the coastline (2198) exhibits higher chloride values ( $200\text{--}400 \text{ mg L}^{-1}$ ) and in spite of the recovery of the potentiometric level (Fig. 4), the TDS value and chloride concentration continue to increase, possibly due to the influence of seawater.

The simple mixing of groundwater with background quality and seawater suggests that the changes in groundwater chemistry at well 2198 can be explained by additional (2–5%) seawater flow into  $V_{2vr}$  (Fig. 8). Water type changes during the last decade also point to the shift towards seawater composition.

Another good indicator suggesting seawater intrusion is the value of  $\text{HCO}_3^-/\text{Cl}^-$  (Fig. 9). Unfortunately, the chemistry data from years 1998–2002 are missing. However, after that period the increase in TDS as well as changes in the  $\text{HCO}_3^-/\text{Cl}^-$  value suggest that the water, enriched with  $\text{Cl}^-$ , is affecting the quality of the pumped water.

Additional information to prove seawater intrusion can come from isotope measurements of the water and soluble constituents. The complex of radiocarbon,  $\delta^{18}\text{O}$  and tritium could indicate possible seawater intrusion with high confidence.

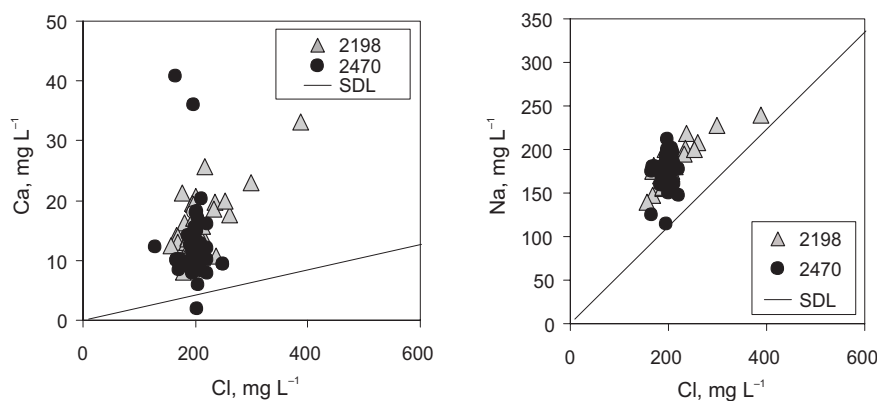
Previous research has shown that radiocarbon activity stays between 1.4 and 2.7 pmc in the area close to well 2198 (Vaikmäe et al. 2001). The intrusion of modern water will considerably increase radiocarbon activities in  $V_{2vr}$  palaeowater. The mixing with modern water can be easily recorded in case of a higher infiltration rate. However, if the amount of modern water stays under 5%, other geochemical processes will subdue the change in  $^{14}\text{C}$  activity in groundwater. For example, intrusion of modern water can stimulate oxidation processes of methane and matured organic material from clay sediments, or dissolution of carbonate minerals, which can add extra stable carbon to the groundwater's carbon pool. Also, the increasing  $\text{Ca}^{2+}$  content will lead to the precipitation of calcite.

The most conservative tracers of geochemical impact are  $^{18}\text{O}$  and D (Clark & Fritz 1997), although in order to shift  $\delta^{18}\text{O}$  values by 1‰, 10% of mixing with modern water is needed. However, earlier research has not shown larger than 0.1‰ fluctuations in  $V_{2vr}$  groundwater, which responds to analytical precision (Vaikmäe et al. 2001; Raidla et al. 2009).

Tritium has a good chance to be an excellent tracer for registering the intrusion of modern water, since in  $V_{2vr}$  palaeowaters only low  $^3\text{H}$  activities have been registered (Vaikmäe et al. 2001). The outcrop area lies about 12–15 km northwards from well 2198 and the lifetime of tritium is only 12.43 years. Therefore, it is essential to know the possible time of seawater journey in order to give precise estimations.

