Oil Shale, 2013, Vol. 30, No. 2S, pp. 336–362
doi: 10.3176/oil.2013.2S.12

ISSN 0208-189X

MINE WATER AS A POTENTIAL SOURCE OF ENERGY FROM UNDERGROUND MINED AREAS IN ESTONIAN OIL SHALE DEPOSIT

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Abstract. *Underground oil shale mining has been applied for ninety years in Estonian deposit in the middle-north part of Baltic oil shale deposit. The underground mining method of oil shale creates underground free space and the mine workings are filled with water after closure, which makes issues of land stability topical.*

Underground water pools or technogenic water bodies with all-the-year-round stable temperature are formed in the filled underground of oil shale mines. These water bodies have a potential for use as a source of heat for heat pumps and reduction of wintertime heating costs. The aim of this research is to calculate the amount of mine water in closed or abandoned oil shale mines in the central part of Estonian oil shale deposit and offer solutions for usage of undermined areas.

Using mine water as a source of heat for heat pump stations means the possibility of using geothermal energy. The first pilot pump in Estonia was launched in Kiikla settlement in 2011. The best solution for such systems is a heat pump complex near Ahtme thermal power plant. The optimal size for the heat pump at Ahtme is 10 MW heat production. Different methods of heat collection for heat pump plants can be applied when other mines will be closed in the future.

A 3D-model of the mined underground area has been created using geometric data of mine plans, acts of closed mines, as well as borehole and land survey data. The main tools chosen for spatial modelling were spreadsheets and Microsoft Access databases for systemising and querying data, MapInfo Professional for georeferencing, Vertical Mapper for interpolating and grid calculations and MODFLOW for pumping simulation. Each step of model creation involved analysis and decision on which values should be used to obtain modelling results. Layer thicknesses and required properties of water body were calculated using interpolated grids and surface elevations.

Keywords: *mine water, undermined areas, oil shale, heat pump, modelling, hydrogeology.*

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1. Introduction

Oil shale mining is of crucial importance for Estonian economy. More than 90% of electricity in Estonia is produced from oil shale which has been mined here for over 90 years, the total production exceeding one billion tonnes. The oil shale deposit is located in the north-eastern part of Estonia (Fig. 1). The objects of this study are shown in Figure 2. The oil shale bed descends 3 m per kilometre towards the south and the oil shale seam comprises interlayered limestone, which is a waste rock stored in waste rock heaps. Oil shale is mined using two methods: underground (room and pillar mining method) and surface (open cast mining method) [1, 2, 3]. The former method created underground free space and, as mining was carried out below groundwater level, the workings filled with water after their closure. Estonian oil shale deposit comprises ten closed mines that are fully or partly filled with water. Eight mines in the central part of the deposit – Ahtme, Kohtla, Kukruse, Käva, Sompa, Tammiku, Mine No 2 and Mine No 4 – form one water body. Ubja and Kiviõli mines are located in the western part of the deposit, further away from other mines [4].

Filling of underground oil shale mines creates underground water pools called technogenic water bodies with all-the-year-round stable temperature. These water bodies have a potential for usage as a source of heat for heat pumps and reduction of wintertime heating costs. Relationships between different mining factors, such as applied mining technology, underground space volume, hydrogeological parameters of closed or abandoned mines and subsided areas, have to be investigated before mine water can be used as a source of heat for heat pumps. The aim of this research is to calculate the amount of mine water in closed or abandoned oil shale mines in the central part of Estonian oil shale deposit and offer solutions to the usage of under-mined areas.

Fig. 1. Location of Estonian oil shale deposit [5, 6, 7].

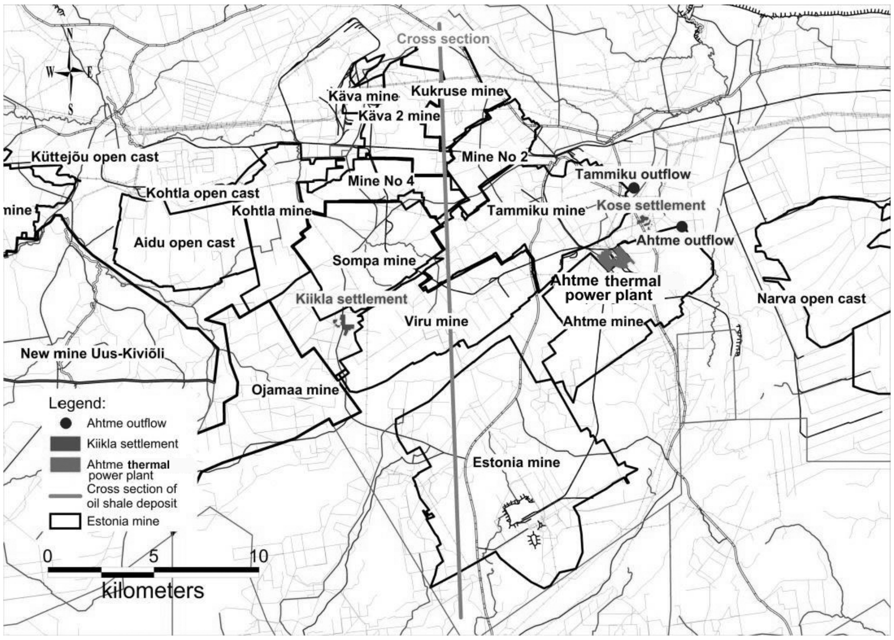

Fig. 2. Objects of the study [16].

2. Oil shale mining area

Despite the shallow depth of the oil shale bedding the underground mining method has been used in several locations instead of the surface method [8]. Underground oil shale mining has been applied in Estonian deposit in the middle-north part of Baltic oil shale deposit for ninety years (Figs. 3, 5) [9–14]. The shallow depth, greater thickness and better quality of the central-northern deposits were the reasons why mining started at Kukruse in 1916, moving towards the edges of the deposit where mining conditions were worse. The technologies used in the northern part of the deposit were mostly hand mining and longwall mining (Fig. 3) with the application of the room and pillar method in newer mines from the 1950s–60s (Fig. 5).

The study area embraces nine closed oil shale underground mines (Table 1) and two operating mines.

