

Impact of the shale mine on the River Purtse hydrological regime in north-east Estonia

Riina Vaht, Mait Sepp and Aarne Luud

ABSTRACT

The present paper studies long-term (1923–2005) changes in the hydrological regime of the medium (100–1,000 km²) river of the Ordovician oil shale field of north-east Estonia. The changing regime in the heavily mined catchments is contrasted with a morphologically similar reference catchment (River Keila) where there has been no mining activity. The Gumbel Method and Rodionov Regime Shifts Algorithm (STARS) were used to study high- and low-water changes of the mining area. The study shows that mine water has no significant impact on the River Purtse annual run-off; however, it has influence on the low water period and minimum flow values, increasing the amount of run-off. Mine water discharge can affect the course of the run-off during the high water period and high water season peaks. Therefore, in terms of the river maximum flows return period, there are no major differences between the mining and natural catchments.

Key words | baseflow, hydrological regime, mine water, minimum and maximum run-off

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INTRODUCTION

The diverse effects of water discharges from abandoned mines have been widely documented in pollution, toxicological and epidemiological studies in recent decades (e.g. Tiwary 2001; Selberg *et al.* 2009). Mining pollution has been found to be a major contributor to the dispersal of contaminant metals at local, regional (Mayes *et al.* 2010) and global scales (Nriagu & Pacyna 1988), and management options for minimising 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 some evidence of changing catchment hydrology in the restored coal mining districts of Appalachia (USA). Negley & Eshleman (2006) pointed out a paired catchment study of water balances is employed to show changes in the hydrological behaviour of a surface mined (and subsequently reclaimed) catchment relative to an adjacent reference catchment. Furthermore, higher storm run-off coefficients, increased total storm run-off and increased short-term peak run-off rates were attributed to reduced infiltration capacity of the land due to soil compaction in land

restoration efforts. Ferrari *et al.* (2009) similarly highlighted the trend towards a flashy hydrograph more indicative of urban catchments than pre-mining conditions in other reclaimed coal mined catchments in Appalachia.

Younger *et al.* (2002) 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 m³/s). This major level, which was commenced in 1897, led to the instantaneous dehydration of karst resurgences in the overlying aquifer which contributed to the diminution of stream baseflow (e.g. the River Alyn) and the dehydration of springs of regionally important cultural value.

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 de-watering efforts) and diminished summer flows due to the effects of the 'cone of depression' development reducing spring flows (e.g. Finlinson & 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 become an increasingly important concern ahead of water quality issues (e.g. Croton & Reed 2007).

One of the most serious problems identified is the constant changes in the groundwater regime and water chemistry within the north-east Estonia mining area which has been studied widely over the last 30 years (e.g. Parakhonski 1983; Rätsep & Liblik 2000; Erg 2003). Due to mining activity, the underlying Ordovician limestone deposits and the aquifer complex have been totally drained by mine pumping operations. As a result, it has created the effect commonly known as ‘cone of pumping depression’ (Erg & Pastarus 2008). This effect stretches up to 35 m in depth and 2.5 km outside of the mining area (Kattai *et al.* 2000), creating groundwater infiltration to the mines. Recently, a variety of models have been used in groundwater studies (Reinsalu *et al.* 2006; Lind 2010) to assess the impact of oil shale mining on hydrogeology. Modeled data from these models have also been used in the current research.

Furthermore, Rätsep & Liblik (2004) and Vaht & Rätsep (2009) have 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 100–1,000 km²), but neglected to assess impacts in smaller (sub 100 km²) systems. It is within the smaller catchments that any abrupt changes in flow regime would be likely to have a greater impact on instream ecology as they would be more volumetrically significant.

