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TECHNOGENIC WATER IN CLOSED OIL SHALE MINES

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The present paper is based on the results of the research conducted in 2004 by the Department of Mining of the Tallinn University of Technology and Estonian Oil Shale Company. The state of the technogenic water body that has formed in the central part of the oil shale deposit is analysed: the water level in the area of the stopped and closed mines, water amount and movement direction, water quality and its changes. The state of the water is assessed and predicted using modelling of the water tables, statistical analysis of the water quality parameters and the pilot model for describing the migration of water. The results show that the technogenic water body studied is in a relatively stable state, and the quality of the groundwater in that area is fast improving approaching the drinking water standards.

Introduction

The Estonia oil shale deposit comprises about ten closed and stopped deep mines that are fully or partly filled with water (Table 1). Eight mines in the central part of the deposit: *Ahtme*, *Kohtla*, *Kukruse*, *Käva*, *Sompa*, *Tammiku* and mines *Nos. 2* and *4* form one water body. After *Ahtme* mine was filled with water in December 2004 (Fig. 1), the water body turned relatively stable. *Ubja* mine and joint *Kiviõli* and *Küttejõu* mine are located in the western part of the deposit, farther away from the other mines. In addition to oil shale mines, *Sillamäe* uranium mine (1949–1952) [1], and *Ülgase* (1922–1938) and *Maardu* phosphorite mines (1942–1965) have been closed in Estonia. The water regime in these mines has not been studied yet and is not discussed in the present paper.

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Table 1. **Closed and flooded underground oil shale mines**

Mine	Closed – (pumps were stopped)	Mined area, km^2 *	Water table a.s.l., m	Outflow regulating the water table	Approximate water volume, 10^6 m^3
Central part of the deposit:					
Kukruse	1967	13	51–54	Mostly into Käva and Jõhvi mines	3.5–6**
Käva and Käva-2	1973	18	51–52	From an old adit into Vahtsepa ditch	9–11**
Mine No. 2 (Jõhvi mine)	1974	13	51–56	Mostly into Tammiku mine, during flood to Jõhvi city	10–11**
Mine No. 4	1975	13	41–42	Mostly into neigh-bouring mines	3–8**
Tammiku	December 1999	40	44–48	Into the Kose River and Viru mine	34
Sompa	February 2000	27	40–45	Into neighbouring mines	23
Kohtla	June 2001	17	39–42	Into Aidu opencast	13
Ahtme	December 2001 – December 2002	35	≈ 47	From drill holes and springs into Sanniku brook	36
Separate mines in the western part of the deposit					
Kiviõli & Küttejõu	1989	29	41 ± 0.5	From a ditch into the Purtse River	Up to 29
Ubja	1960	2	≈ 55	From an adit into the Toolse River	Not determined
Total					≈ 170

* [5]

** Depending on the water level [6]

As a rule, the mine workings and groundwater cone of depression formed during mining fill with water after the cease of mine pumping. The degree of filling depends on the mining depth and the height of outflow. The tunnels of *Ahtme*, *Sompa* and *Tammiku* mines are completely, those of mines *Nos. 2* and *4* almost completely water-filled. The rest of the mines (*Kiviõli*, *Kukruse* and *Käva*) contain areas with dry floor. The museum founded in *Kohtla* mine is dry because of to the draining effect of *Aidu* opencast and the water barriers surrounding the exposition area. The water level changes depending

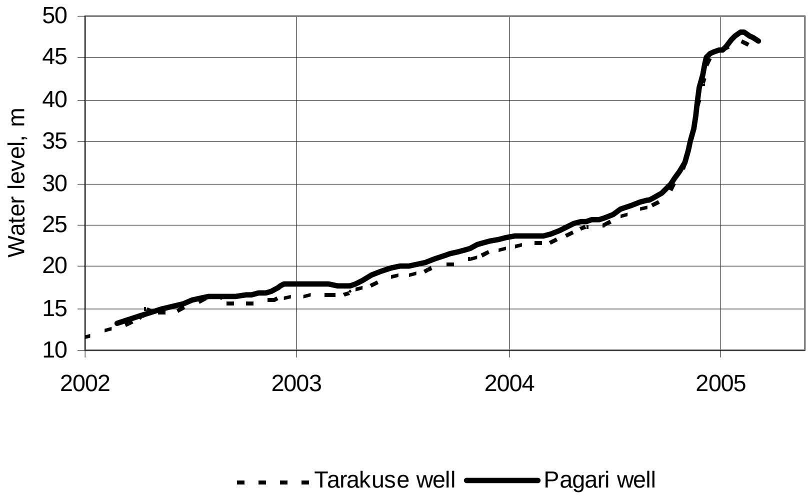

Fig. 1. Increase in the water table in closed Ahtme mine

on the amount of precipitation and water exchange with neighbouring mines. The rate and amplitude of the changes differ from mine to mine.

