SUSTAINABLE GROUNDWATER MONITORING SYSTEM OF EAST-VIRU COUNTY, ESTONIA

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Monitoring of the impact of oil shale mining to the groundwater and verification of the model, monitoring of the flood risks caused by oil shale mining activities

(Intermediate report 2)

2010

1. Background information

The analysis of the extensive monitoring data collected over a relatively long period of time loads to basic understanding of groundwater movement and the influence of pumping of water to groundwater level of different aquifers and different areas. The location of monitoring wells is given on figure 1.

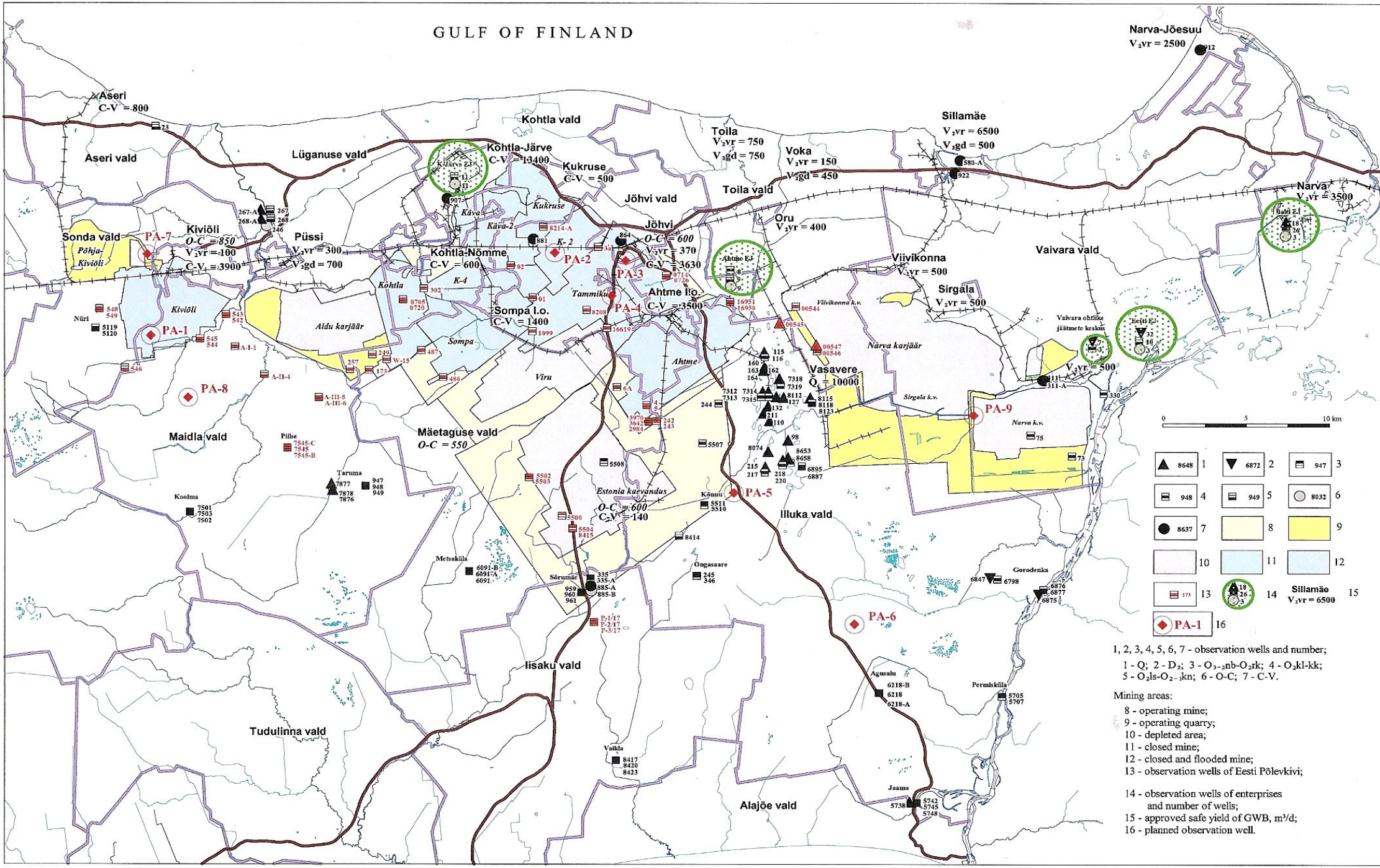
Due to dewatering of oil shale mines, the groundwater level of aquifers in the oil shale basin has lowered up to 15–65 metres and several local cones of depression, influencing each other have formed over an area of 600 km² (Figure 2).

In the present time oil shale is mined on the territory from Kunda River to Narva River, to south from outcrop area of Kukruse stage, in the mines Viru and Estonia and in opencasts Põhja-Kiviõli, Aidu and Narva. At this area 9 liquidated and submerged mines with total area of 220 sq. km-s are also located. Technogeneous load on water environment and particularly on groundwater is the highest at this area in Estonia.

Due to mine and opencast drainage groundwater levels of Ordovician aquifer system have been lowered up to 65 m and the hydrographical system of this region has been also impacted. The upper courses of small rivers have been drainaged, in the rivers, which recharge from the mine water, the chemical composition has been changed: content of sulphates and hardness have been increased. There is also one positive phenomenon for these rivers: the runoff has been regulated. It means that the proportion of maximum runoff to minimum has been decreased. The annual runoff of Purtse River on the area of intensive mining works before and after inflow of mine water has not changed.

Mining works have also impacted the Quaternary aquifer and sporadically drained the Narva aquifuge with thickness up to 17 m.

Ordovician aquifer system consists of fissured carbonate sediments and is divided into 3 aquifers – Nabala–Rakvere, Keila–Kukruse and Lasnamäe–Kunda. Weak aquifuge consists of marl and argillaceous limestone of Oandu and Uhaku stages. The distribution of aquifers and groundwater bodies has been characterized in previous reports of project.



Joonis 1. Seirekaevud paiknemine Ida-Virumal.
Figure 1. Location of monitoring wells of Ida-Viru county.

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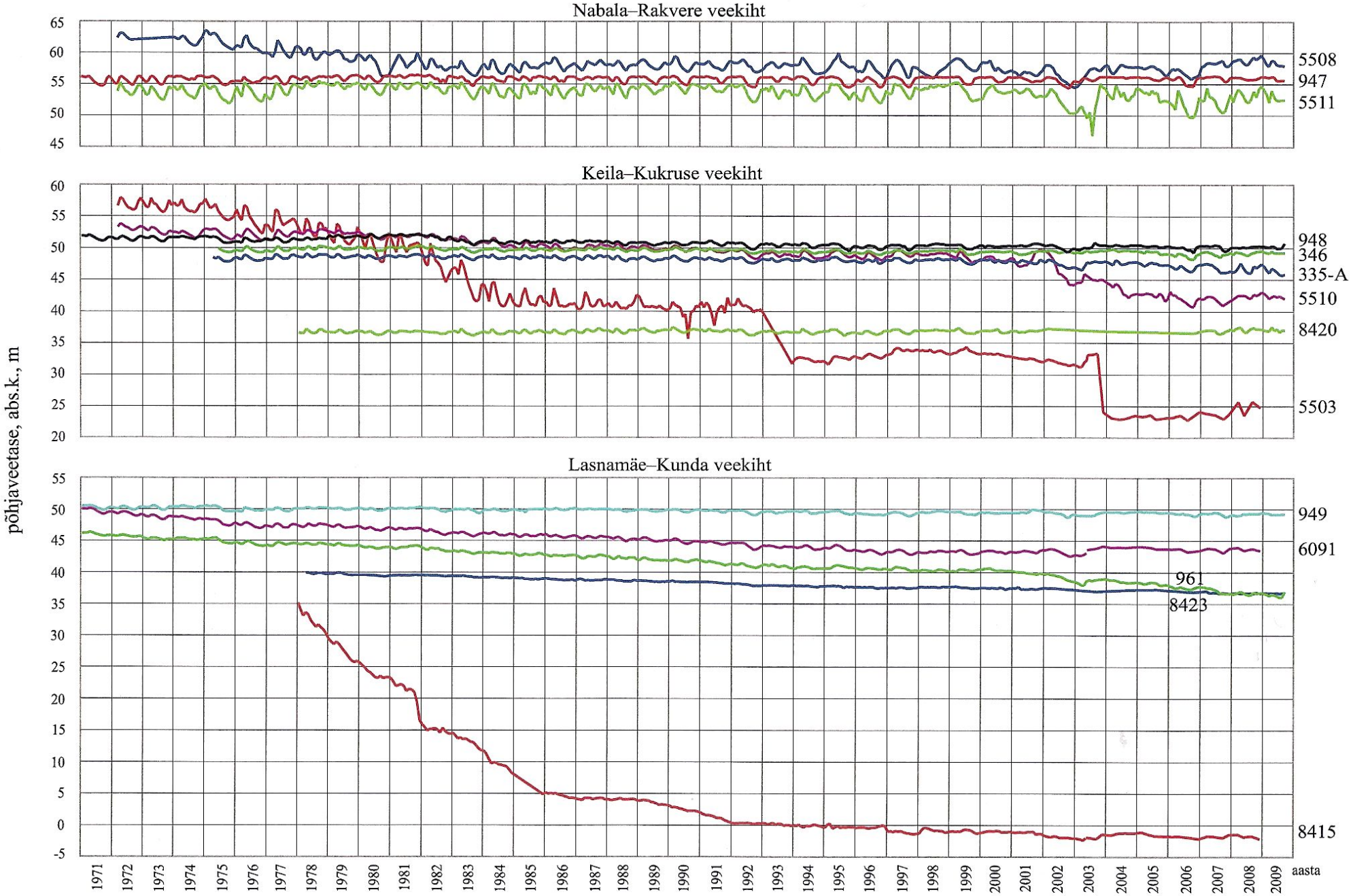

Joonis 2. Veetaseme muutused Ida-Virumaa põhjaveekihtides.
Figure 2. Changes of groundwater levels of different aquifers.

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2. Objectives of groundwater monitoring and influences of mines dewatering in different areas of East-Viru County

The main objective of groundwater monitoring is to produce reliable and comprehensive information on groundwater resources and their quality. This information can be used as a basis for decisions on environmental issues with the following tasks:

1) Estimation of natural temporal and spatial fluxes in the quantity and quality of groundwater under various hydrogeological and climatic conditions.

2) Estimation of the effect of mining activities on the quantity and quality of groundwater.

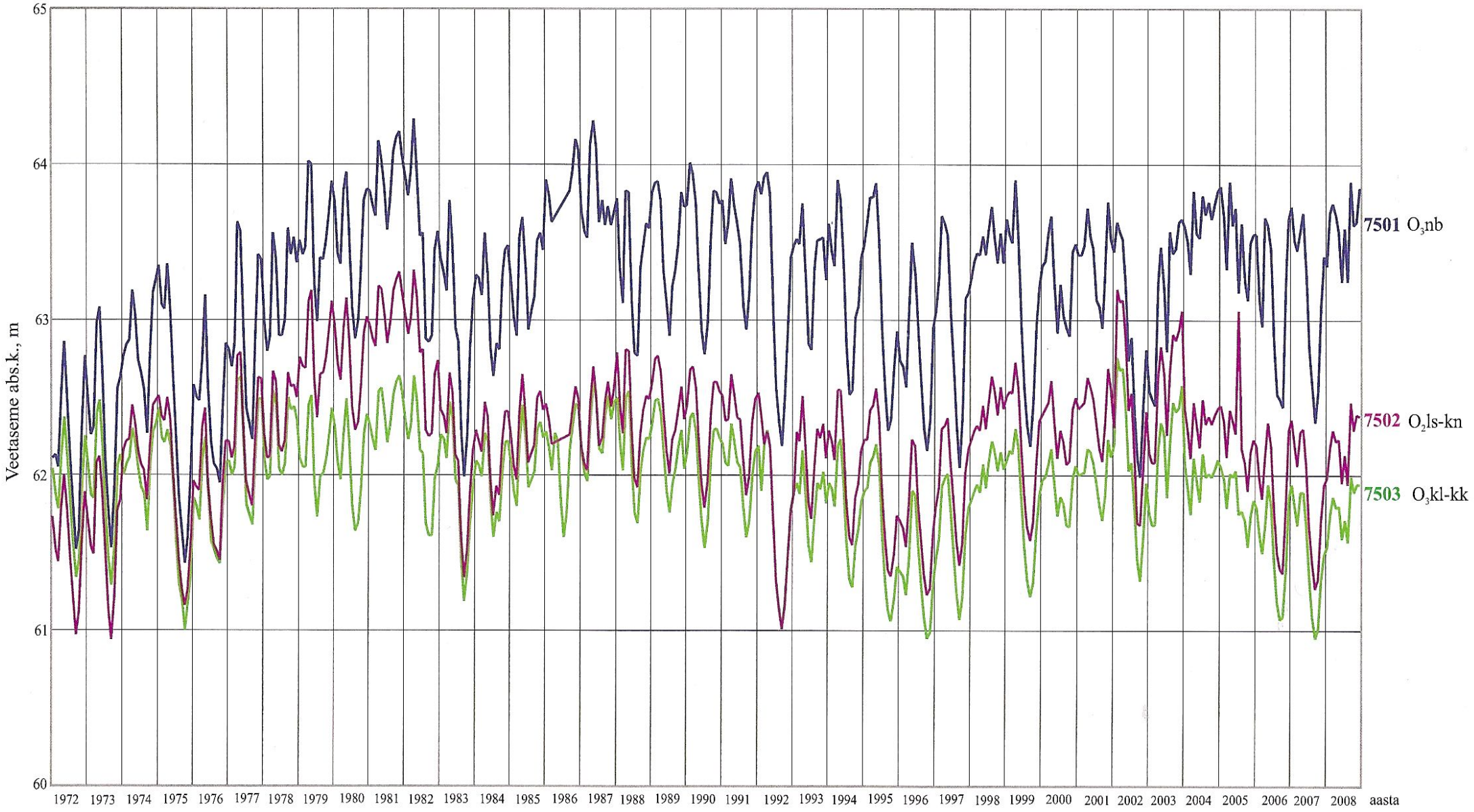
The groundwater status under the influence of mines, opencasts and submerged mines has been investigated in different areas. The location of monitoring wells is given on Figure 1.

In more details the environmental objectives of groundwater monitoring in different areas are presented in the Table 1.

2.1. Fluctuation of the groundwater level under natural conditions

Natural fluctuation of the groundwater level has been investigated by monitoring stations Koolma and Vaikla, which are located far away from oil shale mines and abstraction wells. In natural conditions the changes of groundwater level are mostly depending from climatic conditions. In the beginning of the year the groundwater level is lowering more or less evenly until the beginning of March. When the air temperature rises above 0° C, the melt-water will percolate into the soil and the spring phase of intensive infiltration starts, lasting until snow has melted in the last decade of April. The amplitude of the spring rise of the groundwater level in Quaternary deposits is usually 0.2–0.4 m, in the Ordovician aquifers 0.6–0.8 m.

