TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Civil Engineering and Architecture

Pre-estimating the groundwater level changes in Estonia underground oil shale mine after closure

Eel-prognoositav põhjaveetaseme muutus Estonia kaevanduses peale mäetööde lõppemist

MASTER THESIS

EA70LT

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Tallinn 2017

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material.
All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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TASK FOR FINAL THESIS

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Initial data:

- Relevant studies about mines and mine waters
- Estonia Environmental Board and Environmental Agency
- Estonia Nature Database
- Estonia mine's database

Content of thesis:

- Overview of the Estonia underground mine
- Overview of the hydrogeological situation in the area
- Assessing mining impact to the aquatic environment
- Pre-estimating the groundwater level changes after the mining operations end
- Results and conclusions

Explanatory letter:

Summary in English:

This Thesis is based on the examination of the Estonia mine's hydrogeological condition and pre-estimating the groundwater level change. The Thesis will analyze Estonia mine's hydrogeological conditions and the impact of mining on ground water. The aim is to pre-estimate the ground-water changes after the closure of the mine. For better estimation, the data about the pre-mining situation is used. This Thesis also provides examples of mitigation measures used in Ahtme mine and the results. With high probability, after closure, the water will start to overflow the mining area and causes floodings, therefore is prognosed the water movement in time and water level changes, but also suggested locations for possible over-flow boreholes, to prevent the floodings.

Resümee eesti keeles:

Töö põhineb Estonia Kaevanduse hüdro-geoloogiliste tingimuste hindamisel ning põhjaveetaseme muutuse eel-prognoosimisel. Töö käigus uuritakse Eestis Ida-Virumaal asuva Estonia Kaevanduse hüdro-geoloogilisi tingimusi ning kaevanduse mõju põhjaveele. Töö eesmärk on eel-prognoosida põhjavee muutusi peale kaevanduse sulgemist ning selleks on kasutatud kaevanduse-eelseid andmeid ning toodud ka näiteid Ahtme kaevanduse sulgemisel kasutusele võetud leevendusmeetmetest ja tulemustest. Kuna suure tõenäosusega Estonia kaevanduskäikudest väljub vesi maa peale ja kohati tekib üleujutusoht, on prognoositud vee liikumise ajalist dünaamikat ning tasemeid ja üleujutuste

ennetamiseks on töös tehtud ettepanekud võimalike ülevoolu-puurkaevude asukohtade valikuks.

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Contents

1. Introduction

1.1 Background

In many places around the world more and more ore, coal or oil shale mines are being or already are closed. Once, Europe was one of the most important mining regions in the world and a lot of European countries still have remnants of mining sites (Norway, Sweden, Finland, Germany, Poland, France, etc). Estonia is having many active oil shale mines and oil shale is the country’s most important energy source at the moment. Many new regulations, climate conventions but also mineral resources depletion are the reasons why even Estonia is starting to close mines gradually.

Closed underground mines may cause risks for the environment. Some of the risks are related to the shutdown of the mine water pumping operations that leads to water level rise.

These concern:

1. Pollution of surface and/or groundwater by sulphates and other chemical components;
2. Flooding of zones subsided below the water table level;
3. Additional surface movements in relation to collapse of shallow mine workings.

After closing the mine these risks exist during a short, long or a very long period of time. The period depends on the quantity of the inflow water and the volume of the mine workings (Erg, 2005).

The hydrogeology of underground workings and closed mines has been studied a lot by L, Savitski and V, Savva, but also by K, Erg. Many researchers and companies have also described local environmental impacts, caused by oil shale mining.

1.2 Problem description

Groundwater is essential part of the water cycle. When the rainwater or melted snow percolates through the soil and rocks, it fills the pores, cracks and other gaps underground. Some layers underground that are called aquifers are water-bearing, and the ground water is stored in there. Groundwater level is variable according to the season and weather changes. For example, droughts and rain-free periods, but also pumping out the water from wells cause altogether short decrease in the water level. However, pumping out the water from mines, cause a remarkable long-term change in the water elevation.

The main problem is, that mines have a long working period, sometimes even more than 40 years and the locals have forgotten the pre-mining situation, when the soil above mines were moist and peatlands covered some areas. When the oil shale extraction started, the water was drained away from natural water courses. This, in turn, dried up the land and people started building houses, fields and factories to these areas. Later, when mines were closed, the water filled up the underground passages and started to inundate the houses that were built on the dried up lands. In order to improve the situation, several boreholes were established to direct the redundant ground-water from mine to the closest rivers or ditches. In spring times, the melted snow-water and higher precipitations result in excess water in mines and this causes the pressurized water to spurt out from the boreholes and these are called also ‘witch wells’. These kinds of boreholes have been built on Ahtme, Käva, Kohtla and Kiviõli mines. In Jõhvi, after closing the Mine № 2, the flooding was improved by water collector (Sokman, 2014). After closing the mines, the ground water’s regime and quality starts to change drastically and it may last up to 10-15 years. After-effects will take a long time, as the geotechnological processes abate slowly (Kaširova, 2003).

Therefore, underground mining activities can have a big impact on the aquatic environment, when mines are opened or closed.

1.3 Aim of the Thesis

The aim of the thesis is to give an overview of Estonia mine's hydrogeological situation in 2017 and to pre-estimate the ground water changes in Estonia oil shale mine, after it will presumably be closed in 2032. In this study was used data from Jõhvi weather station, Estonia Land Board Geoportal and a lot of material is from Estonia mine's inside information, collected and observed through the years by the geologists, mining surveyors and environmental specialists.

As the oil shale region in Estonia is quite small, their hydrogeological conditions are also alike. Therefore, examples of other mines are important for better estimation.

Finally, one of the purposes is to suggest possible solutions to prevent or alleviate problems relating to flooding on the areas above underground mines.

1.4 Interested parties

As the Estonia mine's area is quite large, the groundwater level changes after the mine's closure, affect many people. The parties, who are interested about ground water changes on the first hand are the residents of Mäetaguse, Illuka and Iisaku, especially those, who live or are the land owners above the mining field or nearby areas. From the authorities are interested Mäetaguse, Illuka and Iisaku rural municipality councils, Ministry of Environment, Environmental Board, Technical Regulatory Authority, Estonian Green Movement, etc.

2. Theoretical background

2.1 Estonia underground mine

Estonia underground mine is located in the north-east of Estonia, in the middle of the Ida-Viru County and is situated 20 km south from Jõhvi town (Figure 1). The studied area covers the territory of Illuka, Mäetaguse and Iisaku parish and the industrial territory is mainly in Väike-Pungerja village. Above Estonia underground mine, in north-west, are many already closed oil shale mines - Sompa, Kiviõli, Kohtla-Nõmme and Aidu Quarry, but also the newest mine in Estonia at the moment – Ojamaa underground mine, which belongs to VKG (Viru Keemia Grupp). In the north direction are Viru and Ahtme old oil shale mines and north-east are Sirgala and Narva quarry, which are now united to one and carries the name Narva quarry. From all these oil shale mines and quarries (except Ojamaa), only Narva quarry is active at the moment and also belongs to Eesti Energia.

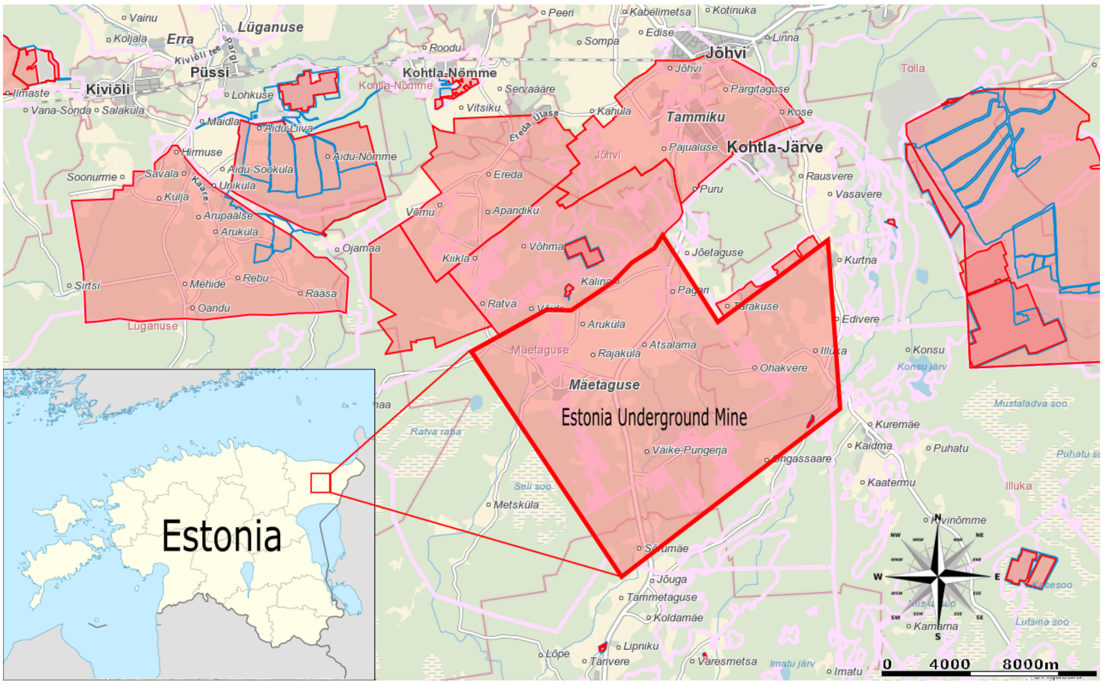

Figure 1. Estonia mine location in Ida-Viru County, Estonia. (Estonia Land Board, 2017)

Estonia mine's mining permit boundaries also extend under the Selisoo mire, Muraka bog and also some smaller protected areas. Mining in the region has had its effect to them since the 1970s. However, before mining in the sensitive area, safety actions and environmental projects are developed, basing on special studies, which all must make mining in those areas safer to the nature (Hendrikson & Ko, 2017).

2.2 Study area

Estonia underground oil shale mine belongs to Eesti Energia's subsidiary Enefit Kaevandused AS. Construction of the mine started in 1964 and it lasted for 8 year. While it was built, it carried the name – 9th Mine, by the time of establishment, it got its final name – Estonia mine and it started operating on 28.12.1972 (Hendrikson & Ko, 2017). At the moment it is the world's biggest active oil shale underground mine (Postimees, 2017).

Estonia mine is one of the most important producers of energy carriers in Estonia. The mining claim area is 141.6 $km^{2,}$ which is comparable with the capital Tallinn (159.31km^2) and the service land area is 7.2 km^2 (Hendrikson & Ko, 2017). The highest population density, above the mining area is the center of Mäetaguse parish – Mäetaguse borough. In Mäetaguse parish lives 1760 individuals, which makes 6.1 people per km^2 (Mäetaguse vald, 2016). Other settlements, above the mining claims, are Väike-Pungerja, Ohakvere, Illuka, Kurtna and some more small villages.

