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TECHNICAL ARTICLE

Impact of Oil Shale Mining on Flow Regimes in Northeast Estonia

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Abstract In addition to the well-documented effects of aquatic pollution, mining operations can have major impacts on hydrological pathways and flow regime in downstream catchments. This paper documents long term (1923–2008) changes in surface drainage areas and runoff characteristics in two small to medium (100–1,000 km^2) rivers draining part of the Ordovician oil shale field of north east Estonia. Through coupling analysis of flow regime with mining records (discharge rates and workings locations) the impact of expansion in oil shale mining through the mid to late twentieth century on downstream flow is assessed. During phases of intense mining, winter and summer baseflow is between 53 and 72% higher than long term average baseflow in the Purtse catchment and between 66 and 92% higher in the smaller Pühajõgi catchment where the volumetric significance of mine discharges is greater. The contribution of pumped deeper groundwater to surface run-off is shown to control the largest increases in mean annual run-off. While flow augmentation is the most common hydrological impact of the mining operations, phases of dehydration are also recognised in streams where cross-watershed transfers reduce the effective catchment area. Implications of the changed flow regime on river quality and management options are considered.

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Introduction

The multifarious effects of water discharges from abandoned mines have been widely documented in recent decades (e.g. Selberg et al. 2009; Tiwary 2001). Mining has been found to contribute to the dispersal of contaminant metals at local, regional, and global scales. Management options for minimising such contaminant releases, particularly to the aquatic environment, have advanced greatly over the last 20 years (e.g. PIRAMID Consortium 2003; Younger et al. 2002). However, far fewer studies have assessed the role that mining can have on hydrological pathways and the resultant physical and ecological effects of such hydrological changes on receiving watercourses. The construction of major drainage levels to underdrain workable ore deposits has long been practiced in upland settings and can lead to effects of spring dehydration in under-drained areas and flow augmentation where drainage levels cross watersheds and discharge (e.g. Mayes et al. 2010; Younger et al. 2002). Younger et al. (2004) highlights the hydrological effects of one of the largest drainage levels in Europe, the Milwr Tunnel in northern Wales (mean flow rate of 1.270 m^3/s). This tunnel, which commenced in 1897, led to the instantaneous dehydration of karst resurgences in the overlying aquifer and contributed to diminution of stream baseflow (e.g. the River Alyn) and the dehydration of springs of regionally important cultural value.

The hydrological effects of surface coal mining and associated restoration works in Appalachia (USA) have been assessed in a number of studies, albeit with a focus on the effects of restoration efforts on hydrologic behavior. Negley and Eshleman (2006) used a paired catchment study of water balances to show changes in the hydrological behavior of a surface mined (and subsequently reclaimed) catchment relative to an adjacent reference catchment. Higher storm runoff coefficients, increased total storm runoff, and increased short term peak runoff rates were attributed to reduced infiltration capacity of the land due to soil compaction in land restoration efforts (Negley and Eshleman 2006). Similar findings by Ferrari et al. (2009) highlighted the trend towards a flashy hydrograph more indicative of urban catchments than pre-mining conditions in reclaimed coal mined catchments in Appalachia.

In analogous settings, the effects of groundwater pumping operations at limestone extraction sites have also been shown to lead to changes in downstream hydrology through winter flow augmentation (due to increased void dewatering efforts) and diminished summer flows due to the effects of cone of depression development reducing spring flows (e.g. Finlinson and Groves 1994; Mayes et al. 2005). Diminished summer flows are a particular issue at active surface mines in arid and semi-arid climates where the maintenance of ecological flows can be even more important than water quality issues (e.g. Croton and Reed 2007).

With the implementation of the Water Framework Directive across the European Union (EU 2000), environmental managers are required to consider the broader impacts of human activity on the ecological, chemical, and physical quality of ground and surface waters. As such, understanding the nature and significance of hydromorphic changes induced by mining are as important to assess in actively mined regions as the more obvious and well documented water quality issues (e.g. Mayes et al. 2010).

The hydrogeological regime and water chemistry in the Ordovician oil shale mining area of northeast Estonia has been studied for the last 30 years (e.g. Erg 2003; Parakhonski 1983; Rätsep and Liblik 2000). Previous analyses (Rätsep and Liblik 2001; Vaht and Rätsep 2009) briefly demonstrated the impact of mining on hydrological regime and runoff in small to medium Estonian river systems (taken here to range from 100 to 1,000 km^2), but neglected to assess impacts in smaller (sub-100 km^2) systems. It is within the smaller catchments that any abrupt changes in flow regime would be more volumetrically significant, given their greater impact on instream ecology there.

This paper assesses the impact of changes in drainage associated with Estonian oil shale mining on hydrological pathways and flow regimes in small- and medium-sized lowland catchments. A variety of groundwater models have been used (Lind 2010; Reinsalu et al. 2006) to assess the impacts of oil shale mining on hydrogeology. The study assessed: (1) changes in catchment area and runoff characteristics over time as a result of mining operations, (2) the vulnerability of small rivers to hydrological regime change in mining areas, and (3) modes and extent of change in contributing drainage areas as a result of mining within different sub-catchments of the River Purtse. Through the combined assessment of long-term hydrological and mining records, the impact of various phases of oil shale mining operations can be assessed in multi-scale catchments.

Materials and Methods

Study Area

The River Purtse (PUR) and River Pühajõgi (PÜH) are located in the western part of the oil shale deposit area in northeast Estonia (Fig. 1). The first oil shale opencast mine was opened in 1918 in the River Purtse catchment area. At present, the mining area covers an area of approximately 430 km^2. Altogether, 24 underground and opencast mines have been operated there (Rätsep and Liblik 2004). During the 1920s, 1940s, and 1970s, more mining areas were opened while some depleted mines were closed in the 1940s, 1970s, and at the end of the 1990s (Fig. 1). Currently, only two underground mines and three opencasts are operating in the area (Reinsalu 2008), with some residual activity in the River Purtse catchment area (Fig. 1). There are no operating mines in the River Pühajõgi catchment area at present.

