THESIS ON POWER ENGINEERING AND GEOTECHNOLOGY AAED02

GROUNDWATER SULPHATE CONTENT CHANGES IN ESTONIAN UNDERGROUND OIL SHALE MINES

KATRIN ERG

TUT
PRESS

ENERGIA- JA GEOTEHNIKA DISSERTATSIOONID AAED02

PÕHJAVEE SULFAATIDE SISALDUSE MUUTUS EESTI PÕLEVKIVIKAEVANDUSTE ALAL

KATRIN ERG

TUT PRESS

Department of Mining
Faculty of Civil Engineering
TALLINN UNIVERSITY OF TECHNOLOGY

Dissertation is accepted for the commencement of the degree of Doctor of Philosophy in Power Engineering and Geotechnology on May 12, 2005

Supervisors: Acad. Anto Raukas, Institute of Geology, Tallinn University of Technology
Prof. emer. Enno Reinsalu, Department of Mining, Tallinn University of Technology

Opponents: Prof. Robert Mokrik, Department of Hydrogeology and Engineering Geology, Vilnius University
Prof. Mait Mets, Department of Mining, Tallinn University of Technology

Commencement: June 20, 2005; Tallinn University of Technology, Department of Mining, Ehitajate tee 5, Tallinn.

Declaration: Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any degree or examination.

ISSN
ISBN

The doctoral thesis consists of a summary and the following papers:

Paper I Erg, K., Kann, J., Raukas, A. 2001. Rational use and environmental impacts of oil shale mining in Estonia. – Ünal, E., Ünver, B., Tercan, E. (eds.). 17th International Mining Congress and Exhibition of Turkey. IMCET Proceedings, Ankara, Turkey, 467–472.

Paper II Erg, K. 2003. Sulphate Balance of Lakes and Shallow Groundwater in the Vasavere Valley, Northeast Estonia. – Oil Shale, **20**, 4, 477–489.

Paper III Erg, K. 2003. Water regime in oil shale flat-lying deposit area of Estonia. – Röhling, H.-G., Steinbach, V. (eds.). MAEGS 13, Geoscience and the European Water Framework Directory, 10-13 September in Hannover, 13th Meeting of the Association of European Geological Societies and Raw Material Symposium of the Hannover Geocenter, Schriftenreihe Deutsche Geologische Gesellschaft, Heft 28, 23–27.

Paper IV Erg, K. Groundwater sulphate content changes in Estonian oil shale mining area. – Oil Shale, 2005. (Accepted).

This thesis is a result of an ongoing research that started in 1982 and is aimed at studying the impact of underground oil shale mining on the hydrogeological situation in northeastern Estonia.

Papers I and III deal with the main problems of human impact arising from oil shale mining. The analysis of the extensive good-quality field data collected over a relatively long period of time leads to a basic understanding of the mechanics of groundwater movement and the influence of pumping of water on the environment. The intricate problem concerns the factors influencing the formation of groundwater quality in the mining area, and the forecast of the situation after the mining has been finished. Paper II describes the increased withdrawal of groundwater and groundwater pollution by sulphate in a large area of the Vasavere buried valley. Paper IV describes the underground mining activities associated with water pollution problems. Most of the chemical pollution caused by mining results from the oxidation of sulphide minerals. A critical component in determining the post-mining water quality is the knowledge of groundwater fluxes, both as the underground mining fills and after steady state conditions have been reached. Simulations of the filling of underground mine were made to generate inputs for underground water basin chemistry predictions.

Papers I is reprinted by permission from the Chamber of Mining Engineers of Turkey.
Paper II and IV are reprinted by permission from the journal Oil Shale.
Paper III is reprinted by permission from the Schriftenreihe Deutsche Geologische Gesellschaft.

Tallinn, April 2005

Katrin Erg

CONTENTS

ILLUSTRATIONS

TABLES

PÕHJAVEE SULFAATIDE SISALDUSE MUUTUS EESTI PÕLEVKIVIKAEVANDUSTE ALAL

Kokkuvõte

Töö käigus uuriti põlevkivimaardla 220 km^2 suuruse keskosa suletud ja töötavate kaevanduste alal levivate Kvaternaari ja Ordoviitsiumi põhjaveekihi sulfaatide sisalduse muutusi. Ordoviitsiumi põhjavee moodustavad põlevkivikaevanduste alal Nabala–Rakvere, Keila–Kukruse ja Lasnamäe–Kunda veekiht. Põlevkivi kaevandamisel kuivendatakse Keila–Kukruse veekiht, kus peale veetaseme alanemise muutub vee keemiline koostis eelkõige sulfaatide sisalduse, vee mineraalsuse ja kareduse poolest. Kaevanduste sulgemisel aga moodustuvad maa-alused foonilisest erineva keemilise koostisega veekogumid.

Töö eesmärk on uurida kaevandamiseelse perioodi vee keemilist koostist, kaevandamise aegseid ja järgseid muutusi Keila–Kukruse põhjaveekihis, leida omavahelisi seoseid kujunenud maa-aluste veekogude vahel ja selgitada Keila–Kukruse ning Lasnamäe–Kunda veekihi sulfaatide sisalduse muutusi suletud põlevkivikaevanduste alal. Töö põhineb AS Eesti Põlevkivi ja Eesti Geoloogiakeskuse vaatlusvõrgu ja autori isiklike vaatluste ning mõõtmiste andmetel.
Olulisemad tulemused võib kokku võtta järgmiselt:

1. põlevkivikaevanduste hüdrogeoloogilist režiimi mõjutavad aeratsioonivöö paksus, geoloogilises läbilõikes esinevad tektoonilised lõhed ja rikked, veetaseme ja surve alanemised, mis põhjustavad vee voolusuundade ning kiiruse muutusi (artikkel I);
2. lihtsamate hüdrogeoloogiliste ülesannete lahendamisel eeldatakse, et põhjavesi voolab homogeenses geoloogilises keskkonnas igas suunas ühtlaselt (isotroopselt); põlevkivi kaeveala on aga anisotroopne ja mittehomogeenne (artikkel III) ning välistab lihtsustatud lähenemise;
3. kaevandamiseelsel perioodil põhjavee keemiline koostis kujunes looduslikes toitumistingimustes (artikkel II); kaevandamisaegsel perioodil vee väljamisel kaevandustest kujunesid mitmete kilomeetrite ulatuses levivad piesomeetrilise rõhu regionaalsed alandused (artikkel I) ja suurenes indikaatorelemendi (SO_4^{2-}) sisaldus kuni 50 korda (looduslik – 2–10 mg/l) (artikkel II, IV);
4. kaevandamisjärgselt, pärast kaeveõõnte veega täitumist, sulfaatide sisaldus suurenes paari aasta jooksul 3–4 korda (1500 mg/l), ent alanes nelja aasta pärast kuni 200 mg/l (artikkel IV);
5. põlevkivikaevanduste sulgemine ja üleujutamine on muutnud Lasnamäe–Kunda veekihi põhjaveevaru moodustumise tingimusi (artikkel IV);
6. suletud kaevanduste vesi on tehnogeensete mõjurite tõttu seotud Lasnamäe–Kunda põhjaveekihiga, seda näitavad sulfaadi sisalduse suured kõrvalekalded foonilisest sisaldusest nii kaeveväljal kui ümbritsevates Lasnamäe–Kunda põhjaveekihi puurkaevudes (artikkel IV);
7. suletud kaevanduse vee eemaldamise ja üleujutuse vähendamise aktiivsete ja passiivsete meetodite seast oleks soovitav valida kas ülevoolu puuraugud (Ahtme kaevandus) või kuivendustunnel (kaevandus nr. 2) (5. ptk);
8. aktiivsed kaevandusvee tasemete alandamsmeetodid põhjustavad suuri aastasiseseid vee keemilise koostise muutusi (5. ptk);
9. suletud kaevanduste vesi vastab põhikomponentide osas Eesti Joogivee Standardile (5. ptk) ja väljapakutud vee töötlemismeetodi tagajärjeks võib olla laiaulatuslik sekundaarne reostus, mistõttu autor ei pea kaevanduste vee eritöötlust otstarbekaks.

Abstract

During the course of the studies changes in the sulphate content in the Quaternary and Ordovician groundwater within ca 220 km^2 area of closed and working underground mines in the central part of the Estonian oil shale deposit. In the area of oil shale mines, the Ordovician groundwater is stored in the carbonate rocks of the Nabala–Rakvere, Keila–Kukruse and Lasnamäe–Kunda aquifers. The oil shale mining causes drainage of the Keila–Kukruse strata. This affects the groundwater regime. Besides, the chemical composition of the water also changes. This concerns, first of all, the content of sulphates, concentration of dissolved mineral salts and hardness of water. In the eight closed mines underground water pools have formed. The chemical composition of water in these pools differs from relevant background values.

The aim of the work was to study the sulphate content of surface (lake) and groundwater in pre-mining period, but also mining and post-mining changes in the Keila–Kukruse aquifer. It was attempted to find out interfaces between underground water pools and to study the sulphate content changes in the Keila–Kukruse and Lasnamäe–Kunda aquifers in the area of closed oil shale mines in a lateral and transversal direction. The thesis is based on the databases of Estonian Oil Shale Company and Geological Survey of Estonia and on the data obtained by the author in the course of her studies. The main results may be summarized as follows:

1. the hydrogeological regime in oil shale mines is controlled by the thickness of the aeration zone, tectonical faults and fractures in the geological section, alteration of hydraulic gradients causing changes in flow direction and rate (Paper I);
2. water table drawdown predictions are generally based on the assumption that geologic materials transmit water equally in all directions (isotropically); however, the oil shale mining area is unisotropic and non-homogeneous (Paper III) and simplified approach is excluded;
3. in pre-mining time the groundwater quality was mainly affected by precipitation (Paper II). During the mining period the sulphate content increased and was up to 50 times as high as under natural conditions (2–10 mg/l)(Papers II, IV);
4. in post-mining time the mines fill with water; the content of sulphates increases sharply – 3–4 times (1500 mg/l) during two years and then, after four years, decreases to 200 mg/l (Paper IV);
5. closing and flooding of underground mines has radically changed the groundwater forming conditions in the Lasnamäe–Kunda aquifer (Paper IV);
6. due to technogenic impact the water of closed mines is connected with the Lasnamäe–Kunda aquifer. Evidence is derived from the deflection of the content of sulphate from natural background both in the mining field and in the observation wells tapping the Lasnamäe–Kunda aquifer in the surroundings of the mining area (Ch. 4);
7. of the active and passive methods applicable to water removal from the closed mines and prevention of flooding of the surrounding area author recommend to choose overflow wells (Ahtme mine) (Ch. 5). Generally, passive treatment technologies are preferred since these are more sustainable and can be made to integrate much better into their surroundings;
8. active water level regulation methods cause mine water depletion and changes in the sulphate content of the water around the year (Ch. 5);
9. generally, the water of closed mines meets the requirements of the Drinking Water Standard of Estonia (RTL 2001/100/1369) (Ch. 5) and the recommended active treatment method can cause large-scale secondary pollution. In view of this, the author of the thesis considers special mine water treatment unpurposeful.

1. INTRODUCTION

In many parts of the world more and more coal, ore and other mineral fields are closed (Rogoz, Posylek, 2000; Barnes, 2000; Younger, 2002). Europe was once the most important mining region in the world and nearly every European country has remnants of historic and even pre-historic mining sites, also closed mines (Norway, Finland, Sweden, Germany, Poland, France, Serbia, etc) (Wolkersdorfer, Bowell, 2004). The importance of mining activities in most European countries declines, but the abandoned or closed sites remain. During the last 10 years, substantial efforts have been put into reclamation of closed underground mine sites all over the world (Wolkersdorfer, Bowell, 2004; Wolkersdorfer, Bowell, 2005). Closed underground mines may or induce risks for the environment. Some of these risks are linked to the shut down of the mine water pumping operations leading to a water level rise. These concern:

1. pollution of surface and/or groundwater by sulphates and others chemical elements;
2. flooding of zones subsided below the water table level;
3. additional surface movements in relation to collapse of shallow mine workings.

After the closing of a mine these risks may exist during a short, long and very long period of time depending on the quantity and flow of water involved and the volume of the mine workings concerned.

The oil shale production in Estonia started in 1916 and until today different number of mines has been operating in the area. In 2005, eight mines have been closed in the central part of the oil shale deposit. Two mines (Viru and Estonia) are in production, and new oil shale reserves are continuously being identified and developed. In the closed oil shale mines, pumping from the working mine is terminated and mine voids are allowed to re-saturate. Flooding of closed mines will generally continue until groundwater achieves a new equilibrium. Before reaching the steady-state the sulphate content sharply increases, some years after flooding it decreases.

The hydrogeology of underground working (Viru and Estonia mine) and closed mines was studied by Savitski and Savva (Savitski, Savva, 2001; Savitski, 2003) and most recently by the researchers of the Department of Mining under the supervision of Reinsalu (Reinsalu *et al.,* 2004). Many other scientists have summarized localized environmental impacts from mining. The data obtained are generally well documented; however, the sulphate migration to the underlying aquifer and in the water of different mines remains relatively unclear.

The aim of the thesis is to examine a long-term database and describe sulphate content changes in groundwater during pre-, mining and post-mining time. It also deals with the distribution of sulphate in the mine water, and with the impact of mine water on the sulphate content of the Lasnamäe–Kunda groundwater aquifer in the area of closed mines. Finally, some possible solutions to the problems relating to flooding of surrounding areas by underground mines water are suggested and one active method for decreasing the sulphate content in the mine water is proposed.

2. GROUNDWATER SYSTEMS IN THE ESTONIAN OIL SHALE DEPOSIT

2.1 DESCRIPTION OF THE OIL SHALE DEPOSIT AREA

2.1.1 Site description

The oil shale area is located in the north-western part of the East-European Platform. Structurally, the largest part of the region lies within the boundaries of the southern slope of the Fennoscandian (Baltic) Shield. Both the surface of the crystalline basement and the overlying Vendian and Palaeozoic sedimentary rocks have a low dip (11-15') to the south (Perens *et al*., 2001). The crystalline basement lies at a depth of 200–300 m.

The Estonian oil shale deposit (Fig. 2.1.1.1) is the largest commercially exploited oil shale deposit in the world. Its total reserves exceed 7 billion tonnes (Paper I), half of which can be mined according to the existing technology, economical and ecological criteria.

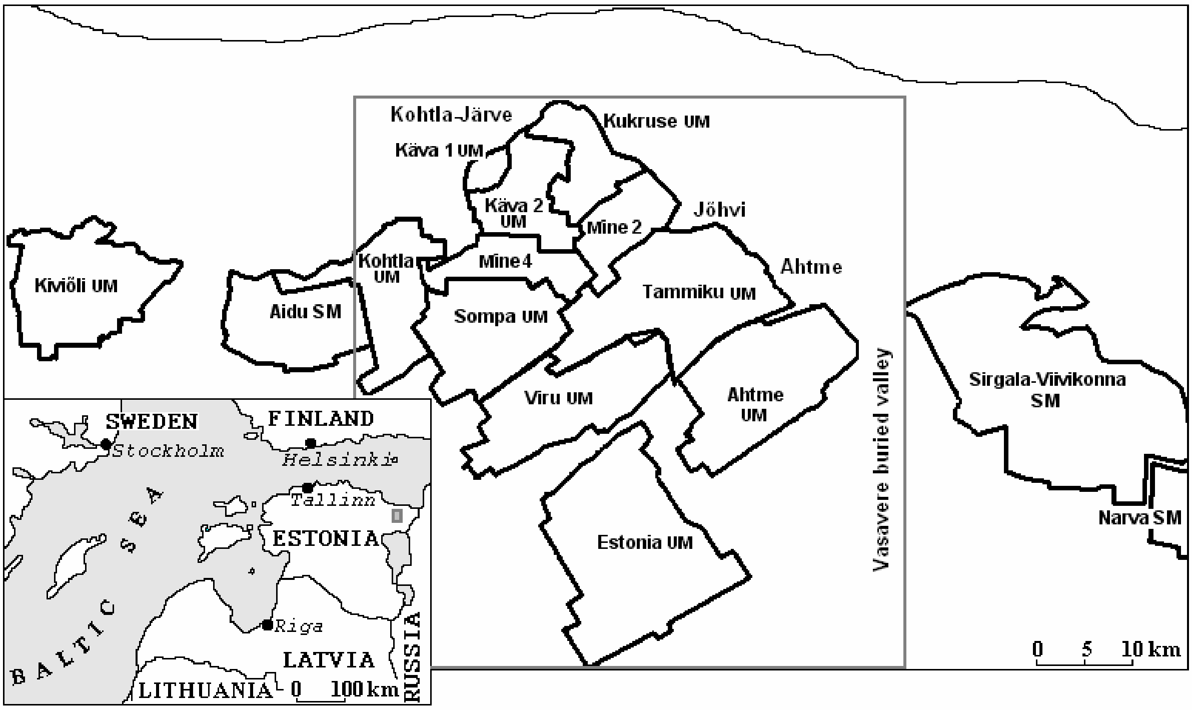


Figure 2.1.1.1 Location map of Estonian oil shale deposit

The oil shale deposit has attracted strong economic interest, which is still continuing. The exploration of oil shale began in Estonia in the first half of the 19^{th} century. Industrial mining of oil shale started in 1916 by the chamber and combined methods. To date, oil shale is the most important mineral resource of Estonia. The annually exploitable layers have an average thickness of 2.8 m and the bedding depth increases in the southern direction. Oil shale consists of 50–70% organic (kerogen) and 30–50% mineral matter (mainly carbonates and terrigeneous minerals) (Aaloe, Viiding, 1983). The sulphur content averages 1.6 % and the net calorific value varies from 6–10 MJ/kg (Bauert, Kattai, 1997). Annual oil shale output increased from 2 million tonnes in 1940 to 31 million tonnes in 1980 (Reinsalu, 1998), and has since decreased to 14 million tonnes in 2004 (Fig. 2.1.1.2).

