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IMPACT OF OIL SHALE MINING AND MINE CLOSURES ON HYDROLOGICAL CONDITIONS OF NORTH-EAST ESTONIAN RIVERS

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The attention is focused on the formation of hydrological and hydrogeological interconnections between the catchment areas of Purtse, Rannapungerja, Pühajõgi and Vasavere rivers after closing (in 1997–2002) and flooding the Ahtme, Tammiku, Sompa and Kohtla oil shale underground mines. The multivariate relationship between the changes in mine water amounts directed into the rivers, annual runoff due to mine water inlets, groundwater underground flow, outflow module and other factors (as variables) were studied. A complex of linear regression formulas was derived to calculate the amounts of mine water outputs into the rivers and water distribution in order to regulate the hydrological regime of investigated rivers.

Introduction

In the area of the oil shale mines located in Ida-Viru County (North-East Estonia), both the underground and terrestrial hydrosphere have been under serious anthropogenic stress. Oil shale has been mined there over more than 85 years, about one billion tonnes on the territory of about 450 km^2, from the depth reaching 70 m. From this area about 260 km^2 have been mined underground [1]. As a result of dewatering and draining the mines (18–20 m^3 mine water per tonne of mined oil shale), deep drawdown cones have formed around the mines that reach quite far from the mined area. After closing the mines these drawdown cones will collapse, and the mining workings (galleries) will be filled by water again [2].

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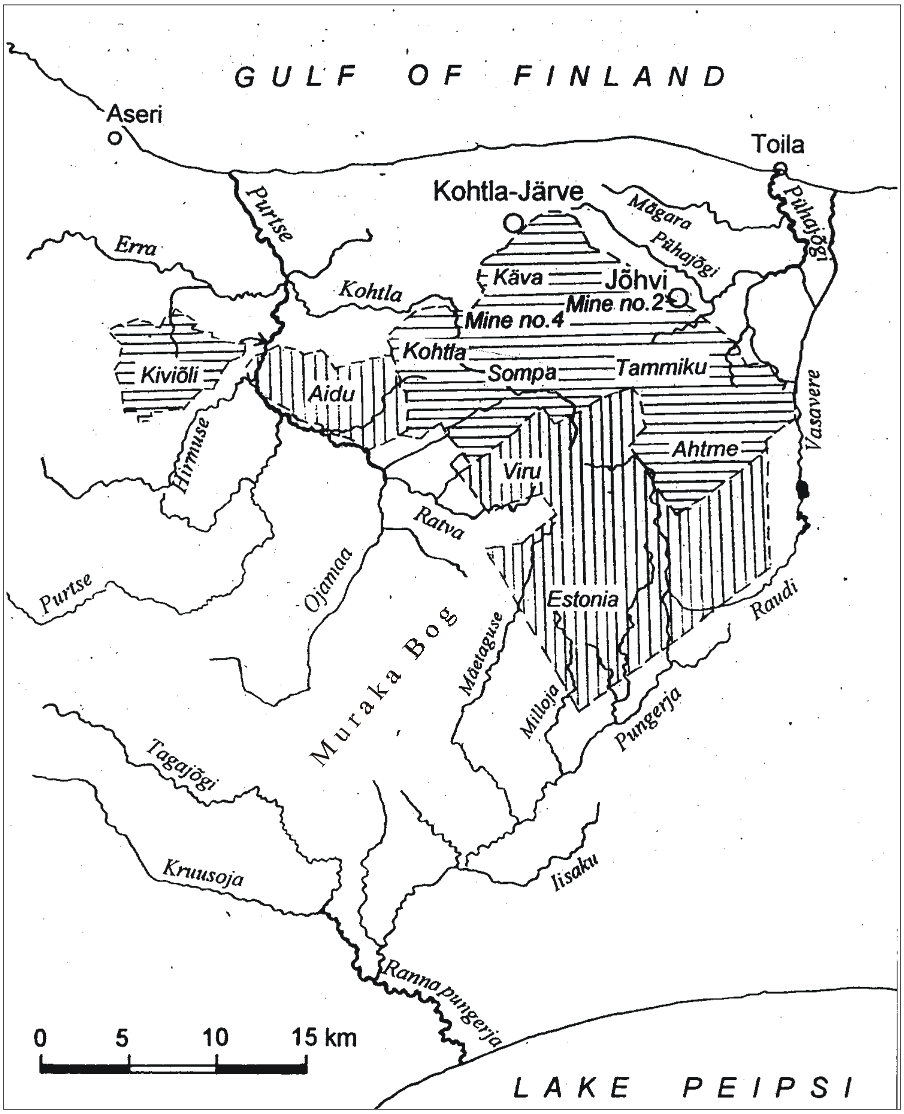