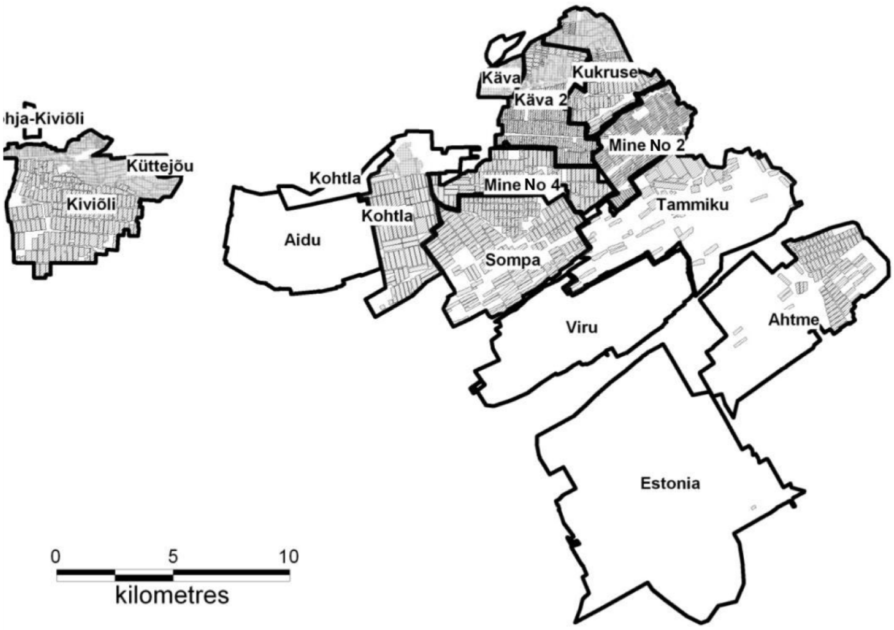

Fig. 3. Hand-mined and mechanised longwall areas (hatched) [16].

Fig. 4. Hand-mined area after oil shale extraction: limestone placed in the limestone wall (Kohtla Mining Museum) [16].

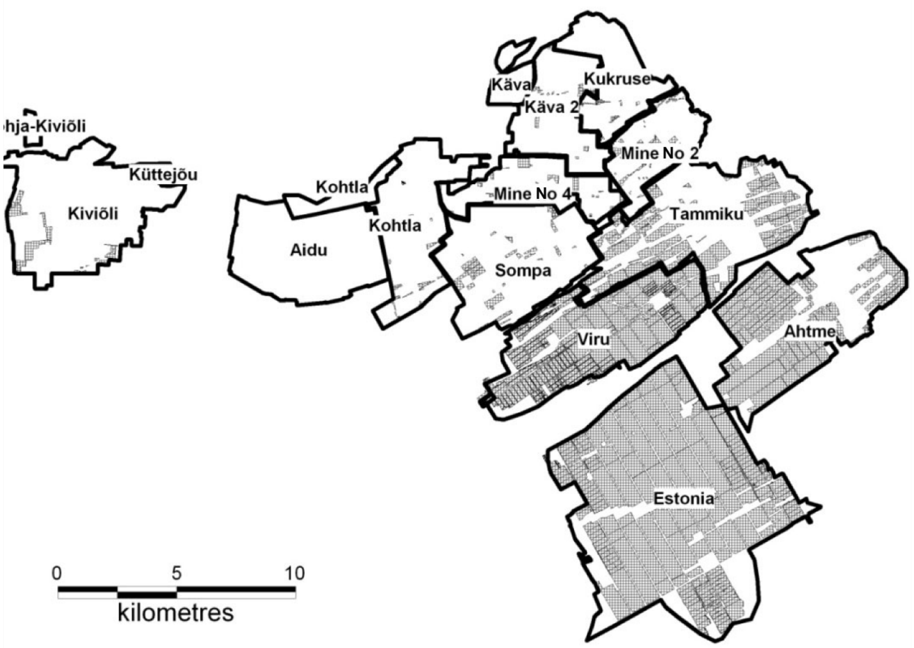

Fig. 5. Room and pillar mining areas (hatched) [16].

Table 1. Closed oil shale mines in the study area [16]

Options	Kukruse	Mine No 2	Käva	Käva 2	Mine No 4	Tammiku	Sompa	Kohtla	Ahtme
Mine opening	1921	1949	1924	1924	1953	1951	1948	1937	1948
Mine closing	1967	1973	1972	1972	1975	1999	1999	2001	2001
Working time, year	46	24	48	48	22	48	51	64	53
Field area, km^2	13.20	12.30	3.47	14.05	12.70	40.00	33.60	18.30	43.30
Mined field area, km^2	15.13	8.57	1.84	11.72	10.43	19.26	18.14	12.14	26.36
Unmined area, km^2	–1.93	3.73	1.63	2.33	2.27	20.74	15.46	6.16	16.94
Thickness of overburden, m	11	13	21	10	12	23	23	15	37
Thickness of oil shale seam, m	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Geological space in oil shale seam, m^3	42.82	24.08	5.22	33.05	29.20	53.92	50.24	33.52	73.53

2.1. Oil shale mining methods

Over the years oil shale mining methods have changed several times due to changes in geological conditions and developments in technology and mining methods, etc. The following is a short overview of the oil shale mining methods formerly and currently employed in Estonian mines.

2.1.1. Hand-mined area (rooms and longwall)

In areas where the hand mining method (rooms and longwall) was in use, the extracted layer thickness was 2.2–2.3 m from the oil shale bottom layer (layer A, see Fig. 7). By hand mining oil shale was loaded onto the hutch while waste rock (limestone) was thrown into the mined area and a limestone wall was constructed (Fig. 4). This caused a smooth subsidence of overburden layers to the limestone walls. Land subsidence kept occurring during a few months after mining. Some subsidence may occur up to two years after mining, after what these areas can be counted as stable. However, some subsidence may occur three to four years after mine closure when the mine is filling with water.

2.1.2. Mining with longwall shearers

Estonia has thirty years of experience in cutting oil shale seam with longwall shearers, the extracted layer thickness being 1.5–2.4 m with panels 180 m wide and up to 600 m long. However, the longwall shearers did not cut the hardest limestone layer inside the seam and for this purpose, road headers were tested in the 1970s.

2.1.3. Room and pillar mining method

The main current underground mining method is room and pillar mining (Fig. 5). The oil shale mine fields are divided into panels by panel drifts. The panels, 600 to 800 m wide and several kilometres long, are then divided into 350 m wide mining blocks. The main operations carried out in rooms include bottom cutting, drilling of blast holes, blasting, loading of blasted rock on the chain conveyer and supporting of the roof by bolts. Formerly, the height of rooms corresponded to the thickness of the commercial oil shale bed, which is mostly 2.8 m. Today, the height of rooms in Estonian oil shale mines is up to 3.8 m when a new room and pillar method is applied, while the width of workings varies from 6 to 10 m. Compared to other oil shale mining technologies the main difference in case of the room and pillar method is that there remain empty room and pillars of unserved ore to support the overburden. Therefore in mined areas there is a lot of free space where mine water can accumulate (Fig. 6).

2.1.4. The undermined area

Underground mined areas are complex and there are problems with predictability of their stability faced with not only in Estonia but also elsewhere in the world. The stability of underground mined areas is conditioned by many factors, e.g., extraction time, mining technology applied, thickness of the extracted seam, etc. At the same time, there may be factors which are unknown yet. The respective calculation and assessment methods are based on simplified models which are rather adequate to enable practical results to

Fig. 6. Room and pillar mining leaves underground free space (Estonia mine) [16].

be obtained. It is quite complicated to determine land stability in Estonian underground mined areas for the purpose of later road construction or other usages. In land stability determination various mining method parameters, such as thickness of layer, type of support, etc., are to be taken into account.