The present study presents the impact of changes in drainage associated with Estonian oil shale mining on the hydrological pathways and regime in medium-sized lowland catchments. Furthermore, analysis of the vulnerability of the rivers’ hydrological regimes in mining areas and the extent of change in contributing drainage areas as a result of mining within different sub-catchments of the River Purtse are also presented. The long-term regime in the River Purtse mine-impacted systems is compared with the morphologically similar River Keila catchment, which offers a useful reference catchment where no mining development has taken place. The unusually long period of hydrometric records in these systems (from 1923 to 2008) provides a rare opportunity to assess changes in run-off characteristics over time as a result of mining operations. A particular focus on baseflow changes is provided.

MATERIALS AND METHODS

Mining area

The Estonian oil shale deposit is located in the north-east Estonia region (Figure 1(b)). The first oil shale opencast mine was opened in 1918 which was also situated on the River Purtse catchment area. Subsequent rapid development of the oil shale deposits of approximately 430 km² has seen 24 deep mines and opencasts operate in this area (Rätsep & Liblik 2004). Currently, only two mines and three opencasts are operating in the whole mining area (Reinsalu 2008), with some residual activity in the River Purtse catchment area.

Rivers

The River Purtse and River Keila are located in the northern part of Estonia Figure 1(a, b) and are classified by Järvekülg (2001) as medium-sized rivers in Estonia (Table 1). The River Purtse was once known as a significant salmon river, but the impact of the oil shale mining and industry over the last 90 years has dramatically altered the balance of the ecosystem (e.g. Truu *et al.* 1997; Rätsep *et al.* 2002). As identified by Golf (1968) and Czaja (2005), the mine water discharge has a strong impact on the river hydrological regime. Therefore, the River Purtse represents typical mine-impacted systems in the oil shale area of north-east Estonia and long-term hydrological and mining records are available (dating back to 1923). One-fifth of its catchment is affected by the mining area and the run-off contains mine water. Previous research from Rätsep & Liblik (2000) estimates that the average mine water content in the River Purtse run-off is approximately 30%. There were 14 underground and opencast mines, and presently there are only four in operation. Five mine water outflows from operating mines and three free flows from closed mines are directed to the River Purtse catchment (Figure 1(b)).

In comparison, the River Keila is located approximately 150 km west of the oil shale mining area. Its catchment has never been affected by mining activity. Both studied rivers have similar hydrogeological conditions and landscape. They are typical Estonian lowland rivers draining to the Baltic Sea on the Estonian Coastal Plain. The catchments

