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IMPACT OF OIL SHALE MINE WATER ON HYDROLOGY AND RUNOFF OF A SMALL RIVER. THE PÜHAJÕGI RIVER CASE STUDY

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The Pühajõgi River runoff components (infiltration, interflow, groundwater recharge) and human impact (discharge of mine water and municipal wastewater) have been studied during three periods (1945–1963; 1978–1990; 2000–2003). This study characterises different hydrological periods: natural state of the river, influence of intensive mining and closing down of mines. The basic balance schemes based on available data have been worked out by linear regression calculations. The collected data is annual and gives a general overview.

The study shows that mine water exerts a significant impact on the river runoff and also confirms that human impact has considerably changed the average runoff of the Pühajõgi River after the 1960's. It was established that the average runoff from the river catchment area enlarged by almost 24%, compared with the average natural surface runoff. During the period when oil shale mines were being closed, the average surface runoff of the Pühajõgi River decreased by more than 38% compared to that of the oil shale mining period. However, the annual amount of precipitation has continued to increase within all observed periods.

Introduction

In North-East Estonia, Ida-Viru County, where oil shale mining and processing is the most important industry, rivers have become greatly transformed by humans for over 80 years.

One of the major changes is the canalised mine water from oil shale mining in the area. The result is a change in river hydrology. Small rivers as

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the Pühajõgi River have been affected the most. Since the 1960s, river tributaries and streams have been under a serious human impact mainly due to mine water from oil shale mines and the municipal wastewater from the biological treatment plant [1]. After closing the mines the mine water outflow was stopped [2]. After a technogenic water body has been formed in closed mines, the outflow continued [3]. Hydrological regime of the river has been totally changed once again.

The Viru–Peipsi Catchment Area Management Plan including the Water Framework Directive (2000/60/EC) [4] has been established to reduce the threat and reinstate the so-called "good status" of water bodies. According to the plan, working out of the best solution to the Pühajõgi River and understanding of the processes taking place in the catchment area are needed to analyse the hydrologic cycle and river runoff.

A previous research by Protaseva and Eipre (1992) [5] has carried out an extreme-value analysis of hydrologic data of the Pühajõgi River including runoff of the highest and lowest periods (using Gumbel´s probability distribution), return period, potential frequency of the rivers yearly and the average runoff during the period 1945–1963.

The aim of the present study was to model the runoff from the Pühajõgi River catchment area in the past. The result was achieved by modifying the Hewlett Runoff Model [6] to create the balance schemes of water circulation for three different periods (1945–1963; 1978–1990; 2000–2003) and to analyse the influences of the mining-technogenical factors.

There are minimal runoff data available from the past. In 1945–1963 the runoff data was recorded daily, therefore the model of that period is the most realistic one and forms the basis for other models. Furthermore, this period (1945–1963) describes the hydrological situation at the beginning of the oil shale mining period and matches for the preferred natural status of the Pühajõgi River. The second period (1978–1990) characterises hydrological situation of the Pühajõgi River when the influx of mine water was greatest, however, the runoff data was measured irregularly. The third period (2000–2003) has been chosen because after the mines were closed, technogenic water started to fill empty mines and inflow into the river stopped [7].

Study area

The Pühajõgi River is located in Ida-Viru County in North-East Estonia (Fig. 1). The river starts at the village of Saka (located 12 km North West from the town of Jõhvi) and flows into the Gulf of Finland. The length of the main river is 28 km, and the catchment covers an area of 196 km^2 [8]. The whole catchment is located in the western part of the Estonia oil shale deposit area. 47% of the catchment area is under primary impact of Ahtme

