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RIINA VAHT

The impact of oil shale mine water on hydrological pathways and regime in northeast Estonia

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UNIVERSITY OF TARTU
PRESS

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This dissertation was accepted for the commencement of the degree of *Doctor philosophiae* in geography at the University of Tartu on October 20, 2014 by the Scientific Council of the Institute of Ecology and Earth Sciences of the University of Tartu.

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Commencement: Scientific Council Room in the University Main Building, Ülikooli 18, Tartu, on 5 December 2014 at 10.15.

Publication of this thesis is supported by the Institute of Ecology and Earth Sciences of the University of Tartu and by the Doctoral School of Earth Sciences and Ecology created under the auspices of the European Social Fund.

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ISSN 1406–1295
ISBN 978-9949-32-712-6 (print)
ISBN 978-9949-32-713-3 (pdf)

University of Tartu Press
www.tyk.ee

CONTENTS

ORIGINAL PUBLICATIONS

This dissertation is based on following publications I – IV:

I. **Vaht, R**. and Rätsep, A. (2009). Impact of oil shale mine water on hydrology and runoff of a small river. The Pühajõgi river case study. Oil Shale, 26 (1), 84–93.

II. **Vaht, R**., Mayes, W. M., Sepp, M., Järvet, A. and Mander, Ü. (2011a). Analysis of long term hydrological records to assess changing regime and pathways in oil shale mining districts of North East Estonia. In: Brebbia, C.A. (Ed) River Basin Management VI, WIT Press, Southampton, pp. 25–36.

III. **Vaht, R**., Mayes, W. M. and Luud, A. (2011b). Impact of oil shale mining activity on flow regimes in Northeast Estonia. Mine Water and the Environment 30 (4), 284–295.

IV. **Vaht, R**., Sepp, M. and Luud, A. (2012). Impact of the shale mine on the River Purtse hydrological regime in north-east Estonia. Hydrology Research. 43 (4), 422–429.

The contribution of the author in the listed publications is as follows:

Publication I:	The author is fully responsible for fieldwork, data collection, analyses and writing.
Publication II:	The author is fully responsible for fieldwork, data collection, analyses and mostly for analyses and writing.
Publication III:	The author participated in the writing and data analysis but is fully responsible for fieldwork and data collection.
Publication IV:	The author is fully responsible for fieldwork, data collection, writing, and mostly for analyses.

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 thesis documents long term (1923–2008) changes in surface drainage areas and run-off characteristics in two small (River Pühajõgi) to medium (River Purtse) sized (up to 1000 km^2) rivers draining part of the Ordovician oil shale field of northeast Estonia. The changing regime in the heavily mined catchments (run-off discharge area) is contrasted with a morphologically similar reference catchment (River Keila) where there has been no mining activity.

Mining activity can change both the runoff regimes and drainage areas of river systems when new mines are opened or closed. Flow increases can occur due to extensive pumping operations, which augment surface flows, while flow decreases may be apparent where groundwater is pumped from across multiple surface catchments and discharged in only one river. Morphological changes to catchment boundaries (watersheds) may also occur due to mine voids themselves. Such changes can be particularly important in low gradient coastal areas such as NE Estonia.

The coupling of flow regime with mining records (discharge rates and workings locations) is undertaken to assess the impact of the expansion in oil shale mining from the mid to late 20th century on downstream flow regime and pathways. The Gumbel Method and Rodionov Regime Shifts Algorithm (STARS) were used to study annual, high and low water changes in the mining area. Well-known run-off models are not used in this research due to the uncertainty of the sizes of the discharge area of the researched rivers in different periods of mining activity. Unfortunately, no solid data have been recorded about the precise size of the researched rivers' (the River Purtse and River Pühajõgi their tributaries) discharge area during the intense mining period. Instead, river run-off has been analysed and compared with well-documented long term precipitation data.

The study shows that during phases of intense mining, summer baseflow is between 53–72% higher than long-term average baseflow in the Purtse catchment, and between 66–92% higher in the smaller Pühajõgi catchment, where the volumetric significance of mine discharges is greater. The reference catchment of the River Keila does not show any significant change in summer baseflow during the study period, suggesting that the changes in the Pühajõgi and Purtse are not controlled by climatic drivers. The assessment of mine flow records highlights the significant augmentation of baseflow in the mined catchments due to pumped groundwaters.

During the low water period, mine water has no significant impact on the runoff from the River Purtse. However, it does influence high water period behaviour, where the average before-peak period is four days shorter, with a

smaller run-off rate, but is usually longer with much higher run-off after the peak period.

The contribution of pumped deeper groundwater to surface run-off is shown to control the largest increases in the mean annual run-off from the River Pühajõgi. Human impact has considerably changed the average run-off from the River Pühajõgi after the 1960s, and the flow augmentation is the most common hydrological impact of mining operations. Phases of dehydration are also recognized in streams where cross-watershed transfers reduce the effective catchment area. One implication of the changed flow regime on a river is a more than 20% increase in run-off.

A secondary impact of the mine water is the influence on stream thermal regime with a constant low (4–6 ^{o}C) temperature apparent in systems subject to groundwater discharge. The river run-off temperature changes may not provide positive effects on instream biota through the sustenance of summer flows. In the case of the River Purtse we can observe changes in the aquatic vegetation period which is about 30 days shorter than in the semi-natural River Keila River. The constant temperature of mine water is also one of the main indicators to ice cover formation in winter, where mine water discharge to the river is intensive after the autumn rainy period throughout the winter. The River Purtse ice cover is fragmentary and mostly shore ice instead of an ice bridge (the most common ice cover on the River Keila) can be observed throughout the winter.

1. INTRODUCTION

1.1. Impact of mining on water regime and quality

Mining pollution has been found to be a major factor controlling the dispersal of contaminant metals and metalloids at local, regional (Cravotta III 2008; Mayes et al. 2010) and global scales (e.g. Nriagu and Pacyna 1988). Management options for minimizing such contaminant releases, particularly to the aquatic environment, have advanced greatly over the last 20 years (e.g. Younger *et al.* 2002; PIRAMID Consortium 2003). There is no doubt that due to anthropogenic activity, there can be significant impacts on catchment morphology, hydrological regime and river ecology (Younger et al. 2004a). However, these are often difficult to identify given the lack of long-term hydrological datasets to assess the significance of any mining-related changes (i.e. datasets describing pre- and post-mining conditions). Given the operational life of most mines is in the order of decades, it is not surprising that such long-term data records and studies are not commonplace.

In Ida-Viru County in North-East Estonia, where the most important industry is oil shale mining and processing, rivers have been modified by humans for almost a century (Kattai et al. 2000). Since the 1920s, the mining area of rivers and tributaries have been under serious human impact, mainly due to mine water from oil shale mines. Some disturbance in run-off may also be caused by the municipal wastewater from the biological treatment plant.

One of the most serious problems identified is the constant change in the groundwater regime. There is extensive evidence that oil shale mining activities in Estonia not only seriously influence the groundwater infiltration in both horizontal and vertical directions (e.g. Shiklomanov 1989; Vallner 2003; Perens et al. 2006), but also river run-off and flow feed (Rätsep and Liblik 2001). Usually the influence of mining activity is much longer than two or three decades. Once the catchment area water circulation has been changed by mine water discharge into the river, the result is a change in river hydrological regime and run-off. These changes are often permanent (Rätsep and Liblik 2004).

The EC Framework 5 project (EVK1-CT-2000-00078) “Environmental Regulation of Mine Waters in the European Union” (ERMITE 2004), has produced a thorough evaluation of European legislation for mine water management from an ecological point of view. Together 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 water. As such, understanding of the nature and significance of any hydromorphic changes induced by mining activity 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). Therefore, it is important to investigate the impacts of mining of flow networks, stream geomorphology and changes in run-off.

The present study is inspired by Aavo Rätsep, who started his research in this area already more than 30 years ago. Running our joint research about mine water impact to the river hydrological regime we soon realised that the physical effects of changing flow paths and regime in mining area are less studied (see Chapter 1.4), although they are as important as water quality. The mining area hydrology is crucial to study for e.g. local water circulation, agricultural interests, and to protect biological diversity (Šípek et al. 2009). Furthermore, the rivers in North Estonia have been known as significant salmon rivers in the past, but the impact of the oil shale industry over the last 90 years has dramatically altered the balance of the ecosystem. Due to its poor ecological state, water quality in some of the oil shale mining area rivers has been previously studied by Truu et al. (1997) and Rätsep et al. (2002).

The multiple effects of water discharges from abandoned mines have been widely documented in pollution, toxicological and epidemiological studies in recent decades all over the world, including in Estonia (e.g. Castilla and Nealler 1978; Parakhonski 1983; Truu et al. 1997; Barnes 2000; Tiwary 2001; Worall and Burt 2004; Selberg et al. 2009). Each study indicates a place-specific case where the size of pollution depends on geological conditions. For example, the sulphate consideration and high pH is a major problem where the aquifer units are composed of limestone materials (Reinsalu et al. 2006; Robles-Arenas and Candela 2010). The mine water from coal mines discharged from underground and open cast mines generally contains a high level of total suspended solids (TSS), total dissolved solids (TDS), heavy metals, and have low pH (Mayes et al. 2005; Šípek et al. 2009). Copper and gold mine water has a heavy impact due to its low pH (Taylor et al. 2002) and the occasional enrichment of cyanide where heap-leaching methods are used.

However, in the present study, the focus of the research is solely on hydrological changes and some secondary aspects of the stream environment such as water temperature and ice conditions.

1.2. Hydrogeological and mine water temperature studies

Due to the opening of new mines and the closing of old mines and of mine water pumping, more models of larger dimensions and of higher precision have been created all over the world for the long-term prognosis of regional groundwater dynamics and more detailed groundwater studies (e.g. Gutt et al. 1990; Sikdar et al. 2004; Vallner 2003; Lind et al. 2008). The hydrogeological regime and water chemistry in the Ordovician oil shale mining area of Northeast Estonia has been studied over the last 30 years (Parakhonski 1983; Norvatov 1988; Erg and Pastarus 2008). During this period many hydrogeological models have been designed and implemented (Vallner 2003; Reinsalu et al. 2006; Lind 2010).

Mining activity and pumping operations in Northeast Estonia have totally drained aquifer complexes, especially those underlying the Ordovician limestone deposit. As a result, an extensive cone of depression stretching up to 35 m in depth and 2.5 km outside of the mining area (Kattai et al. 2000) creates groundwater flow gradients towards the mines (Erg and Pastarus 2008), which can have a devastating impact on local farm wells.

In analogous settings, the effects of groundwater pumping operations at limestone extraction sites have been shown to lead to changes in downstream hydrology through winter flow augmentation (due to increased void de-watering efforts) and diminished summer flows due to the effects of cone of depression development reducing spring flows (e.g. Finlinson and Groves 1994; Erg 2003; 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 become an increasingly important concern ahead of water quality issues (e.g. Croton and Reed 2007).

The impacts of mining activities on wetlands and bogs have been well documented (e.g. Darnell 1976; Cardamone et al. 1984, Linder et al. 1991; Trites and Bayley 2009). In northeast Estonia, where oil shale mining is spreading to the protected peatland area, many studies have also been conducted (e.g. Adamson, 2003; Drenkan, 2003; Valgma et al. 2007; Kalm and Kohv 2009; Savitski and Savva, 2009). These researches differ depending on the material extracted, the methods used and regional differences in topography, geology, soils and climate. Nevertheless, all reports reach the same conclusion: even if mining activity is preformed according to current regulations, mining will have a significant effect upon the hydrological regime and other environmental conditions of the area.