In late spring and in summer, the amount of groundwater mostly decreases due to the intensive evapotranspiration of the soil moisture. As a result, the groundwater level will lower during about 140 days until the first or second decade of September the decrease of evapotranspiration caused by lowering of the air temperature will be balanced with infiltration. The amplitude of groundwater level lowering is in the Quaternary aquifers about 0.2 m in the Ordovician aquifers 0.8–1.5 m (Figure 3) in the warm period. The minimum point of the groundwater level is in September. The summer lowering of the groundwater level can be retarded or even changed to rising because of occasional rain periods. Intensive infiltration recurs in autumn when a systematic rainfall starts and evapotranspiration is low. Then the groundwater table rises



Joonis 3 . Põhjaveetaseme muutused Koolma vaatluskaevude rühma andmete põhjal.
Figure 3 . Changes of groundwater levels by monitoring station Koolma.

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Table 1. Matrix of state groundwater monitoring network by environmental objectives

Environmental objectives of monitoring stations	Aquifer	Monitoring station																			
		Narva quarry	Viivikonna quarry	Väike-Pungerja	Agusalu	Gorodenka	Jaama	Kivisilla	Koolma	Kõnnu	Metsküla	Mäe-taguse	Ongas-saare	Permis-küla	Sõru-mäe	Taru-maa	Vaikla	Nüri	Konsu	Kurtna	Vasavere
Monitoring of natural regime of ground-water	Q																				
	O_3rk–nb								7501								8417				
	O_3kl–kk								7503								8420				
	O_2ls–kn								7502								8423				
Influence of opencasts de-watering on state of groundwater in Estonian-Russian border area	Q		247				5738														
	O_3rk–nb						5742							5705							
	O_3kl–kk	66; 73; 75; 330					5745							5707							
	O_2ls–kn		249; 250; 253; 255				5748														
Influence of mines and opencasts dewatering on state of groundwater at the Puhatu bog area	Q					6875 (D_2nr)		6863													
	O_3rk–nb				6218-B																
	O_3kl–kk				6218	6876; 6798		6864													
	O_2ls–kn				6218-A	6877; 6766		6917													
Influence of mines dewatering on state of groundwater around Estonia mine	Q																				
	O_3rk–nb			5500; 5504						5511	6091-B	5502	245		335; 959						5508
	O_3kl–kk									5510	6091-A	5503	346		335-A; 960						241
	O_2ls–kn									8414	6091				961						
Influence of mines and opencasts dewatering on state of groundwater at the Muraka Bog area	Q															7877					
	O_3rk–nb															947					
	O_3kl–kk															948; 7878					
	O_2ls–kn															949; 7876					
Influence of exhausted mines on state of ground-water	Q																				
	O_3rk–nb																				
	O_3kl–kk																	5119			
	O_2ls–kn																	5120			
Influence of mines and opencasts dewatering on groundwater of Vasavere water intake and to Kurtna Lake District	Q																		98; 215; 218; 8074; 8653; 101	132; 110; 7312; 7314; 211	127; 8139; 128; 8134; 7304; 7318; 8115; 115; 160; 162; 163; 164
	O_3rk–nb																				
	O_3kl–kk																		217; 220; 6895; 8658	117; 7313; 7315	8118; 7305; 116
	O_2ls–kn																		216; 6887	8123	7319

until the soil will freeze in December. During cold winter, the amount of groundwater predominantly decreases due to restricted infiltration.

The fluctuation of groundwater level is the most remarkable in the Nabala–Rakvere aquifer. In the deeper Keila–Kukruse and Lasnamäe–Kunda aquifers the seasonal fluctuation of the head is commonly similar to the fluctuation of the Nabala–Rakvere aquifer, but the amplitude of changes is less and the groundwater level is all time 1.0–1.5 m deeper (Figure 3).

2.2. Influence of dewatering to status of groundwater in Estonian–Russian border area

The changes of groundwater level are caused mainly by dewatering of Sirgala and Narva opencasts. As result of dewatering the minimum seasonal groundwater level has lowered in the Quaternary aquifer about 1 m and in the Keila–Kukruse aquifer about 2 m (Figure 4). The most noticeable lowering has been taken place in Lasnamäe–Kunda aquifer, where groundwater level has lowered by 3 metres (Figure 4). The maximum levels in 1978, 1981, 1990 and 2004 years corresponds to maximum water inflow to Narva opencast (Figure 5).

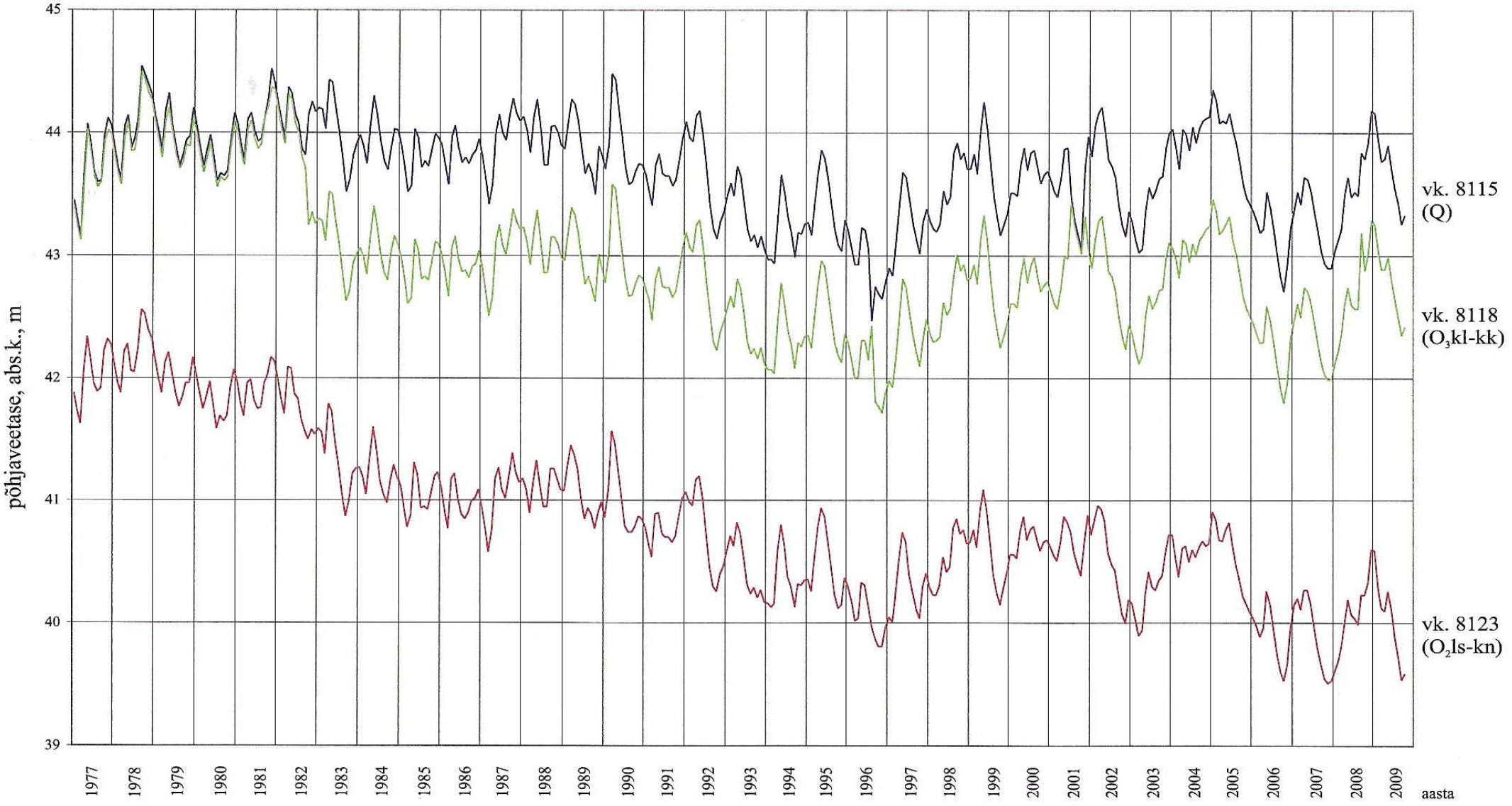
2.3. Influence of opencasts dewatering to status of groundwater at the Puhatu mire complex

Puhatu is the biggest mire complex in Estonia, the area of 57 079 hectares, covering about ⅓ of Alutaguse lowland area. Since 1999 the Puhatu mire area with Poruni primeval forests are under nature protection. The bogs of this region are characterized by wet and vast areas covered with transitional bog or fen communities separated with bog areas. Bogs feeds mainly by precipitation. The changes of groundwater levels depends totally from seasonal climate conditions and oil shale opencast mining has not influenced in the present time the natural groundwater regime (Figure 6). In future it will necessary to evaluate influence of Usnova mining district and peat production to water regime.

2.4. Influence of mines dewatering to status of groundwater around Estonia mine

In spite of low depth of oil shale bedding the underground mining have spread instead of surface mining. The Estonia mine has mining shafts at 70 m below ground and features some of the most advanced mining technology available today. The mines production capacity is 5 million tons of oil shale per year.

The water inflow to mine is continuously arose and in 2008 the total inflow was 96 445 599 m^3 or 263 513 m^3 per day (Figure 7; Table 2).



Joonis 4. Põhjaveetaseme pikaajalised muutused Sirgala põlevkivikarjääride piirkonnas.
Figure 4. Changes of groundwater levels in the area of Sirgala open-cast mine.

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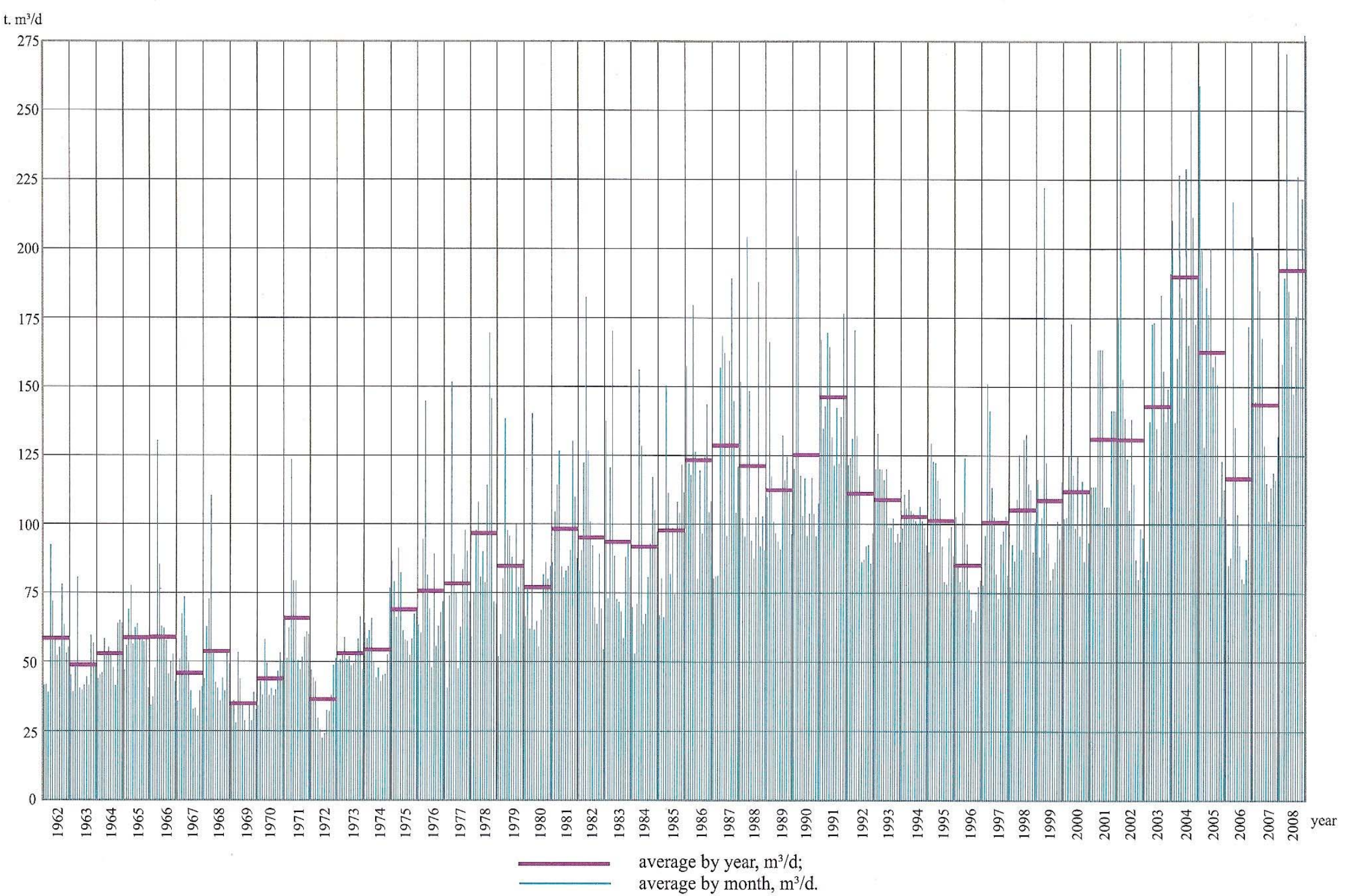
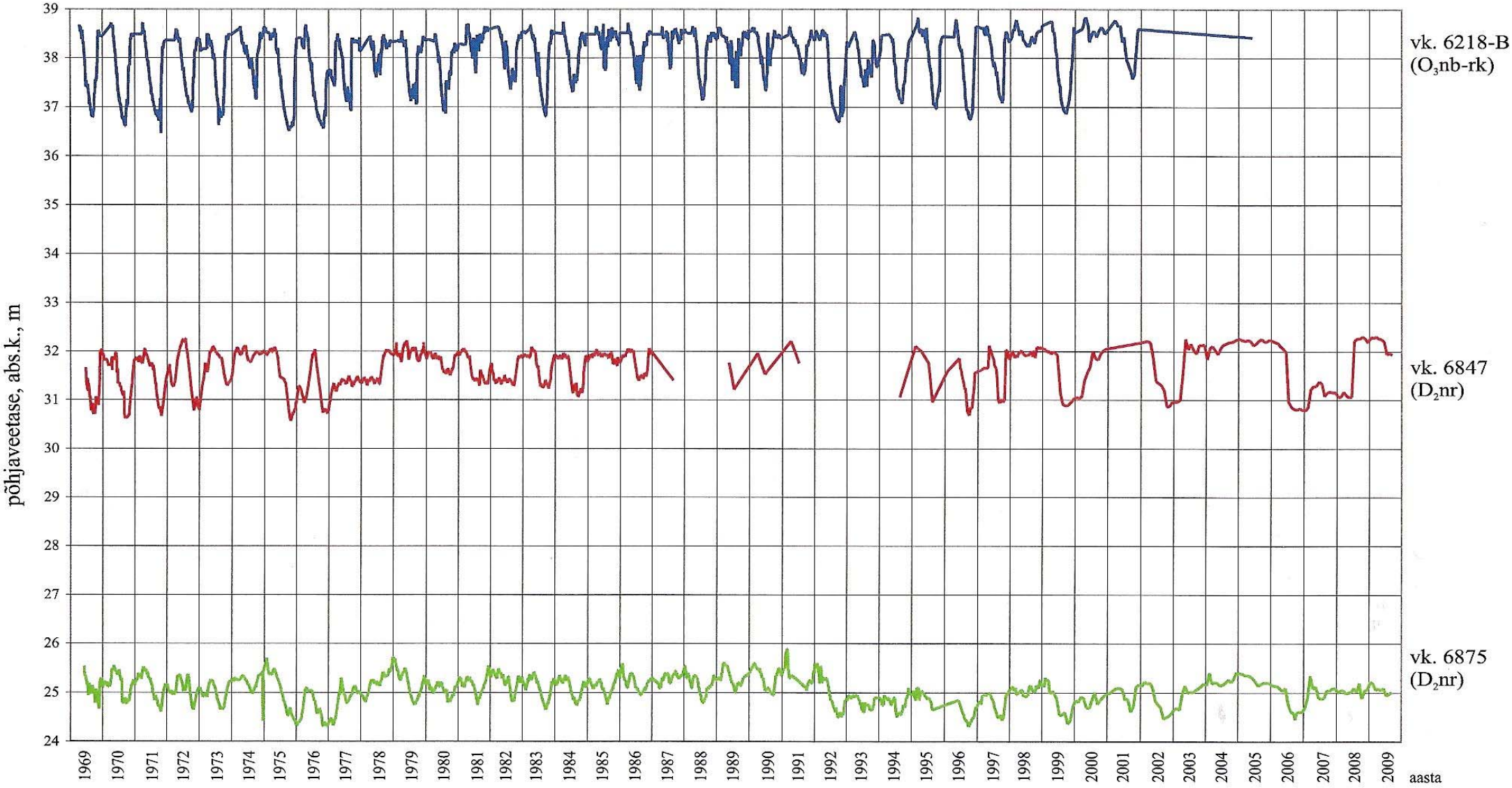


Figure 5. Water inflow to Narva open-cast mine.