The Purtse and Pühajõgi rivers were chosen as being representative of typical mine-impacted systems in the oil shale areas of Estonia. These rivers have been subjected to intense human impact, mainly due to mining, since the beginning of twentieth century (Rätsep and Liblik 2001; Vaht and Rätsep 2009) and long term hydrological and mining records are available.

The River Purtse is a medium size river by Estonian standards (surface catchment area: 809 km^2) but has a similar landscape and hydrogeological conditions to the smaller River Pühajõgi (196 km^2) (Table 1). Both studied rivers are typical Estonian lowland rivers draining to the Baltic Sea on the Estonian northeast coastal plain. The catchments are characterised by low-gradient terrain, with peak catchment elevations in the Purtse (71 m) and Pühajõgi (52 m) rivers associated with artificial semi-coke ash dumps (Pae et al. 2005; Fig. 1). The average slope of both riverbeds is about 1.8 m/km. The greatest slope (up to 5 m/km) occurs in the lower reaches of both streams prior to

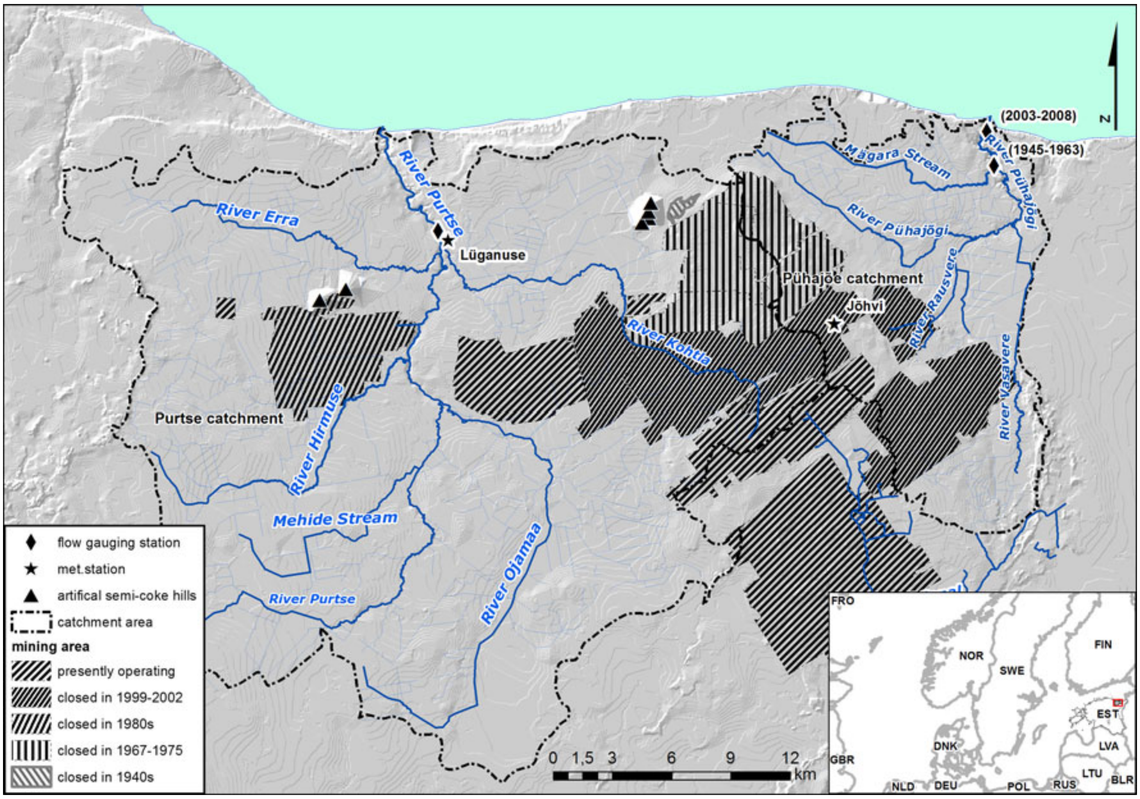


Fig. 1 Topographic map of the oil shale mining district and the River Purtse and River Pühajõgi catchments

discharge into the Gulf of Finland, where the rivers cross the limestone escarpment of the high Baltic Klint. Both catchments contain equally extensive peatland deposits and coniferous forests (Fig. 2). Under natural flow conditions, the perched water tables in the peatland areas are important in sustaining baseflow (Järvekülg 2001; Rochefort and Lode 2006). Surface flow paths are also influenced slightly by land drainage associated with predominantly arable agriculture and karstic features associated with the underlying Ordovician limestone deposits and aquifer complex. The dominant control on hydrogeology of the limestone is, however, mine pumping operations, which have completely drained the Ordovician aquifer. As a result, an extensive cone of depression (Erg and Pastarus 2008; Golf 1968) stretching up to 35 m in depth and 2.5 km outside of the mining area (Erg and Pastarus 2008; Kattai et al. 2000) creates groundwater flow gradients towards the mines. The size of the cone of depression depends on the depth of the mine (Kattai et al. 2000). In the cone of depression area, the direction of the groundwater from different layers has changed and now infiltrates to the mines, where it is pumped out as mine water (Erg 2003; Reinsalu et al. 2006).