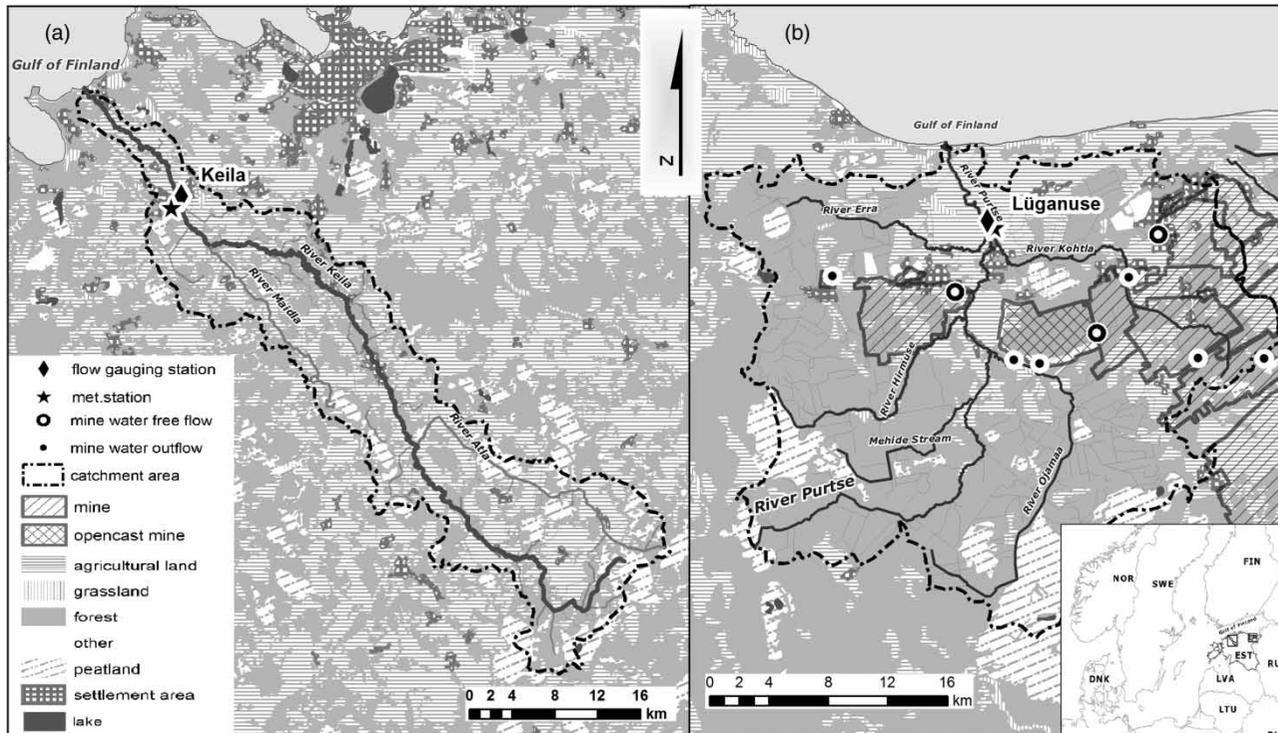


Figure 1 | Location, land cover and mining area of the River Keila (a), River Purtse (b) catchments at the present time.

Table 1 | Summary physical data for the River Keila and River Purtse (Arukaevu 1986; Järvekülg 2001)

	River Keila	River Purtse
Head of the river	Viirika peatland, NW Estonia	Punase peatland, NE Estonia
Catchment area, km ²	682	816
Catchment's shape	Elongated shape	Fan shape
Length of the main river, km	116	51
Long-term average run-off, m ³ /s	6.2	6.8 ^a
Number of major tributaries	2	4
Land usage	Peatland 33% Forest 30% Agricultural land 35%	Peatland 30% Forest 35% Agricultural land 15% Oil shale mining area 20% ^b

^a30% of water forms in mining area.

^bMostly covered by forest.

are characterised by low gradient terrain, with peak catchment elevation ranging from 70 m. The average slope of all the riverbeds studied is about 1.80 m/km. The greatest

slope (up to 5 m/km) occurs in the lower reaches of all streams prior to discharge into the Gulf of Finland, where the rivers cross the limestone escarpment of the high Baltic Klint. Therefore, in the River Purtse rapids have been formed, and the River Keila has a 7 m high waterfall, both with narrow deep valleys (Järvekülg 2001). Furthermore, catchments contain equally extensive peatland deposits and coniferous forests (Figure 1(a, b); Table 1). The catchment 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.

Climate

From the climatological point of view, the rivers belong to different precipitation sub-regions of Estonia. While the River Keila is situated in the so-called north-western district of precipitation (characterised by Keila meteorological station), the River Purtse is situated in the north-eastern district (Jõhvi meteorological station). Mean precipitation in north Estonia is between 640 and 690 mm/yr and the

average evapotranspiration rate is 50–90% of precipitation (Estonian Meteorological and Hydrological Institute (EMHI)). Total rainfall in the areas differs only by 50 mm in the long-term average (1960–2005), with higher average annual rainfall reported at the Keila meteorological station (Jaagus 1992).

The long-term regime of the 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 km² in area typically have average flow rates over 7 m³/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.

Data and methods

The present study run-off analysis is based on precipitation (mm) and run-off (m³/s) data collected by the EMHI, measured during the period 1923–2005 in the catchments. Meteorological and flow gauging stations are situated in the lower course of both catchments just downstream of the catchment outlet to the Baltic location (Figure 1(a, b)) and are calibrated through spot gauging. Precipitation data have been collated from two tipping bucket rain gauges at Keila (aggregated daily data available from 1960 to date, location Figure 1(a)) and Lügause (daily data available from 1939 to date, location Figure 1(b)). Mean oil shale mine water discharge rates (m³/s) and mining area (km²) data have also been collated from digital and hard copy records kept by Eesti Energia Kaevandused Ltd.