Joonis 6. Maapinnalt esimese aluspõhjalise veekihi põhjaveetasemete muutused Puhatu soostiku piirkonnas.
Figure 6. Changes of groundwater levels of Narva (D_3nr) and Nabala–Rakvere (O_3nb-rk) aquifers in Puhatu area.

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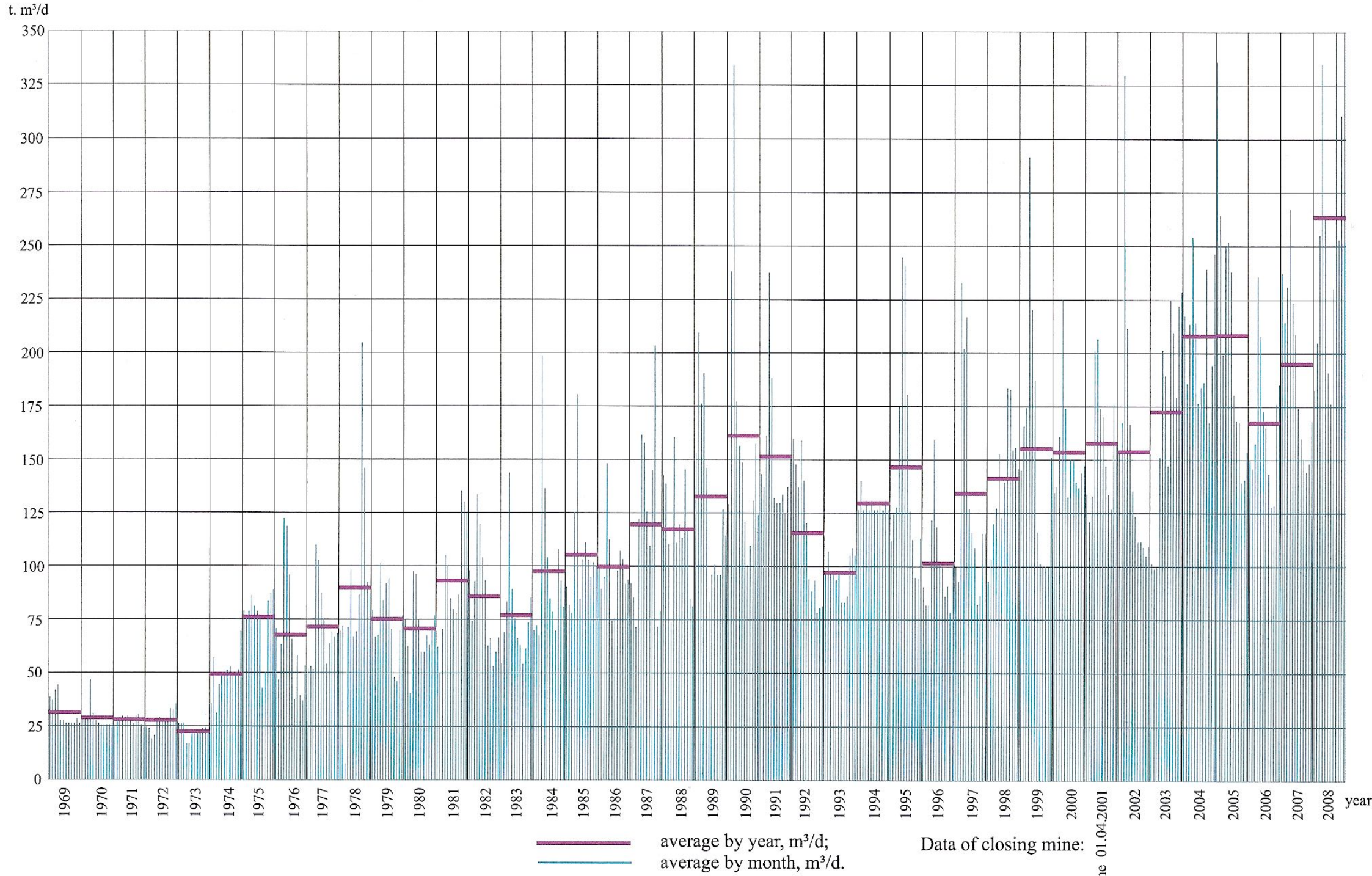


Figure 7 . Water inflow to Estonia mine.

Table 2. Inflow of groundwater into oil shale mines in 2008.

Name of underground or opencast mine	Total in month, m³												Total in year, m³
	Average per day, m³/d												*Average per day, m³/d*
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Aidu opencast mine	3269675	3822492	5693127	6806101	4524897	3799139	3500442	4449260	8048308	5991354	6620061	10248903	66773759
	105473	*131810*	*183649*	*226870*	*145964*	*126638*	*112917*	*143525*	*268277*	*193269*	*220669*	*330610*	*182442*
Viru mine	1174206	1493481	2243697	3079375	1789862	1303962	1297637	2119858	3373474	1755729	2382708	3162591	25176580
	37878	*51499*	*72377*	*102646*	*57737*	*43465*	*41859*	*68383*	*112449*	*56636*	*79424*	*102019*	*68788*
Mining museum	29662	28200	31962	36950	34112	33738	34562	34750	34312	33562	31912	33512	397234
	957	*972*	*1031*	*1232*	*1100*	*1125*	*1115*	*1121*	*1144*	*1083*	*1064*	*1081*	*1085*
Estonia mine	5702673	5979676	7958952	10123879	8217331	5762905	5498699	7185081	10933686	7897647	9386319	11798751	96445599
	183957	*206196*	*256740*	*337463*	*265075*	*192097*	*177377*	*231777*	*364456*	*254763*	*312877*	*380605*	*263513*
Kiviõli mine and opencast mine	8332	6194	4402	2405	4811	10996	320	0	0	0	110	0	37570
	269	*214*	*142*	*80*	*155*	*367*	*10*	*0*	*0*	*0*	*4*	*0*	*103*
Narva opencast mine	3867624	4581416	5865520	8106501	5719732	4935559	4563946	5438435	6773569	4974609	6538064	9027968	70392943
	124762	*157980*	*189210*	*270217*	*184507*	*164519*	*147224*	*175433*	*225786*	*160471*	*217935*	*291225*	*192330*
Põhja-Kiviõli open-cast mine	27300	45780	65320	61530	62580	33180	43890	52290	36330	55170	89530	145780	718680
	881	*1579*	*2107*	*2051*	*2019*	*1106*	*1416*	*1687*	*1211*	*1780*	*2984*	*4703*	*1964*
Total , m³/d	***454177***	***550250***	***705256***	***940559***	***656557***	***529317***	***481918***	***621926***	***973323***	***668002***	***834957***	***1110243***	***710225***

In the longtime changes is possible to see some regularities. At the end of seventies the groundwater level of Rakvere–Nabala and Keila–Kukruse aquifers in the southern part of Estonia mining field arose, but from 1988 the stable state of groundwater levels replaced with lowering (Figures 8; 9). The most influence the dewatering of Estonia mine has expressed to state of Lasnamäe–Kunda and Ordovician–Cambrian aquifers, where the lowering of groundwater head has been up to 10 m (Figure 10).

2.5. Influence of mines and opencasts dewatering to groundwater at the Muraka Bog area

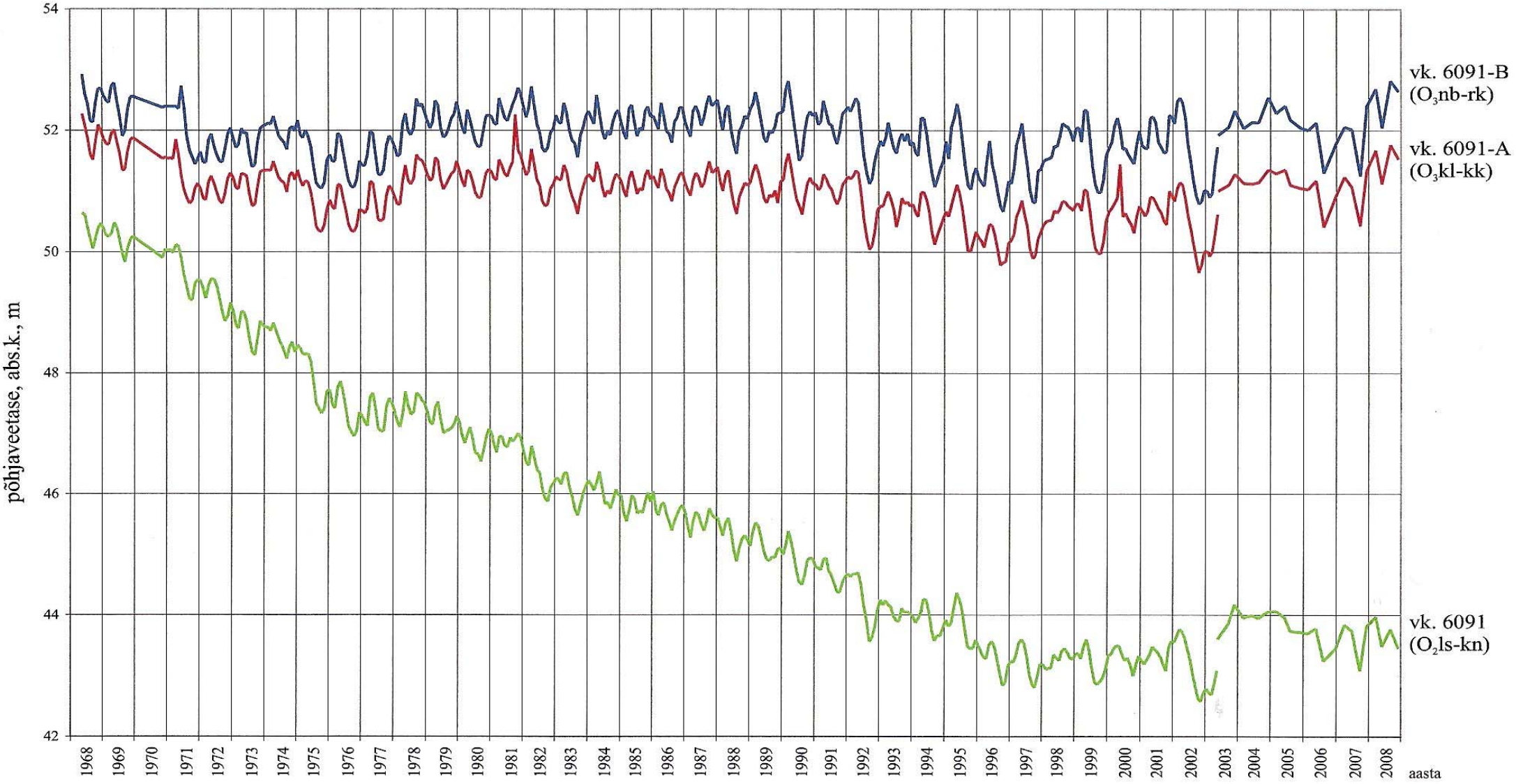
The south–western part of oil shale basin region includes the protected Muraka and Ratva Bogs. The area is surrounded by dewatered Estonia and Viru mines and Aidu opencast (Figure 11). Some kilometers to north from bogs area is planned new Ojamaa and Uus-Kivõli mines. Important question is how much the mines dewatering has changed the groundwater state of bogs and what will happen in future.

The longtime measurements of groundwater show, that the mean levels in comparison with initial groundwater levels has changed not much. In Nabala–Rakvere aquifer the groundwater level has lowered 0.33–0.54 m (Figure 11), in Keila–Kukruse aquifer – 0.60–0.84 m (Figure 12) and in Lasnamäe–Kunda aquifer – 1.05–6.73 m (Figure 13). The changes of groundwater levels of Quaternary and Nabala–Rakvere aquifer are mainly caused by seasonal precipitations. Fixed lowering trend caused by mining activities is visible only in groundwater levels of Keila–Kukruse and Lasnamäe–Kunda aquifers (Figure 14).

2.6. Influence of mines and opencasts dewatering to groundwater of Vasavere water intake and to Kurtna Lake District

Kurtna lakes include 42 lakes of different sizes and depths and with different hydrogeological characteristics. Some of the lakes are linked by canals, ditches or streams. The largest of them are Konsu, Kurtna Suurjärv, Jaala, Räätsma, Suur-Kirjakjärv, Väike-Kirjakjärv and Valgejärv (Figure 14).

The Kurtna Lake District and the Vasavere buried glacial valley have sufficient groundwater resources for systematic abstraction. The Quaternary aquifer has excellent water quality and the status of the area as nature reserve should prevent activities that can cause pollution. The proved reserve of Vasavere water intake is 8000 m^3/d. In 2008 the abstraction was 4628 m^3/d. The water resource of the Kurtna Lake District and the Vasavere buried valley is strongly influenced by dewatering of adjacent oil shale mines, by Estonia mine and closed Ahtme mine from



Joonis 8. Põhjaveetasemete pikaajalised muutused Estonia kaevanduse piirkonnas.
Figure 8. Changes of groundwater levels in surrounding of Estonia mine.

