Groundwater natural background levels and threshold definition in the Cambrian-Vendian groundwater body (Estonia).

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SUMMARY
The Cambrian-Vendian groundwater body was selected for case study within WP4 of the BRIDGE project. Groundwater body plays an important role in drinking water supply of capital Tallinn and other settlements in northern Estonia. Water quality in this deep-seated confined groundwater body is influenced by the intrusion of present-day seawater and pumping-induced upward migration of deeper saline groundwater. The aim of this study is to evaluate the threshold values using the methodology worked out in WP3 and to compare the results with the values proposed by local authorities. A database containing 250 monitoring points was completed and used for the calculations of natural background levels (as the 90 and 97.7 percentile) in groundwater. The threshold values are calculated on the bases of natural background levels and reference values. In case of Cambrian-Vendian groundwater body the receptor is drinking water, thus limit values set by Estonian drinking water standard were used as reference values.

1. INTRODUCTION
The Cambrian-Vendian (Cm-V) aquifer system is the most important source of public water supply in northern Estonia. Within the aquifer system three groundwater bodies (GWB) are distinguished: Cambrian-Vendian, Cambrian-Vendian-Gdov and Cambrian-Vendian-Voronka GWB. Delineation of GWBs is based on the geological and hydrochemical characteristics. The Cambrian-Vendian GWB covers an extensive area in north-western Estonia and plays an important role in water supply of Estonian capital Tallinn and surrounding areas. As a coastal GWB with intensive groundwater abstraction, the possibility of saline seawater and deep-seated groundwater intrusion into GWB is an important issue.

2. CHARACTERISATION OF THE GROUNDWATER BODY
2.1 Physical and hydrogeological description
2.1.1 Geographical boundaries
The Cambrian-Vendian GWB is situated in north-western part of Estonian mainland (Fig 1). It covers an area of 9935 km² and belongs to the West-Estonian river basin district. The areal distribution of the Cambrian-Vendian GWB coincides with Harju river basin sub-district and partly with Matsalu and Pärnu river basin sub-districts. The maximum length of the GWB is 148 km (W-E) and the maximum width of the GWB is 80 km (N-S). GWB is deep-seated and confined, thus there is no possible interactions with dependent ecosystems (Maves 2005).

The topography of the study area is smooth, varying from 0 to 140 m a.s.l. Approximately 2500 km² of the area is covered by peat deposits and 350 km² is presented by alvars, where Paleozoic carbonate rocks crop out on the land surface. Most of the territory is covered by till, glaciolacustrine and glacifluvial deposits. The majority of the area (70%) is in natural state (forests, bogs), agricultural land occupies 20 % and urban/industrial activities 10 % of the study area.
2.1.2 Climate

The climate of the area is moderately cool and humid. Average annual precipitation ranges from 420-820 mm. The mean surface runoff from Estonia is 270 mm/y (Perens & Vallner 1997). Monthly distribution of precipitation and air temperature data in study area is well described by Tallinn meteorological station (Figs. 2 and 3).

Fig. 2. Monthly distribution of precipitation data in Tallinn monitoring station – mean of the period 1961-1990 and data measured in 2006 (Estonian Meteorological and Hydrological Institute).
2.1.3 Water balance

The Cambrian-Vendian aquifer system recharges in Southern Estonia from where it dips towards the discharge areas situated in the depressions of the Baltic Sea and the Gulf of Finland. The length of the deeper branches of the flow system can reach 250 km. In Central and Southern Estonia, the groundwater of the Cambrian-Vendian aquifer system is highly mineralised and can be used as mineral water. In Northern Estonia, fresh groundwater with TDS values below 1.0 g/l are typical. However, the most characteristic feature of these waters is the oxygen isotopic signature, which with δ¹⁸O values of c. -22 ‰ is the lightest composition known in Europe (Vaikmäe et al. 2001). The Cambrian-Vendian aquifer system in southern Estonia contains relict groundwater with TDS values up to 22 g/l. There are problems in determining the age of this groundwater and age estimations have to relay on the data obtained from a groundwater flow model. The model shows that the lateral water movement in this area is directed predominantly towards the north at a prevailing speed of 0.5–1.0 m/y (Vallner 2003). This indicates that the groundwater in this part of the Cambrian-Vendian aquifer may be very old, probably older than 100 ka.

2.1.4 Geology

Structure. Estonia is situated in the North-western part of the East-European Platform. Structurally, its sedimentary beds, lying on the Southern slope of the Baltic Shield, plunge southwards sloping about 3–4 metres per kilometre. The crystalline Paleoproterozoic basement is overlain by Vendian, Cambrian, Ordovician, Silurian and Devonian sedimentary rocks, which are covered by Quaternary deposits (Perens & Vallner 1997).

In Northern Estonia, the Vendian, Cambrian and Ordovician rocks are the only sedimentary rocks covering the crystalline basement, which lies approximately 150 m below the surface (Fig. 4). The crystalline basement mostly consists of gneisses and biotite gneisses (Koistinen et al. 1996) and its upper part (10-150 m thick) is fractured and weathered. Weathering profiles are predominantly composed of kaolinite, illite,
chlorite and montmorillonite, depending on the original bedrock composition and the intensity of weathering.