On the territory flows the river Rannapungerja and Raudi channel, which are used to divert the mine water. Their catchment areas are 594.6 km^2 and 72 km^2 respectively (EELIS, 2017). Rannapungerja flows to lake Peipsi and its length is 63 km. The river Rannapungerja has few tributaries (Milloja and Jõuga main ditches) that are used for mine water collection, as well. The length of Raudi channel is 24 km and it flows through different lakes until it reaches lake Peen-Kirjakjärv, which is a stagnant water-body (EELIS, 2016).

Most of the land in the Estonia mining claim area is used for industrial and office territory (administration and storage buildings, mill), infrastructure (roads and railways), electricity/communication facilities (substations, ventilation šurfs and power lines), water-removal facilities (sedimentation basins) and a remarkable land area is under the spoil heaps.

The landscape is heavily modified only on the industrial territory, where the oil shale spoil tips are higher than 100 m absolute height (60 m from the ground)

(Hendrikson & Ko, 2017). These waste materials are commonly formed of limestone, as well as of smaller quantities of carboniferous sandstone and various other leftovers. The rest of the landscape on the mining claim area has remained almost unchanged compared to pre-mining situation. On the ground are seen only ventilation holes (šurfs), monitoring wells and collapsed surfaces on some previously mined areas.

The mineable seam depth is 50-70 m, which is 15-12 m absolute height (Hendrikson & Ko, 2017). Estonia underground mine uses room and pillar mining that is commonly done in flat or gently dipping bedded ores. Pillars are left in place in a regular pattern while the rooms are mined out. In many room-and-pillar mines, the pillars are taken out, starting at the farthest point from the mine haulage exit, retreating, and letting the roof come down upon the floor. If the pillars are too small the mine will possibly collapse, but if these are too large then significant quantities of valuable material will be left behind, reducing the profitability of the mine (Hustrulid & Bullock, 2001).

As a result of dewatering the over-moist land, the soil in the mining area has become very suitable for agriculture. Compared to the soil map that shows the pre-mining condition, at least 60-70% of the soil was over-moist for agriculture, but now above the mine area are many farms and fields, whom the water-level rise would affect. Soil fertilization has remained unchanged (Eesti Maaviljeluse Instituut, 2003).

The plan is to stop mining operations in Estonia mine in 2032 and after eliminating the equipment, the pumps will be stopped and the underground passages will begin to fill up with the water (Savitski & Savva, 2011). Šurfs - used for ventilation and boreholes with no use, are eliminated and only few wells are left open for monitoring and the mine will be isolated with special barriers, where needed.

3. Geological and hydrogeological situation and climate

3.1 Topography and geology

The area of Estonia mining claim is on the edge of Viru plateau and Alutaguse lowland. The area surrounding the Estonia underground mine is characterized by subdued topography that slopes shallowly towards the Lake Peipsi depression in the south. As seen on Figure 2, relatively high elevation areas (up to 75 m above sea level) can be found at the Jõhvi upland, which extends to the north-eastern limit of Estonia mine. The elevation of the mineral terrain is on average 55–65 m absolute height and declines to 51–46 m at the southern limit of the wetland area. The lowest point is ~45 m absolute height.

Quaternary cover thickness extends to 8 meters in some places, increasing to the east and south direction and contains of soil, sand, moraine, sandy-clayey sediments, clayey moraine and thin peat layers (Hendrikson & Ko, 2017).

The mining claim is located in the Ordovician limestone outcrop area. Ordovician system is formed by carbonate rocks complex – clayey limestone and dolomite, which contain layers of clay, oil shale, and bentonite. Ordovician system thickness increases from 20 m in north, up to 100 m in the studied area’s southern region (Hendrikson & Ko, 2017). Below the Ordovician system lies Cambrian and Vendian sand- and claystones with average thickness 170–200 m (Hendrikson & Ko, 2017).

In the vast area of the mining claim, above Kukruse stage lie Idavere (O_3id), Jõhvi (O_3jh), Keila (O_3kl), Oandu (O_3on), Rakvere (O_3rk) and partly Nabala (O_3nb) stages limestone and marl layers with the average thickness of 40-50 m (Table 1). Surface coating is predominantly composed of 3 m thick moraine, which is in some cases covered with mild clay and sandy loam (Hendrikson & Ko, 2017).

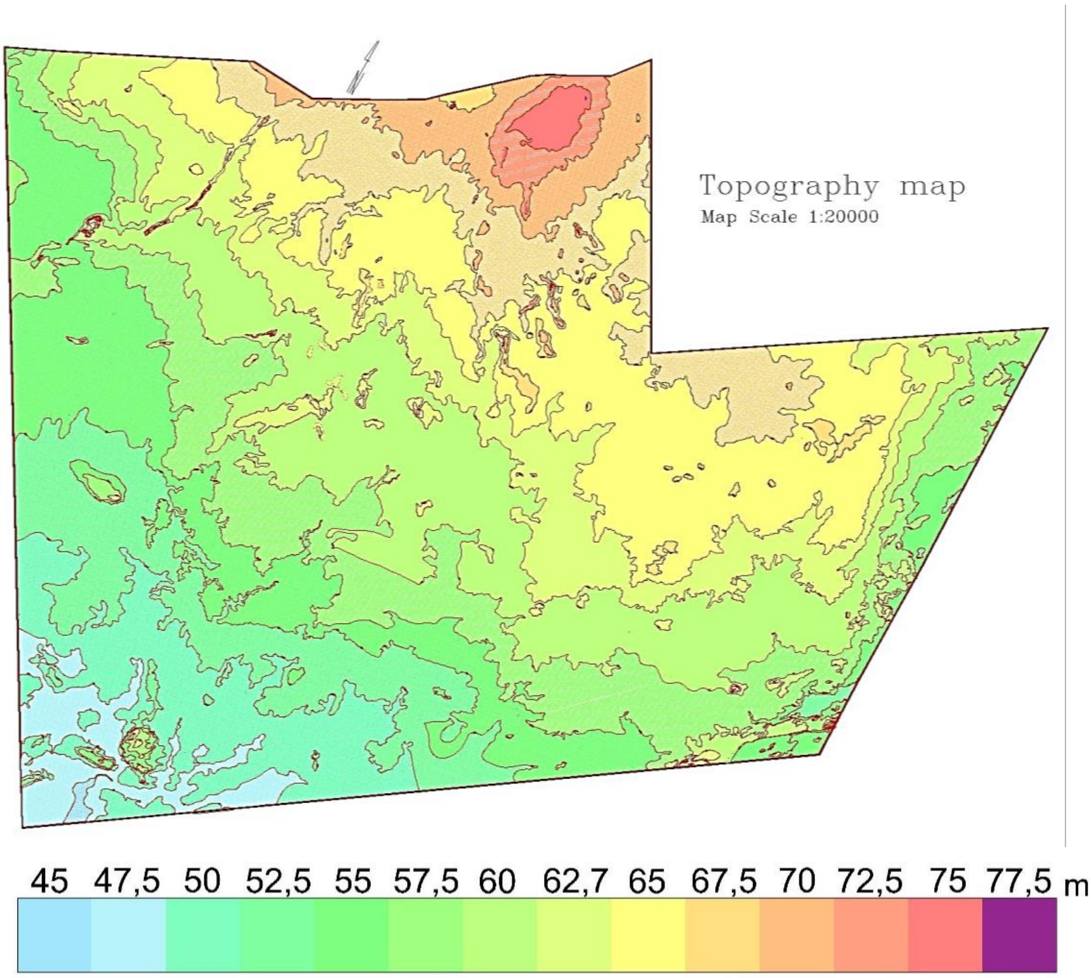

Figure 2. Topography map. Estonia mines absolute heights in the area. Map is created by S. Lind according to Estonia mine's database.

3.2 Hydrogeological condition

3.2.1 Hydrogeology in 1965 (before mining)

According to the data from 1965, Estonia underground mine's absolute height ranged from 48.92 in the south and 77.10 m in the north (Figure 3) (Lugus & Filatova, 1965).

The quaternary sediments were 0.5 – 3 m thick and area was mainly covered with forests and was partly swampy. As the relief is sloped towards the south, the groundwater level was following the surface line. Ordovician water-complex maximum absolute height 70 – 75 m was under the Pagari and Kalina villages and it decreased radially in every direction (Lugus & Filatova, 1965).

Рис. 15

Схематическая карта гидроизогипс Ордовикского водоносного комплекса

Депрессионные воронки шахт —40— Гидроизогипсы и их абсолютные отме

Контур шахтного поля №9

Figure 3. Estonia mine Ordovician water-complex hydro-isohypes in 1965, before the mining. (Lugus & Filatova, 1965)

Nabala-Rakvere water-bearing horizon depth was 2-5 m from the ground surface, in south it was 1-2 m. This water-layer depended the most on the precipitations – the fluctuation was 1-2 m.

Keila-Kukruse water-bearing horizon was 20-25 m from the ground, in the south it was 35-50 m. The water was pressurized and it mainly got its water from the precipitations, fallen to the outcrop area (Lugus & Filatova, 1965).

3.2.2 Hydrogeology in 2017

Estonia mine’s hydrogeology is different from the older mines that are located in the north direction, as it is located in deeper levels. In the area are two water-bearing horizons – Rakvere-Nabala and Voronka, which are figuratively two lakes above the tunneling (Figure 4). Previously, the water that poured in to the mine, mixed with the fine oil shale and in some places the working areas were quite muddy. This was improved by creating and constantly cleaning the water trenches. This method is still in use - water trenches are built with special cutters and the excessive water flows to them. From trenches it is directed to bigger water collecting ditches and finally it is pumped out to the sediment pools.

The water flows to Estonia mine mainly from Ordovician-Cambrian and Cambrian-Vendian aquifers and Voronka water-bearing horizon.

Estonia mining claim area hydrogeological cross-section is represented by the following aquifers and water layers:

1. Quaternary water system
2. Ordovician aquifer system
    - Nabala-Rakvere water-bearing horizon
    - Keila-Kukruse water-bearing horizon
    - Lasnamäe-Kunda water-bearing horizon
3. Ordovician-Cambrian aquifer system
4. Cambrian-Vendian aquifer system
    - Voronka water-bearing horizon
    - Gdov water-bearing horizon
5. Crystalline basement aquifers

The stratigraphy and the depths of the water complexes are shown in Table 1. The following hydrosphere description is based on the reports, made by L. Savitski and V. Savva (Savitski & Savva. 2001).

Quaternary aquifer (Q) gets its water from different type of genesis sediments, which thickness and distribution can be very variable. The water level is fluctuative, depending on weather conditions. Thin soil cover is the reason, why Quaternary water-complex in the studied area is predominantly 2-5 m, except in eskers, where it may be thicker than 15 m. In the studied area's Quaternary sedimentary complex separate aquifer is not formed (except the valleys) (Hendrikson & Ko, 2017).