## WATER EXCHANGE BETWEEN $V_{2vr}$ AND BURIED VALLEYS

As it was mentioned before, at the northernmost edge buried valleys penetrate the Lontova aquitard and  $V_{2vr}$ . Buried valleys can act as water conduits between  $V_{2vr}$  and upper aquifers enabling modern precipitation to



**Fig. 7.** The concentrations of  $\text{Na}^+$  and  $\text{Ca}^{2+}$  plotted against chloride concentration in wells 2198 and 2470. SDL – seawater dilution line.

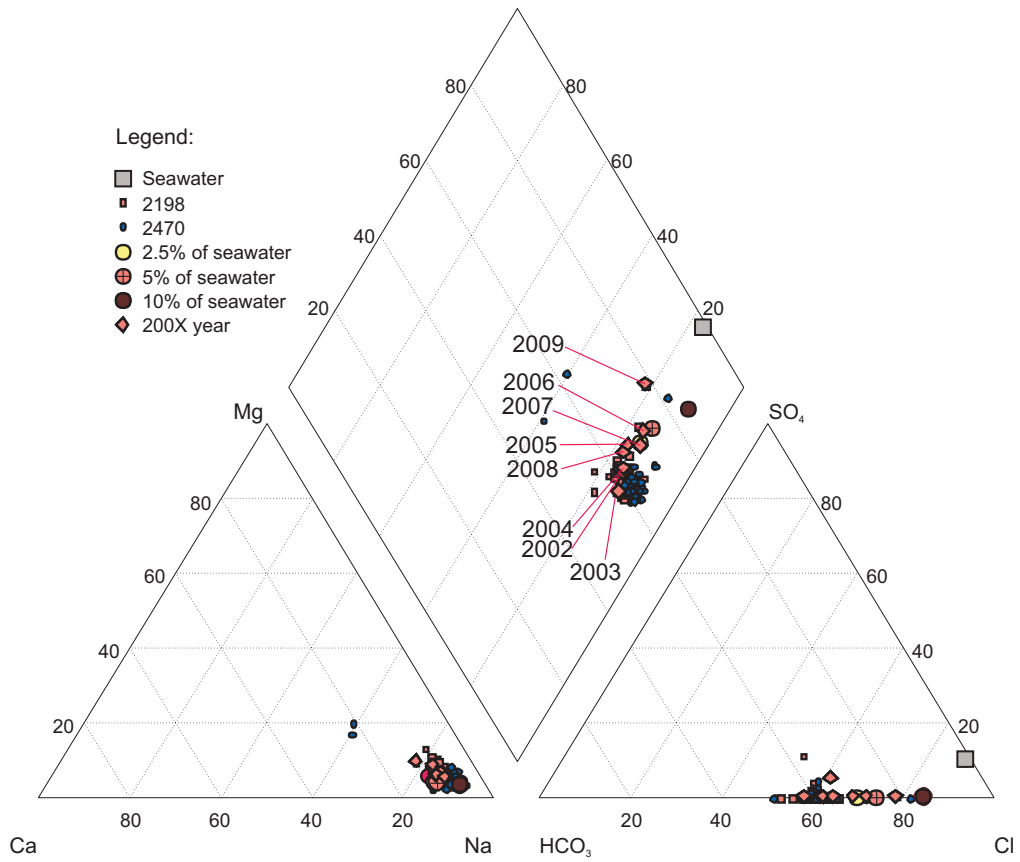


Fig. 8. Changes in water types in well 2198 in recent years.