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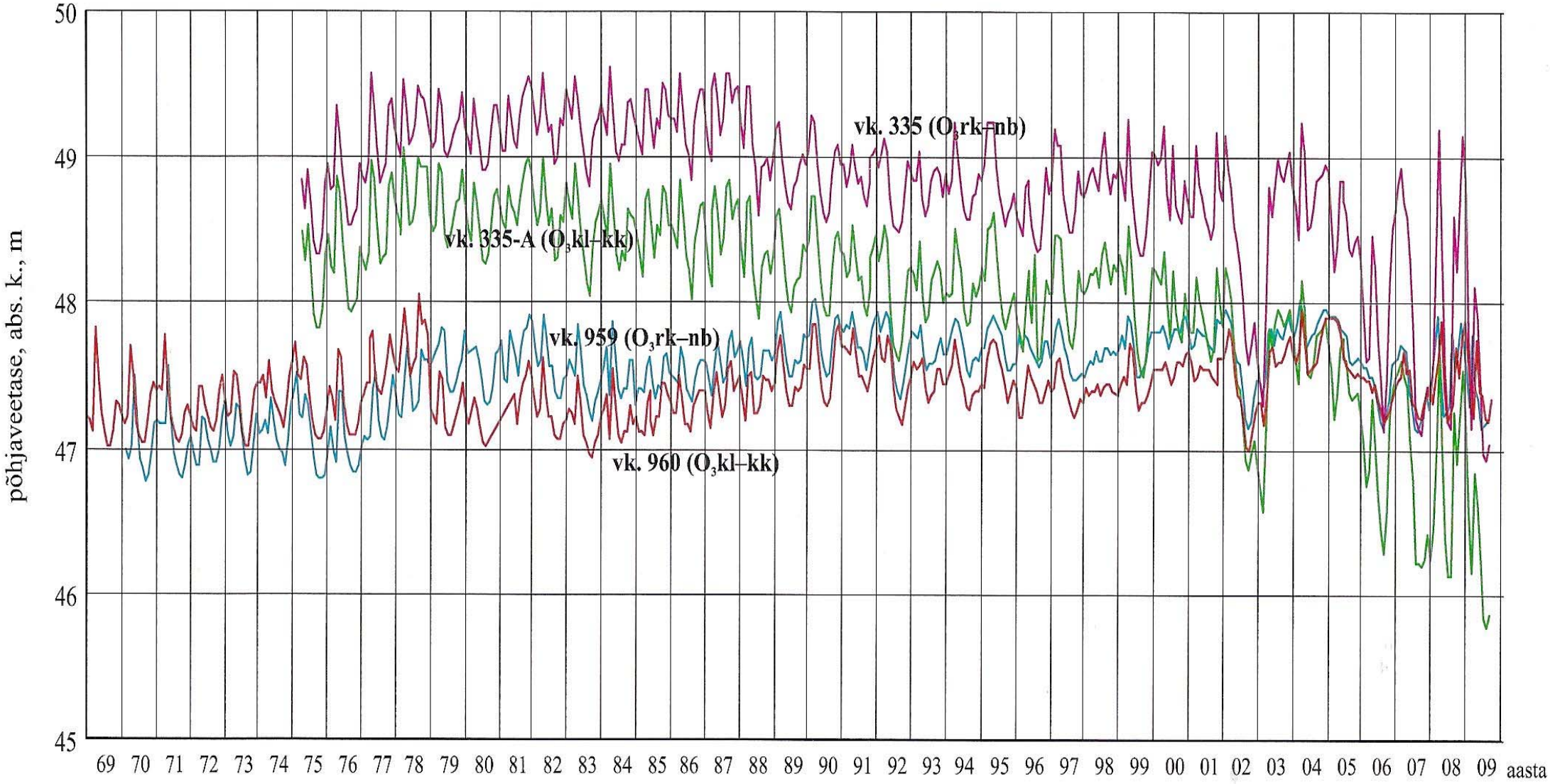
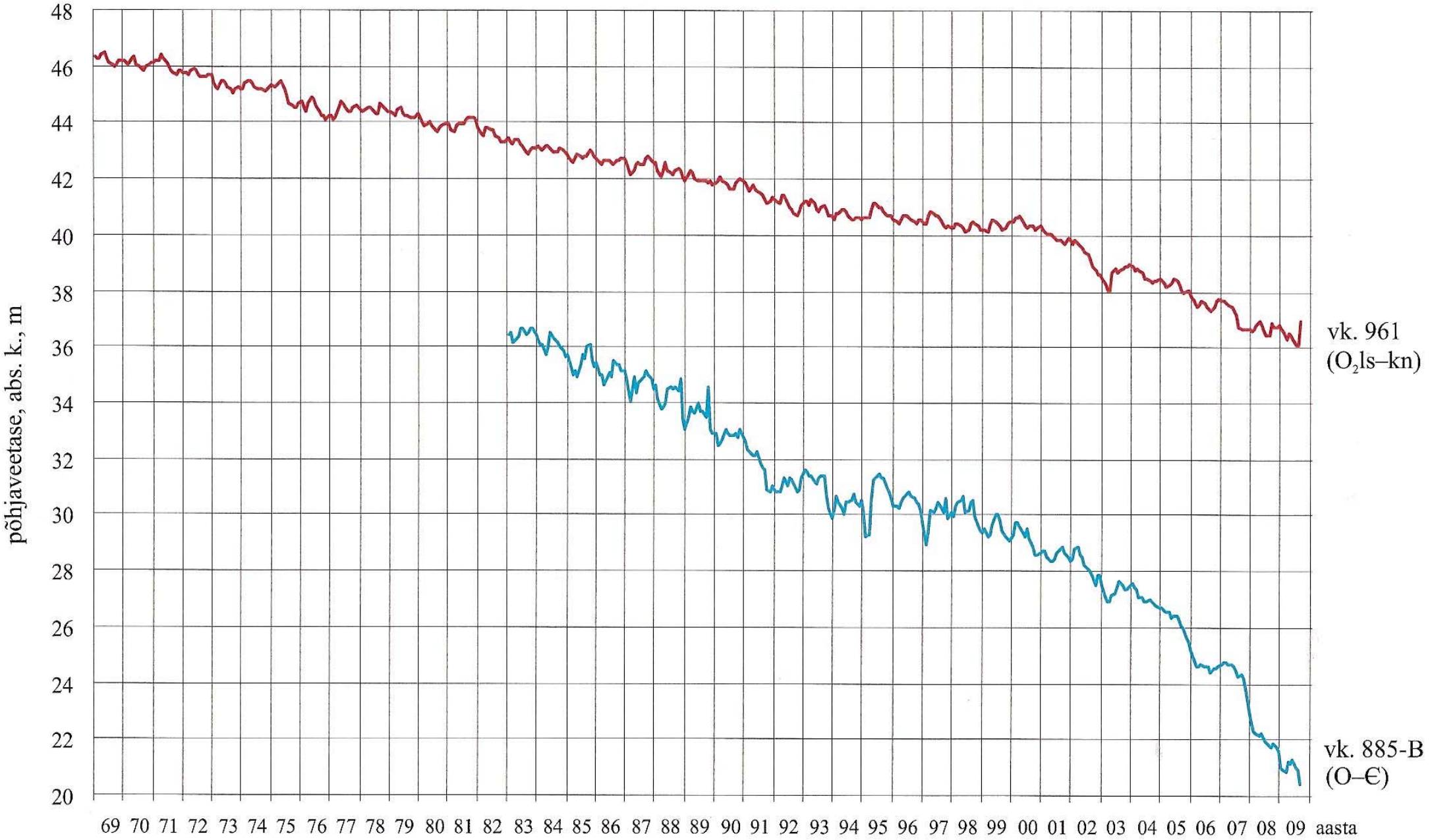


Joonis 9. Rakvere–Nabala ja Keila–Kukruse veekihi põhjaveetaseme pikaajalised muutused Sõrumäe vaatlusjaama seirekaevudes

Figure 9. Changes of long time measurements of groundwater levels Rakvere-Nabala and Keila-Kukruse aquifers in monitoring wells of Sõrumäe monitoring station



Joonis 10 Lasnamäe–Kunda ja Ordoviitsiumi–Kambriumi veekihi põhjaveetaseme pikaajalised muutused Sõrumäe vaatlusjaama seirekaevudes

Figure 10. Changes of long time measurements of groundwater levels Lasnamäe-Kunda and Ordoviitsiumi-Kambriumi aquifers in monitoring wells of Sõrumäe monitoring station

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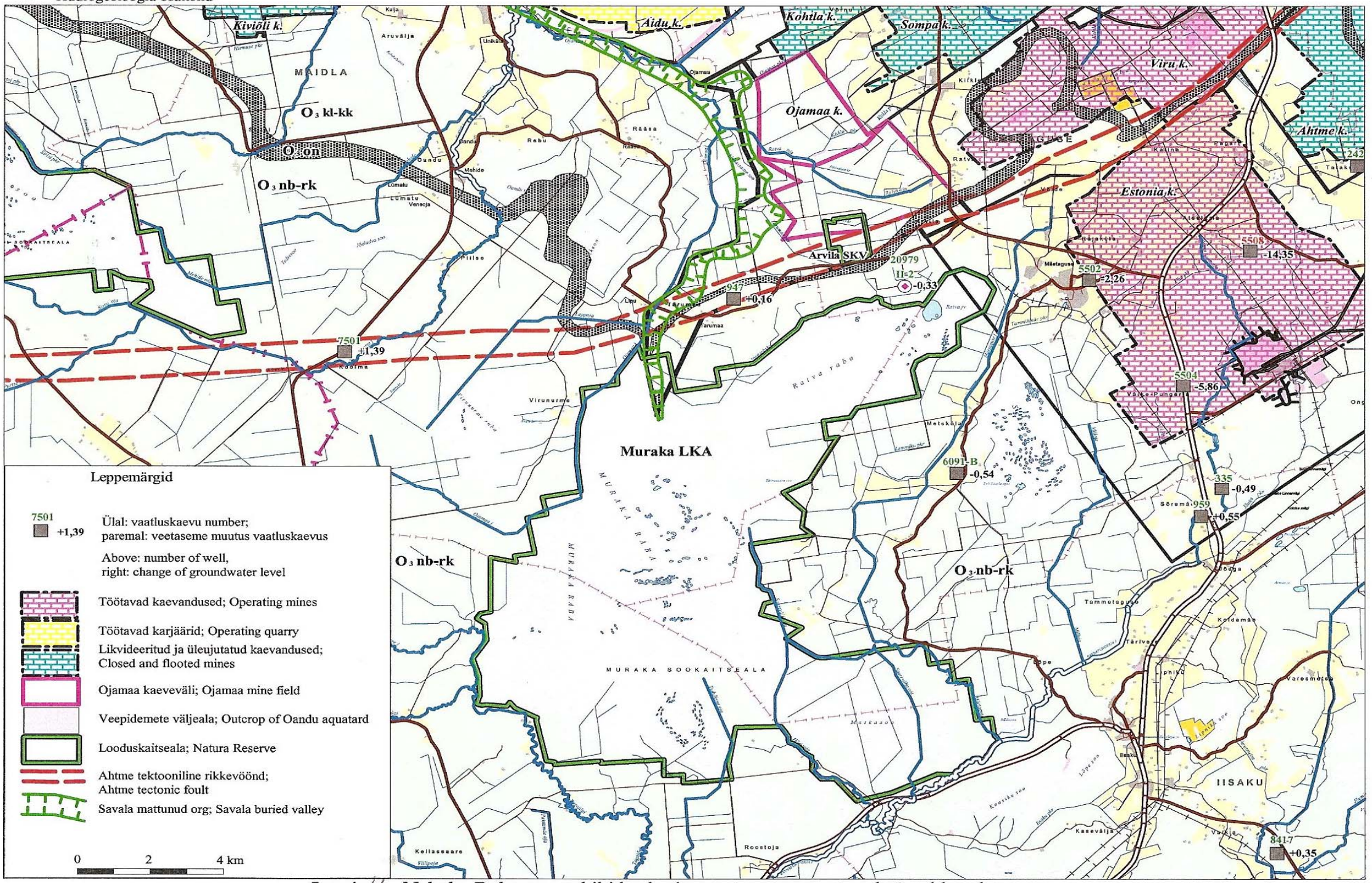

Joonis 11. Nabala–Rakvere veekihi keskmise veetaseme muutused võrreldes algtasemega
Figure 11. Changes of mean groundwater levels in comparison with initial levels.

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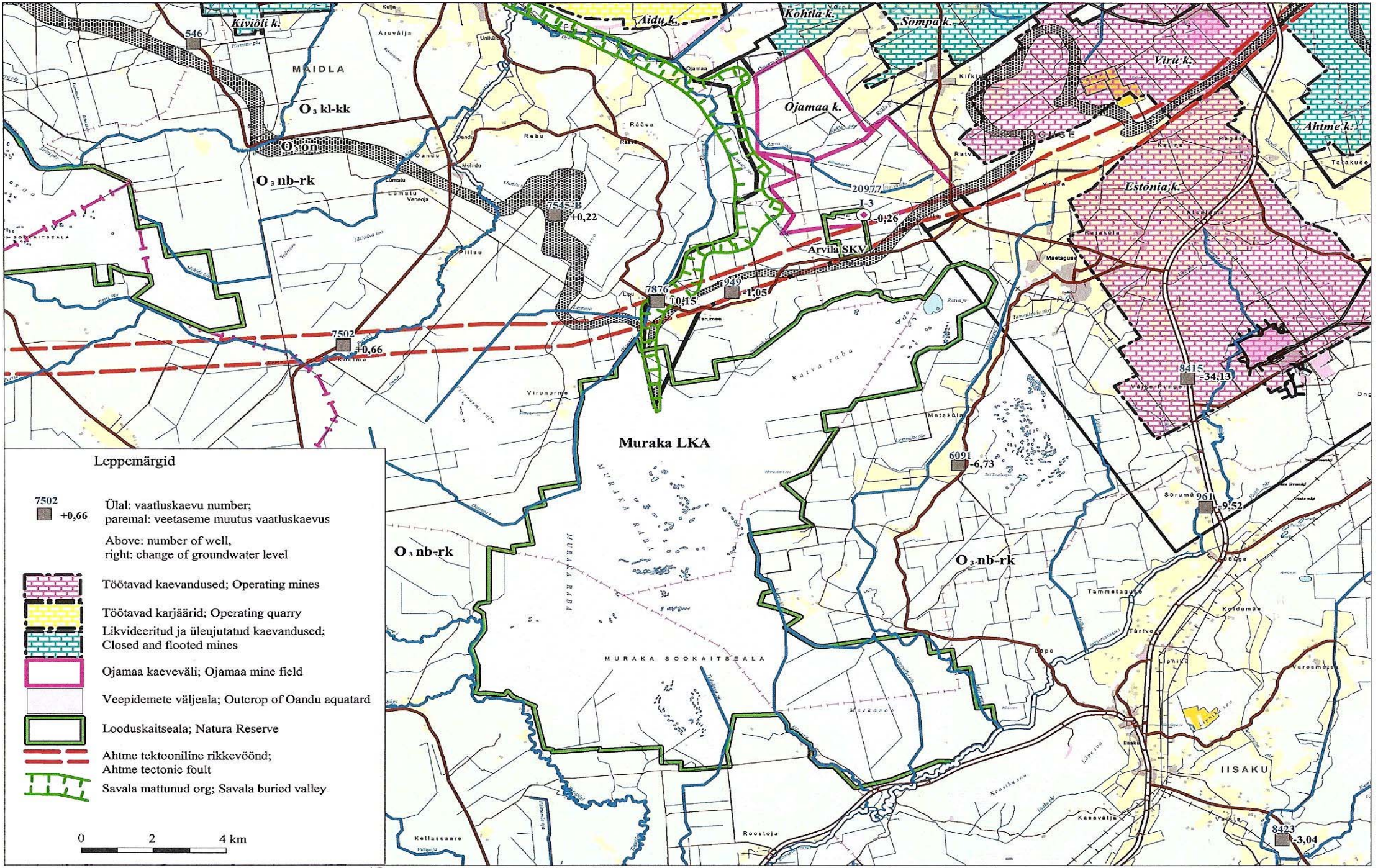

Joonis 13. Lasnamäe–Kunda veekihi keskmise veetaseme muutused võrreldes algtasemega.
Figure 13. Changes of mean groundwater levels in comparison with initial levels.