Several problems have arisen from the flooding of the closed mines. First, the technogenic water body started to affect the amount of the water pumped out of the working mines and its seasonal variation [2]. Clearly, the water of the closed mines will influence also the new mines, planned to be constructed in the *Ojamaa* and *Uus-Kiviõli* mine fields. Second, the environment is affected by the water that in several places has risen to the pre-mining level (of the year 1945) and by the new springs formed. Several projects have been undertaken to fight the flooding, and it has turned out that no sufficient source data for mine planning are available. Third, the water of the closed mines is an easily accessible water resource, thus it is important to know and predict its quality [3]. Prediction of the mine water quality is essential also because of the fact that groundwater elevation in the mine field has started to affect the water supply of the region – the water richer in sulphates runs into the outdated and leaky common wells. It has also been prognosticated that if the groundwater table rises higher than 45–47 m, the water in the Ahtme mine field will affect the water level and quality of the Vasavere intake [4]. Fourth, the land above old mines has subsided and the rocks are fractured, therefore the technogenic groundwater is weakly protected and the contribution of precipitation to groundwater formation is very high.

Water level

The present study is based on the water level measurement data (incl. archive data) provided by the Estonian Oil Shale Company, Geological

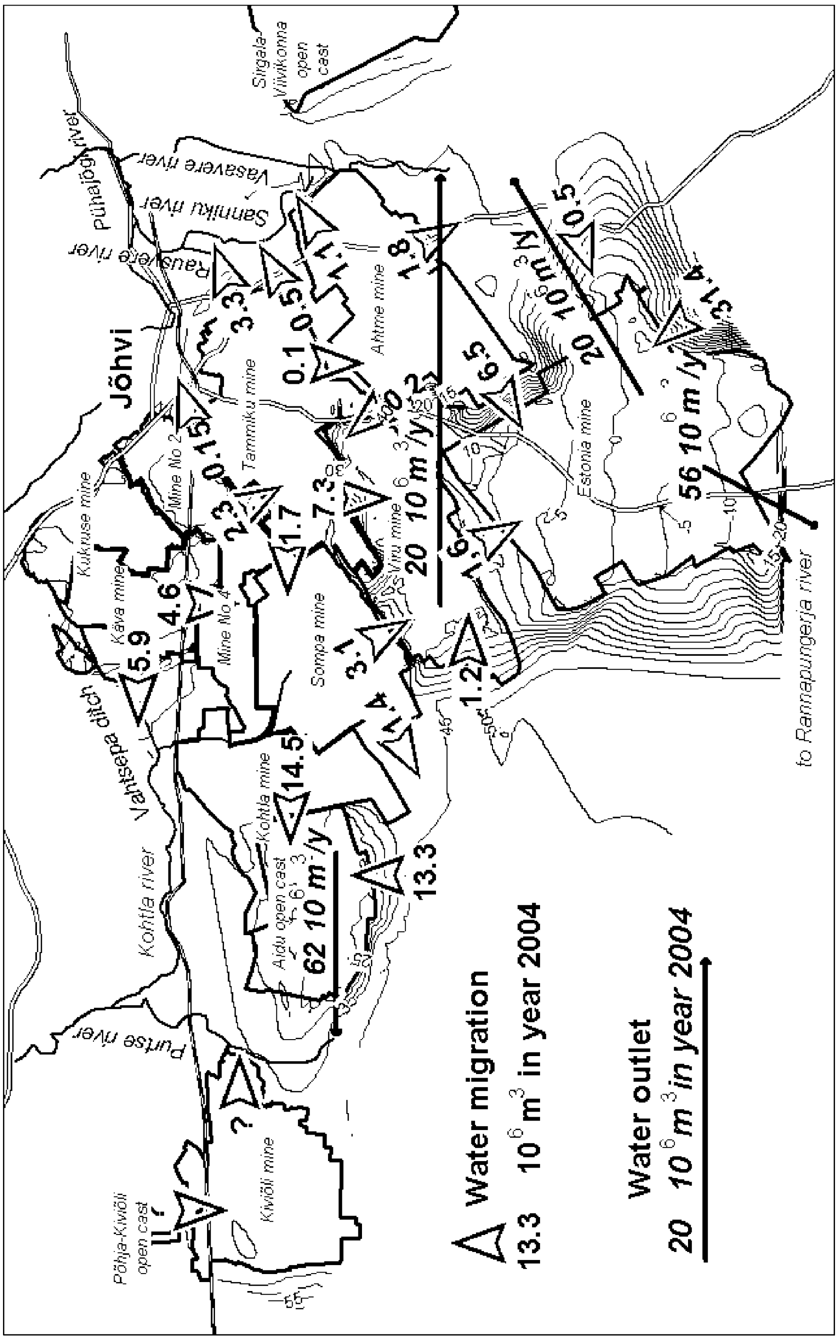

Fig. 2. Map of the technogenic water body

Survey of Estonia and Municipality of the town of Jõhvi. The water levels of the Keila–Kukruse, Lasnamäe–Kunda and Nabala–Rakvere aquifers, closed mines and main outlets were measured on an average period of 20 years. New data were obtained in the years 2003 and 2004. Field works and monitoring started in the spring of 2004 and are still going on.