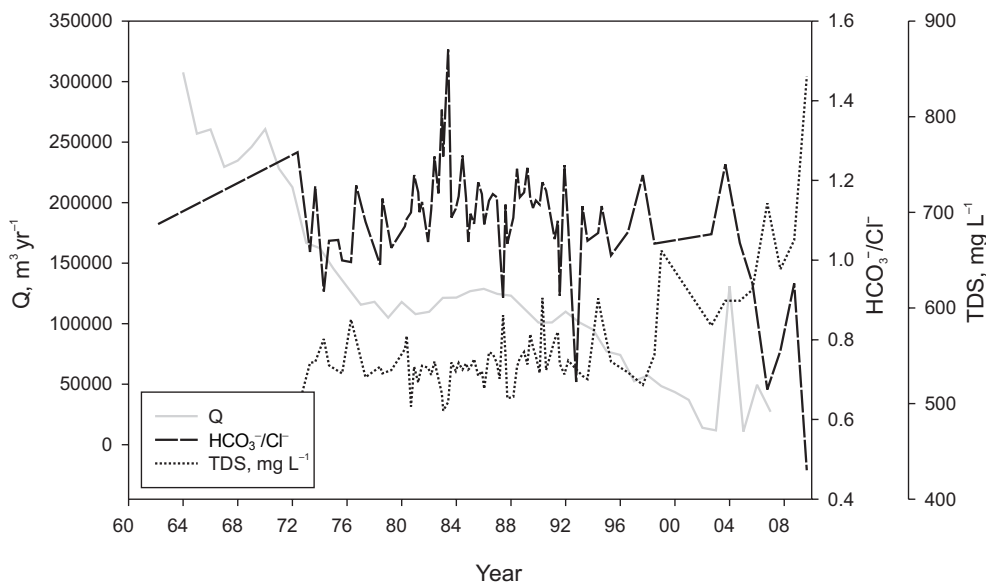


Fig. 9. Changes in groundwater abstraction from well 2198 and those in TDS and  $\text{HCO}_3^-/\text{Cl}^-$  ratios in the abstracted water. Missing chemistry data from years 1998 to 2002 are interpolated.



infiltrate into  $V_{2vr}$ . Infiltration can be intensified by lowering the pressure as a result of groundwater abstraction from  $V_{2vr}$ . The upper aquifers have mostly  $HCO_3^-Ca-Mg$  type of water (Karise 1997) and therefore it adds more  $HCO_3^-$  into  $V_{2vr}$  groundwater.

A good example for showing the leakage of groundwater from buried valleys to  $V_{2vr}$  is the data series from well 2478 (Fig. 10). The value of  $HCO_3^-/Cl^-$  fluctuates here from 1.9 to 12 mostly, and a slight increasing trend has been observed since 1985. The impact of buried valleys can also be viewed in the Piper diagram (Fig. 11), where the most influenced waters (well 2473) are shown on the left. The  $HCO_3^-/Cl^-$  value increases from well 2478 to 2473, respectively, from 1.9 to 60.

The evolution of isotopic composition during mixing between CVAS palaeowater and modern water has not been well studied yet. Still, Vaikmäe et al. (2001) and Raidla et al. (2009) have shown the 10‰ differences in the composition of  $\delta^{18}O$ , arguing that this trend occurs due to the infiltration of modern precipitation into the CVAS. During the process the  $\delta^{18}O$  shifts to more positive values, approaching mean annual  $\delta^{18}O$  values (–10.4‰) of the contemporary local precipitation (Punning et al. 1987). However, the data available today do not allow making generalizations on the subject. The  $^{14}C$  activities are also considerably higher in the above-discussed wells, but the data are controversial and do not enable us to predict changes in  $^{14}C$  content during the infiltration of modern precipitation. The rise in  $^{14}C$  activity does not follow a clear shift in  $\delta^{18}O$  composition. Relatively similar  $\delta^{18}O$  values (fluctuation up to 2‰) could be

accompanied by even three times higher  $^{14}C$  activities (20–60 pmc) (Vaikmäe et al. 2001; Savitski et al. 1993).

#### THE CONCEPTUAL MODEL OF THE FORMATION OF THE CHEMICAL COMPOSITION IN $V_{2vr}$ AND MONITORING SUGGESTIONS FOR THE FUTURE

The baseline chemical composition of  $V_{2vr}$  was formed during the last glaciations, when glacial meltwater intruded into water-bearing rocks.