Interestingly, a comparison of previous studies by White and Schmidt (1966), Gams et al. (1993), Dufresne and Drake (1999) and Reinsalu et al. (2006) shows that underground mining areas and karst areas often have similar hydrogeological conditions. In classical karstic regions the effect of cones of depression can be seen, but to a much smaller extent. Both the karst aquifer and underground mining area contain a water component that appears to be impacted by anthropogenic activities (Harvey and Skelton (1968), Doctor 2008; Erg and Pastarus 2008; Sokman et al. 2008). Although geological conditions are open to pollution (Reinsalu et al. 2006), the water can still be neutralised during percolation through the overlying bedrock (Harvey and Skelton (1968), in most cases during transit through limestone bedrock (Gams et al. 1993).

The secondary issues associated with changes in water temperature in receiving streams are often overlooked in such studies concerning major pumping operations. Given the near-constant thermal regime of deep groundwaters, extensive pumping operations can have obvious knock-on effects on stream surface temperatures, which could in turn influence biota and many chemical processes. Theurer et al. (1985) concludes in his paper: like water pollution, changes in water temperature have equal potential to affect water vegetation period. Rutherford et al. (1997) found that moderate shade levels (ca 70%) may be sufficient in temperate climates to restore headwater pasture stream temperatures to 20°C, an estimate of the thermal tolerance for sensitive invertebrates. Roth et al. (2010) point out that instream temperature elevation is associated with parasitic intrusion proliferative kidney disease in the fish population in Swiss waterways. Research by Akratosa and Tsihrintzis (2006) on changes in temperature and vegetation in a horizontal subsurface flow constructed wetland, as well as research by Stevenson (1983) on microhabitats, argue the importance of water temperature as a factor determining the optimal size of various aquatic systems for water treatment and aquaculture.

1.3. Mining area hydrology studies elsewhere in the world

As Wolkersdorfer and Bowell (2005) point out, far fewer studies have assessed the role mining activity can have in disrupting pre-existing hydrological pathways and the resultant physical and ecological effects of such hydrological changes on receiving watercourses. Perhaps the very first paper indicating mining activity to river run-off is presented by Golf (1968). According to this analysis, two different scenarios on mine water impact on river discharge can be distinguished: 1) an absolute increase in the natural run-off due to mine water, and 2) raised low water levels and lowered flood water levels.

In upland settings, the construction of major drainage levels to underdrain workable ore deposits has long been practiced and can lead to effects of spring dehydration in under-drained areas and flow augmentation where drainage levels cross watersheds and discharge (e.g. Younger et al. 2002; Mayes et al. 2010). Younger et al. (2004b) highlights the hydrological effects of one of the largest drainage levels in Europe, the Milwr Tunnel in northern Wales (mean flow rate of 1.270m^3/s). This major level, which was commenced in 1897, led to the instantaneous dehydration of karst resurgences in the overlying aquifer which contributed to diminution of stream baseflow (e.g. the River Alyn) and the dehydration of springs of regionally important cultural value.

Another interesting piece of research in Europe can be found by Czaja (2005), where the influence of sewage effluent and mine water on the structure of river run-off have been studied. Detailed investigations of the range and directions of changes in river structure and regime were carried out for the area of the Upper Silesian Industrial Region (USIR) of Poland. The results were compared with the results of investigations carried out in the Ruhr Basin of Germany and the Donetsk Basin of the Ukraine and Russia. Result shows changes in the river run-off structure because the wastewater contribution to run-off sometimes exceeds 90% of its volume.

There is some evidence of changing catchment hydrology in restored coal mining districts in Appalachia (USA). In Negley and Eshelman (2006), a paired catchment study of water balances is employed to show changes in the hydrological behavior of a surface mined (and subsequently reclaimed) catchment relative to an adjacent reference catchment. Higher storm run-off coefficients, increased total storm run-off and increased short-term peak run-off rates were attributed to the reduced infiltration capacity of the land due to soil compaction in land restoration efforts (Negley and Eshelman, 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 Australia, two Queensland mine sites were selected by Cote and Moran (2008) for mine water and mining operations, resulting in the capacity to understand the implications of wide spread implementation of leading practice water use and loss rates. Traditionally, mine sites comply with discharge restrictions by undertaking detailed hydrological analyses of relevant catchments. Barrett et al. (2010) found out that such studies can predict which rainfall event may lead to non-compliance.

1.4. Mining area hydrology studies in Estonia

Although mining area hydrology in Estonia has been considered in several previous studies, there are still significant gaps in understanding the impact of mining activities on the rivers in the Northeast Estonian oil shale mining area. Earlier research from Protaseva and Eipre (1992) has established the extreme value analysis of the small oil shale mining area river hydrologic data including highest and lowest period run-off (using Gumbel's probability distribution), return period, the potential frequency of the rivers yearly and the average run-off during the period 1945–1963.

Probably Aavo Rätsep has been the most productive scientist in Estonia to research mining area hydrology. He has briefly demonstrated the impact of mining on hydrological regime and run-off in small to medium Estonian river systems (taken here to be a size range of 100–1000 km^2) and smaller (sub 100 km^2) systems (Rätsep and Liblik 2000, 2001, 2004; Vaht and Rätsep 2009 as Publication I). It is within the smaller catchments that any abrupt changes in flow regime would be anticipated having greater impact on instream ecology as they would be volumetrically more significant.

1.5. Hypotheses

As Golf (1968) stated in his study, different scenarios on mining area hydrological regime and run-off can occur. Therefore this study suggests the following hypotheses.

1) Mining activity changes river discharge area.
2) Mine water discharge affects river run-off seasonally.
3) Mine water discharge influences the physical properties of river water.

1.6. Objectives

Throughout this thesis, the suggested hypotheses will be tested by researching the impact of changes in run-off drainage associated with mining. The catchments of the small River Pühajõgi and the medium River Purtse were chosen as study areas. Non-mining catchment (River Keila) data are used for comparison.

The specific objectives of present study were as follows:

1) To analyse the vulnerability of the different size catchment area and run-off characteristics over time in the Estonian oil shale mining area.
2) To assess the modes and extent of change in contributing discharge areas as a result of mining operation within different sub-catchments of the River Purtse;
3) To compare the long-term regime in the River Purtse mine-impacted riverine system with the morphologically similar semi-natural medium River Keila catchment, which offers a useful reference catchment where no mining development has taken place. A particular focus on baseflow changes is provided. Through the combined assessment of long-term hydrological and mining records (since 1923), the impact of various phases of oil shale mining operations can be assessed in multi-scale catchments and;
4) To analyse the seasonal dynamics of physical properties of water like water temperature, in particular the changes in ice coverage in winter will be considered.

2. DATA AND METHODS

During the study, different models (e.g. POSSUM, STELLA for Environmental Sciences) were used to analyse changes in the River Purtse and River Pühajõgi run-off and circulation scheme. Although the chosen models are designed specifically for mining applications or severely modified catchments (Kruse et al. 2006, ISEE SYSTEMS 2011), the models were still abandoned hence high standard error ($p > 0.6$). Previous researches by Järvekülg (2001) and Pärn and Mander (2011) have pointed out the complex hydrological system of River Purtse, therefore it has been not considered in their hydrological research papers. At the same time Seibert et al (2009) recommends to keep complex systems analysis simple, especially in riparian zone hydrological models.

Alternatively, in present research, the basic circulation balance scheme of the mining area rivers (Fig. 1) such as River Pühajõgi and tributaries of River Purtse were worked out (Vaht and Rätsep 2009; Vaht et al. 2011a as Publication III) using the Hewlett Runoff Model (Burnett et al. 1995). As Post and Jakeman (1996) and Reungoat and Sloan (2002) have pointed out, for the accuracy of the hydrological models, it is important to classify the river considering all the parameters what influences the run-off. Therefore, presented balance scheme has been modified to their hydrological regime where the most influential component like mining activity was considered. The balance scheme has been used to model missing run-off data of the River Pühajõgi. This particular data have been used analysing changes in run-off (Chapter 3.2, 3.3).

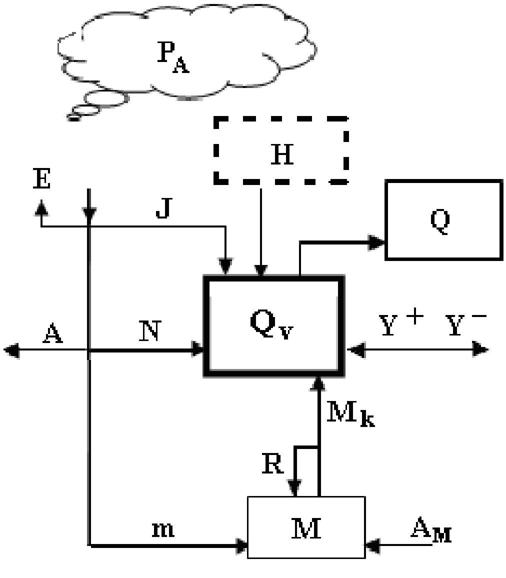


Figure 1. A conceptual water circulation balance scheme of the mining area rivers. Marking the water flows: P_A – precipitation to catchment; E – evaporation and transpiration; J – surface water; N – precipitation water infiltration to non-mined territory; m – precipitation water infiltration to mined territory; M – full amount of mine water; M_K –mine water outflow to catchment area; R – re-infiltration of mine water from canals back to the mine; A – groundwater flow; A_M – horizontal groundwater flow from related fields to mine; H – inflow of wastewater from treatment plants (if there is inflow); Q_V – water reserve of the catchment area; Q – run-off of the river; Y – water flow inwards to (+) or outwards from (¯) the catchment area.