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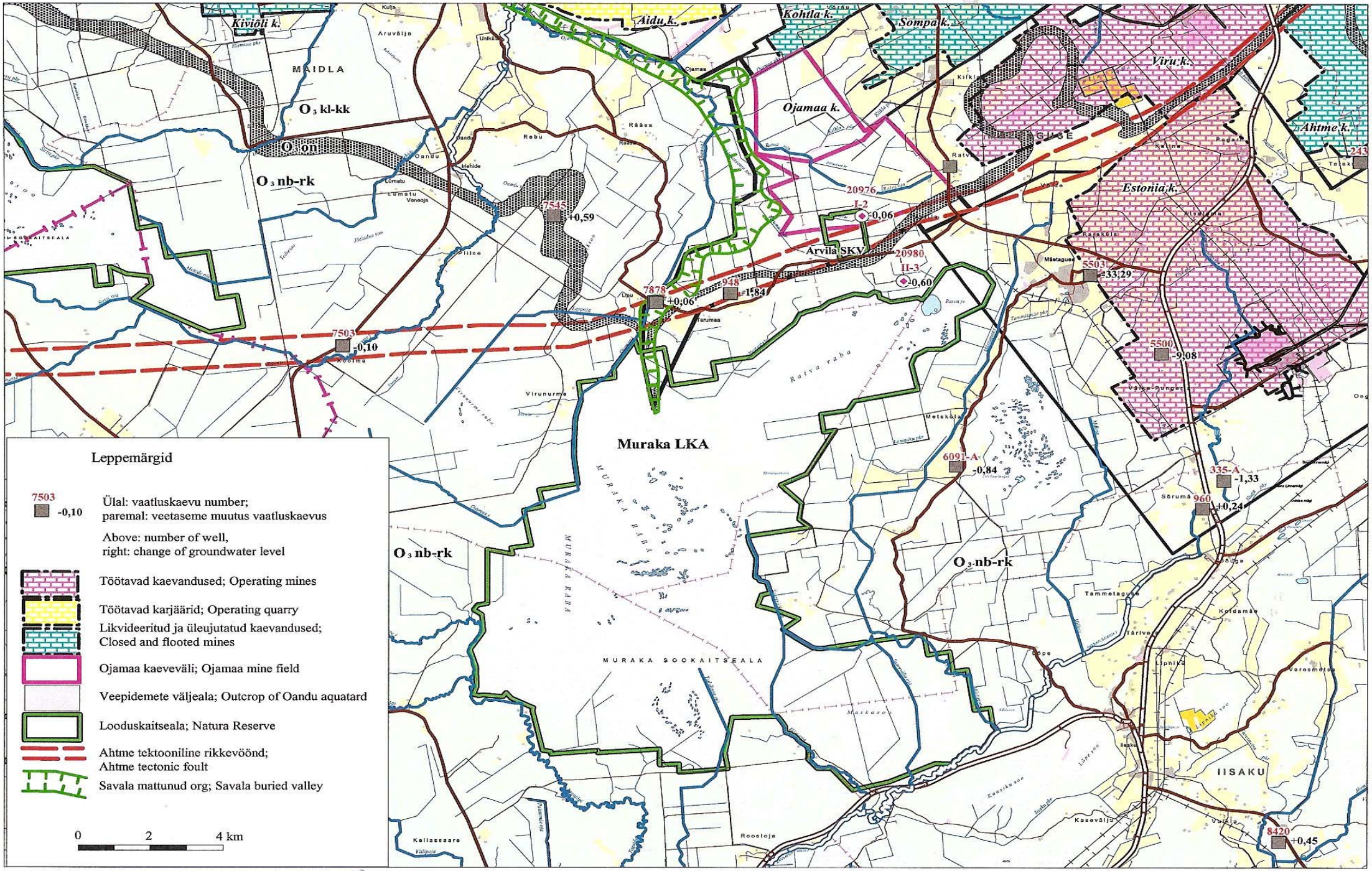

Joonis 12. Keila–Kukruse veekihi keskmise veetaseme muutused võrreldes algtasemega.
Figure 12. Changes of mean groundwater levels in comparison with initial levels.

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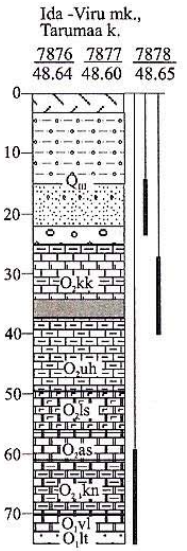

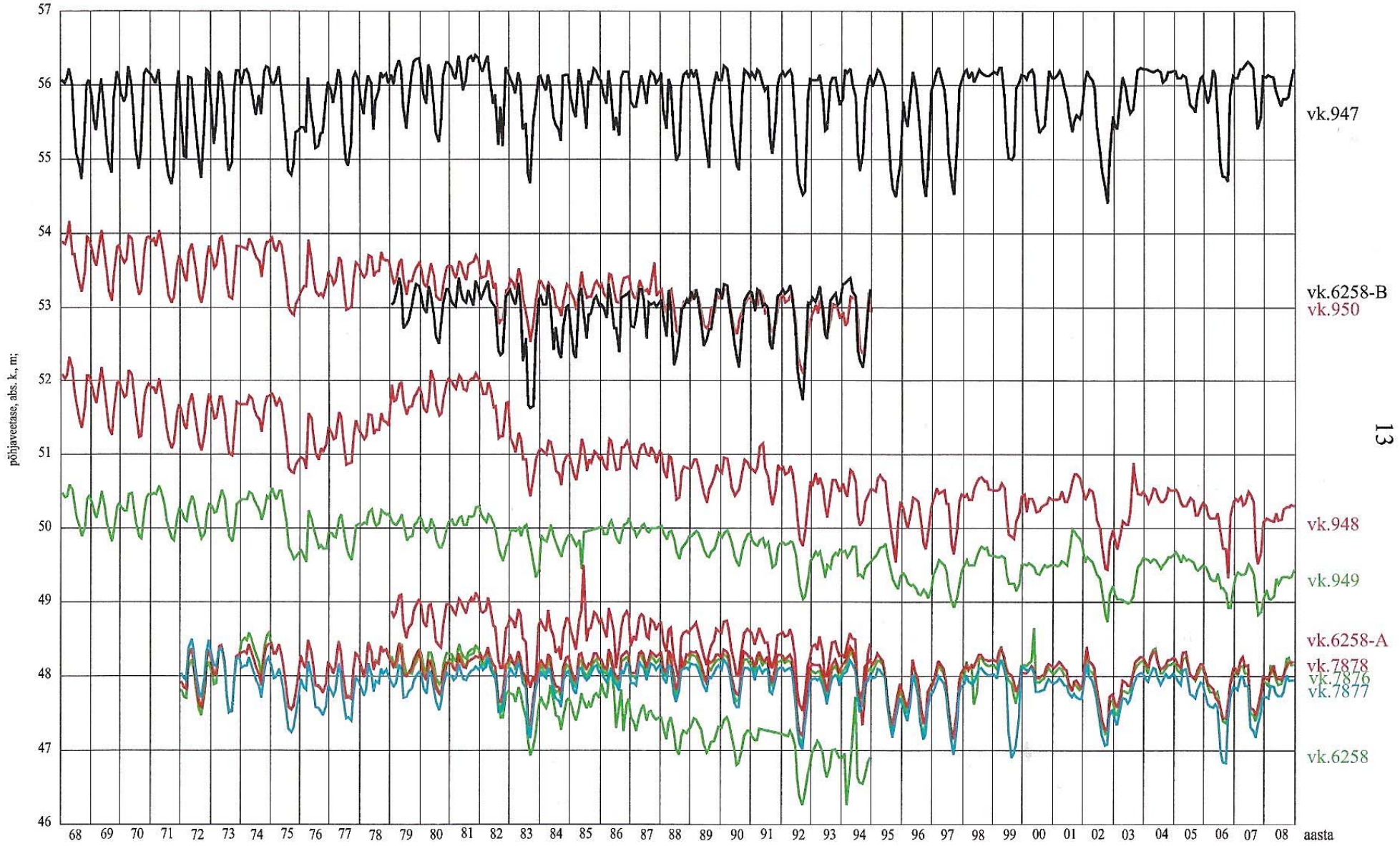

Joonis 14. Põhjaveetaseme pikaajalised muutused Tarumaa k. vaatluskaevude andmetel.
Figure 14. Changes of longtime measurments of groundwater levels in monitoring wells of Tarumaa.

Kvaternaari veekompleks; Quaternary aquifer system
Nabala–Rakvere veekiht; Nabala–Rakvere aquifer
Keila–Kukruse veekiht; Keila–Kukruse aquifer
Lasnamäe–Kunda veekiht; Lasnamäe–Kunda aquifer

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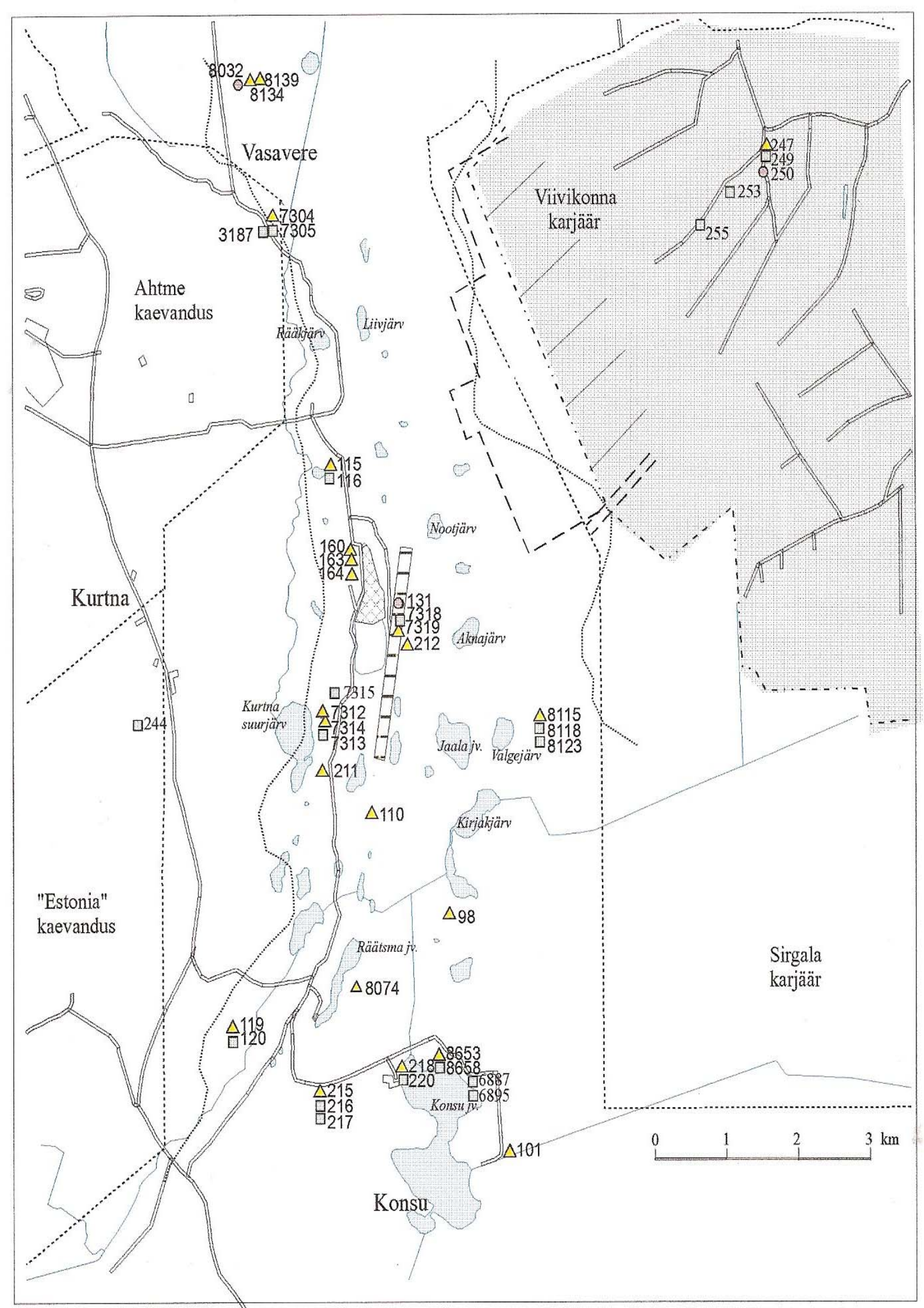
the West and by Viivikonna and Sirgala opencasts from the East. The influence from the east is at present diminished by construction of an infiltration canal along the border of the Viivikonna opencast. The lowering of the water table due to combined abstraction of drinking water and dewatering of the mines is considered to have an undesired impact on the ecology of the many small lakes in the Kurtna Lake District.

The estimate suggests that there is scope for reducing the area that is dewatered, lither by modification of the mining operations, by more efficient closure of mined out areas or by different pumping strategy, e. g. setting up hydraulic barriers by abstraction of water for productive purposes as some distance from the mines. The dewatering of Estonia mine has influenced the state of Lake Konsu too. The natural flow to the lake is estimated at 8 M m³/year and is boosted by discharge of some 18.6 M m³/year of mine water to compensate for the industrial abstraction. It would be recommended to assess the combined impact on quality and quantity of the flow to Lake Konsu for different scenarios of mine discharge and industrial demand. This may require increased monitoring of quantity and quality of the inflow to Lake Konsu. At present in the Lake Konsu area is not visible lowering trends in groundwater levels. As during the last decades the abstraction of water from Lake Konsu has decreased the groundwater level of Quaternary and Keila–Kukruse aquifers in the Lake Konsu area is ascended (Figure 16). Only in Lasnamäe–Kunda aquifer is visible lowering trend in piezometric level (Figure 17).

3. Monitoring of the flood risks caused by oil shale mining activities

The flood risks, caused by oil shale mining activities has been studied by Geological Survey of Estonia during many years (Savitski, 2000; Savitski & Boldõreva, 2005). In 2005 by Katrin Erg was on the databases of Estonian Oil Shale Company and Geological Survey of Estonia compiled dissertation of the degree of Doctor of Philosophy (Erg, 2005).