The mining method and geological conditions determine the size of pillars and underground rooms, use of longwall, and other accompanying details like land stability. Therefore, the volume of empty space in various undermined areas is different. Depending on groundwater level and the mining method used, the free space in an extracted oil shale seam fills with mine water differently. The volume of maximum free space left in different undermined areas is shown in Figure 7.

Analysis of various mining plans (including old ones), mining maps, geological conditions, production schedules, etc., gives an idea of which technology is appropriate to be applied in a certain mine (Fig. 8). The employed mining technology determines the volume of free space remaining after the end of mining operations [15, 16].

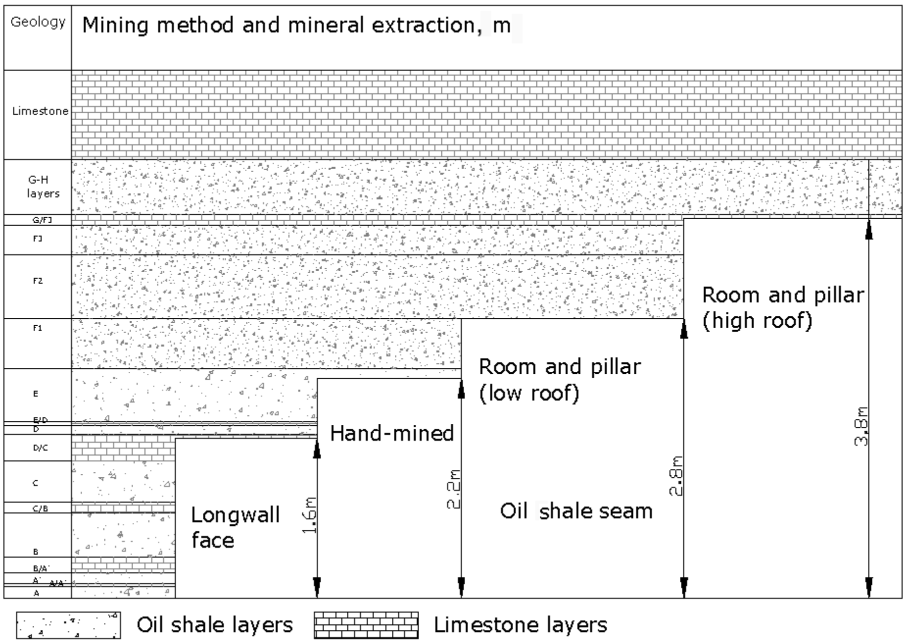

Fig. 7. Maximum free space after mining workings in an oil shale seam [16].

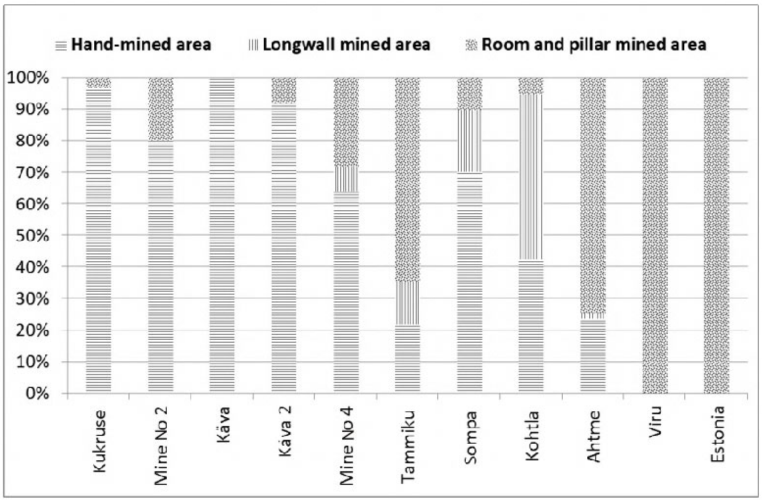

Fig. 8. Mining technologies used in different mining fields, % [16].

3. Mine water as a heat source

Groundwater accumulates in sedimentary rocks via cracks. Cracks in sedimentary rocks determine the main properties of the rock, such as hydraulic conductivity, permeability, specific storage and specific yield, as well as strength [17]. The amount of water in cracks depends on season. In active circulation belts the temperature of water depends mostly on air temperature, while the temperature of groundwater depends on geological conditions and rock bedding depth [17]. The quality of water in closed mines improves with time as the content of sulphates and iron in the mine water decreases, gradually dropping below the maximum level permitted for drinking water within five years after mine closure [18].

The horizontal hydraulic conductivity of an aquifer, vertical hydraulic conductivity of an aquitard, aquifer ratio of vertical to horizontal hydraulic conductivity, and rock-specific yield, as well as the artesian capacity to keep all these parameters within the limits depend on the rock material and layer thickness [19]. The permeability of a porous medium can be defined as the ease with which a fluid can flow through it. This depends on the physical properties of the porous medium, such as grain size and shape, and their arrangement and interconnection between its pores. Water permeability is largely affected by the geological disturbance of the earth’s crust, which makes the aquifer highly anisotropic [18]. The permeability of rock is determined by the size of pores and cracks between its particles [19, 20]. If the rock is of low porosity, water cannot infiltrate into it easily, meaning that the rock is impermeable. On the other hand, if the rock has large pores, water infiltrates easily into it and the rock is considered permeable. When water flows through an area of impermeable rock, a certain amount of water still infiltrates into the ground. As a result, there is a significant surface runoff which leads to a high-volume water flow [21].

Quality of water, especially its greatly varying sulphate content, shall be considered when planning water usage for future applications. The sulphate content in the air of mines still filling with water after their closure is high whereas this content is low in mines which have been closed for two to three years already [16, 22, 23]. Depression cones are created around mining areas during pumping from underground mines. The quantity of pumped-out water from mines depends highly on the amount of precipitation and to a lesser extent on the amount of groundwater or water infiltrating from closed mines. According to performed measurements and calculations, precipitation accounts for up to 70% of the amount of water pumped out of mines [18, 24]. If the hydraulic conductivity of the streambed is high, the cone of the depression may extend only partway across the stream. But if the hydraulic conductivity of the streambed is low, the cone of the depression may expand across and beyond the stream [19]. There are two water levels in the ground – dynamic and static. Dynamic water level is the level of water during continuous pumping and static water level is the level of water before pumping.

Heat can be defined as energy transferred from one matter to another due to differences in temperature. The ability of a matter to transfer heat depends on its mass and temperature. In this study, the primary analytical tools are spreadsheet models and GIS data analysis tools. Mines start to fill with groundwater as soon as the pumping of water from them after closure stops. Technological and hydrogeological modelling allows calculating the amount of water in the mines [24, 25]. Nevertheless, the amount of freely flowing water in underground workings depends on subsidence and closing practice in mines and needs to be determined by pumping tests. Groundwater and underground pool water can be used as a source of heat for a heat pump complex.

3.1. Groundwater

In areas where it is abundant and easily accessible, groundwater is extracted from a well and circulated through the cold side of the heat pump. Groundwater can be used either directly via circulation through the evaporator or indirectly via the use of an intermediate heat exchanger. In most cases, the intermediate heat exchanger is preferable as groundwater may cause corrosion or clogging of the evaporator. After leaving the heat exchanger, the cooled groundwater is directed back into the ground via an injection well.