The paper presents the STARS algorithm to study hydrological changes in the River Keila and River Purtse catchment area. The STARS software (Excel macro) was developed by S. N. Rodionov at the University of Washington (Rodionov 2004; Rodionov & Overland 2005) and is 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 the 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.

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. 1994). Chosen thresholds are *Q* values 25% over 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 the run-off return period of high-flow and low-flow events during the active mining years. Chosen periods represent similar hydrological and meteorological gaps which are identical in both observed rivers.

The Estonian rivers and mining area layers are created by MapInfo. Land cover and topography layers are from Corine Land Cover 2006 with a resolution of 25 m. The presented map is also updated with specific data such as excavation work in the river bed, which was carried out by Estonian Agricultural Board. During 2008 and 2009, additional fieldwork took place on the River Purtse and in the summer of 2010 on the River Pühajõgi and catchment area. A walkover survey of the catchments validated the current flowpaths and catchment boundaries. During 2008 and 2009 additional fieldwork took place on the River Purtse tributaries which were influenced by mine water discharge. A walkover survey of the catchments validated the current flowpaths and catchment boundaries. The run-off of River Purtse and its tributaries were measured regularly three to five times per month with a Hydrometer GP-21M and a Valeport Model 301 electromagnetic flow meter with flat sensor.

RESULTS AND DISCUSSION

The relationship between the natural catchment area, the size and location of the mining area and the amount of mine water discharge with 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 previously (Golf 1968; Hester & Harrison 1994). The groundwater content in the mine water depends mainly on the individual mining area, operating conditions and local hydrogeology (Hester & Harrison 1994; Barnes 2000).

The amount of extra groundwater in the River Purtse is estimated by Vaht (2009) as minimal (up to 5%) and, as seen in Figure 2, it does not appear to affect its long-term annual run-off. This finding would suggest that the River Purtse run-off has not been increased from existing mine water. The previously estimated 30% of mine water in the River Purtse run-off by Rätsep & 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.

During the early period of the 1990s there was an abrupt decrease in mine water discharge (Figure 2), associated with a decrease in mining productivity and the closure of mines (Reinsalu *et al.* 2006). Furthermore, the contribution of mine water as a percentage of catchment run-off declines during the 1990s. These changes are not reflected in the average flow data and regime shift series (Figure 2). 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 are marked on Figure 1(b).

With baseflow periods occurring in both summer (June–August) and winter (December–February) in the temperature controlled plains snowmelt regime in north-east Estonia (Järvekülg 2001), it is helpful to assess the changes specific to summer and winter months that are likely to be of greater ecological significance. The summer baseflow data can be assessed using the Rodionov algorithm which identifies two distinct hydrological periods. Prior to the 1970s, when the mining activity was less active, the July minimum and annual minimum run-off was much lower than during the post 1970s intense mining development (Figure 3(a, b)). It is also seen from Figure 3(a, b) that the mine water discharge keeps run-off minima at higher rates in baseflow. At the same time, the River Keila situation showed no regime shift during high and low water periods. Therefore, it can be concluded that the seasonal run-off regime shift is caused by mine water discharge.

In Figure 3(c, d), the regime shift in annual precipitation data is clearly seen but the annual run-off remains the same. However, as seen in Table 2, the length of the flooding period (total number of ‘rising limb’ and ‘falling limb’