Ordovician aquifer (O) system is comprised of Nabala-Rakvere, Keila-Kukruse and Lasnamäe-Kunda aquifers.

Nabala-Rakvere water-bearing horizon consists of 12-15 m thick fractured dolomite and limestone. Aquifuge above the water layer is moraine and under the water layer is Oandu stage marl and clayey limestone. Ground-water is HCO_3-Ca-type, minerality 290 mg/l and water hardness is ~2 mg·ekv/l.

Keila-Kukruse water-bearing horizon is situated in-between the dolomite intercalation of fractured limestone and clayey limestone. The water-bearing rock is 40-43 m thick. Covering bed is Middle-Ordovician Oandu and Keila regional stages of marl with intercalation of clayey limestone; confining bed is Uhaku regional stage's clayey limestone. In active mining areas this layer's water level is lowered and above the depleted reserve the water level is drained. Chemically the ground-water composition is HCO_3-SO_4-Ca-Mg-type, water hardness is 8.7 mg·ekv/l. This water horizon is the main inflow source in the mines (Savitski, 2003).

Lasnamäe-Kunda water-bearing horizon consists of slightly fractured limestone and dolomite, average thickness is 12 m. Water-bearing horizon's aquifuge in Uhaku regional stage is clayey limestone and underlying rock is Lower-Ordovician Volhovi regional stage's clayey glauconitic limestone.

It is important to notice, that this layer's water is used by small-consumers and part of it flows to the mines, which lowers the groundwater level. Groundwater is unflavored, type HCO_3-Ca-Mg and chemically meet the drinking water requirements.

Ordovician-Cambrian aquifer complex in sandstone extends to regional stage of Pakerord of Lower-Ordovician and to Tiskre regional stage of Lower-Cambrian. The aquifer thickness is 20 m.

Groundwater is pressurized. Chemical composition of water is HCO_3-Cl-Na type, with the hardness of 2.2-4.4 mg·ekv/l. From the micro-components, the aquifer's water has been detected with higher boron content – 0.4 – 0.8 mg/l. So far, it does not exceed the requirement for the quality of the drinking water (1.0 mg/l, regulation nr. 82, 31.July 2001, by the Ministry of Social Affairs) (Riigiteataja, 2017).

Cambrian-Vendian water-complex is formed of Voronka and Gdov aquifers. In the studied area are only few water wells that open Cambrian-Vendian water complex and even less water wells that opens the Voronka aquifer, as it lies in great depths.

Voronka water-bearing horizon is present in fine- and medium grained sandstone, with the average thickness of 15-18 m. Water layer's lap seam is thick coat of Lontova clay, underlying seam is Kotlin's clay. Groundwater is pressurized and the groundwater is unflavored, HCO_3-Cl-Na-Mg type.

Gdov water-bearing horizon lies under the Kotlin's clay, in 18 m thick medium and coarse sandstone. Groundwater's piezometrical level (17-18 m below the sea-level) is known only about the water-wells that open both – the Voronka and Gdov water-layer; it means the Cambrian-Vendian water complex.

Ground-water is Cl-Na type, with minerality – 1298 mg/l. The chloride content reaches to 710 mg/l, which exceeds the drinking-water quality requirements multiple times and is not suitable for drinking (regulation nr. 82, 31.July 2001, by the Ministry of Social Affairs) (Riigiteataja, 2017).

In order to get drinking water, the Cambrian-Vendian water-complex groundwater must be mixed with the groundwater from Ordovician-Cambrian water-complex at ratio of 1:3 (Savitski & Savva, 2001).

Mines have drastically changed the aquifers physical characteristics. The mineable seam's overall porosity has increased because of the extraction. Workings roof deformations and block caving have magnified the rock fractures and the grounds micro-relief has changed, which conduces changes in the surface runoff and in its infiltration (Savitski, 2003).

Table 1. Estonia Vendian - Middle-Ordovician hydrogeological timescale (Data from Estonia mine database).

Global standard		Regional standard				
System	**Series**	**Stages**	**Index**	**Thickness, m**	**Hydrogeology**	**Depth, m**
Quaternary			Q	0.5-10	Quaternary water complex	3
Ordovician	**Middle (O)**	Rakvere	O_2rk	8.0-13.3	Nabala-Rakvere aquifer	18
		Oandu	O_2oa	0.7-4.95	Oandu middle aquitard	21
		Keila	O_2kl	7.0-15.5	Keila-Jõhvi aquifer	65.6
		Jõhvi	O_2jh	6.5-13.6		
		Idavere	O_2id	2.47-9.35	Jõhvi-Idavere thin aquitard	
		Kukruse	O_2kk	6.3-19.15	Idavere-Kukruse aquifer	
		Uhaku	O_2uh	9.75-20.5	Uhaku middle aquitard	80.1
		Lasnamäe	O_2ls	5.8-12.5	Lasnamäe-Kunda aquifer	99.8
		Aseri	O_2as	1.2-5.4		
		Kunda	O_2kn	5.15-9.0		
	Lower (O)	Volhovi	O_2vl	1.85-6.0	Lower-Ordovician aquitard	103.2
		Latorpi	O_2lt	0.05-2.6		
		Varangu	O_2vr			
		Pakerordi	O_2pk	0.15-18.7		
Cambrian	**Lower (C)**	Pirita	C_1pr	11.5-21.95	Ordovician-Cambrian water complex	116.7
		Lontova	C_1ln	31.8-45.2	Lükati-Lontova regional aquitard	198
Vendian	**Upper (V)**	Kotlini	V_2kt	29.9-44.9	Voronka aquifer	220
				13.2-36.0	Kotlini regional aquitard	252.8
				11.7-45.9		
				26.6-46.5	Gdovi aquifer	297
				0.4-19.6		

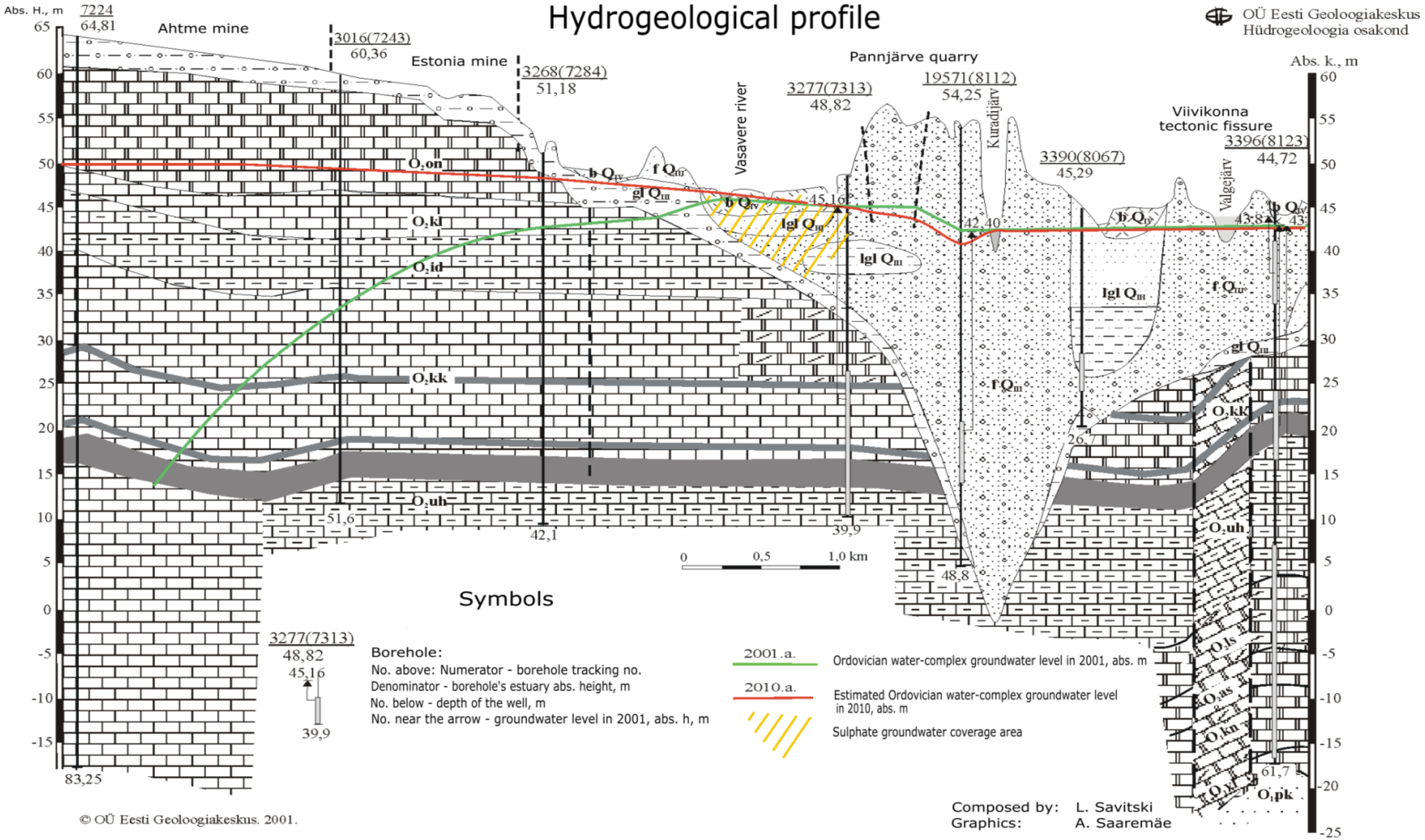

Figure 4. Hydrogeological cross-section of Ordovician water-complex in northern-east Estonia. (According to L.Savitski 2001)

3.3 Climate

Estonia mine is located in the Northern Estonia, where the climate is going from the maritime to more continental. This makes the weather very variable. Intensive cyclones that arise above the Atlantic Ocean make the weather mainly humid. In general, the summers are short, cool and rainy and winters are long. Wind direction is mainly from west or south-west, bringing along the relatively warm air masses in winter and colder air masses in summer (Hansen, 2007). Coldest months are January and February, when the average temperatures are -5.1° and -5.8°C respectively (Figure 5). Warmest months are July and August, with the long-term average temperatures 18.0° and 16.1°C (Estonia Environmental Agency, 2017).