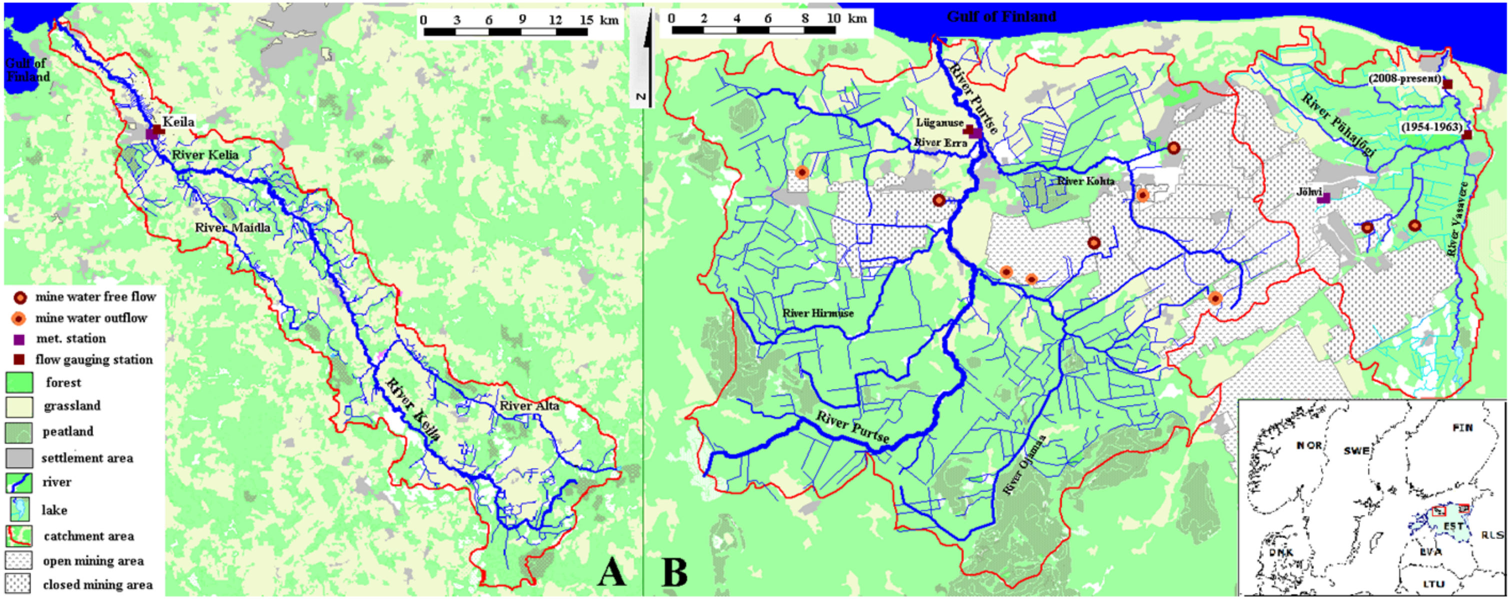


Figure 2. Location, land cover and mining area of the River Keila (A), River Purtse and River Pühajõgi (B) catchments at 2010.

2.1. Study area

2.1.1. Mining area

The Estonian oil shale deposit is located in the Northeast Estonia region (partly seen on Fig. 2B). The River Purtse and River Pühajõgi are located in western part of the oil shale deposit area in Northeast Estonia (Fig. 3). The first oil shale opencast mine was opened in 1916. The most intensive mining period started on 1960s till 1990s. Subsequent rapid development of the oil shale deposits of approximately 430 km^2 totalled altogether in 24 deep mines and opencasts operating in this area (Rätsep and Liblik 2004). During the 1920s, 1940s and 1970s more mining areas were open but in the same time 1940s, 1970s and end of the 1990s depleted mines were closed. Currently only two mines and two opencasts are operating in the whole mining area (Reinsalu 2008). According to Eesti Energia Kaevandused Ltd a new mine is prepared at present.

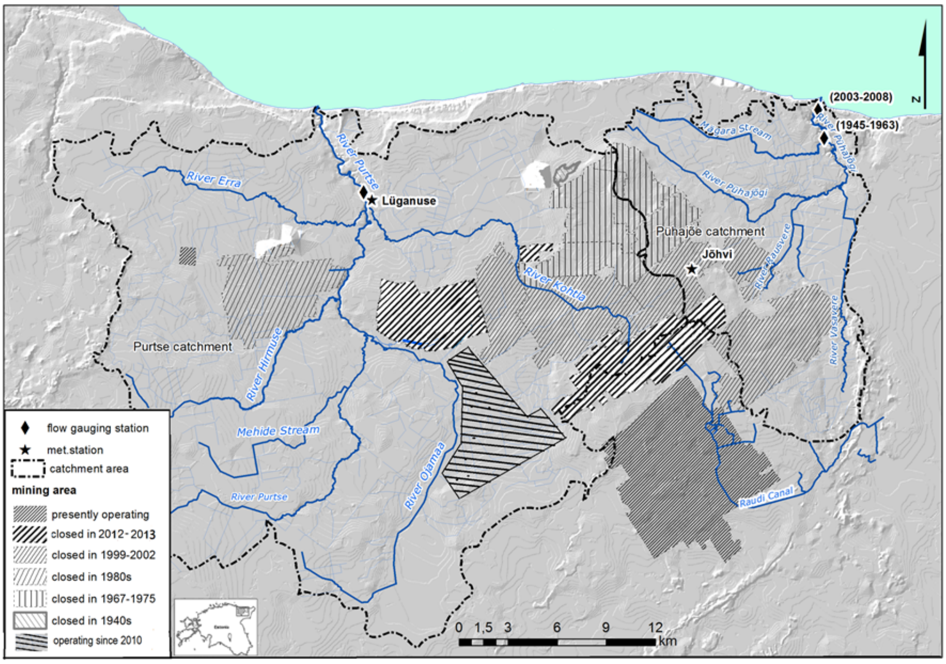


Figure 3. Mining development in the River Purtse and River Pühajõgi catchment area.

In Estonian oil shale deposits tectonic dislocations and especially karst zones in bedrock represent the main problems for mining (Sokman et al. 2008). Karst zones, which dominate in northern area of oil shale deposit, are water-rich (Reinsalu et al.2006). Therefore, various mines have different groundwater infiltration rate (Kattai et al. 2001). Furthermore, there is an effect called re-infiltration which describes a portion of mine water pumped out but infiltrating back to the mines through stream leakage. Re-infiltration rate in different mines varies, however it does not exceed 25% of the mine water discharge (Reinsalu 2005; Kattai et al. 2001).

In Vaht and Rätsep (2009) (Publication I) and Vaht et al. (2011b) (Publication III) a simple linear formula (1) has been worked out to explain the relative importance of mine water (M) and natural water (N) in the catchment ($_{\mathrm{CATCH}}$) driving variations in river run-off (Q_{RIV}). For water balance of the River Pühajõgi and River Purtse tributaries, the mine water re-infiltration (from canals) coefficient is taken 15% (R in Fig. 1). Therefore, only 85% of mine water is takes part of river run-off. The regression describes period 1923–2008 when the mine water discharge is significantly ($p < 0.05$) correlated with run-off in both the River Purtse and River Pühajõgi.

$$Q_{\mathrm{RIV}} = N_{\mathrm{CATCH}} + 0.85M_{\mathrm{CATCH}} \tag{1}$$

2.1.2. Rivers and catchment characteristics

All three rivers: The River Purtse, River Pühajõgi and River Keila are located in northern part of Estonia (Fig. 2). The former two rivers represent typical mine-impacted systems in the oil shale area of Northeast Estonia and have long term hydrological and mining records available (dating back to 1923). The River Purtse and River Pühajõgi have been subjected to intense human impact, mainly due to mining operations since the beginning of 20th century (Vaht and Rätsep 2009 as Publication I; Rätsep and Liblik 2001). In comparison, the River Keila is located approximately 150 km west of the oil shale mining area (Fig. 2A) and also classified by Järvekülg (2001) as medium size rivers in Estonia (Table 1).

The River Purtse is medium size river by Estonian standards (surface catchment area: 809 km^2) but has similar hydrogeological conditions to the smaller River Pühajõgi (196 km^2). The mining activity in the River Purtse started with first ever mine was opened in oil shale deposit. First mining area in the River Pühajõgi was opened in 1918 (Reinsalu 2008). At the moment, there is some residual restoration activity in the Purtse catchment but no present mining activity is going on in the River Pühajõgi catchment area (Table 1): all four mines previously operating are now closed.

The River Purtse run-off natural feed is mostly formed by water from wetlands (Table 1, Fig. 2B). However, one-fifth of the River Purtse catchment is affected by the mining area; therefore, run-off contains mine water. Previous research by Rätsep and Liblik (2000) estimates that the average water formed in mining area which is directed to the River Purtse is approximately 30% of its run-off. There have been 14 underground and opencast mines, and presently there are only 4 in operation. Still, there are five mine water outflows from operating mines and three free flows from closed mines which are directed to the River Purtse catchment (Fig. 2B).

The River Pühajõgi starts at the little village located 12 km northwest from the town of Jõhvi (Fig. 2B) but its upper course is receiving water from wetlands mostly nearby (Järvekülg 2001). 47% of its catchment area is under primary impact of closed mines which are filled with groundwater. The influence of mine water from these mines is insignificant (about 50% of run-off is formed in mining area) and directed to the main river by its biggest tributaries (see Fig. 2B and detailed description in Vaht and Rätsep 2009 as Publication I).

Table 1. Physical characteristics of rivers Purtse, Pühajõgi and Keila (Arukaevu 1986; Järvekülg 2001).

	River Purtse	**River Pühajõgi**	**River Keila**
Catchment area, km^2	809	196	682
Head of the river	peatland, NE Estonia	field canal, NE Estonia	peatland, NW Estonia
The official mean annual Run-off, m3/s	6.82	1.70 (2.1)*	6.2
Length of the main river, km	50	28	116
Tributaries over 10 km length	5	3	2
Catchment morphology	fan-shape	triangular shape	elongated shape
Land usage	peatland 15% forest 35% agricultural 30% oil shale mining area approx 20%**	peatland 5% forest 35% agricultural 10% oil shale mining area approx 50%**	peatland 5% forest 40% agricultural 55%
Operating (closed) oil shale mines in the catchment area	3 (6)	(1)	0
sharing:	(3)		0

* 1.7 is measured in period 1945–1962, 2.1 in period 1978–2010

** Mostly covered by forest

All studied rivers have similar hydrological (see detailed description in Chapter 2.1.3) and landscape conditions. These are typical North Estonian lowland rivers draining to the Baltic Sea on the Estonian Coastal Plain. The catchments are characterised by low gradient terrain, with peak catchment elevation ranging from 52m (Pühajõgi), 70m and 71m (Purtse and Keila respectively). The average slope of the all studied riverbeds is about 1.80 m/km. The greatest slope (up to 5 m/km) occurs in the lower reaches of all streams prior discharge into the Gulf Finland, where the rivers cross the limestone escarpment of the high Baltic Klint. Therefore, in the River Purtse and River Pühajõgi rapids have been formed, and the River Keila has a 7m high waterfall, both with narrow deep valleys (Järvekülg 2001). All catchments are characterised with extensive peatland deposits, agricultural land and coniferous forests (Fig. 2A, B and Table 1). The catchments hydrology is also influenced by land drainage associated with predominantly arable agriculture and karstic features associated with the underlying Ordovician limestone deposits and aquifer complex.

2.1.3. Long term flow regime in observed rivers

According to EMHI, only about half of the precipitation is evaporating in North Estonia. Therefore, the long term regime of the rivers follows a typical temperature-controlled northern temperate zone lowland regime (Shaw et al. 2010). Catchments over 600 km^2 have average run-off over 7m^3/s on that area (Järvekülg 2001). Furthermore, simple comparison between run-off data and precipitation in Fig. 4 shows annual high and low water in studied rivers. The baseflow is sustained predominantly by drainage from extensive peatland and forest-covered peat deposits in headwater areas of the researched rivers under natural flow conditions (Fig. 2, Table 1).