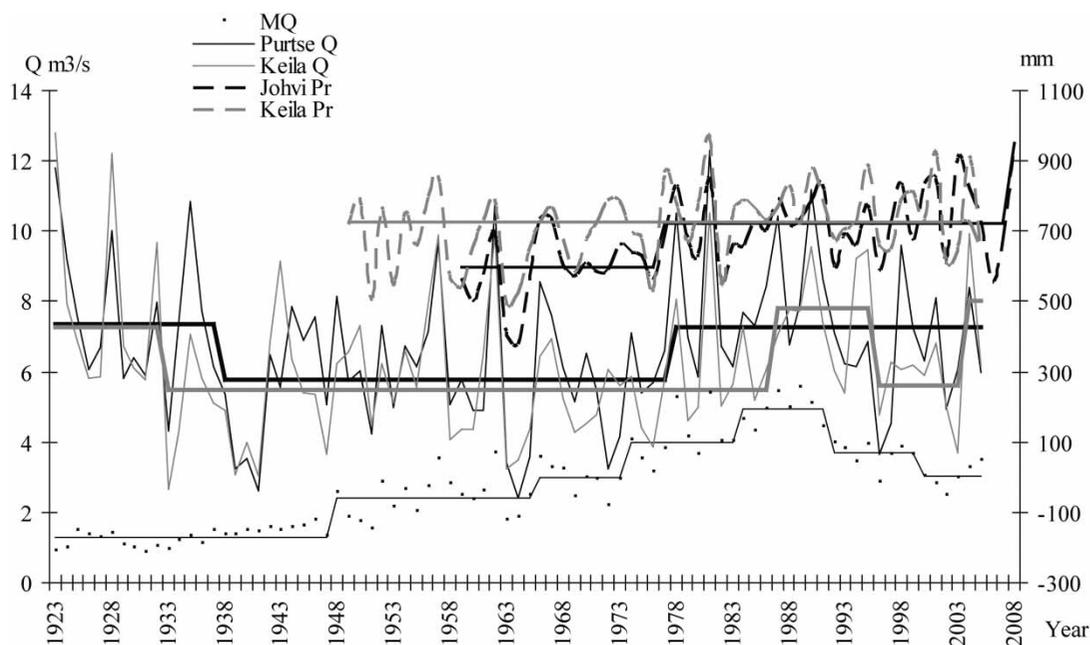


Figure 2 | Regime shift (marked as continuous line) in precipitation (Pr), mine water (MQ) and mean annual run-off (Q) of the River Purtse and Keila.

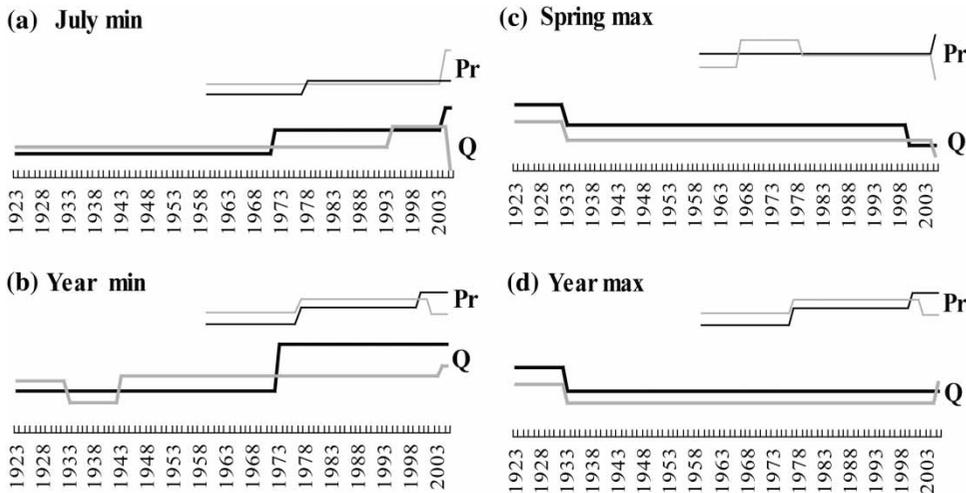


Figure 3 | Regime shift of the River Keila (grey) and River Purtse (black) annual minimum (min) run-off, maximum (max) run-off (Q) and precipitation (Pr).