An essential part of the research was the modelling of the level of the Keila–Kukruse aquifer in the stationary regime. The modelling area included the central part of the deposit – underground mines and *Aidu* opencast. Data from about 50 observation wells were used. The water level of working mines was described at the level of the oil shale bed floor. Closed mines were treated as independent water sub-bodies, where the water level is constant at a certain moment of time (Table 1). The MapInfo Professional software was used, combined with the modelling package Vertical Mapper. The comparison and calibration of the intermediate results obtained and discussions held showed that the best interpolation method was triangulation with smoothing, because in that case interpolation takes place only between data points or observation wells, without modelling the situation outside the study area.

During the first stage of the research the state of the water body in August 2004 was assessed. According to the measurements and calculations performed, precipitation accounts for up to 70% of the water pumped out of mines [2]. The autumn–winter season of 2004 was rich in precipitation, with little snow and relatively warm. Therefore it could be expected that *Ahtme* mine would fill with water sooner than predicted [4]. To check that hypothesis, the model was calibrated at the second stage of the research in December 2004. The contour map of the modelled water table is shown in Fig. 2.

By continuous improvement of the existing and addition of new data more than ten two- and three-dimensional map versions were completed. The model enabled us to assess the water levels in different mines and their border areas and to make assumptions and predictions about the water movement directions.

Water quality

In the years 2000–2004 the department of environmental services of the Estonian Oil Shale Company had the waters of all closed mines analysed. The samples were taken at six sites in four mines in different seasons. Analyses were made at the central laboratory of the Estonian Oil Shale Company (3 analyses), in Tartu Environmental Research Ltd. (2 analyses) and in the Geological Survey of Estonia (12 analyses). Up to 16 quality parameters were determined. The results of the analyses are presented in Table 2.

The quality parameters are arranged in Table 2 in the decreasing order of the variation in measurement results. At first glance only the average contents of iron, sulphates and phenols obtained for the observation period do not meet the drinking water standards. This cannot be a final conclusion. The average

Table 2. **Water quality parameters in closed *Ahtme, Kohtla, Sompa* and *Tammiku* mines**