Data Collection

The present study runoff analysis is based on precipitation and runoff data collected by the Estonian Meteorological and Hydrological Institute (EMHI), measured over varying

Table 1 Summary physical data for the River Purtse and River Pühajõgi

<table>
<tr><th></th><th>River Purtse</th><th>River Pühajõgi</th></tr>
<tr><td>Natural catchment area (km^2)</td><td>809</td><td>196</td></tr>
<tr><td>The mean annual run-off (m^3/s)</td><td>1.70</td><td>6.82</td></tr>
<tr><td>Natural length of the river (km)</td><td>50</td><td>28</td></tr>
<tr><td>Tributaries over 10 km length</td><td>5</td><td>3</td></tr>
<tr><td>Mean precipitation (mm)</td><td>640</td><td></td></tr>
<tr><td>Operating (closed) oil shale mines in the catchment area</td><td>3 (6)</td><td>(1)</td></tr>
<tr><td>Shared</td><td colspan="2">(3)</td></tr>
</table>

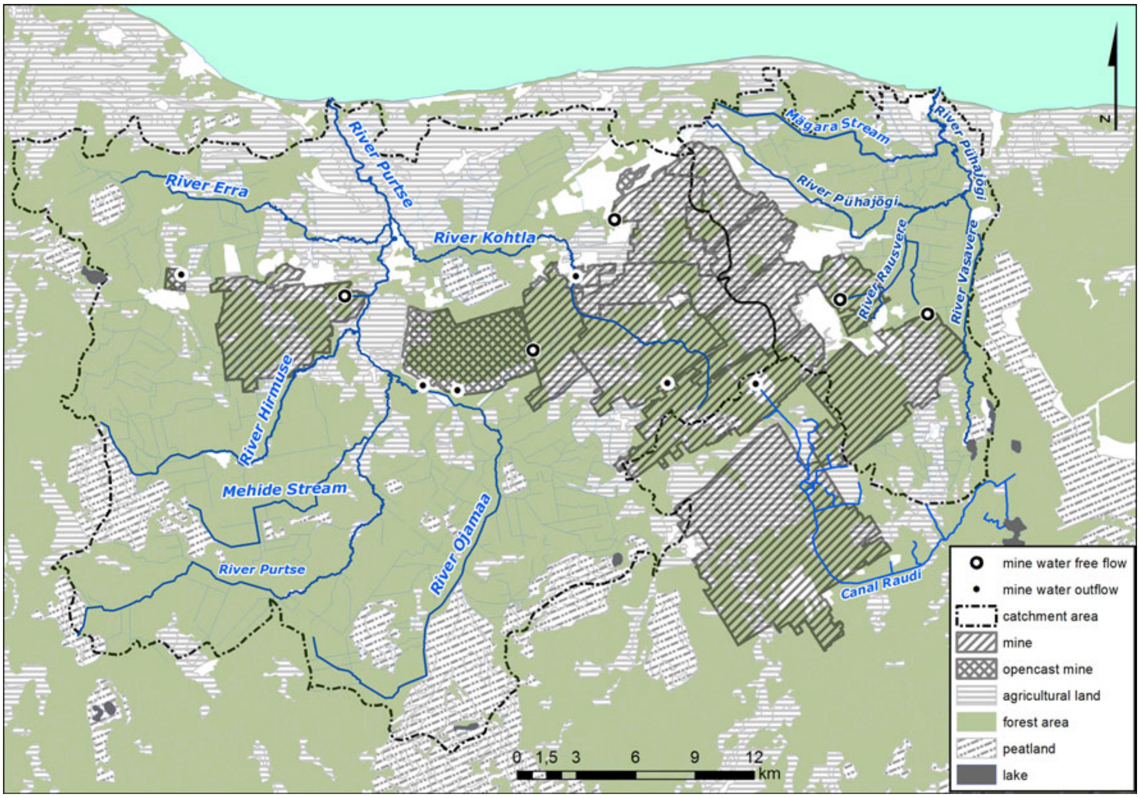


Fig. 2 Land use, mining and mine water outflows (mine water free flow—gravity driven flow; mine water outflow—pumped mine water) in the River Purtse and River Pühajõgi catchments at present time

time intervals in the catchments. Daily flow data was available for the River Purtse over the period 1923–2008 and for the River Pühajõgi between 1945 and 1963. Flow records were collected weekly for the periods of 1978–1990 and 2003–2008 in the Pühajõgi. Flow gauging stations are situated in the lower course of both catchments just downstream of the catchment outlet (Fig. 1) to the Baltic and calibrated by spot gauging. Previously modeled data has been used to account for the gaps in the runoff time series data set for the Pühajõgi River (see Vaht and Rätsep 2009 for a description of the model). Precipitation data has been collated from two tipping bucket rain gauges at Jõhvi (aggregated daily data available between 1960-present, location Fig. 1) and Lüganuse (daily data available between 1939-present, location Fig. 1). Mean oil shale mine water discharge rates (m^3/year) and mining area (km^2) data have also been collated from digital and hard copy records kept by Eesti Energia Kaevandused Ltd.

The River Purtse and the River Pühajõgi runoff frequency analyses during the period 1923–2008 were worked out by simple conceptual daily rainfall-runoff-mine water, using the Hewlett Runoff Model (Watson and Burnett 1995), which has been modified to their hydrological regime. Furthermore, the Gumbel method (Gumbel 1958) has been used to determine recurrence intervals of selected flow conditions using the peak over threshold (POT) method (e.g. Shaw et al. 2010). The chosen thresholds were Q values 25% above the long term (1923–2008) average annual runoff for high flow events (to ensure sufficient peaks within the monitoring period). For low flow events, minima below a threshold of 25% less than the long term average runoff were used. The return period values were assessed alongside mine water and precipitation data to examine any possible relationships between runoff return period of high flow and low flow events during the active mining years. Flow duration curves were developed based on mean daily flows using standard methods (Shaw et al. 2010). Basic deductive statistical analyses were undertaken in SPSS v.15. The data did not conform to a normal distribution even after log-transformation (Kolmogorov–Smirnov $p > 0.05$), so non-parametric methods were employed.