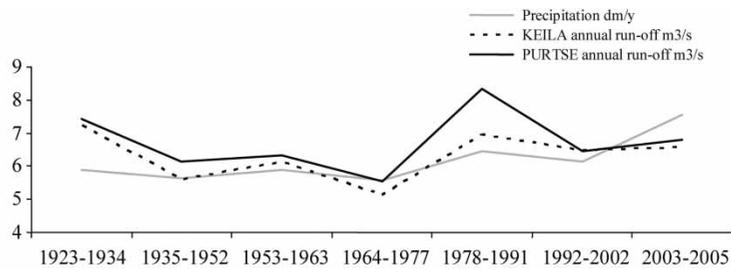
Table 2 | High water period data of the River Keila and River Purtse. Q —mean run-off of observed period and Q_H —increase compared to the long-term average run-off

Rising limb			Peak		Falling limb		
Days	Q (m ³ /s)	Q_H (%)	Q (m ³ /s)	Q_H (%)	Days	Q (m ³ /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

days) in the River Keila is 3 days shorter than that of the River Purtse. Furthermore, to study the River Purtse run-off rate in the whole high water period, the ‘rising limb’ is generally longer but the average run-off is lower (River Keila $Q_H = 274\%$; River Purtse $Q_H = 268\%$; see Table 2). On the contrary, the River Purtse ‘falling limb’ period is shorter and generally higher (River Keila $Q_H = 281\%$; River Purtse $Q_H = 253\%$; see Table 2). This can be an indicator that mine water discharge can affect the length and trend of the spring flooding season. 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 flow usually occurs later than in natural conditions (Rätsep & Liblik 2001). Unfortunately, it is difficult to estimate the actual volume of the mine water influence to the run-off during the high water period, the mining area acts like karst which occurs in both observed catchments and the River Purtse also

acts like a typical peatland area river during the high water period.

Similarly, the Gumbel return period calculations for high-flow POT and annual minima show that the early periods of high-flow POT in the River Purtse ($Q_{25} = 8.50 \text{ m}^3/\text{s}$) and low-flow minima ($Q_{-25} = 5.10 \text{ m}^3/\text{s}$) recurrence corresponds to the precipitation rather than mine water discharge (Figure 4). Although, in falling Q_{-25} and rising Q_{25} , recent decades (from 1978 to 1991) would appear to be related to mining activity given the concurrent increase in precipitation (Figure 4). Mine water discharge increases the River Purtse run-off in the dry season, especially from the 1970s to the present. The water flow continues through the year in the River Purtse tributaries, even in drought years when most of the small Estonian rivers dry out (Järvekiül 2001). Such changes may even provide positive effects on instream biota through sustenance of summer flows.



RIVER PURTSE							
Return period Q25 %	3	1	2	1	5	2	1
Return period Q-25 %	1	5	5	3	0	3	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 4 | The River Purtse and River Keila hydrograph and the Peak Over Threshold (POT) interval in different periods. $Q_{25\%}$ – Peaks over a value 25% greater than long-term average run-off, $Q_{-25\%}$ – minima less than a value 25% lower than average run-off. Used precipitation data are measured in Lügenuse meteorological station.

CONCLUSIONS

Mine drainage operations have clearly had a strong influence on flow regime characteristics in the medium-sized Estonian catchment studied here. The most pronounced effects are related to flow augmentation which are most visible in the River Purtse catchment during low and high water season. The additional groundwater discharged to surface waters by mine pumping operations is likely the key control on this augmentation. However, the 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 the run-off regime also appears to be driven primarily by precipitation.

Baseline studies of flow regime and associated modeling studies are thus essential prior to mining dewatering operations to inform locations in the catchment where impacts of dehydration or flow augmentation are likely to be minimised. 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.

The ecological significance of these changed flow regimes is uncertain and few studies have ascertained the ecological effects of changed regime due to mining. Such assessments should be a focus of future study. Additionally, there may be impacts on aquatic biota associated with changed thermal conditions (with the volumetric significance of

large quantities of relatively cooler groundwater from the mines) and altered water quality (Rätsep & Liblik 2001).

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