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Environmental Challenges in the Joint Border Area of Norway, Finland and Russia

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Centre for Economic Development, Transport and the Environment for Lapland

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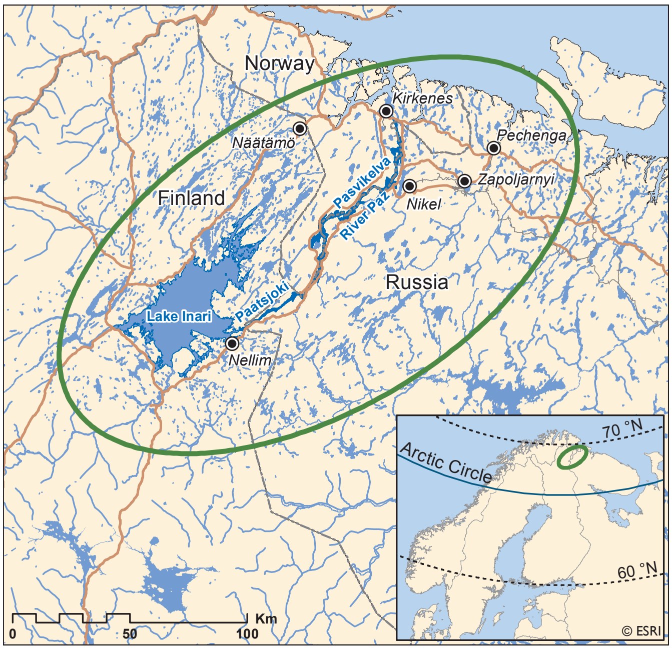

EU ENPI Project *Trilateral Cooperation on Environmental Challenges in the Joint Border Area* was implemented in years 2011–2014 as a collaboration between Finnish, Norwegian and Russian environmental researchers and authorities. This report describes the research that addressed several current areas of interest in the Pasvik watercourse area. The Pasvik watercourse is located in the border area of Finland, Russia and Norway in the northern Fennoscandia and the Kola Peninsula and it is important for the water supply, energy production, fishing, aquaculture, tourism and recreation.

Trilateral cooperation started in Interreg IIIA Kolarctic project of 2003–2006 in which Finnish, Russian and Norwegian environmental authorities and researchers from a number of research institutes developed a joint environmental monitoring programme for the Pasvik River.

Research concentrated on the main water bodies Lake Inarijärvi and the Pasvik River. The main environmental changes are caused by metallurgical industry in Russia and regulation of the Pasvik River for hydropower. Climate change will also affect the state of the environment in the future. The aims of the studies were to develop tools to assess the effects of harmful substances, water level regulation and climate change and to illustrate their effects on different aquatic environments.

The climate change in the border area and the Kola Peninsula was assessed based on a long time series of meteorological observations. A clear change towards increase in temperature and precipitation could be seen. Transboundary pollution was modeled and the results show that SO_2 emissions from the facilities in Nikel and Zapolyarny in the Pechenga area in Russia move to Finnish and Norwegian territory by air. The project developed a monitoring programme to assess the effects and extent of this airborne pollution.

The effects of pollutants, water level regulation and climate change on the ecological condition of the Pasvik River and Lake Inarijärvi was studied. Lake Inarijärvi was found to be in a good state both chemically and biologically, but parts of the Pasvik River suffer from pollution. Water level regulation has changed the ecology of the waterways. Climate change will also cause changes as the rising water temperature will shift the fish species community, for instance.

The existing lake monitoring network was developed further. The small lakes of the border area were monitored and a better monitoring programme based on the most representative lakes and sensitive and cost-effective variables was developed.

The results of the project have wide application. The raw data is of high quality and can be used in future scientific publications. The assessment of climate change in the area and its effect on the regulated water bodies can be of use internationally.

This is the summary report for the project. The project Activities produced detailed expert reports on several different, environmentally relevant subjects in the Pasvik area, which have been compressed into chapters of shortened, simplified reports. Original full text reports are available at www.pasvikmonitoring.org

Chapter 1: Climate change in the border area and modelling of the SO_2 emissions from the Nikel and Zapolyarny facilities

Bjørnevatnet and Nikel. Photo: Juha Riihimäki

1 Introduction

The first part of the project dealt with climate change and transboundary airborne pollutants in the areas surrounding the Pasvik watercourse.

Climate change affects both the nature and human population in the border area of Finland, Norway and Russia. Climate change processes were assessed with a decades-long time series of meteorological observations from the Kola Peninsula. The extensive data set enabled a reliable quantification of the existing changes in climate of the region. Both temperature and precipitation seem to be increasing in the area, and the warming intensity is increasing. However, it should be noted that the climate change is not an evenly distributed process as there are differences between the coastal and continental areas, for example. Detailed assessments of changes in different regions are especially important because they need to be considered in the environmental protection, economic activities and social development of the Kola Peninsula.

The main sources of pollutants in the area are the Pechenganikel mining and metallurgical company's smelter in Nikel and roasting plant in Zapolyarny. Emissions of SO_2 and heavy metals (Ni, Co, Cu, As) are prominent. Total emissions of SO_2 are about 100 000 tonnes annually, 40 000 tonnes from Zapolyarny and 60 000 tonnes from Nikel. Diffusive emissions in Nikel greatly affect areas in the vicinity of the smelter.

Model studies of the sulfur dioxide emissions, dispersion and deposition from Nikel and Zapolyarny industrial plants were performed using two different models, a WRF-Chem model and a TAPM model. Correct information about the emissions is important in order to obtain reliable model results. The model results were compared with monitoring data to verify model performance.

WRF-Chem represents atmospheric processes in a very detailed way. The model is most suited to study processes and specific episodes. Budget routines were included to investigate the different processes of loss of SO_2 from the atmosphere. TAPM can be used to model air pollution for longer time periods and it was run for the year 2011. Both models can be of use in obtaining information of the harmful emissions from the Pechenganikel facilities.

The Pasvik River. Photo S. Grechany.

2 Climate change in the border area

ALEKSANDRA ANTSIFEROVA, OLGA MOKROTOVAROVA, ELENA SIEKKINEN

This assessment of climate change in the Kola Peninsula and the joint border area is based on data of the monitoring network spanning the whole peninsula. Climate data from Russian hydrometeorological stations in Nikel and Janiskoski and from Norwegian automated meteorological station in Svanvik were used for a detailed study of the border area.

Manifestations of climate change are extremely uneven in different areas. Detailed region-by-region assessments of the observed and expected climate changes are especially important because they are to be considered in the course of economic activities in weather-dependent industries and in the regions' social infrastructure development.

The process of global climate change has turned out to be varied and comprises three periods: warming in 1910–1945, slight cooling in 1946–1975, and intensive warming since 1976. Also in the Kola Peninsula the ambient air temperature has changed during 1936–2012. A time series of spatially-averaged yearly anomalies (deviations of the climatic norm of mean values of 1961–1990) of air temperature and linear trends to describe the tendency (average rate) of temperature change in different time intervals illustrates the changes (Figure 1).

The change of annual mean air temperature in the Kola Peninsula was assessed by the values of linear trend coefficient for the three monitoring periods: For the 1st monitoring period (1936–2012) the linear trend coefficient amounts to 0.06°C in 10 years. For the 2nd (1961–2012) it amounts to 0.3°C in 10 years and for the 3rd (1976–2012) it amounts to 0.6°C in 10 years, i.e. the warming intensity is increasing.

Even in the relatively small territory of Murmansk Region the change rate of the average air temperature and precipitation regime is notably different in the western part from that in the central part or at the sea coasts. The geographic distribution of the linear trend coefficients of the mean seasonal anomalies of the air temperature in the period 1976 through 2012 in the territory of Murmansk Region is presented in Figure 2.

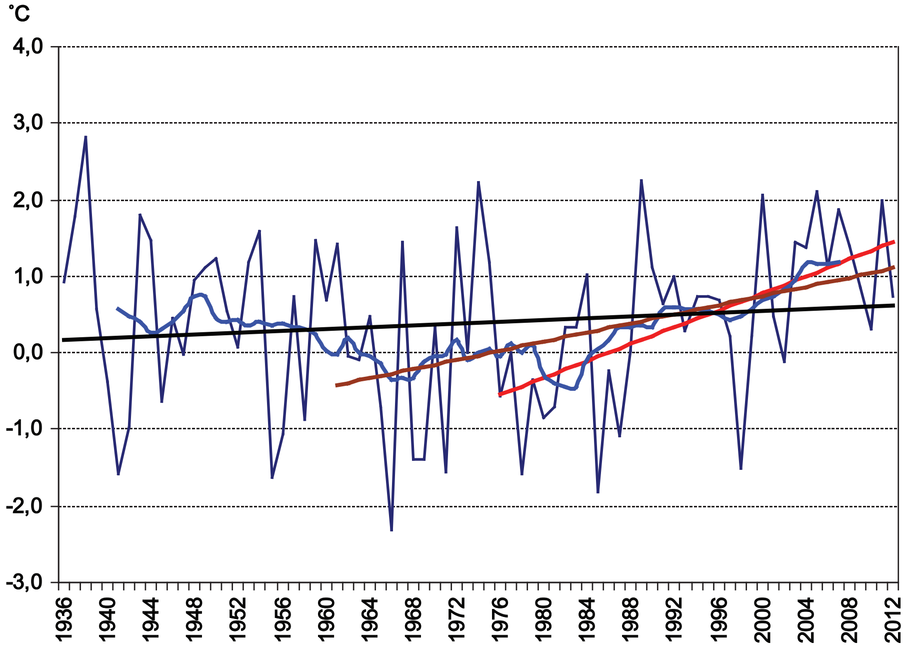

Figure 1. Anomalies of the annual mean (January–December) air temperature (°C), averaged for the Kola Peninsula territory in the monitoring period from 1936 through 2012. The curve correlates with 11-year sliding averaging. The straight lines show linear trends for the periods 1936–2012, 1961–2012, and 1976–2012.

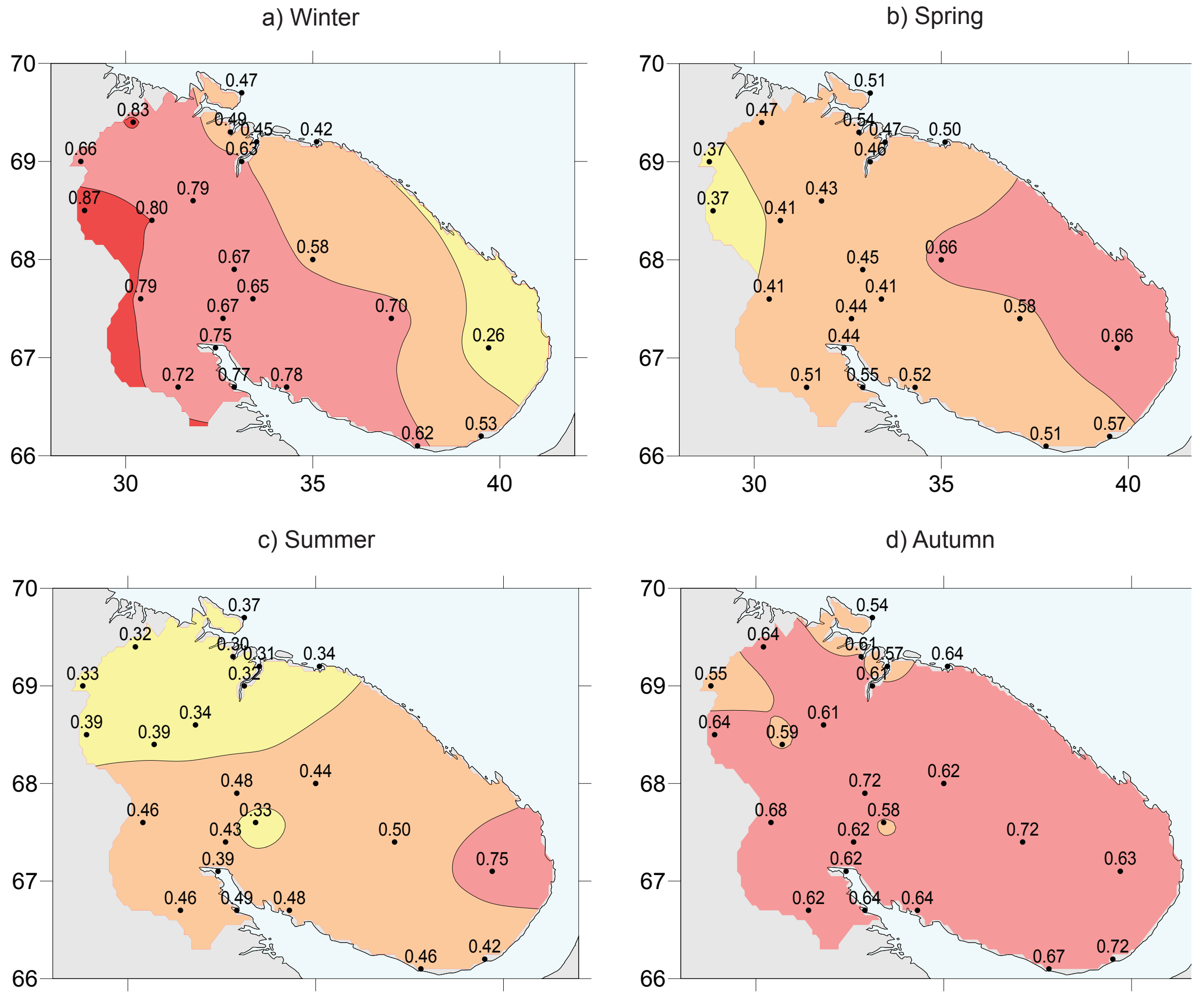

Figure 2. The average rate of seasonal air temperature changes (^{o}C/10 years) in the Kola Peninsula territory according to the monitoring data from 1976–2012. The maximum increase of the mean air temperature is observed in winter in the west of the Kola Peninsula. However, in spring and summer the warming intensity in that area is minimal. The geographic distribution of the mean seasonal air temperature increase is more even in autumn.

Climate change in the border area in the values of mean annual, mean seasonal and extreme air temperatures

The Janiskoski station performs a full range of meteorological observations with radiological monitoring, it monitors cross-border pollutant air transfer and samples precipitations for chemical composition analysis.

Janiskoski, Nikel and Svanvik hydrometeorological stations' temperature regimes are shown in Figure 3. In Janiskoski the mean annual air temperature is -0.7°C. January is the coldest and July is the warmest month with many-year mean air temperatures of -13.3°C and +13.6°C, respectively. In Nikel the mean annual air temperature is +0.2°C. January is the coldest and July is the warmest month with temperatures of -10.7°C and +13.1°C, respectively.

Time series describing the air temperature annual and seasonal anomalies in the period of 1955 through 2012 and linear trends characterizing the tendency (average rate) of the temperature change in different time intervals shows that the warming intensity has been increasing at the both stations. At the same time, the increase of the annual mean air temperature at the Nikel station is higher than that at Janiskoski both yearly and specifically in each season. Just like on an average in the Kola Peninsula, the coldest 11-year observation period at the stations Nikel and Janiskoski was 1976–1988 and the period since 2002 until now is the warmest.

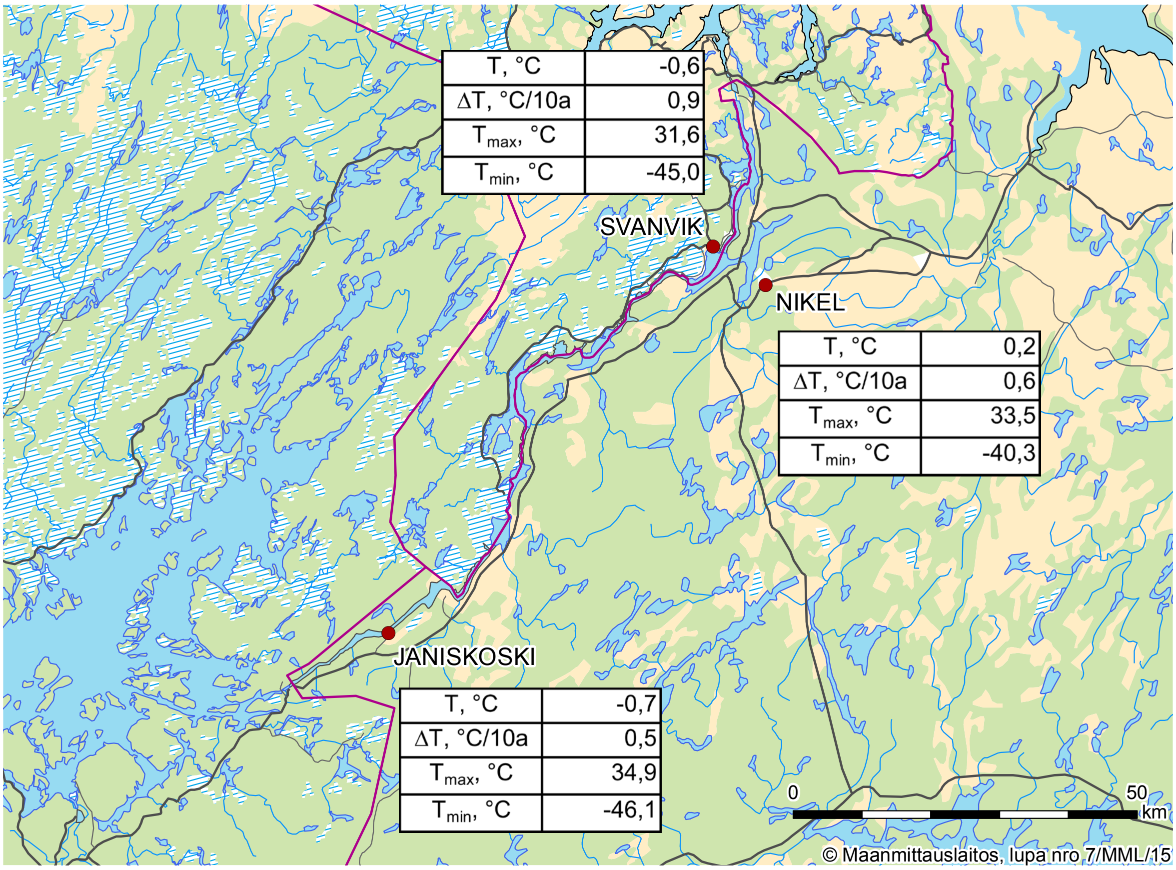

Figure 3. Temperature regime in the areas of Janiskoski, Nikel and Svanvik hydrometeorological stations

Currently, the period of 1961–1990 is regarded as the baseline period for calculations, i.e. the climatic norm. However, there is an opinion that the "baseline" period should be approximated to the present time, i.e. the observation period 1971–2000 should be used (Table 1).

Noticeably, the monthly mean air temperature in the warmest 11-year period is higher than the climatic norm in every month except February. In particular, while there is an increasing trend of the mean air temperature both yearly and, especially, in winter, the monthly mean air temperature in February at the Janiskoski station has been below the climate norm 8 times over the last 11 years, and 2 times the negative anomaly exceeded the average quadratic deviation. This confirms once again the climatologists' warnings that even during the "global warming" period considerable negative anomalies of air temperature are possible.

The seasonal division of the year in the Kola Peninsula is winter: November–March; spring: April, May; summer: June–August and autumn: September–October. One of the signs of the seasonal change from winter to summer and vice versa is a permanent crossing of 0°C positively (beginning of spring) and negatively (beginning of winter). The analyses of the dates of this zero crossing in the period since 1955 show that at the Janiskoski and Nikel stations the duration of the period with daily mean air temperature above 0°C is increasing (≈3 days over 10 years). In other words, winter has begun to start 1.2–0.9 days later and spring 1.9–2.7 days earlier in ten years.

In the Janiskoski and Nikel stations in the period 1955–2012 the number of days with maximum temperature extremes has been growing in all seasons. However, the frequency trends were statistically insignificant. The frequency trends of the minimal temperature extremes in all seasons both in the period since 1955 and since 1976 at both stations are negative but only the trend of the minimal temperature extremes in winter at the Nikel station is statistically significant.

It seems that the severity of the border area climate is decreasing. Meteorological data from the automated Norwegian station Svanvik was used for a more detailed study of the climate in the border area. However, the Svanvik data was shorter and had gaps and some of it had to be restored based on the data of Nikel. Due to this certain calculation errors should be taken into account.

Table 1. Monthly mean air temperature (˚C) for three periods: the climate norm 1961–1990, 1971–2000, and for the warmest 11-year observation period 2001–2012.