**Stratigraphy.** Weathered basement rocks are overlain by water-bearing Vendian and Cambrian silt- and sandstones (with interlayers of clay), which form the Cambrian-Vendian aquifer system. In the eastern part of Estonia, the Vendian sedimentary rocks are divided by a clay layer of the Kotlin Formation ($V^2_{kt}$) into the Voronka ($V^2_{vr}$) and the Gdov ($V^2_{gd}$) aquifers (Fig. 4). The terrigenous rocks of the Cambrian-Vendian aquifer system ($Cm–V$) occur all over Estonia, except for the Mõniste-Lokno uplift area in southern Estonia. The aquifer system is overlain by clays and siltstones of the Lükati-Lontova aquitard ($Cm_{lk-ln}$) (Fig. 4), which has a strong isolation capacity due to its low transversal conductivity of $10^{-7}$ to $10^{-5}$ m/d (Perens & Vallner 1997). However, in places the aquitard and the water-bearing bedrock formation have been penetrated by a relatively dense set of ancient buried valleys filled with loamy till and, in places, glaciofluvial gravel in lower parts of the valleys (Tavast 1997). The valleys are orientated north-west to south-east, approximately perpendicular to north-Estonian coastline.

![Fig. 4. Hydrogeological cross-section of the Cambrian-Vendian aquifer system in Northern Estonia](image)

2.1.5 **Hydrogeology**

2.1.5.1 **Delineation and type of groundwater body**

Groundwater bodies were identified primarily on the basis of hydrogeological characteristics, the amount of water abstraction and administrative and water management considerations.

Estonian groundwater bodies are listed in the Regulation of the Minister of the Environment No 47 of 10 May 2004 “Water classes of groundwater bodies, values of the quality indicators complying with the water classes of groundwater bodies and the procedure for defining water classes”.

Groundwater bodies were identified on the basis of the hydrogeological map prepared by the Geological Survey of Estonia (Tallinn 1998, GIS-map at a 1:400000 scale), the hydrogeological model of Estonia (Tallinn 2002, report text with figures), also the reports of geological and hydrogeological mapping of different areas of Estonia at a 1:50000 scale. The GIS-database of the bore wells cadastre in the Geological Survey of
Estonia by the end of the year 2001 and the existing reports of groundwater resources were used upon the identification of groundwater bodies. During the delineation process, it was agreed, that the eastern border of Cambrian-Vendian GWB is marked with the line, where the clays of Kotlin Formation pinch out and the southern border with the line of TDS approximate value of 1 g/l (Figs. 4 and 5).

Fig. 5. The equipotential lines, TDS content and contours of rock distributions of Cambrian-Vendian aquifer system. The equipotential lines are drawn after Perens & Vallner (1997). The Cambrian-Vendian GWB is situated in North-western part of the area (see Fig. 1).

2.1.5.2 Hydrodynamics

There is an obvious difference between the cross-sections of the Cambrian-Vendian aquifer system in Western Estonia compared to those in the east. In the eastern part, up to 53 m thick clays of the Kotlin Formation (V\textsubscript{kt}) divide the aquifer system into two aquifers (Fig. 4). The upper Voronka aquifer (V\textsubscript{vr}) consists of quartzose sandstone and siltstone with a thickness of up to 45 m in northeastern Estonia. The conductivity of the rocks ranges from 0.6 to 12.5 m/d with an average of 2 to 6 m/d. The transmissivity decreases from 100-150 m\textsuperscript{2}/d in Northern Estonia to 50 m\textsuperscript{2}/d (and less) in the south. Under natural conditions, the potentiometric levels along the coast of the Gulf of Finland are about 1.5-5.5 m a.s.l. The lower Gdov (V\textsubscript{gd}) aquifer is formed by an up to 68 m thick complex of mixed sandstone and siltstone. It directly overlies the Precambrian basement and is confined by the overlying clay of the Kotlin Formation. In northern Estonia, the conductivity of the water-bearing rocks is 0.5-9.2 m/d with an average of 5-6 m/d. Transmissivities in northeastern Estonia are in the range of 300-350 m\textsuperscript{2}/d and decrease in a southerly and westerly direction to 100 m\textsuperscript{2}/d and less. The potentiometric surface in the coastal area is about 3-5 m a.s.l. under natural conditions. Westward of the line where the Kotlin clays pinch out (Fig. 4), the Cambrian and
Vendian water bearing rocks form the Cambrian-Vendian aquifer. The Cambrian-Vendian aquifer system thins out towards south and west Estonia. In northern Estonia, however, its thickness amounts to 90 m and the aquifer system outcrops along the northern coast in the south of the Gulf of Finland. In northern Estonia, the aquifer system is mostly confined by 60-90 m thick clays of the Lontova Formation. However, as mentioned above, in places the aquitard is penetrated by ancient buried valleys. The Cambrian-Vendian aquifer system is underlain by Lower Proterozoic crystalline basement, whose cracks and fissures contain a small amount of water but is not exploited. The lower portion of the basement serves as an impermeable base layer for all the overlying aquifer systems (Vallner 1997).

