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IMPACT OF OIL SHALE MINE WATER DISCHARGES ON PHYTOPLANKTON COMMUNITY OF PURTSE CATCHMENT RIVERS

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The multivariate relationship between phytoplankton abundance and different factors both natural and generated by oil shale mining in the Purtse catchment rivers (Purtse, Kohtla, and Ojamaa) in Augusts 1996–2000 was studied. Impact of oil shale mine water discharges, causing the input of sulfates and chlorides into the rivers, on phytoplankton abundance in river water was characterized by significant negative linear correlation. The amount of annual precipitation influenced positively the characteristics of phytoplankton abundance in river water. The complex of linear regression formulas was derived for characterising phytoplankton abundance in the lower course of the Purtse River using meteorological, hydrological and hydrogeological as well as geochemical data of water circulation.

Closing the Sompa, Tammiku and Kohtla mines in 2000–2001 decreased essentially anthropogenic stress on ecological condition of the Purtse catchment rivers.

Introduction

Numerous oil shale mining and processing enterprises are concentrated on the territory of Ida-Viru County (North-East Estonia) inevitably influencing the ecological condition of rivers of that region. It is obvious that their impact on the river water resources may range from minimal up to severe. The rivers of the Purtse catchment have been under serious anthropogenic stress, because waste waters of oil shale mining and thermal processing which contain sulfates, chlorides, sulfides, oil products and phenols have been continuously discharged into the catchment rivers [1].

There is no doubt that these polluted water flows affect essentially also the river biota, including such aquatic microorganisms as phytoplankton. Phytoplankton abundance and composition in river water characterize in a great measure the ecological state of the aquatic environment. It makes possible to assess the extent and character of anthropogenic load on the basis of this parameter [2, 3]. The living phytoplankton is well known as an indicator of the ecological status of water environment [4]. The influence of oil shale mine water on the evolution of river water microorganisms is persuasively described in the paper [5].

It is axiomatic that such different factors of water circulation as meteorological (natural), hydrogeological, hydrological, geochemical and mining-technological [6] influence the phytoplankton abundance in river water, as mine water discharges into rivers are an inseparable part of catchment water circulation (cycles). In the Purtse catchment it has been taking place throughout several decades, whereby this fact has strongly diminished the fishing importance of the Purtse River.

The aim of this study was both to analyse and determine an associative character of impact of the above-mentioned factors on phytoplankton abundance in the Purtse catchment rivers, and to advance correlative relations