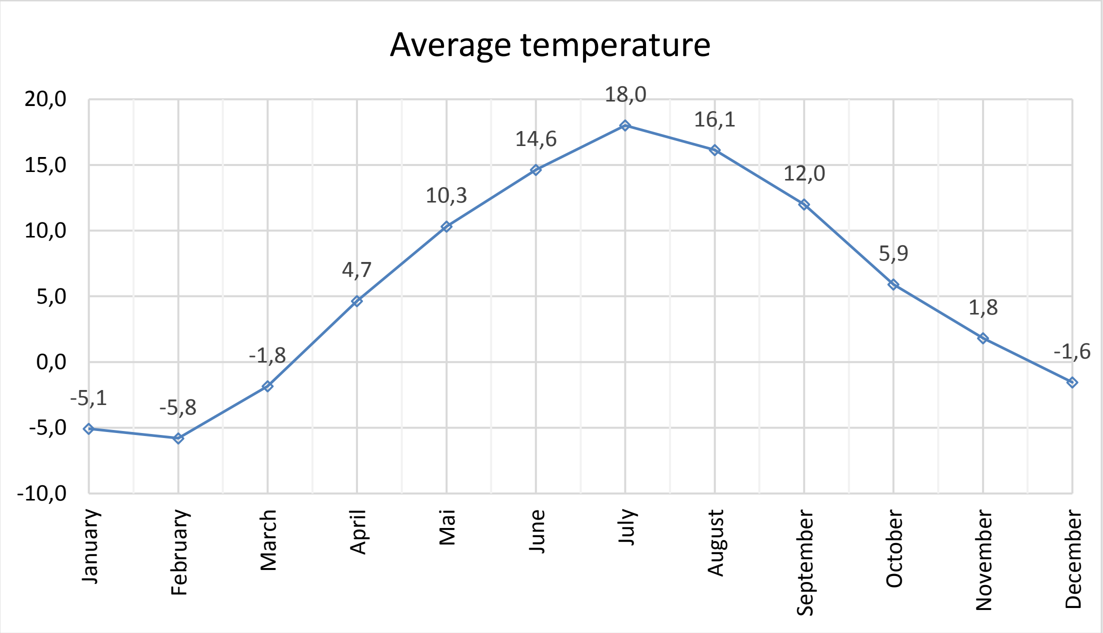

Figure 5. Long-term average temperatures measured in Jõhvi weather station. (Data: Estonia Environmental Agency)

Precipitations throughout the years are related to the activity of cyclones coming from the Baltic Sea. Annual precipitation amount between 1995-2016 is 734 mm/year. According to the Figure 6, since 1995, highest quantities of precipitation were in 1996, 2003 and 2008, when Jõhvi weather station recorded 905 mm, 901 mm and 962 mm, respectively. The years with least precipitations are 2006 and 2015, when the total amount of precipitations were 555 mm and 470.5 mm.

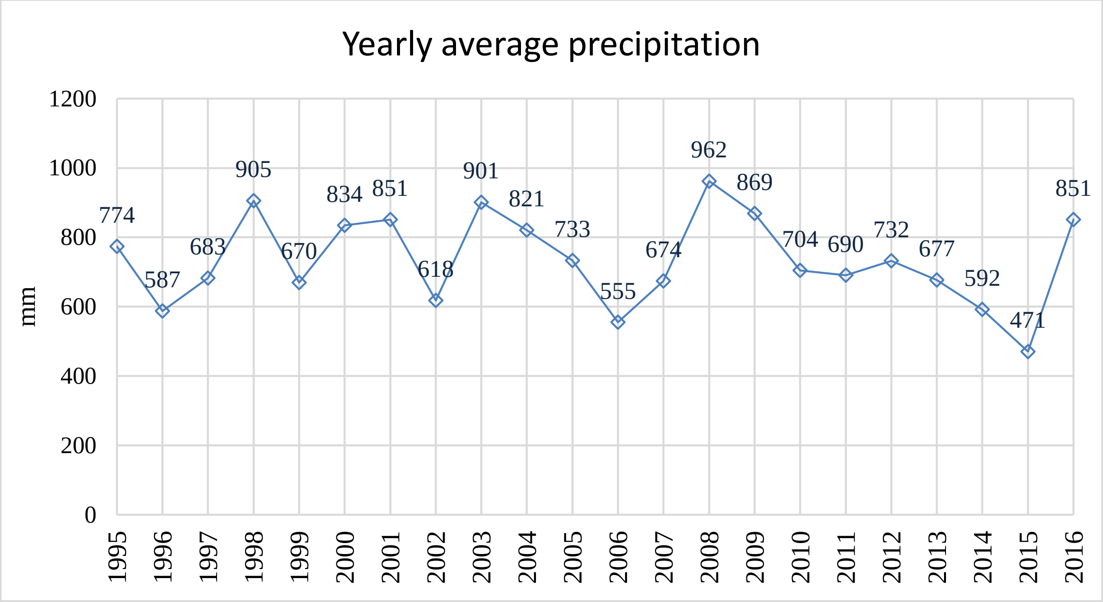

Figure 6. Precipitation trend, measured in Jõhvi weather-station. (Data from Estonia Environmental Agency)

As seen from the Figure 7, between 1995 – 2016, the months with the highest precipitation amounts are June and August, when the mean of precipitation exceeded 93 mm. Months with less precipitations are February and April, with the average quantity of rainfall 31,5 and 34,4 mm respectively.

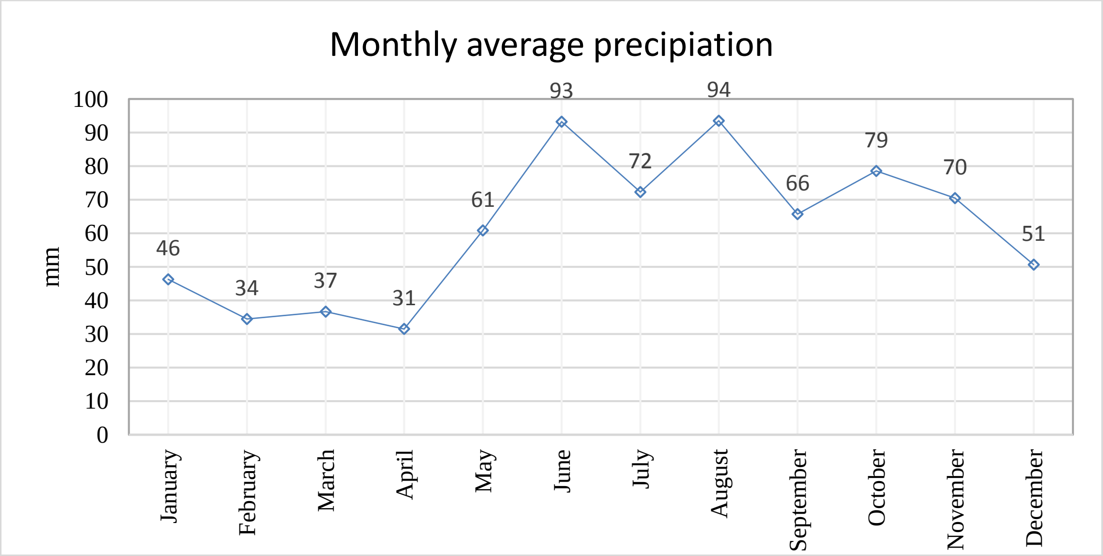

Figure 7. Average precipitations by months, measured in Jõhvi weather-station, observed 1995-2016. (Data from Estonia Environment Agency)

4. The impact on aquatic environment in Estonia mine

4.1 Long-term changes in the ground-water

Before mining, the area above Estonia mine was over-moist and swampy. The storm-water just accumulated on the ground and gradually infiltrated beneath the surface as the area lacked of big rivers and ditches to collect the excess water.

To mine oil-shale, the water must be pumped out – this is the reason why water level is decreased in the whole Estonia's active oil shale mining area. Water inflow and dewatering technology depends mainly on the hydro-geological status and the depth of deposit bedding. Ground-water's level is usually reduced 1-3 m beneath the mineable oil shale seam's depth of bedding (Savitski, 2003). In Estonia mine's area the mineable seam is 50-70 m deep, which is 15-12 m absolute height (Hendrikson & Ko, 2017). Especially, the Keila-Kukruse water-layer (~65.5 m below the surface) has been drained, as it lies directly above the oil shale layer. Local residents' water supply problem was resolved by constructing the wells into Lasnamäe-Kunda aquifer. The deeper the oil shale mining takes place, the higher is the amount of water that needs to be pumped out. On average, each ton of produced oil shale means 10-15 m^3 of ground water that needs to be pumped out (Hansen, 2007).

Mining's bale up range depends highly on the hydrogeological situation, relief in the area and water layer's bedding depth. In Estonia mine territory the Keila-Kukruse water-bearing horizon cone of depression radius is up to 6-7 km, while in Nabala-Rakvere water-bearing horizon it is on average, only 1 km. Long-term gross amounts of out-pumped water in Estonia mine have increased in decays, but since 2008, the bale up from the mine has rather fallen. Mainly, the pumped-out water depends on the weather conditions (Hendrikson & Ko, 2017).

Estonia mine's water diversion quantities increased after the closure of Ahtme mine in 2002, when it started to fill up with the water and now the water partially penetrates the complete pillars between Ahtme and Estonia mine. Ahtme mine water level is being kept on the 43-45 m altitude (Savitski, 2005).

4.2 Mine water inflow dynamics

Water flowing into the mines form as the aquifers are baled up for the drainage. Water layer involvement in inflow debit depends mainly on the hydrogeological conditions – filtration characteristics and the interrelation between water layers or their connection with the surface water. In Estonia, almost all mines' inflows are coming from Ordovician water complex (exception is the Ahtme mine, where 6% of the inflow is coming from Vasavere valley's Quaternary water) (Savitski & Savva, 2001).

As the Ordovician water-complex gets its water from the precipitations, the inflow also depends on the yearly weather conditions. Approximately 42% of the rainwater reaches to the aqueous phases (Savitski & Savva, 2011). Higher flows are in snow-melting periods in spring, when the average air temperature rises above 0°C (Figure 8). The most likely days to have average temperature over 0°C are 25.03-05.04 in spring, and in autumn it is between 05.11-15.11.