The Cambrian-Vendian aquifer system belongs to the regional flow system, which recharges in Southern Estonia, in the Haanja and Otepää heights, where groundwater levels are 180-280 m a.s.l. In these locations, the head declines with depth, indicating the existence of downward groundwater flow. On reaching the completely impermeable portion of the crystalline basement, this flow is directed towards the discharge areas in the depressions of the Baltic Sea and the Gulf of Finland. The length of deeper branches of the regional flow system can reach 250 km. The Cambrian-Vendian aquifer system north of the recharge area belongs to the slow flow subzone according to the vertical zoning of the Estonian hydrogeological cross-section (Vallner 1997). The calculated velocities of deep groundwater movement in the Cambrian-Vendian aquifer system lie between $5 \times 10^{-4}$ and $5 \times 10^{-3}$ m/d. This indicates that during the last ~10 ka the deep groundwater could only have progressed several tens of kilometres and complete water exchange along flow branches would have not been possible. Therefore it appears that, under natural conditions, groundwater recharged during the last glaciation has been preserved in the Cambrian-Vendian aquifer system. This has been confirmed using isotopic tracers (Vaikmäe et al. 2001).

Consideration of the data collected during the BASELINE project and results from earlier studies lead to the convincing conclusion that the isotopically depleted groundwater in the Cambrian-Vendian aquifer of northern Estonia is of glacial origin (Vaikmäe et al. 2001). Results from radiocarbon dating and from noble gas analyses point toward the Fennoscandian ice sheet as a probable source for the groundwater in Estonia, heavily depleted by $^{18}$O. This ties well with the palaeoclimatic and palaeoenvironmental situation in the study area during the late Weichselian glaciation. However, so far there is no convincing answer to the question how and when the meltwater of the ice sheet reached the aquifer system. Earlier studies have indicated that meltwater recharge into the Cambrian-Vendian aquifer system occurred at about 11-12 ka BP, after the retreat of the continental ice from Estonia’s territory and during the formation of the Baltic Ice Lake (Yezhova et al. 1996). The low $^{14}$C concentrations (<5 pmc) suggest an age of the water of about 15-30 ka BP, which in turn implies, that the meltwater intrusion took place much earlier whilst the Estonian territory was still covered by ice.

2.1.5.3 Hydrogeochemistry

The Cambrian-Vendian aquifer system is situated in the passive water exchange zone where reducing conditions occur. The groundwater stored in those conditions is usually rich in trace elements. In the Cambrian-Vendian aquifer system east of Tallinn, for example, concentration of iodide reaches values between 120-280 mg/l.

Four major groundwater types can be distinguished in the diagram (Fig. 6) based on their chemical composition:
The first type is Na-Cl that can be interpreted as a "saline baseline" or relict groundwater of Cambrian-Vendian aquifer system. It may be very old and probably formed long before the last ice age. TDS concentrations in waters of this type are higher that 2 g/l, which means that they are mineral waters. In South-east Estonia, TDS concentrations in deeper part of the Cambrian-Vendian aquifer system even reach values up to 18 g/l. The $\delta^{18}$O values of this water type are higher than -14\%/oo. Relict groundwater of Na-Cl type is widely distributed in the Cambrian-Vendian aquifer system in southern and central Estonia, but are also spread in Voronka aquifer in North-east Estonia. It is also characterised by a very high Cl$^-$ content, ranging from 1083 to 10919 mg/l at. The Na$^+$ content in the groundwater is 684-5222 mg/l.

The second type is Ca-Na-HCO$_3$-Cl or Ca-Na-Cl-HCO$_3$ water. This is the “fresh baseline” water of glacial origin, recharged during the last glaciation (Vaikmäe et al. 2001). The chemical composition of this type of water is formed through the water-rock interaction during the last more than 10 ka. This water type has the largest spatial distribution, spreading from the northern coast to central Estonia, and also shows mixing with other water types (except with type 1) on the Piper diagram. The TDS concentrations vary from 300 mg/l to several g/l. Because of the lack of sampling wells in central Estonia, the exact border between the "saline baseline" waters and “fresh baseline” waters cannot be defined. This is also reflected in the Piper diagram, which shows mixture zones between the different water types, although mixing with type-1 water is not apparent. The relative proportions of HCO$_3^-$ and Cl$^-$ control the different chemical water types. Thus, some waters are classified as different water types even though the actual differences in their chemical concentrations are small.

The third, Na-Cl-HCO$_3$ groundwater type is interpreted as a mixture of glacial melt water with some remains of relict saline groundwater. This groundwater type is distributed predominately in the north-eastern part of Estonia, where the Kotlin clays divide the Cambrian-Vendian aquifer system into two aquifers and where the overlying clays reach their maximum thickness in Estonia. Therefore, intrusion of fresh melt water into the aquifer during the last glaciation was probably less in this area compared to the western part of north Estonia.

