The Future of Oil Shale Mining related to the mining and hydrogeological conditions in the Estonian deposit

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Abstract
Due to high oil price in 2005 number of oil shale mining claims were requested by mining companies in Estonia, which is indicator of rapid oil shale mining development. There will be new mines opened in near future which causes changes in environmental conditions, mainly decrease of water level.

Estonia is leading Oil shale mining country in the world. Oil shale has been mined for 90 years, the peak was 31 Mt in 1981 and has stabilised in level of 13 Mt annually in recent years. 95% of Estonian electricity is generated in oil shale power plants. About 20% of mined oil shale is used for oil and chemical production

Keywords
Mining, oil shale, hydrogeology, technology, modeling, GIS.

Introduction
Mining is performed equally in underground and surface mines accordingly with room and pillar and open cast mining with draglines. In low bedding surface mines, mechanical extraction with shovel-truck operations is used. Traditional depth in low surface mines is up to 15 m, 30m in open cast mines and 80 m in underground mines. Oil shale seam thickness is stable – 2.8 m, the layers are intersecting with hard limestone layers making selective mining or enrichment obligatory for getting required quality.

1 Modelling
Modelling is relatively new approach for planning new and analysing abandoned mines. Modelling itself is convenient way for choosing and selecting and visualising the results but deciding for optimal modelling method and software is complicated task.

There are three main tasks for modelling to solve:
- Mining technology
- Mining development
- Mining influence

2 Technological modelling
For modelling environmental influence mining locations and advancing speed are required. Depending on mining conditions, possible technology, availability of equipment and their productivity, mining areas were chosen. The main criteria for redistricting the deposit are possible mining technologies in certain mining conditions. The main criterion is thickness of overburden.

Since the advancing speed of mining front depends on mining technology and its geometric parameters, the technology has to be modelled for expecting geometric parameters. Geometric models with GIS model allow easily explaining suitable mining technologies in every certain location. Strip and room-and-pillar mining were modelled with Excel software Visual Basic. In addition Surpac, Encom Discover and Modflow software were used for local cases.

3 Spatial modelling
Because of big amount of available drill hole and survey data, GIS and mining modelling systems were used to solve spatial task. Spatial distribution and geographical data were retrieved with Vertical Mapper package. (Fig. 1.) For further visualisation of geological data and mined areas Surpac Vision and Encom Discover were used.

More expensive or not practiced mining technologies in Estonian oil shale deposit give great increase in surface mining area and different mining influence according to water regime and landscape.
Open cast mining with draglines and conveyor bridges and combined stripping methods with excavators and bulldozers allow increasing mineable overburden thickness and moving mines in southern direction. (Fig. 1.)

The development plan was chosen after analysing all potential technologies, risks and expenses. The plan allows evaluating environmental and social impacts of mining until year 2025. (Fig. 2.)

4 Hydrogeological modelling

Due to the low mineral deposits and highly permeable overburden the groundwater has strong influence to oil shale mining, inhabitants and nature. Taking into consideration similar geological conditions, thickness of limestone overburden and bottom layer of the oil shale, the water level and drainage radius were interpolated with MapInfo Vertical Mapper software between measured observation well values. The model visualises mining advancing and changes in decreased water level until the year 2025 when four new mines will be developed. Generated models gave the possibility to give prediction about the wetlands or nature reserve areas what could be affected by mining activity and which mining technologies should be used for decreasing mining influence. Retrieved data gives boundary conditions for dynamic modelling with Visual Modflow software. Water level models show the relation of abandoned mines and water flow in mined area (Fig. 4.).

In addition to modelling, surface miner was tested as landscape designing tool – creating new lake and river areas. Creating infiltration dams during stripping operations were tested to decrease drainage radius of the mine. Both tests showed good results for sustainable mining operations and gave data for further modelling.

Ten oil shale mines in the middle of the deposit have been closed. Water level restoring in these mines gives good practical experience for expecting water level in the neighbourhood of future mines. In addition to good analysing possibilities the 3D models helps to explain water situation to the concerned people. (Fig. 3.)

5 Hydrogeochemical modelling

Geochemical processes which determine seasonal variations were examined in 1979-1981 [8]. The mine water in closed mine were affected by sulphide oxidation. During the mining processes pyrite (FeS2) had been extensively mixed with air oxygen. Oxygen is a master variable in pyrite oxidation [9]. It acts directly in oxidizing the sulphide and the iron (II) as shown by the reaction [10, 11]

\[
\text{FeS}_2 + 7/2\text{O}_2 + \text{H}_2\text{O} \rightarrow \text{Fe}^{2+} + 2\text{SO}_4^{2-} + 2\text{H}^+ \tag{1}
\]

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

\[
\text{FeS}_2 + 14\text{Fe}^{3+} + 8\text{H}_2\text{O} \rightarrow 15\text{Fe}^{2+} + 2\text{SO}_4^{2-} + 16\text{H}^+ \tag{2}
\]

\[
\text{Fe}^{2+} + 1/4\text{O}_2 + \text{H}^+ \rightarrow \text{Fe}^{3+} + 1/2\text{H}_2\text{O} \tag{3}
\]

The dissolution of pyrite leads to high concentrations of sulphates. The water displayed neutral pH and positive Eh in the spring-summer than in other times [8]. These results reflect the increasing of the sulphide oxidation rate during the warm months, other time the sulphide oxidation rate was low, but depend on precipitation.

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. 5.) in water has been caused by oxidation of pyrite in well-aerated water, which percolates down through the overburden. In the water, which fills underground mines, the content of this element is high (Fig. 5. – Ahtme mine), but lowering and still stays 10 times higher than its natural background.

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 SO4 in groundwater was 2 times higher in spring (Fig. 6.) than during the remaining seasons of the year. It can be caused by dissolution of pyrites in oxygen-abundant water in spring.

Mine No 4 closed in 1975 and in 1990 it was water filled. Mainly precipitation, groundwater flow from each side and rising water level 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. 7.). The 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. 7A.

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. 10B). This is promoted by karst and technogenic faults. The Ahtme mine water pool exerted a weak 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. Mine no 4 and also Käva mine pools water amount in the Lasnamäe–Kunda was lower, 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.
5. Conclusions

There is no single software package for modelling complicated mining development plan as a country’s main mineral mining in a rapid increase period. All available packages have to be tested from both simplicity and information exchange side and from advanced results and analysing side. The results depend form local conditions like people, geology, mining traditions and software availability. For Estonian Oil Shale mining modelling – in addition to traditional office software, MapInfo, Vertical Mapper and Modflow have shown good results. In addition to analysing capabilities the visualisation aspect has shown strong importance for working with development plans.

In closed mine workings form underground water basins with higher sulphate content, which may be exacerbated due to the mining methods and underground mining operations.

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;
2. closing and flooding of underground mines has changed the groundwater forming conditions in the Lasnamäe–Kunda aquifer and sulphate content within it;
3. due to technogenic impact the water of closed mines is connected with the Lasnamäe–Kunda aquifer.

This study is related to EstSF grant G5913 “Usage of mined out area”.

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