In connection of closing of four depleted mines (Kohtla, Sompa, Tammiku and Ahtme) in 2000–2004 a large technogenic underground body of water was formed. The area of flooded mines is presently over 220 km² the volume of water in these mines is more than 190 mln. m³ (Table 3).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8139
8134
Vasavere
7304
3187
7305
Ahtme
kaevandus
Räälkjärv
Liivjärv
Viivikonna
karjäär
247
249
250
253
255
115
116
Nootjärv
160
163
164
Kurtna
131
7318
7319
212
Aknajärv
7315
Kurtna
suurjärv
7312
7314
7313
244
Jaala jv.
Valgejärv
8115
8118
8123
211
110
Kirjakjärv
"Estonia"
kaevandus
98
Räätsma jv.
Sirgala
karjäär
8074
119
120
8653
218
8658
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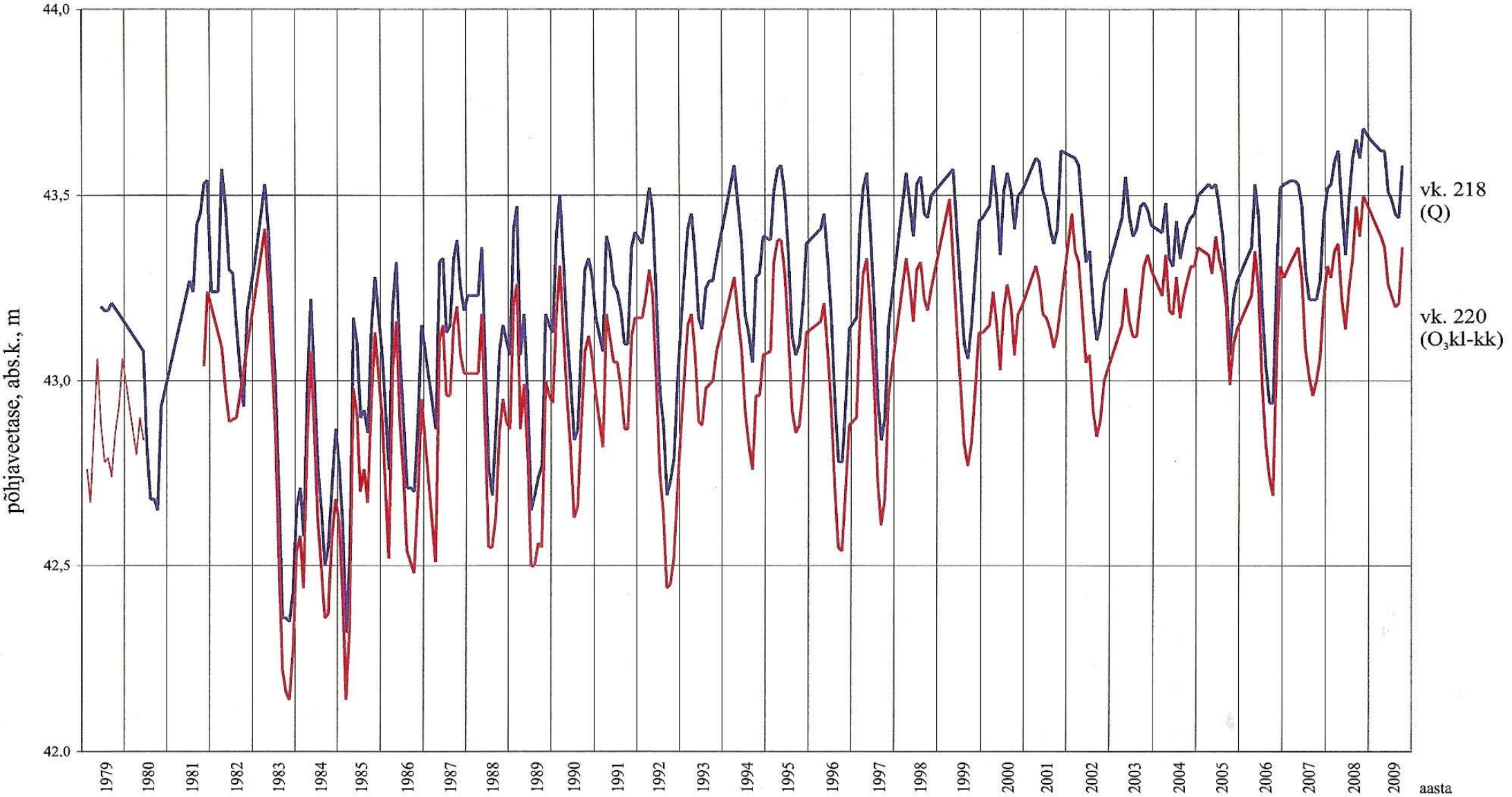
3 km
Konsu



Joonis 16. Põhjaveetaseme pikaajalised muutused Konsu järve piirkonnas.
Figure 16. Changes of groundwater levels in the Lake Konsu area.

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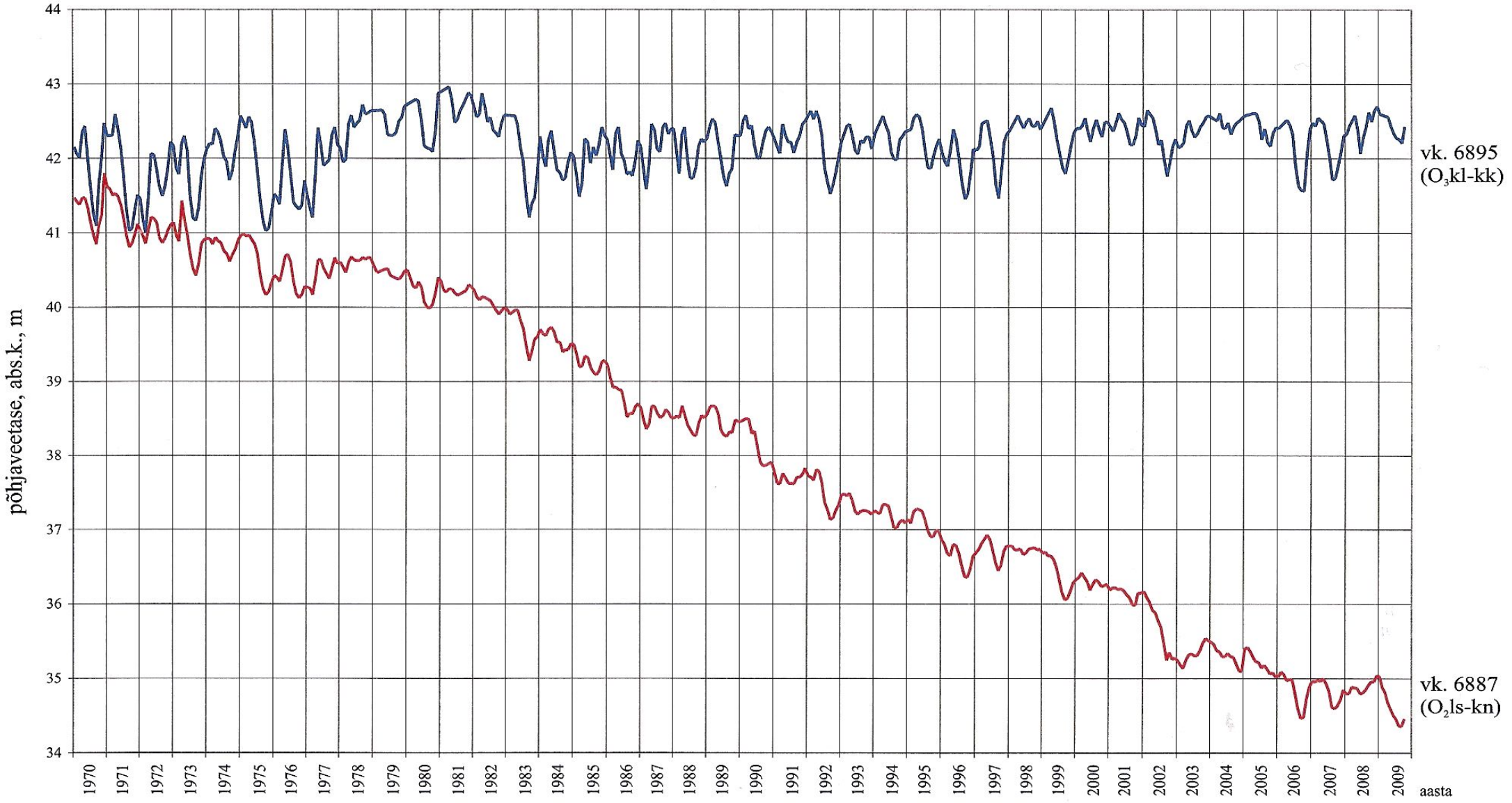

Joonis 9. Sügavallasuvate Keila–Kukruse (O_3kl-kk) ja Lasnamäe–Kunda (O_2ls-kn) veekihtide põhjaveetaseme muutused Konsu järve piirkonnas.
Figure 9. Changes of groundwater levels of Keila–Kukruse (O_3kl-kk) and Lasnamäe–Kunda (O_2ls-kn) aquifers in Lake Konsu area.

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Table 3. Approximate water volume in closed oil shale mines

Mine	Pumping stopped	Mined out area, km²	Water table in 2008 (2002)		Water volume, 10^6 m³
			No of monitoring well	m, a. s. l	
Ahtme	01.04.2002	35	16951	43,35	63
Tammiku	28.12.1999	~40	0714 8208 1099	46,65 46,94 46,00	~40
2. Mine	1974	12,9	3a	51,41 (2002)	7
4. Mine	1975	12,7	302 1b	41,18 (2002) 40,26 (2002)	1,4
Kukruse	1967	13,2	8214A	51,94	3,6
Käva-2	1973	18	2	51,5 (2002)	9
Sompa	02.12.2000	27	480 487	40,18 (2002) 40,5 (2002)	~20
Kohtla	28.06.2001	17	W-15	40,79 (2002)	10
Kiviõli	1989	28,9		40,93 (2020)	~36

As result after closing these mines the water inflow from Viru mine and Aidu opencast is considerably increased (Figure 18; 19). The water in the area filtrates from one mine to another and feeds the waters of operating mines.

As the closed mines are fed by precipitation, in some cases, water levels in two or more adjacent mines will fluctuate in conformity with the seasonal or man-induced reasons. The elevation of the water table in closed Kukruse mine, Mine No 2 and Mine No 4 has been in 2000–2008 about 40–53 m above sea level (Figure 20). Hydrogeological investigations indicate that the elevation of the water table has fluctuated over time, especially in Mine No 2. The maximum elevation was about 51 m above sea level, but seasonally if fluctuated between 50–56 m a. s. l., primarily as a result of variation in climate conditions and amount of precipitation (Figure 20).

If the inflow rate is greater than the outflow rate, the water storage and hydraulic head in the saturated portion of the mine will increase. If outflow are greater than inflows, then the hydraulic head will decline. During the rainy August of 2003, the water table rose 4 m in Sompa underground mine, 2 m in Kohtla, 2,1 m in Kukruse, 1,8 m in Mine No 4 and 0,5 m in Ahtme mine (Figure 20). The arisen hydraulic head in closed mines caused flooding of streets and cellars in Jõhvi Town (Photo 1). Flooded was also the Kohtla Mining Museum.

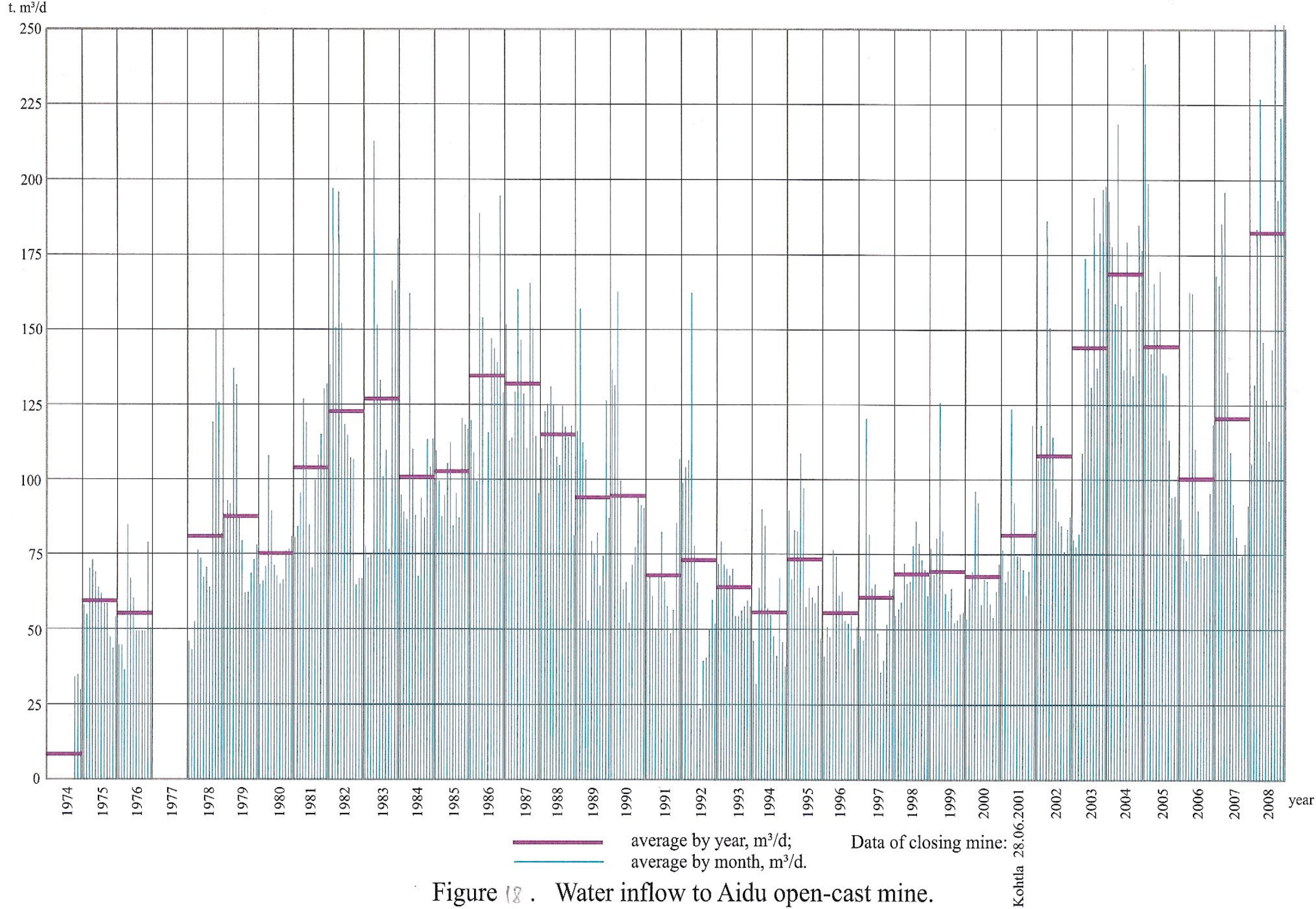


Figure 18. Water inflow to Aidu open-cast mine.