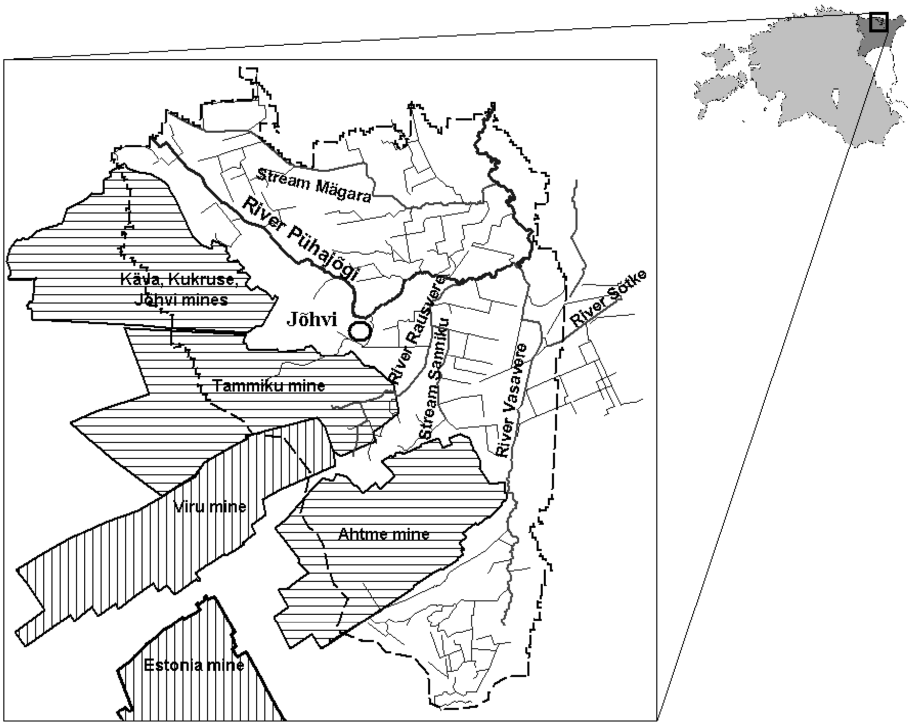

Fig. 1. Location of the Pühajõgi River catchment area (— — ·), closed mines and operating mines .

and Tammiku mines (Fig. 1). One can find closed mines such as Käva (operating times 1924–1973), Kukruse (1916–1967), Jõhvi (1949–1973) [9] and operating Viru mine in this catchment area. However, the influence of mine water from these mines is insignificant. The biggest effect of the mine water influence has come from Ahtme mine (1948–2001) and Tammiku mine (1951–1999) [3, 9].

The most important tributaries of the Pühajõgi River are Stream Mägara (length 14 km), the Vasavare River (13 km), the Rausvere River (10 km) and Stream Sanniku (6 km) [10]. All mine water from Ahtme mine was pumped out and canalised into the Rausvere River and the Vasavere River (4 outputs). 50% of wastewater from Tammiku mine was canalised into the Rausvere River. The other 50% was canalised into the Kohtla River (the Purtse River catchment) [11].

The area of oil shale mining (including the Pühajõgi catchment) is situated on the Ordovician aquifer complex. In this region the Ordovician aquifer complex has been totally drained by mining, creating the effect commonly known as 'the cone of pumping depression'. This effect may stretch up to 2.5 km outside of the mining area [9]. The direction of groundwater flow has also been changed in that region; natural groundwater flowed from the Pandivere upland to Lake Peipsi. Over the time when

Tammiku and Ahtme mines were in operation, the groundwater flow was the opposite [12]. After closing Tammiku and Ahtme mines, the direction of groundwater flow started to change again. By the year 2001 the level of groundwater in mines stabilized at 47 m above sea level again [13], both mines filled up and the overflow headed to the Pühajõgi River.

Data and methods

In this study, the circulation balance schemes of the Pühajõgi River catchment area were worked out (Fig. 2) by using the Hewlett Runoff Model. That model has been modified for the Pühajõgi River catchment area considering the effect of human impact.