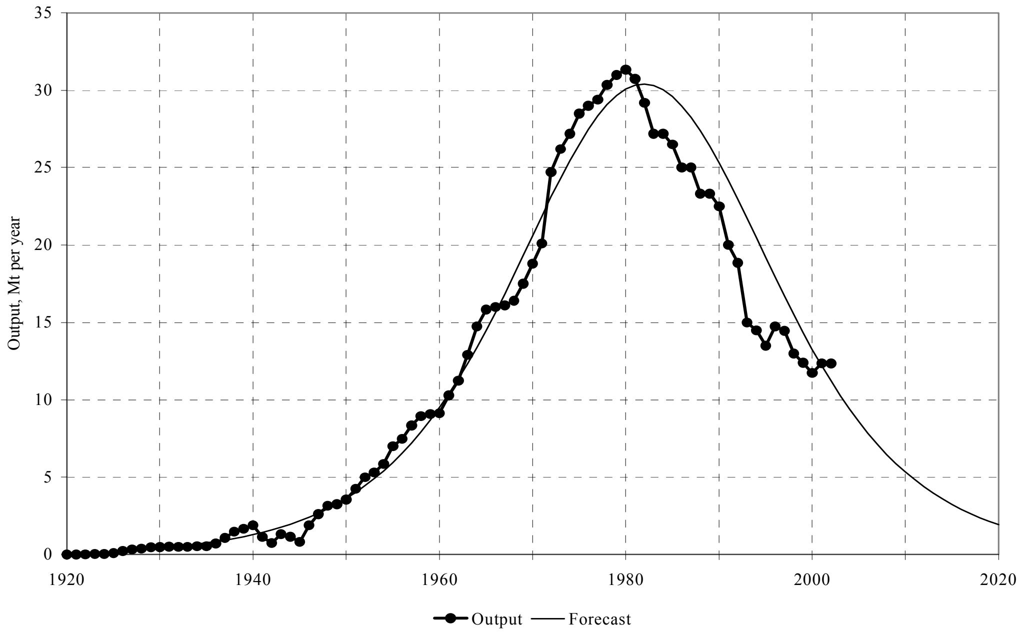


Figure 2.1.1.2 Estonian oil shale annual production (mining output) and forecast (Reinsalu, 1998).

2.1.2. Oil shale mining technologies

The mining method is the major component that influences the environment. The following mining techniques produce associated surface subsidence (Whittaker, Reddish, 1989; Undusk, 1998; Reinsalu *et al*., 2002; Reinsalu, Valgma, 2003):

1. Longwall mining;
2. Room-and-pillar mining.

The methods listed are commonly used in the oil shale mining. The longwall mining was stopped in the Estonian oil shale deposit in 2001. Room-and-pillar mining is a common mining method. It is generally applicable only to large-scale flat-lying deposits. The field of an oil shale mine is divided into panels, which are subdivided into mining blocks, approximately 300–350 m in width and 600–800 m in length each (Pastarus, Toomik, 2001). In case of room and pillar mining, 70–75% of oil shale is mined (Pastarus, 2003), while some oil shale is left in place as pillars to support the overlying strata.

The two most common forms of surface subsidence from room-and-pillar mining are sinkhole collapse and a saucer-shaped depression following pillar failure. In the case of room-and-pillar mining, surface subsidence can occur many years after mining is closed (Toomik, 1998; Undusk, 1998; Toomik 1999; Toomik, Tomberg, 2001). Subsided land is located above hand-mined, advancing-and-retreating mining and longwall mining with double-unit-face areas. The relief of subsided land depends on the quantity of the filling material and filling quality, and on the roof structure. The area of subsidence moulds is in average 55 600 m^2 ranging from 2 500 to 152 500 m^2 in total (Erg *et al*., 2003). The area mined by the room-and-pillar method reaches 100 km^2 (Nikitin, 2003). It has become apparent that the processes in overburden rocks and pillars have caused mining block collapses accompanied by significant subsidence of the ground surface. Up to the present, 73 failures in Estonian oil shale mines have been registered, which make up 11% of the total number of mining blocks and 3% of the mined-out area (Nikitin, 2003). Some of the spontaneous collapses mentioned by mining surveyors cannot be recognized on the surface and some seen on the surface have not been reported. The water regime of subsidence differs from that of spontaneous collapses. Some specific indexes of mining method and technology, which impact the environment, are presented in Table 2.1.1.1.

Table 2.1.2.1. Some geotechnical indexes of mining method and technology (Toomik, 1999; Reinsalu *et al*., 2002)

Mining method	Mining technology	Topography	Mining seam thickness, m	Caves height (opinion) after subsidence, m	Maximal subsidence, m
Longwall mining	Advancing-and-retreating mining	Deformed, lightly undated, stable	2.2	1.1-1.3	0.6-0.7
	Hand-mined	Deformed, undated, stable	2.2	1.0-1.2	0.8-0.9
	Longwall face with continuous miner	Deformed, undated, stable	1.6-2.3	0	1-2
Room-and-pillar mining	Short-term prevention	Not deformed, flat, unstable, spontaneous subsidences	2.8	1-2	1.5-1.7*
	Permanent prevention	Not deformed, flat, stable	2.8	2.8	0.02

* by spontaneous subsidence

2.2 WATER RESERVOIR CHARACTERISTICS

Water reservoirs can be found in almost all underground mines after termination of exploitation and closing of mine workings. Oil shale mining forms large areas of horizontal zones of empty openings and voids, which are defined, after flooding of the mine, as mine water reservoirs in closed mines.

2.2.1 Groundwater boundaries

In terms of groundwater formation and circulation, the groundwater system in the Estonian oil shale deposit can be divided into five principal hydrostratigraphic units. The author of the thesis has focused on the Quaternary and Ordovician aquifers, because these are most closely related to oil shale mining.

For the shallow groundwater of the Quaternary and Ordovician aquifers, the groundwater watershed is the same as the surface-water watershed: the Pandivere Upland in the west and the Narva River in the east. Due to intensive groundwater extraction, an extensive drawdown of piesometric head has formed in the Ordovician aquifer system.

2.2.2 Aquifers and aquitards

The hydrogeological properties divide the water-bearing formations into aquifers and aquitards. An aquifer is a relatively homogeneous water-bearing layer of rock with uniform hydraulic conductivity and sufficient storage capacity to yield water in adequate quantities for extraction and utilization. An aquitard is a layer with low hydraulic conductivity, constituting a natural hydraulic barrier between adjacent aquifers and having a water flow that may be orders of magnitude lower than the flow in the adjacent aquifers. The stratigraphic sequence of the Estonian oil shale deposit comprises 5 significant aquifers (Figure 2.2.2.1) separated by aquitards. Hydraulic properties of the aquifers are summarised in Table 2.2.2.1.

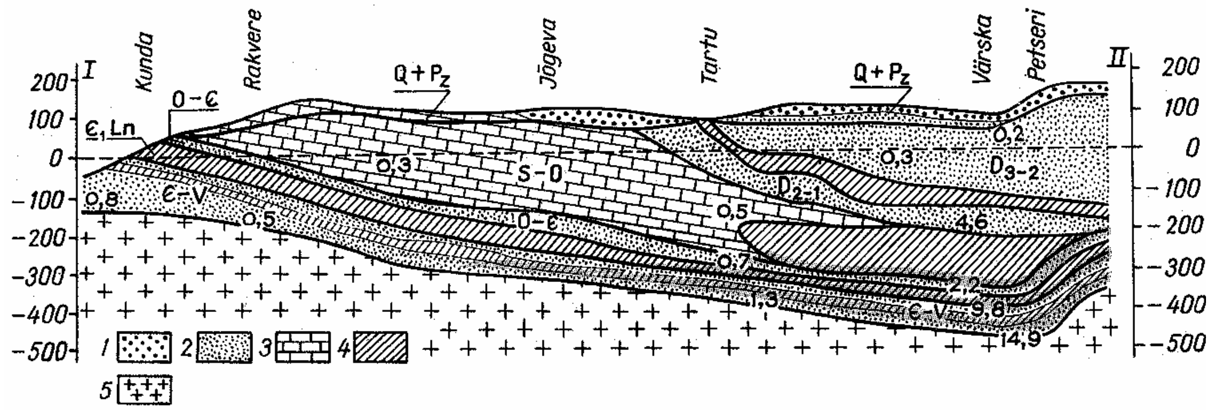


Figure 2.2.2.1 Hydrogeological cross-section of the Estonian bedrock (compiled by V. Karise; Vallner, Heinsalu, 1995): 1 – Quaternary deposits; 2 – terrigeneous (sand- and siltstone) water-bearing rocks; 3 – carbonaceous (lime- and dolostones, marl); 4 – sporadically water-bearing and impermeable rocks (clay, limestone); 5 – crystalline basement.

Table 2.2.2.1. The hydraulic properties of aquifers in the Estonian oil shale deposit (Perens *et al.*, 2001)

Age	Aquifer or aquifer system	Rock type	Depth, m	Thick-ness, m	Water table (piezo-metric), m below surface	Specific capacity, l/sec/m drawdown	Hyd-raulic conduc-tivity, m/day	Trans-missi-vity, m^2/day
Quaternary	Q	Sand, till, peat	0	0-77	+0.3-16	0.001-54	0.02-175	0.1-1980
Devonian	Narva D_2nr	Silt-stone, marl	1-20	0-31	0.6-4.3	0.002-0.24	0.06-3.4	0.26-16.8
Ordovician	Nabala-Rakvere O_2nb-rk	Lime-stone, marl, dolo-stone	2-20	0-50	+0.1-13.2	0.025-11.0	0.40-185	4-2546
	Keila-Kukruse O_2kl-kk		0.5-50	0-44	0.2-28.2	0.007-8.3	0.04-170	0.03-2308
	Lasnamäe-Kunda O_2ls-kn		0.5-100	17-24	0.6-15.6	0.001-2.1	0-48	0.01-187
Cambrian	Ordovician-Cambrian O-C	Sand-stone	30-120	11-22	3.0-20.0	0.08-2.2	1.5-3.5	30-50
Vendian	Voronka V_2vr	Sand-stone	80-170	30-45	34-104	0.2-2.5	5-6	50-140
	Gdov V_2gd		160-300	10-50	21-95	0.2-2.6	3-5	30-150

Quaternary deposits comprise a thin layer of peat, sand and till and unconsolidated glacial sediments that constitute porous aquifers with mainly unconfined groundwater (Perens, Vallner, 1997; Perens, 1998) influenced directly by the meteorological conditions. The surface water percolates directly into the Quaternary cover, and most of the groundwater flows through the cover as the groundwater discharges into springs, streams, rivers and wetlands. The main, Quaternary aquifer in the oil shale deposit is the Vasavere buried valley, which is up to 70 m deep and filled with sand and gravel (Paper II) with very high hydraulic conductivity and storage capacity.

Narva sporadically water-bearing aquifer (D_2nr) occurs at the Narva River and to the south from the Narva Water Reservoir. The aquifer consists of Devonian dolostones, siltstone and marl (Perens, Vallner, 1997). The upper part of the aquifer is weakly water-bearing, whereas the lower part serves as a regional aquitard for the whole Baltic artesian basin.

Ordovician aquifer system (O) consisting of lime- and dolostones with clayey interlayer lenses is found below the shallow cover of the Quaternary deposits across most of the East-Viru County. The limestone may be divided into a near-surface karst aquifer, cutting across the stratigraphic units, and several deep fracture aquifers, corresponding to the stratigraphic units (Vallner 1996; Vallner, Savitskaja, 1997; Perens, 1998.). The upper part of the Ordovician system is heavily karstified and fissured to a depth of 30–40 m (Perens *et al*., 2001), with deep vertical fissures and karst cavities up to half a metre in diameter, forming open channels or filled by sand and soil from the surface. The karstified zone is an excellent aquifer, with high storage capacity and hydraulic conductivity in the karst fractures and cavities. The karst aquifers are closely coupled with the overlying Quaternary aquifers; the karst aquifers are inseparable from the Quaternary aquifers at locations where sand and soil from the surface have been washed or fallen into the fractures and cavities of the karst aquifer. The deeper horizons, where water storage and flow is limited to fractures, are generally poor aquifers; at some locations they may even be weak aquitards. The individual limestone aquifers are separated from each other, both vertically and horizontally, by aquitards of clayey shale. One of these aquitards is the kukersite oil shale. According to the data from 235 pumping tests (Riet, 1976) carried out during oil-shale exploration, the lateral near surface hydraulic conductivity of the Ordovician limestone is in the range of 5–300 m/d, whereas it is only 0.1 m/d (Riet, 1976) at a depth of 80–100 m. The vertical conductivity of the clayey layers separating the water-bearing zones is 10^{-5}–10^{-2} m/d (Vallner, 1980; Jõgar, 1983; Perens, Savitski, 2000). Therefore, these clayey layers serve as aquitards, dividing the limestone into many local aquifers of different vertical and horizontal extent. The water flow in the karst fractures and in the cavities is relatively fast, resulting in good water yields; thus, the specific capacity of wells tapping the upper portion of the aquifer system is in the range of 0.001–11 l/sec/m drawdown, with an average of 0.5–3 l/sec/m (Perens, Vallner, 1997) drawdown.

Ordovician–Cambrian aquifer (O-Є) consists of fine-grained sand- and siltstone of the Lower-Ordovician Pakerort Stage and the Lower-Cambrian Pirita Stage. The thickness of the aquifer is 11–22 m (Perens *et al*., 2001). The hydraulic conductivity is mostly in the range of 1.5–3.5 m/d, and the transmissivity 30–50 m^2/d (Perens *et al*., 2001).

Cambrian–Vendian unites represented by terrigeneous sandstone and calcareous siltstone are found as major horizons below the Ordovician limestone, and as thinner layers within the limestone. The Cambrian–Vendian aquifer is the most important source of public water supply throughout northern Estonia (Savitski, 1999). The aquifer system comprises the Voronka aquifer, utilized throughout northeastern Estonia, and the deeper Gdov aquifer. The Gdov aquifer thins towards the south-east, which limits its use to the western part of the East-Viru County. These rocks form porous aquifers, isolated from each other by aquitards of clayey shale. The groundwater in the deep strata is old and replenished very slowly due to the great thickness of the Cambrian "blue clay" and the Vendian Kotlin shale (clay).

Crystalline basement (PR) consists of igneous and metamorphic rocks, with groundwater flow restricted to fractures. The groundwater contains high concentrations of total dissolved solids (TDS) (Savitski, 2000); under natural conditions, the groundwater is almost stagnant. The lower portion of the crystalline basement serves as an impermeable base for all overlying water-bearing formations in Estonia.