Two main processes that can change  $V_{2vr}$  groundwater quality because of changes in the flow direction are (1) seawater intrusion and (2) water exchange between  $V_{2vr}$  and buried valleys.

Although the investigations of major water intakes in the area, to prove the groundwater resources for the next 20 years, do not predict seawater intrusion, the results of the current study indicate that some of the wells can already be influenced by seawater.

The  $HCO_3^-/Cl^-$  value is the best parameter by now to describe the changes in chemical composition caused by the abstraction of groundwater. The  $HCO_3^-/Cl^-$  ratio fluctuates from 0.9 to 1.3 in waters of natural background composition and any sustained trend under or above these values can be caused either by leakage from buried valleys or by seawater intrusion, respectively, and should be thoroughly examined. The conceptual model representing the natural background composition of  $V_{2vr}$  and its possible changes is given in Fig. 12.

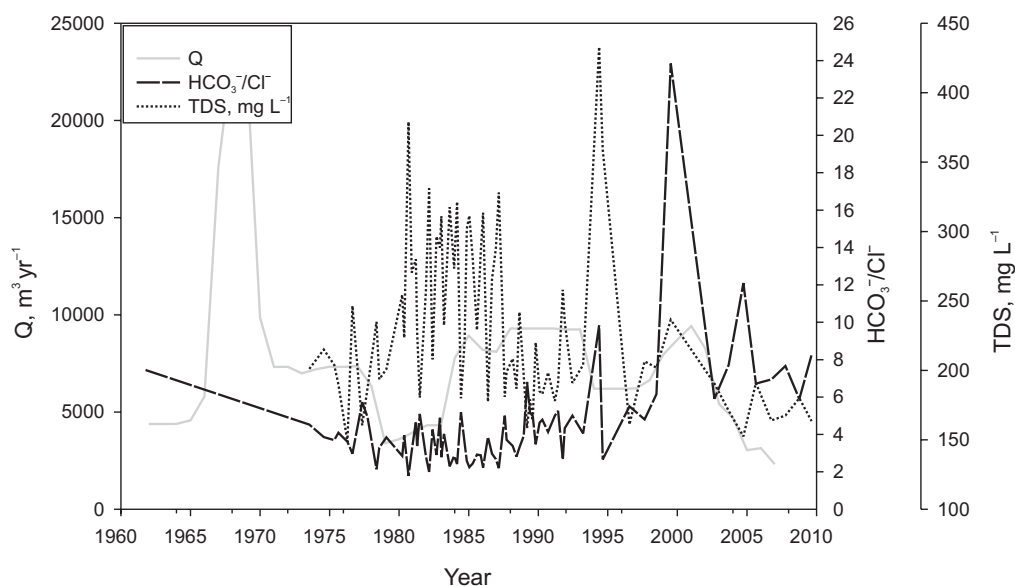


Fig. 10. Change in  $HCO_3^-/Cl^-$  values in well 2478.