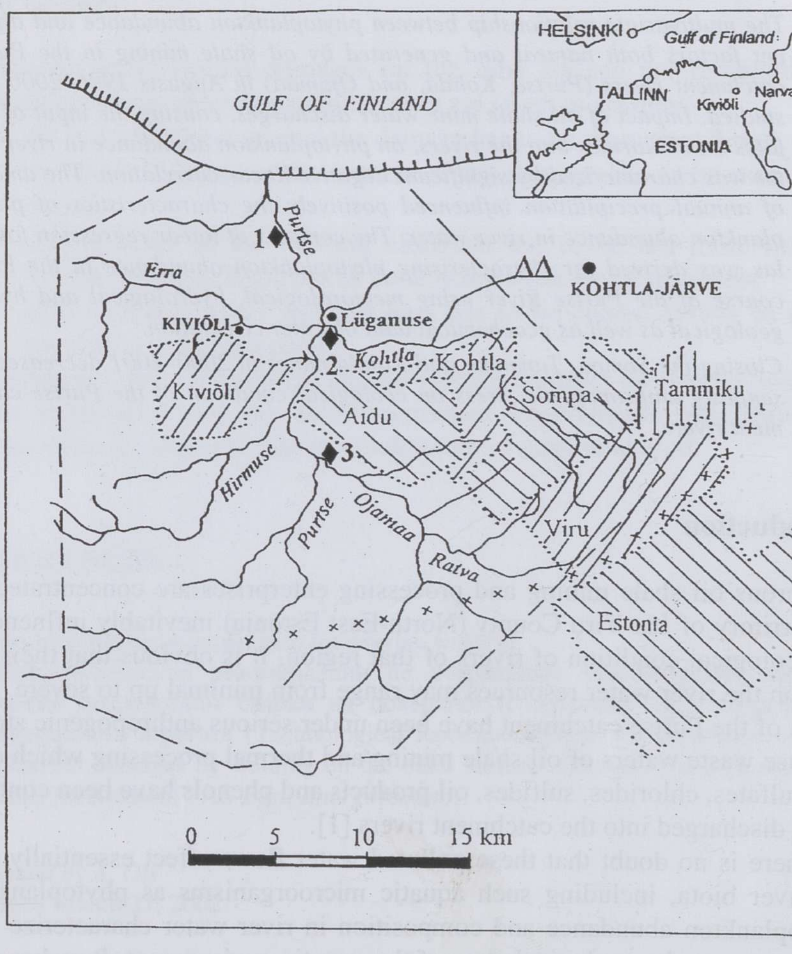

Fig. 1. Location of the Purtse catchment area: "– – –" – border of the catchment area; "•••" – borders of the mines and opencast; × × × – Ahtme tectonic crushed zone; ΔΔ – ash dumps; ◆ – observation and sampling points in the catchment area

between different environmental factors and phytoplankton abundance for the period 1996–2000. The purpose was also to estimate functional relationships (formulas) for predicting phytoplankton abundance on the basis of numerical values of natural, hydrological, hydrogeological and geochemical factors. Analysis of phytoplankton situation is relevant for the composition of water management plans for the Purtse catchment rivers, necessary for achieving sustainability of water resources.

Study Area

The Purtse catchment area is mainly located in Ida-Viru County. It covers an area of about 816 km^2 (~24 % of the total territory of this county). The whole catchment area is located in the western part of Estonian oil shale deposit. There are *Kiviõli*, *Kohtla*, *Sompa* and *Viru* mines, as well as *Aidu* opencast (Fig. 1, streaked areas) in the catchment area. *Kiviõli*, *Kohtla* and *Sompa* mines have been closed by now; *Kohtla* mine was closed only in June 2001. Mine water outputs to the Purtse, Kohtla and Ojamaa rivers (in all ten outputs) have been constructed. Underground water outflow from the closed *Kiviõli* mine (1988) into the Purtse River is marked with an arrow. This whole mining territory within the boundaries of the catchment area has a total area about 200 km^2. Oil shale lies at the depth of 20 m. Thickness of the mined productive layer reaches 2.5 m.

An output to the Kohtla River exists also in the form of ash-dump waters from the Kohtla-Järve oil shale thermal processing plant (*Viru Chemistry Group* Ltd.). Ash-dump waters mix with mine water discharges.

Materials and Methods

Water samples for determination of phytoplankton abundance and composition have been collected from three points (Fig. 1, points 1–3), which are under a severe anthropogenic load due to oil shale mine water discharges.

The samples from the surface layer of the river (2–6 samples in each sampling campaign, in all 24 samples during Augusts of 1996–2001) were collected into plastic bottles and preserved with formaldehyde. The samples were precipitated twice by decantation up to the volume 10–15 ml. Phytoplankton abundance and composition were analyzed on a lined preparation slide using the microscope Carl Zeiss Standard 25ICS. The used magnification interval was 200–1000 [7].

To characterize the factors (as variables) generated by meteorological processes and oil shale mining, the following initial data obtained from the Estonian Meteorological and Hydrological Institute and AS *Eesti Põlevkivi* (*Estonian Oil Shale* Ltd) for the period 1996–2000 were used:

(1) Annual precipitation amounts (S), mm, determined by Jõhvi Meteorological Station
(2) Mean annual discharges (L_v) in the lower course of the Purtse River (at Lüganuse), m^3/s
(3) Annual amounts of mine water (K) pumped out from mines of the observed region, million m^3
(4) Annual inputs of sulfates and chlorides (J_s) from mines (with mine water) into the rivers, thousand t
(5) Average content of sulfates and chlorides (V_s) in mine water discharges, mg/l

The annual values of these factors were found by summarising the corresponding monthly values. Values of composite factors and phytoplankton indicators characterizing the ratio of two parameters were calculated by the authors of the paper (Tables 1 and 2). All above-named factors and determined phytoplankton abundances were examined as variables (both predictor variables and criterion ones), between which, for characterizing the interdependence, the correlation coefficients r were computed for the proper set of paired values of variables using the principles of multivariate common independent causes (multiple path analysis) [8]. The ratio of phytoplankton abundance (A) and number of species (M) as criterion variable was used to characterize the situation of phytoplankton community in the rivers polluted with mine water discharges. The indicator A_{tot} (summarised abundance) as system parameter was used to describe an anthropogenic stress on the catchment rivers (Purtse, Kohtla, and Ojamaa).