Quality parameter Leachates	Unit	Number of measurement results		Numerical data for the entire period (2000–2004)			
		Total	Certain numerical values	Arithmetical mean	Standard deviation	Variation coefficient	Max. levels permitted in drinking water
Total Fe	mg/l	14	10*	0.69	1.16	1.67	<0.2
NO_3^-	mg/l	15	11*	11.7	18.55	1.58	<50
NO_2^-	mg/l	12	7*	0.015	0.0166	1.10	<0.5
SO_4^{2-}	mg/l	15	15	342.4	240.2	0.70	<250
Dry residue	mg/l	14	14	845.5	569.6	0.67	–
Mg^{2+}	mg/l	15	15	51.6	32.58	0.63	–
K^+	mg/l	13	13	12.9	8.11	0.63	–
Ca^{2+}	mg/l	15	15	174.5	107.6	0.62	–
Na^+	mg/l	14	14	10.4	6.33	0.61	<200
Cl^-	mg/l	15	15	16.4	9.74	0.59	<250
Total hardness	mge/l	13	13	13.72	7.04	0.51	–
Oil products	mg/l	15	4*	0.15	0.073	0.49	<0.05
Conductivity	µS/cm	14	14	1095	477.6	0.44	<2500
NH_4^+	mg/l	12	2*	0.017	0.0064	0.39	<0.5
Total phenols	mg/l	15	4**	0.0017	0.00049	0.28	<0.0005
pH		15	15	7.1	0.33	0.05	6.5–9.5

* due to the lack of a certain numerical value the result was smaller than the preciseness of the laboratory tests, but not exceeding the limits permitted in drinking water
** due to the lack of a certain numerical value the result was smaller than the preciseness of the laboratory tests, in two cases not exceeding the limits permitted in drinking water; rest of the samples gave no unique result

Notes:

Quality parameters are ordered according to the variation coefficient.

The shaded lines contain the measurement results the average of which does not meet the Estonian drinking water standard.

The content of benzo(a)pyrene was measured in 11 samples. The results are not included in the table because no certain numerical values were obtained. In all samples the benzo(a) pyrene content was lower than the permitted maximum value.

and standard deviations given in the table have been calculated for all closed mines and for the entire observation period, thus they characterize only the data set and not the quality of water or a particular mine. Variation in the measurement results is caused by influential as well as random factors. Influential factors are the sampling site (mine) and the time span that has passed since the closure of the mine. Let us treat this assumption as a working hypothesis. A random factor is the season when sampling was performed. For example, in the years 2000 and 2001 samples were taken in summer, in 2002–2004 in autumn. Surely the water quality parameters depend also on the location of the sampling site in the mine field. Some part of variations result from the methodology of sampling and laboratory tests. The reliability of iron content analyses carried out in different laboratories could be questioned. The phenol content of mine water, measured repeatedly during mining, has been 0.003 ± 0.001 mg/l, except for *Kiviõli* mine, which has been strongly affected by chemical industry. Here the phenol content of mine water was 0.38 mg/l [7].

For preliminary checking of the working hypothesis we conducted a two-factor (place and time) variation analysis of the sulphate and iron contents of Tammiku and Sompa mine waters. The results of sulphate analysis are given in Table 3. We can see that the hypothesis of the influence of place and time on the sulphate content of water is relatively strong (probability of a counter-hypothesis 18.0 and 18.8% respectively). The residual standard deviation (187 mg/l), however, is too large for making definite conclusions. Obviously the result is influenced by taking samples in different seasons. An analogous result was obtained by the variation analysis of the iron content, whereas the impact of time turned out to be small. Possibly this could result from the treatment of samples in different laboratories.

In spite of great uncertainty of measurement, the sulphate and iron contents decrease with time. This trend is depicted by graphs in Fig. 3. As could be expected, the purification of water is best described by the exponential function. The constants in the formulae (801 and 0.77 mg/l, respectively) characterize the average concentrations at the initial moment of the dilution process (at the closure of mines) and the time factors (–0.386 and –0.507, respectively) show the rate of water purification. The half-life of the concentration calculated on the basis of time factors, i.e. the time period during which the content of a component decrease twice, is about 1.8 years for sulphates and 1.4 years for iron. From the half-life and graphs we may presume that in about five years after the closure of a mine the content of sulphates and iron decreases below the maximum permitted level in drinking water. The highest permitted content of iron in first-class drinking water is 0.2 m/l and that of sulphates 250 m/l.

The data on all mines are included in the graphs of Fig. 3. The measurements revealed varying initial concentrations of sulphates for different mines. The highest concentration was recorded in the first sample from *Ahtme* mine, the lowest in *Kohtla* mine. Actually, this is not the initial level, since the first samples were taken 4–11 months after the pumps had been stopped. Approximating the results obtained from the samples of each mine separately, we get theoretical dilution of the initial concentration level at the zero moment, about 2200 mg/l for *Ahtme* and 300 mg/l for *Sompa*. These values refer to a relation between the depth of the mine and the initial concentration of sulphates. The hydrogeological background of this phenomenon is discussed by Erg [3].