Period	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**	**Year**
Janiskoski hydrometeorological station													
1961-1990	-14.2	-13.1	-8.3	-2.3	4.0	10.0	13.3	10.9	5.9	0.1	-7.0	-12.0	-1.1
1971-2000	-13.6	-12.3	-7.5	-2.2	3.9	10.2	13.5	10.9	6.1	-0.1	-7.6	-11.7	-0.9
2001-2012	-12.1	-13.7	-7.8	-0.8	5.0	10.4	14.1	11.4	6.8	1.0	-5.9	-9.2	-0.1
Nikel hydrometeorological station													
1961-1990	-11.9	-11.1	-6.9	-2.0	3.6	9.6	13.0	11.0	6.5	0.5	-5.7	-9.8	-0.3
1971-2000	-10.9	-9.8	-5.9	-1.7	3.6	9.5	13.2	11.2	6.6	0.4	-5.9	-9.1	0.1
2001-2012	-9.0	-10.5	-5.8	0.0	4.7	9.7	13.8	11.8	7.5	1.7	-4.0	-6.6	1.1

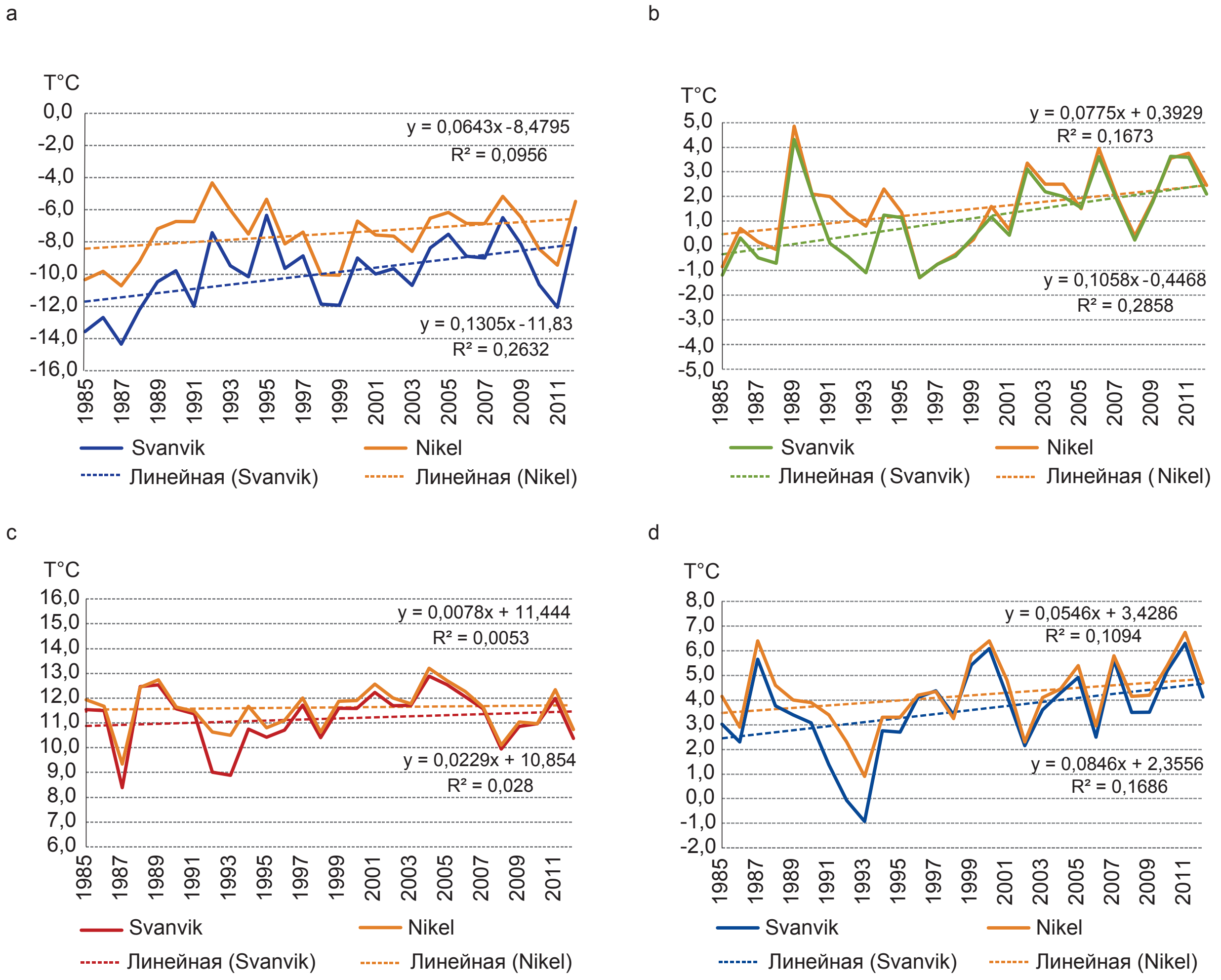

Figure 4. Changes in the mean seasonal air temperature (˚C) in (a) winter, b) spring, c) summer, d) autumn) for the monitoring period 1985 through 2012 at the meteorological stations Nikel and Svanvik. Straight lines show linear trends.

The mean annual air temperature is lower in Svanvik than in Nikel. However, the linear trend coefficient demonstrating the growth rate of the mean annual air temperature in Svanvik is higher and estimated as 0.9°C in ten years during the period of 1985–2012. In the same period in Nikel the linear trend coefficient is almost two times lower and amounts to 0.5 °C in 10 years. The same tendency is observed in all seasons (Figure 4). In Svanvik the largest increase of the mean seasonal air temperature is observed in winter (with the linear trend coefficient for this season equal to 1.3°C in ten years), and the least increase is observed in summer (0.2°C in ten years). Statistical significance can not be determined due to Svanvik's data being partly restored.

Precipitation regime's changes in the values of annual, seasonal and daily maximum total precipitation

The average annual precipitation in the border area is 500 mm. Table 2 presents the many-year mean amounts of precipitation per month, as well as annual total precipitation amounts in the period 1976 through 2012. As a rule, in the summer months the amount of precipitation is 2–2.5 times larger than that in winter. In summer precipitation intensity is considerably higher than that in winter. The daily precipitation of >10 mm in summer is fairly usual. Such precipitation may occur several times during one season. In winter, there are considerably fewer days with precipitation of >10 mm, not every year; 0.5 mm per day is the most common.

Since the middle 1970's an increasing trend of annual precipitation amount has been observed at the Janiskoski and Nikel hydrometeorological stations. This increase is 1.8 mm/month for 10 years at the Janiskoski station and 2.4 mm/month for 10 years at Nikel station.

The changes of total precipitation anomalies are different in different seasons. At the Janiskoski station an increase of seasonal precipitation is observed in all seasons except for winter. In spring, summer, and autumn precipitation is 3–4 mm/month for 10 years. At the Nikel station an increase of precipitation in all seasons is observed and the largest increase is in autumn: 6 mm/month for 10 years.

Heavy rain and snowfall create the greatest problems for various industrial activities. In winter virtually no changes are observed in the number of days with extreme precipitation both at Janiskoski and at Nikel. In spring, the increase in the number of days with extreme precipitation is greater at Nikel than at Janiskoski. In summer, slight increase in the number of days with extreme precipitation is observed at the Janiskoski station while a decrease is observed at Nikel. In autumn, certain increase in the number of days with peak precipitations is observed at the both stations. Noticeably, the changes in all seasons are statistically insignificant.

Table 2. Average precipitation (mm) per month, season, and year.

Janiskoski station												
month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	31	25	26	32	40	61	75	68	50	51	36	29
season	winter 147			spring 72		summer 204			autumn 101		winter 147	
year	524											
Nikel station												
month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	37	28	28	28	32	54	69	60	48	55	40	36
season	winter 169			spring 60		summer 183			autumn 103		winter 169	
year	515											

Wind regime and frequency of various wind speed grades

A typical feature of the border area wind regime is its monsoon pattern, i.e. a clear seasonal change in the prevailing wind directions. In winter southern winds from the mainland prevail in Nikel and due to the local terrain differences south-west winds prevail in Janiskoski (Figure 6). In summer, northern and north-eastern winds from the Barents Sea prevail in Nikel and north-eastern winds are the most frequent in Janiskoski.

The annual mean wind speed in Nikel is 3.8 m/s and fluctuates seasonally within 1 m/s. The wind speed in Janiskoski is somewhat lower with the annual mean of 1.8 m/s and the yearly fluctuation of 0.5 m/s.

In Nikel the highest frequency is observed for the average wind speed within the grade of 2–3 m/s. In Janiskoski over 46 % of wind accounts for very weak wind up to 1 m/s. In Nikel the concentrations of contaminants from the Pechenganikel mining and metallurgical industry in the ambient air may increase during the periods of weak wind, or the so-called stale air. At the Nikel station the number of days with still air and low speed wind has somewhat increased since the middle 1970's, while at the Janiskoski station the number of stale air cases has decreased.

One of the most important parameters of the wind regime is the average number of days with stormy wind (wind speed ≥15 m/s). The number of stormy wind cases increases in the winter months in the period of the highest frequency and intensity of cyclone processes and decreases almost 5 times in summer (Table 3). Since the middle 1970's the number of stormy days has been observed to decrease 3 days in 10 years both at the Nikel and Janiskoski stations.

Conclusions

The climate change in the border area is characterized by thermal regime changes, an increase of the mean annual and mean seasonal air temperature in particular. The intensity of this increase is growing, and it is more significant in winter. In Nikel and Janiskoski the frequency of the days with maximum air temperatures extremes is growing, along with decreasing of the number of days with minimal temperatures.

Both at Janiskoski and Nikel precipitation is increasing. The largest increase is observed at the Nikel station in autumn. In spring and autumn the number of days with extreme precipitation is increasing in Nikel and at Janiskoski the number is increasing in all seasons except winter.

The wind demonstrates monsoon pattern in the border area. In winter, southern and south-western winds prevail, while in summer the prevailing wind directions are north and north-east. At Nikel a decrease in the number of stormy days and a growing number of days with low wind speed can be seen in the period since the middle 1970's and until the present. Both the number of days with stormy wind and low speed wind is decreasing at Janiskoski.

Table 3. Average number of days with gusts of wind 15 m/s or more. The average number of days less than 1 means that such gusts of wind do not occur every year.

Janiskoski station												
month	I 1	II 1	III 1	IV 1	V 1	VI 1	VII 0.2	VIII 0.4	IX 0.5	X 1	XI 1	XII 1
year	10											
Nikel station												
month	I 9	II 9	III 8	IV 6	V 5	VI 4	VII 2	VIII 2	IX 2	X 7	XI 8	XII 7
year	71											

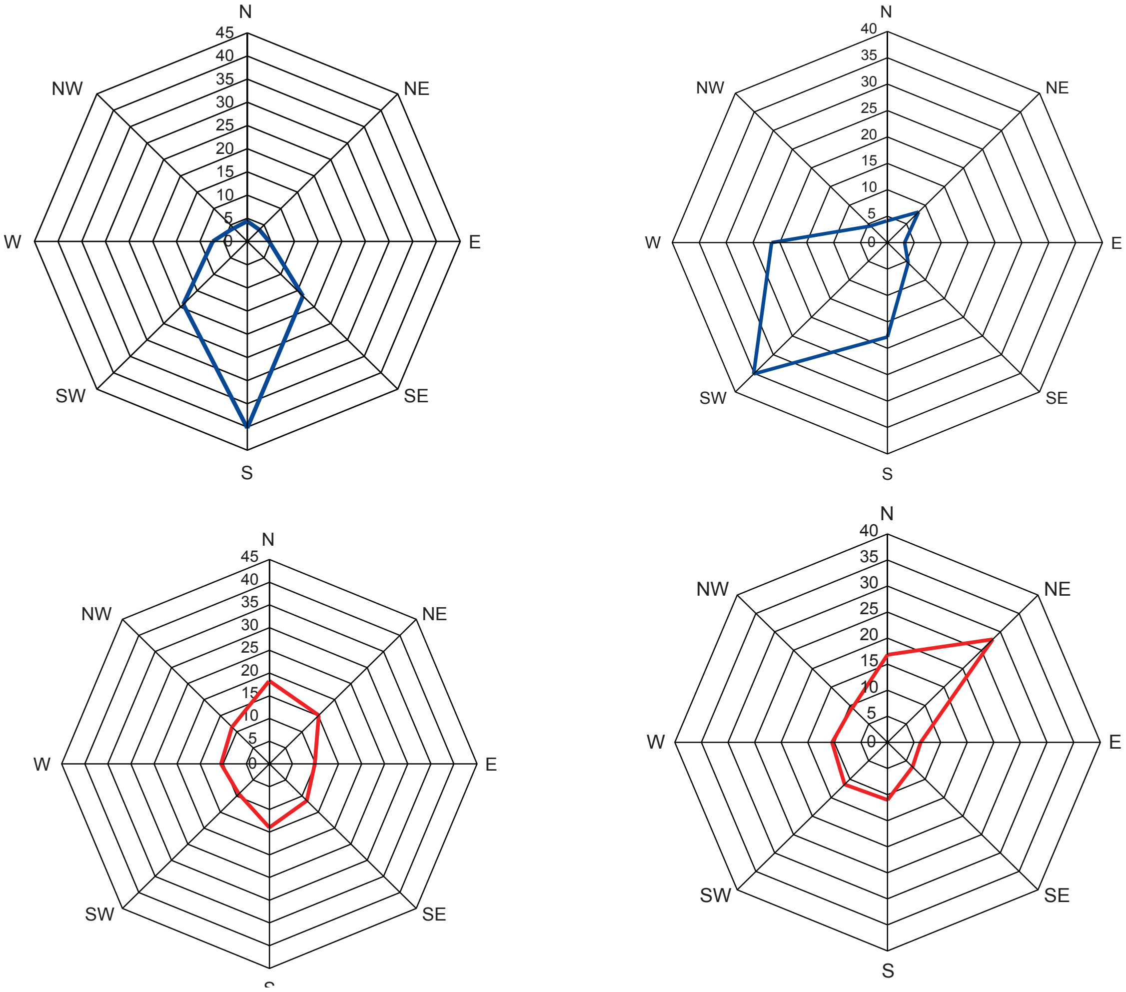

Figure 6. Seasonal frequency of winter (blue) and summer (red) wind directions. In Nikel station (left) the still air frequency is 19% in winter and 9 % in summer. In Janiskoski station (right) the still air frequency is 27 % in winter and 20 % in summer.

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3 Emissions, dispersion and deposition of SO_2 from Nikel and Zapolyarny, model studies

TORE FLATLANDSMO BERGLEN, BJØRG JENNY ENGDAHL, ANNA VON STRENG VELKEN, LIU LI, VO THANH DAM, ØYVIND HODNEBROG, FRODE STORDAL

The soil in the Russian-Norwegian border area is rich in metals and minerals. In 1921 nickel was discovered in the soil near Kolosjoki in the Pasvik Valley, close to the Norwegian border. A smelter was established in the 1930s to exploit these nickel resources. Nickel is an important constituent in stainless steel and hence a strategically important resource. The nickel producing facilities were an important target during World War II. After the war the plants were reconstructed. Now the plants are owned by Kola Mining and Metallurgical Company (Kola MMC), a subsidiary of Norilsk-Nickel[1].

The ore in the border area is rich in heavy metals, but also contains a fraction of sulphur (5–6 %). The industrial processes cause large emissions of sulfur dioxide (SO_2) and heavy metals. The combined SO_2 emissions from the two facilities are reported to be over 100 000 tonnes per year, about 40 % from Zapolyarny and 60 % from Nikel respectively. The emissions from the briquetting facility in Zapolyarny and the smelter in Nikel affect air quality in the area, both on a local and on a regional scale.

NILU has been conducting a monitoring program in the border area since 1974, funded by Norwegian authorities (Ministry of Climate and Environment and Norwegian Environment Agency). At the moment there are two well equipped monitoring stations operating, one at Svanvik, 8.5 km to the west of the city of Nikel and one in Karpdalen, about 30 km north of Nikel and 20 km north-west of Zapolyarny. Both Svanvik and Karpdalen monitor SO_2 and meteorology continuously, in addition there are sampling and analysis of heavy metals in air and precipitation. There is also long term monitoring of SO_2 at Viksjøfjell using passive samplers. These are the stations at the Norwegian side of the border. In Russia there are air quality monitoring stations in Nikel and in Zapolyarny using high resolution monitors[2]. See map in Figure 1 for location of the nickel producing facilities and the monitoring stations in the border area.

As already stated, emissions from the nickel producing facilities in Zapolyarny and Nikel affect the environment both on a local and on a regional scale. In order to quantify the impact of these emissions, there is a need to better understand the sources, dispersion and loss of the pollution from these facilities. Atmospheric models constitute a good tool to better answer this need. In that respect models also constitute a valuable supplement to monitoring. The main focus of the NILU studies is to model the emissions, dispersion, chemical loss and deposition of the SO_2 emitted from the briquetting plant in Zapolyarny and the smelter in Nikel using two different atmospheric models, WRF-Chem (Weather Research and Forecasting with chemistry included) and TAPM (The Air Pollution Model, developed by CSIRO).

The atmosphere is a complex system that behaves according to the laws of physics and chemistry. The basic assumption in modelling is that the atmospheric processes can be solved mathematically. A model is a large set of equations that is solved using supercomputers. However, simplifications, also called parameterizations, have to be made. Parameterization is a method to represent equations using variables and formulas that are easier to solve mathematically.

Both WRF-Chem and TAPM are Eulerian models. This means that the atmosphere is divided into boxes. Then the variables are calculated for each grid box. The models include processes like emissions, chemical loss, dry deposition (loss onto surfaces), wet deposition (loss by rain), and transport between adjacent grid boxes (by wind or convection). For emissions from point sources it is important to have fine resolution near the emission point, in these studies this means the stacks at the smelter, and more coarse resolution at a regional scale. Figure 2 shows the model domains applied in the WRF-Chem model with fine resolution near the Zapolyarny and Nikel facilities (1 × 1 km^2 grid boxes), then a regional model domain

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[1] http://www.nornik.ru/en/about-norilsk-nickel/operations/kola-mmc [URL 17-Dec-2014]

[2] See http://www.kolgimet.ru/index.php?option=com_content&view=article&id=54&Itemid=239 [URL 22-Dec-2014]

Figure 1. Nickel producing facilities (Nikel and Zapolyarny) and monitoring stations for air quality, precipitation quality and meteorology in the border area between Norway and Russia.

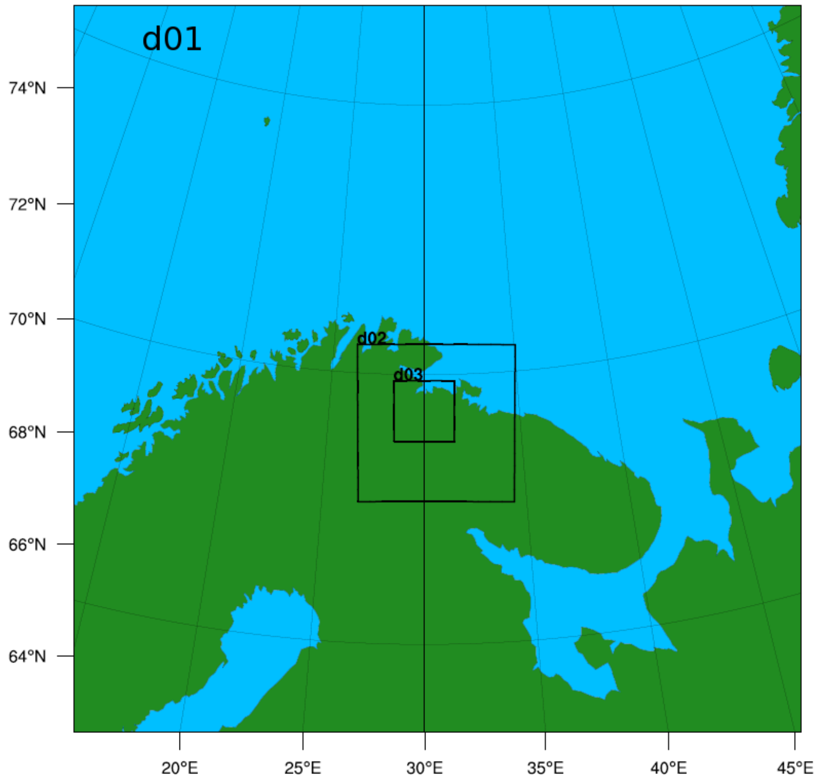


Figure 2. The model domains: domain d01 is the outermost domain, domain d02 is an intermediate/regional domain while domain d03 covers the area close to Nikel and Zapolyarny.

(5×5 km^2 grid boxes), and finally an outer model domain (25×25 km^2 grid boxes).

The SO_2 emissions from Nikel can vary considerably even on a short time scale, from virtually no emissions to large plumes of flue gas pouring out of the smelter and stacks. This variation is probably dependent upon the smelting processes employed but no details are known. Due to this lack of information concerning the emissions variation, the model assumed constant emissions, adding up to 40 000 tonnes SO_2 per year from Zapolyarny and 60 000 tonnes SO_2 per year from Nikel.

In Nikel a large fraction of the flue gas is emitted at ground level, i.e. from the smelter buildings. These emissions affect the air quality in the vicinity of the smelter and also local air quality in the city of Nikel (when the wind is coming from the north). The aim of a stack is to emit pollutants high above the ground so that the flue gas is diluted when it reaches the ground (lower concentrations). The proportion of diffusive ground level emissions is not known. For the Nikel smelter, the model assumed that 50 % were emitted at the ground (diffusive emissions) and 50 % from 160 m above ground level (layer 4 in the model).

WRF-Chem model

WRF-Chem (The Weather Research and Forecast with chemistry included) model has been applied to study two specific episodes (Engdahl et al. 2014). During the summer episode in June–July 2007 there were large emissions combined with stable atmosphere and weak wind. In this study the period 1.–7. July 2007 was investigated. During winter 2010/11 there were many episodes with high concentrations in Karpdalen. Karpdalen is influenced by emissions from both Zapolyarny and Nikel. The period 23. December 2010–7. January 2011 was investigated.

The WRF-Chem model is able to describe air pollution on both local and regional scale. A nested grid was applied to the study area, which was divided into three domains (Figure 2). The largest domain included the northern regions of Fennoscandia, northwest Russia and the Barents Sea with grid box size of 25×25 km^2. The middle domain covered eastern Finnmark, some regions of Northern Finland and the region around Nikel with grid box size of 5×5km^2. The smallest domain concentrated on the immediate vicinity of the emission sources with grid box size of 1×1 km^2. In the vertical the atmosphere was divided into layers, thin layers close to the ground and gradually increasing layers with altitude.

As input data to the model, prescribed meteorological data from WRF were applied. In a way, these data are the same as data used for weather forecast. Data from WRF were compared with analysis data from European Centre for Medium Range Weather Forecast, ECMWF. The WRF data compared well with the analysis data. This means that the meteorological input data represent well the meteorological conditions in the atmosphere, like wind direction and wind speed, temperature, etc. Especially wind direction and wind speed, as well as atmospheric stability are important parameters for dispersion of air pollution. In addition, wet deposition/rainfall is an important loss process for sulphur. As described earlier the model assumed constant emissions of SO_2, 40 000 tonnes per year from Zapolyarny and 60 000 tonnes per year from Nikel. For Nikel 50 % were emitted at ground level and 50 % at 160 m above ground.

During the beginning of the summer episode of 1.–8. July 2007 there was a high pressure system over the Barents Sea and a low pressure system south from the Kola Peninsula. This caused dry weather and absence of strong winds, only some northeastern winds were noted. At the end of the episode the high pressure area had moved eastwards, wind had grown stronger and blew from the east. The northeastern winds transported the emissions from Nikel and Zapolyarny towards the city of Nikel and also some towards Svanvik. The SO_2 concentrations are generally highest in these areas near the smelter. But emissions can disperse over relatively large areas and even far into Finland, Sweden and Norway, though concentrations farther away from the sources are much lower.