Table 1. **Phytoplankton Abundance and Number of Species in the Purtse Catchment Rivers in Augusts 1996–2000**

Indicator	1996	1997	1998	1999	2000
	Sampling date				
	20.08	26.08	24.08	26.08	30.08
In the lower course of the Purtse River (point 1)					
Phytoplankton abundance A_1, cells/l	5,500	6,600	8,700	6,300	27,700
Number of species M_1	12	13	22	12	28
Ratio A_1/M_1	458	508	395	525	989
In the lower course of the Kohtla River (point 2)					
Phytoplankton abundance A_2, cells/l	not determined		16,725	2,625	27,600
Number of species M_2	–	–	13	6	17
Ratio A_2/M_2	–	–	1287	438	1624
In the lower course of the Ojamaa River (point 3)					
Phytoplankton abundance A_3, cells/l	not determined		8,100	11,325	17,700
Number of species M_3	–	–	12	27	23
Ratio A_3/M_3	–	–	675	419	770
Summarised abundance A_{tot}, cells/l $A_{tot} = A_1 + A_2 + A_3$	–	–	33,525	20,250	73,000

Table 2. **Dynamics of Factors Both Natural and Generated by Oil Shale Mining Which Affect Phytoplankton Abundance in the Purtse Catchment Rivers in 1996–2000**

Factor	1996	1997	1998	1999	2000
Annual precipitation amount S, mm	587	724	841	670	834
Mean annual discharge in the lower course of the Purtse River L_v, m^3/s	5.30	6.60	9.60	7.26	6.34
The amount of mine water directed into the catchment rivers K, million m^3/yr	64.9	96.5	98.9	89.4	61.3
Input of sulfates and chlorides into the rivers with mine water J_s, thousand t/yr*	27.3	35.1	26.1	34.6	15.2
Average content of sulfates and chlorides in mine water V_s, mg/l	535	462	335	491	320
Ratio S/L_v	110.8	109.7	87.6	92.3	131.5
Ratio S/K	9.04	7.50	8.50	7.50	13.61
Ratio S/J_s	21.50	20.63	32.22	19.63	54.87

* Share of sulfates in the mixture of sulfates and chlorides is about 92 %.

By linear regression analysis the linear regression formulas (Table 3) in the form of $Y = a + bX$, and the coefficients of determination r^2 were calculated to explain some of the variation of Y by X, using the latter variable as a statistical control [8]. Differences were considered significant at the 95 % confidence level ($p \leq 0.05$).

Table 3. **Linear Regression Formulas for Characterizing Functional Relationship Between Phytoplankton Abundance (A_1 and ratio A_1/M_1) and Different Factors for the Lower Course of the Purtse River in Augusts 1996–2000 ($r^2 > 0.6$, $p \leq 0.05$)**

Regression formula		Coefficient of determination r^2
$A_1 = 39311.79 - 1025.01\ J_s$	(1)	0.77
$A_1 = -21892.15 + 3559.28\ S/K$	(2)	0.92
$A_1 = -7213.51 + 611.57\ S/J_s$	(3)	0.94
$A_1/M_1 = -630.88 + 11.34\ S/L_v$	(4)	0.69
$A_1/M_1 = -202.93 + 84.28\ S/K$	(5)	0.81
$A_1/M_1 = 175.46 + 13.45\ S/J_s$	(6)	0.72

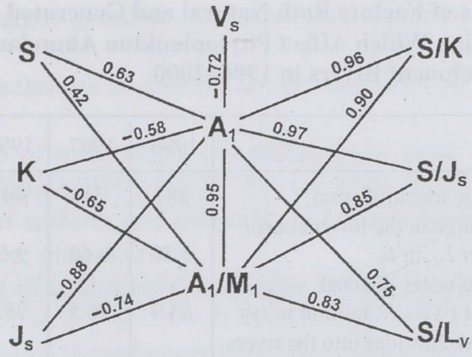

Fig. 2. Correlation graph (path diagram) showing the interdependence between phytoplankton abundance and different environmental factors (at the 95-% confidence limits around *r*) in the lower course of the Purtse River in Augusts 1996–2000. For interpretation of marks see Tables 1 and 2