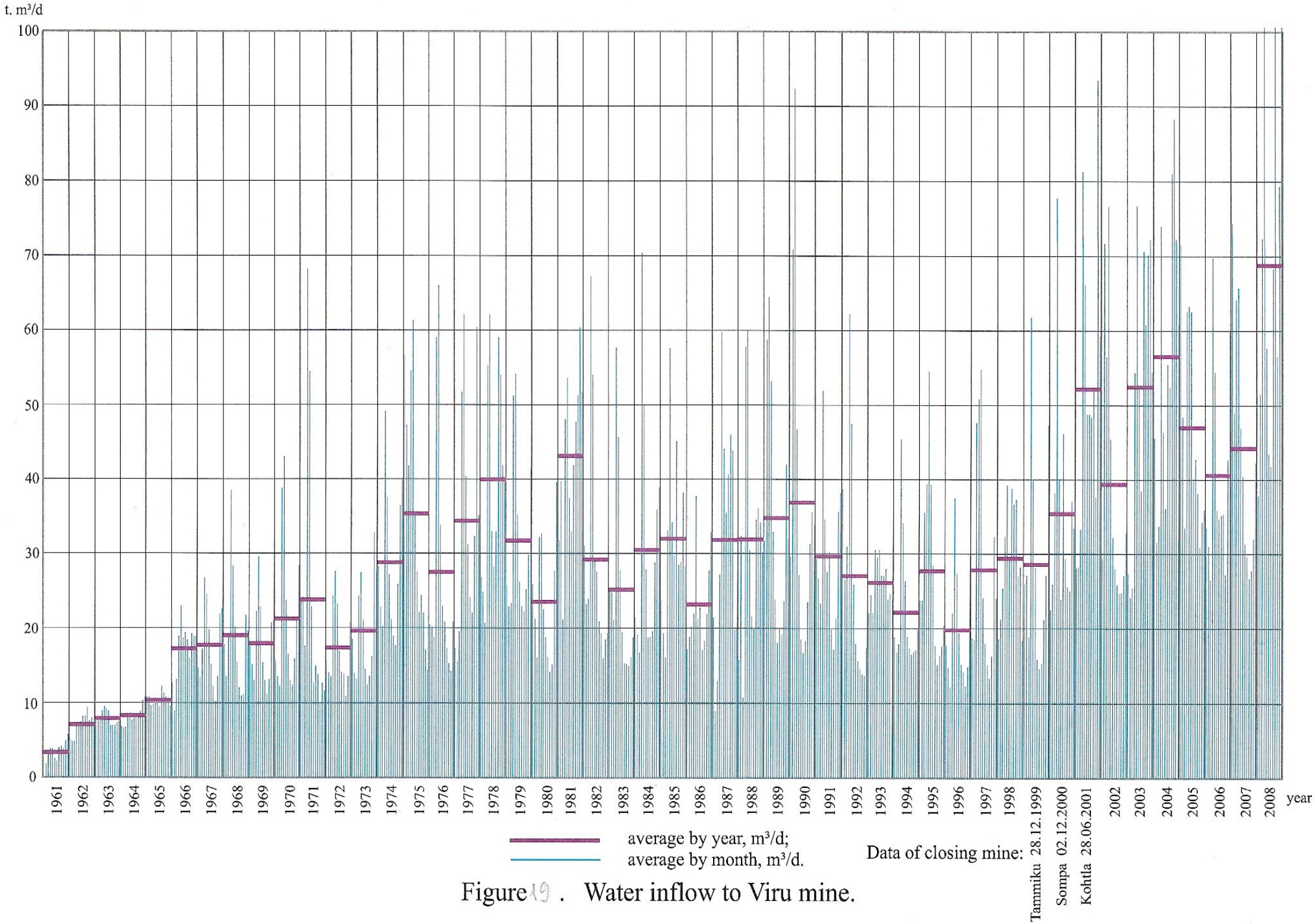
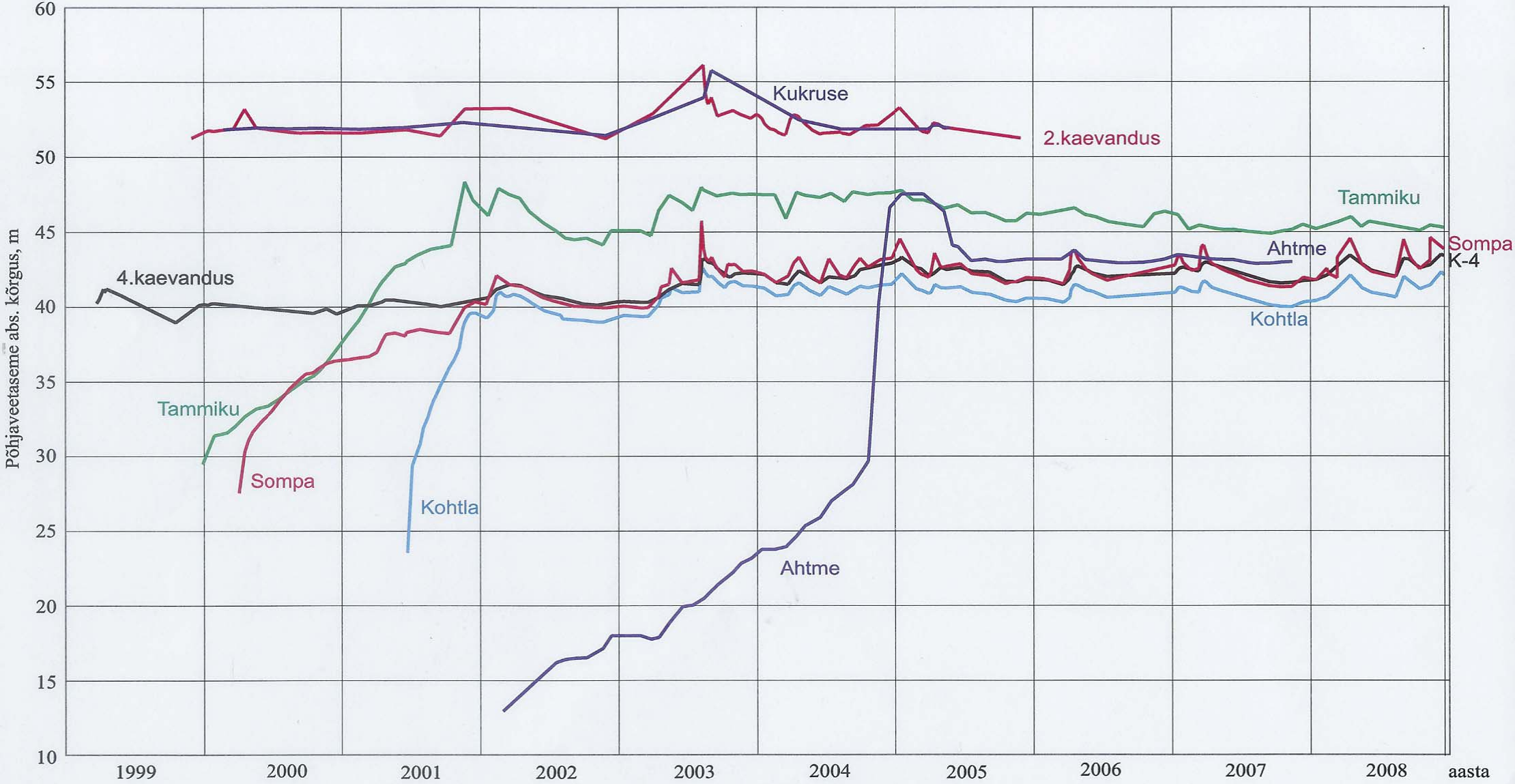


Figure 19 . Water inflow to Viru mine.



Joonis 10. Põhjaveetaseme muutused suletud kaevandustes.
Figure 10. Changes of groundwater levels in the closed mines.

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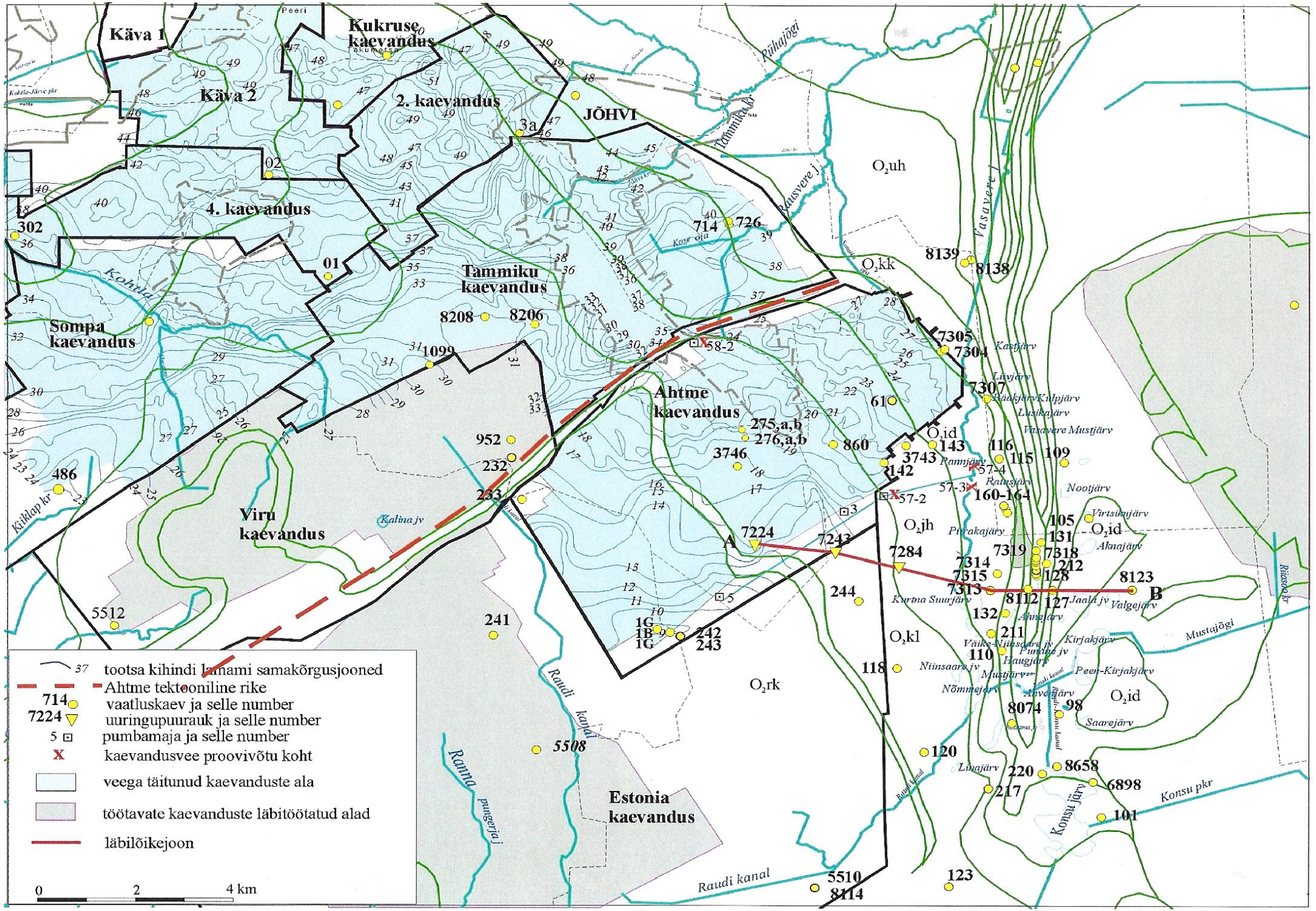


Joonis 3. Eesti põlevkivimaardla keskosa kaevandusettevõtete asukohaskeem

Verification (calibration) of regional model

The numerical model for the regional groundwater flow was developed using the MODFLOW software – finite element subsurface flow system (McDonald, Harbaugh, 1988). MODFLOW considers density – dependent groundwater flow. The three - dimensional groundwater modeling software combines GIS graphical features with finite element solution techniques. MODFLOW is especially suitable for problems involving complex model architecture. The shape of the finite elements is 1D, and triangular or quadratic in 2D and 3D. The finite element grid can be generated manually or automatically with several refinement options. The boundary conditions are simulated as: specified head, specified flux, and head dependent flux. All boundary conditions can be specified either as steady – state or transient. Constrains can also be set on the minimal and maximal flux or on the hydraulic head.

Model structure

Spatially, the 3-dimensional model domain is approximately coincident with the study area and covers a surface of 3376,15 km^2. The domain is discretized into 359 quadratic 3D mesh elements in the horizontal orientation (Figure 2-1). The finite element grid was generated automatically with moderate refinement along the model boundaries and stream nodes. The lateral size of the mesh elements is 500 x 500 m. Vertically, the Model extends from the top of the rock surface to 70 m below sea level (Figure 2-2). The model consists of 9 layers simulating the principal hydrostratigraphic units of the regional aquifers. The 0-77m thick top layer (layer #1) represents at the same time the permeable sediments at the base of the Quaternary sequence when present. The following layer (2) consists from sporadically water bearing Narva stage, what is represented with a hugely variable lithology. The following five layers (layers 3 to 7) constitute the fractured bedrock, and each has a different thickness of 24-50 m. the last two layers (layers #8 and 9) at the base of the 3-D model simulate the lower less fractured sedimentary rock units layer 8 and the deep groundwater flow system (layer 9). They are of equal thickness and extend non – uniformly from the base of the 7 th layer to 70 m below sea level.