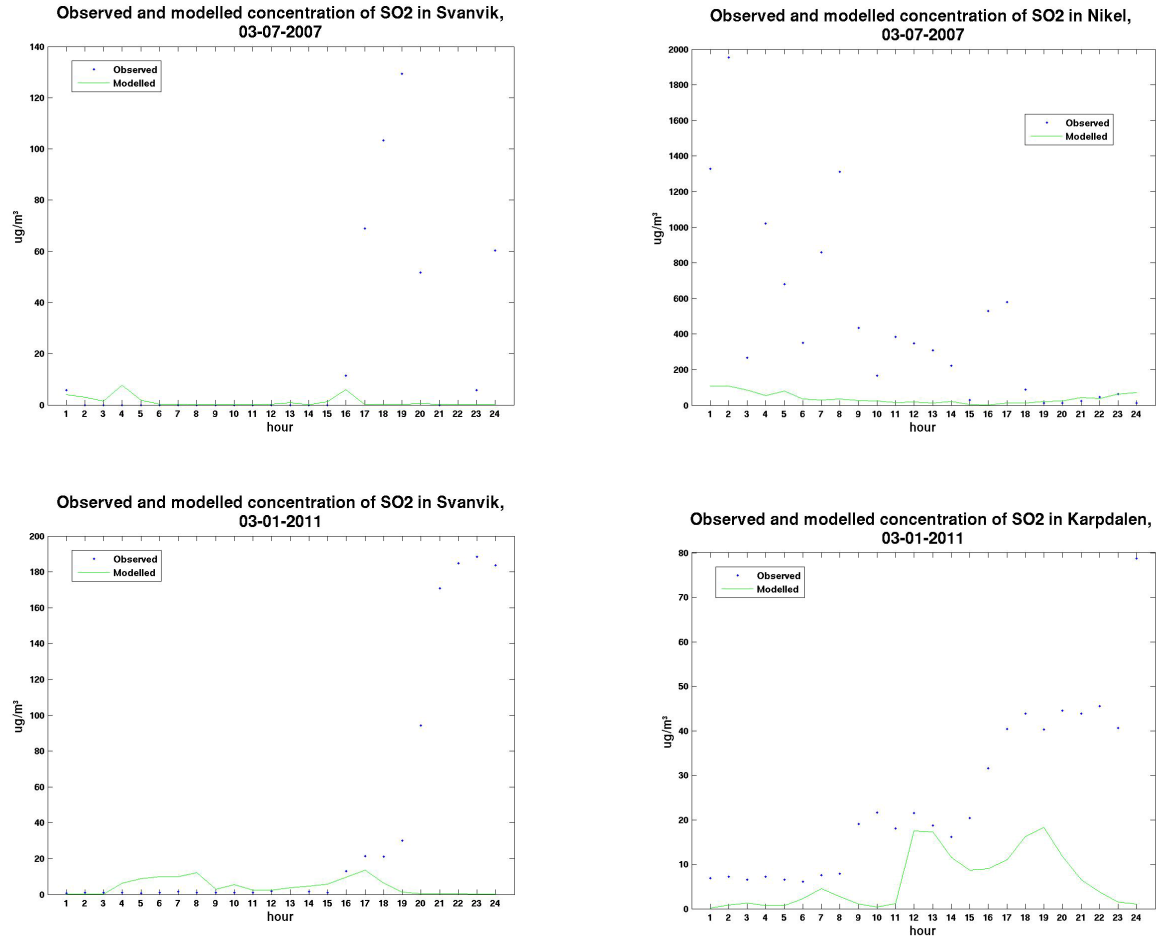
In the beginning of the winter episode of 23. December 2010–7. January 2011 there was relatively weak wind from the west, which changed suddenly into stronger southern wind around the turn of the year. After a while there was some northern wind, but the episode ended with southern wind again. Stable conditions and weak winds transport the emissions slowly away from the city of Nikel and the local concentrations north of the smelters are therefore higher.

Comparison with observations is the only way to verify model performance. Model results were compared with observations of Svanvik, Nikel (only summer episode) and Karpdalen (only winter episode) (Figure 3). Observations show a pattern typical for monitoring stations located close to major emission sources, there are usually very low concentrations when the wind is coming from other directions than the smelter. The gas plume is well defined close to the sources and when the flue gas plume hits the monitoring station, the concentration suddenly increases.

The modelled concentrations are lower than the observed maximum concentrations and the variation in actual concentrations is larger. A possible explanation for this is that in the real atmosphere the gas plume from the stacks is well defined, whereas in the model it will be distributed evenly within the grid boxes ("levelled out" in a 1 × 1 km^2 grid box). Another explanation is that the model emissions are not well represented. The gas is also emitted at the ground level (diffuse emissions), not only from the stacks, but no reliable information exists concerning the ground:stack emission ratio. Especially Svanvik is affected both by ground level emissions and stack emissions. There is also a no information about the time variation of the emissions. In the model constant emissions are assumed whereas in the real atmosphere the emissions will vary considerably on a short time scale. Correct emission information is crucial to obtain more precice model results.

Plots showing the dispersion in the three model domains have been elaborated (Figure 4). During the summer episode the winds were stronger and dispersion more effective on a regional scale. During the winter episode there were stable conditions, weak winds and slow dispersion (results not shown). Short "films" were also made to show the dispersion during the summer episode [3].

A budget quantifying the processes important for SO_2 was elaborated as a tool in the model development. These routines were also helpful in the assess-


Observed and modelled concentration of SO2 in Svanvik, 03-07-2007

Observed and modelled concentration of SO2 in Nikel, 03-07-2007

Observed and modelled concentration of SO2 in Svanvik, 03-01-2011

Observed and modelled concentration of SO2 in Karpdalen, 03-01-2011

Figure 3. Modelled and observed concentrations of SO_2 from (a) Svanvik 3. July 2007, (b) Nikel 3. July 2007, (c) Svanvik 3. January 2011, and (d) Karpdalen 3. January 2011. If the observations are close to 0, they are not visible in the plot (blue dots).

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[3] Please see "films" at [visited 01-03-2015]:
http://folk.uio.no/torefl/WRF-Chem/Domene1_SO2-SO4_delay10.gif
http://folk.uio.no/torefl/WRF-Chem/Domene2_SO2-SO4_delay10.gif
http://folk.uio.no/torefl/WRF-Chem/Domene3_SO2-SO4_delay10.gif

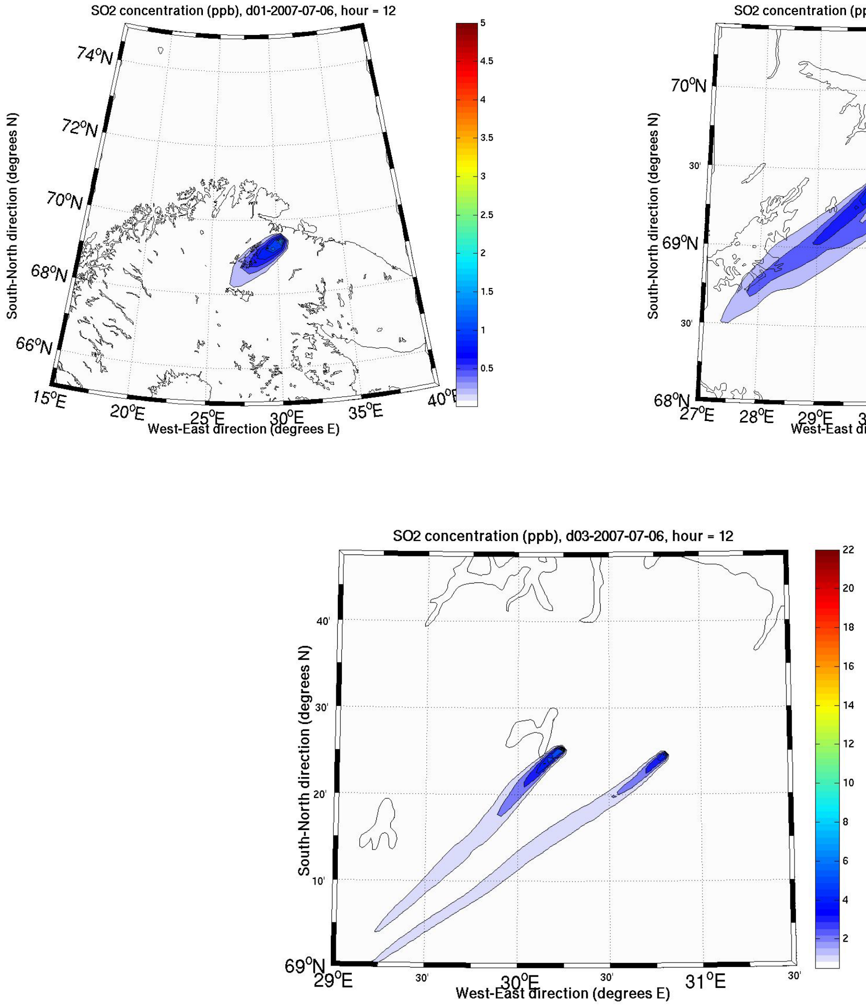

Figure 4. Dispersion of SO_2 for 6. July 2007 at 12h UTC a) model domain 1 (outermost domain), b) model domain 2 (intermediate) and model domain 3 (innermost domain). Please note different scale in plots (a) and (b) compared to plot (c). Unit: ppb (parts per billion, 10^{-9}, mixing ratio) as sum over the lowermost model layers.

ment of the wet deposition parameterization. Wet deposition is an important process and has a large effect on SO_2 and H_2SO_4 concentrations. Thus a budget was calculated to determine the contribution from each single process (dry deposition, wet deposition, transport, chemistry etc.) within the model grid (largest domain).

SO_2 emissions and transport into the model domain are the two most important sources during both summer and winter episodes. Emissions are positively the largest source of SO_2, especially in boxes near Nikel, and transport from the outer edges of the model domain are minor. There is a large difference between the summer and winter episodes concerning the pathways of loss of SO_2 from the atmosphere. Sunlight, especially shortwave UV, drives the chemical processes in the atmosphere (photochemistry) and sunlight is abundant in summer (midnight sun) and absent in winter. Sunlight generates OH, which is the most important oxidant in daytime chemistry. OH also oxidizes SO_2 to H_2SO_4. Chemical loss is the most important summertime process of loss of SO_2 from the atmosphere, the others being wet deposition and dry deposition.

During the winter there is a polar night and total absence of direct sunlight in the border area. Chemical loss is minor in wintertime due to low levels of oxidants in the atmosphere (e.g. OH). Because only a little sulfuric acid is formed, all of the reactions are reduced. The main loss processes during winter are wet deposition and dry deposition.

Deposition, dry or wet, is the final removal process of sulphur from the atmosphere. Sulphur deposited on the ground will eventually contribute to acidification. Oxidation changes SO_2 into H_2SO_4 but does not remove it from the atmosphere.

TAPM model

TAPM (The Air Pollution Model developed by CSIRO) was set up for the border area and run for the year 2011, i.e. the meteorological data represented 2011. The set up concerning model domains and emissions were similar to the WRF-Chem (see previous section). Monthly mean and annual mean concentrations were put to file, as well as results of dry and wet deposition. In addition hourly mean results for the grid boxes representing Svanvik, Nikel smelter, city of Nikel and Zapolyarny were put to file. Model – observation comparison for hourly mean values at Svanvik is shown in Figure 5. Annual mean ground level values for the inner model domain are shown in Figure 6.

For the Svanvik station the model tends to overestimate the peak maximum values, maximum value in the model is 3300 µg/m^3 of SO_2 while observations show maximum 858 µg/m^3, i.e. the model maximum is a factor 4 higher than observed. The model also overestimates the annual mean concentration (model results 23 µg SO_2/m^3 vs observations 7,3 µg SO_2/m^3). It is difficult to compare short term values at Russian stations since the observations are 20-minutes mean while the model calculates 1-hr means. For Zapolyarny and Nikel the model underestimates the observed values concerning annual mean concentrations (results not shown).

Dry deposition is the main loss pathway close to the smelter. The dry deposition results resemble to a large extent the ground level concentrations (results not shown). This is logical since dry deposition is a function of ground level concentration and deposition velocity. Wet deposition is a function of concentrations in the column of air, solubility of the compounds, clouds and rainfall.

To estimate deposition of heavy metals a simple method has been elaborated. The best information available concerning deposition of sulphur and deposition of Ni are the observations from Svanvik and Karpdalen where both components were sampled an analyzed simultaneously during the period 1993–2003. The nss-S:Ni-fraction[4] was about 35 at Svanvik during this period. The basic idea here is then to use the observed nss-S:Ni-ratio from 1993–2003 from Svanvik and Karpdalen and the model calculated deposition of sulphur from TAPM to estimate deposition of Ni. In this study a nss-S:Ni-ratio of 25 and 30 was assumed. This is lower than observed during 1993–2003. But given that the emission of sulphur has decreased and emissions of Ni increased since then the

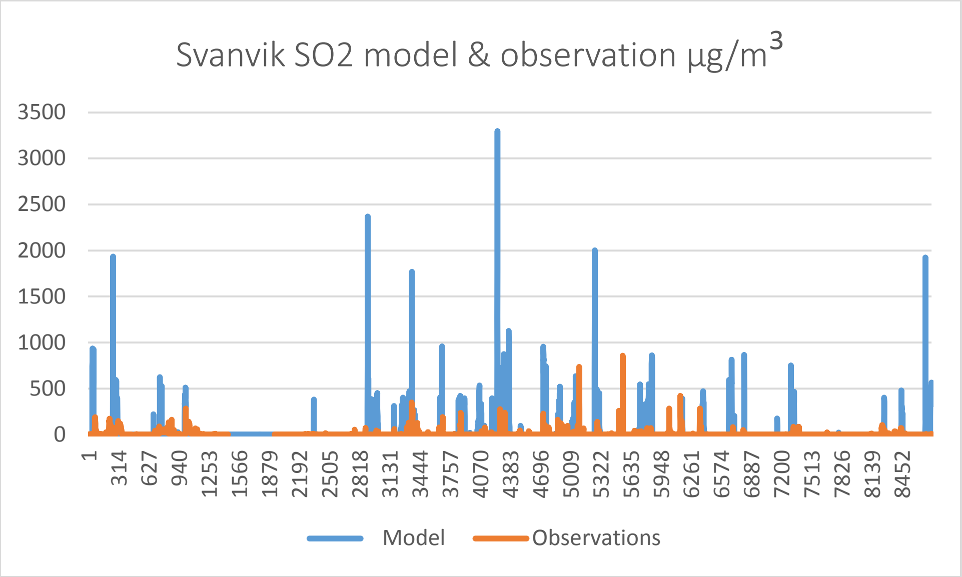

Figure 5. Model results and observations (hourly mean values) from the Svanvik monitoring station, counting hours from 1st January 2011. Unit µg SO_2/m^3.

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[4] nss-S is abbreviation for non sea-salt sulphur

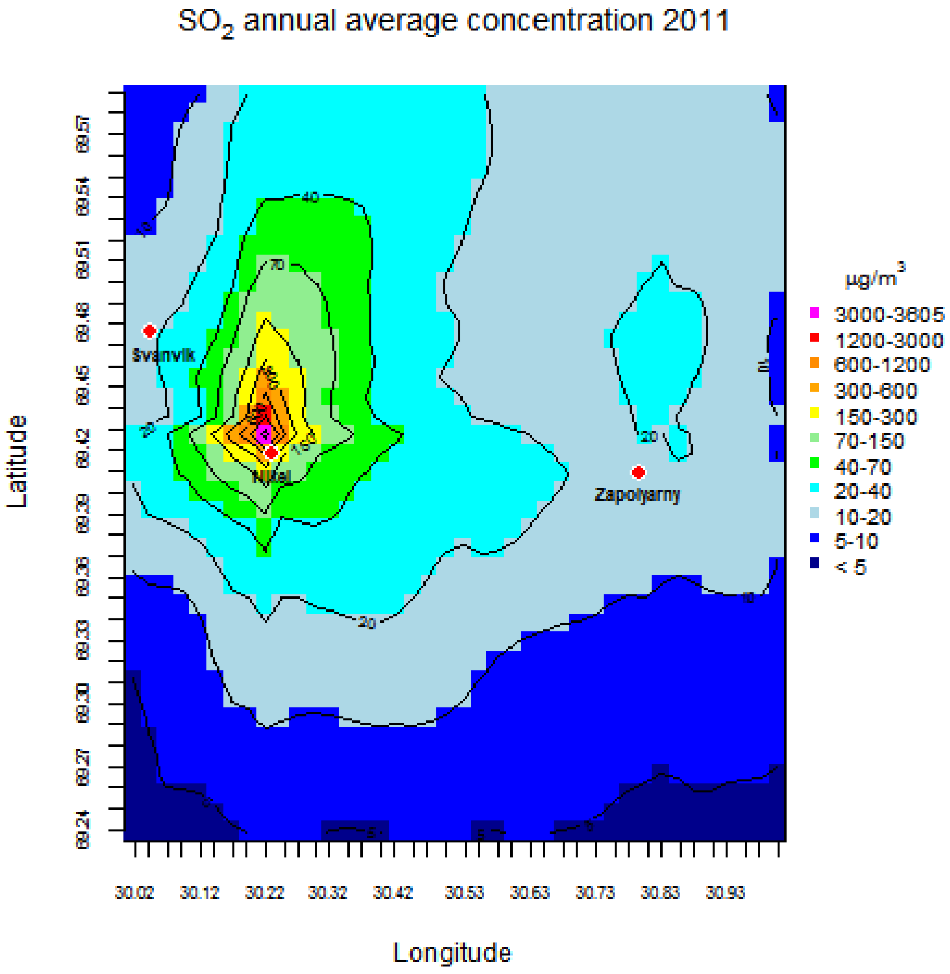

Figure 6. Annual mean concentration of SO_2 for the year 2011 for the area close to Nikel and Zapolyarny. Unit: µg/m³.

ratio is likely lower now than 20 years ago. Ni-deposition for 5 stations and 9 lakes in the border area were estimated. For Svanvik the estimate is lower than observations, but within a factor 2 of the observed values of Ni.

Conclusions

Models represent an important tool to better understand emissions, dispersion and loss of pollutants emitted from smelter facilities in the border area. Correct information about the emissions is crucial in order to obtain reliable model results. Total emissions of SO_2 is about 100 000 tonnes annually, 40 000 tonnes from Zapolyarny and 60 000 tonnes from Nikel. Diffusive emissions in Nikel greatly affect areas in the vicinity of the smelter. It is also important to represent wet deposition correctly in the model. Meteorology, especially wind and stability, are important factors for dispersion from the smelters.

The WRF-Chem model (Weather Research and Forecasting with chemistry included) has been set up for the border area with a nested grid centered on Zapolyarny and Nikel. The periods 1.–7. July 2007 (during the summer episode 2007) and 23. December 2010–7. January 2011 (winter with elevated concentrations) have been investigated. The model tends to underestimate the concentration in episodes. Budget routines were included to investigate the different loss processes. Chemistry is an important loss process in summertime, but not in winter. Wet deposition and dry deposition are the main loss processes of sulphur. Short “films” have been made to show the dispersion.

WRF-Chem does represent atmospheric processes in a very detailed way. However, it is computationally demanding. In that respect the model is most suited to study processes (emissions, dispersion, chemical loss, dry deposition, wet deposition etc.) and to study specific episodes (e.g. summer episode 2007) rather than produce long-term calculations of concentrations and deposition.

TAPM (The Air Pollution Model) was set up for the border area and run for the year 2011. Both short term (hour) and long term (month, year) concentration means were put to file, as well as annual mean of dry and wet deposition. The model overestimates the observed values at Svanvik (both hourly mean and annual mean concentrations), while it underestimates the annual mean observations for the Zapolyarny and Nikel stations. The model shows high values to the north of Nikel, but there are no observations to verify these results.

A method to estimate deposition of heavy metals has been elaborated based on model results of deposition of sulphur and observed sulphur:Ni ratio at Svanvik and Karpdalen.

TAPM is fast to run on the supercomputer, but there is no access to the model code (“black box”). Because of this it is therefore difficult to make sensitivity tests to investigate and analyze the results.

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Pechenganikel after the summer episode of 2007. Photo: Espen Aarnes.

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Chapter 2: Classifications of ecological state and environmental health

JUKKA YLIKÖRKKÖ

Vätsäri wilderness. Photo Jukka Ylikörkkö.

1 Introduction

When assessing the chemical state of surface waters, different limit values and standards are applied in different countries. Similarly the classification of aquatic ecological status is based on different organisms and multiple variables. Therefore the risk assessments and ecological evaluations are often difficult to compare.

The classifications for ecological status and limit values for concentrations of hazardous substances are undergoing updating and changes in Europe, both on national and international level. Intercalibration and harmonization has been done between the EU nations. Standards or classifications are often not suitable for naturally harsh and nutrient poor northern environments. Here the validity of existing standards and metrics for lakes is assessed using data collected in the project.

Literature review and international comparison concerning the national and international classifications, typologies, standards and limit values for ecological state and environmental health has been done as a background[1] for the following work with project data. The most valid tools for analysis and reporting results are selected for trilateral monitoring programme based on this assessment. These outcomes will also support the selection of most representative and cost-effective environmental variables and indicators for aquatic monitoring.

Sediment samples.
Photo: Helén Andersen

Biological diversity metrics are compared between the regions using Kruskal-Wallis test, which is a non-parametric variance analysis suitable for small, skewed data and for groups of unequal size.

Field equipment. Photo: Jukka Ylikörkkö

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[1] See precursory work at www.pasvikmonitoring.org

2 Chemical status

In this part water chemistry data from the Pasvik River (Chapter 3) and lakes in the surrounding regions (Chapter 4) was used. For reference an additional lake LN-2 from north-east of Nikel was included. The lakes can be grouped into 3 areas in relation to Nikel: north-east lake LN-2 is the most exposed to the smelter's airborne emissions, Norwegian lakes in Jarfjord are further away in the same direction and the rest of lakes in Finland and Russia are located south or west of Nikel, upwind of the prevailing wind direction and the least affected by the airborne emissions. The Pasvik River runs roughly along this gradient. It receives heavy metals in wastewater discharge through Kuetsjarvi and some aerial deposition. All values are measured from 1 m depth during project period 2012–2013.

The chemical standards assessed here include the lists of the EU priority substances and northern EU countries' specific pollutants, Russian MAHEM, United States Environmental Agency (USEPA) and Canada. The latter two standard lists concern criteria for aquatic life. The work has been done with standards valid in 2013.

The most common metals have limit values in all national and the EU standards (Table 4). Cadmium, chromium, copper, nickel and zinc have often water hardness-dependent standards. The project lakes' water hardness in $CaCO_3$ content was estimated using calcium and magnesium concentrations. Most locations had soft water: estimated $CaCO_3 < 20$ mg/l. For Kuetsjarvi the hardness was higher: 40 mg/l, and for LN-2 estimation indicated hard water: 125 mg/l. Standards for soft water in Table 4 were calculated for hardness 17 mg/l $CaCO_3$, because the models often do not apply on lower values (CCME 2012).

Project data mean values were compared to chronic and long-term environmental standards, and data maximums to maximum allowable concentrations (MACs) and acute short-term standards.