Table 3. **Results of the variation analysis of the content of sulphates**

Source of Variation	df	MS	F	P-value
Mines (Tammiku, Sompa)	1	91681	2.63	0.180
Years (2002–2004)	4	92788	2.66	0.183
Error	4	34924		
Residual Standard Deviation		187 mg/l		
Total	9			

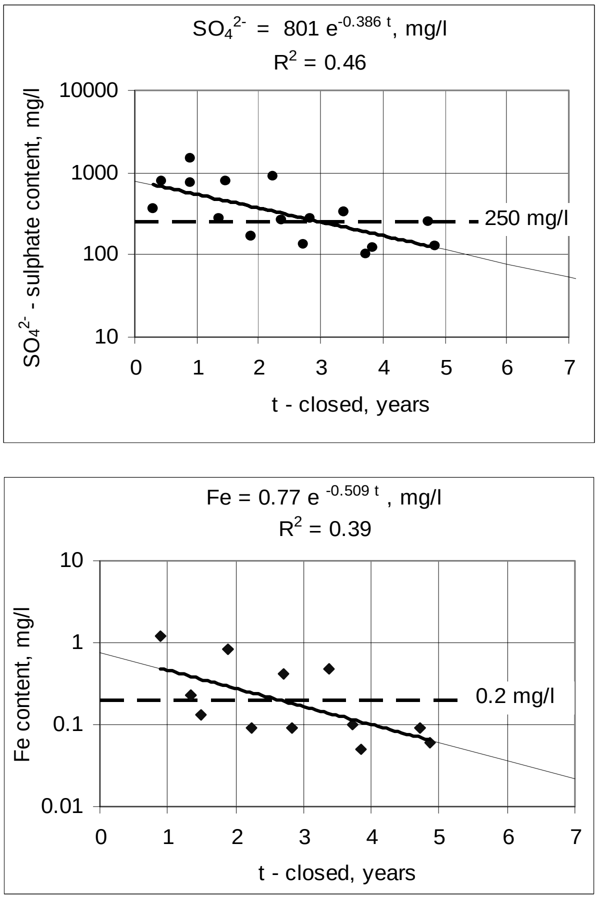

Fig. 3. Decrease in the content of SO_4^{2-} and Fe in closed mines.
250 mg/l and 0.2 mg/l – maximum permitted levels in drinking water.

The water quality parameters for which we had at least 14 reliable measurement results (pH, electric conductivity, total hardness, Cl^-, dry residue, Na^+, Ca^{2+}, Mg^{2+}, K^+ and SO_4^{2-}) were subjected to correlation analysis. From the analysis we could conclude the following:

- The content of sulphates can be considered a good indicator of mine water quality, because it correlates well with most of the other water quality parameters, except for K^+.
- Electric conductivity can be successfully used for rapid assessment of water quality, because it correlates well with sulphates as well as with other main parameters (except for K^+).
- pH is not informative enough, because it does not correlate with any other water quality parameter.

Pilot model of water exchange

Continuous water exchange is going on between the closed mines. The water penetrating into mines is derived mostly from precipitation, less from groundwater. The part of the water not flowing out of the mine (Table 1) infiltrates into the neighbouring mines or feeds aquifers. The water pumped out of the working mines is formed of precipitation, groundwater and the water coming from closed mines. Intensity of water exchange depends on the length (L, km) and thickness (l, m) of the barrier left between the mines, difference between the water levels of neighbouring mines (dh, m) and permeability of the barrier and overburden (k_m, m^2/d). The longer and thinner is the barrier, the greater is the water level difference in neighbouring water bodies, and the higher is the permeability of rocks in the areas separating the mines, the more intensive is the exchange of water.

The water levels of the closed mines are precisely known. The measurements of barriers can be obtained from the plan of mining works, but the length and thickness of the barriers are highly variable. Little data are available on the permeability of pillars and bedrock. As seen in Table 4, the permeability of the Keila–Kukruse aquifer differs up to 10 times within the limits of the deposit.