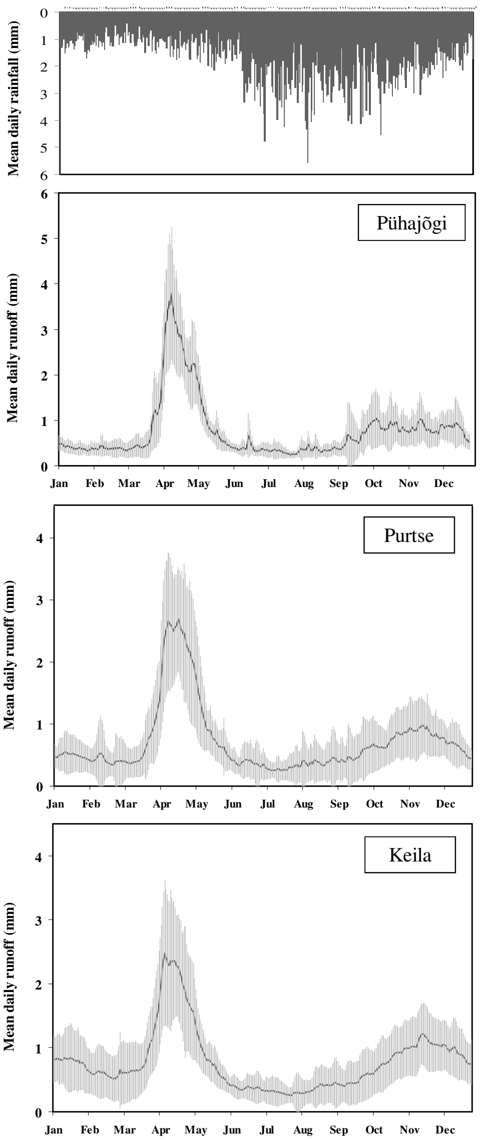


Figure 4. The mean annual run-off of River Pühajõgi, Purtse and Keila respond to precipitation. Grey bars show standard deviation values by Estonian Weather Service (EMHI).

Run-off maxima occur between March and May with snowmelt following spring temperature rises. Flow minima in all catchments occur during both summer (June-August) and winter (December-February) baseflow periods. Because of clear seasonal variation in climate in this region the difference between maximum and minimum run-off can be up to five orders of magnitude on an average annual basis.

2.2. Climate characteristics

From the climatological point of view, the rivers belong to different precipitation sub-regions of Estonia. While the River Keila is situating in the North-Western district of precipitation (characterised by Keila meteorological station), the River Purtse and Pühajõgi River are situated on the North-Eastern district (Jõhvi/Lüganuse meteorological stations). However, strong correlation in seasonal rainfall is apparent between the two areas. In February $r = 0.82$ ($p<0.05$). The weakest, but statistically still significant correlation $r = 0.30$ ($p<0.05$) occurs in July when the precipitation series are affected by heavy showers that are unevenly distributed in time and space. Mean precipitation in North Estonia is between 640–690 mm/yr. Total rainfall in the areas differs by 50 mm in the long term average, with higher average annual rainfall reported at the Keila meteorological station (Jaagus 1992).

The evaporation is one of the most important components in the water balance equation (Burnett et al. 1995). The rate of evaporation depends on the availability of energy and water and a number of other physical and micrometeorological factors. By Estonian Weather Service (EMHI), the average evapotranspiration rate in Estonian rivers is 50–90% of precipitation. Previous researchers (Rätsep and Liblik 2000; Järvekülg 2001; Jaagus 1987; Soovik 2001) have been using various annual evaporation and transpiration data between 275–500 mm which illustrates EMHI evaporation rate to find the catchment area water reserve. The estimated annual evaporation and transpiration (E = 52%) is fixed in our model and illustrates Northeast evaporation rate.

The long-term flow regime of rivers follows a typical temperature-controlled northern temperate zone lowland regime (Jaagus 1992) where seasonal flooding starts with snow melting and the arrival of spring precipitation in March to May. Catchments over 600 km^2 in area typically have average flow rates over $7 m^3/s$ (Järvekülg 2001). Run-off maxima occur between March and May with snowmelt following spring temperature rises. Flow minima in all catchments occur during both summer (June-August) and winter (December-February) baseflow periods.

2.3. Data collection

The main focus is on the River Purtse catchment because of the River Pühajõgi fragmental run-off data availability from past (missing data between 1964–1977 and 1991–2003). Therefore analysis of run-off minima and maxima do not contain data of the River Pühajõgi.

The present study run-off analysis is based on run-off (m^3/s), precipitation (mm), ice cover, (1946–2010) and water temperature (°C) data collected by the EMHI, measured during the period 1923–2008 in the catchments. Mean oil shale mine water discharge rates (m^3/s) and mining area (km^2) data have also been collated from digital and hard copy records kept by the Eesti Energia Kaevandused Ltd. During the periods 1978–1990 and 2000–2008 the annual amount of municipal wastewater (m^3/s) was collected by Jõhvi biological treatment plant (presently known as Järve Biopuhastus Ltd).

In 2009 new mining area was prepared and opened, which changes water balance in the River Purtse catchment. To adjust the influence of newly opened mine more than two years data is needed; therefore our run-off and discharge area analysis stops in 2008.

Daily flow data was available for the River Purtse and River Keila over the period 1923–2008 (about River Pühajõgi data collection see next paragraph). Meteorological and flow gauging stations are situated in the lower course of all catchments just downstream of the catchment outlet to the Baltic (Fig. 1) and calibrated through spot gauging. Precipitation data has been collated from two tipping bucket rain gauges at Keila (aggregated daily data available between 1960–present, location Fig. 2A), Lüganuse (daily data available between 1939-present, location Fig. 2B) and Jõhvi (daily data available between 1960-present, location Fig. 2B).

The River Pühajõgi run-off data was recorded daily only in 1945–1963. That period model is the most realistic and serves as a base for other models describing the hydrological situation at the beginning of the oil shale mining period and matching for the preferred natural status of the River Pühajõgi. Flow records for the periods of 1978–1990 and 2003–2008 have collected weekly in the River Pühajõgi. The period 1978–1990 characterises the River Pühajõgi's hydrological situation when the influx of mine water was greatest. The period 2000–2003 has been modeled separately because after the mines closed, technogenic water started to fill the empty mines and inflow to the river stopped. To account for the gaps in the run-off time series data set for River Pühajõgi previously modeled data has been used here (see Vaht and Rätsep 2009 as Publication I for details).

During 2008–2011 additional fieldwork took place on the River Purtse and in summer of 2010 on the River Pühajõgi and catchment area. Walkover survey of the catchments validated the current flowpaths and catchment boundaries. The run-off of River Purtse and its tributaries were measured regularly 3–5 times per month in 2008–2009 and spring 2011 with a Hydrometer ГР-21M and a Valeport Model 301 electromagnetic flow meter with flat sensor.

2.4. Calculations and statistical analysis of data

The River Purtse and the River Pühajõgi run-off physical properties (1946–2010) like water temperature and ice coverage was analysed by simple linear regression method and run-off frequency analyses during the period 1923–2008 are worked out by simple conceptual daily rainfall-runoff-mine water which is described in Chapter 3. Used analyse have chosen basic to keep low standard error, as an outcome of veracious result in our studies.

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). Chosen thresholds are Q values 25% above of the long-term (1923–2008) average annual run-off for high flow events (to ensure sufficient peaks within the monitoring period). For low flow events minima below a threshold of 25% less than long-term average runoff are used. The return period values are assessed alongside mine water and precipitation data to examine any possible relationships between run-off return period of high flow and low flow events during the active mining years. Chosen periods are representing similar hydrological and meteorological gaps which are identical in both observed oil shale mining area rivers.

To study changes in minimum and maximum run-off in the River Keila and River Purtse catchment area, non-parametric methods (Mann Whitney Test, given data are not normal even after log-transformation: Kolmogorov-Smirnov: $p>0.05$) and Rodionov's Regime Shifts Algorithm (STARS) were used. Basic deductive statistical analyses were undertaken in SPSS v.15. The STARS software (Excel macro) was developed by S. N. Rodionov at the University of Washington (Rodionov 2004, Rodionov and Overland 2005) and based on a sequential t-test analysis. It is designed to characterise abrupt changes in time series. In our studies the shift frequency regime had following parameters: cut-off length was 10, Huber's Weight Parameter was 1 and $p=0.1$, where the co-called pre-whitening number was implemented. It is presumed that regime shift in different parameters are associated when changes occur within a 3 year period.

2.5. Mapping catchment boundaries

To analyse any changes in effective catchment area in the mining territory, the River Purtse tributaries (River Kohtla and River Ojamaa) run-off discharge area maps were created using ArcGis v9.2 and Adobe Illustrator. The Estonian rivers and mining area layers are created by MapInfo (Valgma 2002). Land cover and topography layers are from Corine Land Cover 2006 Map with resolution 25m.

The River Purtse tributaries maps for each period are also based on scheme developed in Fig. 1. Furthermore, maps are appended with the specific data such as:

1. Collected data of walkover survey.
2. Data from previous studies (Reinsalu et al. 2006; Kiristaja 2008) to illustrate mining effects and impact of the created waterways with reference in past. Reinsalu et al. (2006) presented model data has been chosen to present discharge area analysis hence to measured run-off data concurrency.
3. Data from the excavation work in the river beds and catchment, which was carried out by Estonian Agricultural Board.

Changes in other River Purtse tributaries (River Erra and River Hirmuse) discharge area has been estimated using the same data. However, correct maps could not be created because mining area layers were invalid. The most western small mining area on Fig. 2B with mine water outflow is conventionally applied and does not represent the actual boundaries of the mining area.

3. RESULTS AND DISCUSSION

3.1. Mining development and catchment area changes

We can detect different period of mining history. For example, between 1960s and 1980s mining activity was higher than ever and in the 1990s (some cases in 1970s) mines were closed (Reinsalu 2008). After the closure of mines in the last two decades, new massive underground water bodies have developed in the mine voids. Dewatering of oil shale mines lowered groundwater level in the Keila–Kukruse aquifer (Erg and Pastarus 2008) and mine water outflow was decreased, having an influence on river run-off (Vaht and Rätsep 2009 as Publication I).

About one fifth of River Purtse catchment area has been affected by mining activity (Rätsep and Liblik 2000; Fig. 2B). 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. 2B). Moreover, a large volume of groundwater from closed mines continues to drain towards the operational Aidu opencast mine and it subsequently forms part of the pumped Aidu 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 activity is also taking place in the western part of the River Purtse 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 western part of the River Pühajõgi catchment area (Fig. 2B) which all are closed now. The last two working mines in the catchment were 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. 2B). 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, a field observation as part of this research has shown the Raudi canal to be an independent waterway (Vaht et al. 2011 a and b as Publications II and III) and is therefore not included in the analyses below.

Over the different periods, the River Purtse hydrological regime and their tributaries discharge area have been changed due to the oil shale mining. There are three broad scenarios to explain such a change.

1. Effective catchment area changes due to mining activity and mine water redirection.

The size of the river discharge area given/taken territory depends on the change in boundary of the mining area where mine water is directed from and the size of the cone of depression surrounding it (Hester and Harrison 1994). Fig. 5 with

Fig. 6 illustrates that within the broader River Purtse catchment, the River Ojamaa sub-catchment has been increasing in size with mine development predominantly at the expense of the River Kohtla sub-catchment area between 1923 and 2008. The River Ojamaa surface catchment area has increased by approximately 40% (Fig. 5; Period VI). At present, the River Kohtla has lost around half of its pre-mining surface catchment area (Vaht 2009). This is the reason why River Kohtla upstream is dry. The catchment area changes seen in Fig. 6 show the change in effective surface catchment. Unfortunately there are no previous River Kohtla run-off data recorded, therefore we cannot analyse changes in river run-off.