3.2. Underground pool water

The water in underground mines has a stable temperature all the year round. Subjected to the circulation through a heat pump and returned back, the water heats up when mixed with warmer water and the heat of the earth.

The areas, underground workings or outflows where energy could be extracted may be called energy spots. In locating energy spots, limiting factors should be taken into account and a spatial query applied. The limiting factors include water and environmental protection areas, communications, restricted zones and areas, and other related objects [15, 16, 23, 26–28].

4. Methods

An important step in the procedure of building an environmental model is the transformation of a conceptual model into numerical simulation. To simplify model construction, a framework is required that relieves the model developer from software engineering concerns. In addition, as the demand for a holistic understanding of environmental systems increases, an access to external model components is necessary in order to construct integrated models [9, 11, 13, 29–32].

There are several mining software programs that are either freeware (different viewers), independent (GEMCOM Surpac and Minex, MapInfo, AutoCAD, ESRI, etc.) or additional programs (Discover, Map X, etc.), as well as online software programs (EduMine, etc.) [33, 34]. There are problems with the compatibility of projects as different institutions use different software systems. When developing co-operation, there are difficulties in connecting and transferring the data, which in turn poses an economic problem – designers have to have as many different software packages as possible for co-operation to work [15, 16, 35].

The underground space and its parameters should be defined in order to determine the stability of undermined areas and calculate the potential amount of mine water. The situation has to be mapped in 3D as the underground space is created by mine workings, roof structure and related water channels or tubes. Hydrogeological parameters have to be established and evaluated to determine the underground space parameters and classify the mining technologies used.

The classification of technologies helps one define the space that is available for water in abandoned mines. The method and computer program have been developed in order to assess the parameters of the underground mined area of the oil shale deposit and to describe the extent of influence of mining operations on the environment. It provides an opportunity to evaluate the condition of the ground and, taking into consideration possible risks, plan ground usage and construction actions. The computer program enables us to calculate the types of land that should emerge as the result of certain mining methods, e.g., quasistable and subsided land. The calculation method exploits the geological dataset and details of the plan of mining operations, and subsidence caused by mining. The computer program uses an algorithm to calculate areas that are affected by mining (steady, stable, quasistable and subsided land) [15, 16, 36, 37].

The main tools for analysing the amount of water in abandoned oil shale mines is computational modelling with employment of spreadsheet models and designing the water flow by using the MODFLOW program. For computational modelling we need to know the mining technology of the oil shale bed, amount of space in the old mine drifts and movement of water between the mines. The model enables us to assess the level and area of water in different mines and make assumptions and predictions about the direction of water movement [16, 23, 27, 38].

The oil shale block model created with the help of topographic and geological data (stratigraphic, hydrogeologic, LIDAR[*] data), helps us to describe mining conditions, i.e. physico-geological and technological parameters of the oil shale massif and environmental conditions that directly affect oil shale mining. The most common physico-geological parameters to be considered are the thickness, depth, angle and stability of the oil shale massif. The model shows top layers: the surface, layers of limestone, oil shale seam, and ground water levels, which enables us to choose the best available technology for oil shale mining, taking advantage of the knowledge of mining conditions.

MODFLOW is a groundwater modelling program which can be compiled and remedied depending on practical applications. Because of its structure

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[*] LIDAR – Airborne Laser Scanning

and fixed data format, MODFLOW can be integrated with Geographic Information Systems (GIS) technology for water resource management [39]. MODFLOW calculation models are widely used in different countries of the world, e.g. India, China and Canada [39, 40, 41]. Modelled pumping tests have also produced positive results and provided recommendations for better mining management [42].

5. Results

5.1. Geometric properties of the water body

Geometric parameters for construction of the model are oil shale seam bottom elevation, roof height, length, width and height of pillars and workings in the mines, and thickness of overburden that is divided into the required number of sub-layers by storativity values. The main tools used for spatial modelling were spreadsheets and MS Access databases for systemising and querying the data, MapInfo for georeferencing, Vertical Mapper for interpolating and grid calculations and MODFLOW for pumping simulation. Layer thicknesses and required properties were calculated with the help of interpolated grids and surface elevations (Fig. 9). The modelled results show that the flat oil shale layer bottom slopes to the south (Fig. 10). Geological fault zones are visible (rapid changes in elevation) (Fig. 10).

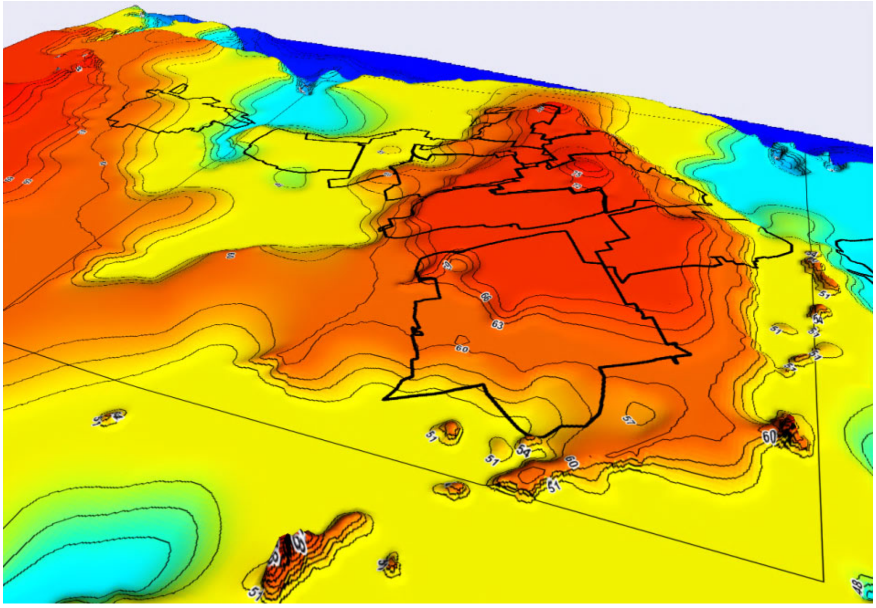


Fig. 9. Ground surface of the study area [16].

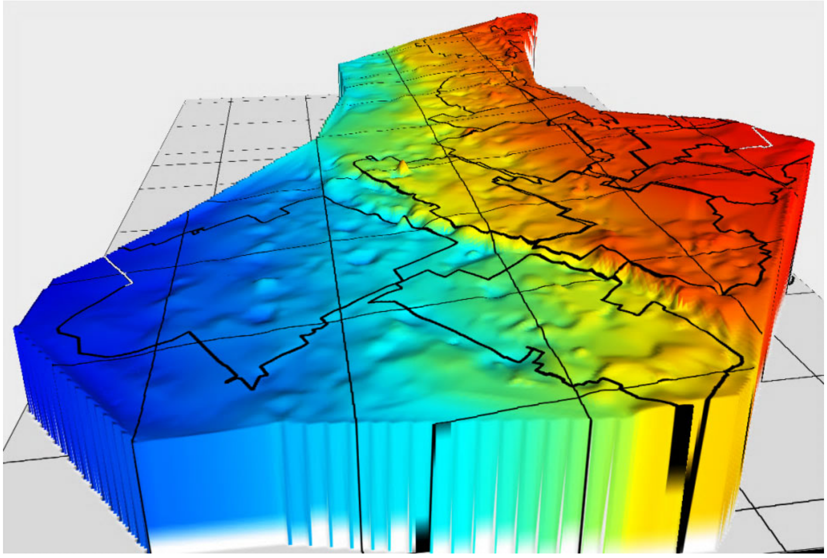


Fig. 10. The flat oil shale layer descending 3 m per km [16].