Fig. 1. Location of mining fields on the Purtse, Rannapungerja, Pühajõgi and Vasavere catchment areas: – closed mines; – operating mines

There is no doubt that in the mined area the specific natural water circulation and groundwater accumulation systems are deformed. Oil shale production seriously influences the hydrological regime of the rivers (Purtse, Rannapungerja, etc.), whereas the mining areas are practically always covered with the territory of catchment areas [3, 4]. Oil shale excavating has inevitably influenced the groundwater movement (infiltration) in both horizontal and vertical directions that must find an expression in the hydrological parameters of the rivers (mean annual runoff, groundwater outflow into the river) as well [5–7].

Due to large dimensions of mining fields (operating mines + closed mines) the catchment areas of different rivers (Purtse, Rannapungerja, Pühajõgi, Vasavere) located in the same fields must be in essential hydrological interconnection, because the velocity of underground water exchange increases essentially, causing in turn the acceleration of groundwater infiltration into the rivers by flooded mines [8].

The aim of this study was to analyze the changes in hydrological regimes of the Purtse, Rannapungerja, Pühajõgi and Vasavere rivers during the period 1997–2002, in connection with the closure of *Tammiku*, *Sompa*, *Kohtla* and *Ahtme* mines (in addition to flooded *Kiviõli* mine, and the mines in surroundings of the towns of Kohtla-Järve and Jõhvi in the earlier period, (Fig. 1)).

The purpose was also to estimate different correlative relations between the quantities of groundwater pumped out from the mines into the rivers, and to analyze the formation of hydrological situation of watercourses, observing the Purtse, Rannapungerja, Pühajõgi and Vasavere catchment areas as an integrated system. An additional purpose was to ascertain more essential functional relationships to predict mine water inflows, considering the latter into different rivers alternately as independent and dependent variables.

Analysis of the new situation is relevant and necessary for drawing water management plans for different rivers to achieve sustainability of water resources and to retain natural water circulation of the surrounding landscape. The results are also important for making plans to mitigate any negative impacts.

Study Area

Investigation area covers the mines operating at present (*Aidu* opencast, *Viru* and *Estonia* mines), and also closed and flooded mines (*Käva*, *Mine No. 2*, *Mine No. 4*, *Kohtla*, *Sompa*, *Tammiku* and *Ahtme*) (see Fig. 1, striped areas). This region covers an area of about 400 km^2. From Figure 1 it appears that the catchment areas of the Purtse, Rannapungerja, Pühajõgi and Vasavere rivers are widely embraced by the above-mentioned mines. The most important tributaries of the Purtse River are Erra, Hirmuse, Ojamaa, Ratva and Kohtla. The Kruusoja, Tagajõgi, Mäetaguse, Milloja, Iisaku and Pungerja rivers belong to the Rannapungerja catchment area. The Mägara River belongs to the Pühajõgi catchment area and Raudi canal to the Vasavere catchment area, respectively (see Fig. 1). As the Pühajõgi and Vasavere are connected hydrologically, it is rational to study their catchment areas as a whole.

Discharge areas are the Gulf of Finland and Lake Peipsi. Hydrographical network is well developed. *Aidu* opencast pumps the draining waters into Kohtla and Ojamaa rivers, *Viru* mine – into the Ratva stream and Raudi canal, and *Estonia* mine – into the Rannapungerja River (through Pungerja and Milloja streams) and Raudi canal. At present all twelve mines have water outputs into the named rivers. Underground water outflow from the closed *Kiviõli* mine (1987) into the Purtse River is marked with an arrow. In *Kohtla*, *Sompa* and *Tammiku* mines the oil shale was mined at the depth of 20–35 m, in *Estonia* mine – at the depth of 70 m [1].

In the old *Kiviõli*, *Käva*, and Nos. 2 and 4 mines oil shale was at the depth of 20 m. The whole mined and unmined area is rich in tectonic disturbances and karst. The major source of mine water is the Keila-Kukruse aquifer providing 80–99% of total groundwater infiltration (depending on the mine depth).