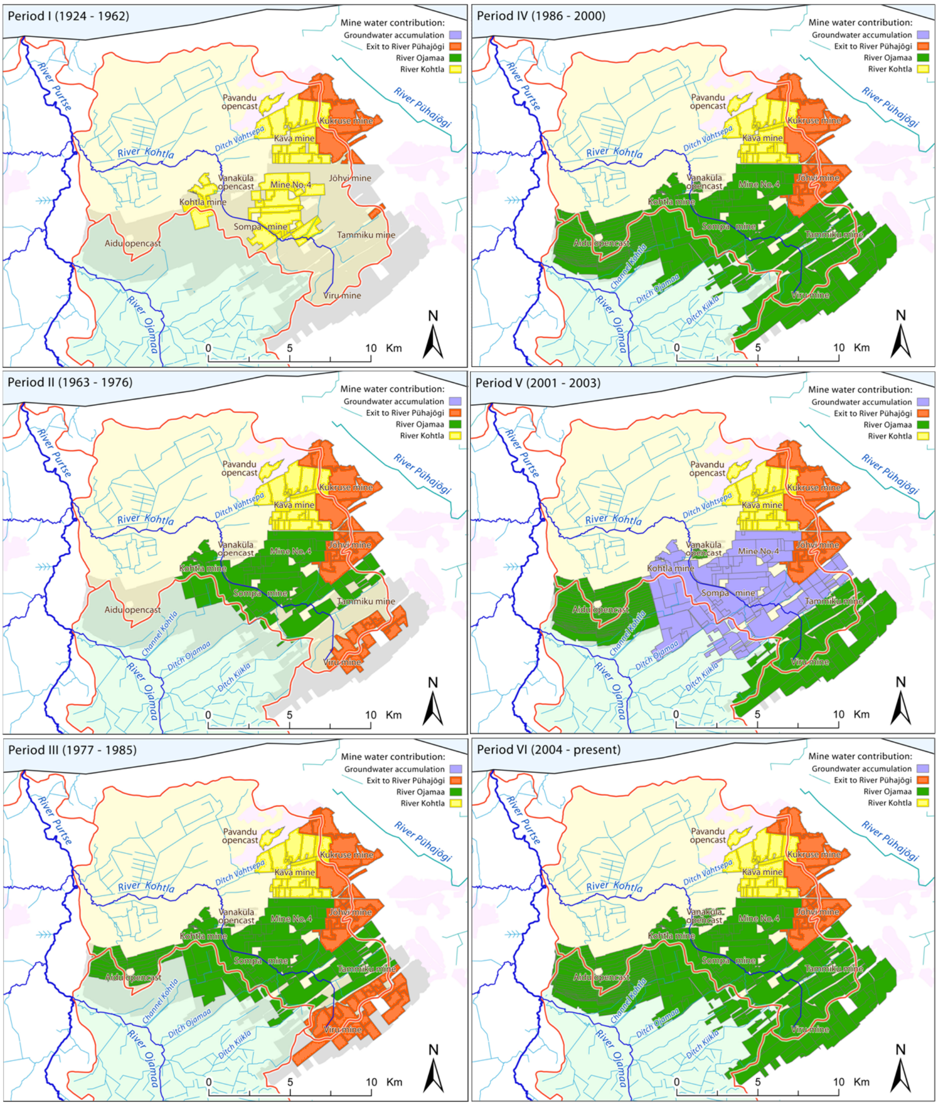


Figure 5. The River Kohtla and the River Ojamaa discharge area maps in different periods.

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).

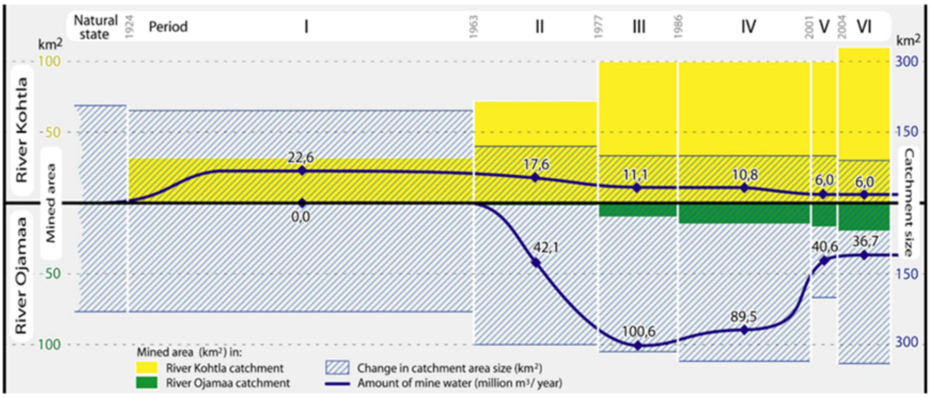


Figure 6. The River Kohtla and River Ojamaa discharge area changes in different periods.

This phenomenon is previously mentioned regarding the Raudi canal and also seen in the western area of River Purtse catchment where a new small Küttejõu ditch has developed additional drainage area to the Purtse. The Küttejõu ditch itself is only 2 km long and has a discharge area estimated to be 27 km^2 with annual run-off up to 25M m^3/yr (measured in fieldwork; Vaht 2009). It has significant impact to the River Purtse tributaries. The Küttejõu ditch was originally created between the River Hirmuse and River Erra as a mine water discharge to the River Purtse (Tambet et al. 2008). At the present time it is a free flow canal draining a closed mine workings. But the closed mine is situating in the Hirmuse and River Erra catchment area and these rivers (Hirmuse and Erra) have lost over 10% of their respective catchment area as a consequence (Table 2; see detailed description in Vaht 2009).

Table 2. Mining area development in the Erra and Hirmuse catchments.

		1922–1954	1955–1987	1988–present
ERRA	Discharged area km^2	101*	91	91
	Mining area km^2	5	6	6
HIR-MUSE	Discharge area km^2	100*	113	88
	Mining area km^2	8	20	20

* The size of the Catchment area

3. The size of the catchment drainage area does not change.
The third observed scenario is where the natural catchment area remains unchanged with mining activity. When comparing the River Purtse and River Pühajõgi natural catchment areas to their present discharge area, we assume that the overall surface catchment area has not changed although there are shared areas of mine workings across the catchments (Fig 3; 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. 2B). However, to compensate this change, 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 (net change of 2 km^2 in the Purtse).

Through analysis of impacts of the mining activity on the catchment area, an interesting pattern has risen. 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 a major influence on flow within the various sub-catchments. As such, outlet flow analyses may not necessarily reveal the overall changes within sub-catchments that may be subject to significant changes in run-off.

3.2. Changes in instream run-off

The relationship between the natural catchment area, the size and location of mine voids, the amount of the mine water discharge and hydrogeological gradients are decisive for variations in downstream run-off. Mine pumping operations not only have the potential to redirect incident meteoric waters from one catchment to another, but crucially lead to the contribution of (potentially deep) groundwater to surface run-off that would not have occurred hitherto (Golf 1968; Hester et al. 1994). The groundwater content in the mine water depends mainly on an individual mining area, operating conditions and local hydrogeology (Barnes 2000).

The groundwater content in the mine water depends mainly on an individual mining area, operating conditions and local hydrogeology (Hester et al. 1994; Artimo et al. 2004). The amount of extra groundwater in the River Purtse is estimated as minimal (up to 5%) and as seen on the Fig. 7 it does not appear to affect its run-off. This would suggest that the River Purtse run-off has not been increased from existing mine water.

Furthermore, during the early period of 1990s there was an abrupt decrease in the mine water discharge (Fig. 7) associated with a decrease in mining productivity. The contribution of mine water as a percentage of catchment run-off declines during the 1990s is consequence of the closure of mines (Reinsalu et al. 2006). These changes are not reflected in the average flow data series. Gravity-driven drainage from mine voids after groundwater tables have rebounded after cessation of pumping are likely to account for the ongoing elevated run-off. The location of these mine water free flow points in the River Purtse and River Pühajõgi are marked on Fig. 2B.

The previously estimated 30% of mine water in the River Purtse run-off by Rätsep and Liblik (2000) is most likely to be dominated by the surface water incident on the mining area which under natural conditions would contribute to the River Purtse run-off. In contrast, groundwater content in the mine water on the River Pühajõgi catchment area is estimated up to 80% (Vaht and Rätsep 2009; Vaht at al. 2011b, 2012 as Publications I, III and IV) and therefore more susceptible to mine water pumping operations. The contribution of mine water discharge (converted to mm/yr over the respective catchment area) to annual average run-off for the River Purtse and River Pühajõgi is shown in Fig. 8. The overall contribution of mine water discharges to downstream run-off is far greater in the smaller River Pühajõgi catchment (annual mine water discharge is 64% of mean annual run-off between in 1923–2008) than the River Purtse (mine water equates to 33% of mean annual run-off between in 1923–2008).

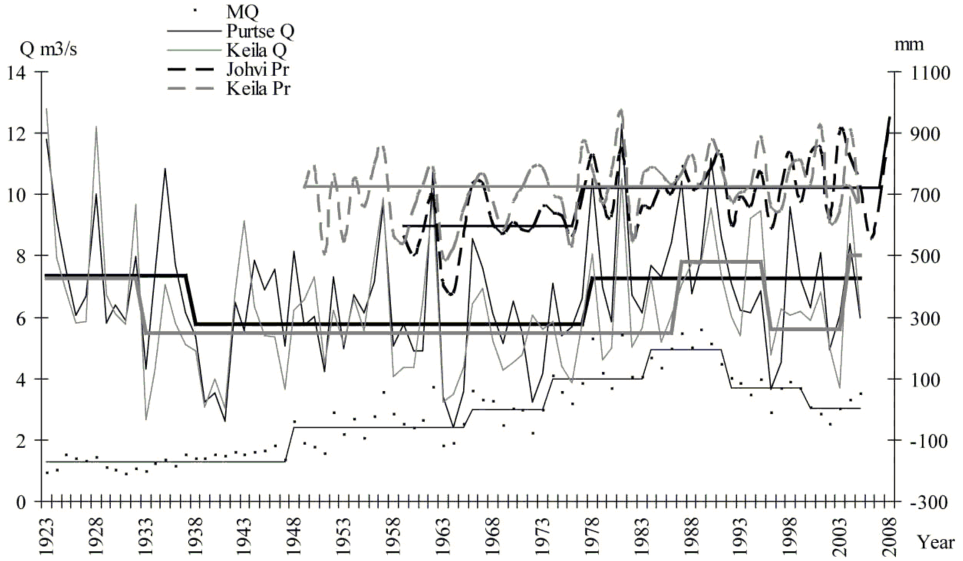


Figure 7. Regime shift (marked as continuous line) in precipitation (Pr), mine water (MQ) and mean annual run-off (Q) of the River Purtse and River Keila.