5.2. Hydrological properties of the water body

After grid calculation, the initial data for the base model shows the average thickness of oil shale seam to be 2.5 m, varying from 1.5 to 3.2 m. The thickness of the overlying rock layer varies from 6 to 66 m (Table 2).

Since in some regions the hydrogeological situation has changed relatively fast due to the closing down of several mining operations and stoppage of pumping, a dynamic model has to be created which simulates the level of groundwater and amount of water in operating and abandoned underground mines, as well as the potential productivity of the wells to be

Table 2. Thickness of oil shale and overburden layers and surface elevation in study-area mines [16]

Mine	Overburden thickness, m			Oil shale thickness, m			Ground surface, m		
	min	avg	max	min	avg	max	min	avg	max
Tammiku	11	23	43	2.8	2.8	2.8	50.0	67.4	80.0
Kukruse	9	11	12	2.8	2.8	2.9	59.9	70.5	79.5
Mine No 2	9	13	22	2.8	2.8	2.8	58.2	70.0	75.9
Mine No 4	4	12	20	2.8	2.8	2.8	49.9	61.7	72.5
Sompa	12	23	34	2.7	2.8	2.8	50.0	62.1	71.5
Viru	32	42	50	2.7	2.8	2.8	57.0	69.4	72.0
Estonia	49	57	66	2.6	2.7	2.8	50.0	63.4	70.0
Kohtla	3	15	54	2.7	2.8	2.8	49.8	51.1	60.0
Käva 1	15	21	30	2.8	2.8	2.8	51.8	59.5	62.0
Käva 2	7	10	13	2.8	2.8	2.8	58.9	66.1	77.8
Ahtme	13	37	55	2.8	2.8	2.8	42.3	63.8	71.2
Tammiku	25.1	35.4	41.8	34.9	47.8	51.1	28.2	45.0	47.4

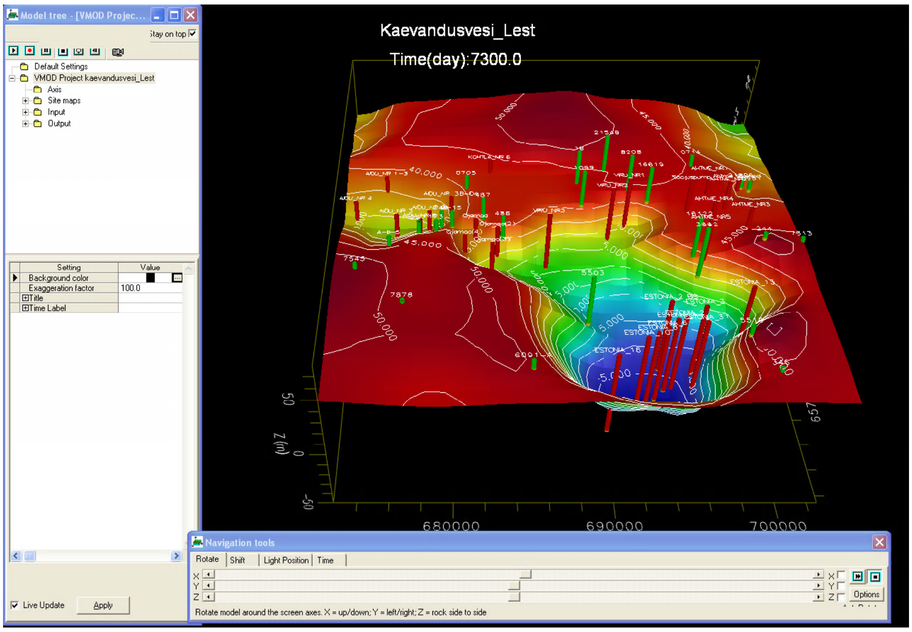
Table 2 (continuation)

Mine	Water level in 2000, m			Water level in 2004, m			Water level in 2008, m		
	min	avg	max	min	avg	max	min	avg	max
Kukruse	51.0	52.1	53.9	49.4	50.0	50.1	51.2	52.1	57.7
Mine No 2	39.2	45.9	51.8	49.2	50.0	51.5	42.6	46.8	51.9
Mine No 4	21.0	39.2	47.5	40.9	42.0	49.7	41.0	42.5	47.8
Sompa	19.8	22.6	38.7	41.4	42.0	45.0	32.6	41.8	45.0
Viru	11.5	24.0	37.0	17.3	26.4	50.0	11.3	24.6	44.8
Estonia	–15.0	1.0	52.2	–18.5	–0.8	25.6	–15.1	0.6	41.5
Kohtla	22.2	34.9	44.2	37.8	41.6	44.4	30.8	40.7	47.5
Käva 1	49.4	51.4	53.3	49.7	50.0	50.5	50.5	51.5	52.1
Käva 2	40.8	51.3	52.7	43.8	50.0	50.8	43.2	51.3	52.4
Ahtme	7.8	20.5	34.8	18.1	26.8	28.6	19.4	42.0	45.1

employed for energy extraction [43]. The main hydrogeological parameters for the hydrogeological model are the porosity, vertical and horizontal hydraulic conductivity, infiltration rate and storage of water aquifers. The dynamic model must be checked with a spreadsheet, as well as the amount of water found in the study area, using the same input parameters as in the hydrogeological MODFLOW model (Table 3; Fig. 11).

Table 3. Parameters for a MODFLOW hydrogeological model [16]

Seam	Specific storage	Specific yield	Effective porosity	Total porosity	Conductivity		
	Ss, 1/m	Sy			Kx, m/d	Ky, m/d	Kz, m/d
Quaternary sediments	4.5	0.14	0.045	0.14	15	15	1.5
Limestone overburden up to 20 m	1.5	0.14	0.015	0.45	30	30	3
Limestone overburden 20 m and deeper	1	0.12	0.1	0.3	8	8	1
Unmined area (defaults)	1	0.12	0.01	0.3	25	25	2.5
Kukruse mined area	5	0.67	0.05	0.25	300	300	30
Käva 2 mined area	5	0.67	0.05	0.25	300	300	30
Käva 1 mined area	5	0.67	0.05	0.25	300	300	30
Pavandu open cast mined area	5	0.25	0.05	0.25	100	100	10
Mine No 4 mined area	5	0.25	0.05	0.25	150	150	10
Kohtla mined area	5	0.11	0.05	0.25	150	150	10
Kohtla open cast mined area	5	0.25	0.05	0.25	80	80	8
Aidu open cast mined area	5	0.25	0.05	0.25	100	100	10
Sompa mined area	5	0.25	0.05	0.25	500	500	50
Mine No 2 mined area	5	0.25	0.05	0.25	200	200	20
Tammiku mined area	5	0.25	0.05	0.25	500	500	50
Ahtme mined area	5	0.25	0.05	0.25	500	500	50
Viru mined area	10	0.3	0.1	0.3	1000	1000	100
Estonia mined area	10	0.3	0.1	0.3	1000	1000	100
Limestone of oil shale bottom	1	0.12	0.1	0.3	10	10	1
Aquitard at bottom of limestone					10^{-6}	10^{-6}	10^{-7}



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Rotate model around the screen axes. X = up/down; Y = left/right; Z = rock side to side

Fig. 11. A screen shot of the dynamic mine water flow model [16].