Mapping Catchment Boundaries

To analyse any changes in effective catchment area in the mining territory, runoff discharge area maps were created for the River Purtse tributaries using ArcGis v9.2 and Adobe Illustrator. The Estonian rivers and mining area layers were created using MapInfo, incorporating land cover and topography layers from Corine Land Cover 2006, which had a resolution of 25 m. The River Kohtla and River Ojamaa runoff discharge area maps are appended with data from previous studies (Kiristaja and Rannus 2008; Reinsalu et al. 2006) to illustrate mining effects and the impact of the created waterways. These maps were updated with specific data, such as excavation work in the river bed, which was carried out by Estonian Agricultural Board. During 2008–2009, additional fieldwork took place on the River Purtse and in the summer of 2010 on the River Pühajõgi and catchment area. Walkover survey of the catchments validated the current flow paths and catchment boundaries. The runoff of River Purtse and its tributaries were measured regularly 3–5 times per month with a Hydrometer ГР-21 M and a Valeport Model 301 electromagnetic flow meter with a flat sensor.

Result and Discussion

Long Term Regime

Mean precipitation in northeast Estonia is 640 mm/year and average evapotranspiration rate is 50–90% of precipitation (EMHI, year). Therefore, annual mean runoff in the River Purtse is 6.82 and 1.70 m^3/s in the River Pühajõgi. Figure 3 shows the mean annual precipitation and runoff in the Purtse and Pühajõgi, respectively. The long term regime of the rivers follows a typical temperature-controlled northern temperate zone lowland regime (Shaw 1994). Runoff maxima occur between March and May with snowmelt following spring temperature rises. Flow minima in both catchments occur during both summer (June–August) and winter (December–February) baseflow periods. This baseflow is sustained predominantly by drainage from extensive peatland deposits in headwater areas of the Purtse and forest-covered peat deposits in the Pühajõgi under natural flow conditions (Fig. 2). Because of clear seasonal variation in climate in this region, the difference between maximum and minimum runoff can be up to five orders of magnitude on an average annual basis.

Mining and Catchment Area Change

About one fifth of the River Purtse catchment area has been affected by mining (Fig. 1). Currently, there are five mine water outflows from operating mines and three free flows (i.e. gravity-controlled drainage associated with groundwater rebound after cessation of pumping operations) from closed mines directed to the River Purtse (Fig. 2). Moreover, a large volume of groundwater from closed mines continues to drain towards the operational Aidu opencast mine and subsequently forms part of the pumped Aidu

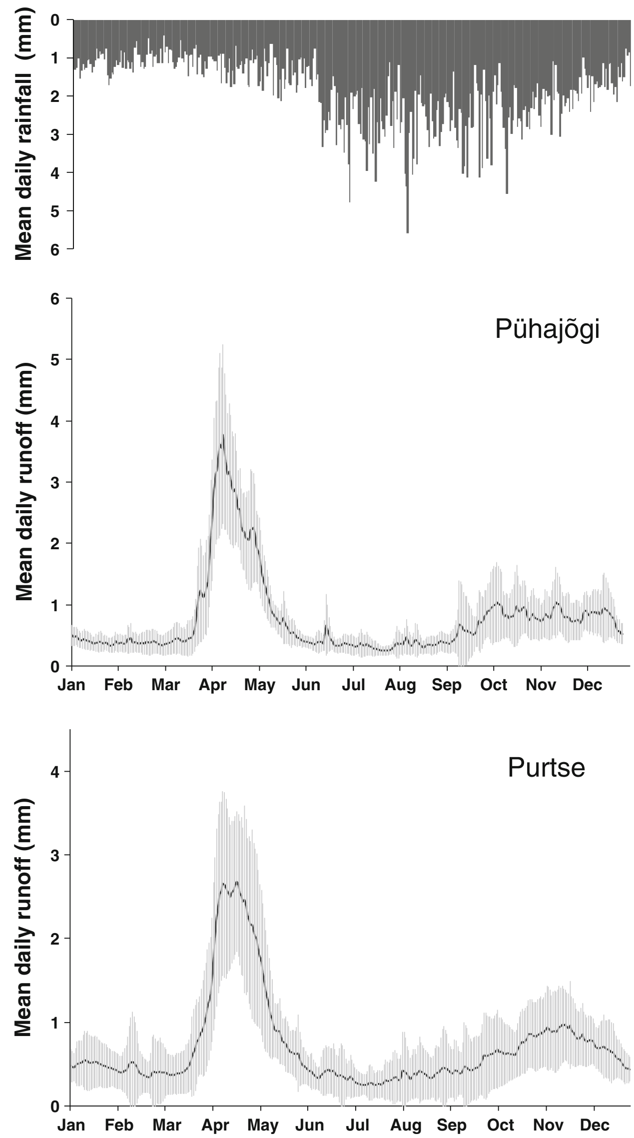


Fig. 3 The mean annual precipitation and runoff of the River Purtse and River Pühajõgi

mine water (Reinsalu et al. 2006), which is directed via one of its outflow canals into the River Ojamaa. Therefore, the biggest impact of oil shale mine water is centered on the eastern part of the River Purtse catchment area, where its tributaries, the River Kohtla and River Ojamaa, are situated. Mining is also taking place in the western part of the River Purtse (Fig. 2), but its volumetric impact to the tributaries (River Erra and River Hirmuse) is smaller (Vaht 2009).

There have been only four oil shale mines in the western part of the River Pühajõgi catchment area (Fig. 2), which all are closed now. The last two working mines in the catchment were finally closed in 2002. Groundwater rebound in the area was complete by 2004 (Reinsalu et al. 2006), and there have subsequently been two consistent gravity discharges flowing to the River Pühajõgi (Fig. 2). Previous studies have suggested a hydrological link between the Raudi Canal (an artificial waterway created in the 1960s) and the River Pühajõgi (Rätsep and Liblik 2004). However, field observation conducted as part of this research has shown the Raudi Canal to be an independent waterway (Fig. 1) and therefore, it is not included in the analysis below.