Water permeability is largely affected by the geological disturbance of the Earth crust (mostly karst zones), which makes the aquifer highly anisotropic [8, 9]. In the Estonia mine field twofold difference in the permeability in the northeastern and southeastern directions has been recorded. According to the data by Domanova, anisotropy is especially great in the area of tectonic dislocations, where permeability in various directions may differ several times. Water exchange between the mines is inhibited by extensive karst zones running along the mine field boundaries between *Sompa* and *Viru*, and *Ahtme* and *Tammiku* mines. At the same time, karst zones running transversely to the mine boundary increase the water exchange between *Sompa* and *Kohtla* mines. Additionally, the water exchange is affected by the properties of the mined area, which depend on the roof handling methods used. In the area

Table 4. **Permeability of the Keila–Kukruse groundwater aquifer in the mining district**

District	Permeability, m^2/d	Estimated difference in water tables, m	Filtration module		Publication
			m/h	m/d	
Kohtla – Aidu, northern part	1200	5	10	240	[8]
Kohtla – Aidu, central part	780	10	3.25	78	
Kohtla				6–60	[7]
Viru				10–40	
Aidu, generalized	393	10	1.6	39	[4]
Ahtme, generalized	335	10	1.4	34	
Tammiku				4–20	[7]
Ahtme				1–15	
Ahtme – Estonia	90	10	0.38	9	[4]
No. 2 – Tammiku			0.24	6	[10]

mined using roof caving the water-bearing horizon is thicker and of higher permeability than in the area of room-and-pillar mining.

Because of high uncertainty the calculation of the water amounts moving between the closed mines is complicated, not only due to the variability in *L*, *l*, *k*, but also due to the lack of the relation uniquely describing all the situations. Therefore the present study makes use of the balance method, which unites the amounts of the water pumped out of the working mines, and of precipitation and groundwater infiltrating into the mine. The relation between these amounts is expressed by the approximate formula

$$q_{\mathrm{ij}} = 365.25 \times L_{\mathrm{ij}} \times k_{ij} \times (dh_{\mathrm{ij}}/2) / (1000 \times l_{\mathrm{ij}}),$$

where

q_{ij} – the amount of the water migrating from one mine ($_{\mathrm{i}}$) to the other ($_{\mathrm{j}}$), million m^3/y,

L_{ij} – length of the barrier between these mines, km,

l_{ij} – average thickness of the barrier, m,

dh_{ji} – difference between the water levels of two closed mines at the moment of modelling, m,

k_{ij} – factor characterizing the permeability of the area between the mines (barriers and overlying rock), which, with some reservation, can be considered as generalized permeability, m^2/d.

As model input we use the measurements of the barriers between the mines, volume of the water pumped out of the working mines (especially changes in it due to the closure of neighbouring mines), amount of precipitation and its relation to mine pumping [2]. The variable parameter of the model is generalized permeability, which is used to balance the model. Permeability was fitted into the model taking into consideration the information available (Table 4), location of mines with respect to tectonic fault zones and the orientation of the karst zones lying between the mines. The balanced model can be used for calculating the migrating water amounts by fluctuations in water level, for example during floods and heavy rains, but also for planning water level regulations.

The model output is the matrix of water exchange (Table 5), where

- "North" denotes the northern closed mines *No. 2*, *Kukruse*, and *Käva* and its satellite mines
- "West" denotes the western closed mines *Kohtla*, *Sompa* and *No. 4*
- "Vasavere" is the area east of Ahtme and Estonia mines
- The water amounts in the matrix of water exchange are given in million m^3/y, whereas (+) shows the amounts infiltrating into the mine ($_i$) from the mine ($_j$) and (–) shows the amounts migrating from the mine ($_i$) to the other mine.

Explanations to the matrix of water exchange are given in Table 6. Water movement inside the water body and the amounts of mine pumping are shown in Fig. 1. The values presented characterize the state of the water body in the year 2004, but as we have to do with a pilot model, these are all approximate.