The temporal course of closing different mines in the studied area is as follows:
1999 – closing *Tammiku* and *Sompa* mines was started;
2000 – *Tammiku* and *Sompa* mines were closed;
2001 – *Kohtla* mine was closed, closing *Ahtme* mine was started;
2002 – *Ahtme* mine was closed.

After closing the above mines the mine water output into the Purtse River from *Aidu* opencast and into the Pühajõgi and Vasavere rivers from *Estonia* and *Viru* mines is continued.

Material and Methods

The initial data about the Purtse, Pühajõgi, Vasavere and Rannapungerja rivers (Table 1) were obtained from publications [9, 10].

Table 1. **The Rivers, Targets for Mine Water Outputs, and Hydrological Data of Their Catchments [9, 10]**

Hydrological data	River		
	Purtse	Pühajõgi + + Vasavere	Rannapungerja
Catchment area S_v, km^2	816	352	601
Mean annual runoff L_v, m^3/s	6.8	3.3	9.38
Outflow module M_v, l/s·km^2	8.33	9.38	8.99
Mine water outputs from the mines:			
in 1988–1999	*Aidu* (opencast), *Sompa*, *Kohtla*, *Viru*	*Tammiku*, *Ahtme*, *Viru*, *Estonia*	*Estonia*
after 2002	*Aidu* (opencast), *Viru*	*Viru*, *Estonia*	*Estonia*

The necessary facts about changes in annual amounts of mine water pumped out from mines (variables Y_1, Y_2 and Y_3) in the observed region for the period 1997–2002 (Table 2) were received from *AS Eesti Põlevkivi* (*Estonian Oil Shale* Ltd.).

Table 2. **Variation of Annual Amounts of Mine Water Directed into the Catchment Rivers during the Period 1997–2002 and the Values of Composite Variables for System Analysis, million m³/yr**

Designation	1997	1998	1999	2000	2001	2002
Variable Y_1 (Purtse catchment rivers)	96.5	98.9	89.4*1	61.3*1	49.5*2	55.2
Variable Y_2 (Pühajõgi and Vasavere catchments' rivers)	48.4	49.6	46.6	39.6	40.8*3	23.0*3
Variable Y_3 (Rannapungerja catchment rivers)	37.7	38.5	42.0	43.0	44.2	44.3
Composite variables:						
$Y_1 + Y_2$	144.9	148.5	136.0	100.9	90.3	78.2
$Y_2 + Y_3$	86.1	88.1	88.6	82.6	85.0	67.3
$Y_1 + Y_3$	134.2	137.4	131.4	104.3	93.7	99.5

*1 Closing *Tammiku* and *Sompa* mines; *2 closing *Kohtla* mine; *3 closing *Ahtme* mine.

The values of mine water amounts (Y_1, Y_2 and Y_3) were examined as variables (both predictor and criterion ones), between which, for characterizing the interdependence, the correlation coefficients r were computed for the proper set of paired values of variables using the principles of multivariate common independent causes (multiple path analysis) [11]. The values of composite variables ($Y_1 + Y_2$, $Y_2 + Y_3$ and $Y_1 + Y_3$) were also used (Table 2) for realizing the principles of system analysis [12].

Table 3. **Linear Regression Formulas for Characterizing Functional Relationship Between Annual Amounts of Mine Water Discharged (Table 2) into Different Catchment Rivers ($p \leq 0.05$)**

Regression formula		Coefficient of determination r^2	Dependent variable	Independent variable
$Y_3 = 50.51 - 0.22Y_2$	(1)	0.55	Y_3	Y_2
$Y_1 + Y_3 = 43.42 + 0.63(Y_1 + Y_2)$	(2)	0.95	$Y_1 + Y_3$	$Y_1 + Y_2$
$Y_1 = 370.73 - 7.10Y_3$	(3)	0.84	Y_1	Y_3
$Y_2 = 444.49 - 0.74Y_1 - 8.35Y_3$	(4)	0.78	Y_2	Y_1 and Y_3
$Y_2 = -2.31 + 0.37(Y_1 + Y_3)$	(5)	0.56	Y_2	$Y_1 + Y_3$
$Y_1 = 402.52 - 7.86Y_3$	(6)	0.93	Y_1	Y_3
$Y_2 = 16.22 + 0.33Y_1$	(7)	0.57	Y_2	Y_1
$Y_2 = 147.32 - 2.55Y_3$	(8)	0.55	Y_2	Y_3

With the help of linear regression analysis, the linear regression formulas (Table 3) in the form of $Y_j = a + bY_k$ and $Y_j = a + b_1Y_k + b_2Y_l$ (the indexes $j...l$ indicate the numbers of variables) and the coefficients of determination r^2 were calculated to explain some of the variation of Y_j by $Y_{k,l}$, using the latter variable(s) as a statistical control [11]. Differences were considered significant at the 95-% confidence level ($p \leq 0.05$).

