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Rational Use and Environmental Impacts of Oil Shale Mining in Estonia

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ABSTRACT: In Estonia, oil shale is produced by underground and surface mining. The excavation methods used cause serious damage in the environment, especially the topography, which hampers further use of mined-out areas. Oil shale mining also has a serious impact on the environment due to the pollution of surface and groundwater by polluted mine drainage waters, lowering of the groundwater level, changing of soil properties and high level of air pollution. Another serious problem relates to high mining losses. The decline in mining activities and the introduction of new technologies together with economic measures have improved the situation, but much needs to be done in the coming years.

1 INTRODUCTION

The Estonian oil shale deposit (Fig. 1) is the largest commercially exploited oil shale deposit in the world; its total resources exceed 7 billion tonnes. The resource of the prospective Tapa deposit is about 2.6 billion tonnes. The Baltic Oil Shale Basin, covering ca. 50 000 sq. km, is situated mainly in northeast Estonia with part of it extending eastward into Russia. Oil shale has been mined in Estonia since 1916, with a maximum annual output of 31.3 million tonnes in 1980 (Fig. 2). During more than eighty years, about 870 million tonnes of oil shale has been mined (together with a lost 1.6 billion tonnes). Currently, oil shale is mined in six underground mines and in three opencast pits with an annual output about of 10 million tonnes. The main oil shale sequence is of Middle Ordovician (Llandeilo - Early Caradoc) age. It contains up to 50 laterally continuous seams alternating with limestone layers. Oil shale layers thin or die out towards the peripheral parts of the deposit This is accompanied by a decrease in the kerogen content. The highest productivity (conditional fuel per sq. m) has occurred in the northern part of the Estonian mining area between Kukruse and Jôhvi (1.5 t/sq. m). Here, the calorific value of oil shale is 10-12 MJ/kg. At the outer boundary of the deposit the calorific value is 1.7 times lower, and the yield about 3 times lower (Bauert and Kattai, 1997). With the southward dip of the layers, the depth of the commercial bed increases to 100 m, which hampers the mining. As a result, the prime cost grows abruptly towards the periphery of the area. Due to the dewatering of oil shale mines, the groundwater level of Quaternary and Ordovician aquifers in the oil shale basin has fallen by 15-65 metres, and several local cones of depression, influencing each other, have formed over an area of 600 sq. km (Vallner, 1997).

2 BRIEF OVERVIEW OF MINING TECHNOLOGIES

The first oil shale mines were located in areas where it was either exposed on the ground or it occurred relatively close to the surface and therefore mainly opencast mining was used. In earlier times, underground mining was introduced in areas where the thickness of overburden exceeded 5-8 metres; now it starts from several tens of metres. The technologies used exert a substantially different effect on the topography and water regime. The cavities generated by subsurface mining cause deformations that reach up to the surface and hamper further use of the mined-out areas. In Estonian underground mines, oil shale has been produced by pillar and double stall mining, double face longwall stall mining, fully mechanised narrow web mining in the longwall stall system and room pillar mining (Toomik, 1999). In all cases, the mining plot is rectangular in shape. Therefore, after mining a new artificial topography is formed on undermined areas, where the small hollows alternate with hillocks. In places where the Quaternary cover contains loamy deposits, the surface water accumulates in such hollows and the land use is limited

As a result of opencast oil shale mining, the area of quarries covered with waste rocks increases by several hundred hectares annually. Of a total of 10,000 hectares spoiled by mining activities, most has been reclaimed and reforested. Some hundred hectares have been returned to agricultural use, but such areas are far from being of top quality.