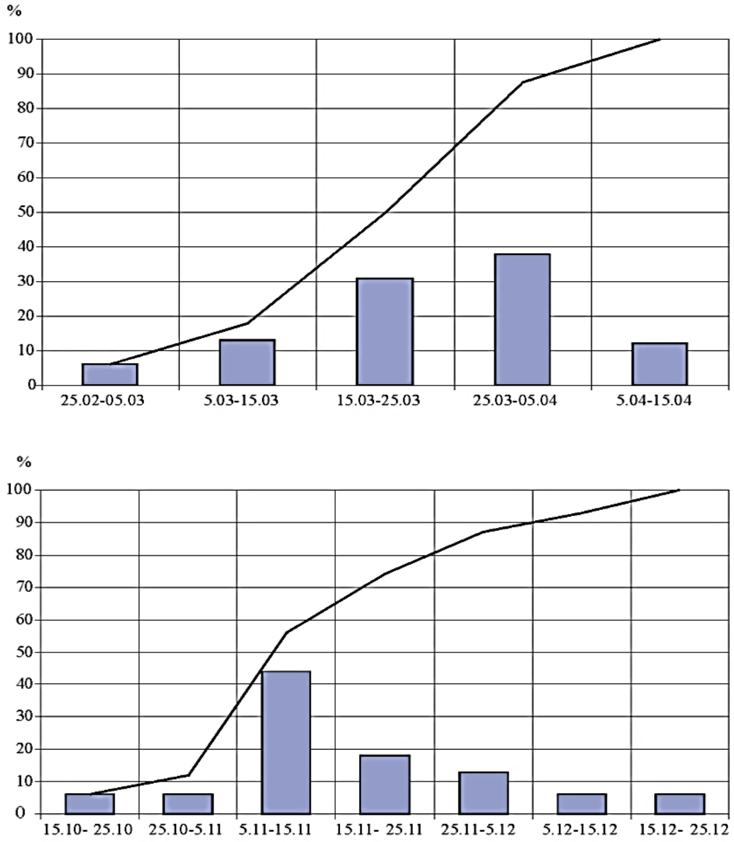

Figure 8. Air temperature repeated crossing 0°C, according to Jõhvi weather station. (L. Savitski,. 2001)

The interrelation between precipitations and pumped out water is shown on the Figure 9. Water inflow and pumped out water differ very slightly, as very small amounts of inflows pour to lower Lasnamäe-Kunda water-bearing horizon and to the neighboring mines, like Ahtme and Viru. After stopping the pumps, the mine will start to fill up with water. It means that all the gunnies, damaged parts above the mines and cone of depression fills with water. The filling duration will depend on the mining methods and conditions, hydrogeological parameters and weather conditions (Savitski & Savva, 2001). The last ones are evaluated by the basis of average, maximum and minimum values.

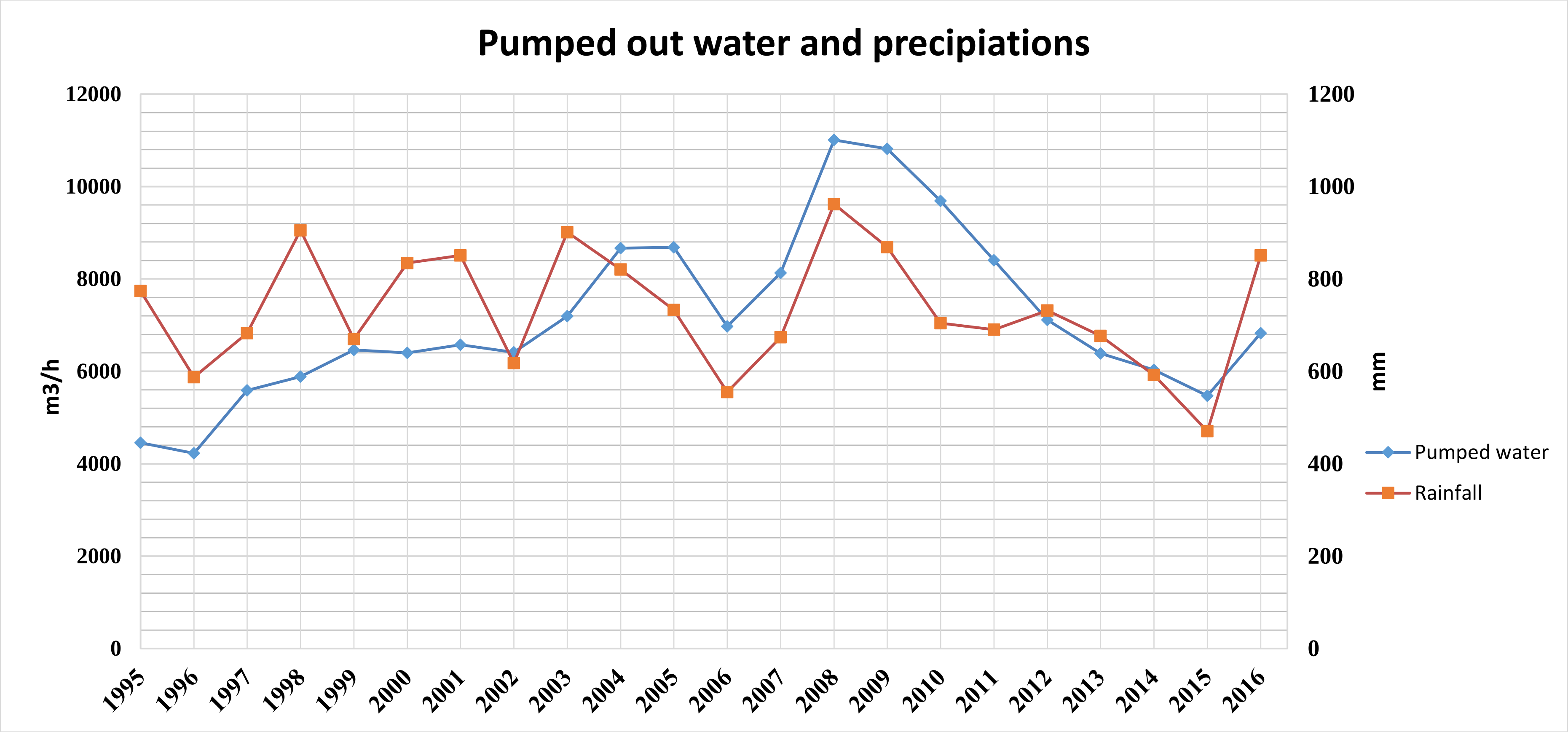

Figure 9. Graph showing the interrelationship between precipitations and pumped out water. Data is collected 1995-2016 by Estonia mine workers.(Estonia mine database)

4.3 Mine water outflow dynamics

The pumped out water in Estonia mine is directed to Lake Peipsi through rivers and special draining systems. Upper courses of many water bodies near the mine are heavily modified aiming to discharge mining water. Many ditches, channels and sediment basins have been created. Water regime is mainly anthropogenic in the area and depends on the mine waters discharge direction. Mitigation measures are focused only on the direct problems, for example, water pipes fulfillment with sediments, floods, barriers created by beavers, etc (Hendrikson & Ko, 2017).

In the mine passages are drilled trenches with cutters, where the water will be collected and directed to bigger and deeper ditches. These canals lead the water to the pumping station and then the excess water will be pumped out to sedimentation bonds. Mine water undergoes cleaning (mainly the suspended solids) in sedimentation bond, from where it moves on to natural water bodies. Sediment basins and water drain systems play an important role in mines and quarries. In Estonia mine are 6 sedimentation bonds at the moment, one of them is underground and the rest are on the ground level. In the mine area are altogether 10 pumping stations and their work quality is electronically controlled with Scada systems (Sokman, 2014). From all the sediment pools, the water is directed to the natural water bodies – river Rannapungerja and Raudi channel. On the basis of the valid permit for the special use of water, 45-50 million m^3/year of mining water from Estonia underground mine is directed to river Rannapungerja and its additional courses - Milloja and Jõuga main ditch. This is almost 73% of all of the Estonia mine's effluent (Hendrikson & Ko, 2017). Rest of the water is directed through sediment basin nr. 3 to Raudi channel, which in turn flows through lake Nõmme that belongs to Kurtna Nature Area. From that point, the mine water flows through lakes Särg- and Ahvenjärv until reaches to the lake Peen-Kirjakjärv and finally ends up at Mustajõgi. Lake Mustajõgi in turn flows to Narva reservoir, where it goes to the Gulf of Finland. Part of the mine water that is discharged to Raudi channel, is directed via Raudi-Konsu ditch to lake Konsu.

The discharged mine water has highly changed lake Nõmme's natural balance, as the mine-water's chemical composition is different from the natural lake water. The water exchange in lake Nõmme is 17 times per year, as a result of mine water flow-through (Hendrikson & Ko, 2017).

The water level in many lakes decreased drastically in the end on 1980's. For example – in lakes Martiska, Kuradi and Ahnejärve, the recession was up to 3-4 meters and this has caused irreversible changes in the composition of water. At the present time, the water level has rised in places, for the reason that in Kurtna-Vasavere water intake, the groundwater abstraction has been reduced. Yet, the water level has not reached the level that was 60 years ago (Hendrikson & Ko, 2017).

Elevated sulfate ion may become problematic to the lake conditions after the mining operations, when input of the mine-water will stop or significantly decline and the concentration of dissolved oxygen decreases. Oxygen deficit may lead to sulfate ion ($SO4^-$) reduction, which would result in the formation of toxic (to the aquatic life – primarily to the fishes) compound - hydrogen sulfide (H_2S). Hydrogen sulfide concentration rise will accelerate the internal phosphorus loading from sediments to the water body and this in turn would cause more sulfates to reduction as a chain reaction. The result is a deterioration of the lakes ecological balance and the water-bodies fast eutrophication (Hendrikson & Ko, 2017).

4.4 Impact to the ground-water

In the specific area, mining mainly affects the Nabala-Rakvere and Keila-Kukruse aquitards, by lowering the water levels and this in turn, dries up the water wells that are used by locals. Water level in the wells that use Lasnamäe-Kunda water layer may decrease, but generally, the wells remain usable. Influence below the Ordovician-Cambrian water-bearing horizon is not significant and to Cambrian-Vendian water-bearing horizon there is no impact.

A great impact to the ground-water is also mine fires. In Estonia mine have been two significant fires. First of them was in the November 1988, happened for unknown reasons and it lasted 48 days. The fire resulted in the groundwater pollution – pyrolytic phenols got into the mine water and this was a great threat to the water purity of groundwater and overall water bodies. Second fire occurred in October 2008, when conveyer belt took fire. This time, the fire lasted approximately 3 days, but it also influenced the ground water (Varb & Tambet, 2008).

Impact to the ground-water will alleviate after closing the mine, but the groundwater-bodies' natural situation recovering takes a long time - higher mineralization and sulphate hardness will remain and water levels in elevated areas will never reach the pre-mining level, also, in lower levels may occur excessive humidity and artificial springs (Hendrikson & Ko, 2017).

4.5 Minewater quality

Besides the fact that the ground water level is lowered for mining, also water's chemical composition of minerality, sulphates and water hardness has changed in the growth direction (Savitski, 2003).

Mine water's physical-chemical quality is lowered by Fe, NH_4^+, BHT_{20} content and the suspended matter, like SO_4^-, Cl^-, HCO_3^-, K^+, Na^+ increases a bit; heavy metal ion content is lower than in the north-east natural waters (Paat & Viil, 2008). Sulphates content in mines ranges from 300 to 1000 mg/l (Savitski, 2003). For comparison - in rainwater it is ~6 mg/l, in rivers it ranges from 0 to 630 mg/l and the seawater contains ~2700 mg/l (WHO, 2004). In drinking water the limit is 250 mg/l, higher sulphate content changes notably the water's taste (Riigiteataja, 2017). The concentration of suspended solids in the out-pumped mine water depends on the distance between the mining operations and pumping stations.