Table 4. **Parameters of Hydrological and Hydrogeological Changes in Catchment Areas Due to Oil Shale Mining between 1997 and 2002**

Parameter	Catchment area (river)		
	Purtse	Pühajõgi + + Vasavere	Rannapungerja
Change of the amount of mine water pumped out ΔV, million m^3/yr (%)	–49(~50) decrease	–26(~52) decrease	+6(~14) increase
Change of mean annual runoff due to mine water inlets, m^3/s	–1.5 decrease	–0.9 decrease	+0.2 increase
Calculated values			
Change (prognosis) in groundwater underground flow into the river ΔL_v, m^3/s	+2.1 increase	+1.5 increase	–1.7 decrease
Outflow module component related with mining M_v^k, l/s·km^2	2.60	4.13	2.84

On the basis of hydrological data of the catchments from Table 1, the following values of changes in hydrological regime for investigated rivers in 1997–2002 were calculated (see Table 4):

- the changes in groundwater underground flow ΔL_v (m^3/s) into the river

$$\Delta L_v = \frac{S_k}{S_v} \cdot L_v$$

- the outflow module components M_v^k (l/s · km^2) related to oil shale mining

$$M_v^k = \frac{S_k}{S_v} \cdot M_v$$

In these formulas:

S_k is area of underground mining fields, km^2, in the catchment region (for Purtse catchment area S_k is about 253 km^2, for Rannapungerja catchment – 190 km^2, and for Pühajõgi + Vasavere catchments – 155 km^2 [1]);
S_v is total catchment area, km^2 (see Table 1);
L_v is mean annual runoff, m^3/s (see Table 1);
M_v is outflow module for catchment area, l/s · km^2 (see Table 1).

Results and Discussion

Changes in Annual Amounts of Mine Water

From Tables 2 and 3 and corresponding correlation graph in Fig. 2 it appears that in the period 1997–2002, when four mines (*Tammiku*, *Sompa*, *Kohtla* and *Ahtme*) were closed, the dynamics of mine water outputs (millions of cubic meters per year) into the Purtse, Pühajõgi, Vasavere and Rannapungerja catchments' rivers and interdependence (interaction) between them had an integrated character. Both the correlation between simple (Y_1, Y_2 and Y_3 – mine water amounts into the rivers by Table 2) and composite (Y_1+Y_2, Y_2+Y_3 and Y_1+Y_3) variables is remarkably high ($r=0.60$–0.97) (Fig. 2).

A zone of closed and flooded mines has formed to the north of *Viru* and *Estonia* mines. Therefore, in this area surface water infiltration into the closed mines and water exchange increased significantly, and with the change of aeration conditions a new geochemical environment has formed. For the Purtse and Pühajõgi rivers the share of groundwater in the catchment water circulation will be increased, and with that the input of sulphates and chlorides from the mines into the rivers (with mine waters) decreases accordingly [3].

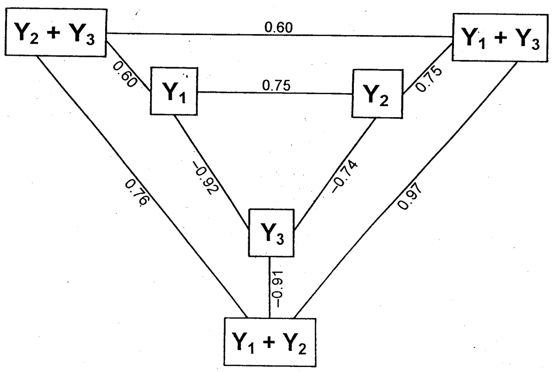

Fig. 2. Correlation graph (path diagram) showing the interdependence between annual amounts of mine water directed into the rivers (at the 95-% confidence limit around *r*) in 1997–2002. Variables, million m^3/yr: Y_1 – amount of mine water pumped into the Purtse River; Y_2 – amount of mine water pumped into the Pühajõgi and Vasavere rivers; Y_3 – amount of mine water pumped into the Rannapungerja River

The formed situation increases hydrological and hydrogeological connection (dependence) between the rivers of Purtse, Pühajõgi and Vasavere catchments. However, the operating *Viru* and *Estonia* mines restrain unavoidably the water underground infiltration from flooded mines into the rivers of Pühajõgi and Vasavere catchments, whereas the underground watercourse is certainly in part directed in direction of extensive drawdown cone caused by the operating mines.