Table 5. **Matrix of water exchange, year 2004, 10^6 m^3/y**

↓Elements of the water body →	Aidu	Estonia	Viru	Ahtme	Tammiku	North	West	Vasavere	Jõhvi city	Sum
Working mines:										
Aidu	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**14.46**	**0.00**	**0.00**	**14.46**
Estonia	**0.00**	**0.00**	**1.64**	**6.48**	**0.00**	**0.00**	**0.00**	**0.48**	**0.00**	**8.60**
0.00	**0.00**	**–1.64**	**0.00**	**0.18**	**7.23**	**0.00**	**3.07**	**0.00**	**0.00**	**8.83**
Technogenic water body; closed mines (sub-bodies):										
Ahtme	0.00	–6.48	–0.18	0.00	0.07	0.00	0.00	–1.07	0.00	–7.65
Tammiku	0.00	0.00	–7.23	–0.07	0.00	2.28	–1.69	–0.50	0.00	–7.22
North	0.00	0.00	0.00	0.00	–2.28	0.00	–4.60	0.00	–0.15	–7.03
West	–14.46	0.00	–3.07	0.00	1.69	4.60	0.00	0.00	0.00	–11.24
Geographical sites:										
Vasavere	0.00	–0.48	0.00	1.07	0.50	0.00	0.00	0.00	0.00	1.09
Town of Jõhvi	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.15

Table 6. **Water exchange between mines**

Mines, technogenic water sub-bodies and geographical sites	Water exchange, 10^6 m^3/y	Comments
Working mines:		
Aidu	14.46	Inflow from closed *Kohtla* mine
Estonia	8.60	Main inflow from closed *Ahtme* mine, less from the direction of working *Viru* mine, partly also from the east
Viru	8.83	Inflow from closed *Tammiku* and *Sompa* mines, slight outflow into *Estonia* mine
Technogenic water body; closed mines (sub-bodies):		
Ahtme	–7.65	Outflow mainly into *Estonia* mine and into the catchment area of the Pühajõgi River through springs and outflow wells
Tammiku	–7.22	Intensive water exchange with other parts of the water body, out flow into the catchment area of the Pühajõgi River through a caving at Kose
Northern closed mines *Käva*, *Kukruse* and *No. 2*	–7.03	Feeds other closed mines, outflow via Vahtsepa ditch into the Kohtla River
Western closed mines *Kohtla*, *Sompa* and Mine *No 4*.	–11.24	Intensive water exchange with other parts of the water body, feeds mostly *Aidu* opencast
Geographical sites:		
Vasavere	1.09	Water inflow mostly from *Ahtme* mine, to some extent also from closed *Tammiku* mine
Town of Jõhvi	0.15	Water infiltrates from closed mine *No. 2*

Conclusions and recommendations

No great changes in the water level of closed mines and its seasonal variation are expected if no measures are taken. The situation should not change after the closure of presently working mines either. In future the water level of flooded *Aidu* opencast will be regulated by an outlet into the Ojamaa River at 40–42 m level, which will be also the common water level in Kohtla and *Sompa* mines. In the area of *Viru* and *Estonia* mines the groundwater will rise to the pre-mining level, which will result in an increase in groundwater flow into the Pühajõgi River at the eastern margin of *Tammiku* and *Ahtme* mines.

It may turn necessary to regulate water level in the mining district. In order to reduce the flow of groundwater from mine *No. 2* to the lower, area of the town of Jõhvi, the following options could be considered:

- outlet of water at 51 m level at the northern boundary of the mine, near the adit of unbuilt mine *No. 1*

- blasting of the barrier between mine *No. 2* and *Käva* and *Tammiku* mines to enable water outflow towards the Kohtla River (at a level of 51 m) or into the Pühajõgi River (at 45–47 m level)
- building of a pumping station regulating the water level and operating seasonally, but this is evidently not efficient due to great expenses.

In order to reduce the water amounts penetrating into working mines and towards Vasavere intake, it would be purposeful to lower the water level in several closed mines:

- to 45 m level in *Tammiku* mine, by dredging the present outlet
- to 42–43 m level in *Ahtme* mine, by drilling artesian wells

The quality of the water of closed mines is improving. The content of sulphates and iron in mine water decreases and in about five years after the closure of the mine is below the maximum level permitted in drinking water.

Monitoring the water quality in closed mines should be aimed mostly at protecting the water body from surface-derived pollution. The sampling methods should be improved, with indicating justified times and places for taking water samples. In some cases the number of parameters measured could be reduced.

As no reliable data are available about the formation and distribution of phenols in the water of closed mines, corresponding investigations are needed before the use of the water. Although phenols are generally believed to originate from the waste of shale oil plants or from burning spoil dumps, the possibility of their formation during decomposition of kerogen in water-filled mines cannot be excluded either. This hypothesis deserves further special study.

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