5.3. Amount of mine water in undermined areas

The amount of water in different seams was calculated using a spreadsheet model. The amount of water in the top layers of oil shale was estimated taking into account the porosity and thickness of seams. The mining technology applied and thickness of oil shale layer determine the free space in a certain mine filling with mine water (Table 4). The amount of water in the extracted oil shale layer was calculated considering these factors (Table 4). The results of calculations show that the amount of water was the highest in Ahtme mine (Fig. 12, Table 4). In mining areas water is mostly found in the extracted oil shale seam (Fig. 13, Table 4).

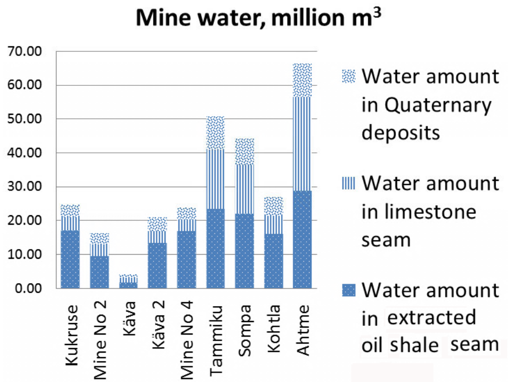

Fig. 12. Amount of mine water in different mines [16].

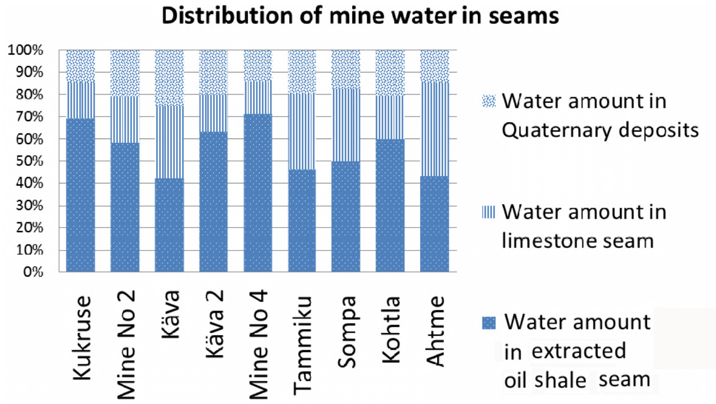

Fig. 13. Relative amount of mine water in different seams [16].

Table 4. Amount of mine water in study-area mines

Options	Kukruse	Mine No 2	Käva	Käva 2	Mine No 4	Tammiku	Sompa	Kohtla	Ahtme
Mined oil shale seam thickness, m									
Hand-mined face	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Hand-mined rooms	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Room and pillar	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Drifts	2.83	2.81	2.83	2.82	2.8	2.8	2.77	2.76	2.79
Longwall face	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Mined field area, km^2									
Hand-mined face	11.28	6.87		9.16	7.71	4.36	12.70	3.80	6.33
Hand-mined rooms	3.50	0.00	1.84	1.73	0	0	0.06	1.36	0.05
Room and pillar	0.29	1.70		0.79	1.08	11.81	1.86	0.55	19.22
Drifts	0.06	0.00	0.00	0.04	0.69	0.36	0.00	0.02	0.30
Longwall face	0	0		0	0.95	2.74	3.52	6.41	0.46
Total mined area	15.13	8.57	1.84	11.72	10.43	19.26	18.14	12.14	26.36
Mine water amount, mln m^3									
Water amount in Quaternary sediments	3.66	3.37	1.04	4.19	3.34	9.94	7.76	5.48	9.96
Water amount in limestone seam	3.94	3.40	1.37	3.56	3.47	17.32	14.46	5.30	27.61
Water amount in extracted oil shale seam	17.05	9.54	1.74	13.29	16.92	23.51	21.93	16.14	28.75
Total	24.65	16.30	4.14	21.04	23.74	50.77	44.15	26.91	66.32
Mine water amount distribution in seams, %									
Water amount in Quaternary sediments	14.8	20.7	25.0	19.9	14.1	19.6	17.6	20.4	15.0
Water amount in limestone seam	16.0	20.8	33.0	16.9	14.6	34.1	32.7	19.7	41.6
Water amount in extracted oil shale seam	69.2	58.5	42.0	63.2	71.3	46.3	49.7	60.0	43.3

5.4. Water required for a heat pump

The criteria for site selection were the following: existing heat pipe, presence of at least 5000 consumers, additional heating option, large amount of mine water. Considering these criteria, the most favourable location for a heat pump complex is on top of Ahtme oil shale mine (Fig. 14) which is located near Ahtme thermal power plant. The heat pump complex can use the underground water pool in Ahtme mine for heat production. The amount of mine water in the mine is 69 million m^3. The heat consumption is 10 MW in the summer period and 50 MW in the winter period. Knowing the required heating capacity and using Equation 1, a spreadsheet model is used for calculating the amount of water required for a heat pump (Table 5).

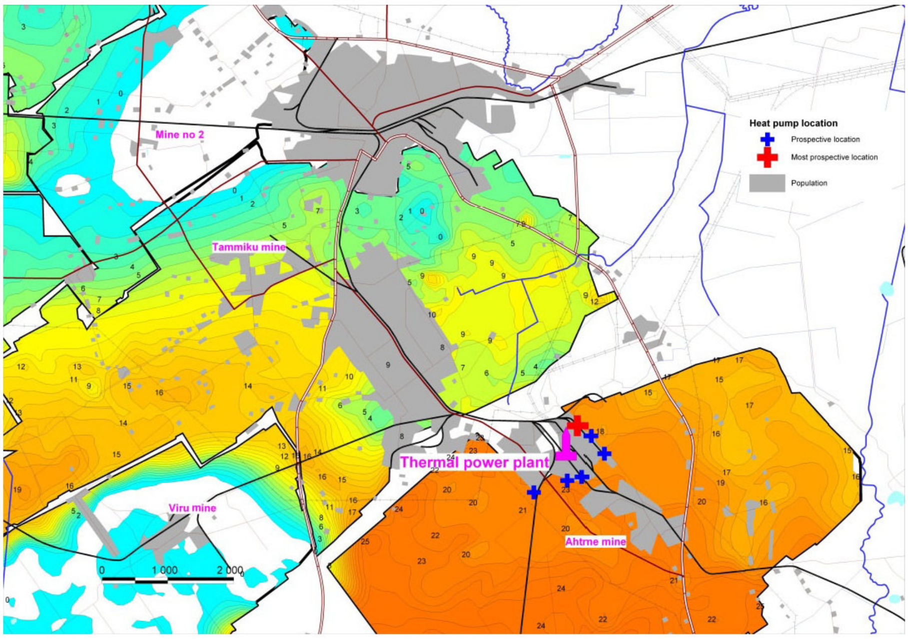

Fig. 14. Prospective locations for a heat pump in Jõhvi and Ahtme areas, figures showing the water pressure from the bottom of the oil shale seam [16].