The 33 EU priority substances that include persistent organic pollutants, organochloride and organophosphorus compounds and pesticides were not analyzed in water in the scope of this project.

Major ions

Lake LN-2 has both the maximum and average sulphate concentration above all the listed standard values (Figures 1–2, Table 1). Results from the lakes in the other regions or in the Pasvik River were substantially below the lowest standards. Regional maximum and average values against the lowest standard are summarized in Table 1 and Figures 1 and 2.

Table 1. The lowest standards for major ions with the corresponding maximum (short-term) or highest average (long-term) in certain lakes or regions in 2012–2013 sampling period. Standard-exceeding results **emphasized**.

	Lowest standard (mg)	LN-2/ (mg)	Kuetsjarvi (mg)	Jarfjord max. (mg)	Small lakes max. (mg)	Pasvik max. (mg)
Na short-term	120 MAHEM	4.3	4.1	4.0	1.6	1.7
Mg short-term	40 MAHEM	10.3	4.4	1.1	1.2	1.3
K short-term	10 MAHEM	0.70	0.95	0.44	0.54	0.50
Cl- short-term	300 MAHEM	5.7	3.9	5.6	1.8	1.6
Cl- long-term	120 Canada	4.0	3.2	-	1.7	1.4
SO4 short-term	100 MAHEM	**126.0**	34.1	4.6	3.5	6.4
SO4 long-term	50 Canada	**118.5**	30.0	-	3.3	4.6

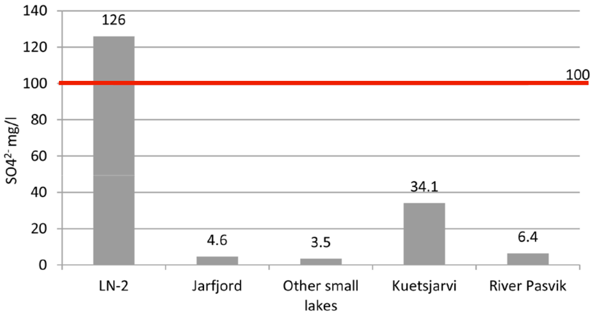

Figure 1. Maximum measured sulphate in Lake LN-2, regionally in small lakes, Kuetsjarvi and other parts of the Pasvik River with the Russian MAC (100 mg/l).

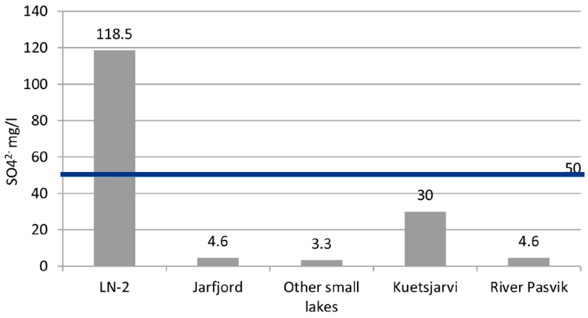

Figure 2. Average sulphate levels in in Lake LN-2, regionally in small lakes, Kuetsjarvi and other parts of the Pasvik River with the Canadian alert level for long-term average (50 mg/l).

Metals

Metals are given as dissolved concentrations in filtered (0.45 µm) samples unless stated otherwise. Nickel and copper are the main metals emitted by industry in the study area. Both are found on high levels in the nearest lakes (LN-2 and Kuetsjarvi) and in some of the Jarfjord lakes (Table 2, Figures 3–7).

Some of the standards represent added risk in addition to the background concentration. Regional background concentrations were not noted in the following results. The lowest MAC for copper is 1 µg/l by MAHEM. There are single results from all the lake groups that exceed this concentration. USEPA acute standard for soft water (<17 mg/l $CaCO_3$) is also rather low (c. 2 µg/l), but this is only exceeded by potentially polluted lakes, closest to or downwind from the smelter.

The lowest long-term average standard for copper is by the UK (1 µg/l). This is again exceeded by several lakes (all of Jarfjord, LN-2, Kuetsjarvi, Shuonijaur and Lampi 222). Using Swedish standard (4 µg/l) five lakes remain exceeding (3/5 in Jarfjord, LN-2 and Shuonijaur).

Lake LN-2 is a more complex case because its water is hard due to high base cation content and so toxicity of metals, including copper, is decreased. The US and Canadian standards react to increasing hardness, but even adjusting the standards to hard water (125 mg/l $CaCO_3$) LN-2 exceeds them.

There is a wide variety of methods for deriving the copper standards from LC_{50} (lethal concentration 50 %) or EC_{50} (effect concentration 50 %) studies and as apparent there are more and less strict approaches to the safe concentration. The natural background dissolved copper levels may vary from 0.3 to 1 µg/l depending on catchment size and soil quality (e.g. Naturvårdsverket 2008).

The lowest MAC for nickel is 10 µg/l by MAHEM. This is exceeded by LN-2, Kuetsjarvi and single lakes in Jarfjord and in the Pasvik River (Table 2). Long-term nickel standards are exceeded only by the Lake LN-2 and Kuetsjarvi. Standards are again in relation to water hardness, and higher for hard water in LN-2. Background nickel is estimated to vary naturally 0.2–0.5 µg/l according to Naturvårdsverket (2008). The lowest standards seem to separate the polluted lakes rather well.

Table 2. The lowest standards of copper (Cu) and nickel (Ni) with the corresponding maximum (short-term) or highest average (long-term) in certain lakes or regions in 2012–2013 sampling period. Soft water standards apply hardness < 17 mg/l $CaCO_3$ and hard water values for LN-2 hardness 125 mg/l $CaCO_3$. Standard-exceeding results **emphasized**.

	Water hardness	Lowest standard (µg/l)	LN-2 (µg/l)	Kuetsjarvi (µg/l)	Jarfjord max. (µg/l)	Vätsäri-Russia max. (µg/l)	Pasvik max. (µg/l)
Cu short-term	general	1.0 MAHEM	**17.3**	**19.0**	**2.7-9.16**	**1.1-5.4**	**1.0-4.4**
Cu long-term	hard	2.9 CA	**14.7**	**13.6**			
	soft	1 UK			-	**4.7** (Shuonijaur)	**1.8-2.6**
Ni short-term	general	10 MAHEM	**354.0**	**161**	**16.7** (Børsevatn)	9.3	**22.0** (Vaggatem)
Ni long-term	hard	63 USEPA	**298.3**	**126**			
	soft	11.7 USEPA			-	8.5	11.5

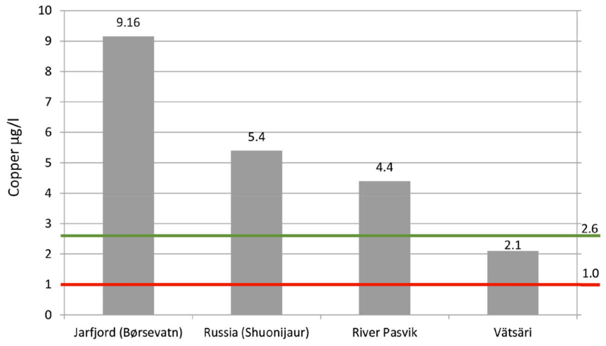

Figure 3. Maximum measured copper in certain small lakes, the Pasvik River and Vätsäri area. The lines show short-tem standard values: USEPA (2.6 µg/l) and Russian MAC (1.0 µg/l)

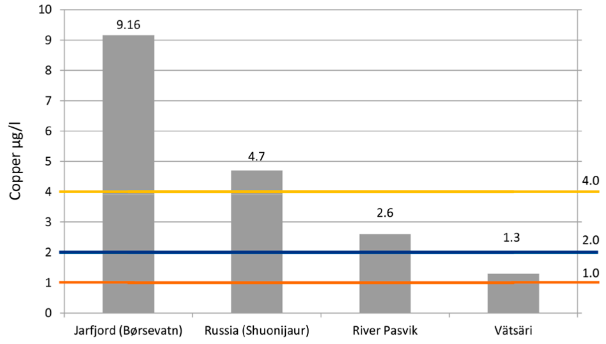

Figure 4. Average copper in certain small lakes, the Pasvik River and Vätsäri area. The lines show long-term standard values for soft water: the UK (1 µg/l), Canada (2 µg/l), Sweden (4 µg/l) .

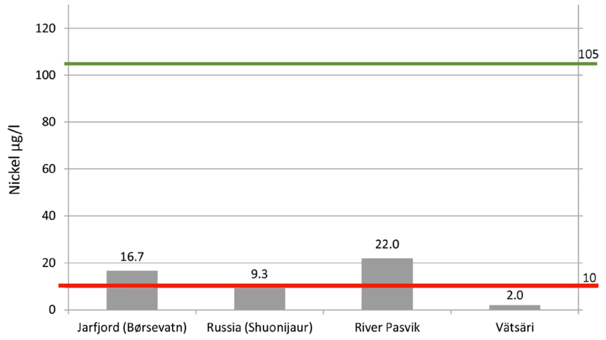

Figure 5. Maximum measured nickel in certain small lakes, the Pasvik River and Vätsäri area. The lines show short-term standard values: USEPA (105 µg/l) and Russian MAC (10 µg/l).

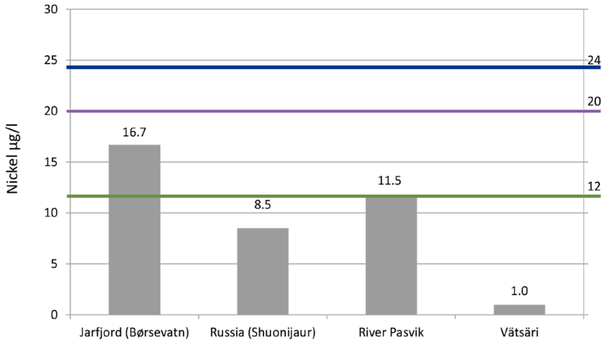

Figure 6. Average nickel in certain small lakes, the Pasvik River and Vätsäri area. The lines show long-term standard values for soft water: USEPA (12 µg/l), EU EQS (20 µg/l) and Canada (24 µg/l).

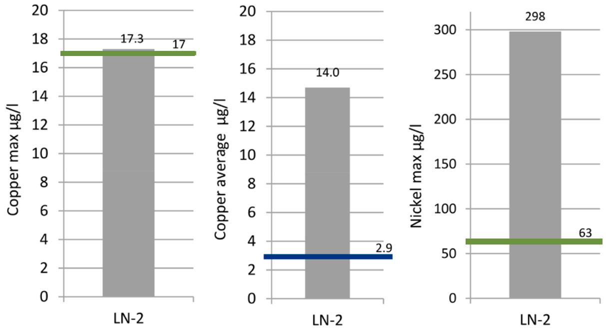

Figure 7. Lake LN-2 maximum and average copper and maximum nickel. Lines show correspondent standard values adjusted for the lake's water hardness by the USEPA criteria.

Several other measured metal concentrations are the highest in LN-2 yet below the lowest standard (Table 3). These include maximum total aluminum and cadmium.

Aluminum is measured both as total and labile. Total aluminum maximum concentrations are clearly the highest close to Nikel, but do not exceed the lowest standard values.

Manganese MAC by MAHEM (10 µg/l) is exceeded by many lakes. Considering the past results measured from streams (Salminen 2005) and the monitored lakes in the area, 10–20 µg/l still represents the Mn background level in lakes in the area. The only notably high manganese concentration is found in Lake LN-2 (max. 123 µg/l). Manganese is not noted in national standard lists, but for example USEPA (2010) refers to results from LC_{50} experiments with mussels, which indicate Mn on the order of tens of milligrams to be toxic.

Iron MAC by MAHEM (100 µg/l) is also exceeded by several water bodies. The standard is again rather low compared to the regional background level (Salminen 2005). In long-term all the iron standards are met.

There seems to be elevated zinc concentration in Lake LN-2, which does not meet the lowest standards in maximum or long-term concentrations. Background levels in the region's streams are generally less than 1 µg/l for Zn (Salminen 2005) and the content in all the other lakes is clearly below the standard.

Nutrients and trophic status

Ammonium, nitrate and phosphate

MAHEM MACs for ammonium (400 µg/l) and nitrate nitrogen (9100 µg/l) are the lowest of considered standards. All the measured results were notably below the standard MACs. Among the lakes the maximum measured ammonium nitrogen concentration varied from 9.0 to 60.0 µg/l, in the Pasvik River 9.0–85.0 µg/l, and the maximum nitrate nitrogen 3–49 µg/l in the lakes and 1–46 µg/l in the river. All the maximum measured phosphate phosphorus concentrations were below MAHEM MAC (150 µg/l), varying from 1 to 9 µg/l in the lakes and 1–5 µg/l in Pasvik river.

pH

The measured minimum pH values from the lakes and the Pasvik River mostly exceeded the 6.5 limit, which is most often used standard for minimum pH. Lake Sierramjärvi had lower minimum (5.8), which seems to be a single anomaly when observed in long time scale. The lake is in the reference area and minimally affected by anthropogenic pressures.

COD

The highest measured chemical oxygen demand values were 6.8 mg/l (Virtuovoshjaur) and 5.8 mg/l in Pasvik River (Ruskebukta). Russian MAC for COD is 15 mg/l.

Trophic status

Using the Canadian trophic status criteria for mean total phosphorus, the lakes are ultra-oligotrophic (< 4 µg/l) or oligotrophic (< 10 µg/l). The Pasvik River water reservoirs are all oligotrophic (< 10 µg/l total P), except for Ruskebukta, which is meso-eutrophic in terms of total phosphorus (22 µg/l). This is consistent with the previous studies and other obtained results (see Chapter 3).

Conclusions

Russian maximum allowable concentrations and Canadian or US environmental agency criteria for the protection of aquatic life are the most comprehensive national standard lists and therefore useful in assessing chemical status. Moreover these are most often the lowest and strictest standards. For example the USEPA criteria are set as a result of lethal dose and effect dose studies with zooplankton, some benthic animals and fish to minimize the risk to aquatic biota (e.g. USEPA 2014).

Sulphate accumulation is a key issue in the study area. That is detected by the lowest standards, which represent an early level of contamination.

Nickel concentration is elevated in lakes near the Nikel smelter and this is detected by all the standards. However there is a great difference between different criteria and whether water hardness is considered.

There are some unnecessarily low standards for copper, manganese and iron. These are Russian national maximum concentrations and considering the background concentration they may be too sensitive for the study area. Use of other criteria or lowest observed toxic concentration as a reference points out better the potential pollution in lakes downwind of the Nikel smelter.

Eutrophication is generally not a key issue in the study area.

Table 3. The lowest standards for metals with the corresponding maximum (short-term) or highest average (long-term) in certain lakes or regions in 2012–2013 sampling period. Standard-exceeding results **emphasized**.

	Lowest standard (µg/l)	LN-2 (µg/l)	Kuetsjarvi (µg/l)	Jarfjord max. (µg/l)	Vätsäri-Russia max. (µg/l)	Pasvik max. (µg/l)
Al short-term	750 USEPA	134.0	113	12.0	50.0	86.0
Al long-term	87 USEPA	47.0	49.6	-	36.8	65.0
Cd short-term	0.35 USEPA	0.14	0.12	0.01	0.09	0.02
Cd long-term	0.03 CA	0.11	0.06	-	0.05	0.02
Mn short-term	10 MAHEM	**123**	**48**	6.09	**13.2** (Virtuvuoshjaur) **11.0** (Kochejaur)	**25** (Vaggatem)
Fe short-term	100 MAHEM	**233**	**238**	49.0	**185** (Virtuvuoshjaur) **174** (Kochejaur)	**365** (Vaggatem) **139** (Skrukkebukta)
Fe long-term	300 CA	143	108	-	106	223
Co short-term	10 MAHEM	6.6	2.2	0.15	0.25	0.3
Zn short-term	10 MAHEM	**18**	7.8	1.7	5.2	2.9
Zn long-term	8 SWE	**13,65**	4.7	-	2.9	1.2
Pb short-term	6 MAHEM	0.2	0.2	0.2	0.4	0.4

Table 4. Metal standard concentration by the EU priority substance list, Canadian (CCME 2011, Meays & Nordlin 2013), the US (USEPA 2012) criteria for aquatic life, Russian MAHEM MAC values for Pasvik River, Swedish specific pollutants (Naturvårdsverket 2008) and the UK proposal for specific pollutants (UKTAG 2008). The most sensitive value for each variable bolded.

A. Long-term standards (µg/l)

	Al	Cd	Cr (III)	Cr (VI)	Fe	Cu	Ni	Zn	As	Se	Pb	Hg	Cl	SO4
EU EQS		0.08[3]					20.00				7.2[5]	**0.05[5]**		
CA	100[1]	**0.03[2]**	8.90	**1.0**	**300**	2.00	24.86[2]	30.0	**5**	**1.0**	1.0[2]	0.026	**120 000**	**50 000**
US	**87**	0.07[2]	20.19[2]	**1.0**	1000	2.01[2]	**11.65[2]**	26.7[2]	150	5.0	**0.3[2]**		230 000	
SW EQS						4.00		3/8.0[4]						
UK			**4.70**	3.4	1000	**1.00[6]**		8.0[6]						

B. Short-term standards and MACs (µg/l)

	Al	Cd	Cr (III)	Cr (VI)	Fe	Cu	Ni	Zn	As	Se	Pb	Hg	Cl	SO4
EU MAC		0.45[3]									-	0.07[5]		
CA													640	128 000[7]
US	**750**	**0.35[2]**	422.42[2]	**16.00**		2.64[2]	104.78[2]	26.70[2]	340		8.56[2]		860	
RUS MAC	40 (labile)	5	70.00	20.00	**100**	**1.00**	**10.00**	**10.00**	**50**	**2.0**	**6.00**	**0.01**	**300**	**100 000**
UK			32											

[1] when pH ≥ 6.5
[2] when water hardness 17 mg/l $CaCO_3$ (USEPA, Canada)
[3] when water hardness < 40 mg/l $CaCO_3$
[4] when water hardness < 24/> 24 mg/l $CaCO_3$
[5] lead and mercury measured with their compounds
[6] when water hardness < 50 mg/l $CaCO_3$
[7] when water hardness < 30 mg/l $CaCO_3$

3 Typology

Typologies and their categories have been discussed about in the precursory work.[1] Project data from lakes (Chapters 4 and 5) was primarily used for type categorization. Older water quality data was used alongside when available. The results are shown in Table 1.

Finnish typology separates North-Lapland lakes above pine forest line as a type itself. The range of this type was estimated by modeling from latitude, longitude and altitude (Mikkola p.c. 2013). Based on the geographical model three of the project lakes in area belong to 'North-Lapland' type (Table 1). All the lakes are at least 3 meters deep in average. Therefore, based on their size (< 40 km^2) and water colour (< 30 mg Pt/l), the rest fit in type 'small and medium-sized clear water lakes'. Alkalinity threshold of 0.4 meq/l, on average, for calcium-rich lakes was not exceeded.

Norwegian typology starts from division to altitudinal zones. All the project lakes fall into the 'Forest' zone below tree line. The size category is either small (< 5 km^2) or large (> 5 km^2). The third tier describes alkalinity. Kuetsjarvi exceeds the average alkalinity threshold (0.2 meq) and so represents moderately calcium rich type. At last the lakes are categorized for clarity based on colour (mg Pt/l) or total organic carbon (TOC). Most lakes are clear based on water colour values in the project data and available data from previous years. Lake Vaggatem in the Pasvik River watercourse is set to 'humic' water colour category (colour > 30 mg Pt/l) by the Norwegian authority and so it will be considered as such.

As a result the lakes represent two different types according to Finnish system and four types in Norwegian typology. Geographical location divides the lakes in Finnish typology; size, alkalinity and colour in the Norwegian. The resulted types describe partly different aspects: the size category is different and the Norwegian system has more alkalinity categories. Water clarity is uniformly assessed and expressed by both typologies.

The lakes closest to Nikel smelter are high in calcium. This is mostly due to dry deposition of calcium compounds from the industry and partly natural state because of calcareous bedrock. Based on alkalinity measures, however, they are, at most, moderately alkaline.

The Pasvik River is heavily modified for hydropower and it has to a large extent lost its river character. The large reservoirs are considered as humic lakes in Norway. In Finnish typology these would be similarly heavily modified or artificial humic lakes or lakes with short retention time in case the retention is less than 10 days. Lake Vaggatem is presented as an example here.


Photo:Esko Jaskari.

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[1] www.pasvikmonitoring.org

Table 1. Categories used in Finnish and Norwegian typologies and the resulting types for different project lakes.

	Size (km^2)	Altitude (masl)	Calcium (mg/l)	Alk. (mekv/l)	Colour (mg Pt/l)	TOC (mg/l)	FI type		NO type	
FI										
Lampi 222	< 5	222	< 4	< 0.2	< 30	< 5	6.1	Small and medium size clear	12	Forest zone calcium-poor clear
Harrijärvi	< 5	127	< 4	< 0.2	< 30	< 5	6.1	Small and medium size clear	12	Forest zone calcium-poor clear
Pitkä-Surnujärvi	< 5	126	< 4	< 0.2	< 30	< 5	6.1	Small and medium size clear	12	Forest zone calcium-poor clear
Sierramjärvi	< 5	254	< 4	< 0.2	< 30	< 5	1	North-Lapland lakes	12	Forest zone calcium-poor clear
RU										
Shuonijaur	5–40	180	< 4	< 0.2	< 30	< 5	6.1	Small and medium size clear	12	Forest zone large calcium-poor clear
Ala-Nautsijarvi	5–40	159	< 4	< 0.2	< 30	5–15	6.1	Small and medium size clear	12	Forest zone large calcium-poor clear
Toartesjaur	< 5	195	< 4	< 0.2	< 30	< 5	6.1	Small and medium size clear	12	Forest zone calcium-poor clear
Virtuovoshjaur	< 5	182	< 4	< 0.2	< 30	5-15	6.1	Small and medium size clear	12	Forest zone calcium-poor clear
Riuttikjaure	< 5	190	< 4	< 0.2	< 30	< 5	6.1	Small and medium size clear	12	Forest zone calcium-poor clear
Kochejaur	< 5	133	< 4	< 0.2	< 30	5–15	6.1	Small and medium size clear	12	Forest zone calcium-poor clear
LN-2	< 5	210	> 20	< 0.2	< 30	< 5	6.1	Small and medium size clear *	12	Forest zone calcium-poor clear
Kuetsjarvi	5–40	21	4–20	0.2-1	< 30	5–15	6.1	Small and medium size clear	14.7	Forest zone large moderately calcium-rich
NO										
Gardsjøen	< 5	82	< 4	< 0.2	< 30	< 5	6.1	Small and medium size clear	12	Forest zone calcium-poor clear
Holmvatnet	< 5	156	< 4	< 0.2	< 30	< 5	1	North-Lapland lakes	12	Forest zone calcium-poor clear
Rabbvatnet	< 5	83	< 4	< 0.2	< 30	< 5	6.1	Small and medium size clear	12	Forest zone calcium-poor clear
Durvatn	< 5	231	< 4	< 0.2	< 30	< 5	1	North-Lapland lakes	12	Forest zone calcium-poor clear
Børsevatn	< 5	178	< 4	< 0.2	< 30	< 5	6.1	Small and medium size clear *	12	Forest zone calcium-poor clear
Vaggatem	5–40	51	< 4	< 0.2	30–90	5–15	7.1.	Medium-sized humic lakes	13	Forest zone large calcium-poor humic lakes

*borderline case on the modeled forest line

4 Phytoplankton

Data processed here consist of phytoplankton densities and chlorophyll a contents for Vätsäri and Russian lakes (Chapter 4). The sampled zone for phytoplankton was 0–2 m in Finland and 0–10 m in Russia and Norway. Sampling was conducted during growing season in June–September. For detailed sampling methods see Chapter 4 Biology.