The fourth, Ca-HCO$_3$ groundwater type is found in northern Estonia, in areas around the ancient buried valleys, where intrusion of fresh groundwater from overlying aquifers and/or rainwater occur. The intensity of such fresh water intrusions varies spatially and temporally, depending on the extent of groundwater exploitation near the valleys. The intensive groundwater abstraction in the late 1970’s, for example, caused the development of extensive depression cones around Tallinn and Kohtla-Järve (Fig. 5) (Vallner 2003). In these areas, the groundwater drawdown of 25 and 35 m, respectively, resulted in intensive freshwater intrusions into the aquifer through the buried valleys and caused the changes in groundwater chemistry and its isotopic composition.
2.1.5.4 Groundwater receptors

The freshwater of Cambrian-Vendian aquifer system provides the main source of public water supply and the evolution of groundwater chemistry can be followed through many wells drilled within a distance of about 50 km south of the coast line. As a result of intensive groundwater abstraction, two extensive depression cones have formed in this area (Fig. 5) with centres around the capital city Tallinn and around Kohtla-Järve mining industry region in Northeast Estonia (Vallner 2003). Cambrian-Vendian GWB is deep-seated and confined, thus there is no possible interactions with dependent ecosystems (Maves 2005).
2.2 Identification of pressures

The Cambrian-Vendian GWB plays an important role in water supply of Estonian capital Tallinn and surrounding areas. As a coastal GWB with intensive groundwater abstraction, the possibility of saline seawater and deep-seated groundwater intrusion into GWB is an important issue. Deep-seated and well-protected confined groundwater body is not influenced by artificial recharge as well as diffuse and point source pollution. Pressures listed below are in accordance to Article 5 of the Water Framework Directive report, Estonia (Compliance 2005).

2.2.1 Groundwater abstraction

- Water abstraction for public water supply. Very important pressure especially to the Cambrian-Vendian GWB in the city of Tallinn and its vicinity.
- Water abstraction for industry. Less important pressure to the Cambrian-Vendian GWB in the city of Tallinn and its vicinity.
- Impact of seawater on groundwater (seawater intrusion). Important pressure to the Cambrian-Vendian GWB.
- Upconing of saline groundwater. Important in the Cambrian-Vendian GWB, where salty water can be found at places in the basement rocks forming the base of the GWB. In case of the absence of aquitard in the areas with intensive water abstraction the more saline water may endanger the present water quality of the GWB body, especially in the city of Tallinn and its vicinity.
2.3 Conceptual model

The most serious consequence of intensive groundwater use in North Estonia is the formation of regional depressions in potentiometric levels around Tallinn and Kohtla-Järve (NE Estonian industrial area). A basin-wide model simulation showed that overexploitation has caused the changes in the direction and velocity of groundwater flow (Vallner 2003). As a result, lateral and vertically rising groundwater flows support the transport of connate brackish water from the deeper parts of the aquifer system and from the underlying crystalline basement to the groundwater intakes and also promote seawater intrusion (Yezhova et al. 1996, Vallner & Savitskaja 1997, Mokrik 1997, Savitski 2001, Karro et al. 2004). The result is the deterioration in groundwater quality abstracted for drinking and industrial purposes. In order to follow the changes in water chemistry (salinisation, mixing), the best indicators are the values of EC and Cl concentration.

2.4 Existing natural background levels

Extensive data set collected during the last about 55 years exists in the Geological Survey of Estonia (GSE), which contains more than 1500 analyses from 967 wells for Cambrian-Vendian aquifer system. The database contains the information of main compounds of groundwater chemistry: pH, TDS, Na⁺, K⁺, Na+K, NH₄⁺, Ca²⁺, Mg²⁺, Fe²⁺, Fe³⁺, Fe tot, Cl⁻, SO₄²⁻, NO₂⁻, NO₃⁻, CO₃²⁻, HCO₃⁻, SiO₂, hardness (Perens et al. 2001). Data are also available from a number of unpublished (mainly various reports of GSE) and published (Mokrik & Vaikmäe 1988, Mokrik 1997, Perens & Vallner 1997, Savitskaja 1999, Vaikmäe et al. 2001, Karro et al. 2004) investigations. The results of
these studies provided extensive information on the hydrogeology, geochemistry and lithology of the aquifer system.

In order to avoid poor quality data, all samples collected earlier than 1988 were neglected for natural background level estimations. If more than one analyses for sampling point was available an average values for the sampling points was calculated. Consequently a database, containing 250 monitoring points, was completed for the calculations of Cm-V GWB natural background levels.

Calculation of average value was used in order to get natural background values. The results of calculations are given in Table 1.

Table 1. Natural background values for Cambrian-Vendian GWB calculated as average values

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<th>Component</th>
<th>Unit</th>
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<th>Average</th>
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2.5 Review of impacts

Human action that results in saline groundwater entering the fresh water aquifer is termed saline water encroachment. 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 (Fig. 9). Coastal groundwater aquifers are particularly threatened by salt-water intrusion from both sources (Custodio 2002).
Fresh groundwaters of the Na-Ca-HCO$_3$-Cl type characterise the upper part of the Cambrian-Vendian aquifer system in North-Estonia (Perens et al. 2001) owing to the hydrochemical differentiation and to stratification due to density differences of water types. The lower part of the Cambrian-Vendian aquifer system and the weathered crystalline basement are characterised by groundwaters of Na-Ca-Cl-HCO$_3$ and Ca-Na-Cl types with TDS content of 1.4 to 5.0 g/l. The long-term pumping has induced the upward movement of salty deep-seated groundwater into wells. A relatively fast 1.5 to 3.0-fold increase in TDS and in concentrations of major ions in abstracted groundwater is the consequence of heavy pumping. The aquifer is not in hydraulic continuity with seawater and on the Kopli Peninsula in Tallinn the simple upconing of saltwater-freshwater interface does not take place (Karro et al. 2004).