5.5. Technological solutions for using a heat pump complex

Using mine water in heat pumps must comply with environmental protection requirements and the best possible technical solution in this case is pumping the water through a drill-hole onto the ground surface (Fig. 15) [16, 27, 44, 45]. After lowering the temperature of the mine water in the heat pump by about 1 to 4 degrees, the water is directed back to the mine or water source. If we use water from underground pools, the recommended temperature reduction must be at least four degrees. If the temperature is lowered less, larger volumes of mine water will be needed (Table 5). A heat pump complex, which produces 10 MW of heat, uses 2151 m^3/h mine water, produces 87 650 MWh heat per year and consumes 29 217 MWh of electricity (COP = 3). A heat pump complex, which produces 50 MW of heat, uses 10 755 m^3/h mine water.

Table 5. Dependence of the required amount of water on heat production and temperature reduction [16]

Heat required, MW	Change in temperature, °C	Initial water temperature, °C	Final water temperature after heat pump, °C	Water required, m^3/h
10	1	8	7	8604
10	2	8	6	4302
10	3	8	5	2868
10	4	8	4	2151
50	1	8	7	43 021
50	2	8	6	21 511
50	3	8	5	14 340
50	4	8	4	10 755

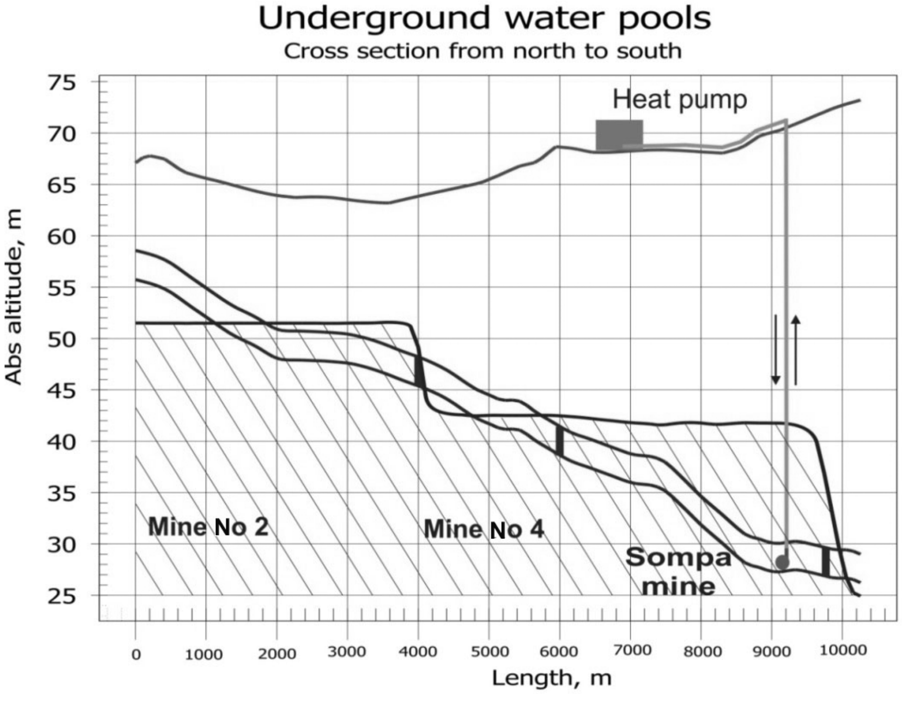

Fig. 15. North-south cross section of the underground mining area and an example of a heat pump installation [16, 27]: top layer – ground surface; two parallel lines – oil shale seam; hatched area – measured and interpolated groundwater level; vertical line – mine water movement.

The best possible solution is to build a 10 MW heat pump complex which allows optimal heat production throughout the year. In addition, it is necessary to use a thermal power plant for heat production during the winter season. The best location for a heat pump is near Ahtme thermal power plant. Figure 14 shows potential locations for a heat pump where the existing district heating network can be made use of and, if needed, the temperature in the heating network increased using the heat from the thermal power plant.

The best possible technical solution for usage of mine water in heat pumps in Ahtme is:

1) to pump the water through a drill-hole onto the ground surface;
2) to direct the water to a heat exchanger unit;
3) to lower the mine water temperature in the heat exchanger of the heat pump by about 1–4 degrees;
4) to direct the mine water back to the mine.

If we use water from underground water pools, the recommended temperature reduction must be more than one degree, which depends on the efficiency of the heat exchanger. If the temperature is lowered less, the volume of mine water needed for a heat pump is higher.

The heat pump complex in Ahtme will consist of both water and heat pumps. The parameters of pumps of Ahtme complex are shown in Table 6. The parameters of Ahtme 10 MW and 50 MW heat pump complexes are shown in Table 7. In Kiikla settlement, the installed heat pump is operating as a pilot unit exploiting mine water as a heat source. The COP values and other parameters for the Kiikla heat production unit are shown in Table 8.

Table 6. Parameters of pumps for Ahtme complex [16]

Pumping station		
Producer	Pleuger pumps	Unit
Capacity	1200	m^3/h
Head	34	m
Motor output	165	kW
Heat pump station		
Producer	Acwell	Unit
Heating capacity	1536	kW
Power input	366	kW

Table 7. Parameters of Ahtme heat pump complexes

ΔT	Heat production, kW	Water needed, m^3	Pumps needed	Electricity for pumps, kW	Heat pumps needed	Electricity for heat pumps, kW	Total electricity consumption, kW	COP
10 MW heat pump complex								
1	10000	8592	8	1,320	7	2562	3882	2.58
2	10000	4296	4	660	7	2562	3222	3.10
3	10000	2864	3	495	7	2562	3057	3.27
4	10000	2148	2	330	7	2562	2892	3.46
50 MW heat pump complex								
1	50000	42959	36	5940	33	12078	18018	2.78
2	50000	21480	18	2970	33	12078	15048	3.32
3	50000	14320	12	1980	33	12078	14058	3.56
4	50000	10740	9	1485	33	12078	13563	3.69

Table 8. Kiikla 500 kW heat pump [46]