Few mine waters also contain benzo(a)pyrene (Kiviõli). Benzo(a)pyrene ($C_{20}H_{12}$) is a co-product from the oil-shale combustion. It gets to the exhausted mines from the waste heaps, oil shale chemical enterprises and as a side effect of the mine fires. Specifically, in Kiviõli mine it is a result of an old widespread oil spill (Savitski, 2003).

Water hardness is mainly caused by the amount of calcium and magnesium, and to a lesser extent, iron in the water. Ground water hardness in mine water is occurring from weathering of limestone, sedimentary rock and other calcium bearing minerals (Regional District of Nanaimo, 2017). On the occasion of the water temperature and acidity changes in surface waters (primarily in lakes), the balance changes and carbonates may deposit in the water-body analogously to travertine

(Hendrikson & Ko, 2017). Also, when the mine waters miscible with natural water, the substance quantities usually dilute to normal levels. For example, the mine water's quality is suitable to cultivate the rainbow trout.

The mine water composition is monitored regularly, by taking analyses from sampling points, which are fixed with the permit for the special use of water. Allowed water removal capacity is regulated with the permit for the special use of water, issued by the Ministry of Environment's local environmental department in Jõhvi.

It is important to consider, that although the mine-water's contaminants meet the substances limits set with the permit for the special use of water, relatively large amounts of mine water change the hydrological regime and also the overall water-body's chemical composition (Hendrikson & Ko, 2017). Several Kurtna lakes, that were naturally closed lakes with low water exchange, are now lakes with an active flow, as a result of mine water inlet. This, in turn, has likely changed the lakes' flora and fauna. The good side of the active flow is that the mine water that passes the lakes prevents their eutrophication. Also, it is important to note, that Lake Nõmme and Kirjakjärv were considered as part of Natura 2000 in 2004, when the lakes hydrological regime was already influenced by the flow-through mine water (Hendrikson & Ko, 2017).

4.6 Groundwater monitoring

Ida-Viru County's hydrosphere has been shaped a lot by anthropogenic activity. The biggest amounts of groundwater extractions in Estonia have gathered in this area; mining the oil shale dries up large areas, which causes the depression cones; oil shale and chemical industries have been pollution sources. Ground-water in the whole area is under the technogenous influence, which obliges to monitor the water constantly, to assess the condition of the hydrosphere and identify the interrelationships between the aquifers' groundwater, surface water and rain water. Continuous monitoring of ground-water allows to solve current and future problems, evaluate the water inflow to mines, assess mines' rational water discharge and to evaluate the impact to the technogeneous and natural factors in the environment (Savitski, 2003).

5. Example from the Ahtme Mine

5.1 Ahtme mine

Ahtme, an old oil shale mine, is located few kilometers south from Jõhvi and it started working operations in 1948 and was closed on 2002. Ahtme mine is 55 m above the sea level and has 33.4 km² of depleted area (Savitski & Savva, 2001). Depleted volume is $W = 94.706 \cdot 10^6$ m³ and according to V. Savva's and L. Savitski's calculations approximately 30% of this are the pillars that hold the ceiling and also the unexcavated crush belt and collapsed areas.

The underground area started filling up in 2002 and stabilized in 2005 (Figure 10), ranging between 41.4 and 42.5 m abs. height (Erg, 2017). After filling up, the mine started to flood the areas above. Further water-level rise is restricted with three overflowing water-wells (Figure 11), from where the water is directed to ditch Sannikoja, which flows to river Pühajõgi. Constructing the over-flow boreholes keeps the water, with higher sulphate concentration, away from Vasavere groundwater body, as well (Perens & Savitski 2011). Boreholes are coated with 50 cm diameter tubes. Since the boreholes were constructed, the floodings have disappeared. At the moment, the water level in Ahtme mine is held at 42-43 m altitude (Alkranel OÜ, 2011). The last years' frequent rainfalls have raised the water level in the boreholes a bit (Erg, 2017).

The Keila-Kukruse horizon's ground water has had problems with water hardness and sulphates high concentrations, but by the 2016 both parameters have decreased. The content of phenols is within the groundwater limits.

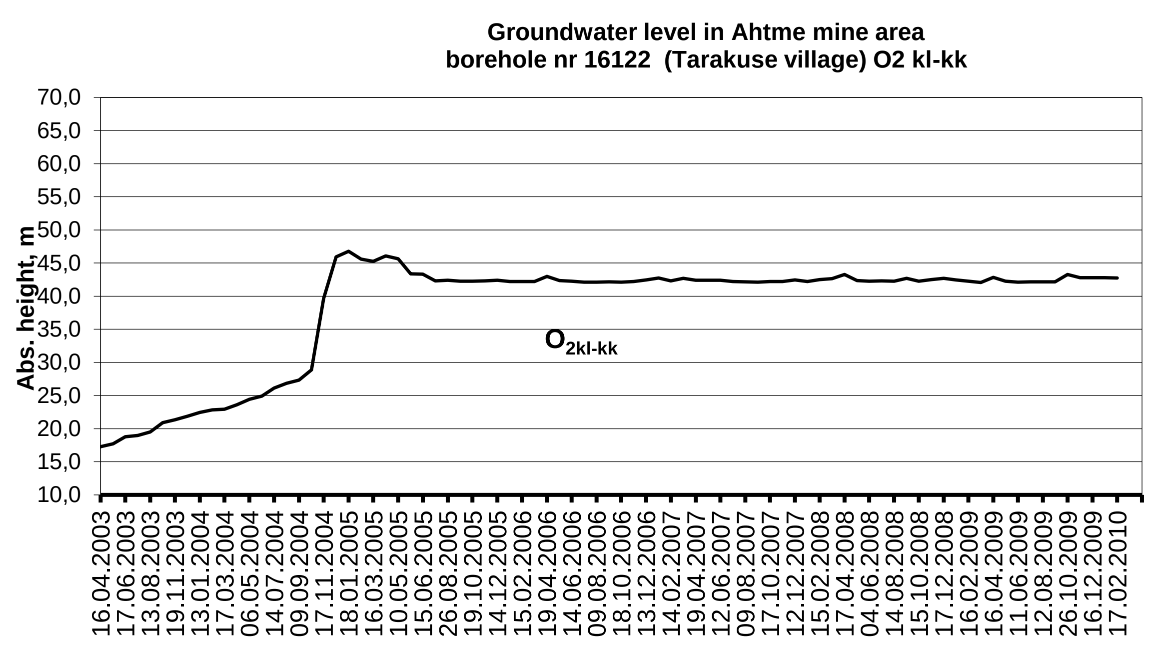

Figure 10. Water-level rise in the monitoring well 16122, in Ahtme mine area. (Data: Estonia Mine's database)

On the Figure 11 are photos, to illustrate the Ahtme mine overflow boreholes and to give an approximate visualization of them. Three wells are not in a straight row, but at a small angle. All the pipes' diameters are 500 mm. The area is covered with gravel and pebbles, to reduce the erosion from the slopes. Water flowing from the holes is directed to Sannikoja and the flow is usually fast. Photos (Figure 11) are made in the middle of May, when the flow is not rapid, but in the rainy or snow-melting periods, the water bursts out from the wells.

Figure 11. Ahtme three overflow boreholes and a visualized scheme of the boreholes. (Photos taken in 17.05.2017 by S. Lind)

6. Methodology

6.1 Data collection

To prepare for the pre-estimation, several scientific articles, books older than 50 years and previous case studies were studied in advance. This helped to acquire an apprehension of the topic and collect the data that was necessary to compile and analyze the research.

Used data is mainly from Estonia mine’s database, collected and observed through years by local geologists, mining surveyors and environmental specialists, and also from Estonia Weather Service and Estonia Land Board Geoportal. Previously, L. Savitski and V, Savva have done many researches about the mines’ hydrogeology, assessed the mines, that are already closed or set up for closure, impact to ground-water. These works have been examined, in order to understand the mines’ influences to the ground-water system.

Mainly used programs in the Thesis are AutoCad, InkScape, Photoshop, Excel, etc.

6.2 Water level change pre-estimation

To estimate the groundwater change, on the first hand was needed to know the water level in the area before mining. In 1948-1965, Lugus, A. and Filatova, F. have done thorough studies in the Estonia mine area. According to their data, the Ordovician water level,eee recorded between the 1948-1965, was 70-75 m absolute height in the north and it decreased rationally in every direction (Lugus & Filatova, 1965). At that time, the area was rather marshy and over-moisturized, especially the southern parts, where the ground surface is lower. When mining operations started, the whole area was drained and the swamps turned into forests.

In 1965, Nabala-Rakvere water layer was noted to be 2-5 m below the ground in north and 1-2 m in south, but nowadays, Nabala-Rakvere water-bearing horizon is approximately 15-18 m below the ground. Furthermore, Keila-Kukruse, that was 20-25 meters below the ground, is now at a depth up to more than 65 meters from the ground.

In 2032 when all the mining operations are finished and the equipment removed, the pumps that were used to eliminate the excessive water from the passage ways are stopped. After that the workings in the mine starts to fill up and the water level will rise but it does not reach its former heights.

The water inflow is shown on the Figure 12, where the last 21 years have been taken into account to assess the average inflow amount. According to this table, three different scenarios have been worked out.

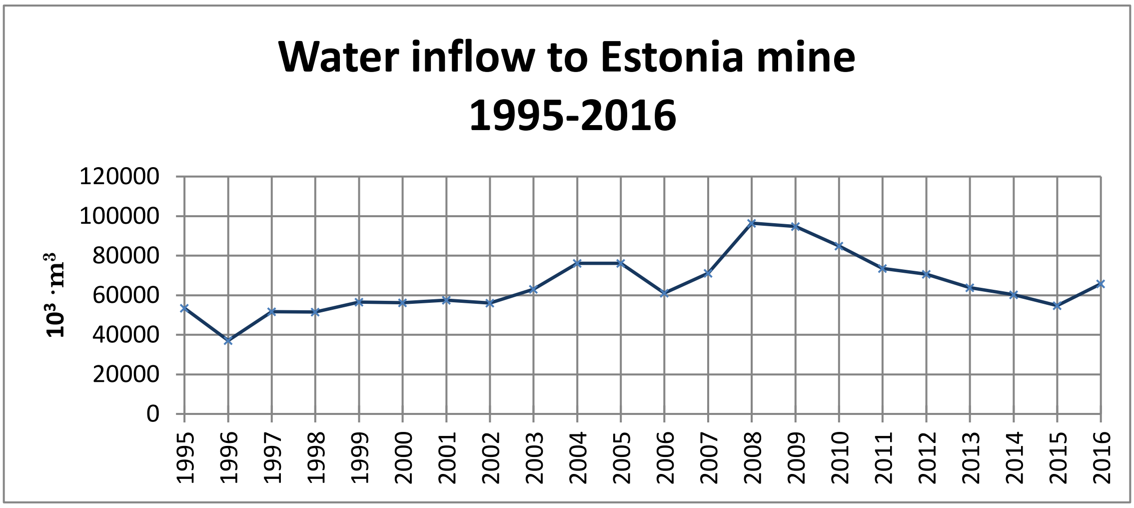

Figure 12. Water inflow to Estonia mine 1995-2016. Measured by Estonia mine's automatic pumping stations. (Estonia mine's database)

According to the data from 01.01.2017, Estonia mine's depleted volume W is $1.86 \cdot 10^8$ m³.