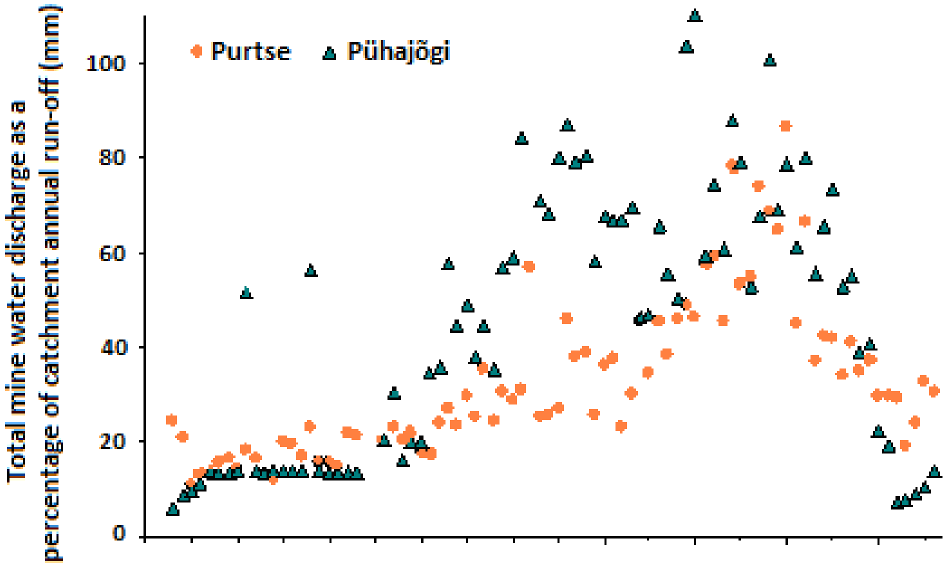


Figure 8. Mine water proportion in the River Pühajõgi and River Purtse run-off.

Both, the River Purtse and River Pühajõgi catchments 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. 8) from 1923–1945 and post–1990. The second period of more intensive mining activity covers the intermediate years 1945–1990 (Fig. 8). Furthermore, simple linear regression (Equation 1) shows relative importance of mine water and natural water in driving variation in river run-off (Q). The river Pühajõgi average mine water discharge (1923–2010) determination coefficient ($R^2_{(PÜH)} = 0.42$) is also greater degree than is the River Purtse run-off ($R^2_{(PUR)} = 0.35$). To comparison, an undisturbed natural river has the value $R^2 = 0$ and in a canal which run-off contains mainly mine water $R^2 = 1.0$.

The length of the flow records in the catchments (in the River Pühajõgi case some of the run-off is modelled (see Vaht and Rätsep 2009 as Publication I) provides a rare opportunity to assess the influence of mine water discharge on catchment-scale run-off. The mining area rivers show similar patterns in the pre–1945 phase, with discharged mine water accounting for between 10% and 23% of total annual run-off. As oil shale mining expanding post–1945 there is a rise in the volumetric importance of the mine water, which peaks at slightly over 110% of catchment outlet run-off in the River Pühajõgi in 1980 and 86% of catchment outlet run-off in the River Purtse in 1990. The contribution of mine water as a percentage of catchment run-off declines during the 1990s in both catchments towards pre-mining levels in the River Purtse and at levels slightly elevated above 1923 levels in the River Pühajõgi (Fig. 8).

A more pronounced pattern is apparent in the River Pühajõgi, albeit based on a more limited time series (1954–1963, altogether 219 months). Flow duration curves were constructed from measured daily mean flows for the periods 1945–1950 (minimal mining phase: Fig. 9) and 1951–1963 (intense mining phase: Fig. 9). These curves also show consistently higher flows under all conditions during the mining phase than when mining was less well established. One of the main controls on the increased baseflow in the River Pühajõgi catchment is likely to be the Tammiku mine which can contribute up to 80% of the flow to the river during low flow periods. According to Kattai et al. (2001) up to 85% of groundwater from deeper aquifers can take part forming Tammiku mine water. The extra groundwater is the reason why we can see annual run-off rise in River Pühajõe (Table 1).

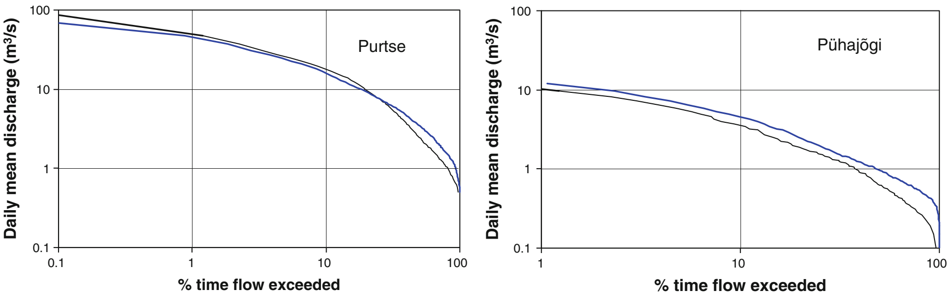


Figure 9. Flow duration curves of the River Purtse and River Pühajõgi. Intense mining (1951–1963) is marked as blue and lesser intense mining (1945–1950) as black.

3.3. Changes in run-off minima

With baseflow periods occurring in both: summer (June-August) and winter (December-February) in the temperature controlled plains snowmelt regime in northeast Estonia (Fig. 4). It is informative to assess the changes specific to summer months that are likely to be of greater ecological significance.

Fig. 10 illustrates a significant ($p < 0.05$) increase in Purtse summer baseflow, which is most pronounced from the mid-1970s and corresponds with increasing mining activity. No significant trend in run-off is apparent in the similarly sized Keila data or in mean daily summer rainfall ($p < 0.05$). Also, Gumbel return period calculations for annual minima show the River Purtse low flow minima ($Q_{-25\%} = 5.1$ m^3/s) recurrence corresponds to the mine water discharge rather than precipitation (Fig. 11). The average groundwater discharge to the in the whole mining area to the mines is approximately 30% (Reinsalu et al. 2006; Kattai et al. 2000). The amount of extra groundwater in the River Purtse is estimated to have increased by up to 5% based on water balance analyses (Vaht 2009).

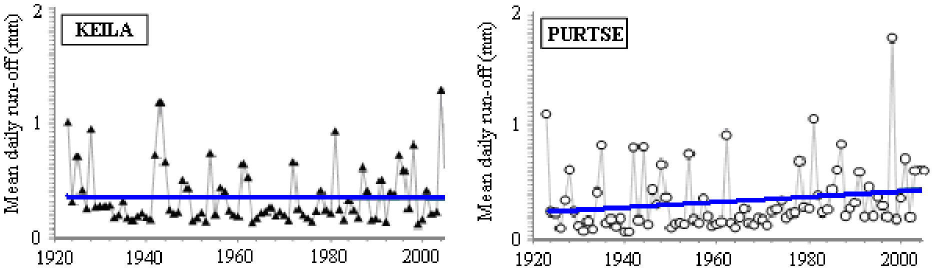
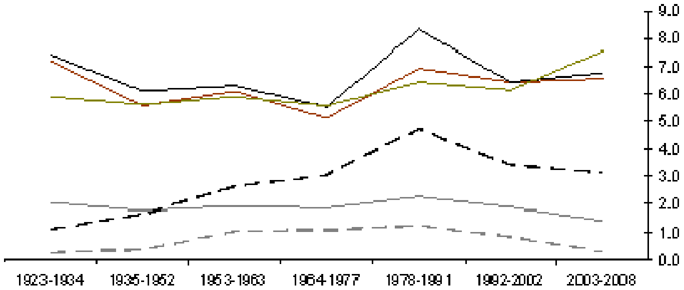


Figure 10. Trend in summer (June-August) daily baseflow run-off in the River Keila ($p < 0.05$; $R^2 = 0.3$) and River Purtse ($p < 0.05$; $R^2 = 8.8$).

A similar pattern to the River Purtse in low flow occurrence is seen in the River Pühajõgi (1.28 m^3/s) (Fig. 11). Baseflow minima show no clear trend with all phases being annual or sub-annual in recurrence in the River Pühajõgi, although falling baseflow in recent decades would appear to be related to mining activity given the concurrent increase in precipitation (Fig. 8, Fig. 11). Because of mine water discharge to the catchment area, the water flow continues through the year in the River Pühajõgi riverbed even in drought years when most of the small Estonian rivers dry out (Järvekülg 2001).



	1923-1934	1935-1952	1953-1963	1964-1977	1978-1991	1992-2002	2003-2008
PIVER RURTSE							
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
RIVER KEILA							
Return period Q25 %	4	1	3	0	4	2	0
Return period Q-25 %	2	5	5	4	1	0	1

Figure 11. The River Purtse (black), Pühajõgi (grey) and Keila (brown) hydrograph with mine water (dotted line) and precipitation (green). Numbers beneath illustrates the Peak Over Threshold (POT) interval in different periods. $Q_{-25\%}$ – minima less than a value 25% lower than average run-off, $Q_{25\%}$ – Peaks over a value 25% greater than long term average run-off.

The summer baseflow data can be assessed using the Rodionov algorithm which also identifies same two distinct hydrological periods. As seen on Fig. 12A, B after 1970s, (mining activity was more intense) the July minimum and annual minimum run-off was much higher than prior 1970s (low mining development) and the mine water discharge keeps river run-off minima at higher rates. The River Purtse and River Pühajõgi median summer baseflows (Jun-Aug) are consistently and significantly higher during from 1953 onwards (Table 3). Although, in the River Pühajõgi case we can analyse only the period 1945–1963, still there are significant change between non-mining and mining period run-off.

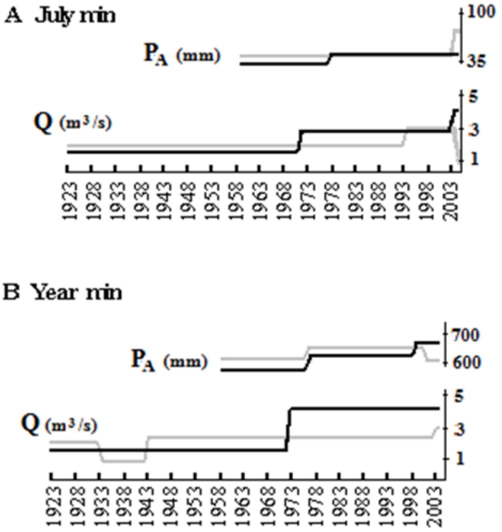


Figure 12. Seasonal occurrence of the River Purtse (black) and River Keila (grey) minimum run-off (Q) and precipitation (Pr).

There was no recorded significant difference in the River Keila median summer baseflow between the phases. There are also no significant differences in median and range summer rainfall and different periods (Table 3) during these two contrasting periods of mining intensity (regime shift changes in the River Purtse catchment precipitation appears years later), suggesting that the hydrological changes are most likely driven predominantly by mining activity.

Table 3. Median and range of summer (Jun-Aug) daily flow and rainfall during differing periods of mining activity in the rivers Purtse, Pühajõgi and Keila.

	River Purtse			**River Pühajõgi**			**River Keila**		
	Non-mining	Mining	Significant?	Non-mining*	Mining*	Significant?	Non-mining	Mining	Significant?
Median flow (m^3s^{-1})	1.3	2.0	YES	0.38	0.63	YES	3.0	2.6	NO
Range	0.27–61.9	0.29–43.9		0.1–7.75	0.21–5.2		0.35–29.5	0.28–44.0	
Median rainfall (mm)	74.7	72.6	NO	73.6	73.1	NO	74.7	72.6	NO
Range	17–205	4–196		0–205	10–166		17–205	4–196	

Non-mining phase = 1923–1952; Mining phase = 1953–2005.
* Non-mining phase = 1945–1952; Mining phase = 1953–1963.