Over the different periods, the hydrological regimes of the Purtse and Pühajõgi rivers and their tributaries have been changed due the oil shale mining. There are three broad scenarios of change that have resulted:

1. *Effective catchment area changes due to changes in mine void size* The size of the given/taken territory depends on the changes in the mining area where mine water is directed from and the size of the cone of depression surrounding it (Hester and Harrison 1994). Table 2 and Fig. 4 illustrates that within the broader River Purtse catchment, the River Ojamaa sub-catchment has increased in size with mine development, predominantly at the expense of the River Kohtla sub-catchment area, between 1923 and 2000. The River Ojamaa surface catchment area has increased by approximately 40% during this period Fig. 4 (Period VI), while the River Kohtla lost about 44% of its pre-mining surface catchment area (Table 2).
2. *Artificial waterways change hydrological pathways*: The construction of new canals in mining terrain can have direct effects on surface hydrology and effective catchment area (Czaja 2005; Shaw et al. 2010). This phenomenon can be seen in the western area of the River Purtse catchment, where the new small Küttejõu ditch has developed additional drainage area to the Purtse. The Küttejõu ditch itself is only 2 km long, with a discharge area estimated to be 27 km^2 and an annual runoff up to 25 M m^3/year (Vaht 2009), it has significantly impacted the River Purtse tributaries. The ditch was originally created between the River Hirmuse and River Erra as a mine water discharge to the River Purtse (Fig. 2). At present, it is a free flow canal draining the workings of the closed mine, which is situated in the Hirmuse and River Erra catchment area. These rivers (Hirmuse and Erra) have lost over 10% of their respective catchment area as a consequence.
3. *The size of the catchment drainage area does not change* The third observed scenario is where the natural catchment area remains unchanged by mining. When comparing the River Purtse and River Pühajõgi natural catchment areas to their present discharge area, it is apparent that the overall surface catchment area has not changed, although there are shared areas of mine workings across the catchments (Table 1). Based on the Eesti Energia Kaevandused Ltd mining area data, it is evident that part of the River Kohtla natural surface catchment now forms part of the River Pühajõgi discharge area (Fig. 2). However, to compensate, the River Ojamaa discharge area has synchronously expanded to the Raudi canal catchment area. Therefore, analysing the locations of mine water pumps and so-called given/taken territory sizes between the catchment areas, the overall net change in catchment area is considered minimal (a net change of 2 km^2 in the Purtse). While the overall drainage area of the Purtse has remained relatively constant in recent years, the mining induced changes to flow paths and groundwater discharge points have had major effects on flow within the various sub-catchments. Thus, outlet flow analyses may not necessarily reveal overall changes within sub-catchments that have been subjected to significant changes in runoff.

Changes in In-stream Runoff

The natural catchment area, size and location of the mining area, and hydrogeological gradients are responsible for

Table 2 The River Kohtla and River Ojamaa discharge area data in different periods; italicised row marks period when closed mines were filling with groundwater

Period	Size of mining area (km^2)	River Kohtla		River Ojamaa	
		Run-off discharge area (km^2)	Mine water discharge (m^3/s)	Run-off discharge area (km^2)	Mine water discharge (m^3/s)
Before 1923	0.8	198	0	231	0
1924–1962	43	196	0.91	230	0
1963–1976	83	120	0.63	280	1.5
1977–1985	111	115	0.35	285	3.14
1986–2000	142	115	0.33	300	2.76
2001–2003	*143*	*112*	*0.19*	*200*	*1.59*
Present time	146	112	0.19	325	1.77