First scenario considers the years with minimum water inflow. To achieve this, from the Table 3, five years with minimum water inflows has been taken out in order to calculate the average minimum inflow, which is $49706.4 \cdot 10^3$ m³.

$$t = \frac{W}{Q} = \frac{1.86 \cdot 10^8}{49706.4 \cdot 10^3} = 3.7 \text{ years}$$

As seen from calculation, when there will be years with very low precipitations, filling up the mine would take approximately 3.7 years. The water level rise in time in case of minimum inflow is figuratively shown on Figure 13.

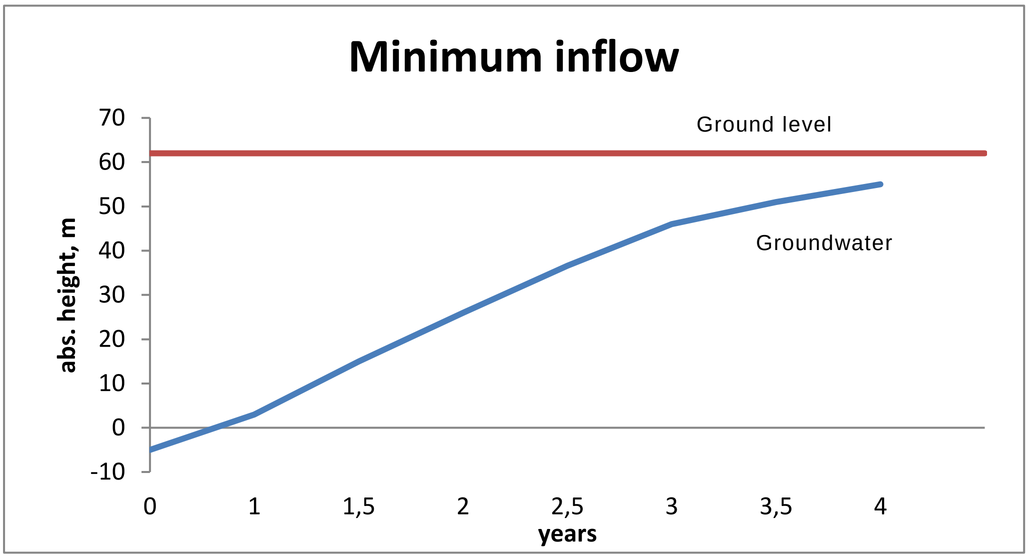

Figure 13. Figurative chart showing an approximate water level rise in case of minimal inflow. (Made by S.Lind)

In second scenario, calculation is based on the maximum inflow years. It shows the mine passage-ways filling up with the water in the years with high precipitations. The average of the five years with maximum inflow is 85659.2 $\cdot 10^3$ m^3.

$$t = \frac{W}{Q} = \frac{1.86 \cdot 10^8}{85659.2 \cdot 10^3} = 2.1 \text{ years}$$

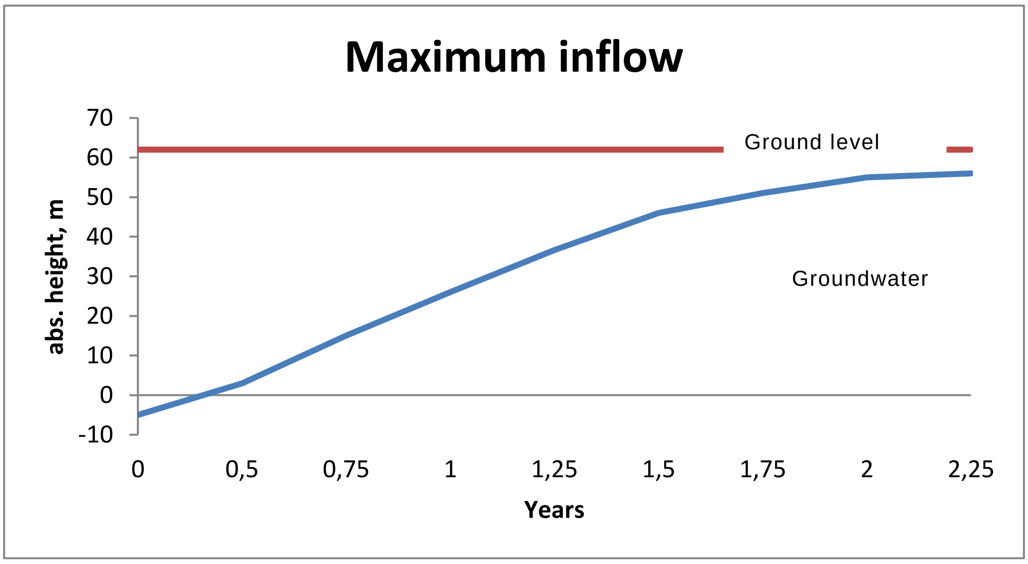

Figure 14. Figurative chart showing approximate water level rise in case of maximum inflow. (Made by S. Lind)

The shortest time when the fulfillment would take place is 2.1 years. The water level rise in time in case of maximum inflow is figuratively shown on Figure 14.

Finally, the last calculation is done with the average inflow, calculated on the basis of all the 21 years. This calculation shows the overall average fulfilling time, when the inflow amount corresponds to the annual average. The 21 years average inflow volume is 72484.3 $\cdot 10^3$ m^3.

$$t = \frac{W}{Q} = \frac{1.86 \cdot 10^8}{72484.3 \cdot 10^3} = 2.5\ years$$

The estimated filling time will be 2.5 years, when the annual precipitations will remain with the averages and the average filling in time is shown on Figure 15.

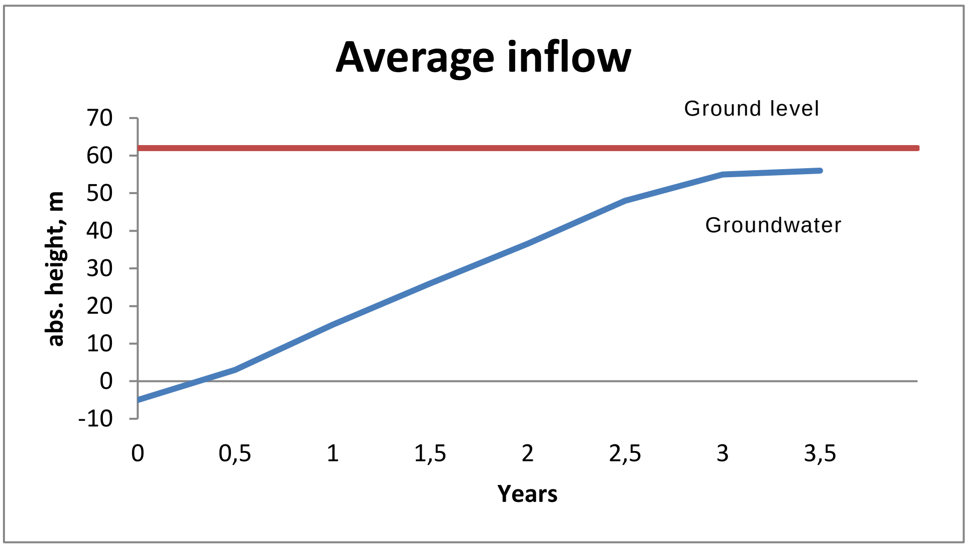

Figure 15. Figurative chart showing an approximate water level rise in case of average inflow. (Made by S. Lind)

Certainly, one must consider that the mine has also outflows to lower Lasnamäe-Kunda water-bearing horizon and to other neighboring mines. Therefore, the fulfillment may vary by few months.

6.3 Groundwater chemical composition possible change

After the closure of the mine, the hydro-dynamical balance will start to recover, cone of depression will shrink or disappear and the water exchange with surface water will abate (Savitski, 2003).

According to Savitski's work about mines that are already closed or set up for closure, the first year after the Ahtme mine closure, the sulphate contents in ground water rose rapidly up to 1493 mg/l and water hardness to 34.5 mg·ekv/l, but in the following year both contaminants were decreased 9 and 3.5 times, respectively (Savitski & Savva, 2005).

Table 2. Ground-water chemical composition changes, after closing the Kiviõli mine (L.Savitski. 2003).

Year	**Water hardness mg·ekv/l**	**SO^{4-} contents mg/l**	**Minerality mg/l**
1988 (before closing)	21	732	1610
1989 (after closing)	29,8	1241	2250
1993	11,8	295	826
2000	8,7	231	780

In Kiviõli mine chemical composition change can be seen in table 2. According to this information, it can be infered that the first years after the closure, the chemical composition will considerably change. The main reason for the increase is that the inflowing water will get into contact with the rocks (pyrite oxidation) and the technogeneous processes (blastings, mine fires or other leftovers). By the time, the processes will stabilize, which can be confirmed by the results of Ahtme and Kiviõli mine, but will remain higher than normal for at least a decade (Savitski, 2003).

7. Results and suggestions

7.1 Results

After closing the Estonia mine, presumably after 2032, the mining impact to the ground water reduces, but the water’s natural composition will never recover. Ground-water level will rise, approximately in 2-4 years, but in elevated regions it will be lower than in pre-mine situation. In lower areas the soil possibly become over-moist and wetlands might arise (OÜ Alkranel, 2011).

Closing the mine will cause a great influence to the Lasnamäe-Kunda aquifer also in nearby areas. It is a problem as the Lasnamäe-Kunda water-bearing horizon is the main drinking water source in the Estonia mine area. Therefore, as the lowered Keila-Kukruse water-bearing horizon, which does not meet the drinking water requirements, is situated above Lasnamäe-Kunda aquifer, it is important to prevent the mixing of aquifers.

Quality of the drained water will decrease from the first year up to more than 10 years after the closure. The amounts of sulphades and water hardness will increase rapidly within the first year after the closure of the mine, but it will recover after few years back to normal, as seen from the previously closed mines (Ahtme, Kiviõli). Also, after the Estonia mine closure, the mine water might contain the benso(a)pyrene, as the mine has had two serious underground fires in 1988 and 2008.

From the topography map (Figure 16) can see that the lowest areas are situated in the south corner of the mine area. The lowest place is 47.5 m absolute height and with the water-level rise, this area is potential place for flooding. The south-east region is lower when compared to the rest of the mine area and it is possible that the water will start to pour out from this corner as well.