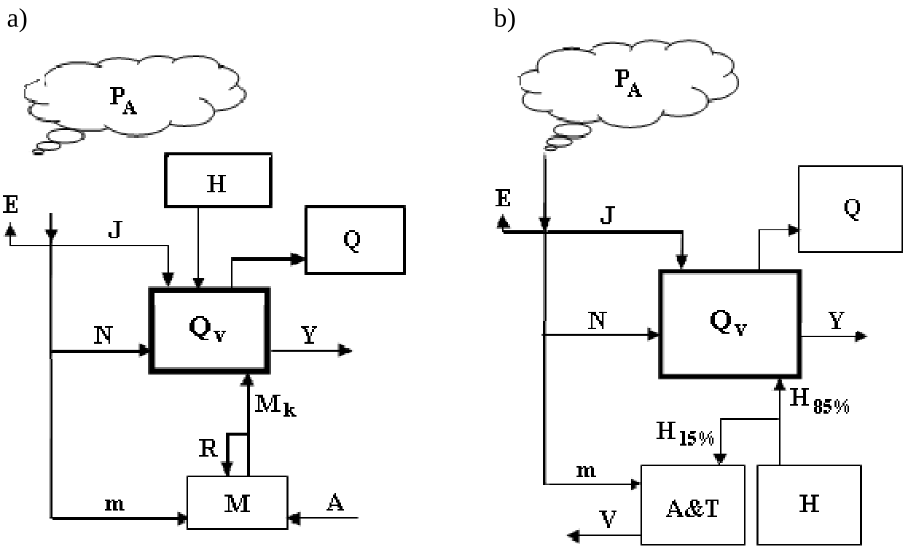

Fig. 2. A conceptual water circulation balance scheme of the Pühajõgi River catchment area illustrates three periods 1945–1962 (a), 1978–1990 (a) and 2000–2003 (b). Marking the water flows: P_A – precipitation water to catchment area; *E* – evaporation and transpiration of catchment area; *J* – surface water; *N* – precipitation water infiltration in unmined territory; *m* - precipitation water infiltration in mined territory; *M* – mine water; *R* – re-infiltration of water outflow from canals into the mines; M_k – pumped out mine water to catchment area; *A* – horizontal groundwater flow from related fields; *H* – inflow of wastewater from treatment plants; Q_v – water reserve of the Pühajõgi River catchment area; *Y* – water flow outwards from the catchment area; *Q* – runoff of the Pühajõgi River catchment area; *A&T* – closed Ahtme and Tammiku mines; *V* – mine water from closed Ahtme and Tammiku mines to Viru mine.

Data for the period 1945–2003 was provided from a number of different enterprises and organizations. To characterise the factors by meteorological processes, runoff and oil shale mining, the following data were used:

1. Annual precipitation amounts (P_A), mm, during the period 1945–2003 determined by Jõhvi Meteorological Station.
2. Mean annual runoff of the Pühajõgi River (Q), m^3/s, measured during the period 1945–1962; 1978–1990 (the only runoff data available for the Pühajõgi River).
3. Annual amount of mine water (M) pumped out from mines of the observed region, million m^3/y, during the periods 1945–1962 and 1978–1990 by Eesti Põlevkivi Ltd.
4. Annual amount of municipal wastewater (H) from Jõhvi biological treatment plant, million m^3/y, during the periods 1978–1990 and 2000–2003 [14].

Hydrological conditions of the Pühajõgi River catchment area are calculated using mathematical-statistical methods (linear equation) [2, 7] presented in Table 1. The most influential components were used to create balance schemes. However, the data is general and the balance schemes do not give the precise review of the Pühajõgi River hydrological regime.

Evaporation is one of the most important components in the water balance equation. The rate of evaporation depends on the availability of energy and water and a number of other physical and micrometeorological factors. Previous researchers [1, 7, 8, 15, 16] have been using various

Table 1. **Linear equations for characterizing functional relationship between annual amounts of mine water discharged, precipitation and runoff of the Pühajõgi River**

Description	Formula
The amount of precipitation of catchment area	(1) $P_A = PS$,
The Pühajõgi River catchment area runoff	(2) $Q = P - E - T$ or (3) $Q = T + H + M_k - Y$
Water reserve in Pühajõgi catchment area divides	(4) $T = J + N + M$
Water reserve in mining area	(5) $M = R + M_k$
Horizontal groundwater flow in unmined area (by Darcy's law)	(6) $Q_I = k \cdot S_D \cdot I$