2.2.3 Groundwater recharge sources, flow systems and discharge areas

The groundwater is recharged by percolation of rain and melt water through the unsaturated top soils. The annual precipitation varies between 500–750 mm/y or 1370–2060 $m^3/(d \cdot km^2)$ (Vallner, 1997) in the oil shale area. The main recharge is the Pandivere Upland, from which groundwater flow is directed to the Gulf of Finland and to the Narva River. The upper unconfined Quaternary and Ordovician aquifer systems are recharged by precipitation, and their vulnerability totally depends on the thickness and permeability of the superficial cover layers. In the outcrop areas, the Ordovician aquifer is recharged from the Quaternary deposits and, therefore, this aquifer can easily be polluted in areas with a thin Quaternary cover.

The local flow system mainly comprises the unconfined (or locally confined) shallow groundwater, moving from its recharge area toward the nearest ditches and rivers, and discharging directly into the sea. The total net infiltration first enters the Quaternary cover; part of the groundwater flows downward into the underlying bedrock, part discharges through springs or flows directly into the sea. In order to dewater the oil-shale mining areas, 159–226 millions m^3 of groundwater depending on the amount of precipitation (Kattai *et al.*, 2000) were extracted in northeastern Estonia in the 1980s. To date, oil shale is excavated in Viru and Estonia underground mines. For excavation of oil shale the mines must be dewatered. In the region of oil shale mining on an average 15 million m^3 of water is being pumped out of mines monthly (Fig. 2.2.3.1).

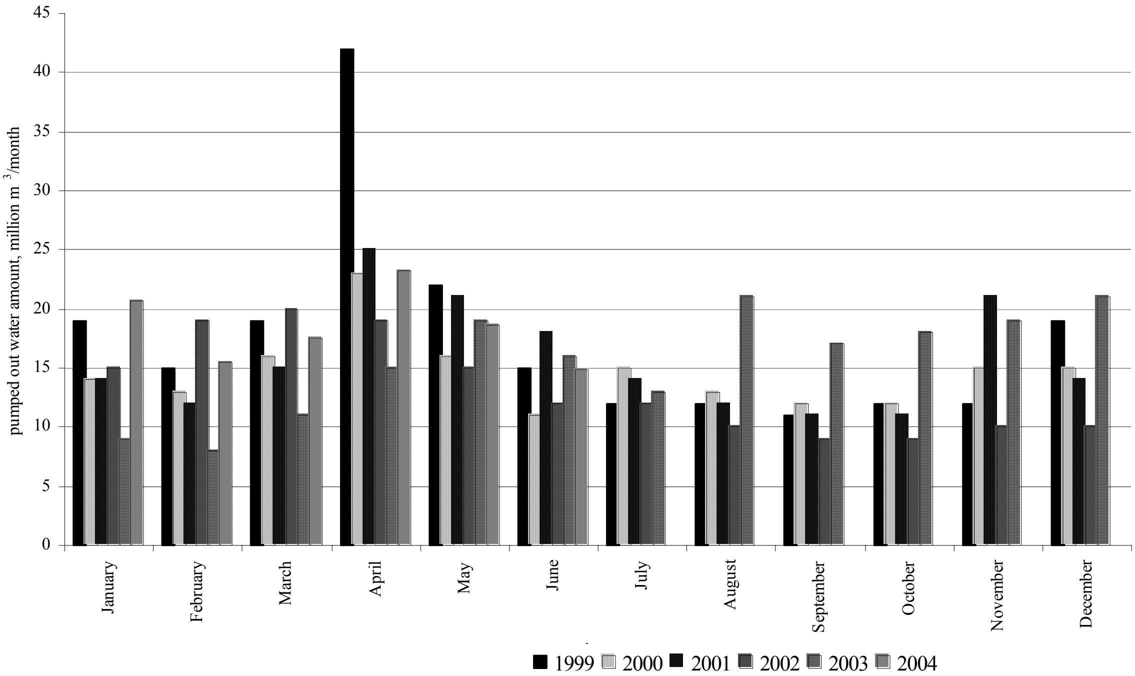


Figure 2.2.3.1 The amount of water pumped out from surface and underground mines monthly (Paper III)

3. MATERIAL AND METHODS

3.1 GROUNDWATER MONITORING

The groundwater level and chemistry observations were carried out in different monitoring areas (Table 3.1.1) where the natural groundwater regime has been affected by mining.

Table 3.1.1 Database of groundwater observation wells and analyses

Institution	Area	Ground-water level/ surface water table	Ground-water chemistry
Estonian Geological Survey observation wells	Dewatering impact to groundwater in mine area	44	13
	Closed mine impact to groundwater	2	2
	Groundwater observation in Vasavere buried valley	28	10
Estonian Oil Shale Company observation wells	Dewatering impact to groundwater in mine area	28	-
	Closed mine impact to groundwater	23	4
Author's research	Dewatering impact to groundwater in mine area	20	10
	Closed mine impact to groundwater	2	2
	Surface water (lake) observation in Vasavere buried valley	5	33
	Groundwater observation in Vasavere buried valley	5	3

The official data on the chemical content of water and water regime were received from the Estonian Oil Shale Company for the period 1991–2004 and from the Geological Survey of Estonia for the period 1970–2004. The author carried out hydrogeological studies in the closed mines area and lakes of the Vasavere buried valley in 1982-1993 and 2004. During the investigations samples were taken from tectonic faults, karst fissures, mine dewatering system in Viru and Estonia underground mines, and pumped public supply and private boreholes in the surroundings of closed mine to describe the content of sulphate in the Keila–Kukruse and Lasnamäe–Kunda aquifers. Groundwater samples were obtained from permanently installed groundwater monitoring wells. The chemical analysis of more than 20 constituents was carried out from each of the up to 70 sampling sites. Sulphate-ion is the most important indicator in the underground mining area. Springs, lakes and rivers were also sampled to get a reasonably complete hydrochemical understanding of the hydrogeological cycle in this area.

3.2 HYDROGEOLOGICAL MODELLING

To investigate water movement different hydrogeological models have been compiled by various institutions and authors. In the Geological Survey of Estonia, Vallner (2003) constructed a hydrogeological model for the Estonian territory and adjacent areas, covering a total of 88 032 km^2. The 13 model layers include all main aquifers and aquitards from the ground surface down to the impermeable part of the crystalline basement. Three-dimensional distribution of groundwater heads, flow directions, velocities, and rates as well as transport characteristics can be simulated by this model. Groundwater flow of the oil shale mining area was modelled by Savitski and Savva (Savitski, Savva, 2001; Savitski, 2003).

A hydrodynamic model predicts the surface elevations and current velocity field across the model grid (Paper IV). It provides the flow data that can be used to run other models such as water quality (Paper IV). A water quality model simulates the chemical reactions that take place within the modelled underground water basin. Depending on the requirements of the study the simulation can be limited to a single or some determinants. In papers II and IV sulphate transport processes are explained using different types of models. In the central part of the oil shale mining area the sulphate distribution in the groundwater of Quaternary deposit (Paper II), Keila-Kukruse and Lasnamäe-Kunda aquifers

(Paper IV), and the closed mine water level were modelled. The used software was MapInfo Professional together with spatial analysis modelling package Vertical Mapper. Comparing intermediate results, calibration can be achieved by different interpolation methods (Badman *et al*., 2000), including triangulations with smoothing, inverse distance weighting, rectangular (bilinear), kriging, custom point estimation and natural neighbour. The latter is the most suitable interpolation method for sulphate distribution and water level was natural neighbour (NN) (Paper IV). This area stealing method creates natural neighbourhood regions for each data point and each grid cell. Cell values are derived using a point-weighting system based on the area of overlap of the grid cells natural neighbourhood region and the regions of surrounding data points. Therefore, it is important that the tool used is demonstrated to be suitable for the problem to be solved.

4. GROUNDWATER QUANTITY AND SULPHATE DISTRIBUTION THREATS

4.1 SURFACE AND GROUNDWATER SULPHATE CONTENT IN PRE-MINING TIME

4.1.1 Surface and shallow groundwater sulphate content in the Vasavere buried valley

Natural water quality in the surface water results from the influences of the following three factors: the chemistry/mineralogy of the deposit the water contacts, water contact time and flow path. The data available on the state of lake water sulphate content before World War II is quite limited. However, the earliest published data, characterising the water sulphate content of Kurtna lakes (Fig. 4.1.1 A) at the end of the 1930s can be found in literature (Riikoja, 1940). In 1937, the sulphate content was in the range of 1-7 mg/l (Paper II) in the lakes and, presumably, also in the groundwater. Variations in the sulphate content seem to have been caused mainly by natural factors in the lakes or surrounding deposits. At that time the land use was rather modest and the area was sparsely populated. The location of lakes (Fig. 4.1.1 A) and the content of sulphate compounds in the water of the lakes in the Vasavere buried valley at the end of the 1930s are presented in Fig. 4.1.1 B.

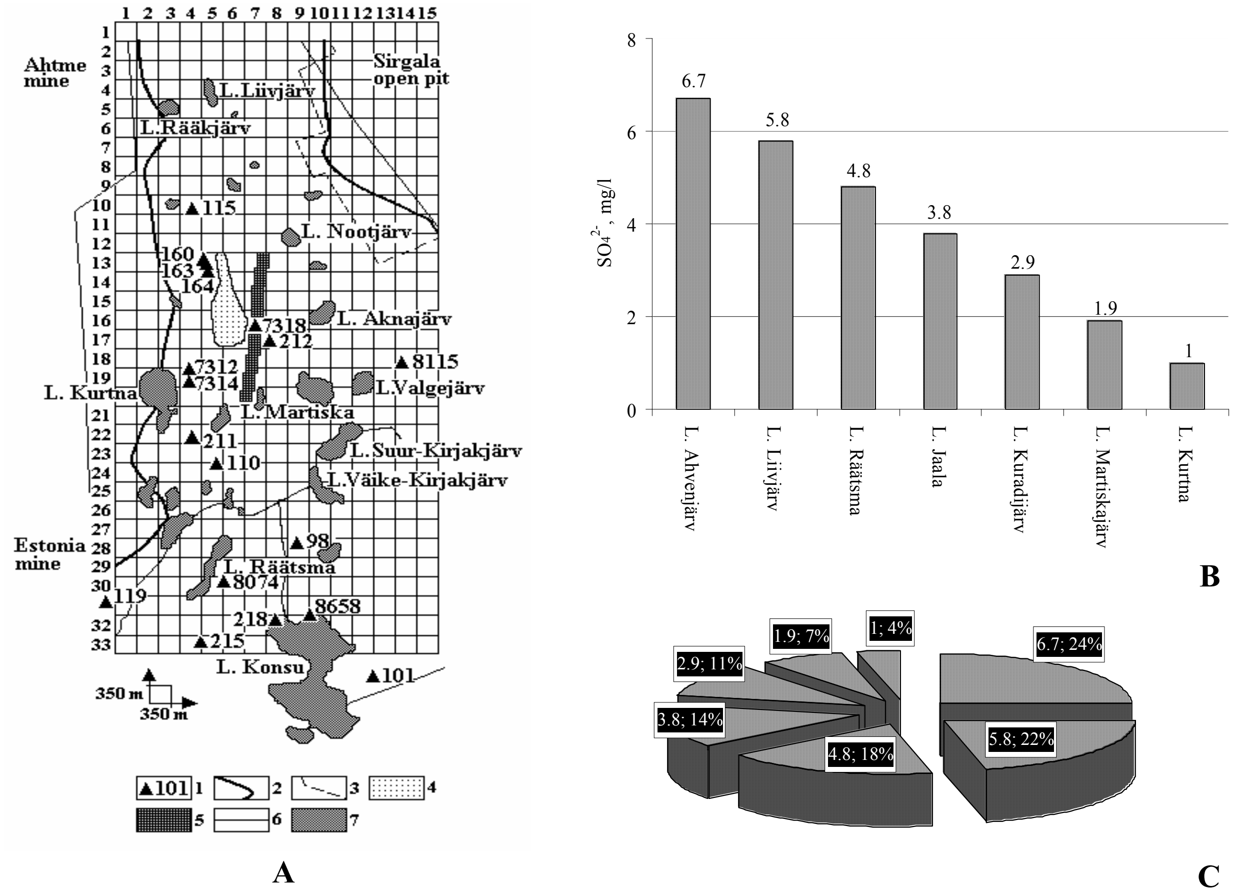


Figure 4.1.1. Location of Kurtna lakes (A) (Paper II): 1 – well of Quaternary aquifer, 2 – boundary of the buried valley, 3 – peat cutting area, 4 – sand pit, 5 – water intake, 6 – boundary of surface and underground mines, 7 – lakes in the Vasavere buried valley; the sulphate content of some lakes in August 1937 (Riikoja, 1940) (B, C).

In the Vasavere buried valley down to the depth of 70 m the groundwater was of HCO_3–Ca–Mg type with a mineralization of 0.5 g/l (Riikoja, 1940). Modelling based on the oldest available data suggested low sulphate content in both the lakes and shallow groundwater in August 1937 (Fig. 4.1.2).

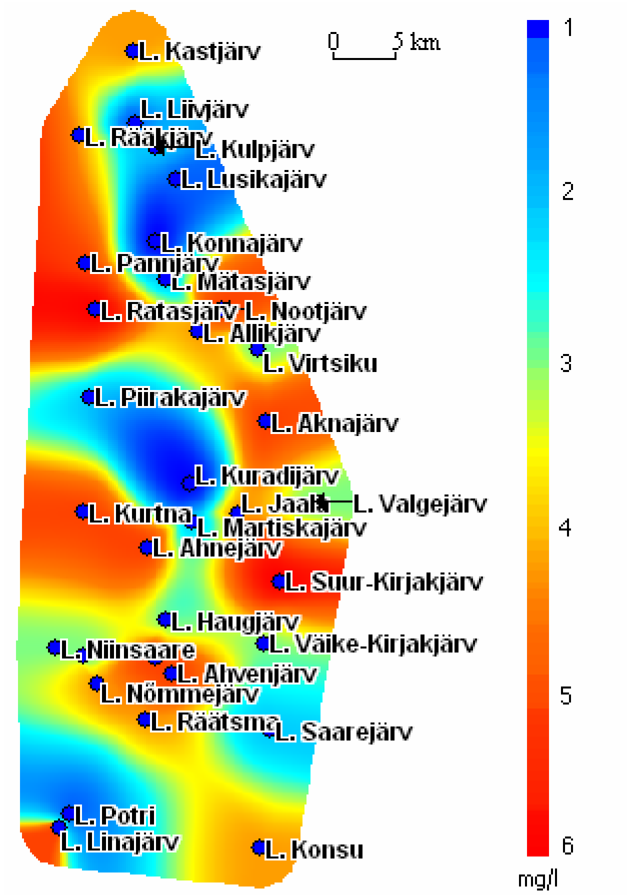


Figure 4.1.2. The sulphate content in lakes and shallow groundwater in August 1937

From the figure follows that part of the lakes (Ratasjärv, Ahvenjärv, Rääkjärv, Ahnejärv, Aknajärv, Kastjärv, Suur-Kirjakjärv, Pannjärv, Räätsma, Jaala and Nootjärv) feed from groundwater. Evidence is derived from the high sulphate content (4–7 mg/l) in the water. In the lakes, where it is lower than 4 mg/l the groundwater feed is insufficient and the sulphate content in the lake water is affected by the chemical or mineral composition of different deposits (L. Kuradijärv, Kulpjärv, Saarejärv, Konnajärv, Mätasjärv, Väike-Kirjakjärv, Allikjärv, Liivjärv, Lusikajärv, Nõmmejärv, Piirakajärv, Valgejärv, Haugjärv, Mustjärv, Niinsaare, Potri, Särgjärv, Linajärv, Martiska, Konsu, Virtsiku and Kurtna).

Comparing the recent data with those from the end of the 1930s, it is possible to evaluate the extent of man-made changes, first of all, in lakes and, supposing that the sulphate content of the groundwater was approximately the same, in the shallow groundwater as well (Fig. 4.2.2.1, Paper II).