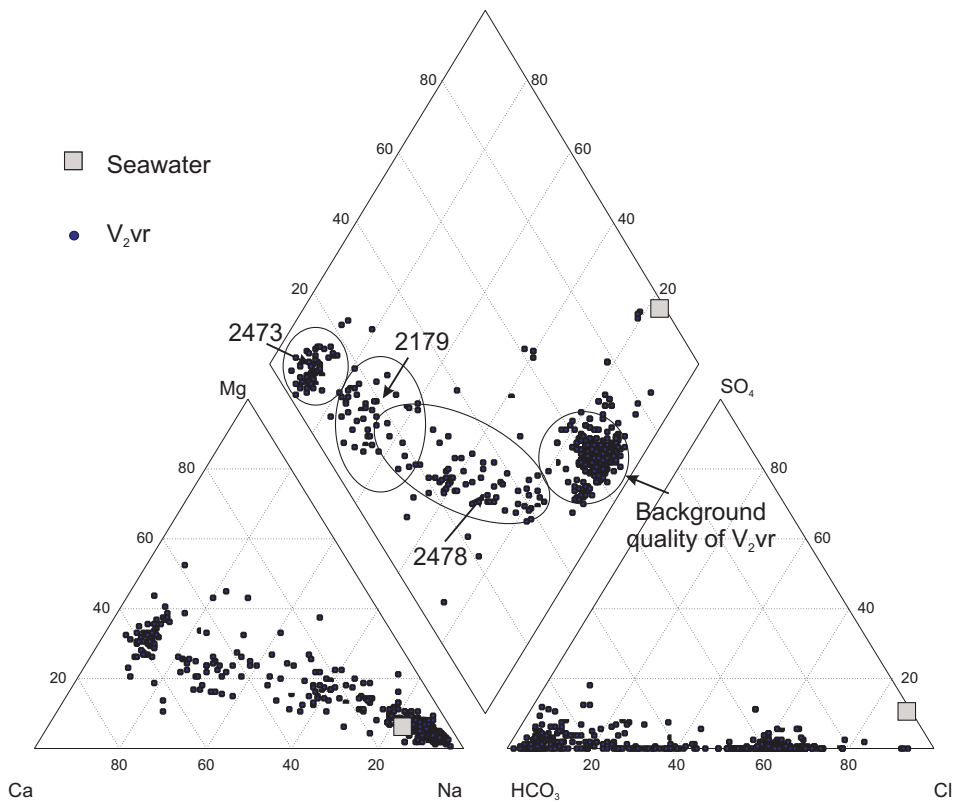


Fig. 11. Piper diagram showing the change in  $V_{2vr}$  groundwater chemistry caused by the leaking water from buried valleys.

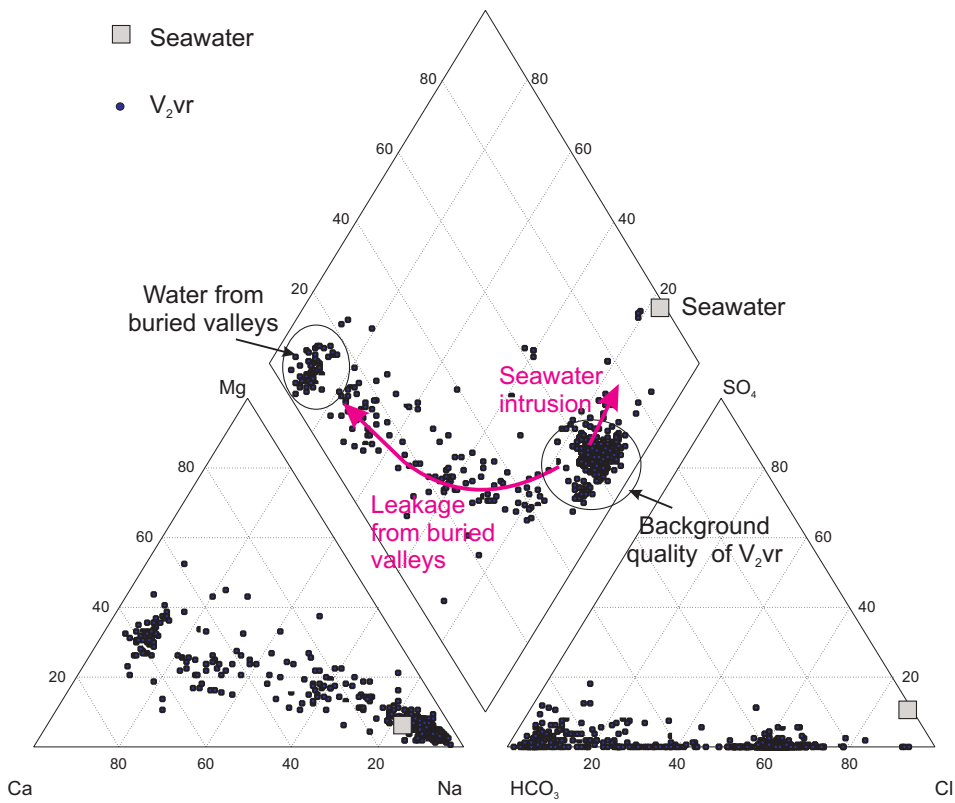


Fig. 12. Conceptual model of the formation of the chemical composition of the  $V_{2vr}$  groundwater body.