3.4. Changes in high water period run-off

Similarly to run-off minima, Gumbel return period calculations for high flow POT show that the River Pühajõgi high flow POT (2.12 m^3/s) recurrence corresponds to the mine water discharge rather than precipitation (Fig. 11). Recurrence interval for high flow events diminishes during the most intense mining phase, which is likely to be due to the attenuating effect of pumping operations.

Similarly, the River Purtse POT (8.50 m^3/s) corresponds to the precipitation rather than mine water discharge and there are no regime shift changes in spring maximum run-off (Fig. 13A). Although, in rising Q_{25} recent decades (since period 1978–1991, see Fig. 11) would appear to be related to mining activity given the concurrent increase in precipitation (Fig. 13B).

Mining activity is also influences the length of the flooding period (total number of "before peak" and "after peak" days). On the average, the River Keila is 3 days shorter than that of in River Purtse. To study the River Purtse run-off rate in the whole high water period, the "before peak" period is generally longer but the average run-off is lower (River Keila Q_H=274%; River Purtse Q_H=268%, see Table 4). On the contrary, the River Purtse "after peak" period is shorter and generally higher (River Keila Q_H=281%; River Purtse Q_H=253%, see Table 4).

Previous studies have also pointed out the additional mine water (containing extra groundwater from deeper layers) inflows to Estonian rivers in oil shale mining districts (Rätsep and Liblik 2001). However, it is hard to estimate the actual volume of the mine water influence to the run-off during the high water period. The mining area can behave as a karst which occurs in both observed mining area catchments suggesting them as typical peatland area river.

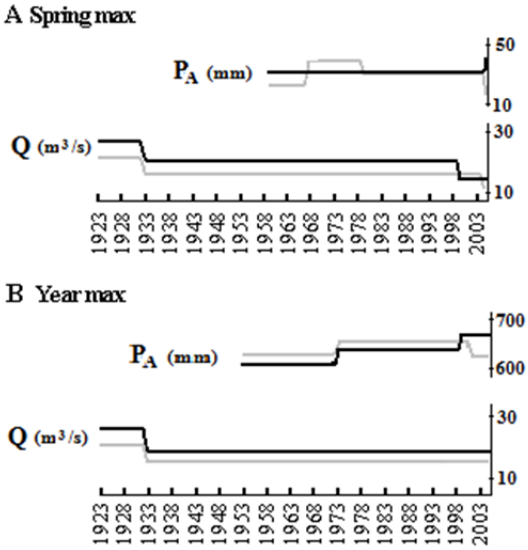


Figure 13. Regime shift of the River Keila (grey) and River Purtse (black) spring-time vs annual maximum run-off (Q) and precipitation (Pr).

There is a lack of any other major change in land use or land management beyond mining development (e.g. Fig. 2B, Table 1) that could have driven such changes. According to Estonian Agricultural Board major forest and peatland drainage canals were excavated before 1940s. Furthermore, stated by EMHI, in Estonia the amount of precipitation is higher than evaporation rate; still groundwater is not used in agriculture (Tamm and Tamm 1997). The forested and peatland changes to the agricultural land area were taking place during the 1940s (Mander and Palang 1994) but after that has remained relatively constant. Changes in run-off appear in 1970s. There is agriculture and farming impact to the groundwater quality (e.g. Tamm and Timmusk 1997; Pärn and Mander 2007), but agriculture does not disturb groundwater hydrological regime as much as mining activity (Rätsep and Liblik 2004).

Table 4. High water period data of the River Keila and River Purtse. Q – mean run-off of observed period and Q_H – increase compared to the long-term average run-off.

Before peak			Peak		After peak		
Days	Q (m3/s)	Q_H (%)	Q (m3/s)	Q_H (%)	Days	Q (m3/s)	Q_H (%)
			KEILA				
16	17	274	39.7	614	40	13.5	218
			PURTSE				
20	18.2	268	51.9	763	39	17.2	253

3.5. Run-off temperature influence to the water vegetation and ice formation.

Under natural flow conditions most of the cases, perched water tables in the peatland areas are important in sustaining baseflow (Rochefort and Lode 2006; Järvekülg 2001). Cutting off the natural run-off feed and directing mine water to the riverbed that could be of significance for aquatic biota by changing the physical characteristics of streams during baseflow.

Previous research by Rätsep et al. (2002) studies multivariate relationship between phytoplankton abundance and different factors generated by oil shale mining in the Purtse catchment. But for understanding how vegetation (with phytobenthos) growths responds to physical properties of mine water discharge, water temperature and water vegetation in the River Purtse (Lüganuse gauging station) were analysed in this study.

Additionally, there may be impacts on the ice conditions associated with changed thermal conditions (with the volumetric significance of large quantities of relatively cooler groundwater from the mines) and changes in water quality. Kattai et al. (2000) points out low but constant mine water temperature (4–6 °C) which is directed straight to the riverbed (according to the fieldwork, mine water temperature in the settling tank, which is used in opencast mining is mostly same as in river). Still, in Fig. 14 it is clearly seen that in July and April (third decade) the River Keila run-off is much higher than that in the River Purtse, probably because most of the mine water is discharged straight to the riverbed. Furthermore, post–1960 period the difference between water temperatures is greater. In observed period 1947–2010 the difference is about 1.5 degrees in July and 1.0 degrees in April but in period 1961–2010 difference is respectively 1.9 degrees and 1.2 degrees (Fig. 14).

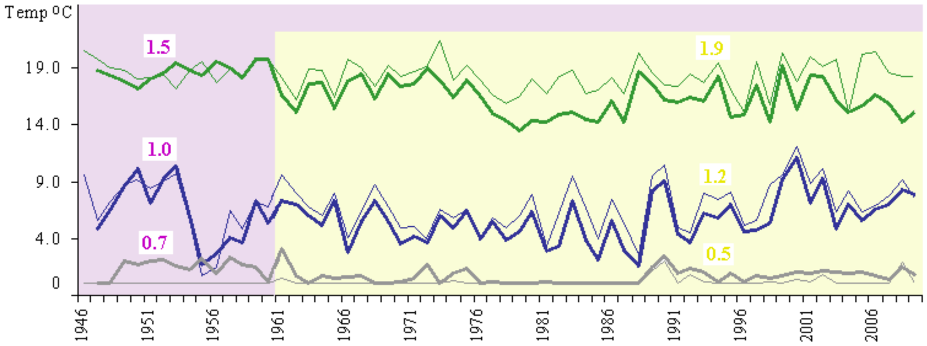


Figure 14. The water temperature of River Keila (thin line) and River Purtse (bold line) in July (green) and April third decade (blue) throughout the observed period (1946–2010; violet) and active mine water discharge period (1961–2010, yellow). Number in the box characterises difference between the temperature figures. Grey line is annual water temperature.

According to EMHI observations, the vegetation period in the River Keila starts already end of April or beginning of May. First vegetation sights appear mostly in the River Purtse in mid June. End of the vegetation period is about 2 weeks later than in the River Purtse (Oct-Nov). Therefore, water temperature changes may not provide positive effects on instream biota through sustenance of summer flows. Jõgede hüdrobioloogiline seire 2010 (2011) reporting shows poor phytoplankton condition in the River Purtse, especially on Lüganuse gauging station area just after River Kohtla inflow. Unfortunately, more than 30 days between the beginning of the vegetation period cannot be fully explained by mine water discharge because the River Purtse vegetation observation did not start before the year 2002. It might be partly explained by pollution in the River Purtse run-off (Truu, et al. 1997; Rätsep et al. 2002), however, Estonian Environmental Monitoring 2004–2006 (2008) shows high pollution load by phenols also in the River Keila.

According to Põlula Fish Farming Centre, since 2008 a new population of salmon has been introduced again to the River Purtse. Fortunately, the new population has survived and bred in the last three years. Monitored data by Ministry of Environmental Central Lab is indicating the River Purtse pollution loads are decreasing. Still, until 2010, no research could be found about influence of pollution decrease and temperature changes to new salmon population in the River Purtse. However, water temperature is an important factor as any other water physical condition and water quality to initiate upstream and downstream migration of several fish species (Jonsson 1991) and population viability (Lopa et al. 2011) or even a fish energy budget and weight (e.g. Elliot 1976; Jensen, 1990).

The constant thermal regime of mine water is one of the main indicators to ice cover formation in winter where mine water discharge to the river is intensive after autumn rainy period throughout the winter. According to EMHI ice observation, 90% of the observed cases (1946–2010) the ice conditions were recorded on average 10 days earlier on the River Keila, although its mean baseflow is faster in the gauging station area. Mostly differences in ice forming are seen after 1960s. Usually first ice condition appears is shore ice in both rivers (River Purtse and River Keila). After shore ice, long-term incomplete ice cover or ice bridge are formed in the River Keila. More than 60% of cases ice conditions can be seen until the end of March. However, in the River Purtse shore ice is the main ice condition throughout the winter and incomplete ice cover or ice bridge is rare sight (for example during the 1990–2010 there are not ice bridge recorded). About 50% of cases the shore ice was not long-term but fragmental. About 20% of observed winters freeze-up appears for short (up to 5 days) period. Again, more ice bridges in the River Purtse are recorded before 1960s. Unlike summer months, constant mine water discharge in winter (February) keeps the River Purtse water temperature average 0.7 degrees higher than River Keila (Fig. 14).

Changes in ice coverage can be as crucial to ecology as summer temperature changes in river water. Gerten and Adrian (2000) can see clearly that in rivers where ice coverage does not form during the winter, development of zooplankton is up to two weeks earlier than that in ice-covered rivers. Unfortunately, EMHI does not collect zooplankton data from rivers, therefore it is rather hard to estimate real damage to the River Purtse ecology. Still, more research needs to be carried out to have better idea how mine water is changing river ecology. Present studies are indicating phytoplankton species changes due to pollution (Jõgede hüdrobioloogiline seire 2010, 2011; Pinnaveekogumite operatiivseire 2010, 2011;) but does not take into account the physical changes in river flow.

4. CONCLUSIONS

Mine drainage operations have clearly had a strong influence on flow regime characteristics in mining area rivers of Northeast Estonia.

As stated in hypotheses, mining activity in the catchment area can change river run-off discharge area. There are three different scenarios: discharge area can increase/decrease (1), catchment area would not change (2) or new waterway with reasonable sized discharge area can be created (3). To minimize the impacts of mining, it is crucial to keep catchment area water in the catchment. Unfortunately, most of studied cases (River Purtse tributaries) mine water is directed to the closest waterway outside the catchment. The consequence can be quite significant as in the River Kohtla case where it has lost almost half of its catchment area and run-off. The strategic placement of mine water discharge points in positions that minimise flow path changes and minimise the volumetric significance of change in flow in receiving water courses would limit the extent of any impacts.