Pilot project in Kiikla 500 kW heat production unit

Date	Heat production, MWh	Elecricity for heat pump, kWh	Electricity for pumps, kWh	Total electricity consumption, kW	Amount of water pumped, m^3	Water from mine, °C	Water to mine, °C	ΔT	COP
14/04/2011	3.909	1622		1622	1841	6.0	5.0	1.0	2.41
18/04/2011	14.122	5929		5929	7396	6.1	5.4	0.7	2.38
19/04/2011	2.594	1201	7867	9068	1807				0.29
20/04/2011	3.559	1415	341	1756	1488	6.4	5.7	0.7	2.03
21/04/2011	2.104	655	268	923	1534	6.1	4.9	1.2	2.28
25/04/2011	8.381	2749	1245	3994	6852	6.4	5.1	1.3	2.10
27/04/2011	3.355	1108	542	1650	3094	5.8	4.8	1.0	2.03
29/04/2011	3.321	1131	632	1763	3151	5.9	4.6	1.3	1.88
02/05/2011	6.970	2421	893	3314	4671	6.2	5.2	1.0	2.10
04/05/2011	4.954	1743	558	2301	2856	6.1	5.2	0.9	2.15
06/05/2011	4.820	1649	599	2248	2978	6.6	5.2	1.4	2.14
09/05/2011	5.175	1669	877	2546	4317				2.03
30/09/2011		881	873	1754					0.00
18/10/2011	45.684	15600	3468	19068	24673				2.40
27/10/2011	29.015	9671	1800	11471	10498				2.53
31/10/2011	11.828	4299	842	5141	4753				2.30
08/11/2011	20.068	6081	1538	7619	8688				2.63

6. Discussion

The results obtained are important in light of the fact that, according to plans, Aidu open cast and Viru underground mine will be closed in 2014. Pumping in these mining sites will stop and mining fields start to fill with mine water. Shutting down these mining fields will also change the water regime in the region and, hence, new potential places for using mine water as a source of heat for heat pumps are considered. However, collection of heat from mine water can be carried out using other methods. Instead of pumping the mine water through the heat exchanger of a heat pump, it would be more expedient to establish an underground heat exchanger net for heat collection if the drifts are still dry, which enables us to use the mine water heat more effectively.

The structure of Estonian oil shale deposit, where limestone interlayers and oil shale strongly differ in properties, enables its raw material to be easily separated using gravitational methods. Run of mine (ROM) is first selectively crushed, screened and then sent to the dense-media suspension. After the screening, part of the material is sent for the separation of fine grains with high heating value [47, 48, 49]. The investigations have demonstrated that the heating value of energetic oil shale can be mainly increased by enrichment of fine-grained oil shale, using hydrocyclones, pneumatic separators and settling centrifuges [50, 51].

The outcome of oil shale enrichment depends on the preliminary underground processing of ROM: the more limestone is left underground the more fine-grained oil shale there is and the importance of its enrichment in the separator increases. The growing amount of fine-grained oil shale, in turn, increases the quantity of limestone taking up the underground space and leaving less room for mine water. Thus, in the future, the applied oil shale mining technology will determine the amount of free space in mined areas, as well as the potential usage of mine water as a source of heat for heat pump complexes [16, 52]. The selection of technology depends directly on economic considerations, but, if economic issues are set aside, then the best available technology (BAT) criteria have to be used [16, 52, 53, 54].

There is Kose settlement located near the Ahtme mine water outflow to the Sanniku stream. The distance between the settlement and the outflow is 500 m. The Ahtme outflow works all the year round and it is worthwhile to set up a heat pump complex there to produce heat for Kose settlement. It must be taken into account that the amount of mine water flowing out from Ahtme mine is dependent on rainfall.

7. Conclusions

In Estonia, more than 90% of electricity is produced from oil shale which has been mined here for over 90 years, the total production exceeding one billion tonnes. The oil shale is mined in two ways: underground (room and pillar mining method) and surface (open cast mining method). The underground mining created underground free space and, as extraction took place below the groundwater level, the workings filled with water after closure.

The subject of this paper became topical many years ago and several research projects funded by research organizations as well as private companies were carried out. The aforementioned projects dealt mainly with two subjects: stability of undermined areas and mine water balance. Filled underground oil shale mines create underground water pools called technogenic water bodies which have a stable temperature all the year round, but which are not yet exploited as a source of heat for heat pumps and for reduction of wintertime heating costs. In order to use mine water as a source of heat for heat pumps, the relationships between the mining technology applied, volume of underground space, hydrogeological parameters of closed or abandoned mines and subsidences have to be elucidated. At present, these relationships are unknown yet. The aim of this research is to find these relationships and offer solutions to usage of undermined areas.

An oil shale block model has been created with the help of topographic and geological data (stratigraphic, hydrogeologic, LIDAR data). It describes mining conditions, i.e. geological and technological parameters and environmental conditions that directly affect oil shale mining. The most common parameters are oil shale layer thickness, depth, angle, rock stability, etc. The oil shale block model shows top layers: the surface, layers of limestone, oil shale seam, and groundwater levels.

There are many new technologies to assess undermined land, such as 3D scanning and LIDAR. Using the aerial photograph and altitude data (known as LIDAR data) it has been found that the longwall mining areas have sunk less than predicted. It is not possible to give general recommendations and permissions for building, road construction or other land usage as every specific case has to be considered separately, depending on mining conditions and method.

In a particular mining area water is mostly found in the extracted oil shale seam (Fig. 13, Table 4) and can be exploited as a source of heat for heat pumps. These areas can be called energy spots. Limiting factors, such as water and environmental protection areas, techno-communications, restricted zones, etc., should be taken into account and a spatial query applied to locate the energy spots.

The best possible technical solution to using mine water in heat pumps is to pump the water through a drill-hole onto the ground surface (Fig. 15). Water is directed back to the mine or water source after lowering the temperature of mine water in the heat exchanger by about 1–4 degrees. The usage of water from underground pools is efficient with a temperature reduction of at least four degrees. The amount of mine water to be consumed is higher if the temperature is lowered less and this may deteriorate the stability of land and pillars in the oil shale mine.

The results of the study are of high importance in view of the fact that there are plans to close Aidu open cast and Viru underground mine in 2014. Pumping in these mining sites will stop and mining fields start to flood with mine water. The closing of the mining fields will also change the water regime in the region. New potential places for using mine water as a heat source for heat pumps are offered. It is also possible to collect heat from mine water by using another method. Instead of pumping the mine water through the heat exchanger of a heat pump, it is expedient to establish an underground net for heat collection if the drifts are still dry.

The selection of a technology depends directly on economic considerations, but, if economic issues are set aside, then the BAT criteria have to be used. In the future, the oil shale mining technology will determine the amount of free space in mined areas, as well as the potential usage of mine water as a source of heat for heat pump plants.

Acknowledgements

This research is part of the Estonian Research Fund (ERF) Grant No. 8123 – "Backfilling and waste management in Estonian oil shale industry", the Estonian Archimedes Foundation project "Doctoral School of Energy and Geotechnology II", the European Union Baltic Sea project MIN-NOVATION "Mining and Mineral Processing Waste Management Innovation Network http://mi.ttu.ee/min-novation/. Study of the local power supply in Ida-Viru County", and the Estonian Archimedes Foundation research project AR12007 'Sustainable and environmentally acceptable Oil shale mining'.

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Received October 25, 2012