4.1.2 Groundwater quality of oil shale deposit

Monitoring of groundwater in the mining area was started in the 1960s. Groundwater is characterised by a high content of hydrocarbonate, calcium ions, and a low content of sulphate (Karise *et al.*, 1982; Vallner, 1994). There is no essential difference between the groundwater in the Keila–Kukruse and the Lasnamäe–Kunda aquifers (Table 4.1.2). In 1982, we (Karise *et al.*, 1982) studied the following observation wells: 1099 (Tammiku mine), 486 (Sompa mine), 8214A (Kukruse mine) and 3a (Mine no 4), which belong to the groundwater monitoring network of the Geological Survey of Estonia and are in use until today.

Table 4.1.2. The chemical composition of water in the Ordovician aquifer system in underground mine areas in 1985-2004 (Karise *et al.*, 1982; Erg, Punning, 1994; Savitskaja, 1999; Erg, 2000; Perens, 2005; Paper IV).

Index; elements	Number of analyses		pH	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+
Ordovician aquifer	Mine ceiling, wall	Tectonic faults, karst		mg/l					
Overlying	28	15	7.4-7.5*	287-424*	3-10*	2-10*	34-77*	22-39*	6-14*
Underlying	22	20	7.4-7.6*	275-342*	5-15*	2-10*	40-94*	6-28*	2-12*

*chemical composition of water in tectonic faults and karst

The data presented in Table 4.1.2 were obtained (Karise *et al.*, 1982) by regular long series of analysis of water samples, taken from the mine ceiling, wall and containing water flowing out of the undamaged bed at the time Ahtme, Viru and Estonia mines were working. Tectonic faults and karst play an essential role in the formation of the chemical composition of water, especially at local scales. In that case, the value of the hydraulic conductivity increases and intensive efflorescence of chemical elements takes place. In the oil shale deposit where tectonic faults are widespread general mineralization was approximately twice as high as that usually characteristic of a water aquifer. The concentrations of Na, Ca, Cl and SO_4 are also higher in Viru and Ahtme mines close to the Ahtme tectonical fault (Table 4.1.2).

4.2 WORKING MINE IMPACT ON THE SURFACE AND GROUNDWATER REGIME AND CHEMISTRY

4.2.1 Underground mining impact on the groundwater regime

Observation wells are located relatively unevenly in the underground mine and surrounding area. The density of groundwater observation wells is high in the Vasavere buried valley, in the area of Sompa mine and Mine no. 4 (Fig. 4.2.1.1). Surface water was studied in 33 lakes within the Vasavere buried valley.

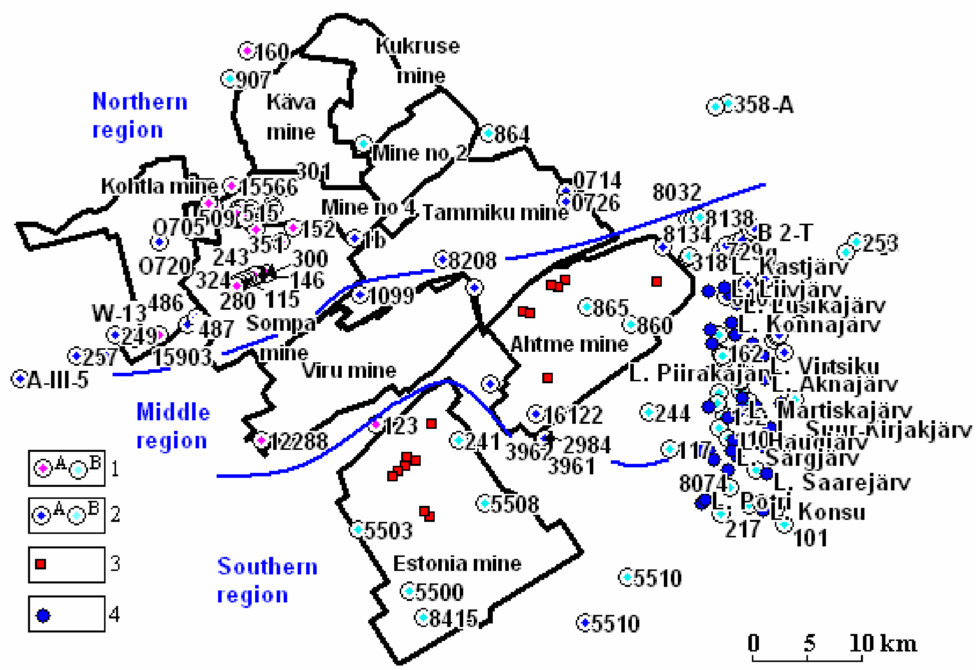


Figure 4.2.1.1 Location of observation wells in the underground mine area, and lakes in the Vasavere buried valley: 1 – water level and chemistry observation well in the Keila–Kukruse (A) and Lasnamäe–Kunda (B) aquifer, Geological Survey of Estonia; 2 – water level observation well in the Keila–Kukruse (A) and Lasnamäe–Kunda (B) aquifer, Estonian Oil Shale Company; 3 – observed groundwater in karst and tectonical faults; 4 – monitored lakes.

According to hydraulic properties (Table 2.2.2.1), the oil shale mine area can be subdivided into three major regions (Paper I): northern, middle and southern (Fig. 4.2.1.1, Table 4.2.1.1). The northern and middle regions are embraced by the Keila–Kukruse water aquifer with the maximum bedding depth of 50 m.

Table 4.2.1.1 The structure of regions and hydraulic conductivity of sedimentary rocks in underground mines (Paper I)

Region	Depth of bedding of industrial layer, m	Hydraulic conductivity, m/d	Aquifers	Type of feeding regime of aquifer	Mines
northern	0...25	20...70	Keila–Kukruse	infiltration, free-surfaced	Kukruse, Käva, Mine 2, Mine 4, Kohtla, Tammiku, Sompa
middle	25...50	15...20	Keila–Jõhvi, Idavere–Kukruse	infiltration, free-surfaced, pressurized, insufficient infiltration in the southern part of middle region	Sompa ja Tammiku southern part, Viru, Ahtme
southern	50...70	< 10	Nabala–Rakvere, Keila–Jõhvi, Idavere–Kukruse	insufficient infiltration, pressurized	Estonia

The Ordovician aquifer spreads under a thin layer of Quaternary deposits, being considerably split. According to this, the infiltration of atmospheric precipitation is highest in the northern region. In the middle region both feeding and outflow conditions change due to different hydraulic properties (Table 2.2.2.1) of the rocks. Hydrogeologic conditions in the southern region are more complicated than in the northern and middle region, because of very irregular hydraulic properties of the Nabala–Rakvere aquifer.

Underground mines have the potential to impact surface, but especially groundwater systems on a relatively large scale. Mining in the oil shale deposit, started in 1916, has changed the groundwater regime and water chemistry. In the flat-lying sedimentary rocks underground mining is routinely accompanied by rock fracturing, dilation of joints, and separation along bedding planes. Rock movements occur vertically above the mine workings and at an angle projected away from the mined-out area. These changes in the rock mass alter the water transmitting capabilities (Table 4.2.1.2) of the limestones of the Nabala–Rakvere (O_2nb-rk) stages in the southern part of the oil shale deposit; the limestones of the Keila–Kukruse (O_2kl-kk) stages throughout the oil shale deposit; and the limestones of the Lasnamäe–Kunda (O_2ls-kn) stages throughout the oil shale deposit by creating new fractures and enlarging the existing ones. This typically results in detectable changes in permeability, storage capacity, groundwater flow direction, groundwater chemistry, surface water contact with groundwater, and groundwater levels. Groundwater inflow from the Keila–Kukruse aquifer is biggest in closed and working underground mines (Table 4.2.1.2) (Savitski, 2000).

Table 4.2.1.2. The contribution of different aquifers to the formation of mine water, based on long-term observations (Savitski, 2000).

Mine	Inflow, thousand m^3/d		The water aquifer, which forms the inflow, %			
	min	max	Q	O_2nb-rk	O_2kl-kk	O_2ls-kn
Kohtla	22	69			99.19	0.81
Ahtme	30	86	6.0	6.9	86.29	0.88
Tammiku	45	89			99.63	0.37
Viru	20	37		8.2	91.16	0.64
Sompa	45	151			99.65	0.35
Estonia	101	161		21.0	78.70	0.30

During oil shale mining the regional groundwater conditions have changed; however, local groundwater conditions within the oil shale area have experienced fluctuations over the years resulting from surface runoff events and pumping activities. Due to mining technology, the level of groundwater has lowered below the level of oil shale stratum. As a result of dewatering, the groundwater level of the Ordovician aquifer has lowered by 15 m in the north (1967–1975) and 70 metres in the south (Paper I); several local cones of depression, influencing each other, formed over an area of 600 sq km in the middle of the 1980s. Dewatering increased abruptly in the end of the 1970s and the tendency continued in the 1980s (Fig. 4.2.1.2). At that time the oil shale production was at its highest reaching 31 million tonnes.

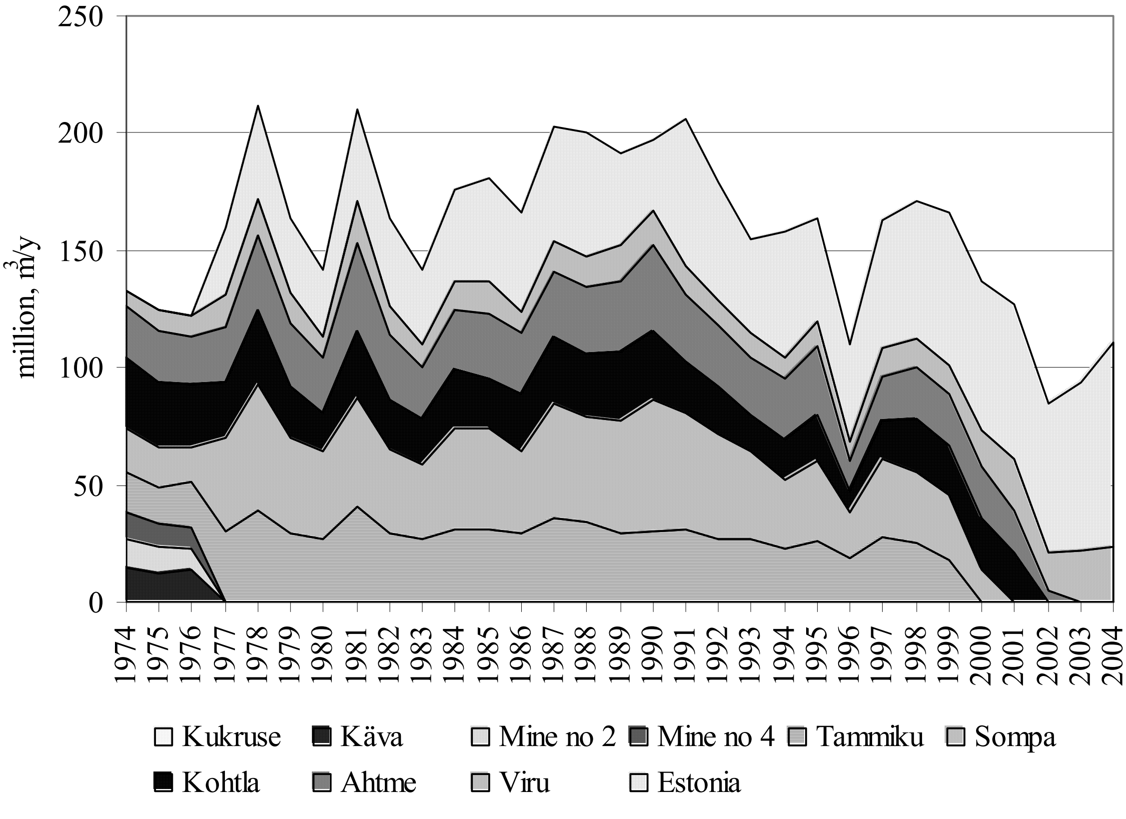


Figure 4.2.1.2 Dewatering of underground mines in 1974-2004.

The mine dewatering has been relatively constant during the period 1991–95, both in individual mines and in total, which has been in the range of 550 000–700 000 m^3/d (160–200 million m^3/y). In 2003 the annual water outlet of the mining enterprises in operation did not exceed 100 million m^3 after Tammiku and Sompa mine had been flooded. The water pumped out is directed through sedimentation pools into outlet channels and rivers discharging either into the Gulf of Finland or Lake Peipsi.

4.2.2 Underground mine impact on the surface and groundwater chemistry

Several studies (Ilomets, 1987; Ilomets, 1989; Punning, 1994; Domanova *et al.*, 1995; Domanova, Krapiva, 1996; Domanova, Fyodorov, 1997; Liblik, Punning, 1999; Savitski, 1999; Erg, 2000; Punning, 2000; Savitski, 2000) have been completed in the oil shale deposit, especially in the Vasavere buried valley with regard to the lake water quality.

The rise in the sulphate content of lake water is evidently due to human impact. In recent years the content of sulphate has increased both in the closed lakes and in those (L. Nõmmejärv, Särgjärv, Ahvenjärv and Konsu) influenced by mining waters directly (discharge) in the southern part of the Vasavere valley or indirectly (infiltration lakes Kastjärv, Pannjärv and Rääkjärv) by mining dewatering system waters, having the sulphate values in the range of 160–259 mg/l (Paper II) (Fig. 4.2.2.1).

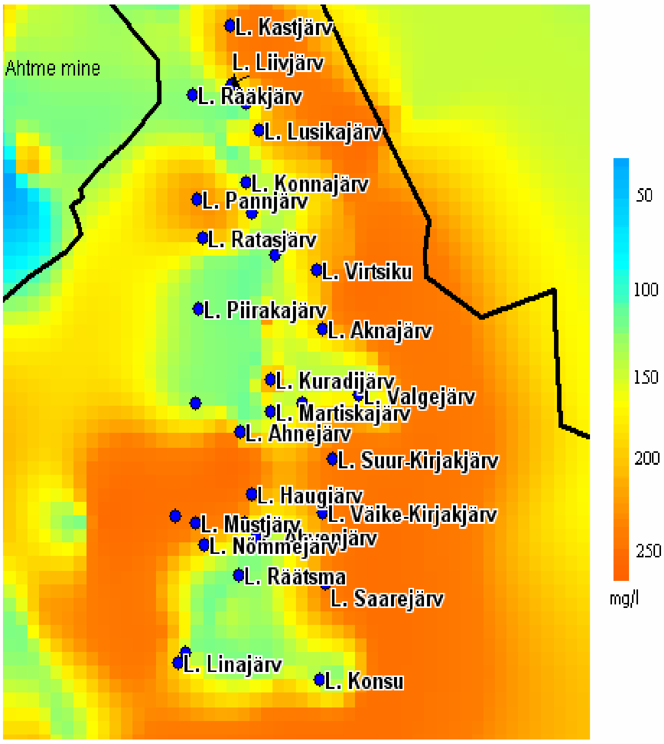


Figure 4.2.2.1. Sulphate content in the surface and shallow groundwater in 2000

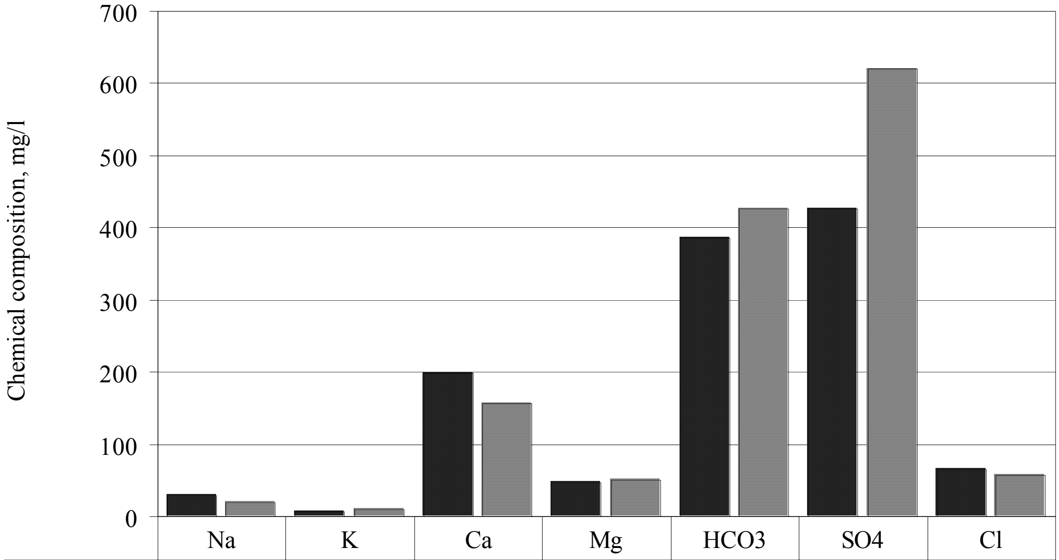
If, for example, in 1937 the sulphate content in the lakes Nõmmjärv and Konsu was 5.8 and 1.0 mg/l (Fig. 4.1.2), then in 2000 it was 259 and 184 mg/l (Fig. 4.2.2.1), respectively; in the shallow groundwater the content of sulphate increased more than 50 times during 1937–2000.