Secondly, mine water discharge can affect river run-off seasonally or can influence river hydrological regime annually. The amount of the additional groundwater discharged to surface waters by mine pumping operations is likely the key control on this augmentation. However, influence of the mine water discharge and amount of extra groundwater in the mine water depends mainly on an individual mining area and site-specific drainage changes. This can encompass both with engineered points of discharge of pumped mine water, as well as the more stochastic position of gravity-driven free flows after pumping has ceased. As an example, the River Pühajõgi run-off has been increased more than 20% in recent years mainly due to large amount of groundwater infiltration to the mine water which is directed to the river. These influences are visible in the hydrographs of the study catchment during different phases of mine development which themselves can be mapped based on mining company records and topographic datasets. On the contrary, current analyses show that the annual mine water discharged to the River Purtse catchment area does not affect its long-term annual run-off due to the low percentage of extra groundwater in the mine water. Long-term variability in run-off regime shift appears to be driven primarily by precipitation. However, mine water discharge can affect the River Purtse baseflow minima, thus increasing the amount of the run-off during summer months and changes in high water period.

The third hypothesis about mine water influence to the river water physical properties needs further research. However brief analysis of water physical characteristics show changes in water temperature and ice conditions. Therefore, we can acknowledge further mine water impact on the run-off but it will be a focus of future study.

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SUMMARY IN ESTONIAN

Põlevkivi kaevandamisest tingitud hüdroloogilise režiimi ja vooluhulga muutused Kirde-Eesti jõgedes

Maavarade kaevandamisega mõjutatakse tugevasti looduskeskkonda, eelkõige hüdroloogilist režiimi, aga ka maastikku tervikuna. Vaatamata suhteiselt rohketele kirjandusallikatele selles valdkonnas võib nentida, et kaevandusala veerežiimi muutusi on suhteliselt vähe uuritud. Viimastel kümnenditel on kirjutatud nii Eestis kui ka väljaspool mitmeid teadustöid, milles käsitletakse depressioonilehtri kujunemist, põhjavee veekvaliteedi muutusi ning põhjavee režiimi olukorda ja taastumisest kaevandusalal. Selliste uurimistööde arendamine sai vajalikuks 1970ndatel kui Kirde–Eestis hakati sulgema esimesi suuremaid põlevkivikaevandusi. Selle tulemusena täitusid kaevandused põhjaveega ning tekkisid suured maa-alused veereservuaarid. Samuti täitusid veega kaevandusperioodil kuivaks jäänud talude kaevud. Tollal oli oluline teada, kuidas põhjavesi uutes tingimustes käitub ning milline on selle reostusaste.

Mitmed uurimistööd (Perens et al. 2006; Vallner 2003; Erg and Pastarus 2008) on pööranud erilist tähelepanu just Kirde-Eesti põlevkivi kaevandamise hüdrogeoloogia probleemidele. Lisaks hüdrogeoloogiale pühendatud töödele võib nii Eestis kui ka väljaspool leida uurimusi kaevevälja põhja- ja pinnavee kvaliteedi kohta. Kahjuks on minimaalselt uuritud kaevandusvee mõju pinnavee režiimile, mille kohta leidub seni vaid üksikuid töid üle maailma (Golf 1968; Czaja 2005). Samal ajal on sellise aspekti uurimine oluline, sest kaevandusvee suunamisega jõgedesse võivad muutuda jõe vooluhulk ja veetemperatuur, samuti jõevee füüsikalis-keemilised parameetrid.

Käesolevas väitekirjas püstitatakse järgnevad hüpoteesid:

1) kaevandusvee sissevool jõevette muudab tema vooluhulka
2) kaevandustegevus võib muuta jõe toiteala suurust,
3) kaevandusvee sissevool jõevette võib mõjutada tema füüsilisi parameeterid.

Hüpoteeside kontrollimiseks valiti uuritavateks jõgedeks kaevandusalal Eesti mõistes keskmise suurusega Purtse jõgi, väike Pühajõgi ning ning kaevandustegevusest mitte puudutatud poollooduslik (keskmise suurusega) Keila jõgi. Sissejuhatavas osas peatutakse põgusalt momentidel põlevkivi kaevandamise ajaloos, mil Purtse valglale rajati olulisemad kaevandusvee äravoolukraavid. Sellest lähtuvalt esitatakse Purtse lisajõgede hüdroloogiline periodiseering koos vastavate kaartidega, kus kirjeldatakse põhjalikumalt kolme erinevat stsenaariumi, kuidas kaevandustegevus ning kaevandusvee suunamine jõkke võib muuta jõe toiteala suurust ning vooluhulka. Kõigi kolme stsenaariumi esinemist on võimalik jälgida Purtse jõe valglal. Lisaks analüüsitakse jõevee temperatuuri ja jääkatte muutusi.

Töös kasutatakse Riigi Ilmateenistuse (EMHI) poolt mõõdetud päevaseid hüdroloogilisi vaatlusandmeid Keila ja Purtse jõe puhul 1923aastast ning Pühajõe puhul katkendlikult alates aastast 1945. Kuna EMHI poolt on juba 20. sajandi algusest (alates 1960ndast aastast järjepidevalt) mõõdetud ka päevaseid sademete andmeid, siis oli autoril võimalus modelleerida puuduvad Pühajõe aastakeskmised vooluhulgad.

Purtse jõgi asetseb peaaegu täielikult Eesti põlevkivimaardlal, kus intensiivset kaevandamist alustati 1918. aastal. Tänaseks hõlmavad endised ja praegused kaevandused ca. 430 km^2 suuruse ala. Läbi aastate on kaevandamise aktiivsus Purtse valglal olnud väga erinev, kuna kõrvuti uute kaevanduste avamisega hakati ammendunud kaevevälju ka sulgema. Esimene Kohtla jõe (Purtse lisajõgi) valglale jäänud Pavandu karjäär suleti juba 1927. aastal. Välja saab tuua kümnendid (1920ndad, 1940ndad ja 1970ndad), mil uute kaevanduste avamine oli eriti hoogne ning perioodid (1970ndad, 1980ndad ja aasta 2000), kui kaevandusi järjest suleti. Vastavalt kas siis rajati või jäid kuivaks kaevandusvee ärajuhtimiseks kaevatud veekraavid, mis omakorda muutsid Purtse lisajõgede valglate hüdroloogilist režiimi.

Käesolevas väitekirjas on veerežiimi ja selle muutuste iseloomustamiseks kasutatud klassikalist Gumbeli meetodit ning mitte-parameetrilisi statistilise analüüsi meetodeid. Kliimamuutuste mõju uurimisel vooluhulgale kasutati Rodionovi (STARS) meetodit. Koostatud kaartide aluseks on võetud põlevkivi kaevandustegevuse arengukava (Valgma 2002) MapInfos koostatud kaardikihte, mis lõimiti kokku ArcGis v9.2 ja Adobe Illustraatori programmide abil. Maakatte ja topograafia kaardifailid (lahutusvõimega 25m) kuuluvad sarja Corine Land Cover. Kaardikihtidele on lisatud aastatel 2008–2011 läbi viidud välitööde vaatlusandmeid ning Põllumajandusministeeriumi maaparanduse ja maakasutuse büroo poolt kogutud andmeid.

Kaevandusala voolurežiimi spetsiifiliseks tunnuseks on vooluhulga suurenemine, mis toimub peamiselt alumiste põhjaveekihtide infiltratsiooni tõttu kaevandusse, kus see omakorda kaevandusvee osana jõkke suunatakse. Inflitratsiooni suurus on ruumiliselt väga varieeruv ja sõltub kaevanduse geoloogilisest ehitusest ning sügavusest. Kuigi umbes 20% Purtse valglast on mõjutatud kaevandustegevuse poolt, võib aasta keskmise vooluhulga suurenemine olla minimaalne. See on seotud vähese lisapõhjavee sissevooluga kaevandusse (kuni 5% väljapumbatavast kaevandusvee kogusest). Rodionovi meetodil režiimi muutuse analüüs näitab korrelatsiooni pigem sademete muutustega 1970ndatel kui kaevandusvee sissevooluga.

Vastupidine näide on Pühajõgi, kus kaevandusvee suunamisel on selgelt tugev mõju voolurežiimile. Lisapõhjavee sissevool valgla kaevandustesse (umbes 50% valglast on kaevanduste all) moodustab kuni 80% kaevandusveest, mis tõstab jõe keskmist vooluhulka üle viiendiku pikaajalisest keskmisest vooluhulgast.

Kui Purtse jõe puhul aasta keskmises vooluhulgas muutusi näha pole, siis madalvee periood kaevandusvee mõjust puutumata ei jää. Käesoleva töö analüüsid näitavad kaevandusvee selget mõju keskmisele vooluhulgale madalvee perioodil. Väiksemate lisajõgede puhul, mis madalvee ajal kippusid kuivama, on näha pidevat voolavat vett sängis.

Võrreldes Purtse jõe suurvee perioodi poolloodusliku Keila jõe andmetega, siis näeme väiksemaid muutusi ka suurvee käitumises. Üldine suurvee periood kestab Purtse jõel keskmiselt 3 päeva kauem. Suurveetipp Keila jõel jõuab kätte küll neli päeva varem, kuid selle perioodi vooluhulk on Purtse omast kõrgem. Seevastu peale suurvetippu toimub Purtse jõe suurvee langus ühtlasemalt ning kõrgema keskmise vooluhulgaga.

Vooluhulga vähenemine jões on peamiselt tingitud valgla vee väljasuunamisega kõrvalasuvasse jõkke, nagu on näha Purtse lisajõgedel. Samuti võib uue kraavi kaevamine luua morfoloogiliselt täiesti uue vooluveesängi koos muutunud valglaga, mida võib näha Purtse jõe läänepoolsete lisajõgede vahel. Seetõttu on äärmiselt oluline õigesti valida kaevandusvee väljalaskekohtade positsioonid, mis aitab paremini reguleerida jõgede toiteala voolurežiimi.

Võrreldes Purtse ja Keila jõe jääolude muutusi, siis alates vaatluste algusest (1945) jääb harvemaks täieliku jääkatte kujunemine Purtse jõel. Üha sagedasemaks nähtuseks saab olema kallasjää teke antud jõel. Kui kaevandusvesi on seisnud settebasseinis, kus veetemperatuur tõuseb vooluhulga temperatuurile ligilähedaseks, võib lisavee suunamine väiksematesse jõesängidesse anda ökoloogiliselt positiivse tulemuse. Kui kaevandusvesi suunatakse otse jõkke, muudab ta kohe jõevee tempetatuuri ning koos sellega ka veetaimestiku kasvuperioodi pikkust. Põhjalikum jõevee füüsikaliste parameetrite muutuste uurimine on kavandatud tulevikus.

ACKNOWLEDGEMENTS

The thesis are supported by EDF grants No. 7510 and 7527, Target Funding Projects SF0180127s08 and SF0280009s07 of the Ministry of Education and Science of Estonia.

Author is sincerely thankful to Dr. Will Mayes for fluent and productive collaboration. Further appreciation goes to Professor Ü. Mander for his contribution to the guidance. Their tutoring has given me huge support in this research field. Also, thank you to PhD Aavo Rätsep who I have enjoyed working with and has been my inspiration throughout this research.

I am grateful to my fieldwork group: MSc Airi Saaremäe, BSc Eero Piirisalu, Professor Margus Pensa and PhD Mait Sepp. Special thanks to PhD Aarne Luud who helped me with presented maps. I am also grateful to PhD Arvo Järvet sharing hydrological data needed for present work.

Special thanks go to my family supporting me all these years and accepted my long absence due to studies. Finally, I am so grateful to my friends encourage me to continue when I was thinking about quitting.

Thank you all!

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