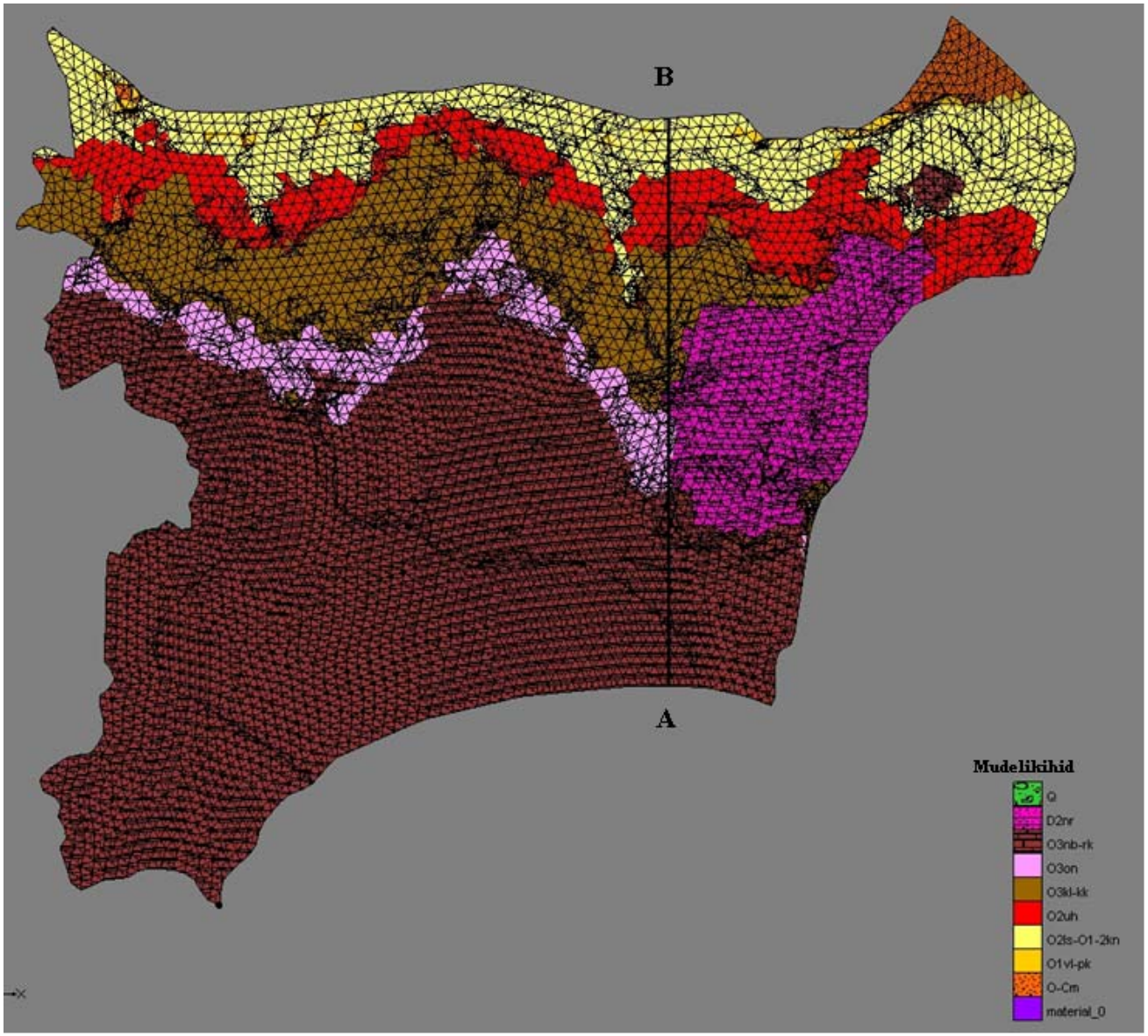


Figure 2-1. The 3-dimensional model domain of East-Viru County

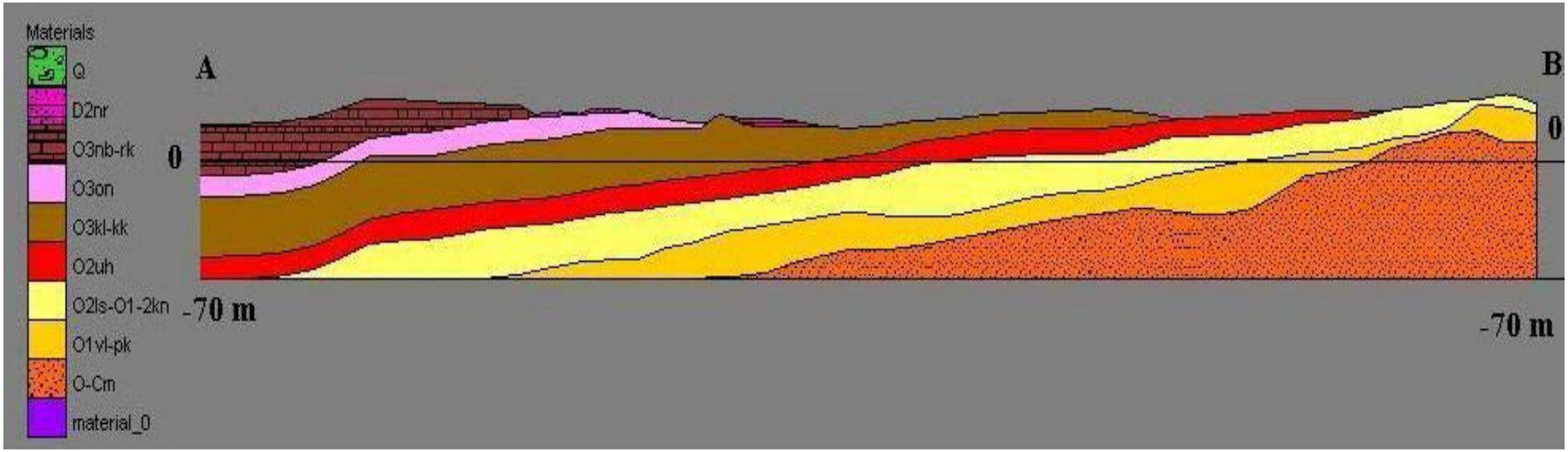


Figure 2-2. Cross-section of East-Viru model layers

The model boundaries were selected to correspond as much as possible with the natural geomorphological and hydrological features The southern boundary, defined by Lake Peipsi, is simulated as a specified head boundary with a water level of 30 m (Figure 2-3). The east boundary is defined by River Narva and west boundary by existing water levels in boreholes. The northern boundary was aligned parallel to the Gulf of Finland to simulate the junction between the Paleozoic platform and the Precambrian rocks. The model base at -70 m was also defined as a no-flow boundary. The withdrawal rates for oil shale opencasts and mines were imposed as a specified head to the corresponding nodes. All the quarries and underground mines, which covers a surface of 404,51 km^2, are simulated spatially with specific head. The average recharge rate of 67,5 mm/y, estimated by observations of the Jõhvi measuring station, was applied as uniform initial value over the recharge zone.

The hydraulic conductivity was assigned to layer #3 as an initial value of 10,5 m/d. The same spatial distribution and value was assigned to fractured rock layers #3 to 8. For layer 9, a uniform hydraulic conductivity value of 0,1- 2,5 m/s was used. As sedimentary rocks are generally much more permeable in the horizontal direction, a vertical conductivity factor of 0.2 m/d was assumed for all layers.

Model calibration

The numerical model was calibrated under steady – state conditions through a series of groundwater flow simulations (Figure 2-4). The conceptualization of the regional flow and the relatively complex model architecture were precisely defined in the preliminary stage of the model development. In order to constrain model results, parameters such as thickness of model layers, boundary conditions and hydraulic conductivities of fractured rock and solid rock units were assumed to be entirely known. With this assumption, the only parameters contributing to the uncertainty of the model simulations were: the hydraulic conductivity of layers2-5, and the distribution of the area recharge rate. The calibration was carried out by comparing the simulated heads against the measured groundwater levels in fractured aquifers. From 78 measurements, 20 were chosen as calibration targets. Most these data were collected in wells situating in nearby area of mining (Figure 2-5).

Allowing both the recharge rate and the horizontal hydraulic conductivity for layers to vary for each mesh element results in a large number of variables and precludes the use of the

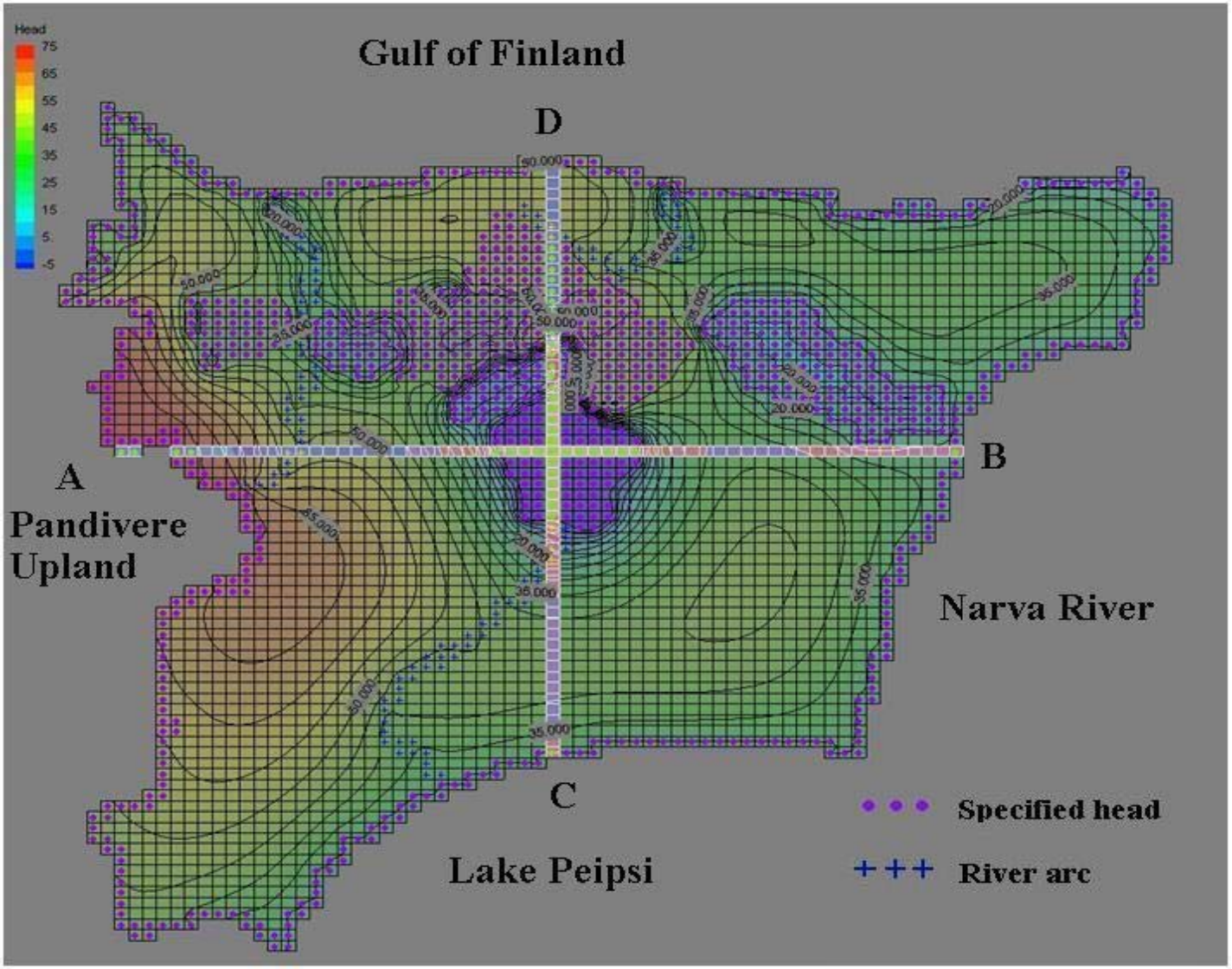
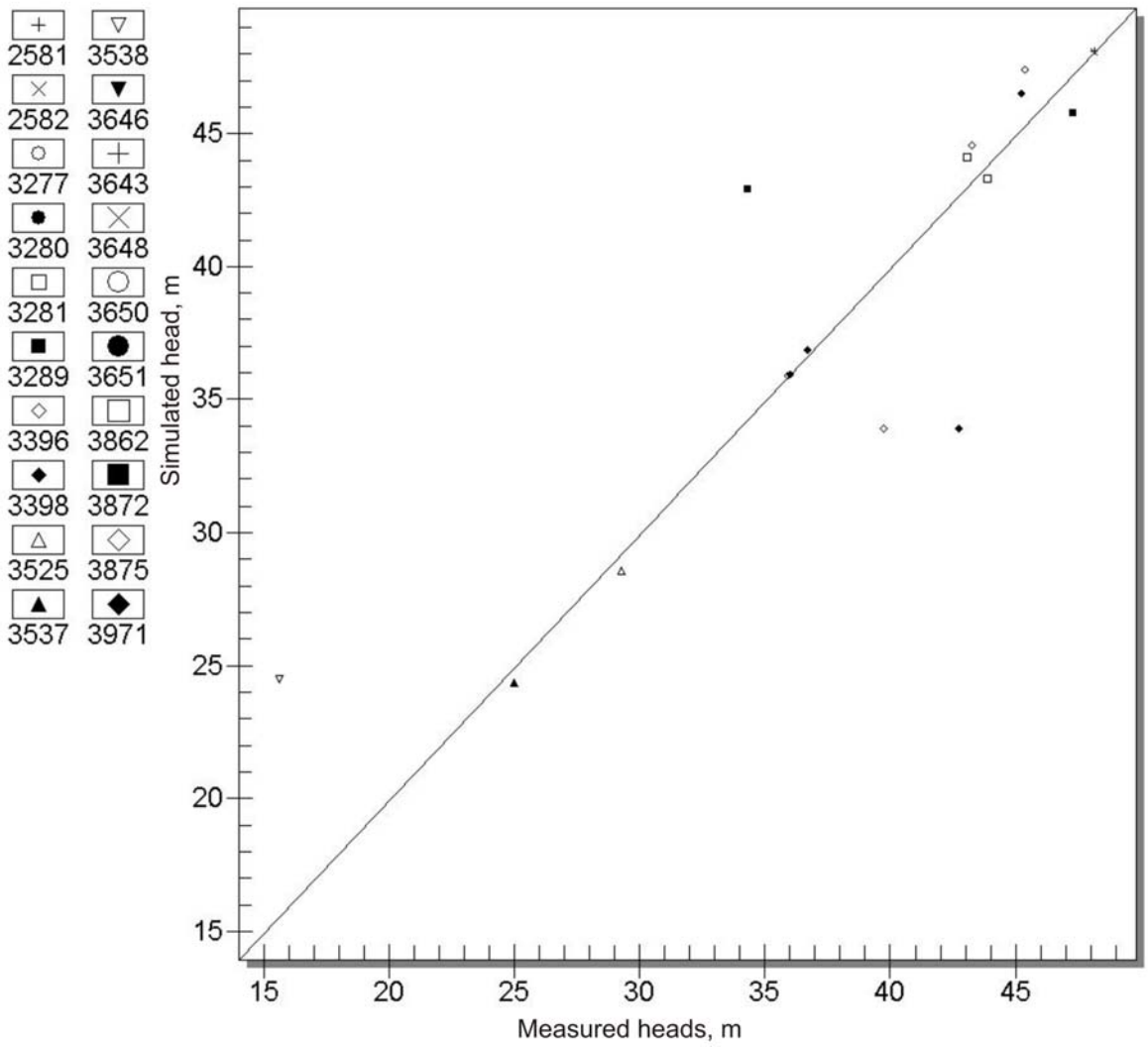


Figure 2-3. Boundary conditions and river arcs



Pilt 2-4. Modelleeritud ja mõõdetud veetasemete vaheline vastavus 20 seirekaevu põhjal.
Fig 2-4. Simulated vs . measured head at 20 calibration targets.

Figure 2-5. Location of monitoring wells of oil shale mining area.

automatic calibration tool PEST embedded in MODFLOW. To parameterize PEST, pilot point method was used. With pilot point method, a set of scatter points were defined where the hydraulic conductivity would be assigned Each point acts as an independent parameter and the K values for the grid are interpolated from the pilot points. Pilot points can be thought of as a 2D scatter point set. Instead of creating a zone and having the inverse model estimate one value for the entire zone, the value of the parameter within the zone is interpolated from the pilot points. The pilot point method allows for a more continuous and potentially more complex distribution of values throughout the model domain.

Calibration was performed by trial and error until achieving a reasonable agreement between the simulated and measured heads. During the calibration, the maximal simulated recharge rate was limited to 675 mm/year as the maximal possible value. The observed and simulated potentiometric surfaces are shown in the Figure 2-4.