In addition, water inflow into the closed *Ahtme* mine decelerates. From Figure 2 it appears that mine water output from *Estonia* mine into the Rannapungerja River (variable Y_3) is in strongly negative correlation with mine water outputs into the Purtse River (variable Y_1, $r = -0.92$) and Pühajõgi and Vasavere rivers (variable Y_2, $r = -0.74$). On the basis of these correlations we may conclude that the mine water output from *Estonia* mine into the Rannapungerja River plays a very significant role in the formation of the water cycle balances for the Purtse, Pühajõgi and Vasavere rivers.

Nevertheless, the above negative correlation between variables Y_2 and Y_3 ($r = -0.74$) is somewhat mitigated by mine water output into the Purtse River from *Aidu* opencast, as indicated by the significant positive correlation between composite variables $(Y_1 + Y_2)$ and $(Y_1 + Y_3)$ ($r = 0.97$, see Fig. 2). In the case of increasing variable Y_1, variable Y_2 also increases in some measure, but the relation between variables Y_2 and Y_3 with negative correlation affects contrarily the value of variable Y_2. For mitigation of this it would be rational in every way to increase technologically the mine water output into the Pühajõgi and Vasavere catchments (variable Y_2) by the use of variable Y_3 (mine water output from *Estonia* mine), directing additional 15–20 millions m^3 mine water from *Estonia* mine into the Raudi canal every year. It would accelerate flooding of the workings in the closed *Ahtme* mine. As a result of the combined effect of natural (meteorological and hydrological) and anthropogenic (mining-and-technological) factors, a persistent tendency for improvement of hydrological conditions of the Pühajõgi and Vasavere rivers may be achieved.

It is possible to improve situation for variable Y_2 (mine water output into the Pühajõgi and Vasavere catchments) not only by variable Y_3 (increasing mine water output from *Estonia* mine), but also with the help of variable Y_1 (output into the Purtse catchment), using the water moving in aquifers in closed mines in direction of Pühajõgi and Vasavere catchments. It confirms the fact that variables Y_1 and Y_3 are of the same sign in corresponding regression formulas (Formulas (4) and (5), see Table 3). Also Formulas (7) and (8) confirm the same fact. This tendency becomes especially pronounced in the time of large-scale rainfalls which may result in major floods [13]. If the value of variable Y_3 decreases, the value of variable Y_2 certainly increases too (Formula (8). Increase in variable Y_1 enlarges also positively the value of variable Y_2 (Formula (7).

All linear regression formulas given in Table 3 enable to prognosticate well the mine water outputs into the catchments' rivers investigated, for the interval indicated in Table 2 and for the purpose of their mutual regulation. For example, when using regression Equations (3), (4) and (6), prognosticated mine water outputs into the rivers differed from factual ones on an average only by 3%, which is a good result. The proposed model system is useful when preparing projects for improving hydrological conditions of the rivers in the Purtse, Pühajõgi, Vasavere and Rannapungerja catchments while using mining-and-technological data (water pumping from the mines and a large network of the mine water outputs to the catchments' rivers).

Total Effect of Hydrological and Hydrogeological Factors

It appears from Table 4 that significant decrease in mine water outputs into the Purtse, Pühajõgi and Vasavere catchments' rivers in 1997–2002 generated the growth of groundwater underground flow ΔL_v (the calculated value) into the rivers, due to flooding of mines. This matter must be considered positive. However, the groundwater infiltrates generously into the depression cone engendered by operating *Estonia* and *Viru* mines; because of that the output of mine water into the Rannapungerja River has increased, causing again the negative change in underground outflow into the river (Table 4, $\Delta L_v = -1.7$).