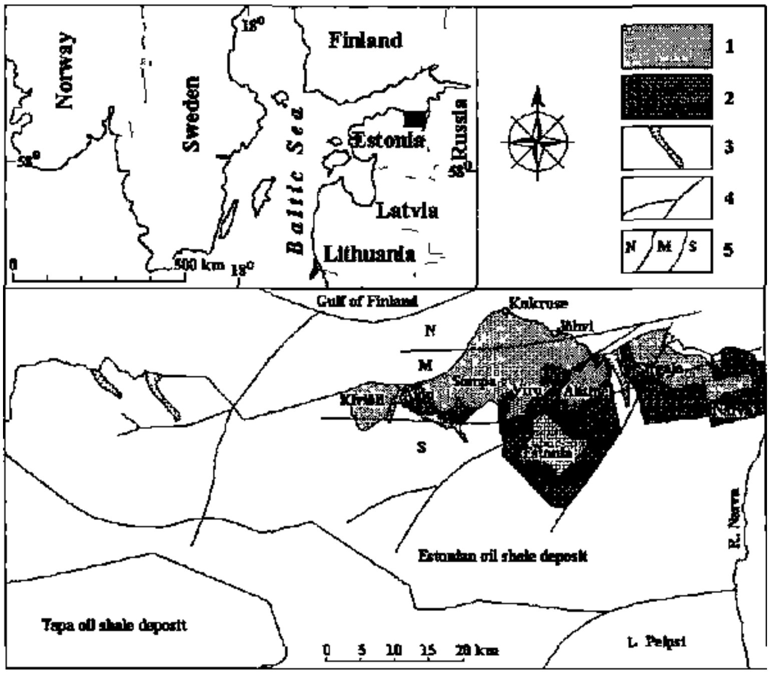

Figure location map of Estonian and Tapa oil shale deposits
1 - oil shale mines and open pits, 2 - claims and names of mines and open pits, 3 - buried valleys, 4 - tectonic faults, 5 - water regime regions N-northern, M-middle and S-southern

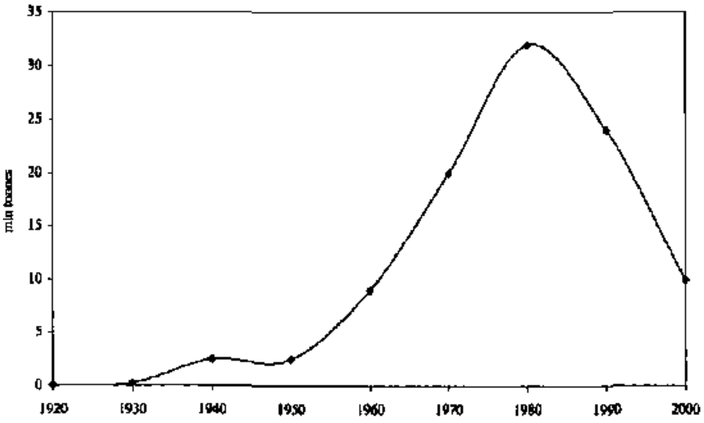

Figure 2 Consumption of oil shale in Estonian oil shale deposit

3 LOSSES AND USAGE OF OIL SHALE

During the last decades, a serious problem has occurred relating to high mining losses. To support the roofs of mining shafts, up to 30% of mineable oil shale has been left intact as pillars. Supplementary losses occur during the hauling and benefaction steps, increasing the net losses to as high as 50%. The vigorous intensification of agriculture and industry during Soviet occupation was accompanied by a sharp increase in the exploitation of mineral resources and mining losses were not the top-priority problems. Over the years 1945-1990, the population of Estonia increased some 1.4 times, the number of workers and employers 3.8 times, industrial output 4.2 times, the production of mineral resources 15 times, and the generation of electric power 100 times. Great losses in mining and concentrating are due to the complicated structure of the productive layer. Some layers remain unmined because of their inconsiderable thickness, or because of thick limestone interlayers or high content (up to 50 per cent) of limestone concretions. The most effective step in minimising production losses would be the application of mining technologies that would enable the excavation of all oil shale layers to their full length. Therefore, in the Estonian National Environmental Strategy (Estonian... 1997), opencast mining is recommended whenever possible. A revision of consumer claims for the quality of oil shale might also contribute to rational utilisation of oil shale reserves. Attention should also be paid to studies concerning the technological possibilities of burning and processing oil shale with low calorific value.

The Baltic Thermal Power Plant (project capacity 1624 MW) and the Estonian Thermal Power Plant (project capacity 1610 MW) are the main oil shale consumers. Together with some smaller local power plants, they use more than 80% of the mined oil shale. About 15% of the mined oil shale is used for crude oil retorting. The number of various products derived from crude oil totals about fifty. The retorting of oil shale and upgrading of shale oil to commercial products also have a severe impact on the surrounding environment.