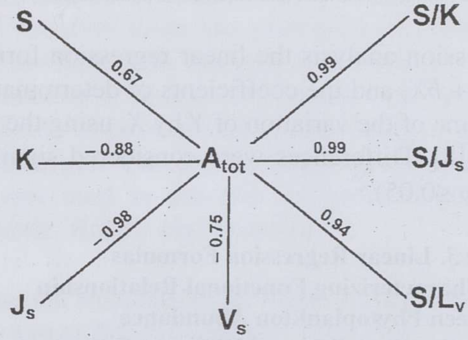

Fig. 3. Correlation graph characterizing the impact of different factors (at the 95-% confidence limits around *r*) on phytoplankton abundance in the Purtse catchment rivers in Augusts 1998–2000. For interpretation of marks see Tables 1 and 2

Results and Discussion

Interaction Between Phytoplankton Abundance and Different Environmental Factors both Natural and Caused by Oil Shale Mining

From Tables 1 and 2 and their interpretation in Figs 2 and 3 it appears that the changes of phytoplankton abundance (A_n, A_{tot}, ratio A_n/M_n, where index *n* indicates the number of sampling point) in Augusts of 1996–2000 are essentially dependent on dynamics of the factors both natural and generated by oil shale mining in the same period. On the basis of the data obtained by correlation analysis (see Figs 2 and 3) it is clearly seen that the impact of meteorological (*S*), hydrological (L_v), hydrogeological (*K*) and geochemical (J_s, V_s) factors on phytoplankton abundance of the Purtse catchment rivers

V_s) factors on phytoplankton abundance of the Purtse catchment rivers has an integrated character. It is particularly clear when composite factors (ratios S/K, S/J_s and S/L_v) and indicator A_1/M_1 are used for correlation analysis. Almost all correlation coefficients are remarkably high (r >0.83). The impact of precipitation (S) on phytoplankton abundance is generally positive (r = 0.42–0.67), but the impact of hydrogeological and geochemical factors on phytoplankton abundance significantly negative (r = –0.58÷ –0.98).

Therefore, increasing phytoplankton abundance (A_1, A_{tot}, ratio A_1/M_1) is followed by a growth of numerical values of ratios S/K, S/J_s or S/L_v. As seen from Figs 2 and 3, phytoplankton abundance is very well correlated with these factors: $r = 0.91 \pm 0.08$. The ratios A_2/M_2 and A_3/M_3 (criterion variables) for the Kohtla and Ojamaa rivers, respectively, also correlate very well with both the annual precipitation amount S and the amount of mine water directed into rivers K, and also with the ratio S/K. Accordingly, using ratios of phytoplankton abundance and number of species is rational in describing the ecological situation of the rivers fallen under anthropogenic load. Dynamics of this parameter is specific to each river polluted due to oil shale mining operations.

The year 1999 was poor in precipitation (S = 670 mm), and the Kohtla River was also essentially affected by ash-dump waters from the Kohtla-Järve oil shale thermal processing plant as seen by the numerical values of the corresponding characteristics ($A_2 = 2625$, $M_2 = 6$, and $A_2/M_2 = 438$). Therefore the harmful impact of oil shale mining on the Kohtla River was combined with pollution from oil shale thermal processing.

Changes in the ratio S/K have certainly an effect on the temperature of the river water, because the temperature of the mine water pumped out from mines is only 7.5 ± 0.5 °C. After sedimentation basins the temperature of mine water rises by 5–7 °C. There are also significant positive correlations between phytoplankton abundance indicators A_{tot}, A_1, A_2 and A_3: $r = 0.92 \pm 0.06$.

Table 3 gives linear regression formulas for calculating phytoplankton abundance indicators A_1 and A_1/M_1 on the basis of numerical values of the factors both natural and generated by oil shale mining for the Purtse River. The coefficient of determination for derived regression formulas is r^2 >0.6 enabling to use these formulas for prognosticating phytoplankton abundance using meteorological and oil shale mining data (see Table 2).