Items: P – data of precipitation; S – data of catchment area; E – total evaporation and transpiration; T – water supply in the Pühajõgi catchment area (all precipitation water after evapotranspiration in catchment area); H – data of wastewater from treatment plants; M_k – pumped out mine water that actually reaches the river and forms part of river runoff; Y – water flow outwards the catchment area; J – surface water; N – precipitation water infiltration in unmined territory in the Pühajõgi catchment area; M – precipitation water infiltration in mining area (the influence of mining area is different in every observed period); R – part of pumped out mine water, what is infiltrating back to the mines; k – a constant describing the ability of a geologic material to transmit water (coefficient of permeability); S_D – the cross-section area (unmined area) of flow; I – hydraulic gradient.

annual precipitation water data between 400–900 mm and evaporation and transpiration data between 275–500 mm (50%–90% of precipitation water) to find the catchment area water reserve. The current research estimated that the amount of catchment area water is in proportion to the amount of precipitation water and evaporation in that area. The amount of the water reserve of the Pühajõgi catchment area is calculated from the possible maximum annual precipitation water (900 mm) and the possible maximum evaporation (470 mm) presented by Jaagus [15]. The estimated annual evaporation and transpiration (E = 52%) is fixed in our model.

The surface water J is also obtained and comprises approximately 5% of the precipitation water [16].

Re-infiltration of water from outflow canals into the mines R is 15% of all pumped out mine water [9]. Re-infiltration of different mines on the Pühajõgi River catchment area may vary, it will not exceed 25% (together with groundwater) [17]. R (15%) characterises the average re-infiltration of different mines which are situated on the Pühajõgi River catchment area. 85% of pumped-out mine water M_k is canalised into the catchment area and takes part of the river runoff [9].

In Table 1 Eq. (6) includes constant k, which characterises the volume of water moving through the soil vertically and being part of groundwater flow. Using Darcy's law [6], the constant k can be calculated, which illustrates groundwater movement in the Pühajõgi River catchment area. In the present research statistical analysis k = 0.3 m/d. The constant k is applied because previously no data existed on water moving through the soil vertically in this area. Furthermore, hydraulic gradient of unity I = 1 because it is hard to adjust with the present hydrological regime.

Results and discussion

During the period 1945–1962 the annual average runoff measured for the Pühajõgi River Q = 1.7 m^3/s (53.6 million m^3/yr) [8]. There was no presence of wastewater from treatment plants. A small percentage of the catchment was affected by the mining area, however, the influence of mine water was minimal. The interflow of horizontal groundwater to the mines has been considered in our model equal with outflow (A = 0). According to the model the mine water amount was equal to 12% of precipitation water. The rest of the precipitation water contains surface water (5% of precipitation water) and water infiltration in unmined territory (31% of precipitation water). 12% of the water reserve of the Pühajõgi catchment area was drained off by different ditches and groundwater.

The period 1945–1962 resembles that of 1978–1990 (Fig. 2a). The main differences between the periods were in data of wastewater from treatment plants, influence of mine water and horizontal groundwater flow. There were further differences in data on precipitation and catchment area water reserve.

There are three main reasons why the annual average runoff of the period 1978–1990 was highest, Q = 2.1 m^3/s (calculated data in Table 2):

1. The amount of precipitation water exceeded that of the period 1945–1962.
2. The territorial influence of the mining area was much bigger (up to 47%) than during the period 1945–1962. The amount of mine water was equal to 23% of precipitation water.
3. Extra wastewater was discharged from Jõhvi biological treatment plant to the Pühajõgi River. It was almost 10% of the water reserve of the catchment area.

The interflow of horizontal groundwater was higher than that of outflow (A = 3.6 million m^3/yr, which is 10% of pumped out mine water). However, surface outflow was lower than that during the previous period because the Pühajõgi River catchment area was connected with the Sõtke River catchment area by a regulator and part of the Pühajõgi River water was redirected.