Isotopic composition gives additional information about governing processes. The glacial water has  $\delta^{18}\text{O}$  value from  $-18.4\text{‰}$  to  $-21.3\text{‰}$ , and the groundwater residence time measured by the  $^{14}\text{C}$  method is 22 000–23 000 years. Any change by seawater intrusion or leakage from buried valleys can be detected by isotopes. Radiocarbon and tritium are the isotopes which can be used with high confidence for detecting modern seawater intrusion.

Based on the above-said, the future monitoring of  $\text{V}_2\text{vr}$  must focus on changes in the natural composition of groundwater caused by abstraction. The Piper diagram and  $\text{HCO}_3^-/\text{Cl}^-$  value should be used to assess the changes in major chemistry in order to define any possible trends caused as a response to abstraction. In case of discovered trends detailed studies are required, whereas the complex of isotope methods, especially  $^{14}\text{C}$ ,  $^3\text{H}$ ,  $\text{D}$ ,  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ , can be used to detect the intrusion of seawater or water exchange from buried valleys.

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## Põhjavee kvaliteedil tuginev põhimõtteline mudel Voronka põhjaveekogumi seireks ja kasutuseks

Andres Marandi, Enn Karro, Valle Raidla ja Rein Vaikmäe

Hüdrogeoloogiline põhimõtteline mudel on lihtsustatud arusaam reaalses looduslikus süsteemis toimuvatest protsessidest. Selleks, et põhjavee varusid oskuslikult majandada, on vaja teada peamisi põhjavee kvaliteedi kujunemist mõjutavaid tegureid. Kirde-Eestis asuv Voronka põhjaveekogum on hea näide suure tarbimiskooormusega põhjaveekihi, mille keemilise koostise kujunemise tundmine toetab säästva ja jätkusuutliku põhjaveekasutuse planeerimist. Voronka põhjaveekogumi looduslik keemiline koostis formeerus viimase mandrijäätmise ajal, mil liustiku sulaveed tungisid suure rõhu tingimustes Kambriumi-Vendi põhjaveekompleksi moodustavatesse kivimitesse. Tänapäeval võivad Voronka põhjaveekogumi vee looduslikku keemilist koostist mõjutada kaks intensiivsest põhjaveekasutusest tingitud protsessi: 1) merevee sissetung põhjaveekogumisse ja 2) tänapäevase põhjavee lekkimine põhjaveekogumisse mattunud orgude piirkonnas. Veekasutuse mõju põhjaveekogumi ressurssidele on võimalik hinnata põhjaveeseire abil, mis tulevikus peaks keskenduma just põhjaveekogumi loodusliku koostise muutuste jälgimisele. Põhjaveekasutusest tingitud loodusliku põhjavee koostise muutust kirjeldab Voronka põhjaveekogumi puhul kõige paremini  $\text{HCO}_3^-/\text{Cl}^-$  väärtus, kusjuures selle väärtuse püsiv, statistiliselt oluline tõus markeerib veevahetust ürgorgude kaudu ja langus viitab võimalikule merevee sissetungile põhjaveekihti. Probleemsetes kohtades, kus trend on avastatud, on toimunud muutuste analüüsimiseks vajalik rakendada  $^{14}\text{C}$ ,  $^3\text{H}$ ,  $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$  ja  $\delta^{13}\text{C}$  isotoopide uuringuid põhjavees.