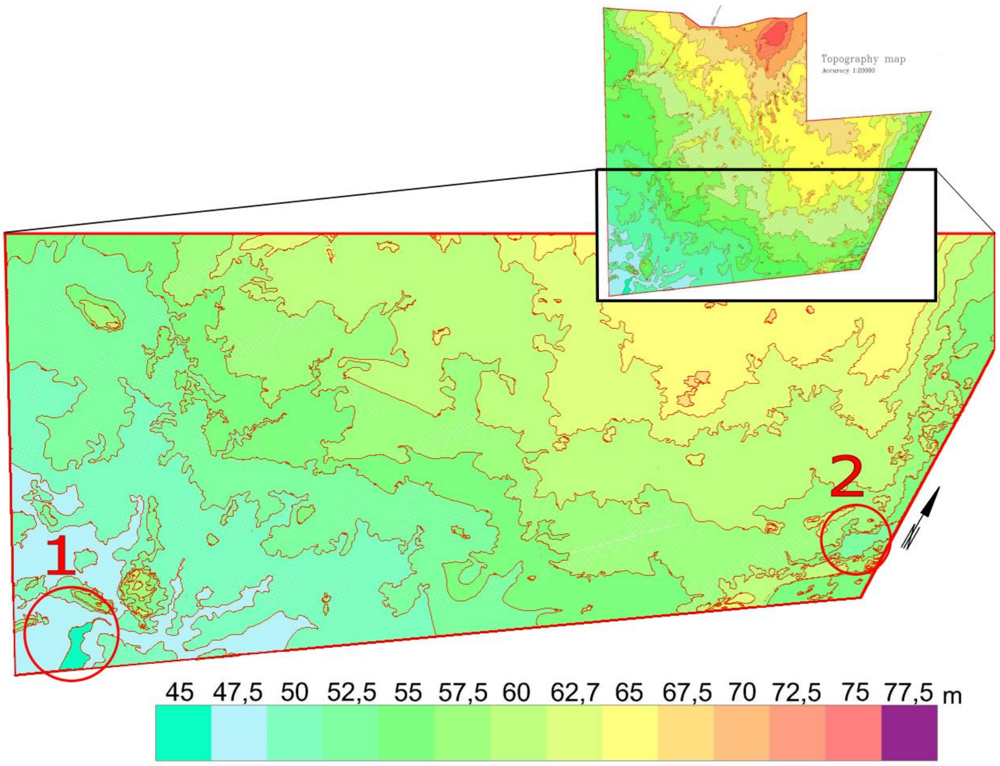

Figure 16. Close-up scheme to the Estonia mine's lowest areas. (Figure made by S. Lind, 28.05.2017)

7.2 Suggestions

In many closed mines, the water level is regulated to a fixed height, which generally does not exceed the initial. As in Estonia mine, the initial water level was 70-75 m, it is recommended to determine the water level at least 10-15 m below the average point in the area. This would make the preferable absolute height 42-47 m. This water level height should prevent the high water under forests, paludification and ground deformation (Savitski & Savva. 2011). Eliminating the Estonia mine and filling it with water up to 42-47 m, will cause no changes in the soil or ground surface, because the water level will be held 3-20 m below the ground.

To control the water level are needed over-flow boreholes (Ahtme) or water collector. In this case, bore-holes are more reasonable to establish, as the area is quite large. At least 3-4 overflow boreholes should be constructed to the southern corner of the mine, as the ground is the lowest there. This means that the water will accumulate to this region. The suggested area is also marked on Figure 16 with red circle № 1. Outflowing water will be directed to river Rannapungerja. Another 1-2 over-flow boreholes should be created in the east side of the mine area and it is marked with № 2 on Figure 16. The water from eastern part will be drained to Raudi channel, so the water will flow to the lakes in Kurtna.

The boreholes’ water amount is essential to monitor (approximately 4 times per year), by setting up the appropriate devices. Besides the water volume, it is important to control the water’s contaminants (SO^{4-}) and specially the hazardous substances (oil, phenols, PAH (polycyclic aromatic hydrocarbon)).

As a majority of lakes that are used to discharge the Estonia mine water, belong to the Kurtna Nature Area and their condition should remain stable even after the mine closure. Therefore, before the end of mining operations, special surveys must be carried out about the lakes’ self-purification capabilities and the possible situation stabilization measures. In the study, it is important to figure out the minimal inflow to the lakes, to ensure that there will be enough oxygen and water hardness, so the accumulated sulphate-ions reduction would not endanger the ecosystem condition. Specially should be assessed the lake Nõmme, which aquatic environment is highly modified by the mine water inflow. One possibility to ensure the lakes water exchange is to direct the excessive water through Raudi channel to the lakes.

CONCLUSION

Closing the mines and the following water-level rise has a great influence to groundwater resources in the mining area. The Thesis analyzes the Estonia mine's ground water situation with the purpose to pre-estimate the water level change after the mine's closure in 2032. This work is important, since thousands of people live in the Estonia mine area, who are affected by the ground water level increase and the changes in the quality of mine's water.

Firstly, this study gives a general overview about the Estonia mine, its hydrogeological situation and assesses the mining impact to aquatic environment. Especially, the impact has been evaluated to mine water inflow and outflow, but also to the mine water's quality.

As the region of Estonian oil-shale is rather small, the hydrogeological situation after closing oil shale mines is also analogous. Therefore, many examples have been taken from other closed mines, like Kiviõli and Ahtme, for better estimation.

During the research, it was confirmed that after the end of mining operations the mine starts to filling up, but does not reach its former heights. The mine's filling up time is evaluated by the basis of average, maximum and minimum inflow values. According to the calculations, the mine will fill with 2-4 years, depending on the inflow amounts. The duration may vary, as the mine has outflows to lower water-bearing horizon and to other mines. In the long run, it was found that the water level rises to the point where a risk for excessive moisture in the lower areas occurs.

Furthermore, it was affirmed that in addition to the water-level changes, the ground water's quality will change. When the inflowing water gets into contact with the rocks and technogeneous leftovers, it causes rapid decrease of SO^{4-} in the mine water, higher water hardness and changes in the minerality. However, the quantities will fall in the following years, but will remain higher than normal for more than 10 years.

Finally, the author has suggested to keep the water level approximately 42-47 m absolute height, to prevent excessive soil moist. To prevent or alleviate the flooding problem in the mining area, up to 5 over-flow boreholes should be constructed to the lowest areas above the mine, in order to control the water level. The outflowing water will be directed to river Rannapungerja and Raudi channel. It is important to use Raudi channel, so the water will flow to Kurtna lakes. This would be as a mitigation measure to prevent the eutrophication of the lakes. Also, to maintain the groundwater purity, it is suggested to monitor the mine water at least 4 times per year.

All in all, the aim of the paper and all research problems that were set in the beginning of the Thesis were met. Furthermore, the author has made recommendations for further work about Estonia mine's hydrogeological situation.

KOKKUVÕTE

Kaevanduste sulgemine ja sellega kaasnev veetaseme tõus mõjutab oluliselt põhjaveevarusid kaevanduste piirkonnas. Antud töös analüüsitakse Estonia kaevanduse põhjavee olukorda, et eel-hinnata põhja-vee muutusi pärast kaevanduse sulgemist. Magistritöö olulisus seisneb Estonia kaevanduse põhjavee tõusu ja kvaliteedi muutuse hindamises, kuna see mõjutab suurel määral kohaliku elanikkonda.

Kõigepealt antakse üldine ülevaade Estonia kaevandusest, selle hüdro-geoloogilistest tingimustest ning hinnatakse kaevanduse mõjusid vee-keskkonnale. Eriti on väljatoodud kaevandamise mõju sissevoolule ja väljavoolule ning kaevanduse vee kvaliteedile.

Töös on toodud ka näiteid teistest kaevandustest. Eesti põlevkivi maardla on koondunud Ida-Virumaale ning selle tõttu on kaevanduste hüdro-geoloogilised tingimused üsna sarnased. Estonia kaevanduse sulgemisel kaasneva põhjavee muutuste eel-prognoosimisel on toodud näiteid juba suletud kaevandustest (Ahtme, Kiviõli) ning autoripoolse hinnangu andmisel tuginetud üsna palju just näidetele.

Uuringu käigus sai kinnitust, et peale mäetööde lõppemist, kaeveõõned hakkavad täituma veega ning vesi kerkib üsna loomuliku veetaseme lähedale, kuid ei saavuta siiski enne-kaevandamise aegseid tasemeid. Vastavalt töö autori arvutustele kestab kaeveõõnte täitumine 2–4 aastat, olenevalt vee sissevoolu kogustest, mis omakorda sõltub ilmastikutingimustest. Seega on vaadeldud kolme stsenaariumi – kaevanduse täitumise aeg minimaalse, maksimaalse ja tavalise juurdevoolu korral.

Lisaks on töö käigus uuritud põhjavee kvaliteedi muutusi peale kaevetööde lõppu. Antud uuringu käigus jõuti järeldusele, et sarnaselt teistele suletud kaevandustele, tõuseb Estonia kaevanduses esimesel aastal järsult sulfaatide kogus, karedus ja mineraalsus kuni 3 korda. Siiski, järgnevate aastatega see langeb, kuid oma loodusliku taseme saavutamiseni kulub enam kui kümme aastat.

Autor on lisanud soovitusi hoida veetase absoluutkõrgusel 42-47 m, et hoiduda pinnase muutumisest liigniiskeks. Samuti pakub autor välja idee rajada Estonia kaevanduse alale kuni 5 ülevoolu-puurauku, mille abil saaks veetaset kontrollida. Ülevoolu-puuraugud tuleks rajada kaevanduse lõuna ning ka kagu ossa, kus maapind on madalam. Kaguosa puuraukudest välja voolav vesi on mõistlik juhtida Raudi kanalisse, et vesi voolaks jätkuvalt läbi Kurtna järvede. Sellega oleks võimalik vältida järvede kinnikasvamist ning enesereostust (Nõmme järv). Autor on veel lisanud ettepaneku vee kvaliteeti seirata vähemalt 4 korda aastas, tehes vajalikud uuringud eriti SO^{4-}, fenoolide ja nafta uuringuteks.

Kokkuvõtteks võib öelda, et töö käigus on leitud vastused kõigile töö alguses püstitatud eesmärkidele ja probleemidele. Lisaks on autor juhtinud tähelepanu uuringu kordamisele vähemalt viis aastat enne kaevanduse sulgemist.

RECOMMENDATIONS FOR FUTHER WORK

This Thesis is concerned on the ground water changes after Estonia mine closure in 2032. As the research has been done 15 years before the closure, a lot can change in the specific area and therefore, the work is needed to re-do approximately 5 years before the mine’s closure in order to get better overview of the current situation then and perhaps new and better technologies have emerged to control the water level. To conclude, since this paper is based on future estimations, more tests on ground water and the hydrogeology should be done in the future.

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