Results and discussion

Chlorophyll

The measured chlorophyll a was low in Vätsäri lakes: less than 2 μg/l (Table 1). The reliable detection limit in the analysis is 1 μg/l. The studied lakes in Russia had similarly low chlorophyll content, apart from Lake Shuonijaur. Lake chlorophyll a is a phytoplankton metric in Finnish, Norwegian and Swedish classification. All systems give consistent good or high status class to measured chlorophyll results. The Norwegian reference value for northern clear water lakes is the lowest, thus it would be the first metric to react to a rise in chlorophyll content.

Species diversity

Even though diversity indices are not used for phytoplankton classification in any country the number of species between the regions is compared in Figure 1. Norwegian Jarfjord and Finnish Vätsäri are neighbouring regions with rather similar trophic status. Some of the Jarfjord lakes have very high copper content (see Chapter 4) and therefore the species diversity is expected to be lower than in Vätsäri. Russian lakes locate more south and are mostly bigger in surface and catchment area, which should contribute to higher phytoplankton species diversity.

The Russian lakes differ from the other two regions with significantly higher number of species (Kruskal-Wallis, $p = 0.01$). Jarfjord lakes tend to have fewer species, but in this data set no difference to Vätsäri could be verified.

Conclusions

Growing season chlorophyll a content gives an indication of the phytoplankton biomass and thus of the general trophic status. Applying the limit values for correct type in any of the national classifications should reveal possible status deterioration. Therefore chlorophyll content should be measured systematically from all the locations.

Biomass of harmful cyanobacteria (blue-green algae) is a straightforward and commonly used phytoplankton metric of eutrophication for which taxa biomasses would be required. It would be a good additional tool for assessing phytoplankton communities.

Phytoplankton seasonal changes should be considered when using it as a quality element. Phytoplankton classification is recommended to be based on more than one growing season sample. In Norway five annual samples are recommended (Direktoratsgruppa 2013).

Table 1. Average measured chlorophyll in June–September 2013 and the current type-specific reference values, high/good (H/G) class limit values and consequent status classes in Finnish, Norwegian and Swedish lake classification.

		Finnish[1]			**Norwegian[2]**			**Swedish[3]**		
	Chlorophyll a (µg/l)	**Ref. (µg/l)**	**H/G (µg/l)**	**class**	**Ref. (µg/l)**	**H/G (µg/l)**	**class**	**Ref. (µg/l)**	**H/G (µg/l)**	**class**
Vätsäri										
Harrijärvi	1.65	3	4	high	1.3	2	high	2	4	high
Lampi 222	< 1									
Pitkä-Surnujärvi	1.25									
Sierramjärvi	< 1	2	3							
Russia										
Shuonijaur	2.44	3	4	high	1.3	2	good	2	4	high
Ala-Nautsijarvi	0.78						high			
Toartesjaur	1.44									
Riuttikjaure	0.41									
Virtuovoshjaur	0.6									
Kochejaur	1.05									

[1] Finnish types: small and medium size clear lakes or (Sierramjärvi) North-Lapland lakes.
[2] All lakes forest zone calcium-poor clear water (L-N5) type
[3] Ecotype for phytoplankton: Northland clear lakes.

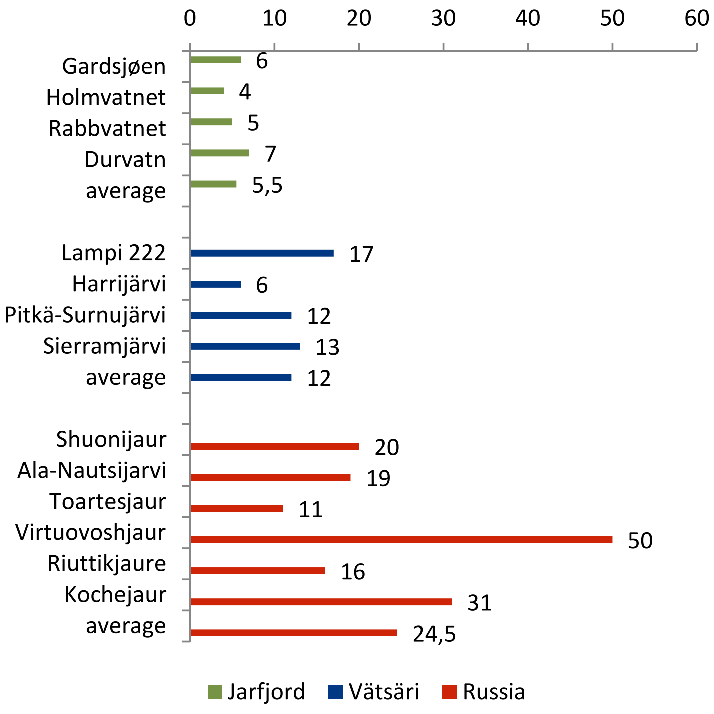

Figure 1. The number of phytoplankton species in each lake and the regional averages.

5 Periphytic diatoms

Diatom communities have been traditionally studied in rivers and there are only few metrics that apply to lake littoral habitats. Here diatom communities were assessed using Diatom Assessment of Lake Ecological Status (DALES) for nutrient level, saprobity index for organic pollution and community metrics for general quality. The material includes Chapter 4 lake data.

Results and discussion

Diversity

Diatom species diversity and their relative abundances were estimated with Shannon entropy (Shannon & Weaver 1962) (Table 1). The index value increases with both species number and growing equality in abundance. Evenness value is derived from the index to illustrate how evenly the species are distributed. The results between the three regions were compared using a non-parametric Kruskal-Wallis test.

Species diversity is used in ecological assessment, but they are not among the northern Water Framework Directive classification tools. Based on water quality analysis (See Chapter 4, Water quality), Vätsäri lakes represent the most undisturbed small lakes and Jarfjord lakes represent slightly polluted, small, clear water lakes in the same region. Pollution impact was expected to show in lower diversity in Jarfjord. Due to their more southern location and greater size the Russian lakes are expected represent ecologically divergent lake types with more species.

Species richness and diversity in the diatom samples was the highest in Vätsäri area and lowest in Jarfjord, with regional average of 60 and 28 spp. respectively. The difference is statistically significant (Kruskal-Wallis, $p = 0.05$). The number of species in Russian lakes varied widely from 22 to 56, being 40

Table 1. Number of diatom species, Shannon entropy and evenness value for each lake calculated from diatom species. For Vätsäri lakes values are averages of 2–3 sampling stations.

	No. of species	Shannon	Evenness
Vätsäri			
Lampi 222	50.7	2.98	0.76
Harrijärvi	37.5	2.51	0.69
Pitkä-Surnujärvi	83.3	3.54	0.8
Sierramjärvi	67.0	3.08	0.73
Average	59.6	3.00	0.75
Russia			
Shuonijaur	22	1.54	0.5
Ala-Nautsijarvi	30	3.03	0.89
Toartesjaur	46	3.18	0.83
Virtuovoshjaur	46	2.82	0.74
Riuttikjaure	56	3.58	0.89
Average	40.0	2.83	0.77
Jarfjord			
Gardsjøen	23	2.08	0.66
Holmvatnet	22	2.34	0.76
Rabbvatnet	31	2.7	0.79
Durvatn	34	2.97	0.84
Average	27.5	2.5	0.76

on average. Shannon entropy or evenness was not significantly different between the three areas.

Diatom Assessment of Lake Ecological status

DALES index was developed in the UK for lake diatom community assessment. It is an average score per taxa method in terms of eutrophication impact. The sample taxa were mostly found among the UKTAG (2008) list of species or genuses. In case species level was not found the genus alone was used. Genera that weren't listed were ignored in calculation.

The reference index value for low alkalinity water (<10 mg $CaCO_3$/l) is 20. Against this, all the sampled lakes gained high status class (EQR >0.8) (Table 2). The index values somewhat reflected the water quality: the values were highest in the southern lakes, which are more humic and higher in nutrients. The difference was due to higher proportion of *Nitzschia* and certain *Gomphonema* and *Navicula* species. *Fragilaria* on genus level gives high score compared to some individual species in the genus, and so having many *Fragilaria sp*. in the data also raises the index value.

Saprobic index

Sladecek (1973) saprobic index resulted oligosaprobic level and clean water quality class for majority of lakes (Table 3). Shuonijaur diatom community was found to be mesosaprobic and it exceeded the Russian standard limit for clean water class with two other lakes.

Table 2. DALES index values, their respective ecological quality ratios (EQR) and mean 2012-2013 total phosphorus content for each lake. Against the reference value (20) and high/good threshold (36), all results represent high status.

	DALES	Class	P tot. mean (µg/l)
Vätsäri			
Lampi 222	14	high	2.0
Harrijärvi	6		2.3
Pitkä-Surnujärvi	20		4.0
Sierramjärvi	26		3.8
Russia			
Shuonijaur	26	high	4.8
Ala-Nautsijarvi	27		3.0
Toartesjaur	28		7.5
Virtuovoshjaur	21		8.5
Riuttikjaure	36		7.0
Jarfjord			
Gardsjøen	20	high	
Holmvatnet	12		
Rabbvatnet	19		
Durvatn	23		

Table 3. Diatom periphyton inferred water quality estimation by the saprobic index (S), the consequent saprobic level and the Russian standard water quality class (II clean; III moderately polluted).

	S	Saprobic level	Class
Vätsäri			
Lampi 222	1.16	α-oligosaprobic	II
Harrijärvi	1.25	α-oligosaprobic	II
Pitkä Surnujärvi	1.22	α-oligosaprobic	II
Sierramjärvi	1.44	α-oligosaprobic	II
Russia			
Shuonijaur	1.63	β-mesosaprobic	III
Ala-Nautsijarvi	1.57	α-oligosaprobic	III
Toartesjaur	1.46	α-oligosaprobic	II
Virtuovoshjaur	1.39	α-oligosaprobic	II
Riuttikjaure	1.42	α-oligosaprobic	II
Jarfjord			
Gardsjoen	1.55	α-oligosaprobic	III
Holmvatn	1.34	α-oligosaprobic	II
Rabbvatn	1.45	α-oligosaprobic	II
Durvatn	1.22	α-oligosaprobic	II

pH reconstruction by diatom analysis

Diatom communities can be used in estimation of their environment pH with method by Moiseenko & Razumovskii (2009). The results come close to measured pH values which represent neutral water (Table 4). This supports the assumption that recently measured pH values represent the prevailing long-term level in the lakes.

Community indices

Finnish classification of type-specific species and percent model affinity give variable results (Table 5). The indices are currently based on rather small reference lake data which most likely explains the moderately low results: the studied lakes are not affected by any large scale impact and therefore the results should indicate at least good status class. The larger lakes (> 5 km) were not classified for the lack of representative reference data.

Conclusions

DALES index seemed to have an approximate reaction to nutrient level. Index taxa did not perfectly match the northern taxonomic composition and some species had to be dropped out or listed on genus level which caused unwanted variation to index values.

Saprobic index gave reasonable results in primarily pointing out the one mesosaprobic lake. Lakes in Vätsäri and Jarfjord were found to be oligosaprobic, as expected. Diatom community as pH estimator proved to be an accurate indicator of cation-anion balance.

The data was scarce both spatially and temporally, consisting of only 4–5 lakes per area and only one diatom sample from most of them. There were also some differences in the sampling efforts between the regions and also in the regional catchment properties that were not controlled in the study. All this may contribute to the observed diversity results. Nevertheless, changes in species richness would be a straightforward ecological metric easy to monitor in the future.

Table 4. The diatom-inferred pH and chemical measured pH for the investigated lakes. Vätsäri lake values are averages from three parallel samples.

Lake	pH (diatom)	pH (chemical)
Vätsäri		
Lampi 222	6.8	6.7
Harrijärvi	6.7	6.7
Pitkä Surnujärvi	6.9	6.7
Sierramjärvi	7.0	6.8
Russia		
Shuonijaut	6.8	6.8
Ala-Nautsijarvi	7.3	7.0
Toartesjaur	7.0	6.9
Virtuovoshjaur	7.0	6.9
Riuttikjaure	7.2	7.1
Jarfjord		
Gardsjoen	6.9	6.8
Holmvatn	6.9	6.8
Rabbvatn	7.0	7.0
Durvatn	7.0	7.0

Table 5. Average ecological quality ratio (EQR) of the Finnish type-specific species and percent model affinity metrics. Results vary from 0.4 < moderate > 0.6 to 0.6 < good > 0.8.

	FI type	Class (EQR)
Vätsäri		
Lampi 222	6.1	good (0.6)
Harrijärvi	6.1	good (0.6)
Pitkä-Surnujärvi	6.1	good (0.6)
Sierramjärvi	1	good (0.6)
Russia		
Shuonijaur	-	-
Ala-Nautsijarvi	-	-
Toartesjaur	6.1	good (0.6)
Virtuovoshjaur	6.1	moderate (0.5)
Riuttikjaure	6.1	good (0.6)
Jarfjord		
Gardsjøen	6.1	good (0.6)
Holmvatnet	1	moderate (0.5)
Rabvatn	6.1	moderate (0.4)
Durvatn	1	moderate (0.5)

6 Zoobenthos

Benthic macroinvertebrate metrics for biological classification are studied here as they are considered in the Finnish, Norwegian and Swedish classifications and Russian standards. Finnish and Swedish indices are primarily community indices. The Norwegian approach is to detect the main impact and use relevant metrics. Here acidification and chemical pollution are considered the principal impacts. Swedish and Norwegian systems apply additional multimetric indices that were not possible to calculate by hand.

In addition to the small lakes zoobenthos data from lakes in the Pasvik River was collected. Lake Kuetsjarvi and Vaggatem results are included here to create a gradient in terms of industrial pollution.

Littoral data was collected using a kick-net (mesh size 0.5 mm) with total of 1.5–2 minutes of sampling. Profundal samples are collected with 2–5 Ekman grab samples. Data sampling details are available in the publication Ylikörkkö et al. (2015).

Results and discussion

Community metrics

The Finnish littoral indices, type-specific species and percent model affinity (PMA), lack reference data for clear northern lakes where taxa is scarce. The indices use more southern data as comparison, resulting in falsely poor and bad values for both littoral indices. For this reason the littoral results will not be considered further.

The profundal samples had very few individuals, especially in Jarfjord and Vätsäri. The above mentioned weakness was also apparent in profundal PMA, which yielded low results (Table 1). Some lakes had so few taxa that PMA would have been 0, which is not a useful result. Profundal Invertebrate Community Metric (PICM) requires certain indicator Chironomidae and Oligochaeta on species level to assess benthos status. PICM species were not found in half of the lakes. This is likely because of extremely low density of invertebrates in the studied lakes and not because of true oxygen depletion. When there were indicator species for PICM calculation, the presence of relatively sensitive *Sergentia* and *Cladotanytarsus* resulted in high index values and high status class (Table 1).

Swedish average score per taxon (ASPT) method measures littoral ecological quality through taxa indicator values in relation to pollution (Naturvårdsverket 2007). The index value is an average of all indicator taxa. It also describes the community diversity, namely the proportion of resilient Chironomidae and Oligochaeta to the more sensitive mayflies (Ephemeroptera), caddisflies (Trichoptera), stoneflies (Plecoptera), etc. The higher the score the more sensitive species it holds. The Swedish indices use regional reference states based on Illies' ecoregions and the studied lakes belong to 'boreal upland'.

The results from APST vary from moderate to high (Table 2). There is no evident explanation for moderate results, other than low distribution of fauna. There is a wide variance in the results even in the reference lakes, which shows in lowered class boundaries. Likely the reference data does not suit well the northernmost lakes.

Benthic quality index (BQI) is the Swedish profundal metric. The index is an average score per taxon method for Chironomidae species in terms of their tolerance to oxygen depletion.

For most lakes there were no indicator species identified and thus no material to calculate the index from. There was mostly one or at most two indicator species in profundal samples that enabled index calculation. Results indicate mainly good status class (Table 3). In Harrijärvi the presence of *Chironomus plumosus* dropped the status to poor. As there were very few taxa small differences in the community reflected as drastic changes in the index value. In addition, the class limit values were set higher than usually, requiring more than 70 % of the reference value to reach good status.

Table 1. The Finnish lake type, profundal PMA and PICM status classes. The index could not be used if indicator taxa for PICM calculation was not present.

	FI Type	PMA	PICM	Final status
Vätsäri				
Lampi222	6.1	-	no taxa	-
Harrijärvi	6.1	Good	Good	Good
Pitkä-Surnujärvi	6.1	Good	no taxa	Good
Sierramjärvi	1	-	High	High
Russia				
Shuonijaur	6.1	High	High	High
Ala-Nautsijarvi	6.1	Good	High	High
Toartesjaur	6.1	Moderate	High	High
Virtuovoshjaur	6.1	-	no taxa	
Riuttikjaur	6.1	Poor	High	High
Kochejaur	6.1	-	no taxa	-
the Pasvik River				
Vaggatem	7.1	-	no taxa	-
Kuetsjarvi	6.1	Good	High	High
Jarfjord				
Gardsjøen	6.1	High	High	High
Holmvatnet	1	-	no taxa	-
Rabbvatnet	6.1	Moderate	High	High
Durvatn	1	-	no taxa	-

Table 2. The average score per taxon (ASPT) value and the corresponding status class. Reference value for ‘boreal upland’ is 5.6. The status class boundaries are set lower than usually: high/good threshold 3.36 (60 % of the reference).

	ASPT	Class
Vätsäri		
Lampi222	3.5	High
Harrijärvi	1.9	Moderate
Pitkä-Surnujärvi	2.5	Moderate
Sierramjärvi	2.8	Good
Russia		
Shuonijaur	4.4	Good
Ala-Nautsijarvi	3	Good
Toartesjaur	2.9	Good
Virtuovoshjaur	4.8	High
Riuttikjaure	5.7	High
Kochejaur	4.4	Good
the Pasvik River		
Vaggatem	2.9	Good
Kuetsjarvi	2.7	Good
Jarfjord		
Gardsjøen	2.1	Moderate
Holmvatnet	5.3	High
Rabbvatnet	2.7	Good
Durvatn	6.1	High

Table 3. Benthic quality index (BQI) value and the corresponding status class. The reference value for ‘boreal upland’ is 3.25. The class limit values are set higher than usually: high/good threshold 3.1, good/moderate threshold 2.28 (70 % of the reference).

	BQI	Class
Vätsäri		
Harrijärvi	1	Poor
Sierramjärvi	3	Good
Russia and the Pasvik River		
Shuonijaur	3	Good
Kuetsjarvi	3	Good
Jarfjord		
Gardsjøen	3	Good
Holmvatnet	3	Good

Index for acidification

Norwegian ‘Raddum’ index for acidification measures the presence of indicator taxa in the littoral zoobenthos community (Direktoratsgruppa 2009). It is based on a list of indicator values from 0 to 1 for certain taxa. Observed taxa are given scores and simply the highest score i.e. the most sensitive species makes the index value. Taxa that were not found in reference list were excluded.

The index results vary from no impact (1) to moderately (0.5) and strongly acidified (0.25) (Table 4). There were three lakes where the only indicator species were tolerant and so the results indicate severe acidification (0). However, water quality in any of the lakes does not support noticeable acidification. The difference between index values 1 and 0 was made in many cases by a single species, e.g. just one individual of *Gammarus* in the sample. Evidently the index was worsened by naturally low diversity and density of benthic fauna. The index does show consistently low values in Jarfjord, where acidification has been observed in other lakes (Puro-Tahvanainen et al. 2011; Chapter 4 Water quality). So far it cannot be ruled out that benthic communities in the studied lakes haven’t suffered from acidic deposition.

According to the Norwegian classification the amphipod *Gammarus* species are used as an indicator of good status class (Direktoratsgruppa 2009). They are considered sensitive especially to acidification. In the studied lakes *Gammarus lacustris* was found in lakes Sierramjärvi and Lampi 222 in Vätsäri.

Index for organic pollution

Woodiwiss index, or so called ‘Trend Biotic Index’ (Woodiwiss 1964), is a standard tool in Russia to analyse littoral zoobenthos communities in terms of organic pollution impact. The index is based on the presence or absence of key taxonomic groups: Ephemeroptera, Plecoptera, Trichopera, *Asellus* sp. etc. Taxa abundances are not considered. The index value decreases from 10 to 0 towards pollution.

The results indicate mainly clean (>7) status (Table 5). Shuonijaur, Kuetsjarvi and Vaggatem yielded slightly deteriorated values (6–7). The result is sensible as these lakes lie closest to pollution sources of the Pechenganikel. Certain Jarfjord lakes yield the lowest values (3–4), which is a result of fewer key taxa.

Table 4. The Raddum index for acidification values for the studied lakes. 1 indicates no acidification, 0.5 moderate, 0.25 strong and 0 the most severe acidification.

	Raddum value
Vätsäri	
Lampi222	1
Harrijärvi	0
Pitkä-Surnujärvi	1
Sierramjärvi	1
Russia	
Shuonijaur	1
Ala-Nautsijarvi	1
Toartesjaur	1
Virtuovoshjaur	1
Riuttikjaure	1
Kochejaur	1
the Pasvik River	
Vaggatem	1
Kuetsjarvi	1
Jarfjord	
Gardsjøen	0.25
Holmvatnet	0
Rabbvatnet	0.5
Durvatn	0

Table 5. The Woodiwiss/Trend Biotic Index and the corresponding status for the studied lakes littoral data (I: clean, II: clean, III: moderately polluted).