4 ENVIRONMENTAL CONSEQUENCES

The majority of Estonia's mineral resources, particularly oil shale and phosphorite, are concentrated in the northeast Estonia region. In this densely inhabited agricultural and industrial area the interests of different institutions are in conflict. Unfortunately, in this area, with weak natural protection against pollution, the human impact has already led to undesirable changes. Oil shale mining has exerted great influence, not only on the topography, but it has also polluted surface and groundwater. In waste dumps near benefaction facilities, the residual organic matter is prone to self-ignition, polluting the air. In this paper, we shall concentrate on the problems of water pollution, most dangerous in the area with thin Quaternary cover.

Due to the excavation of the oil shale, the water regime is upset: the groundwater begins to move concentrically towards the excavation cavities. The irregular spreading on industrial oil shale in the carbonate rocks mainly causes a comparatively big and uneven influx of water into the mines and open pits. The Ordovician aquifer is mainly replenished by infiltrating atmospheric precipitation, by water from water basins and water pumped out of the mines. The process is facilitated by the spatial irregularities in the hydraulic properties of the rocks, the rather thin layer of the Quaternary sediments and the shallow depth of the oil shale deposit.

Different excavation methods cause an increase in "technological" fissures (fissures caused by explosions during excavation) and in the drainage of the Ordovician aquifer, especially the Keila-Kukruse layer (Fig. 3). When forecasting water influx, one must take into account natural as well as mining conditions, especially the development ofexcavation cavities during the exploitation of the bed. The following equation has been used to calculate the water balance:

$$\sum I - \sum O = \Delta S$$

where the inflow $\sum I$ includes all forms of recharge, such as: seepage from streams, ponds and lakes; subsurface inflows; and infiltrated precipitation. The total outflow $\sum O$ includes every kind of discharge, such as subsurface outflows, evapotranspiration, abstraction of mine water, etc. ΔS represents the change in storage during the period studied.

Research shows that approximately 90-95% of the influx comes from the surface, which includes the atmospheric precipitations, together with infiltration of the water pumped out in the regions of erosion and technological fissures. Only 5-10% of it originates from the industrial oil shale layer. The annual mean water influx amounts to 27 000 m^3 per hour.

A noticeable and regular increase in the amount of infiltrating water occurs all over the bed as the excavation work proceeds. The seasonal irregularity of infiltration depends upon the depth of the excavation, its technology, the lithological composition and cleavage of the rocks and meteorological conditions. Thus two maxima in spring and autumn and two minima - in winter and in summer - of the yearly water influx can be discerned.

The infiltration of water into excavation cavities is due to natural and mining-induced causes. The natural conditions determine the hydrogeological structure and, accordingly, the groundwater regime (Table I).

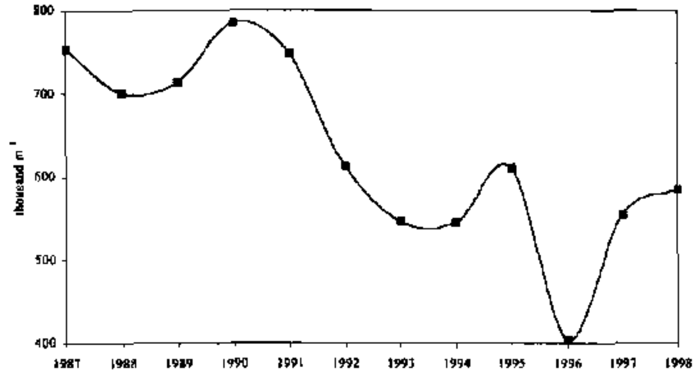

Figure 3. Dewatering of oil shale mines and open pits.

Table 1. Hydrogeological structure and groundwater regime in natural conditions.

Sub-group	*Natural conditions*	*Influence*
geological	rock types, tectonical damage, neo-tectonic movements, cleavage,	permeability of rocks, structural and filtration irregularities
physico-geographical	topography, hydrometrical and hydrological parameters of water basins, atmospheric precipitation	formation of feeding and out-flow areas, regime of surface and groundwater

Table 2. Groundwater regime changes by technological conditions.