A very significant role in the formation of the chemical composition of groundwater is played by depressions that have developed during the exploitation of underground mines. Their impact is two-fold: infiltration and water exchange increase significantly and with the change of aeration conditions a geochemical environment with new physico-chemical properties is formed. In the mining processes pyrite (FeS_2) is extensively mixed with air oxygen. Significant enrichment of water with the sulphates takes place due to oxidation of pyrite found in the aeration zone of carbonate rocks. It acts directly in oxidizing the sulphide and the iron (II) as shown by the reaction (1) (Singer, Stumm, 1970; Karise *et al.*, 1982; Triegel *et al.*, 1993; Williamson, Rimstidt, 1994; Erg, 2000, Paper IV)

$$FeS_2 + 7/2\ O_2 + H_2O \longrightarrow Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+ \qquad (1)$$

or indirectly by generating Fe(III) which then oxidizes pyrite. The reaction formulas are as follows

$$FeS_2 + 14\, Fe^{3+} + 8\, H_2O \longrightarrow Fe^{2+} + 2\, SO_4^{2-} + 16\, H^+ \tag{2}$$
$$Fe^{2+} + \tfrac{1}{4}\, O_2 + H^+ \longrightarrow Fe^{3+} + \tfrac{1}{2}\, H_2O \tag{3}$$



	Na	K	Ca	Mg	HCO3	SO4	Cl
closed mine	30	7	199	47	385	426	65
active mine	20	10	156	50	427	620	57

Figure 4.2.2.2. Chemical composition of mine water (Karise *et al*., 1982; Paper III)

The water displayed neutral pH and positive Eh in the spring-summer period (Karise *et al*., 1982). These results reflect the increasing sulphide oxidation rate during the warm months leading to high (up to 500 mg/l) (Karise *et al*., 1982) concentrations of sulphate in the mine water. In other seasons the sulphide oxidation rate was low. The groundwater in the oil shale deposit is of $Ca(Mg)SO_4(HCO_3)$ type (Fig. 4.2.2.2).

4.3 HYDROGEOLOGICAL REGIME AND SULPHATE DISTRIBUTION IN THE CENTRAL PART OF THE OIL SHALE DEPOSIT IN POST-MINING TIME

Upon closure, the Ordovician aquifer system becomes highly permeable; this can permanently alter the pre-mining flow regime both physically and chemically. Due to the open nature of the mine-void aquifer, there is post-mining transfer of the resulting mine pool potential throughout the interconnected mine workings. This is an important factor regarding the potential for mine pool breakout since the areas within and adjacent to the down dip portions of the mine workings can often realize abnormally high post-mining heads comparative to pre-mining values.

4.3.1 Post-mining groundwater regime

When the underground mines are closed the pumping of water stops and the old shafts and tunnels fill up with water. The hydraulic conductivity is mainly determined by the degree of fracturing, by local karst and by human impact. As a rule, the hydraulic conductivity of host rock is at its highest near the surface and lowers gradually downwards. This causes the highest influx of shallow groundwater into shallow (40 m) underground mines (Table 4.2.1.1). Long-term observation results (Karise *et al*., 1982; Savitski, 2000) show that the inflow to the mines varies with the seasons. Of the total water amount 20% falls to the winter months, 29% to the spring months, 27% to the summer months and 24% to the autumn months. Rainfall is characterized by an inter-annual irregularity. The above shows that the inflow is irregular in mines. This is characterized by the irregularity coefficient, which is received when the maximal inflow is divided by minimal inflow ($K = Q_{max} / Q_{min}$); the daily coefficient of irregularity is between 2 and 30 in the oil shale deposit area (Figure 4.3.1.1)

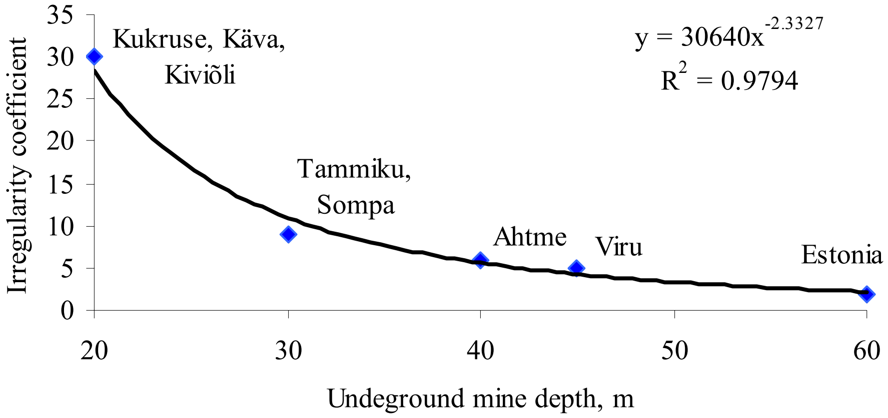


Figure 4.3.1.1 Irregularity coefficient dependence on the mine depth.

The weather impact on the mine decreases with the depth of the mine. Figure 4.3.1.1 shows that the coefficient of inflow irregularity decreases by 2.3% when the depth of the mine increases by 1%.

In the area of underground oil shale mines the water level was studied in about 70 wells. Fig. 4.3.1.2 shows only these wells, which are located in the closed Tammiku, Ahtme, Sompa and Kohtla mines.

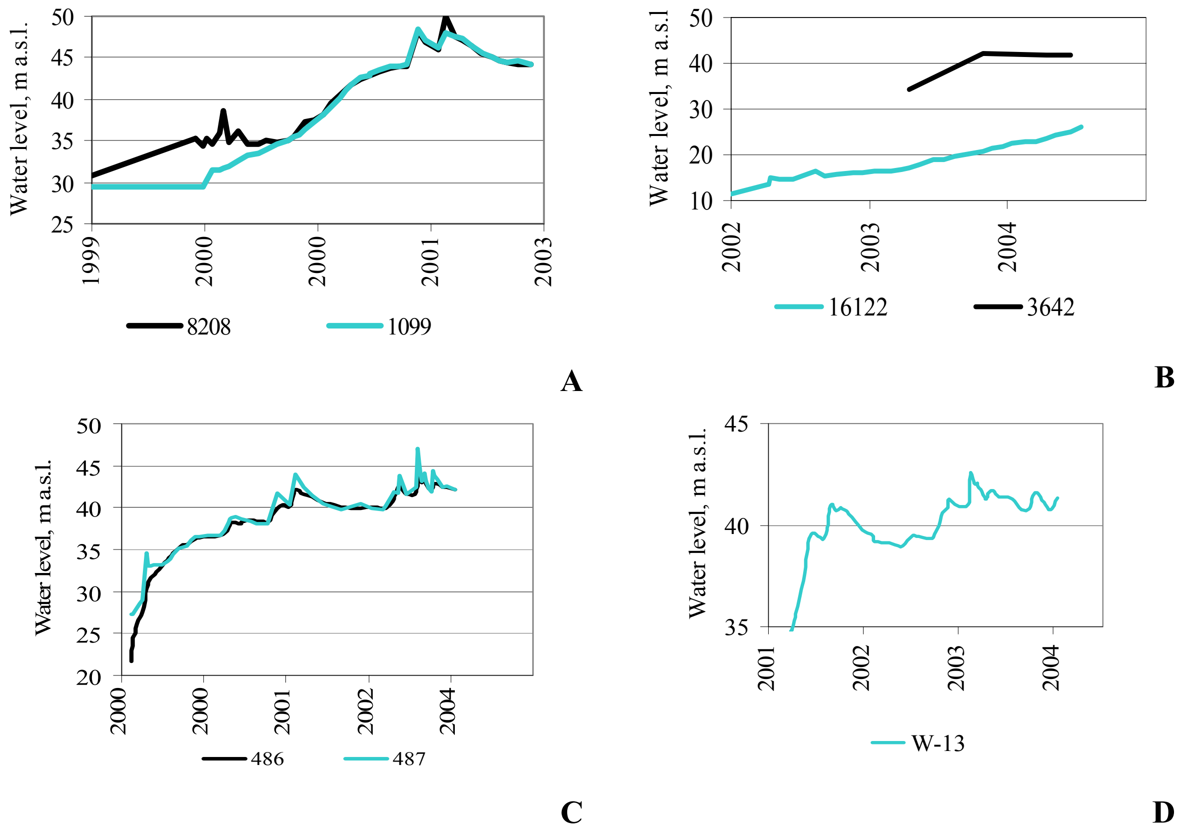


Figure 4.3.1.2 Flooding of underground mines: A – Tammiku; B – Ahtme; C – Sompa; D – Kohtla (Reinsalu *et al.*, 2004).

In underground oil shale mines, there may be a number of disconnected pools at the early stage of flooding. Before flooding water sub-pools may exist at various locations and elevations within the mine. The abundance of sub-pools is greatest at the back of the mine where recharge and leakage collect. These sub-pools tend to coalesce and form a main pool, which will rise from the back of the mine in an up-dip direction. As flooding progresses, the sub-pools join into a single main pool with big water volume (Table 4.3.1.1). However, the main pool may stabilize at a lower elevation, if water-control measures are implemented or the mine spills into an adjacent mine.

Table 4.3.1.1. Approximate water volume in closed underground oil shale mines

Underground mine	Work started	Closed (pumping stopped)	Water table in 2003, (Savitski, Boldõreva, 2005)		Mined out area, km^2 (Reinsalu *et al.*, 2002)	Water volume (approximately), 10^6 m^3	
			Obs.well no.	m, a.s.l.		(Savitski, Boldõreva, 2005) in 2003	Author's results, 2004
Kukruse	1916	1967	8214A	52	13	3.6	5
Käva	1924	1973	2	51.5	18	9	10
Kohtla	1937	28.06.2001	W-15	41	17	10	13
Ahtme	1948	1.04.2002	16122	25	35	60	63
Sompa	1949	2.12.2000	487	43	27	23	23
Mine 2	1949	1974	3a	51.41	13	7	7
Tammiku	1951	28.12.1999	714 8208 1099	47.95 50.04 47.92	40	~40	42
Mine 4	1953	1975	302 1b	41.18 40.26	13	1.4	2.0

The flooding situation is a transient scenario, while the flooded case is a steady state one. In transient groundwater flow systems, hydraulic head is continuously changing with time, with minor seasonal or annual fluctuations. In 2003, the volume of water in the pools of the closed underground mines was about 160 million m^3 (Domanova, 1999; Savitski, Boldõreva, 2005); in 2004 it amounted to 170 million m^3 (author's results) (Table 4.3.1.1).

The elevation of the water table in 1990 was about 42–53 m above sea level (Fig. 4.3.1.3 A) in Käva and Kukruse mines, Mine no 2 and Mine no 4.

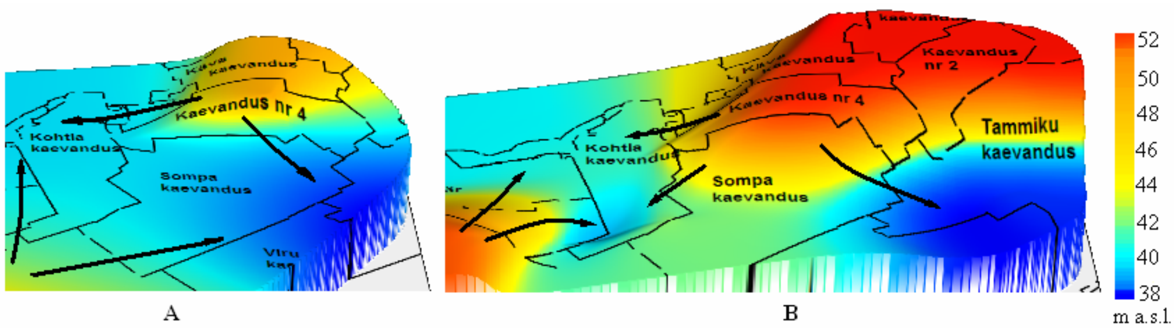


Figure 4.3.1.3. Water level in the Keila–Kukruse groundwater aquifer in 1990 (A) and in 2003 (B).

In 2004 it was hypothesized that much larger variation in the water level could occur as a result of technogenic karstification processes (Reinsalu *et al.*, 2004). In some cases, water levels in two or more adjacent mines will fluctuate in conformity with the seasonal or man-induced stresses. Hydrologic investigations indicate that the elevation of the water table has fluctuated over time, especially in Mine no 2. The maximum elevation was about 51 m above sea level, but seasonally it fluctuated between 50–56 m above sea level, primarily as a result of variation in climate and increased precipitation.

If the inflow rate is all the time greater than the outflow rate, the water storage and hydraulic head in the saturated portion of the mine will increase. If outflows are greater than inflows, then the hydraulic head will decline. During the rainy August of 2003, the water table rose 4 m in Sompa underground mine, 2 m in Kohtla, 2.1 m in Kukruse, 1.8 m in Mine no 4 and 0.5 m in Ahtme mine. Closed mines water filling and restoration of Keila-Kukruse underground water level in 2003 is presented in figure 4.3.1.3 B.

Estonia and Viru underground mines are advanced from shallow to deep cover and lie below regional drainage elevations. As mining progresses, groundwater can infiltrate into the mine. Therefore, the mine is progressively dewatered to allow mining to continue. As deeper mines are commonly separated from shallower up dip mines by thick barriers of unmined oil shale, the shallow closed mines may be flooded while deeper mining continues. One of several regulatory issues regarding the closure of such mines is long-term discharge of water after the mines have fully flooded. Following mine closure, pumping from the active mine is terminated and mine voids are allowed to re-saturate. Flooding of closed mines will generally continue until groundwater achieves a new equilibrium, either by surface discharge of mine water or by controlled pumping and treatment. Eight of the underground mines located in the central part of the oil shale deposit were flooded in 2004 by groundwater, which caused flooding in the northern part of Jõhvi Town.

4.3.2 Water sulphate content in closed mines

4.3.2.1 Sulphate content changes after mine closure

During mining the water level drowning and increasing aeration zone cause intensive pyrite oxidation, which is the biggest groundwater pollution problem associated with underground mining. After mine closure the water level rising and pyrite oxidation decrease. The most noticeable change will take place in the sulphate content. Evidently, the rise of sulphate anions (Fig. 4.3.2.1.1) in water has been caused by oxidation of pyrite in well-aerated water, which percolates down through the overburden. Mine pool water is a subset of groundwater, subject to broadly similar hydrochemical processes. In natural groundwater the sulphate content is very low (Table 4.2.1.3). In the water, which fills underground mines, the content of this element is high (Table 4.3.2.1.1 – Ahtme mine), but lowering and still stays 10 times higher than its natural background.

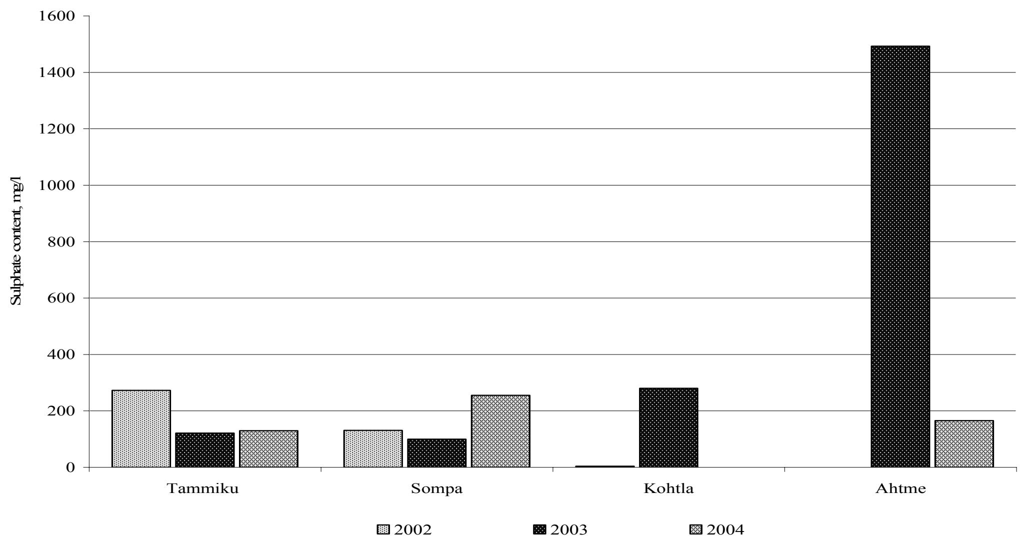


Figure 4.3.2.1.1 The sulphate content of groundwater in underground mines: Tammiku observation well no 0714; Sompa – 486; Kohtla – 0705; Ahtme – 16122 (Reinsalu *et al*., 2004).