	Woodiwiss	**Status**
Vätsäri		
Lampi222	9	I
Harrijärvi	9	I
Pitkä-Surnujärvi	9	I
Sierramjärvi	9	I
Russia		
Shuonijaur	7	II
Ala-Nautsijarvi	8	I
Toartesjaur	8	I
Virtuovoshjaur	10	I
Riuttikjaure	8	I
Kochejaur	10	I
the Pasvik River		
Vaggatem	7	II
Kuetsjarvi	6–7	II
Jarfjord		
Gardsjøen	3	III
Holmvatnet	4	III
Rabbvatnet	8	I
Durvatn	6	II

Number of families and EPT-families

Number of families in littoral and riparian zones is a metric in the Canadian zoobenthos assessment. The number of Ephemeroptera, Plecoptera and Trichoptera (EPT) families together is a widely used parameter in Canada and also as part of Swedish multimetric zoobenthos index 'MILA'. The parameters are only used as a part of greater entity or multimetric index and there are no reference values available. Nevertheless, the number of families and the number of EPT families in littoral samples are studied here. Expectations were similar to those for periphyton diversity: pollution-affected Jarfjord area ought to express lower family diversities.

The only notable difference in family diversity between the areas was indeed lower number of all families in Jarfjord (Table 6). On average there were 6 families, in comparison to 12 families both in Vätsäri and the Russian lakes. The difference was statistically close to significant (p=0.06, Kruskal-Wallis). In Jarfjord the number of EPT families was also lower, but there was no statistical significance between the areas (p=0.38, Kruskal-Wallis).

In the Pasvik River littoral family diversity was rather low in Vaggatem. The location is prone to several factors that add up to the result, including water level regulation and slight pollution. Effects of water level regulation on littoral benthos have been studied in Keto et al. (2008), where the decline in Ephemeroptera and Trichoptera taxa were observed to result from regulation. There were no EPT-families found in the 2013 samples in Vaggatem. Moderately polluted Lake Kuetsjarvi expressed fairly average results. However, there are more nutrients in Kuetsjarvi (See Chapter 3 Water quality) than in the other small lakes and thus it's not completely comparable to them.

Table 6. The number of families and the number of EPT families in the studied lakes' littoral data.

	Families	EPT-families
Vätsäri		
Lampi 222	11	2
Harrijärvi	10	4
Pitkä-Surnujärvi	12	5
Sierramjärvi	16	6
Average	12.3	4.3
Russia		
Shuonijaur	8	2
Ala-Nautsijarvi	11	3
Toartesjaur	10	5
Virtuovoshjaur	13	6
Riuttikjaure	10	5
Kochejaur	18	9
Average	11.7	5
the Pasvik River		
Vaggatem	6	0
Kuetsjarvi	11	5
Jarfjord		
Gardsjøen	4	0
Holmvatnet	3	1
Rabbvatnet	8	5
Durvatn	9	4
Average	6.0	2.5

Conclusions

Many of the mathematical indices proved to be prone to falsely low results due to low abundance of benthic fauna. This shows in large-scale drop in status with loss of just one species. At the moment, many of the community indices are too uncertain to be applied in status assessment.

Ephemeroptera, Plecoptera and Trichoptera species are considered sensitive to acidification, pollution and water level regulation. The number of families and EPT families are feasible diversity metrics that could be used in detecting changes in time, presuming the sampling efforts are standardized. Similarly the Woodiwiss/Trend Biotic Index pointed out the communities lacking EPT indicator species.

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Fixing oxygen samples.
Photo: Esko Jaskari

Chapter 3: The ecological condition of the Pasvik River and Lake Inarijärvi

Macrophyte studies in Lake Muddusjärvi. Photo: Jukka Ylikörkkö

1 Introduction

The areas of interest in Chapter 3 were Lake Inarijärvi, the Pasvik River and the major lakes in the Pasvik watercourse. The ecological status of Lake Inarijärvi and the Pasvik River were estimated by using defined indicators sensitive for hydrological change induced by climate change and water level regulation. The presence and amounts of contaminants in the water, fish tissues and bottom sediments of the watercourse were determined. The effects of climate change, contaminants, water level regulation and species introductions and invasions in the Pasvik River were estimated by analyzing a long time series of fish population in two main lakes.

The water quality in the Pasvik area has been monitored for longer than biological indicators of ecological status. The newest trends in water quality have been published in a separate report *Pasvik Water Quality until 2013* (Ylikörkkö et al. 2014) which is a continuation of earlier reports of 2007 and 2011.

The main reason for the monitoring of the water quality in the Pasvik watercourse is the Pechenganikel copper-nickel smelter complex on the Kola Peninsula. Lake Inarijärvi and the upper part of the Pasvik River are affected mainly by low levels of atmospherically transported pollutants whereas the lower part in the vicinity of the combine and the areas downstream are affected by both direct waste water discharge and atmospheric deposition. Along the Pasvik watercourse there is also discharge of water from the Pasvik hydropower plant cascade. The issues tied to the hydropower stations include changes in the rivers' regime resultant from construction of water reservoirs, upsetting of the natural water balance and impact on the hydro-chemical regime of small rivers and their self-cleaning capacity.

Lake Inarijärvi is situated in the upstream of the Pasvik watercourse and is free of direct emissions from the Pechenganikel. There is some nutrient loading from diffuse and point sources and the Pasvik River regulation inflicts moderate water level fluctuation. The water quality is excellent and the measured chemical indicators have stayed on the same levels throughout the monitoring programme.

In the Pasvik River and the directly connected lakes the water monitoring data of the observation period confirms certain stabilization of the established hydro-chemical regime, pollutants' concentrations and pollution indicators. Copper, nickel, and sulphates are the main pollutants of the basin. The monitoring data also shows that pollutants are brought into the water bodies of the river basin system both directly with wastewater and by way of long-range transboundary air transport. The most polluted water body in the basin is the Kolosjoki River where the Pechenganikel combine plant wastewater is discharged, as well as the stream connecting the Lakes Salmijarvi and Kuetsjarvi. The concentration of metals and sulphates in the water notably increases downstream from Lake Kuetsjarvi. In Lake Kuetsjarvi the concentrations of copper and nickel are clearly elevated and have changed insignificantly in the last years of the monitoring period

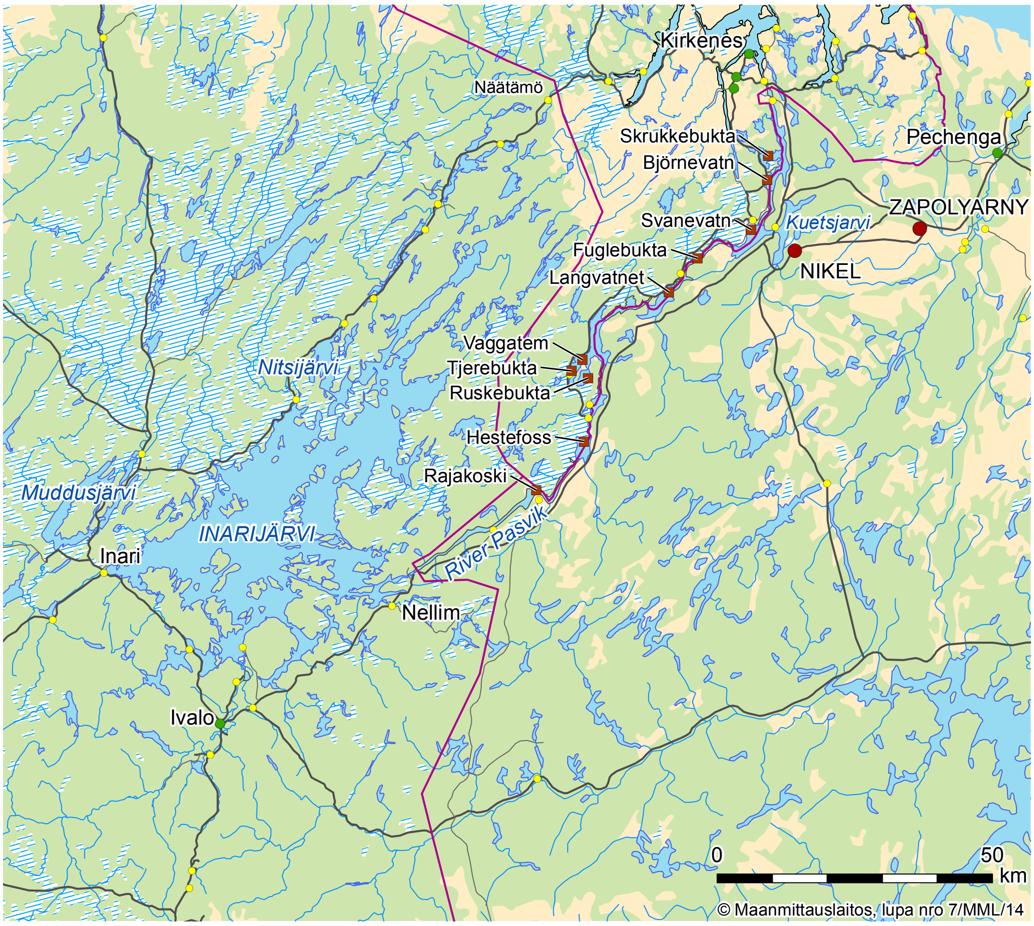

Figure 1. Map of the study area.

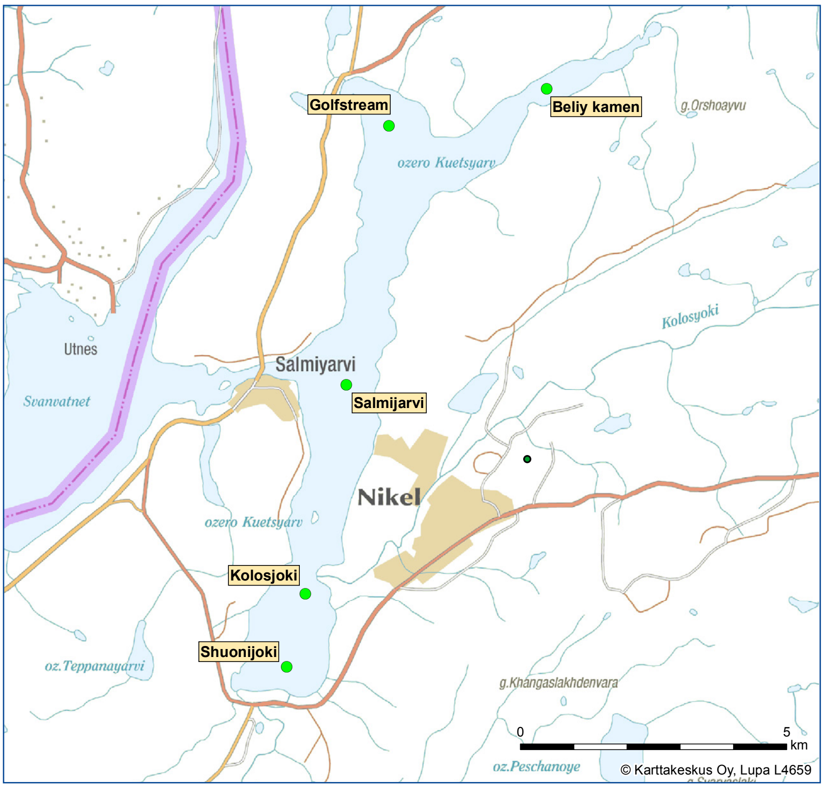

Figure 2. Map of the monitoring stations of Lake Kuetsjarvi.

2 Climate change impacts on hydrology and water level fluctuation

SEPPO HELLSTEN AND JUHA RIIHIMÄKI

Climate change forecasts used in this study (see generally Veijalainen et al. 2012) estimate annual mean temperature in Lake Inarijärvi watershed to increase 3.6 °C in 2040–2069 compared to annual mean temperature during 1971–2000 and increase on mean winter temperature (December–February) is estimated to be 5.1 °C. Annual mean precipitation is estimated to increase 12 % and winter mean precipitation 16 %. These changes would affect also the yearly hydrological cycle altering timing of high and low water levels and discharges on lakes and rivers.

The hydrological model, Watershed Simulation and Forecasting System (WSFS) (Vehviläinen et al. 2005), was used to estimate climate change impacts on hydrology of the Pasvik River catchment (Figure 1). Climate chance scenario used was mean of 19 global climate models calculated by Finnish meteorological institute FMI (Jylhä et al. 2009) with emission scenario SRES A1B (IPCC 2000).

Effects of climate change induced changes on the Pasvik River hydrology and Lake Inarijärvi water levels were analyzed using DHRAM calculation programme on the Pasvik River and water-level fluctuation analysis tool (Regcel) on Lake Inarijärvi. Scenario period used in this study was 2040–2069 and reference period used was 1971–2000.

Materials and methods

Regcel model developed in the Finnish Environment Institute (SYKE) was used to enable assessment of the ecological impacts of water-level regulation on aquatic macrophytes, benthic invertebrates, fishes and nesting of waterfowl. Indicators for Lake Inarijärvi were calculated for reference period 1971–2000 and the average values of that period were compared to indicators calculated for the scenario period 2040–2069.

The Dundee Hydrological Regime Assessment Method (DHRAM) was used for water flow analysis. This approach compares differences between the affected and unaffected flow data and is therefore descriptive. It resembles the Regcel application, but uses only discharge data without any measured biological response. The method assessess the degree of hydrological alteration, presuming that the change is having an ecologically harmful impact on naturally adapted biota. Discharge factors are divided into five different groups, in which both mean value (A) and coefficients of variation (B) are used as indicators. Comparisons between un-affected and affected situations are calculated as an absolute change (%). Hydrological change thresholds used for allocation of

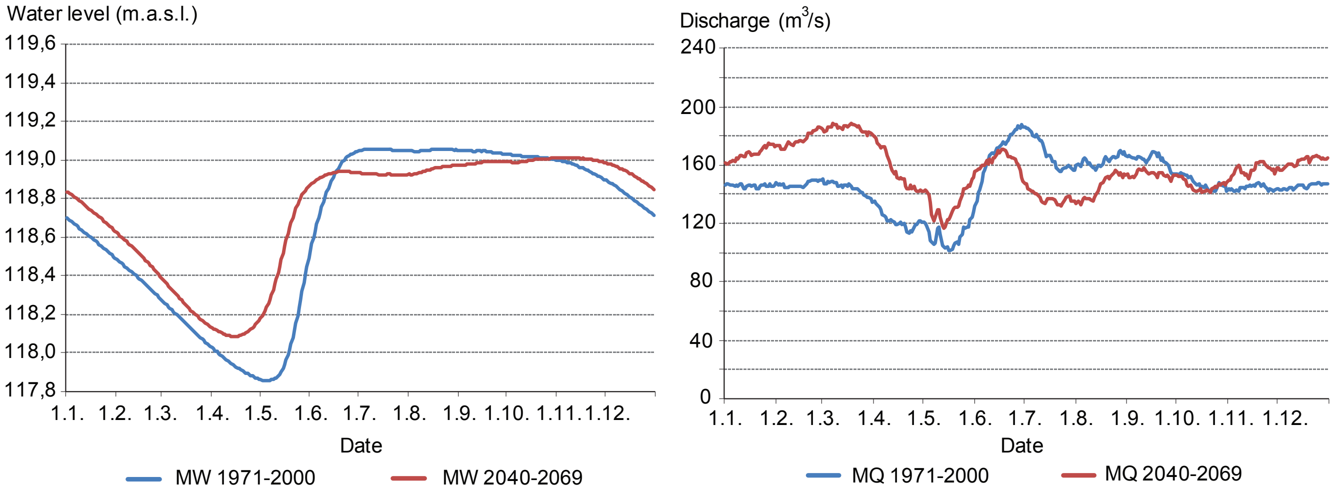

Figure 1. Simulated water level fluctuations (left) and simulated discharges (right) for the reference period and the scenario period at Lake Inarijärvi.

final impact points and the final impact classes can be found in Black et al. (2000).

In our study DHRAM was applied to compare the regulated water flow (reference period) in Kaitakoski (1970–2000) and simulated flow for climate change scenario (2040–2069).

Results

Regcel

Results for the water level fluctuation indicators of Lake Inarijärvi are presented on Table 1. Simulated water levels have quite clear influence in some of the indicators although there are many indicators where there is no change or it is negligible.

Magnitude of spring flood is an indicator that describes "cleaning effect" of spring high water levels transporting the dead organic material to upper shore areas. Higher spring flood is considered to inhibit excessive growth of shore vegetation. Spring flood magnitude in Lake Inarijärvi is very small in reference period and there is no spring flood at all in scenario period.

Water level change during growing season in Lake Inarijärvi is smaller in scenario period than in reference period. The change is calculated by subtracting 75 % fractal of water levels of the first ice-free month from the 75 % fractal of water levels of the rest of the growing season (from 30 days after ice-out to 30th September). If the indicator value of the water level change were negative (water level is lowering during the growing season), it would promote zonation of littoral vegetation and would have positive effect on shore habitat diversity. However, the indicator value is positive (water level is rising during the growing season) in both reference period and scenario period indicating unfavorable conditions. Nevertheless, the indicator value is smaller (and better) in scenario period."

Carex zone is the optimum growing level of sedge (*Carex)* species being important habitat for northern pike spawning. Change in maximum vertical extension of *Carex* zone and decrease of water level during spawning of northern pike is negligible. However, although indicator minimum water depth in the *Carex* zone during the spawning of northern pike is having negative value indicating that water levels at Lake Inarijärvi stays below optimum zone for *Carex* species during spawning period, the direction of the change between reference period and scenario period is positive.

Extent of frozen productive zone describes how much of the littoral productive zone is frozen during winter. It is important factor affecting organisms (aquatic vegetation, invertebrates and eggs of autumn spawning fish species) that can't tolerate freezing. Decrease of extent of frozen productive zone over 10 percentage points is positive effect. Also changes in other similar indicators depending of water level changes during ice covered period i.e. extent of ice pressure zone and magnitude of winter drawdown have similar positive effects.

Table 1. Water level fluctuation indicators calculated with Regcel model and assessment of effect of climate change on environment. "+" = positive effect, "-" = negative effect.

Water level fluctuation indicator	Reference period 1971–2000	Climate change scenario 2040–2069	Effect
Magnitude of spring flood (m)	0.03	-0.01	
Water level change during growing season (m)	0.21	0.10	+
Maximum vertical extension of the Carex zone (m)	0.24	0.25	
Extent of frozen productive zone (%)	33.63	21.99	+
Extent of ice pressure zone (%)	50.83	37.18	+
Extent of disturbed productive zone (%)	38.27	32.07	+
Water level rise during the nesting of birds (m)	0.18	0.13	+
Magnitude of winter drawdown = water level decrease during the ice cover period (m)	1.20	0.92	+
Decrease of water level during spawning of northern pike (m)	0.00	0.01	
Minimum water depth in the Carex zone during the spawning of northern pike (m)	-0.44	-0.23	+
Mean number of days per year when water level > 119,35	9.7	6.4	+

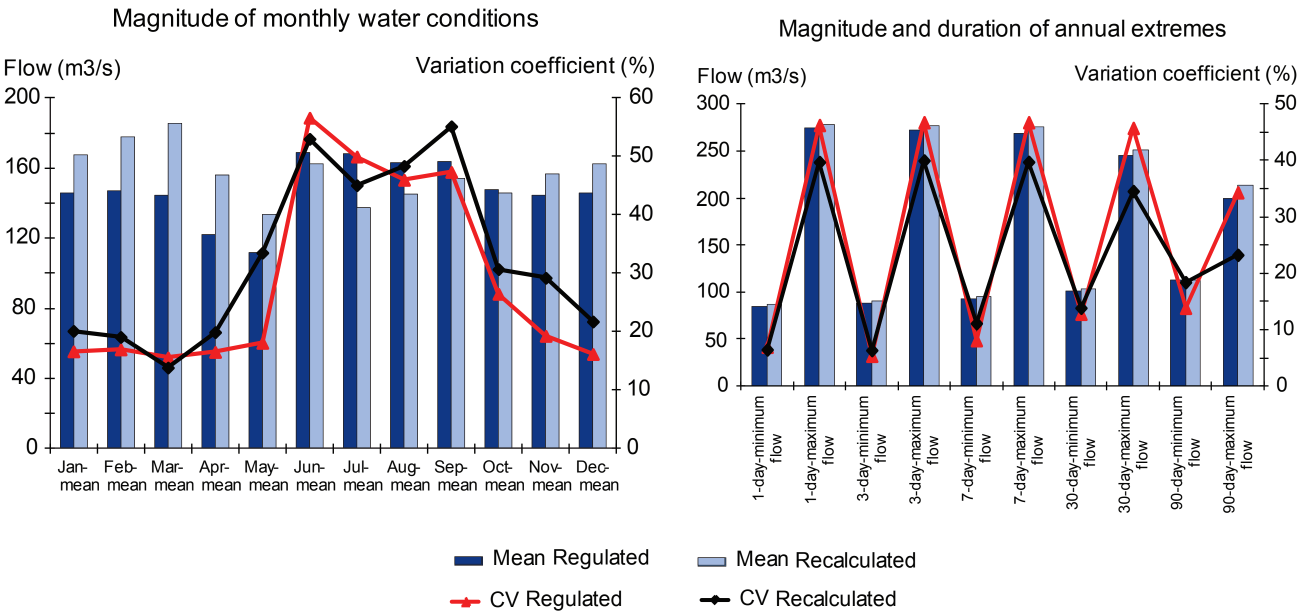

Figure 2. Magnitude of monthly water conditions and magnitude and duration of annual extremes in the Pasvik River. Comparison of current (1970–2000 deep blue, red line) and climate change (2040–2069, light blue, black line) hydrology.