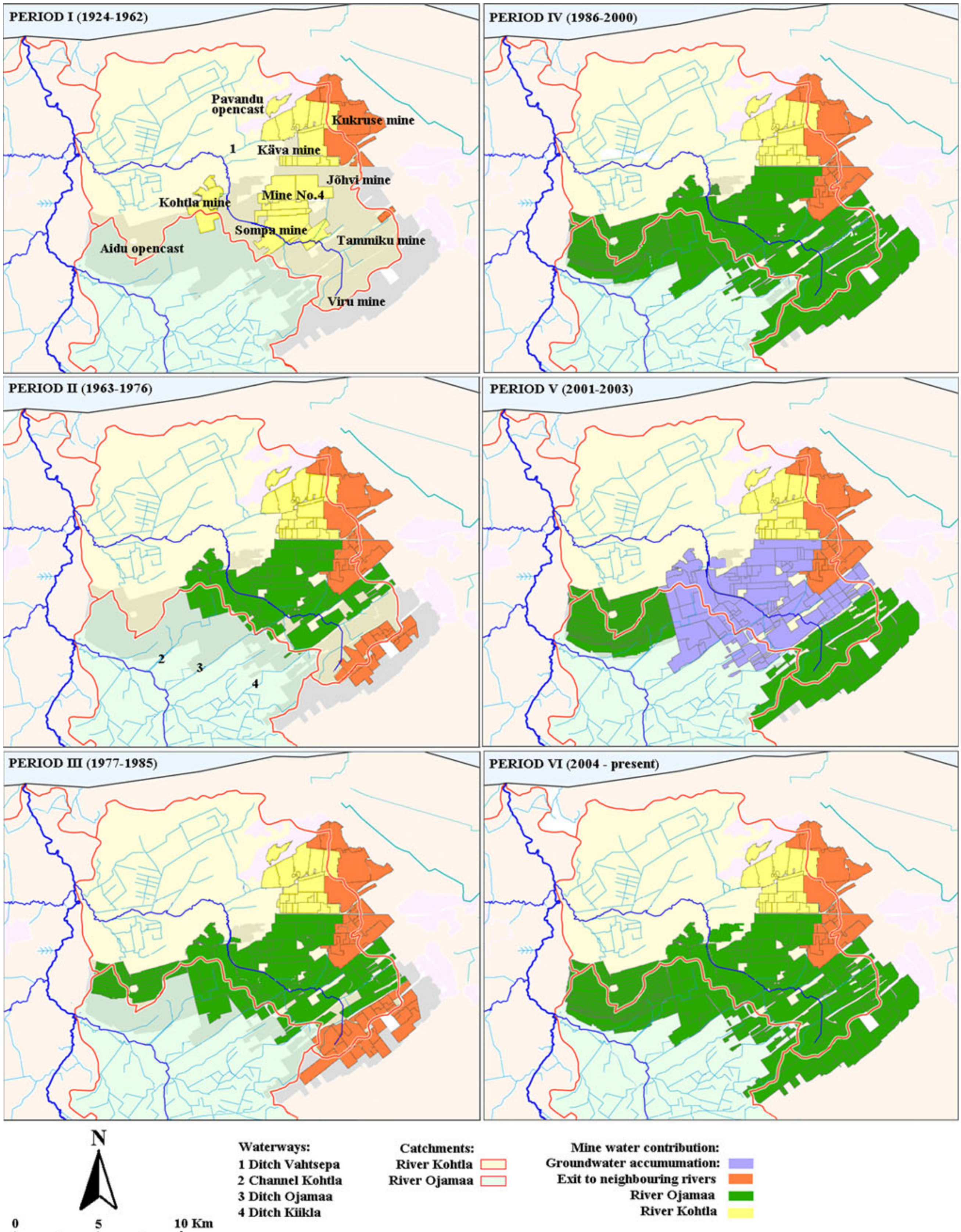


Fig. 4 Evolution of mine water contributions within the River Kohtla and the River Ojamaa discharge areas over time

Table 3 Median and range of flow and rainfall during differing periods of mining activity

Period	River Purtse						River Pühajõgi					
	Non-mining		Mining		Significant?		Non-mining		Mining		Significant?	
	WIN	SUM	WIN	SUM	WIN	SUM	WIN	SUM	WIN	SUM	WIN	SUM
Median flow ($m^3\ s^{-1}$)	2.2	1.3	3.8	2.0	*	*	0.52	0.38	1.0	0.63	*	*
Range	0.31–49.5	0.27–61.9	0.36–84.6	0.29–43.9			0.06–7.2	0.1–7.75	0.08–11.1	0.21–5.2		
Median rainfall (mm)	31.3	74.7	29.9	72.6	#	#	32.3	73.6	33.5	73.1	#	#
Range	10–92	17–205	4–106	4–196			14–75	0–205	4–106	10–166		

WIN winter, *SUM* summer

* Difference significant at $p < 0.001$, # difference not significant at $p > 0.05$

variations in downstream runoff. Mine pumping operations not only have the potential to redirect incident meteoric waters from one catchment to another, but contribute (potentially deep) groundwater to surface runoff that would not have occurred hitherto (Golf 1968; Hester and Harrison 1994). The groundwater content in the mine water depends mainly on the site-specific mined area, operating conditions, and local hydrogeology (Barnes 2000).

Figure 5 show how the aggregate mine water volume discharged (converted to mm/yr over the respective catchment area) from mines in the Purtse and Pühajõgi watersheds have changed relative to stream runoff since 1923. Both catchments show similar patterns in the pre-1945 phase, with discharged mine water accounting for between 10 and 23% of total annual runoff. As oil shale mining expanded post-1945, there was a rise in the volumetric importance of the mine water, which peaked at slightly over 110% of catchment outlet runoff in the River Pühajõgi in 1980 and 86% of catchment outlet runoff in the River Purtse in 1990. The contribution of mine water as a percentage of catchment runoff declined during the 1990s in both catchments towards pre-mining levels in the River Purtse and at levels slightly above 1923 levels in the River Pühajõgi. The overall contribution of mine water discharges to downstream runoff was far greater in the smaller River Pühajõgi catchment (annual mine water discharge was 64% of mean annual runoff from 1923 to 2005) than the River Purtse (where it was 33% of mean annual runoff for the same time period).

The length of the flow records in the catchments provides a rare opportunity to assess the influence of mine water discharge on catchment scale runoff. Figure 5 presents flow duration curves constructed from daily flow data for the Purtse and Pühajõgi rivers during differing periods