This is naturally accompanied by intensive removal of the sulphates recharging Ordovician carbonate rocks. Significant enrichment of water with the sulphates takes place in the carbonate rocks in the aeration zone. There is increasing evidence that portions of the water infiltrating through the soil surface may move rapidly through the aeration zone along preferred flow paths such as macrospores and fractures. In many cases, the water has low pH and contains elevated levels of sulphate ions.

In recent years, in the area of oil shale mines, the chemical composition of groundwater has been stable. The content of SO_4 in groundwater was 2 times higher in spring (Fig. 4.3.2.1.2) than during the remaining seasons of the year. It can be caused by dissolution of pyrites in oxygen-abundant water in spring.

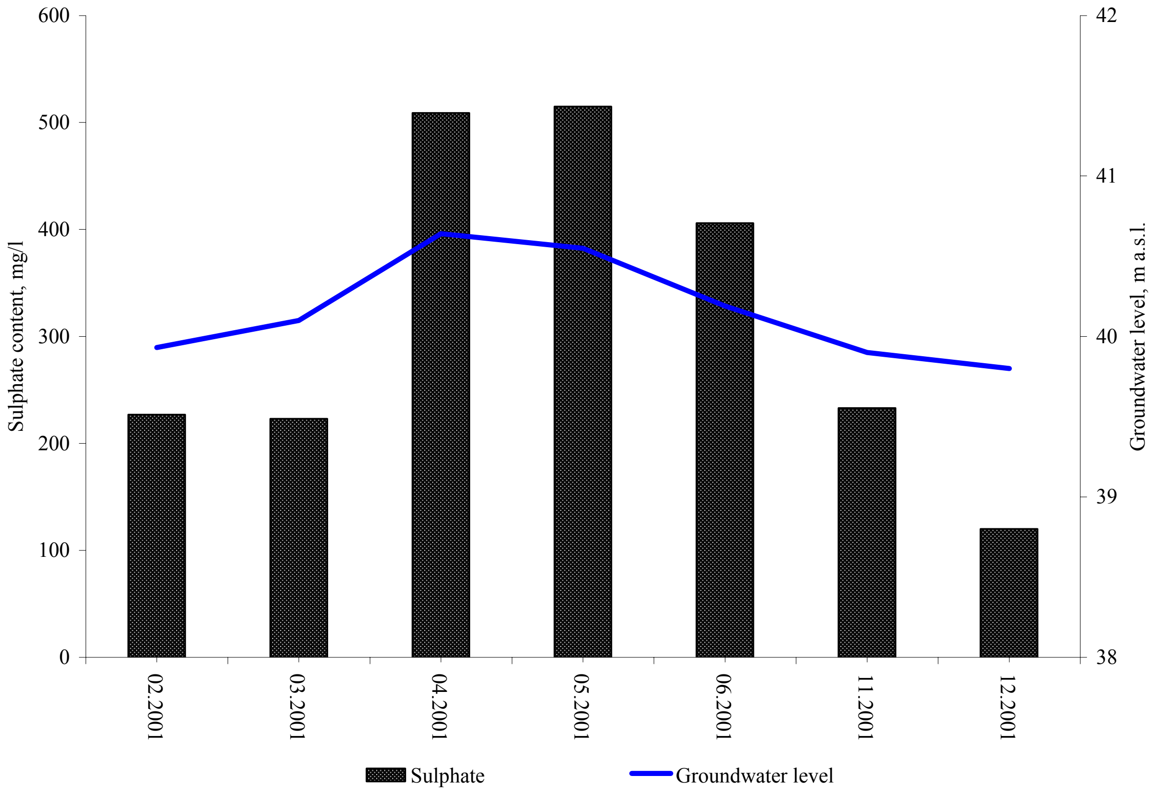


Figure 4.3.2.1.2 The sulphate content in the water of the underground oil shale Mine no 4 in 2001.

Mine No 4 closed in 1975 and in 1990 it was water filled. Mainly precipitation, groundwater flow from each side and water level rising caused fluctuations in the sulphate content in Mine No 4. The sulphate content in the water filling up mine is high; in the closed mines it is low (Fig. 4.3.2.2.1).

4.3.2.2 Lateral distribution of sulphate in the water of closed mines

Reasons may be in mine filling, which depends on precipitation and a consequence will be water level rising. This water washes the already oxidising pyrite products out of the limestone and the sulphate content in groundwater will increase. The sulphate may distribute in a lateral direction many times higher than in transversal direction. This may be explained with the permeability of groundwater aquifer or aquifer system. Sulphate distribution in underground mine water in 2003 is shown in Fig. 4.3.2.2.1.

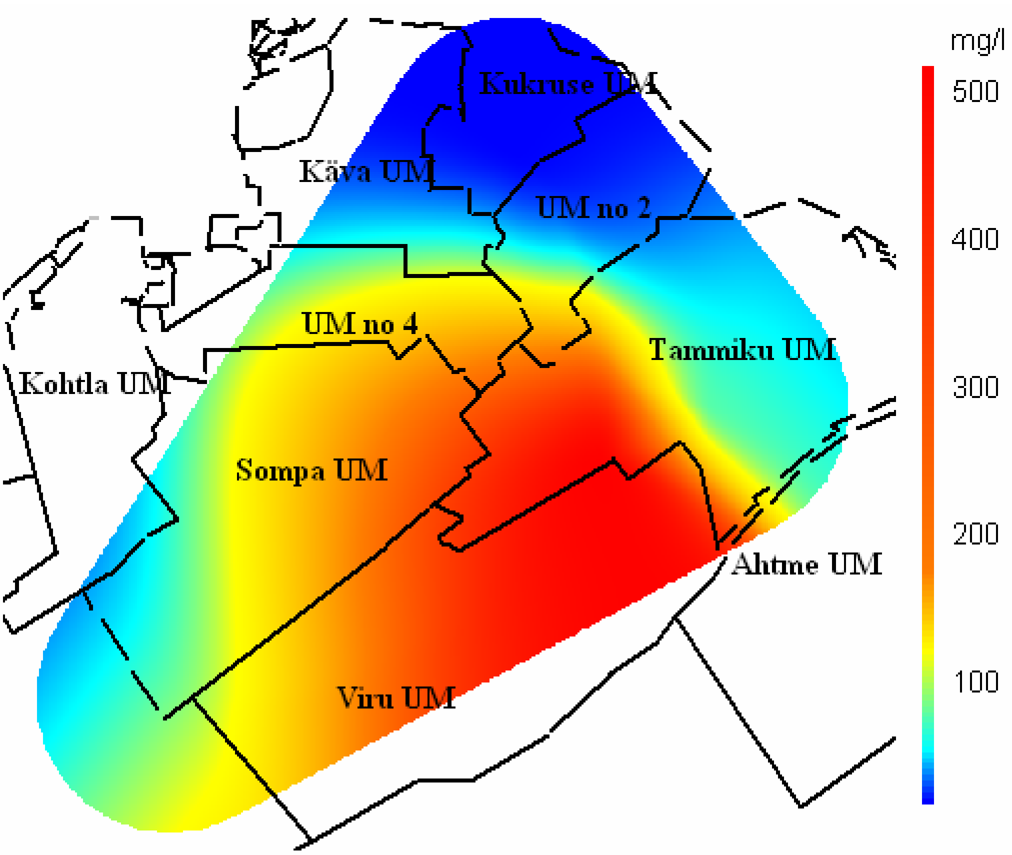


Figure 4.3.2.2.1 The sulphate content in the Ordovician Keila–Kukruse aquifer of underground oil shale mine area.

4.3.2.3 Transversal distribution of water sulphate from closed mines water pool to the Lasnamäe–Kunda aquifer

After the closing of oil shale mines the sulphate content in the Lasnamäe–Kunda aquifer is higher than the natural level of the same aquifer. The effects of mine filling and other closure measures can be evaluated on the basis of infiltration of Keila-Kukruse or mine pool water to the Lasnamäe-Kunda aquifer. Based on the chemical data of Lasnamäe–Kunda aquifer from the period of pre-mining time and after closure the amount of mine water in the above- mentioned aquifer can be estimated. Infiltration rate may be calculated from the equation (Cravotta, Kirby, 2004)

$$C = \frac{Q_{K-K}C_{K-K} + Q_{L-K}C_{L-K}}{Q},$$

where C – element content in mixed water,
$C_{K\text{-}K}$ – element content in the Keila–Kukruse aquifer,
$C_{L\text{-}K}$ – element content in the Lasnamäe–Kunda aquifer,
$Q_{K\text{-}K}$ – water amount in the Keila–Kukruse aquifer,
$Q_{L\text{-}K}$ – water amount in the Lasnamäe–Kunda aquifer,
Q =1, mixed water amount.

From here

$$Q_{K-K} = \frac{C - C_{L-K}}{C_{K-K} - C_{L-K}}$$

On the bases of this equation, it is possible to estimate the amount of water mixed in every single case. Judging by the sulphate content, the amount of water in the Lasnamäe–Kunda aquifer is relatively large in water pools of different underground oil shale mines (Table 4.3.2.3.1).

Table 4.3.2.3.1 The share of underground oil shale mine pool water volume in the Lasnamäe–Kunda aquifer by the sulphate content

Observation well (Savitskaja, 1999)	Underground mine	Mixed water sulphate content, mg/l	Sulphate content		Mine pool water capacity in the Lasnamäe-Kunda aquifer, %
			Lasnamäe-Kunda aquifer, mg/l	Keila-Kukruse aquifer, mg/l	
15955	Sompa	446	126	1196	30
19629	Tammiku	597	229	780	67
15485	Mine no 4	395	406	300	10
13513	Mine no 2	369	250.6	500	47
13583	Käva	323	171.6	1289	14
14388	Kukruse	159	140	200	32

In 2003, in the earliest closed underground mines (Kukruse, Mine no 2) the sulphate content was high in the Lasnamäe–Kunda aquifer. In the western part of Tammiku mine the Lasnamäe–Kunda aquifer was very high in sulphate (Fig. 4.3.2.3.1). This is promoted by karst and technogenic faults. The Ahtme mine water pool (Table 4.3.2.3.1) exerted a weak (27%) influence on the Lasnamäe–Kunda aquifer. In the southern part of Kohtla mine and in the northern part of Sompa mine the sulphate content in the Lasnamäe–Kunda aquifer was between 200-320 mg/l (Fig. 4.3.2.3.1). Mine no 4 and also Käva mine pools water amount in the Lasnamäe–Kunda was lower, 10 and 14%, respectively (Table 4.3.2.3.1), than in the other mines. In this region a relatively impermeable aquitard may be located between mine pool area and the Lasnamäe–Kunda aquifer. The distribution of sulphate in the Lasnamäe–Kunda aquifer may be due to the circumstance that the permeability of carbonated rock in a lateral direction can be up to 100 times higher than in a transversal direction. The same effect is observed in the Keila–Kukruse aquifer.

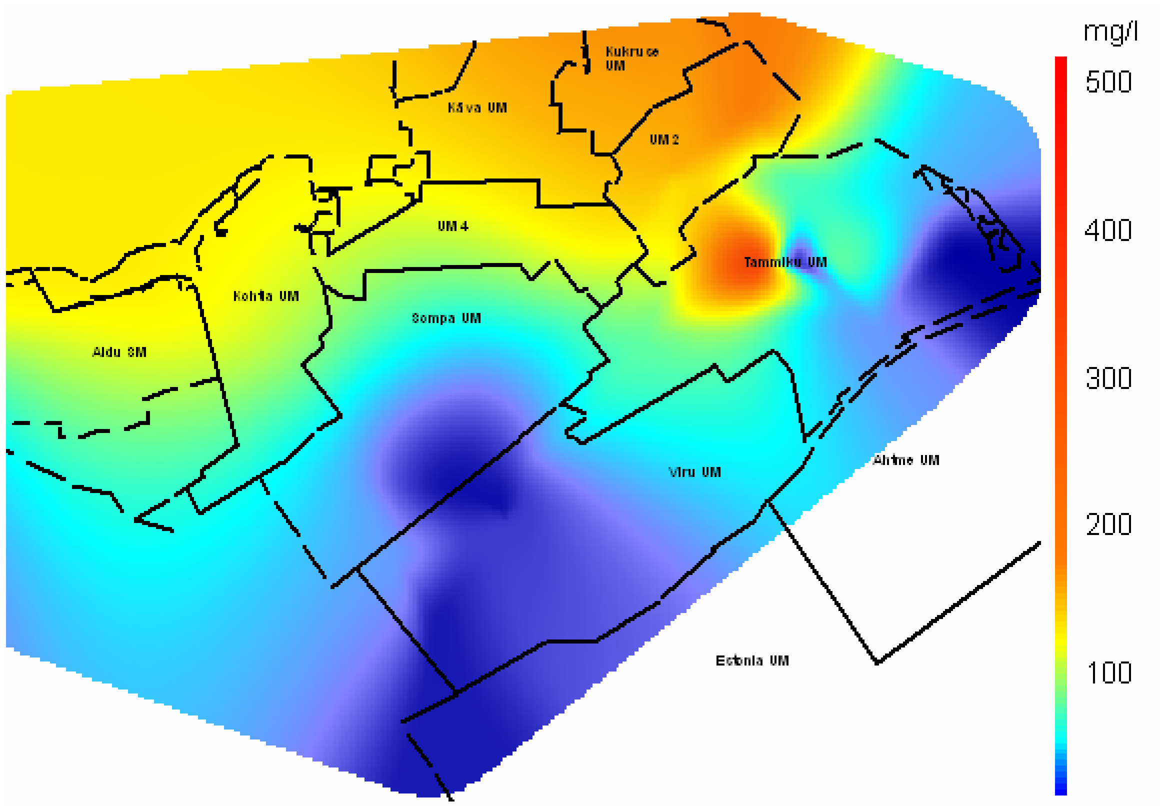


Figure 4.3.2.3.1 The sulphate content in the Lasnamäe–Kunda aquifer of underground oil shale mine area.

5. POSSIBLE SOLUTIONS TO THE GROUNDWATER MANAGEMENT PROBLEMS IDENTIFIED IN UNDERGROUND MINES

5.1 GROUNDWATER MANAGEMENT PROBLEMS

Some of the negative consequences that mine closure can have for the water environment are now well documented in Western Europe (Banks *et al*., 1997; Younger, 2002), but also in Poland (Rogoz, 1974) and Czech Republic (Reichmann, 1992), providing a useful check-list for possible eventualities during the restructuring of the mining industry in Eastern and Central Europe. The final closure of an entire deposit is usually accompanied by the termination of decades of regional-scale dewatering, which can have diverse consequences, including:

1. flooding of the mine workings and surrounding strata, possibly causing geotechnical problems, such as renewed subsidence; and
2. discharge of water from the flooded workings to adjoining surface and subsurface water bodies, which can cause localized surface flooding and aquatic pollution.

As more and more European coalfields are closing the European Commission research projects are now addressing some of the more pressing of the above issues, such as the need to develop long-term, low-cost methods for the remediation of mine-water pollution and the development of environmental regulation strategies for mine waters that take full cognizance of the social and economic needs of EU member states. Basically the same investigation must be done in the Estonian oil shale flat-laying deposit.

5.2 POSSIBLE SOLUTIONS

During the last 4–5 years, substantial efforts have been put into reclamation of closed underground mine sites. Related hazards include the subsidence – uneven downward movement of the ground caused by a cave in underground workings – and mine flooding.