In June 2001 the *Kohtla* mine was closed. The amount of mine water going into the Purtse River decreased to 26 million m^3/yr, and annual precipitation amount in 2001 was about 810 mm. Using Formula (2) from Table 3 gives 89,000 cells/l for the phytoplankton abundance for the lower course of the Purtse River in August 2001. This computational outcome differed from the measured phytoplankton abundance (94,000 cells/l) only by 5,000 units (5.3 %), which was considered a good result. For the period 1996–2000, the proposed model system showed a perfect fit between observed and modelled phytoplankton abundance for the lower course of the Purtse River. Application of the proposed linear regression formulas is rational for composing the projects to improve aquatic biota's conditions of the Purtse River.

At present only the *Aidu* opencast has remained the main generator of mineral pollutants (sulfates, chlorides), discharging the mine water into the Purtse River through the Ojamaa River.

Table 4. **Phytoplankton Composition in the Purtse Catchment Rivers in Augusts of 1996–2001**

Year	Dominant species
	In the Purtse River (point 1)
1996	*Cyclotella* sp.
1997	*Cocconeis placentula, Nitzschia palea*
1998	*Diatoma elongatum, Achnanthes* sp.
1999	*Gomphonema olivaceum*
2000	*Gomphonema olivaceum, Rhoicosphenia curvata, Cocconeis placentula*
2001	*Gomphonema olivaceum*
	In the Kohtla River (point 2)
1998	*Phormidium* sp.
1999	*Gomphonema parvulum*
2000	*Navicula placentula, Gomphonema parvulum*
	In the Ojamaa River (point 3)
1998	*Achnanthes* sp., *Diatoma elongatum*
1999	*Stephanodiscus astraea, Meridion circulare, Dinobryon divergens*
2000	*Gomphonema olivaceum, Gomphonema parvulum*

Phytoplankton Composition

In all water samples, in the phytoplankton complex just diatoms dominated (70 % and more), being specific for watercourses (rivers) [9, 10]. Only in August 1998 *Phormidium* sp. (cyano-procaryota) dominated in the phytoplankton complex for the Kohtla River. From Table 4 one can see that among the dominants some nonplanktonic (littoral, epiphytic or benthic) forms from the genera *Cocconeis*, *Gomphonema*, *Meridion*, *Achnanthes* existed, which can be characterized also as mesosaprobic species. A drastic growth in phytoplankton abundance in the lower course of the Purtse River (94,000 cells/l in August 2001) creates the basis for restoration of fishing importance of catchment rivers. However, the inlet of ash-dump waters into the Kohtla River must also be fully stopped.

Conclusions

Oil shale mine water discharges into the Purtse catchment rivers until 2000 have seriously depressed the vital activity of phytoplankton in the catchment rivers (Purtse, Kohtla, Ojamaa). The indicators of phytoplankton abundance (as well as its composition) are in a good linear correlation with meteorological factors (annual precipitation amount) and those generated by oil shale mining (annual discharge of the river, amount of mine water, input of sulfates and chlorides and their content in mine water). As the impact of precipitation on phytoplankton abundance in August is generally positive ($r = 0.42–0.67$), the impact of hydrogeological and geochemical factors on phytoplankton abundance is characterized by negative correlation coefficients ($r = -0.58 \div -0.98$).

In 1996–2000 the impact of different environmental factors on phytoplankton abundance of the Purtse catchment rivers has been attained an integrated character, causing quite complicated situation in forming of vital activity conditions of phytoplankton, due to mine water discharges. Using ratio of phytoplankton abundance and number of species is rational to describe deviations in the river ecological situation by changes of anthropogenic influence due to operations of oil shale mining and processing. The linear regression formulas ($r^2 > 0.6$, $p \leq 0.05$) for calculating phytoplankton abundance in the lower course of the Purtse River are suggested (on the basis of numerical values of environmental factors).

Due to closing the *Sompa*, *Tammiku* and *Kohtla* mines in 2000–2001, anthropogenic stress on ecological situation of the Purtse catchment rivers has essentially decreased. Phytoplankton abundance has substantially risen in the lower course of the Purtse River. In the amount of phytoplankton different species of diatoms dominated (70 % and more). The situation after closing the mines needs more detailed investigations in order to describe main changes in vital functions of phytoplankton in the Purtse catchment rivers.

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