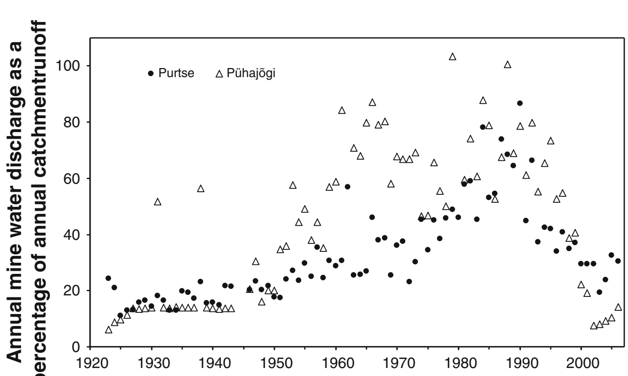


Fig. 5 Proportion of mine water in the River Pühajõgi and River Purtse runoff

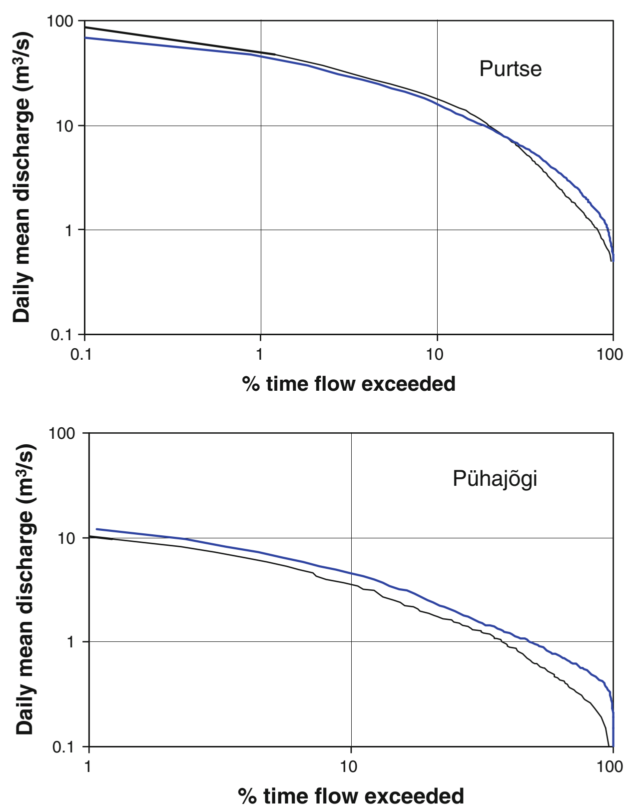


Fig. 6 Flow duration curves of the River Purtse and River Pühajõgi. Intense mining is marked as *blue* and lesser intense mining as *black*

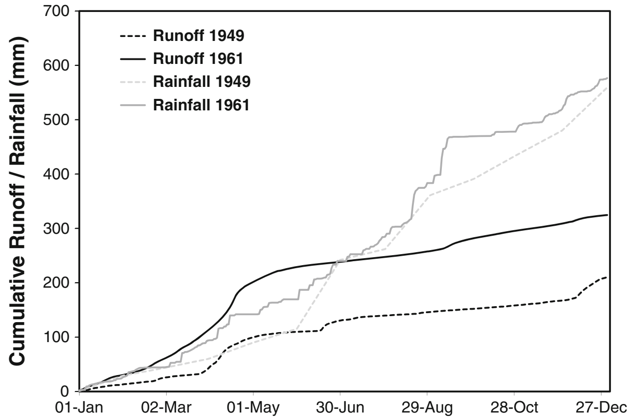


Fig. 7 The cumulative runoff in the River Pühajõgi during 2 years of similar total rainfall

of mining activity. In the River Purtse, the curves are aggregated into two periods: the period of minimal mining activity (as indicated by the reduced significance of mine water discharge to surface flows: Fig. 5) from 1923 to 1952 and 2003 to 2005. The second period of more intensive mining activity covers the intermediate years 1953–2002 (Fig. 5).

Simple linear regressions can be used (1, 2) to explain the relative importance of mine water (M) and natural water (N) in driving the variation in river runoff (Q). Using recorded mine water data, it is important to consider that only 85% of the mine water contributes to river runoff. Using catchment scale hydrological balances, Kattai et al. (2000) demonstrated that typically 15% of pumped mine water re-infiltrates back to the mines through stream leakage. The regression describes period 1923–2008 when the mine water discharge was significantly ($p < 0.05$) correlated with runoff in both the River Purtse and to a slightly greater degree in the smaller River Pühajõgi. For comparison, the river, under natural conditions, would have a r^2 value = 0 and the canal, which contains mainly mine water, would have a r^2 value = 0.99–1.

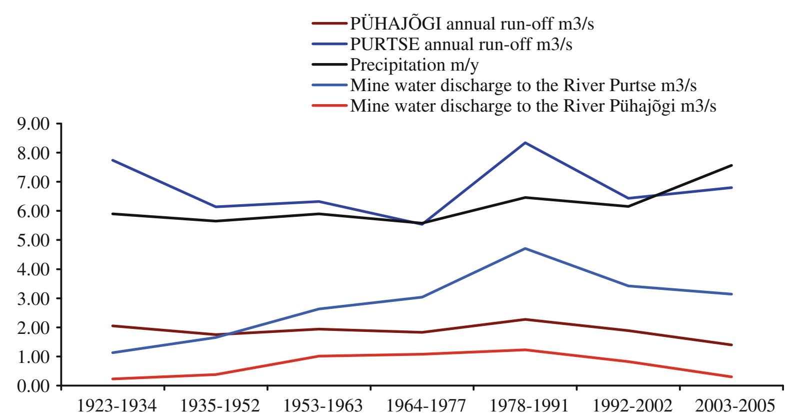
$$Q_{PUR} = N_{PUR} + 0.85M_{PUR} \Rightarrow r^2 = 0.35 \quad (1)$$

$$Q_{PÜH} = N_{PÜH} + 0.85M_{PÜH} \Rightarrow r^2 = 0.42 \quad (2)$$

The comparison of flow duration curves derived from mean daily flows during these time periods shows baseflow (<$Q95$ flows) to be higher during the mining phase than during the non-mining period. Both median summer baseflow (June–August) and winter baseflow (December–February) were significantly higher during mining phases than non-mining phases (Mann–Whitney: summer $W = 7{,}788{,}097, p < 0.001$; winter $W = 9{,}166{,}214$, $p < 0.001$: see Table 3). There were no significant differences in either median winter or summer rainfall during these two contrasting periods of mining intensity (Mann–Whitney: summer $W = 4{,}188$, $p > 0.05$; winter $W = 3{,}661$, $p > 0.05$), suggesting that the hydrological changes are most likely caused by mining activity.

A more pronounced pattern is apparent in the River Pühajõgi, albeit based on a more limited time series (18.3 years). Flow duration curves were constructed from daily mean flows for the periods 1940–1950 (minimal mining phase: Fig. 6) and 1951–1962 (intense mining phase: Fig. 6). The curves show consistently higher flows under all conditions during the mining phase than when mining was less well established. Median winter and summer baseflows were consistently and significantly higher during the 1951–1962 phase (Mann–Whitney: summer $W = 274{,}167$, $p < 0.001$; winter $W = 930{,}181$, $p < 0.001$). At the same time, there was no significant difference in median recorded rainfall between the phases (Mann–Whitney: summer $W = 2{,}165$, $p > 0.05$; winter

Fig. 8 Hydrograph of the River Purtse and River Pühajõgi and the peak over threshold (POT) interval in different periods. $Q_{25\%}$—peaks more than 25% greater than long term average runoff, $Q_{-25\%}$—minima less than 25% lower than average runoff



	1923-1934	1935-1952	1953-1963	1964-1977	1978-1991	1992-2002	2003-2005
RIVER PURTSE							
Return period Q25 %	3	1	2	1	5	2	1
Return period Q-25 %	1	5	5	3	0	3	0
RIVER PÜHAJÕGI							
Return period Q25 %	6	2	3	3	12	4	0
Return period Q-25 %	0	0	1	1	0	1	0

$W = 1{,}625$, $p > 0.05$). One of the main controls on the increased baseflow in the River Pühajõgi catchment is likely the Tammiku mine, which can contribute up to 80% of the flow to the river during low flow periods.