As a general principle, site specific solutions have been developed, according to the permits and the legislation in consultation with the supervising authorities. The solutions applied shall be self supporting and permanent. A requirement, however, is a sufficient protection of the remediate areas from improper land use alternatives. Water stored in a closed underground oil shale mine breaks through a barrier and flows into the mine. This water will damage the rock strata in the mine roof, floor and walls. Possible solutions:

1. pump or overflow the water from the mine and release it, untreated, into the stream;
2. pump or overflow the water from the mine and fully treat it to prevent any effects to the receiving stream, or
3. leave the water in the mine.

After the mine closure environmental risks exist during a short, long and very long time depending on the quantity and flow of the water involved and the volume of the mine workings concerned. In recent years, a number of oil shale mines has been closed in northeastern Estonia; this has led to the rising of mine water level. It has been normal practice in some cases to allow this recharge to take place and to deal with the consequences as they become apparent. Allied to these problems is the potential for further subsidence events relating to the rising groundwater intercepting and flooding near the working Viru and Estonia mines.

5.2.1 Water level regulation methods

Most mine water originates in the closed underground oil shale mines and flows in the surface or into nearby streams and floods surrounding areas. Different active and passive water level regulation methods can be used to prevent flooding.

Passive methods are the following:

1. leaving the water in the mine;

In that case the work is carried out starting with feasibility studies for each discharge. These studies consider many issues including the mining situation, appropriate treatment technology, planning and land availability.

2. another implication of underground water movement may be an overflow well

The overflow well as a passive method is preferred since it is more sustainable underground water flood prevention near Ahtme mine and Mine no 2. The well diameter may be 450 (best) or 600 mm, not more because of importance of time effect for sulphate content changes.

Active methods are

1. pump the water from the mine and release it into the stream.

Most of pumped-out underground mine water does not need any treatment and can be easily released into a stream.

2. if working mines remained, the safety implications of water build up were given due regard and often pumping operations were established at closing mines to protect connected mines which were to remain in production.

Such situation is observed in the southern part of Estonian oil shale deposit where Viru and Estonia mines are still working and the already closed Sompa, Tammiku and Ahtme mine are located in their immediate vicinity.

3. tunneling

Tunnels have been driven in some mining districts. Where topographic features permit, a drain tunnel may also be driven to serve a single mine, for example Mine no 2.

4. some success has been achieved by filling, which was studied in the 1980s (Karise, *et al*., 1982) or grouting mine voids.

However, this method is expensive and the results are inconsistent.

5.2.2 Water sulphate content regulation methods

Like the water table regulation methods, the water chemistry regulation methods can also be grouped into passive and active ones. Passive method is not treating the water and releases it into the stream.

Active methods are:

1. pump or overflow water out of the mine and release it into the stream or
2. pump or overflow the water from the mine and fully treat it to prevent any effects on the receiving stream.

One of effective remedial strategies capable of reducing or preventing pollutant loads from underground mines is Gas Redox and Displacement System (GaRDS) (Ritchie, 1994, Tasse *et al*., 1994), which is a new approach devised for stabilising sulphide minerals by manipulating the atmosphere in mining voids. This prevention technique offers the potential for low cost and effective control of drainage from underground mines via oxygen displacement. To date, the key method of controlling sulphide oxidation (Ritchie, 1994) in underground mines is to flood the workings once the mining ceases.

GaRDS is fully compatible with the existing closure strategies for underground mines, and is expected to rapidly improve drainage water quality emerging from enclosures and prevent further sulphide oxidation. This novel approach is based on using the highly reduced gas mixtures generated by natural bacterial degradation of organic matter to passively displace oxygen (i.e. air) from shafts and the unsaturated fractured rock mass surrounding the subsurface voids (Tasse *et al*., 1994). By maintaining highly reducing conditions, the sulphides can be stabilised. The passive displacement of air by a reducing gas mixture does not require any power supply or pumps. If the GaRDS approach is successful, it could be applied at numerous defunct and temporarily closed mine sites.

Underground mining introduces air directly into zones of sulphide-bearing rock, and the receding water table which accompanies tunnelling and dewatering, causes air to be drawn into fractures within the rock mass surrounding the mine workings. Both of these processes result in dramatically enhanced sulphide oxidation. The oxidation products are subsequently dissolved by rainwater infiltration, and metal-rich water is collected in the underground voids and exits from adits. The flooding of underground mines aims to return groundwater to pre-mining levels and thereby minimise further sulphide oxidation. GaRDS aims (Tasse *et al*., 1994) to passively displace air from the mining voids and fractured rock mass above the water table by introducing biogas to the mine once all shafts and adits have been closed. The biogas is comprised of carbon dioxide and methane (CO_2 and CH_4) produced by anaerobic bacteria breaking down crude organic matter. The GaRDS technique works in two ways, physically displacing oxygen and chemically reversing the acid generating reactions and stabilising the acid producing minerals. Sealing all man-made exits (e.g. adits, shafts, drillholes, etc) with low-cost barriers displaying low gas permeability will dramatically lower gas diffusion into or out of mine workings. At the topographically lowest exit to the mine workings, a barrier configuration will allow all drainage out, whilst the mine remains substantially sealed to gas flow. As CO_2 and CH_4 gas production progresses, oxygen and nitrogen initially contained within underground workings will be expelled through the remaining pathways of least resistance – rock fractures in the unsaturated zone. This will eventually lead to a situation where the atmosphere within the voids and rock fractures is almost exclusively CO_2 and CH_4 (i.e. CO_2: ≈49% CH_4: ≈49%, residual gases will include: CO, H_2, H_2S, NH_3, N_2, O_2, C_2H_6, etc) (Tasse *et al*., 1994). Eventually, it is expected that small volumes of both CO_2 and CH_4 will evolve from the fractured rock mass at the ground surface. Under these circumstances, oxidation of sulphides in the unsaturated zone and mining voids will have been effectively terminated. The relatively high density of CO_2 will ensure that air is effectively displaced from all accessible voids and fractures.

In most settings, sulphide oxidation at mine sites is controlled by ambient oxygen concentrations. The key oxygen source is air, and other components of air are effectively inert with respect to sulphide oxidation (Tasse *et al*., 1994). This is not the case with the system proposed here. GaRDS generates gases which are not inert with respect to either oxygen or sulphides. For example, CH_4 can react with oxygen to produce CO_2, and CO can react with oxygen to produce CO_2. Minor concentrations of H_2S will also be a potential oxygen consumer, further lowering trace amounts of ambient oxygen to stabilise sulphides. H_2S is also expected to encourage the precipitation of secondary pyrite by reacting with available aqueous ferrous iron. The general equilibrium depicting the oxidation of iron sulphide is as follows:

$$FeS_2 + 3.5\ O_2 + H_2O = Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+$$

The GaRDS approach is to remove oxygen from this equilibrium, and thereby prevent it from proceeding. Pyrite will remain completely stable in the presence of the reducing gas mixture.

Generally, passive treatment technologies are preferred since they are more sustainable and can be made to integrate much better into surroundings. Relatively high sulphate content in water of different closed mines in summer-autumn months meets the requirements of the Estonian Drinking Water Standard. This water maybe used for technological purposes, but also as a drinking water resource under high observation and only in summer-autumn months.

6. CONCLUSIONS

Natural hydrogeological conditions in northeastern Estonia have been disturbed by the mining industry and consumption of the groundwater in Kohtla-Järve, Jõhvi and other towns.

Deeply fractured carbonates, together with the effects of mining, have facilitated the rapid spread of aquatic pollution from the Keila–Kukruse to the underlying Lasnamäe–Kunda groundwater aquifer.

The mine dewatering was relatively constant during the period 1991–95, both in individual mines and in total, which has been in the range of 550 000–700 000 m^3/d (200–250 million m^3/y). Annual water outlet of the mining enterprises in operation was approximately under 100 million m^3 (2003) after Tammiku and Sompa mines had been flooded, but in 2004 (August of that year was rainy - 128 mm/d) the outlet increased over 100 million m^3. The water of working mine with a relatively high sulphate content is guided to natural water bodies. Preliminary outlets after sedimentation pools are the Ratva Creek and the Ojamaa River (Viru underground mine) and Raudi Channel (Viru and Estonia underground mine) into the Gulf of Finland.

In the eight closed mines underground water pools have formed. In these pools the sulphate content of water differs from relevant background values. Closed underground mines may or induce risks for the environment. These may be short, long and very long term risks depending on the quantity and flow of the water involved. Some of these risks are linked to the shut down of the mine water pumping operations leading to a water level rising and flooding of the surrounding areas as it already happened in the northern part of Jõhvi Town (51 m a.s.l.), where the closed Mine no 2 in some areas is about 57 m a.s.l. and water level has risen to 53-56 m a.s.l. (2004) (Reinsalu *et al*., 2004).

The main results may be summarized as follows:

1. comparing the data obtained at the end of the 1930s with the present ones, it is possible to evaluate the extent of man-made changes, first of all, in lakes and, supposing that the groundwater chemical content was approximately the same, also in shallow groundwater (Fig. 4.2.2.1, Paper II);
2. hydrotechnogenic influxes generated by human activities have deformed the hydrochemical conditions of the surface water and shallow groundwater in Kurtna lakes of the Vasavere buried valley (Paper II);
3. the hydrogeological regime in oil shale mines is controlled by the thickness of the aeration zone, tectonical faults and fractures in the geological section, alteration of hydraulic gradients causing changes in the flow direction and rate (Paper I);
4. water table drawdown predictions are generally based on the assumption that geologic materials transmit water equally in all directions (isotropically); however, the oil shale mining area is unisotropic and non-homogeneous (Paper III) and simplified approach is excluded;
5. after the closure of a mine when the pumps will be stopped the water level will stabilize at its pre-mining level. The predicted time is three years when the mine will be filled.
6. closing and flooding of underground mines has radically changed the groundwater forming conditions in the Lasnamäe–Kunda aquifer (Paper IV);
7. due to technogenic impact the water of closed mines is connected with the Lasnamäe–Kunda aquifer. Evidence is derived from the deflection of the content of sulphate (an indicator element) from natural background both in the mining field and in the observation wells tapping the Lasnamäe–Kunda aquifer in the surroundings of the mining area (Paper I, IV);
8. in pre-mining time the groundwater quality was mainly affected by precipitation (Paper II). During the mining period the sulphate content increased and was up to 50 times as high as under natural conditions (2–10 mg/l)(Papers II, IV);
9. in post-mining time the mines fill with water; the content of sulphates increases sharply – 3–4 times (1200 mg/l) during two years and then, after four years, decreases to 150–200 mg/l (Paper IV);

10. of the active and passive methods applicable to water removal from the closed mines and prevention of flooding of the surrounding area we would recommend to choose overflow wells (Ahtme mine) (Ch. 5). Generally, passive treatment technologies are preferred since these are more sustainable and can be made to integrate much better into their surroundings;
11. active water level regulation methods cause mine water depletion and great changes in the sulphate content of the water around the year (Ch. 5);
12. generally, the water of closed mines meets the requirements of the Drinking Water Standard of Estonia (RTL 2001/100/1369) (Ch. 5) and the author's recommended active treatment methods can cause large-scale secondary pollution. In view of this, the author of the thesis considers special mine water treatment unpurposeful.

Acknowledgements

Many people were involved in the research for this thesis. I would like to thank all of them who had helped me in any way during these four years of doctoral studies. Particular thanks are due to the supervisors Acad. Anto Raukas, who initiated the study and supported me throughout it, and Prof. Enno Reinsalu, who introduced me to the interesting field of mining methods and technologies.

I would like to thank my colleagues at the Department of Mining and Institute of Geology at the Tallinn University of Technology. Special thanks go to Helle Kukk for revising the English language of this thesis.

I wish to express my sincerest gratitude to several colleagues who have also been actively interested in mining impact on the environment and whom I have been lucky to work with – Ljudmilla Kolotõgina and Kalmer Sokman from Estonian Oil Shale Company, Prof. Elly Triegel from the Pennsylvania State University, Dr. Karel Kovar from IAHS. I am thankful for their co-operation, useful advice and friendship.

Finally, special thanks go to my parents for having given me good education and creating a pleasant home, where books and all the knowledge inside them had an important place.

This study was undertaken with the financial support by the grant No. 5913 of the Estonian Science Foundation.

References

Aaloe, A., Viiding, H. 1983. Lithological classification of oil shale. – Proceedings of Estonian Academy of Science. Geology, **4**, 157–162.

Badman, T. D., Gravelle, M. A., Davis, G. M. 2000. Seabed imaging using a computer mapping package: an example from Dorset. – The Quarterly Journal of Engineering Geology and Hydrogeology, **33**, 2, 171–175.

Banks, D., Younger, P.L., Arnesen, R.-T., Iversen, E.R., Banks, S.D. 1997. Mine-water chemistry: the good, the bad and the ugly. – Environmental Geology, **32**, 3, 157–174.

Barnes, T. M. 2000. Treatment of the gravity minewater discharge at Deerplay Mine, Burnley, UK. – Proceedings, 7th International Mine Water Association Congress, 344–351.

Bauert, H., Kattai, V. 1997. Kukersite oil shale. – In: Geology and Mineral Resources of Estonia. Raukas, A., Teedumäe, A. (eds.). Tallinn, Estonian Academy Publishers, 313–327.

Cravotta, C. A., Kirby, S. C. 2004. Effects of Abandoned Coal-Mine Drainage on Streamflow and Water Quality in the Shamokin Creek Basin, Northumberland and Columbia Counties, Pennsylvania, 1999-2001 by Water-Resources Investigations Report 03-4311. In cooperation with the Northumberland County Conservation District, Bucknell University and the Pennsylvania Department of Environmental Protection, New Cumberland, Pennsylvania, 63 p.

Domanova, N. 1999. Experience of underworking a water basin (in conditions of Estonian oil shale deposit). – Oil Shale, **16**, 2, 117–123.

Domanova, N., Fyodorov, V. 1997. Application of infiltration basins as water protection structures (in the Kurtna Landscape Reserve). – Oil Shale, **14**, 3, 363–374.

Domanova, N., Krapiva, A. 1996. Water level regime of the Kurtna group of lakes. – Oil Shale, **13**, 2, 101–114.

Domanova, N., Norvatov, Y., Petrova, I. 1995. Study of hydrodynamic conditions of the Vasavere buried valley. – Oil Shale, **12**, 1, 3–14.

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

Erg, K. 2000. Vasavere ürgoru hüdrogeoloogiline režiim ning sulfaatide (SO_4^{2-}) sisaldus pinna- ja maapinnalähedases põhjavees. Magistritöö, Tallinn, 44 lk.

Erg, K., Punning, J.-M. 1994. The influence of oil shale mining on groundwater resources and quality. – In: Kovar, K., Soveri, J. (eds.) Groundwater Quality Management. IAHS Publication No. 220, Wallingford, 3–10.

Erg, K., Reinsalu, E., Valgma, I. 2003. Geotechnical processes and soil-water movement with transport of pollutants in the Estonian oil shale mining area. Rezekne. – Proceedings of the 4th International Scientific and Practical Conference "Environment. Technology. Resources". June 26-28.2003, 79–84.

Ilomets, M. (comp.). 1987. Kurtna järvestiku looduslik seisund ja selle areng. Tallinn, Valgus, 235 lk.

Ilomets, M. (comp.). 1989. Kurtna järvestiku looduslik seisund ja selle areng II. Tallinn, Valgus, 180 lk.

Jõgar, P. 1983. Geofiltration condition of Pandivere Upland, Estonia. – Proceedings of Estonian Academy of Sciences. Geology, **32**, 2, 69–72 (in Russian).

Kala, E. 1995. The geological map of Estonia. 1:2 500 000. Estonian Geological Survey, Tallinn, 2 (in Estonian and English).

Karise, V., Pill, A., Johannes, E., Erg, K. 1982. Water chemical content forming in Estonian oil shale mining area. Manuscript in Institute of Geology. Tallinn, 286 p. (in Russian).

Kattai, V., Saadre, T., Savitski, L. 2000. Eesti põlevkivi: geoloogia, ressurss, kaevandamistingimused. Eesti Geoloogiakeskus, Tallinn, 226 lk.