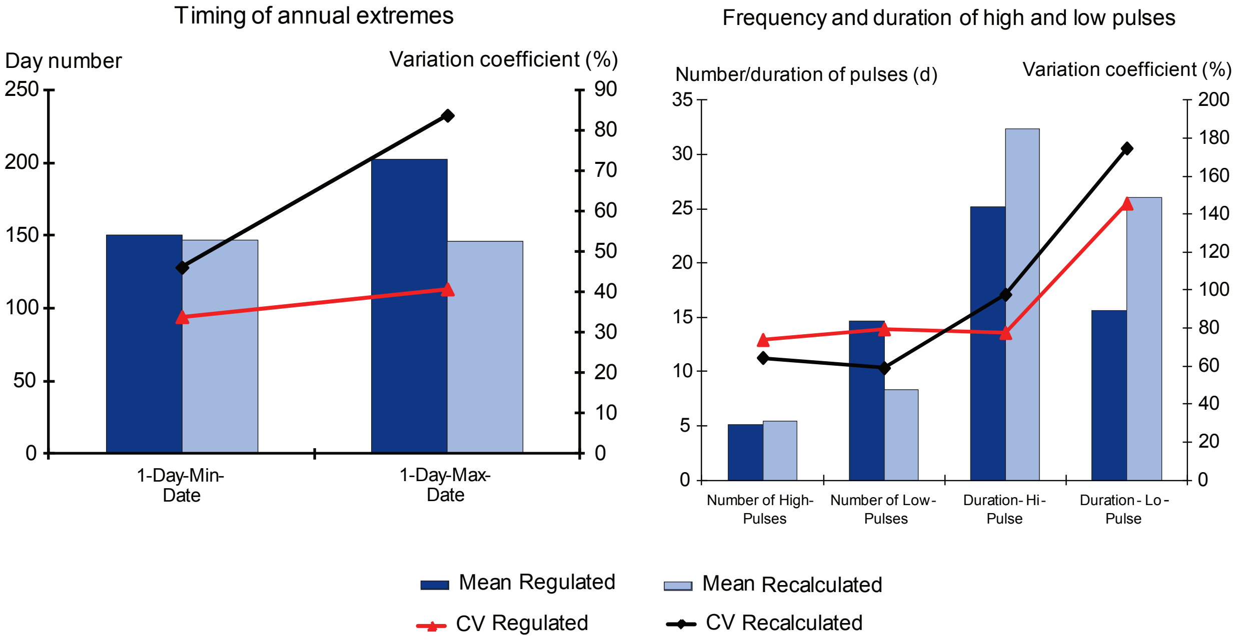

Figure 3. Timing of annual extremes and frequency and duration of high and low pulses in the Pasvik River. Comparison of current (1970–2000, deep blue, red line) and climate change (2040–2069, light blue, black line) hydrology.

Productive littoral zone between mean high water and mean low water is disturbed by wave action during open water period and by freezing and ice pressure during ice covered period. These disturbances also have an effect on littoral biota restricting survival of sensitive species. Change in extent of disturbed productive zone, although only 6.2 percentage points, is positive.

Water level rise during the nesting of birds can destroy nests near the water. Decrease in water level rise is only 0,05 m but the direction of change is positive and it can have an positive effect on nesting success of birds.

Wave action induced erosion is significant disturbance affecting littoral habitats on Lake Inarijärvi and water levels above 119.35 m.a.s.l. are considered to be the conditions when erosion in Lake Inarijärvi is increasing substantially (Puro-Tahvanainen et al. 2011). Decrease in mean number of days per year when water level is greater than 119.35 m.a.s.l. has a positive effect on erosion sensitive shores mitigating disturbance caused by erosion.

DHRAM

DHRAM analysis was applied to water flow data from the Kaitakoski station, situated at the outlet of Lake Inarijärvi. The difference between flow situations was also quite clear; with very much higher spring flow and lower flow during summer.

There are relatively large changes between the reference period and the climate change scenario period in flow situations according to the DHRAM analysis. When comparing monthly water level fluctuations, there is a clear change from summer months to winter as a consequence of climate change. However, summer and the increase in variation are the main factors affecting the situation (Figure 2).

Magnitude and duration of annual extremes shows no significant change in terms of final impact points although the values of the extremes have changed slightly (Table 1, Figure 2). The timing of annual extremes has changed significantly, but there has been also increasing variation as a consequence of climate change (Figure 3). Change in flood timing reaches 2 final impact points, which is quite significant from the point of view of ecology.

More relevant ecological change is visible in the frequency and duration of high and low pulses (Figure 3). There are more high and low pulses, but mean duration is significantly lower. This situation can cause environmental stress for most biota, which cannot adapt to rapid changes (Richter et al. 1996).

There are no big differences in the rate and frequency of change in conditions. DHRAM analysis showed only a weak trend; a total of impact 2 points were reached, which according to Black et al. (2000) indicates a low risk of impact.

Conclusions

Climate change impacts on hydrology and water level fluctuation indicators were analysed in the Pasvik River catchment. Two different hydrological analysis systems were applied. Water level data for Lake Inarijärvi was analysed using Regcel model. The model enables assessment of the ecological impacts of water-level regulation on aquatic macrophytes, benthic invertebrates, fishes and nesting of waterfowl.

The results in water level fluctuation indicators showed that changes in water level fluctuation would have mainly positive effects on environment brought by decrease in fluctuation. Water level change during growing season in Lake Inarijärvi being smaller in scenario period than in reference period promotes zonation of littoral vegetation and would have a positive effect on shore habitat diversity. Decrease of extent of the zone disturbed by wave action, extent frozen productive zone, extent of ice pressure zone and magnitude of winter drawdown all have positive effects on survival of sensitive littoral biota. Decrease in water level rise can have a positive effect on nesting success of birds and decrease in mean number of days per year when water level is greater than 119.35 m.a.s.l. has an positive effect on erosion sensitive shores.

General flow data for the Pasvik River was analysed by the DHRAM programme. The method is rapid, but the biological response was partly unclear. The analysis showed that the climate change induced change in flow regimes would have low risk of impact. Both Regcel and DHRAM method can be effectively used to assess hydrological and ecological effects of climate change on lakes and rivers using measured and simulated water level and discharge data.

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The Pasvik River.
Photo: O. Pershin.

Carex zone in the Pasvik River.
Photo: Juha Riihimäki.

The rocks of Lake Inari reflect water level fluctuation.
Photo: Heidi Salow.

3 Toxic substances on the sediments of the Pasvik River

VLADIMIR DAUVALTER, GUTTORM N. CHRISTENSEN, HELÉN JOHANNE ANDERSEN

Lakes and reservoirs (and their sediments as storage of physical and chemical disintegration products of a wide range of chemical substances) serve as collectors of all substances delivered into their catchment area. Sediments are an important information source about climatic, geochemical and environmental conditions that existed in the catchment area and in the reservoirs itself, which allows estimating today's ecological state of the air and aquatic environments. Heavy metals' concentrations in the sediments allow estimating contamination intensity and history of the investigated lakes.

Sediment cores from the river-and-lake system of the Pasvik River were used to estimate the effect of the Pechenganikel mining and metallurgical company activity on the waterway's status. Maximum concentration of the investigated heavy metals (nickel (Ni), copper (Cu), cobalt (Co), zinc (Zn), cadmium (Cd), lead (Pb), mercury (Hg) and arsenic (As)) in the sediment surface layers was identified in Lake Kuetsjarvi receiving waste waters from the Pechenganikel Company. Heavy metal content decrease in the sediment surface layers is observed downstream the Pasvik River from waste water inflow, although contamination is considerably high. In the lakes polluted only by air transport and household sewage there was no increase in the Ni, Cu, Co, Zn content emitted by the Pechenganikel but great increase of chalcophile elements' (Pb, Cd, Hg and As) concentration was discovered. The average sedimentation rate in the lakes under study appeared to be higher (1–3 mm/year) than on an average for the lakes of the northern Fennoscandia (less than 1 mm/year). Phosphorus content increase is detected towards sediment surface in some lakes which may give evidence of eutrophication process development.

Materials and methods

Sediment cores for heavy metal analysis were collected at five stations of Lake Kuetsjarvi (1. White Stone, 2. Gulf Stream, 3. Salmijarvi, 4. Kolosjoki, 5. Shuonijoki) and in lakes Ruskebukta, Vaggatem and Skrukkebukta (Introduction, Figures 1 and 2). Sediment cores for persistent organic pollutants (POPs) were collected in lakes Vaggatem, Kuetsjarvi and Skrukkebukta. The upper 3 cm of the sediment core was sliced in 1 cm sections.

Industrial impact on the lake ecosystem was determined using the contamination factor (C_f) of each priority heavy metal contaminant (Ni, Cu, Co, Zn, Pb, Cd, Hg and As) (method of Håkanson, 1980, 1984). In this approach the following classification of C_f^i was used: $C_f^i<1$ – low; $1 \le C_f^i<3$ – moderate; $3 \le C_f^i<6$ – considerable; $C_f^i \ge 6$ – high contamination factor. Similarly, in C_d description the classification was used based on the calculation that C_f values are summed up for 8 elements: $C_d<8$ – low; $8 \le C_d<16$ – moderate; $16 \le C_d<32$ – considerable; $C_d \ge 32$ – high degree of contamination indicating serious anthropogenic pollution.

Results and discussion

Background concentrations of heavy metals

Sediment samples taken from the deepest core layers allow determining the heavy metal background concentrations in the course of lake contamination studies. These layers reflect the natural geochemical features of drainage and allow estimating the reservoir contamination extent and also discovering metal concentration anomalies for the purpose of mineral deposits' detection (Tenhola & Lummaa 1989). The heavy metal background concentrations play an important role in determining the effect of anthropogenic industrial activity on aquatic ecosystems as long-term industrial load on the catchment areas has resulted into change of natural conditions of sediment chemical composition forming.

The maximum background concentrations of most heavy metals (Ni, Cu, Zn, Co, Cd, Hg and As) were found at the stations of Lake Kuetsjarvi which is accounted for by the fairly high sedimentation rate in the lake. The background concentrations in Lake Kuetsjarvi have been found to be 2–10 times higher than in other lakes under study. The highest Pb concentrations were detected in lakes Ruskebukta and Skrukkebukta. Generally, the average background concentrations of almost all heavy metals (except Cd) in the Pasvik River reservoir catchment areas are higher than the average background concentrations in sediments of the North-West of Murmansk Region and border area of the neighbouring countries (Kashulin et al. 2009).

According to factor analysis the chemical composition of the sediment background layers is influenced by natural peculiarities of the Pasvik River drainage (physical parameters and geochemical peculiarities) and the processes in the lake itself (biological processes, changes in reductive-oxidative conditions etc.).

Three groups were clearly identified by cluster analysis: the first group includes channel reservoirs (lakes Ruskebukta, Vaggatem and Skrukkebukta), the second is the Lake Kuetsjarvi stations 1 and 3 with minimum sedimentation rate where the deepest sediment layers are the most approximated to the natural background values and the third is the Lake Kuetsjarvi station 4 and 5 with the maximum sedimentation rate where background sediment layers most likely were never reached.

Vertical distribution of elements in the sediments

Waste water from the Pechenganikel integrated plant is the main contamination source of Lake Kuetsjarvi and surface waters in the territory of industrial area. heavy metals (Ni, Cu, Zn, and Fe (iron)) and organic substances (xanthates) are the main components of the waste waters (Dauvalter 2002).

Even though the Pechenganikel reduced its heavy metal discharge into Lake Kuetsjarvi there is no observed decrease of concentrations in the sediments in Lake Kuetsjarvi and almost all the elements have surface maximums. Only Hg is characterized by maximum concentrations at depths 2–4 cm of sediment cores almost at all of the lake stations (Figure 1). No significant changes were found in the vertical distribution of Ni, Cu, Co and Zn concentrations in sediments of Ruskebukta and Vaggatem situated upstream from Lake Kuetsjarvi. A slight increase of Ni and Cu concentrations is observed in the upper 4 cm sediments of Lake Vaggatem, which is connected with airborne industrial pollution from the Pechenganikel. However an increasing trend of concentrations of chalcophile elements (Pb, Cd, Hg and As) was discovered in the surface layers of these lakes in comparison with the background content. The greatest increase was observed in Lake Ruskebukta for Hg. This phenomenon is probably connected to the global atmospheric pollution of the Northern hemisphere and not directly connected with the Pechenganikel because this part of the Pasvik River catchment area is not significantly affected by the discharges (Pacyna & Pacyna 2001; Hagen et al. 1991). A slight decrease of Cd concentration is also found in the upper layer in Lake Vaggatem.

In the sediments of Lake Skrukkebukta situated downstream from Lake Kuetsjarvi the maximum concentrations of Ni, Cu, Co, Cd and Pb were found in the upper 1 cm layer (Figure 1). A significant increase of heavy metal concentrations as compared to the background was detected in the upper 3 cm of sediments.

Concentration decrease of aluminium (Al), magnesium (Mg), potassium (K) and calsium (Ca) is observed towards to sediment surface of Lake Kuetsjarvi (Figure 2) which can be related to the inflow of a large amount of sulphate in the content of waste waters from the Pechenganikel Company causing release of alkaline and alkaline-earth metals and Al from the suspended particles and sediments and their transition into a dissolvable form (Baklanov & Makarova 1992). The sulphate content in the water of Lake Kuetsjarvi is 2–3 times higher than in all the other lakes of the Pasvik River system under study. Such regularity was also discovered in sediments of Lake Skrukkebukta.

Increase of Mn and Fe concentrations is observed towards the sediment surface almost at all the stations of Lake Kuetsjarvi. Increase of phosphorus (P) content is also observed in the surface layers of sediments of Lake Kuetsjarvi and the other lakes. This can indicate development of eutrophication processes, related to the inflow of household sewage and the river flow regulation and resulting into the flow deceleration, stagnations, and, finally, accumulation of nutrients in aquatic ecosystems. Phosphorus accumulated in sediments can be a source of this nutrient permeating into the water layers (Lennox 1984; Sandman et al. 1990; Shaw & Prepas, 1990).

Factor analysis was performed to discover the main factors influencing chemical composition formation of the sediments. The first factor is effect of discharged waters and emissions from the Pechenganikel Company, the second factor is natural processes taking place in the water layer and the sediments of reservoirs and the third factor comprises reductive-oxidative processes and eutrophication.

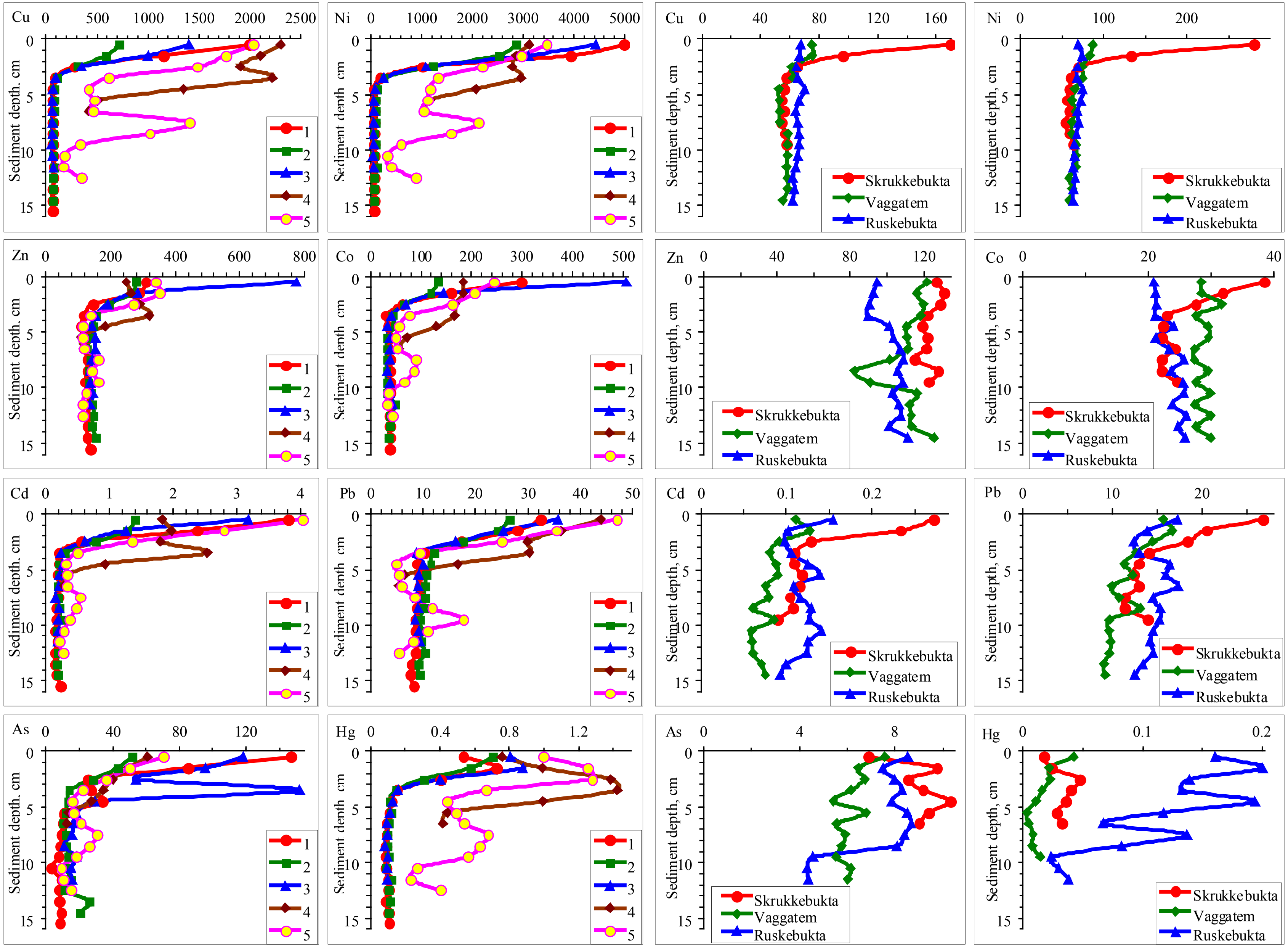

Figure 1. Vertical distribution of heavy metal concentrations (μg/g) in bottom sediment columns of Lake Kuetsjarvi (stations 1–5) and in the Pasvik River lakes (red = Skrukkebukta, green = Vaggatem, blue = Ruskebukta).

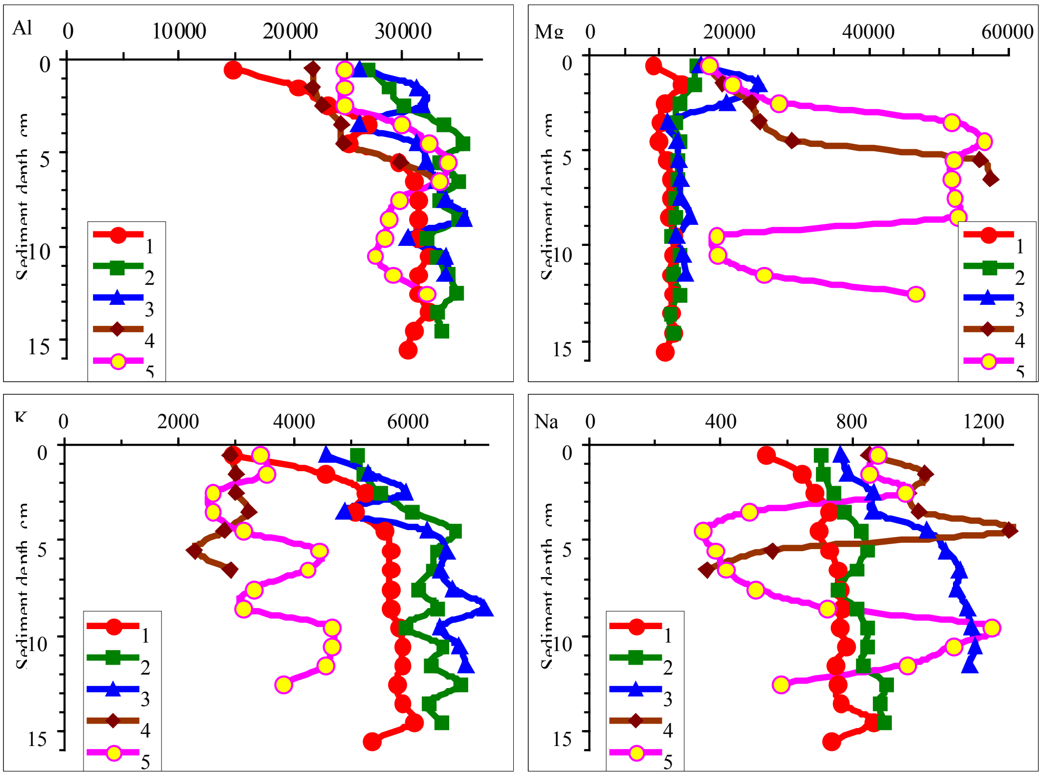

Figure 2. Vertical distribution (sediment depth, cm) of Al, Mg, K and Na concentrations (µg/g) in sediments of Lake Kuetsjarvi.

Element distribution in the surface layers of bottom sediments

Pechenganikel emissions are the main source of increased heavy metal concentrations of the Pasvik River system. This is especially intensive in Lake Kuetsjarvi. The highest Ni and Cu concentrations exceeding the background values 10–380 times are observed at a distance ≤10 km from the Pechenganikel (Dauvalter 1994, 1995, 1999). The background concentration exceeding reduces up to 3–7 times at a distance of 10 to 40 km from the pollution source. Co concentrations were 4–10 times higher than the background at a distance of ≤15 km from the pollution source and up to 3 times higher in other lakes, which is evidence of the emissions' impact.

The main part of the industrial waste water from the Pechenganikel enters Lake Kuetsjarvi. The highest concentrations of heavy metals were observed at the deepest station 1 (Ni, As), at stations 4 and 5 (Cu, Cd, Pb, Hg) situated nearest to the Pechenganikel waste water discharge area and also at station 3 (Zn, Co), closest to the channel connecting Lake Kuetsjarvi and the Pasvik River watercourse. In the lower course of the Pasvik River in Lake Skrukkebukta the maximum concentrations of Ni, Cu, Co, Zn, Cd and Pb were found in the surface sediment layer which is related to the contaminated water inflow from Lake Kuetsjarvi

Concentration increase of chalcophile elements (Pb, Cd, As and Hg) was observed in the upper sediment layers in the lakes of the Pasvik River upper stream. High concentrations were observed in Lake Ruskebukta (the highest As and Hg concentrations except for Lake Kuetsjarvi), which proves that atmospheric emissions of the Pechenganikel are not the major contamination source of chalcophile elements. The highest Fe and Mn concentrations in the surface layers of sediment were recorded at station 1 of Lake Kuetsjarvi and the highest concentrations of alkaline-earth metals (Ca, Mg and Sr (strontium)) and P are also discovered in Lake Kuetsjarvi. Increased P content was observed in Ruskebukta, which is related to the water flow regulation and household waste water discharge from the populated localities on lake shores.

Factor analysis was performed to identify the main factors influencing the formation of chemical composition of today's sediments in the surface 1 cm layer of the investigated reservoirs. The first factor consists of the development of lakes' contamination processes and the second factor combines values characterizing the biological activity of the reservoirs as well as some of the main elements in the Earth crust (Na (sodium) and Mg). Most likely the processes taking place in the reservoirs play the main role despite of the heavy contamination in Lake Kuetsjarvi.