Examining the values of parameters given in Table 4 as independent variables, it was found that the change in the amount of mine water pumped out (ΔV) correlates positively with the change in groundwater underground flow into the river (ΔL_v) ($r \approx 0.70$). However, the change in outflow module (M_v^k, see Table 4) caused by oil shale excavating correlates negatively with the change in groundwater underground flow ΔL_v ($r \approx -0.84$). This fact supports peculiar and reverse (by plus and minus signs) correlative relations between mine water outputs into different rivers, derived by the system analysis and shown in Fig. 2. Therefore, interaction between all considerable components of water circulation scheme (infiltration of precipitation water into the mines, mine water pumped out into the rivers, groundwater exchange between closed mines and movement at the sites of tectonic damage, total river flow into the Gulf of Finland and Lake Peipsi) for Purtse, Pühajõgi, Vasavere and Rannapungerja rivers is of a combined and developed character [4, 14].

The total effect of hydrological and hydrogeological factors will increase essentially when the *Viru* and *Estonia* mines are also closed and flooded. Then a flooded underground mining field with an area of about 250 km^2 will remain between the Purtse, Rannapungerja, Pühajõgi and Vasavere catchments. This causes an extensive groundwater movement (mainly in the Ordovician aquifer complex) and water exchange between different catchment basins. Also the groundwater outflow into the rivers and in the direction of aquifer outcrop will increase. The transformation of the rivers runoff and their dynamics is difficult to prognosticate at the time being.

In all likelihood, the rate of underground water exchange will increase essentially, by reason of that the possible groundwater pollution (oil products and phenols from oil shale processing plants) will also spread faster. In this case hazardous contamination may spread quite freely from one catchment to another (for example, from the Purtse catchment to the Rannapungerja one) by the Keila-Kukruse aquifer, whereas its geological structure is crushed. Thus, a new anthropogenic-and-natural water cycling will be formed, which covers all three catchment areas with disturbed geological environment. Hydrological conditions of the northern part of the Muraka Bog will improve: natural groundwater level and surface water regime will be restored.

Conclusions

This study of hydrological conditions of the Purtse, Rannapungerja, Pühajõgi and Vasavere rivers resulting from closing *Ahtme*, *Tammiku*, *Sompa* and *Kohtla* oil shale mines in 1999–2000 has given the following results:

- Using the methods of linear regression and system analysis, it was found that due to considerable changes in mine water outputs, the hydrological and hydrogeological interconnections between the water cycles of the above-mentioned rivers has attained an integrated character. It was found that mine water output from *Estonia* mine into the Rannapungerja River simultaneously results in significant changes in the water balance of Purtse, Pühajõgi and Vasavere rivers. This new situation must be taken into account at organizing mine water outputs from operating mines (*Estonia* and *Viru*) and regulating water regime in the catchments' rivers.
- It was found that different correlations with an opposite sign between mine water annual output amounts into the given rivers (as independent variables) have an equally high value ($r = 0.60–0.97$). Combined effect of the hydrological, mining-and-technological and hydrogeological factors developed in the catchment areas will not disappear after the end of active oil shale mining and closing the mines in the years to come.
- Changes in groundwater outflow into the riverbeds (cubic meters per second) correlate with changes in the amounts of mine water outlets (million cubic meters per year) positively ($r \approx 0.70$), but with changes in the catchment outflow modules related with underground mining (liter per second per square kilometer) – negatively ($r \approx –0.84$). Such a varying correlation shows persuasively that in the observed area, a new anthropogenic-and-natural water cycling has formed, where disturbed geological environment assumes an essential function. The amount of groundwater outflow into the riverbeds (cubic meters per second) is proportional to the area of flooded underground mined field (square kilometers) in the region of the catchments.
- For prognostication of the amounts of mine water outputs into the investigated rivers and water distribution to regulate appropriately their hydrological regime, the linear regression formulas ($r^2 = 0.55–0.95$, $p \leq 0.05$) are calculated. It is reasonable to direct additionally about 15–20 million m^3 mine water per year from *Estonia* mine (by Raudi canal) into the Pühajõgi and Vasavere rivers.

The studied catchment areas undergone essential changes in hydrological and hydrogeological conditions during the last years demand now a different kind of approach. In the period of heavy rains the changes in hydrological situation may lead to large-scale flooding followed by environment degradation (subsidence of ground, formation of swampy areas) in the vicinity of settlements previously affected by mining. The situation will change essentially again when *Estonia* and *Viru* mines are closed and flooded in the future. Underground water exchange between the river catchments accelerates, and as a result hazardous contamination may quite easily spread on a wide area.

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