![Diagram](image)

Fig. 9. Salt-water upconing beneath a well. a – saltwater-freshwater transition zone in an idealised coastal aquifer. b - upconing of saline groundwater caused by well pumping from an overlying fresh-water zone in Tallinn, Estonia.

The excessive pumping of the fresh water aquifer may result in the development of depressions of potentiometric levels and in deterioration in the groundwater quality through overall salinisation of abstracted water as well as introduction of potentially toxic chemical elements. A barium anomaly with maximum Ba$^{2+}$ concentration of 6.37 mg/l was distinguished in Cambrian-Vendian aquifer system that is widely used as drinking water source in North-Estonia. The probable natural sources of the anomaly are the crystalline basement and its weathering zone. Groundwater in the clayey weathering core is hydraulically connected with overlying Cambrian-Vendian aquifer system, thus the upconing of deeper-seated groundwater, caused by intensive exploitation of wells, is possible (Marandi et al. 2004).

2.5.1 **Monitoring networks (groundwater)**

Groundwater monitoring in Estonia is divided into 3 special programs:

1) basic monitoring
2) monitoring of agricultural areas (Pandivere Upland)
3) monitoring of industrial areas in NE Estonia.

1) Basic monitoring is divided between 7 monitoring districts, each of them having different hydrogeological conditions and human impact intensity (water abstraction,
industries, agriculture etc). Basic monitoring covers whole Estonian territory and all aquifers – 80 investigation sites with 340 wells. Monitoring districts are separated as follows:

- natural conditions: VII, VI (islands), II (Pandivere)
- intensive groundwater abstraction: I (Tallinn), III (NE Estonia: Sillamäe and Kohtla-Järve), V (Pärnu), IV (Tartu)
- dewatering of mines and quarries, industrial activities – impact to groundwater: III (NE Viru).

Within the basic state monitoring program 48 wells from Cambrian-Vendian aquifer system are monitored.

The groundwater level has been measured in 306 wells with a frequency of 3-5 times a month in uppermost aquifers and once a month in deeper aquifers. In 18 wells the water level was measured episodically. The chemical analyses were performed from 22 wells twice a year (upper aquifers with an intensive or good water-recharge, samples were taken in spring with a high water level and in summer during the dry period) and 48 deeper wells once a year (slow groundwater movement and stable chemical composition). Estonian groundwater monitoring is ongoing already since 1950s, for most aquifers we have observation period of 20-30 years. Therefore the chemical composition of the groundwater is quite well studied, however not all micro-components are investigated in groundwater. In state monitoring the following chemical parameters are covered: pH, TDS, Na\(^+\), K\(^+\), Na+K, NH\(_4\)+, Ca\(^{2+}\), Mg\(^{2+}\), Fe\(^{2+}\), Fe\(^{3+}\), Fe\(_{tot}\), Cl\(^-\), SO\(_4^{2-}\), NO\(_2^-\), NO\(_3^-\), CO\(_3^{2-}\), HCO\(_3^-\), SiO\(_2\) and hardness. However, in some cases the shortened list of problematic parameters (like NH\(_4\)+, NO\(_2^-\), NO\(_3^-\), Cl\(^-\), Fe\(^{2+}\), Fe\(^{3+}\), Fe\(_{tot}\)) has been analysed.

2) Agricultural areas monitoring – Pandivere Upland
The special groundwater monitoring is ongoing on Pandivere Upland since 1992 and the main task is to check the impact of agricultural activities to uppermost aquifer (Silurian-Ordovician in that region). In 2000 there was 36 investigation sites (14 springs, 6 karstic points, 16 wells). The frequency of sampling was 4 times per year from 36 sampling sites and 160 additional samples were taken from high-risk areas. Measured parameters include Cl\(^-\), NH\(_4\)+, NO\(_3^-\), and SO\(_4^{2-}\).

3) Industrial areas in NE Estonia
The monitoring network covers the high-risk industrial area of semi-coke ash hills in Kohtla-Järve region. There were 13 monitoring wells in 1999 network, the monitoring frequency was 4 times a year. Concentrations of total oil products, aromatic hydrocarbons (benzene, toluene, xylene), As and phenols were measured in uppermost aquifers (Ordovician and Cambrian-Ordovician).

As proposed in study conducted by Maves in 2005, groundwater quality of Cm-V GWB will be monitored in 80 stations in future (Fig. 10).
2.5.2 Effects of abstraction on groundwater quantity

Intensive groundwater extraction has led to the formation of two extensive depressions of potentiometric level (Fig. 5) and to the increase of water exchange.

2.5.3 Effects of abstraction on groundwater quality

The most serious consequence of intensive groundwater use in North Estonia is the formation of regional depressions in potentiometric levels around Tallinn and Kohtla-Järve (industrial area in NE Estonia). A basin-wide model simulation showed that overexploitation has caused the changes in the direction and velocity of groundwater flow (Vallner 2003). As a result, lateral and vertically rising groundwater flows support the transport of connate brackish water from the deeper parts of the aquifer system and from the underlying crystalline basement to the groundwater intakes and also promote seawater intrusion (Yezhova et al. 1996, Vallner & Savitskaja 1997, Mokrik 1997, Savitski 2001).