Liblik, V., Punning, J.-M. (eds.) 1999. Impact of oil shale and processing on the environment in North-East Estonia. – Publication of Institute of Ecology, Tallinn Pedagogical University, 6, Estonian Academy Publishers, Tallinn, 223 lk.

Nikitin, O. 2003. Mining block stability analysis for room and pillar mining with continuous miner in Estonian oil shale mines. – Oil Shale, **20**, 4, 515–528.

Pastarus, J.-R. 2003. Long-term stability monitoring of the mining blocks in Estonian oil shale mines. – Proceedings of the 4nd International Conference "Environment. Technology. Resources." Noviks, G. (ed.). Rezekne Augstskolas Izdevnieciba, Rezekne, Latvia, June 26-28, 206–211.

Pastarus, J.-R., Toomik, A. 2001. Roof and pillar stability prognosis in Estonian oil shale mines. Rock Mechanics. – Proceedings of the ISRM Regional Symposium EUROCK 2001 "Rock Mechanics a challenge for society". Särkkä, P., Eloranta, P. (eds.), A.A. Balkema/Lisse/Abingdon/Exton(PA)/Tokyo, Espoo, Finland, 4-7 June 2001, 849–853.

Perens, R. (ed.) 2005. Groundwater state in 1999-2003. Geological Survey of Estonia. Tallinn, 43–50 (in Estonian).

Perens, R., Andresmaa, E., Antonov, V., Roll, G., Sults, Ü. 2001. Groundwater management in the northern Peipsi–Narva river basin. Background report, seminar "Support to Estonian–Russian Joint Peipsi–Narva Transboundary Water Commission through Capacity Building and Development of Recommendations" (CEE 008, supported by the Swedish Environmental Protection Agency), Tartu, Estonia, April 18-19, 2001.

Perens, R., Savitski. L. 2000. Hydrogeological conditions and problems on the left bank catchment area of the Narva River. – In: The Narva River and Reservoir (articles of hydrology, ecological conditions and water management), 24–35 (in Estonian and Russian).

Perens, R. 1998. The hydrogeological map of Estonia. Estonian Geological Survey, Tallinn, 2 p (in Estonian and English).

Perens, R., Vallner, L. 1997. Water-bearing formation. – In: Geology and Mineral Resources of Estonia. Raukas, A., Teedumäe, A. (eds.), Tallinn, Estonian Academy Publishers, 137–145.

Punning, J.-M. (ed.). 1994. The influence of natural and anthropogenic factors on the development of landscapes. The results of a comprehensive study in NE Estonia. Publication of Institute of Ecology, Estonian Academy of Sciences, 2, Tallinn, 227 p.

Punning, J.-M. 2000. Oil shale and the environment. – Oil Shale, **17**, 2, 77–79.

Reichmann, F. (ed.) 1992. Impact of Mining on the Environment of the Czech Republic: Map, Explanatory Text and Legend. Cesky geologicky ustav ve spolupraci s Kartografii, Praha.

Reinsalu, E. 1998. Is Estonian oil shale beneficial in future? – Oil Shale, **15**, 2, 97–101.

Reinsalu, E., Toomik, A., Valgma, I. 2002. Kaevandatud maa. – TTÜ mäeinstituut, 97 lk.

Reinsalu, E., Erg, K., Lind, H., Rannik, E., Valgma, I. 2004. Põlevkivi kaevandamise AS ettevõtete tööst tulenevate hüdrogeoloogiliste muutuste prognoosi koostamine. Etapp 4. Allmaamäetööde mõjust tulenevate hüdrogeoloogiliste muutuste prognoos. Aruanne. TTÜ mäeinstituut, Tallinn, 41 lk.

Reinsalu, E., Valgma, I. 2003. Geotechnical processes in closed oil shale mines. – Oil Shale **20**, 3, 398–403.

Ritchie, A. I. M. 1994. Sulfide Oxidation Mechanisms: Controls and Rates of Oxygen Transport. – In: Mineralogical Association of Canada, Short Course Handbook on Environmental Geochemistry of Sulfide Mine-Wastes; Waterloo Ontario May 1994. Jambor, J. L., Blowes, D. W. (ed.).

Riet, K. 1976. Eesti põlevkivimaardla ordoviitsiumi karbonaatse kihtkonna üldistatud filtratsioonimoodulid. – Geoloogilised märkmed, 3, Rõõmusoks, A., Kivila, H. (toim.) Tallinn, 88–92.

Riikoja, H. 1940. Zur kenntnis einiger Seen Ost-Eestis, insbesondereihrer Wasserchemie. – Eesti Teaduste Akadeemia juures oleva Loodusuurijate seltsi aruanded, XLVI, Tartu, 1–167.

Rogoz, M. 1974. Water capacity of coal mine workings. Prace Glownego Instytutu Gornictwa, Komunikat 628, Katowice (in Polish).

Rogoz , M., Posylek, E. 2000. Hydrogeological problems connected with closure of mines on the Upper Silesian Coal Basin. – Proceedings, 7th International Mine Water Association Congress, 319–330.

Savitskaja, L. 1999. Groundwater state in 1997-1998. Tallinn, 113 p.

Savitski, L. 2000. The hydrogeological conditions. – Estonian oil shale. P. Vingissaar (ed.). Tallinn, Estonian Academy Publishers, 2000, 93–104.

Savitski, L. 2003, Suletud ja suletavate kaevanduste mõju põhjaveele. Report of Geological Survey of Estonia. 94 p.

Savitski, L., Boldõreva, N. 2005. Observation area of Ida-Viru. Groundwater state in 1999-2003. Tallinn, 43–50 (in Estonian).
Savitski, L., Savva, V. 2001. Hüdrogeoloogiliste muutuste prognoos Eesti põlevkivimaardla kaevandustööde piirkonnas. 3. etapp Ahtme kaevanduse sulgemine. Report of Geological Survey of Estonia, 54 p.
Singer P. C., Stumm, W. 1970. Acidic mine drainage: the rate – determining step. – Science, 167, 1121–1123.
Tasse, N., Germain, M.D., Bergeron, M. 1994. In American Chemical Society Symposium Series 550, Environmental Geochemistry of Sulfide Oxidation; ACS Washington DC August 1992. Alpers, C.N., Blowes, D.W. (eds.)

Toomik, A. 1998. Environmental heritage of oil shale mining. – Oil Shale, **15**, 2, 170–183.

Toomik, A. 1999. Allmaakaevandamise mõjud maapinnale ja nende hindamine. – Põlevkivi kaevandamise ja töötlemise keskkonnamõjud Kirde-Eestis. Liblik, V. & Punning, J.-M. (toim.). TPÜ ÖI publikatsioonid 6, 109–129.
Toomik, A., Tomberg, T. 2001. Blast vibration intensity in the changing hydrogeological conditions. – Oil Shale, **18**, 1, 5–14.
Triegel, E. K., Guo, L., Silver C. 1993. Effects of Formation Geochemistry and Microbial Activity on the Monitoring of Ground Water Quality in Sulfidic Marine Deposits. – Groundwater Quality Management. Erg, K. (comp.). Volume of poster papers. Tallinn, 124–129.
Undusk, V. 1998. Safety factor of pillars. – Oil Shale, **15**, 2 special, 157–164.
Vallner, L. 1980. Balance and geohydrodynamical classification of groundwater of Estonia. Estonian hydrogeological problems. Vallner, L. (ed.) Estonian Academy of Sciences, Tallinn, 11–120 (in Russian).
Vallner, L. 1994. Problems of groundwater quality management in Estonia. – Groundwater quality Management. Kovar, K., Soveri, J. (eds.), IAHS Publication, 220, 449–460.
Vallner, L., Heinsalu Ü. 1995. Põhjavesi ja allikad. – Eesti Loodus. Raukas, A. (toim.), Tallinn, Valgus, 302–318.
Vallner, L. 1996. Groundwater. Estonian Environment. Past, Present and Future. Raukas, A. (ed.), Ministry of Environment, Tallinn, 60–71.
Vallner, L., 1997. Groundwater flow. – In: Geology and Mineral Resources of Estonia. Raukas, A., Teedumäe, A. (eds.), Tallinn, Estonian Academy Publishers, 145–152.
Vallner, L. 2003. Hydrogeological model of Estonia and its applications. – Proceedings of the Estonian Academy of Sciences. Geology, **52**, 3, 179–192.
Vallner, L., Savitskaja, L. 1997. Groundwater extraction and safe yield. – In: Geology and Mineral Resources of Estonia. Raukas, A., Teedumäe, A. (eds.), Tallinn, Estonian Academy Publishers, 159–162.
Whittaker, B. N., and Reddish, D.J.1989. Subsidence-Occurrence, Prediction and Control: Elsevier, 528 p.
Wolkersdorfer, C., Bowell, R. 2004. Contemporary Reviews of Mine Water Studies in Europe, Part 1. – Mine Water and the Environment. **23**, 4, 162–182.
Wolkersdorfer, C., Bowell, R. 2005. Contemporary Reviews of Mine Water Studies in Europe, Part 2. – Mine Water and the Environment. **24**, 1, 2–37.
Williamson, M. A., Rimstidt, J. D. 1994. The kinetics and electrochemical rate-determining step of aqueous pyrite oxidation. – Geochim. Cosmochim. Acta, **58**, 5443–5454.
Younger, P.L. 2002. Coalfield closure and the water environment in Europe. – Mining Technology, **111**, 3, 201–209.

Curriculum Vitae (CV)

Personal details:
Name: Katrin Erg
Date and place of birth: December 19, 1957, Abja-Paluoja, Viljandi county
Citizenship: Estonian
Family status: single, child

Contact:
Address: 5, Ehitajate tee, 19086, Tallinn, Estonia;
Telephone: +372 620 3853;
E-mail: erg@staff.ttu.ee

Education:

Educational establishment	Time	Education
Võhma School and A.H.Tammsaare nominal Tartu 1. Secondary School	1976	Graduate from secondary schools
Tartu State University, Faculty of Biology and Geography, Department of Geology	1981	Higher education. Diploma of engineer-geologist
Tallinn University of Educational Sciences	2000	Higher education. M.Sc in geoecology

Language skill
Estonian (native), fluent in English, Russian and Finnish

Trained at
Water Problems Institute, Russian Academy of Sciences, Moscow 1987.

Professional employment:

1980 - 1990	Institute of Geology, Estonian Academy of Sciences - technician, senior technician, engineer, junior research scientist, research scientist;
1990 - 1992	Institute of Ecology and Marine Research, Estonian Academy of Sciences - research scientist;
1992 - 1998	Institute of Ecology - research scientist;
1998 - 2002	Institute of Geology, Tallinn Technical University - leading engineer;
2002-present	Department of Mining, Tallinn University of Technology - assistant

Research and professional activities:
Hydrogeology, hydrochemistry, water regime of oil shale surface and underground mines
Member of International Association of Hydrological Sciences, Estonian Mining Association, Estonian Union of Scientists and Estonian Geological Association

Diplomas thesis:

1981	Diploma project entitled: "Artificial hydrogeological conditions in the area of the Rakvere phosphorite deposit" (in Estonian).
2000	Master of Science, (*Magister scientiarum*) in geoecology Tallinn University of Educational Sciences. The thesis entitled: "The hydrogeological regime of the Vasavere buried valley and sulphate content in surface and groundwater" (in Estonian).

Honours/awards

1995	Award of the Republic of Estonia in bio-, geo- and agricultural sciences as the co-author of the monograph "The influence of natural and anthropogenic factors on the development of landscapes"

Publications:

Number of scientific papers: 42. Other publications in the relevant area:

Erg K., Punning J.-M. 1993. The influence of oil-shale mining on groundwater resources and quality. – Proceedings of Conference on Groundwater Quality Management, IAHS Publication No 220. Tallinn, 3–11.

Erg K. 1994. The hydrogeological regime. – In: Punning J.-M. (ed.) The influence of Natural and Anthropogenic Factors on the Development of Landscapes. The results of a comprehensive study in NE Estonia. Inst. of Ecol., Estonian Acad. Sci., Publ. 2, Tallinn, 94–101.

Erg K. 1994. The sulphate groundwater formation in North-East Estonia. – In: Suokko, T., Soveri, J. (eds.) Future Groundwater Resources at Risk. Publ. Academy of Finland, Helsinki, 4, 175–179.

Erg K., Punning J.-M. 1994. The influence of oil-shale mining on groundwater resources and quality. – In: Kovar, K., Soveri, J. (eds.) Groundwater Quality Management. IAHS Publ. 220., Oxfordshire, 3–10.

Erg, K. 2001. Shallow groundwater pollution research in the Estonian oil shale mining area. – NordSoil 2nd Nordic-Baltic Conference. Possibilities for cooperation between the Nordic and the Baltic countries in solving soil and groundwater problems - R&D projects and business opportunities. Tallinn, 28–31.

Kink, H., Erg, K., Metslang, T, Raukas, A. 2001. Human impact on the groundwater management in North Estonia. – Seepõld, M. (ed.) Proceedings of the Symposium Environmental Impact and Water Management in a Catchment Area Perspective. Tallinn, 187–196.

K. Erg, Raukas, A. 2001. Groundwater management for control of pollution: A case study for oil shale mining in Northeast Estonia. – Seepõld, M. (ed.) Proceedings of the Symposium Environmental Impact and Water Management in a Catchment Area Perspective. Tallinn, 180–186.

Erg, K., Raukas, A., Tavast, E. 2003. Groundwater elevation trends in the buried valleys of Estonia. – INQUA International Symposium on Human impact and geological heritage. 12-17. May 2003, Tallinn, 67–69.

Erg, K., Reinsalu, E., Valgma, I. 2003. Geotechnical processes and soil-water movement with transport of pollutants in the Estonian oil shale mining area. – Proceedings of the 4th International Scientific and Practical Conference "Environment. Technology. Resources". Rezekne, June 26-28. 2003, 79–84.

Curriculum Vitae (CV)

Isikuandmed:
Nimi: Katrin Erg
Sünniaeg ja koht: 19. detsember 1957; Abja-Paluoja, Viljandi Maakond
Kodakondsus: Eesti
Perekonnaseis: vallaline, laps

Kontakt:
Aadress: Ehitajate tee 5, 19086, Tallinn, Eesti;
Telefon: +372 620 3853;
E-mail: erg@staff.ttu.ee

Haridus:

Õppeasutus	Lõpetamise aeg	Haridus
Võhma 8-kl ja A.H.Tammsaare nim. Tartu 1. Keskkool	1976	Keskharidus
Tartu Riiklik Ülikool, Bioloogia-Geograafia Teaduskond, geoloogia osakond	1981	Kõrgharidus. Diplomeeritud geoloog-insener
Tallinn Pedagoogiline Ülikool	2000	Kõrgharidus. Magister geoökoloogias

Keelteoskus
Eesti (emakeel), kõnes ja kirjas valdan inglise, vene ja soome keelt

Täiendõpe
Vene Teaduste Akadeemia Veeprobleemide Instituut, Moskva, 1987.

Teenistuskäik:

1980 - 1990	Geoloogia Instituut, Eesti Teaduste Akadeemia - tehnik, vanemtehnik, insener, nooremteadur, teadur;
1990 - 1992	Ökoloogia ja Mereuuringute Instituut, Eesti Teaduste Akadeemia - teadur;
1992 - 1998	Ökoloogia Instituut - teadur;
1998 - 2002	Geoloogia Instituut, Tallinna Tehnikaülikool - juhtivinsener;
2002-present	Mäeinstituut, Tallinna Tehnikaülikool - assistent

Teadustegevus:
Hüdrogeoloogia, hüdrokeemia, pealmaa- ja allmaakaevanduste veerežiim. Liikmena Rahvusvahelises Hüdroloogiateaduste Liidus (IAHS), Eesti Mäeseltsis, Eesti Teadlaste Liidus ja Eesti Geoloogiaseltsis.

Kaitstud lõputööd

1981	Diplomitöö: “Rakvere fosforiidimaardla hüdrogeoloogilised tingimused”
2000	Magistritöö: “Mattunud Vasavere ürgoru hüdrogeoloogiline režiim ja sulfaadi sisaldus põhja- ning pinnavees”

Tunnustused

1995	Eesti Vabariigi riiklik teaduspreemia bio-, geo- ja põllumajandusteaduste erialal monograafia “The influence of natural and anthropogenic factors on the development of landscapes” kaasautorina.