During the period 1999–2001 discharge of the Ahtme and Tammiku mine water to the Pühajõgi River had stopped, and these mines had started to fill up with technogenic water (Fig. 2b). Eesti Põlevkivi Ltd [18] confirms that during the period 2000–2003 no mine water had been directed into the Pühajõgi River catchment area. They also confirmed that approximately 15% of the municipal wastewater from the treatment plant never reached the Pühajõgi River catchment area, because it infiltrated into Ahtme and Tammiku mines. The groundwater system of the Ahtme and the Tammiku

Table 2. **The numerical values (million m^3/yr) of the Pühajõgi River circulation components**

Period / Components		1945–1962		1978–1990		2000–2003	
P_A		131		140		157	
E		68.1		72.8		81.6	
J		6.6		7		7.9	
N		40.6		28		33	
m^*		16.1		32.6		34.5	
$M = M_k + R + A^{**}$	M_k	16.1	13.7	39.9	30.9	34.5	0
	R		2.4		5.4		0
	A^{**}		0		3,6		0
H		0		6.8		2.1 (85%)	
Q_v		60.9		72.6		43.1	
Y		7.3		4.4		3.5	
Q^{***}		1.7		2.1		1.3	

* During the periods 1945–1962 and 2000–2003 $m = M$.

** M is mine water, which divides into R, M_k and A.

*** Q (m^3/s).

The period 1945–1962 is calculated on measured data, others two periods are modeled. The initial data are from the Estonian Meteorological and Hydrological Institute, Eesti Põlevkivi Ltd and publication [13].

mining area is also linked with the Viru mining area. The Ahtme and Tammiku mine water approximates to 7 million m^3/yr which infiltrates into Viru mine. There are also minimal mine water flows into Estonia mine and the already closed mines [3]. Statistical information regarding the influence of horizontal groundwater in the Pühajõgi River catchment area has been purposely left out due to no precise data available. We can assume the fact that horizontal groundwater outflow and inflow were equal, because there was no mine water pumping during the period 2000–2003. In Fig. 2b consideration has been given to the fact that after closing down the mines, the influence of the cone of pumping depression had decreased. This resulted in the Pühajõgi River runoff being at its lowest ever (1.3 m^3/s).

The numbers in Table 2 indicate the average water flows (million m^3/yr), and the model result may vary, because the amount of mine water was not measured. The estimate of the standard error of the present statistical analysis is approximately 15%. This approximation is estimated due to the lack of previous data available regarding the Pühajõgi River catchment area. Furthermore, the method of calculation of the mine water amount was different for every mine, and the result was often estimated. The most common way was to calculate basing on electricity used by water pump [18]. Even so, the mine water has greater influence on the Pühajõgi River runoff than the precipitation water. The highest average annual runoff was during the period 1978–1990; however the amount of annual precipitation water has been steadily rising during the last 50 years [17, 19].

Conclusions

It can be seen from the presented schemes that the Pühajõgi River runoff during the three observed periods is different. The results of the hydrological study of the Pühajõgi River enabled to draw the following conclusions. The predominant factor responsible for changes in the runoff is largely mine water and also municipal wastewater directed to the Pühajõgi River catchment area.

In the period of 1945–1962 the Pühajõgi River average runoff has been measured as $Q = 1.7$ m^3/s. The runoff was formed mainly by precipitation water. The influence of the mine water was minimal. Since the beginning of the 1960s oil shale production has seriously influenced the hydrological regime and conditions of the Pühajõgi River catchment area.

At the present time, almost half (47%) of the Pühajõgi River catchment area is situated on the oil shale mining area. Until 1999 all water from Ahtme and Tammiku mines was canalised to the Pühajõgi River, therefore the average runoff enlarged by almost 24% (modeled result).

Since 1999, the water pumped from Ahtme and Tammiku mines to the Pühajõgi River has stopped. The groundwater is infiltrating to Ahtme and

Tammiku mines instead of taking part in water circulation of the Pühajõgi River. During the period of 2000–2003, the average runoff of the Pühajõgi River had decreased by more than 38% compared with the period 1978–1990 and 23% compared with the period 1945–1962. In the period 2000–2003 the influence of mine water was minimal, due to groundwater in the Pühajõgi River catchment area filling closed Ahtme and Tammiku mines.

At the present time the average runoff of the Pühajõgi River is still low, however, Ahtme and Tammiku mines are filled with technogenic water, and the overflow of mine water is canalised to the Pühajõgi River. Not all groundwater from Ahtme and Tammiku mines joins the runoff of the Pühajõgi River, due to groundwater infiltration to Estonia and Viru mines [3]. It is estimated by the authors of the present work that the hydrological runoff flow of the Pühajõgi River will rise when Estonia and Viru mines will be closed and flooded in the future.

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