A case study was conducted at Kopli Peninsula in Tallinn in order to assess the possible causes for the increase in TDS contents in groundwater of Cambrian-Vendian aquifer (Karro et al. 2004). Groundwater production wells trapping the Cambrian-Vendian aquifer system at Kopli Peninsula are situated close to the sea. The production wells in the water supply plants have depths between 107-40 m and cut, more or less, through the full thickness of the aquifer system. For comparison, a groundwater monitoring well penetrating into the fractured basement and two wells opening Lontova aquitard were included into the study.
Groundwater abstraction varied between years, ranging from 10-1300 m$^3$/d during 1978-2002 and in 1992 has resulted in a drop of the potentiometric surface of the Cambrian-Vendian aquifer system by 17 m at Kopli Peninsula. At about the same time, groundwater extraction decreased due to declining industrial and agricultural production on the one hand and more sustainable groundwater use on the other hand. As a direct result, the potentiometric surface level of the aquifer system has steadily risen during the last 10 years and is now at -4.0 m a.s.l. (Savitski 2001).

Fresh groundwaters of Na-Ca-HCO$_3$-Cl type are characteristic in the upper part of the Cambrian-Vendian aquifer complex in Tallinn region (Perens et al. 2001). In the deeper part of the aquifer system and in the crust of the weathering crystalline basement, groundwaters of Na-Ca-Cl-HCO$_3$ and Ca-Na-Cl type and with TDS content of 1.4- 5.0 g/l are common. In the upper part (-50 m a.s.l.) of the aquifer system, the groundwater has chlorine contents of 100 mg/l, which increase with depths to 350 and 2500 mg/l at 100 and 130 m, respectively (Savitski 2001, Boldøreva et al. 2002).

The large-scale variations in TDS (0.5-4.6 g/l) and major ion concentrations in the water of production wells are evident from data collected during 1978-2002. The maximum values (water chemistry during 1994-1996) clearly exceeded the permissible concentrations in major components as set by the Estonian Drinking Water Standard (2001) and by the Drinking Water Directive of the EU (Directive 1998). In subsequent years the TDS content in the groundwater slightly decreased. The most distinct temporal changes in water chemistry occurred in well 613 (Fig. 11), where the TDS content reached concentrations of up to 1.5 g/l increasing by a rate of 50 mg/l per year.

![Fig. 11. Temporal changes of TDS in the Cambrian-Vendian aquifer on Kopli Peninsula, Tallinn (abstraction well no 613). In the other wells of the Kopli Peninsula, a less dramatic increase in TDS was observed.](image)

Major cations and anions constitute the bulk of the mineral matter contributing to the TDS. Consequently, most major ions (Na, K, Ca, Mg, SO$_4$, Cl) display the same trends as TDS with the exception of HCO$_3$. In comparison to other major ions, HCO$_3$ shows
the smallest concentration range, and these relatively stable HCO$_3$ concentration explain why, at high TDS values, bicarbonate remains insignificant in determination the groundwater chemical type. When TDS exceeds 0.9 g/l, Cl type waters dominate. The Cambrian-Vendian aquifer system at Kopli Peninsula is confined by Lontova aquitard (k=10$^{-7}...10^5$ m/d), which protects the aquifer from infiltrating modern water. Thus, anthropogenic sources are unlikely to have any impact on the groundwater chemistry. Considering the hydrogeological situation in the study area, there are three major processes which can be responsible for the increase in TDS values: (1) intrusion of present-day seawater, (2) pumping-induced upwards migration of deeper salt water from areas below the freshwater and (3) a combination of these two processes.

2.5.4 Pollutants selected for threshold methodology evaluation

The overexploitation of groundwater resources has caused the changes in groundwater flow and the transport of saline water from the deeper parts of the aquifer system and also promotes seawater intrusion. The pollutants, which well describe the salinisation process in Cambrian-Vendian GWB are predominately the values of EC and Cl concentration.

3. GROUNDWATER STATUS EVALUATION BY THRESHOLD VALUES

3.1 Application and evaluation of proposed threshold methodology

The Regulation of the Minister of the Environment No 47 of 10 May 2004 “Water classes of groundwater bodies, values of the quality indicators complying with the water classes of groundwater bodies and the procedure for defining water classes” sets the criteria for the assessment of the threat to groundwater bodies due to pressures. All the pressures, which alone or together may change the groundwater status into a poor water class pursuant to the criteria of the above-mentioned Regulation, have been considered as significant. The possibility of the potential impact of pressures on more than 10% of the area of a groundwater body was used as an additional criterion upon the assessment of the significance of pressures. Pursuant to that regulation the water classes expressing the qualitative and quantitative status of a groundwater body are:

- good – natural water and close to natural water;
- poor – water polluted or polluted strongly as a result of human activity.