Figure 7 shows the cumulative runoff in the River Pühajõgi during 2 years of similar total rainfall (559 and 577 mm, respectively, in 1949 and 1961). This is useful in highlighting the broadly similar seasonal runoff response—both years display the dominant influence of winter and spring rainfall, but the rise was much more pronounced during intense mining (1969), giving cumulative annual runoff that was 54% greater than in 1949.

Ascribing controls on this increased baseflow in both study catchments appears to relatively straight-forward given:

- the synchronous increase in pumped mine water volumes,
- the fact that there was no significant ($p > 0.05$) difference in annual average or baseflow seasonal average rainfall during the compared time periods, and
- the lack of any other major change in land use or land management beyond mining development (e.g. Fig. 4) that could have driven such changes. According to the Estonian Agricultural Board, the major forest and peatland drainage canals were excavated before the 1940s. Furthermore, the amount of precipitation in Estonia is higher than the evaporation rate (Tamm and Tamm 1997), and groundwater is not used in agriculture. Some of the forested and peat land were converted to agricultural land during the 1940s (Mander 1994) but after that land use has remained relatively constant. Agriculture and farming does impact groundwater quality (e.g. Pärn and Mander 2007; Tamm and Timmusk 1997), but does not disturb the groundwater hydrological regime as much as mining does (Rätsep and Liblik 2004).

Similarly, Gumbel return period calculations for high flow peaks over threshold (POT) and annual minima show that the River Pühajõgi high flow POT (2.12 m^3/s) and low flow minima (1.28 m^3/s) recurrence corresponds with the mine water discharge rather than precipitation (Fig. 8). The recurrence interval for high flow events diminished during the most intense mining phase, which was likely due to the attenuating effect of pumping operations. Previous studies have also suggested that because of the additional mine water inflows to Estonian rivers in oil shale mining districts, catchments have attenuated peaks and peak flows usually occur later than in natural conditions (Rätsep and Liblik 2001). Baseflow minima show no clear trend, with all phases recurring annually or sub-annually in the River Pühajõgi, although falling baseflow in recent decades would appear to be related to mining, given the concurrent increase in precipitation (Figs. 5, 8). Because of mine water discharge to the catchment area, water flow continues through the year in the River Pühajõgi riverbed even in drought years when most small Estonian rivers dry out (Järvekülg 2001). Such changes may even provide positive effects on instream biota through sustenance of summer flows.

There River Purtse similarly had a 25% increase in POT (8.50 m^3/s) in average runoff (Fig. 8), although the recurrence interval again lengthened during the period of greater average runoff and mining influence. This again would be expected, given the attenuating effects of large mine water contributions to runoff. A similar pattern to the River Pühajõgi in low flow occurrence is seen in the River Purtse. Mine water discharge increased runoff in the dry seasons, especially from the 1970s to the present. The average groundwater discharge to the mines is approximately 30% (Kattai et al. 2000; Reinsalu et al. 2006). The amount of groundwater contributed to the River Purtse is estimated to be increased by up to 5%, based on a water balance analysis (Vaht 2009). These observed increases in baseflow are in contrast to the patterns of spring flow derogation often cited with shallower mineral workings (e.g. Finlinson and Groves 1994).

Conclusions

Mine drainage operations have clearly had a strong influence on flow regime characteristics in the small and medium sized Estonian catchments studied here. The most pronounced effects are related to flow augmentation, which are most visible in the smaller River Pühajõgi catchment and during baseflow conditions. The additional groundwater discharged to surface waters by mine pumping operations is likely the key control on this augmentation. The amount of extra groundwater in the mine water depends mainly on the site-specific mine area and drainage changes. In accordance with the engineered discharge of pumped mine water, as well as the more stochastic position of gravity-driven free flow after pumping has ceased. These influences are visible in the hydrographs of the study catchments during different phases of mine development, which were mapped based on mining company records and topographic datasets.

The annual mine water discharged to the River Purtse catchment area does not affect its annual runoff due to the low percentage of extra groundwater in the mine water. Long-term variability in runoff appears to be driven primarily by precipitation. However, mine water discharge has influenced the high and low flow periods. For example, in the River Purtse, winter and summer baseflow was 53–72% higher than long term average baseflow when mining was intense. It was much higher in the smaller River Pühajõgi (66–92%) because the volumetric significance of mine discharges was greater. Furthermore, during the same period of intense mining, high flow POT occurs more often and low flow minima less in the River Pühajõgi, which also indicates changes to the hydrologic regime.

Baseline studies of flow regime and associated modeling studies are thus essential prior to mine dewatering operations to determine locations in the catchment where impacts of dehydration or flow augmentation are likely to be minimized. The strategic placement of mine water discharge points in positions that minimize flow path changes and minimize the volumetric significance of change in flow in receiving water courses would limit the extent of any impacts. Therefore, from a water management point of view, baseline hydrogeological studies that take into account connection of subsurface and surface systems are essential before the development of deep mine pumping operations and associated mine water drainage canals. Directing water out of the catchment area can have a major effect on river runoff, as seen in the River Kohtla case. Future studies on the effects of such regime changes on instream ecology would be informative for broader assessment of the influence of deep mining on instream ecology.

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