Sub-group	*Technological conditions*	*Influence*
geometrical	location of mines and quarries, horizontal and vertical parameters	changing of feeding and out-flow areas and of the movement of surface and groundwater
geomechanical	technological cleavage, surface subsidence	change of structural and hydraulic properties of sediments and rocks
technological	inundation of excavation cavities	alteration of geofiltrational conditions on the boundary between closed and active mines and open pits

Exploitation of the mines and quarries brings about changes in the groundwater regime, which is characterised by alteration in the feeding and outflow conditions (Table 2).

A water level depression occurs around excavation cavities, its dimension depending on the hydraulic conductivity and storage capacity of the rocks, and the amount of pumped-out water.

According to hydraulic properties, the oil shale bed can be subdivided into three major regions: northern, middle and southern. The northern and middle regions are enclosed by the Keila-Kukruse water layer, with a maximum bedding depth of 45-50 m. There are two separate water layers that coincide with the industrial oil shale layer 25 m deep. In the northern region, the Ordovician aquifer spreads under a thin layer of Quaternary sediments, and is considerably split. According to natural conditions, the infiltration of atmospheric precipitation is biggest in this region in comparison with the rest of the bed. The dissected topography and the thickness of Quaternary sediments regulate infiltration.

The amount of water Q infiltrating into the excavation cavities of the northern region is determined by two important parameters: the surface of the excavated area F and the intensity of filtration, i.e., specific consumption - w_{inf}

$$Q = f(F, w_{inf}).$$

The northern region of the bed is characterised by a surface regime. Buried valleys, bog areas, water basins and closed mines serve as local feeding sources. In the middle regmt wth feeding and outflow conditions change due to the different hydraulic properties of the rocks. Two water layers spread over the excavation area - the Keıla-JÖhvİ and the Idavere-Kukruse - separated by the metabentonid interlayer. Infiltration conditions in the southern region are more complicated than in the two regions described above, because, in addition to the water layers mentioned, the Nabala-Rakvere layer, characterised by very irregular filtering properties, joins the intersection. The structure of the regions described is presented in Table 3.

Table 3. The structure of the regions.

Region	*Depth of bedding of industrial layer, m*	*Water layers*	*Type of feeding regime of water layer*	*Mines*
northern	25	Keila-Kukruse	infiltration, free-surfaced	closed mines
middle	25-50	Keila-Jöhvi Idavere-Kukruse	infiltration, free-surfaced, pressurised	Sompa, Viru, Ahtme
southern	50-70	Nabala-Rakvere, Keila-Jöhvi, Idavere-Kukruse	infiltration, pressurised	Estonia

In the middle and southern regions, the intensity of the infiltration and the depth of mining determine the amount of water influx into the excavation cavities. When taking into account the influence of the mining depth, the outflow parameters, i.e., the relation K/m, are used, where K is the hydraulic conductivity and m is the thickness of the deposit. The formula used for calculating the amount of filtrating water in the middle region is:

$$Q = f(K/m, w_{inf}).$$

The regime of the drained water complex is locally phreatic or confined. Feeding areas consist of buried valleys, bogs and lakes as well as the Nabala-Rakvere water layer. For calculating the amount of filtering water in the southern region, the following formula has been used:

$$Q = f(K_i/m_i, w_{inf}).$$

The drained aquifer is pressurised and widespread. Local feeding areas consist of bogs and lakes. The chemical composition of the bed water changes in accordance with the amounts of influx into the mines and quarries and the magnitude of filtration.

Drainage of wells causes the depletion of groundwater, which reaches a depth of 20 m in the northern region and 70 m in the southern region of the mining area. Strong depletion of wetls can be observed; the infiltration of contaminants grows and the main aquifers are chemically polluted over a large area. A study of the wells (1980-1998) in the rural areas surrounding some towns showed that of the 173 sampled wells, 95% had a high sulphate concentration, 91% were contaminated with oil products, 60% were contaminated with phenol dérivâtes and 53% did not meet microbiological standards.

5 CONCLUSIONS

Mining processing and utilisation of oil shale in Estonia has produced serious environmental consequences. These consequences exert an influence far beyond the boundaries of the mining area and long after the cessation of mining. Mined-out areas with their disturbed balance of ground and surface water regimes and soft surface layers favouring the infiltration of the surface water are especially sensitive to pollution and other undesirable effects. The decline in mining activities (Fig. 2) and the introduction of new technologies together with economic measures (resource charges, pollution taxes) give us hope that the situation will improve in the very near future.

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