Quality indicators of the good water class:

- human activity or saltwater intrusion has not caused the elevation of the concentration of solutes (as measured by conductivity);
- human activity or saltwater intrusion has not caused elevated of chloride ion content;
- nitrate ion content does not exceed 50 mg/l and the elevation tendency of the content of nitrates does not cause significant deterioration of the ecosystems dependent on groundwater;
- ammonium ion content in naturally aerobic groundwater does not exceed 0.5 mg/l or in naturally anaerobic aquatic environment does not exceed 1.5 mg/l or if, in case of exceeding the value of the quality indicator the natural origin of ammonium ion in groundwater has been proved;
- the content of plant protection products does not exceed 0.1 µg/l;
• pH is between 6–9;
• dissolved oxygen content does not indicate decreasing tendency caused by human activity or the oxidizability of water is \( \leq 5 \text{ mg/l } \text{O}_2 \);
• there are no hazardous substances to the aquatic environment or their content does not exceed the limit values of hazardous substances to the aquatic environment established by the Regulation of the Minister of the Environment No 12 of 2 April 2004 “Maximum Limits for Hazardous Substances in Soil and Groundwater” (RTL 2004, 40, 662) or, if in case of the occurrence of the hazardous substances to the aquatic environment mentioned in this Regulation the natural origin of these substances has been proved.

Several previous studies have shown low level concentrations of hazardous elements in Cambrian-Vendian groundwater, because it’s deep confined aquifer protected from pollution by two aquitards in one hand and water bearing rocks have low level content of hazardous elements on the other hand. The most important pressure for Cm-V groundwater body is water abstraction and the changes caused by that. Therefore EC, and the content of Cl-ions are the most important monitoring elements for Cm-V groundwater body. Nevertheless, some micro compounds were also used in TV calculations, in order to test the methodology.

A data set from Ministry of Environment was used for TV calculations. The data of natural background levels was collected during the study of Estonian groundwater bodies (Maves 2005). Reference values for substances were obtained from decrees of Ministers of Social affairs and Environment.

• Regulation of the Minister of Social Affairs of 02.01.2003 no 1 “Quality and control requirements for surface and ground water intended for the water supply”
• Regulation of the Minister of Social Affairs of 31.07.2001 no 82 “Quality and control requirements for potable water and methods for analyses”.
• Regulation of the Minister of the Environment No 47 of 10 May 2004 “Water classes of groundwater bodies, values of the quality indicators complying with the water classes of groundwater bodies and the procedure for defining water classes”
• Regulation of the Minister of the Environment No 12 of 2 April 2004 “Maximum Limits for Hazardous Substances in Soil and Groundwater”

For TV calculations, a WP3 methodology was used and TV-s for three different cases for two different NBL’s (percentiles 90 and 97.7) were found. Three cases for TV value calculations are:

**Case 1:** If NBL<REF, then TV=(REF+NBL)/2
**Case 2:** If NBL<1/3*REF, then TV=2*NBL
**Case 3:** If NBL>REF, then TV=NBL

The results of TV calculations according to natural background levels and reference values are given in Table 2.
Table 2. Natural background levels, reference values and threshold values calculation methods for Cambrian-Vendian groundwater body, Estonia.

<table>
<thead>
<tr>
<th>Substance</th>
<th>NBL</th>
<th>Unit</th>
<th>REF</th>
<th>n</th>
<th>NBL</th>
<th>TV1</th>
<th>TV2</th>
<th>TV3</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
<td>97.7</td>
<td>µS/cm</td>
<td>2500</td>
<td>49</td>
<td>1486</td>
<td>1993</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl⁻</td>
<td>97.7</td>
<td>mg/l</td>
<td>250</td>
<td>228</td>
<td>397</td>
<td>397</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>97.7</td>
<td>mg/l</td>
<td>250</td>
<td>216</td>
<td>42.3</td>
<td>84.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba²⁺</td>
<td>97.7</td>
<td>mg/l</td>
<td>0.7</td>
<td>65</td>
<td>3.1</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>97.7</td>
<td>mg/l</td>
<td>0.01</td>
<td>100</td>
<td>0.015</td>
<td>0.015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hg</td>
<td>97.7</td>
<td>mg/l</td>
<td>0.0004</td>
<td>44</td>
<td>0.0005</td>
<td>0.0005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>97.7</td>
<td>mg/l</td>
<td>1.5</td>
<td>219</td>
<td>1.30</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td>97.7</td>
<td>mg/l</td>
<td>0.001</td>
<td>73</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>As¹</td>
<td>97.7</td>
<td>mg/l</td>
<td>0.005</td>
<td>66</td>
<td>0.01</td>
<td>0.008</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A data from proposed monitoring network of Cambrian-Vendian groundwater body was assessed for calculated threshold values. The results from 80 monitoring wells are given in Table 3.

Table 3. Calculated threshold values and statistics of 80 monitoring wells of Cambrian-Vendian groundwater body.

<table>
<thead>
<tr>
<th>Cl⁻</th>
<th>SO₄²⁻</th>
<th>NH₄⁺</th>
<th>EC</th>
<th>As</th>
<th>Ba</th>
<th>Hg</th>
<th>Cd</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of monitoring wells*</td>
<td>80</td>
<td>75</td>
<td>80</td>
<td>20</td>
<td>47</td>
<td>26</td>
<td>42</td>
<td>52</td>
</tr>
<tr>
<td>Min</td>
<td>7.2</td>
<td>1.3</td>
<td>0.05</td>
<td>181</td>
<td>0.0006</td>
<td>0.07</td>
<td>0.0003</td>
<td>0.0001</td>
</tr>
<tr>
<td>Max</td>
<td>530.7</td>
<td>49.1</td>
<td>1.80</td>
<td>1086</td>
<td>0.0160</td>
<td>0.65</td>
<td>0.00050</td>
<td>0.0033</td>
</tr>
<tr>
<td>Aver</td>
<td>169.3</td>
<td>15.8</td>
<td>0.41</td>
<td>629</td>
<td>0.0025</td>
<td>0.24</td>
<td>0.00020</td>
<td>0.0004</td>
</tr>
<tr>
<td>TV 97.7</td>
<td>397.0</td>
<td>84.6</td>
<td>1.4</td>
<td>1993</td>
<td>0.0008</td>
<td>3.1</td>
<td>0.0005</td>
<td>0.001</td>
</tr>
<tr>
<td>Wells above TV</td>
<td>8</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>TV90,0</td>
<td>287.0</td>
<td>67.6</td>
<td>1.2</td>
<td>1831</td>
<td>0.0005</td>
<td>2.4</td>
<td>0.0005</td>
<td>0.0008</td>
</tr>
<tr>
<td>Above TV</td>
<td>14</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>% above TV</td>
<td>10</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>% above TV</td>
<td>17</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>TV – s proposed by Maves</td>
<td>250</td>
<td>50</td>
<td>0.5</td>
<td>1800</td>
<td>0.008</td>
<td>-</td>
<td>0.0008</td>
<td>0.003</td>
</tr>
<tr>
<td>Wells above TV</td>
<td>14</td>
<td>0</td>
<td>23</td>
<td>0</td>
<td>2</td>
<td>-</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>% above TV</td>
<td>17</td>
<td>0</td>
<td>28</td>
<td>0</td>
<td>3</td>
<td>-</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

* - No of monitoring wells indicates the number of wells where the data is available from previous investigations (max 80 wells)

The content of Cl-ion is the only component that could change the groundwater body into bad status. According to Estonian regulations, less than 10 % of monitoring points
can be above TV. If natural background levels would have been calculated according to 80 monitoring wells, then 97.7 percentile was 453 mg/l and 90 percentile was 372 mg/l. In this case, the percentage of wells with TV values above limit would have been respectively 2.5% and 10%.

The TV-s proposed by Maves (Maves 2005) are more or less in the same scale as calculated by BRIDGE methodology. Cl-ion and ammonium are the only components that differ significantly. As the values proposed by Maves are lower, then there are more wells that are above TV-s. Ammonium ion causes additional values above TV, although previous investigations have shown that higher content of ammonium ion is natural in anaerobic conditions in Cm-V GWB.

4. CONCLUSIONS

The Cambrian-Vendian GWB plays an important role in water supply of Estonian capital Tallinn and surrounding areas. As a coastal GWB with intensive groundwater abstraction, the possibility of saline seawater and deep-seated groundwater intrusion into GWB is an important issue. Deep-seated and well-protected confined groundwater body is not influenced by artificial recharge as well as diffuse and point source pollution.

Natural background levels and threshold values were calculated for Cm-V GWB during the BRIDGE project in Estonia. An official database from Ministry of Environment, which was compiled during the previous study, where all historical data of groundwater bodies was collected and prepared for GWB characterisation (Maves 2005) was used as a base for BRIDGE calculations. Consequently, data from 250 measuring points was used for BRIDGE calculations.

Several previous studies have shown low level concentrations of hazardous elements in Cambrian-Vendian groundwater, because it’s deep confined aquifer protected from pollution by two aquitards in one hand, and water bearing rocks have low content of hazardous elements on the other hand. The most important pressure for Cm-V groundwater body is water abstraction and the changes caused by that. Therefore EC and the content of Cl-ions are the most important monitoring elements for Cm-V groundwater body. Nevertheless, some micro compounds were also used in TV calculations, in order to test the methodology.

Bridge methodology worked well for most of components, and the monitoring results were lower than calculated TV-s. The content of Cl-ion is the only component that could change the groundwater body into bad status because 18 % of monitoring stations had average Cl- concentration higher than TV. According to Estonian regulations, less than 10 % of monitoring points can be above TV.

Natural background values and threshold values calculated in BRIDGE project were compared to the ones proposed by Maves (2005). BRIDGE values were less strict in most cases.
5. REFERENCES


Joogivee kvaliteedi-ja kontrollinõuded ning analüüsimetodid (2001) (The quality and monitoring requirements for drinking water and methods of analysis) SOMm RTL 2001/100/1369.


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Regulation of the Minister of Social Affairs of 02.01.2003 no 1 “Quality and control requirements for surface and ground water intended for the water supply”.

Regulation of the Minister of the Environment No 12 of 2 April 2004 “Maximum Limits for Hazardous Substances in Soil and Groundwater”.

Regulation of the Minister of the Environment No 47 of 10 May 2004 “Water classes of groundwater bodies, values of the quality indicators complying with the water classes of groundwater bodies and the procedure for defining water classes”.