Two groups of reservoirs were determined by cluster analysis. The first group is the water area of Lake Kuetsjarvi (stations 2–5). The second group forms of the lakes situated downstream and upstream from Lake Kuetsjarvi (Skrukkebukta, Ruskebukta and Vaggatem), which are characterized by less contamination of the sediment surface layers due to greater distance from the smelters. Station 1 of Lake Kuetsjarvi stands apart, probably because it is the deepest station and specific physical chemical and geochemical peculiarities of this water area made a contribution to the sediment chemical composition. This station is also characterized by the highest contamination degree among all the investigated stations.

Factor and degree of contamination

Contamination intensity of reservoirs can be estimated by comparing heavy metal concentrations in the surface layer to the background values of sediments. Determination methods of factor and degree of contamination of water ecosystems by heavy metals in sediments using C_f and C_d are described in Håkanson (1980, 1984). Determination methods of sediment contamination by industrial enrichment factor are described in Alhonen (1986), Ouellet & Jones (1983) and Tolonen & Jaakkola (1983).

Maximum values of C_f (high contamination) for almost all of the studied heavy metals are observed in the sediments of Lake Kuetsjarvi. Only for Zn (except for station 3) and Pb the moderate and considerable contamination were observed. Stations 1 (Ni), 3 (Zn, Co and As), 4 (Cu), 5 (Cd, Pb and Hg) are characterized by the higher contamination factors. In general the highest value of contamination degree was recorded at the station 1.

Impact of the waste water from the Pechenganikel as significant Ni contamination was also observed downstream in Lake Skrukkebukta. The C_f values for Cu and Cd are on the borderline between moderate and considerable and moderate contamination is observed for the other metals. Among the lakes situated upstream from the Pechenganikel Company the high Hg contamination is found in Lake Ruskebukta. Low and moderate values of C_f are observed for other metals in lakes Ruskebukta and Vaggatem.

In general, Lake Kuetsjarvi (high value of C_d) is characterized by the maximum contamination by all the studied contaminants. Lake Skrukkebukta has C_d value on the boundary between low and moderate and low values of C_d are recorded in lakes Vaggatem and Ruskebukta.

Persistent organic pollutants in sediments

Previous screening studies of persistent organic pollutants (POPs) in bottom sediments revealed higher levels of several environmental contaminants in Lake Kuetsjarvi compared to other lakes in the Pasvik River (Christensen et al. 2007).

The highest concentrations of ∑PCB were measured in sediments from Lake Kuetsjarvi downstream from the Nikel city (Figure 1). The levels of ∑PCB in lake sediments from Vaggatem and Skrukkebukta were comparable. The levels in surface sediment (0–1 cm) were approximately 4 times higher in Lake Kuetsjarvi compared to Vaggatem and Skrukkebukta. The highest concentrations of PCB were detected in the 2–3 cm layer from Lake Kuetsjarvi. These results are comparable with previous study from the Pasvik River (Christensen et al. 2007) and the concentrations of ∑PCB in Lake Kuetsjarvi are elevated compared to other lakes in Northern Norway (Skotvold et al. 1997, Christensen et al. 2008).

The highest concentrations of ∑DDT were measured in sediments from Skrukkebukta (Figure 2). DDT was also detected in the surface sample from Vaggatem. The concentrations of DDT in all the sediment samples from Lake Kuetsjarvi were below the detection limit. There are no known sources of DDT in the area. However, DDT was previously used as pesticide in agriculture but tit was banned in the early 1970s. In a previous study the highest levels of DDT were detected in sediments from Lake Kuetsjarvi (Christensen et al. 2007).

Polybrominated diphenyl ethers (PBDE) were only detected in sediments from Skrukkebukta and Vaggatem (Christensen et al. 2015).

Based on the results from this study there is no clear time trend of the historical development of POPs in the sediments from these lakes. It is recommended that a more extensive sediment survey be carried out with dating of the sediments, which will give detailed information about historical trends for POPs and heavy metals.

The higher levels of PCB and mercury in the analysed sediment samples downstream from Nikel compared to upstream clearly indicate emissions of these compounds from Nikel. The source might be related to the activity in the metallurgical smelter or other industrial activity, contaminated areas in the city or landfills.

The results from this sediment study and the results from the study of contaminants in fish are comparable in that sense that the highest levels of POPs are found downstream from Nikel. However there are several very interesting questions that need further investigations: the time-trends for PCB, DDT, PBDE and mercury and where the sources in the Nikel city are, for example.

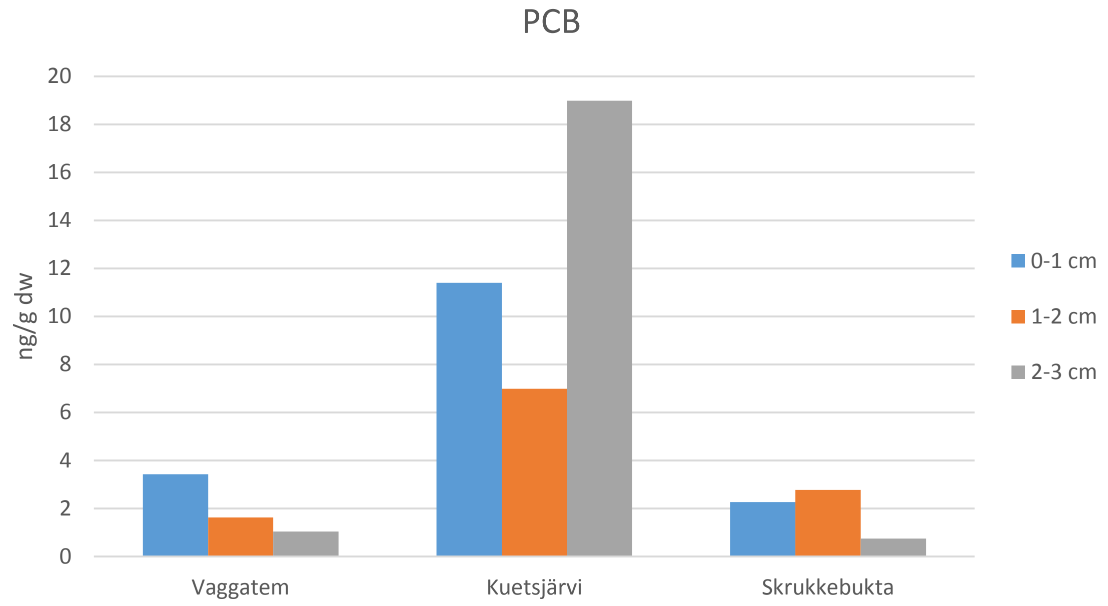

Figure 1. Levels of ∑PCB (ng/g dw) in three layer (0–1 cm blue bars, 1–2 cm red bars, 2–3 cm green bars) of bottom sediments from lakes Vaggatem, Kuetsjarvi and Skrukkebukta.

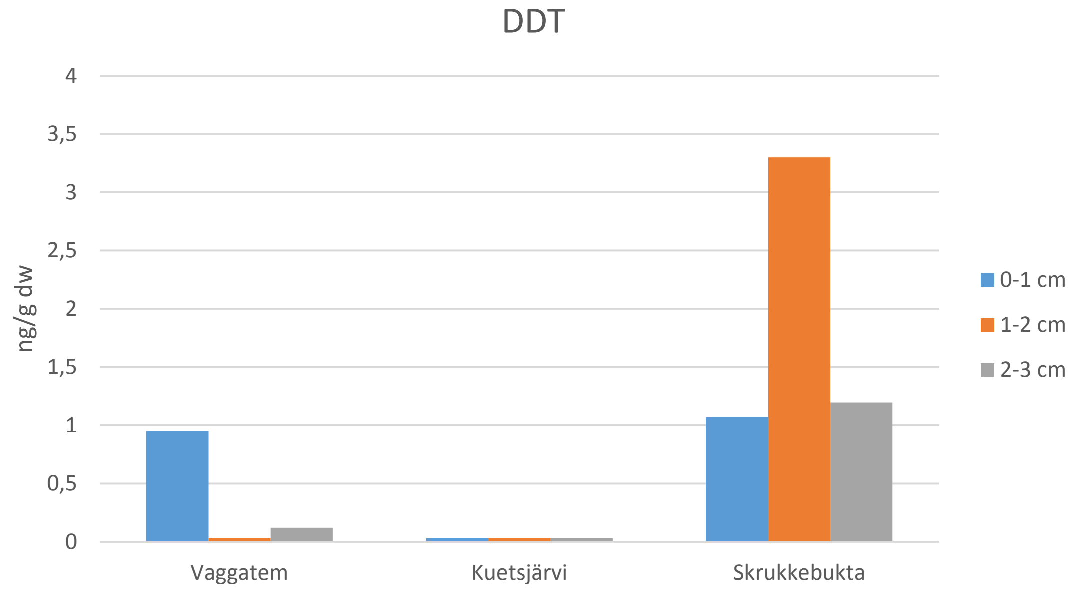

Figure 2. Levels of ∑DDT (ng/g dw) in three layer (0–1 cm blue bars, 1–2 cm red bars, 2–3 cm green bars) of bottom sediments from lakes Vaggatem, Kuetsjarvi and Skrukkebukta.

Conclusions

The highest background concentrations of most of the heavy metals (Ni, Zn, Co, Cd, Hg and As) in the sediments are observed in the southern part of Lake Kuetsjarvi, which is accounted for by the geochemical and morphometric peculiarities of the lake and its catchment area. In general the average background concentrations of almost all the heavy metals (except Cd) in the catchment reservoirs of the Pasvik River are higher than the average background concentrations in the North-West of Murmansk Region and the border territories.

The Pechenganikel emissions result into the maximum concentrations of all the investigated heavy metals in the surface layers of the sediments of Lake Kuetsjarvi. Almost all heavy metals have surface maximum and despite the reduction of discharge into Lake Kuetsjarvi and atmospheric emissions by the Pechenganikel there is no observable decrease in the content. Downstream from the Pechenganikel in Lake Skrukkebukta maximum concentrations of Ni, Cu, Co, Cd, and Pb are found in the upper 1 cm layer of sediments and large increase of heavy metal concentrations in comparison to the background is distinguished in the upper 3 cm of the sediments.

In lakes Vaggatem and Ruskebukta upstream from the Pechenganikel no great changes in the vertical distribution of Ni, Cu, Co and Zn concentrations are found in the sediments, although there is a slight increase of Ni and Cu concentrations in the upper 4 cm in Lake Vaggatem. However, a slight increase in concentration of chalcophile elements was discovered in the surface layers of lakes Ruskebukta and Vaggatem in comparison to the background content. The largest increase is observed in Lake Ruskebukta for Hg.

In general Lake Kuetsjarvi (high value of C_d contamination degree) is characterized by maximum contamination by all the studied contaminating elements. Lake Skrukkebukta has the C_d value on the boundary between low and moderate. Low values of C_d are found in lakes Vaggatem and Ruskebukta, which are the least polluted of the studied lakes.

Industry is the main source of contaminants in the Pasvik region. Photo: Sergey Sandimirov

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4 Plankton communities of the Pasvik River

DMITRII DENISOV

Phytoplankton

Phytoplankton communities are an integral part of the status assesment of water bodies in subarctic regions. Phytoplankton algae play an important role in primary production of aquatic ecosystems. Various indicators of the status of algae communities are successfully used in assessment of water trophic status, level of organic pollution and intensity of eutrophication processes. The structure and taxonomic composition of phytoplankton communities in lake-and-river systems in different seasons are necessary for building and improvement of bioindication systems and expansion of understanding of the diversity of conditions within one water body depending on environment and industrial load. Data on the composition of communities is important also for identifying the crucial factors of water bodies' development in high-latitude regions in the course of local and global changes in the natural environment. Special interest is held by the study of annual phytoplankton dynamics in monitoring long-term industrial pollution and changes in the climate system dynamics.

Materials and methods

Different areas of the Pasvik watercourse traditionally used for assessment of the water quality and the aquatic ecosystem status were sampled. The sampled water bodies were Rajakoski, Vaggatem, Ruskebukta, Tjerebukta, Skrukkebukta and Lake Kuetsjarvi (Introduction, Figure 1).

Sampling for assessment of species composition, abundance and biomass of phytoplankton was performed in 2012 in July and August; additional samples from Lake Kuetsjarvi were taken in June for assessment of the seasonal dynamics of phytoplankton indicators. Sampling and analysis of phytoplankton samples was performed according to the standards GOST 17.1.3.07-82 (RF) with the use of the recommended standard methods according to the scheme adopted at INEP KSC RAS. Species composition was identified according to several field guides (Krammer 2000, 2002, 2003, Lange-Bertalot 2001, Tikkanen 1986, Barinova & Medvedeva 1996, Krammer & Lange-Bertalot 1986, 1988, 1991a, 1991b). The taxonomic diversity was assessed with Shannon-Weaver index (1949).

Phytoplankton pigments were determined to assess the algae photosynthetic activity. The chlorophyll a concentration and phytoplankton biomass in a water body reflect its trophic status accurately enough according to Kitaev's trophic scale (Table 1).

Table 1. Kitaev's trophic scale (1984)

	Oligotrophic		Mesotrophic		Eutrophic		Hypereutrophic
	α	β	α	β	α	β	
Chlorophyll a, mg/m^3	<1.5	1.5-3	3-6	6-12	12-24	24-48	>48
Phytoplankton biomass, g/m^3	<0.5	0.5-1	1-2	2-4	4-8	8-16	>16

Table 2. Water quality classification according to saprobity index S (GOST 17.1.3.07-82)

Saprobity index	Water quality class	Pollution range
<1.00	I	Very clean
1.00-1.50	II	Clean
1.51-2.50	II	Lowly polluted
2.51-3.50	IV	Moderately polluted
3.51-4.00	V	Polluted
>4.00	VI	Highly polluted

Based on the taxonomic composition of phytoplankton, assessment of water quality class was made on the basis of saprobity index (S) using Pantle-Buck method modified by Sladecek. (Pantle & Buck 1955, Sladecek 1967). Saprobity is the pollution of the water body with organic substances. Water quality classification according to GOST 17.1.3.07-82 (RF) is presented in Table 2.

Results and discussion

Species composition and structure of phytoplankton communities

Totally 95 algae taxa one order lower than genus from seven systematic groups were identified in the phytoplankton composition of the Pasvik river-and-lake system: Cyanophyceae – 9, Chlorophyta – 25, Charophyceae – 8, Chrysophyceae – 5, Dinophyta – 8, Bacillariophyceae – 37, Euglenophyceae – 1. The number of taxa at each station is presented in Table 3. The species abundance (number of discovered taxa) was the highest close to Lake Kuetsjarvi (Salmijarvi, 52 taxa) as a result of combination of different type water masses and a current. Species abundances in the sampling place were variable, second highest was 31 taxa in Rajakoski and third highest 27 taxa in Ruskebukta. Lowest abundances were in Tjerebukta (11), Vaggatem (18) and Skrukkebukta (19).

In different parts of the Pasvik River the structure of communities, species composition and quantitative parameters of phytoplankton show considerable differences (Figures 1 and 2). Diatoms, blue-green algae and yellow-green algae were found the most abundant; green algae accounted for a large portion (up to 51 %) in Lake Kuetsjarvi. Peridiniales (5 %) and charophytes (< 1%) were rare at all the stations.

In Ruskebukta the phytoplankton abundance is two orders higher than in other sections. The cause was a mass occurrence of diatom *Urosolenia eriensis,* which is a typical benthic species, and its transition to planktonic state confirms eutrophication. This correlates with the hydrochemical analysis results as Ruskebukta has the highest concentrations of nutrients (primarily nitrates and phosphates) in the Pasvik River. Blue-green algae were the most abundant (up to 52 %) in Rajakoski, mostly due to abundance of *Oscillatoria tenuis,* which is another sign of eutrophication.

Abundance of green algae separates Lake Kuetsjarvi from the other stations. The phytoplankton communities are considerably different in the southern and northern parts of the lake. In the northern part yellow-green algae, diatoms and green algae are abundant; in the southern part, where the polluted wastewater from the Pechenganikel plant is discharged, blue-green algae were actively developing (Figure 1b). At the outflow, where Lake Kuetsjarvi is connected to the

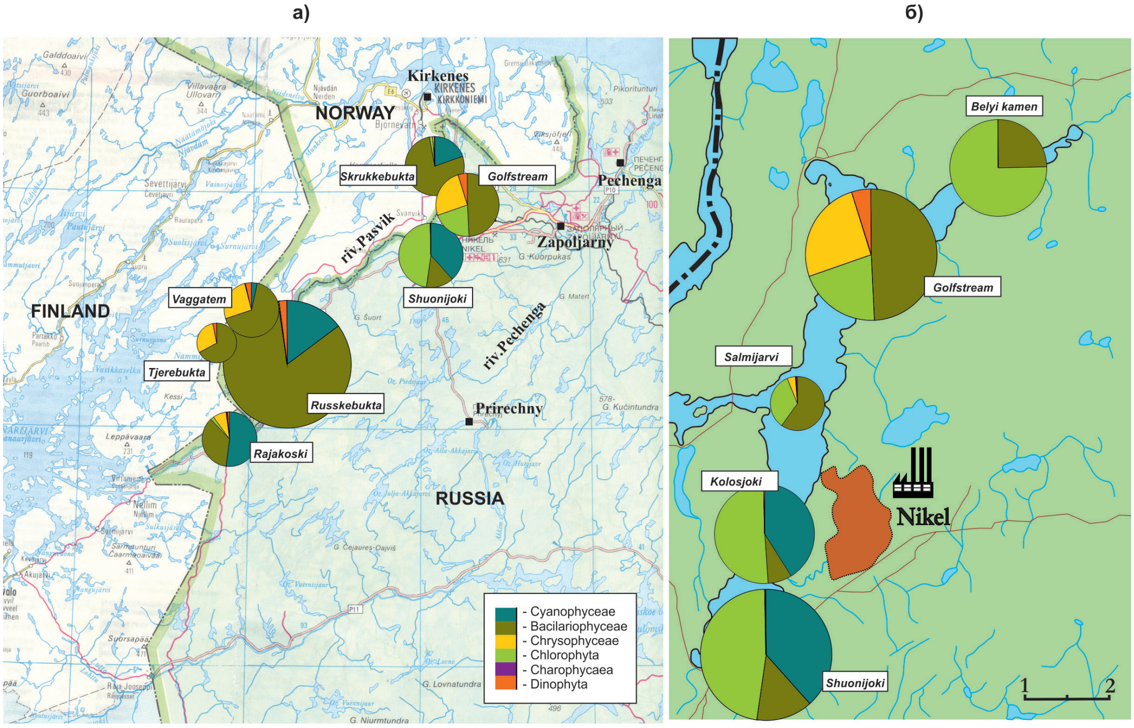

Figure 1. Phytoplankton communities of the Pasvik River in August-September 2012: a) all stations; b) Lake Kuetsjarvi.

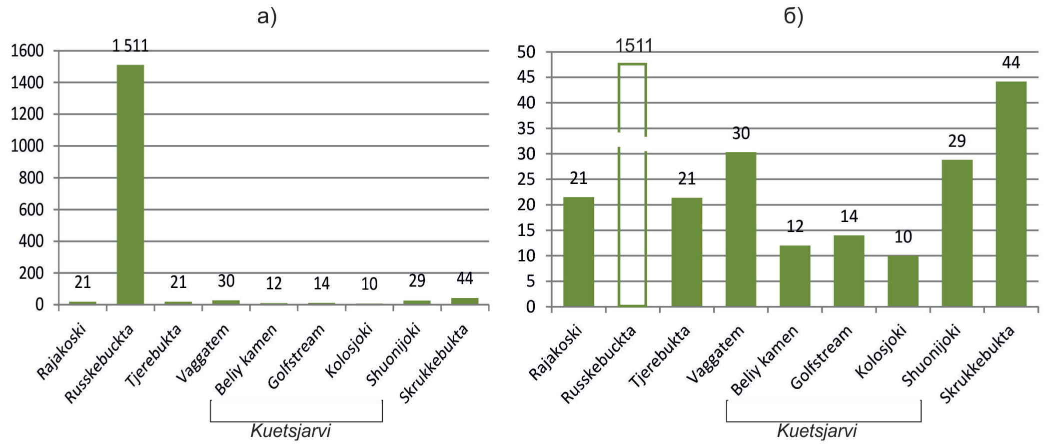

Figure 2. Total phytoplankton abundance of the Pasvik River in August–September 2012, mln.cells/m^3: a) differences between Ruskebukta and other stations; b) differences between other stations.

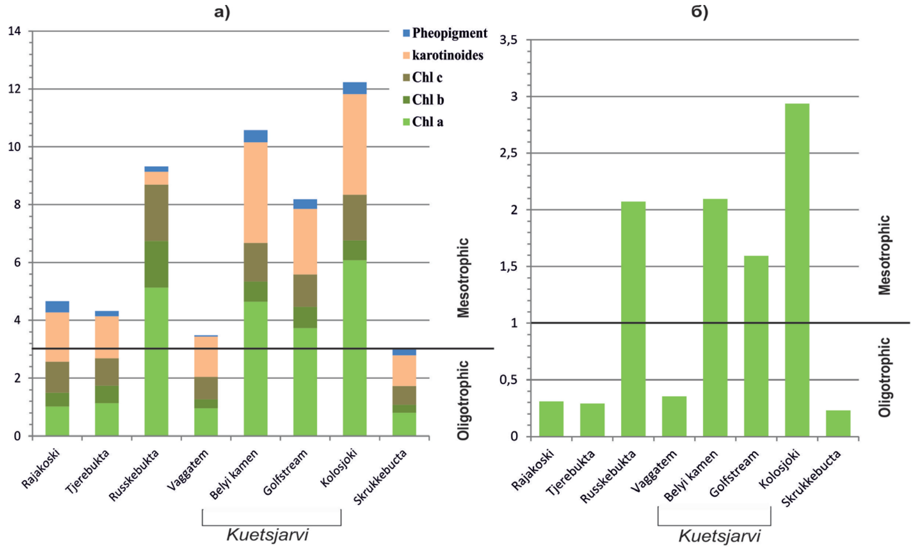

Figure 3.Trophic status of the different parts of the Pasvik River according to Kitaev (1984): a) phytoplankton photosynthetic pigments, mg/m^3; b) phytoplankton biomass, g/m^3.

Pasvik River, the algae abundance was found to be minimal while the range of species was large. This is possibly a result of mixing of hydro-chemically different water masses, which creates suitable conditions for development of various phytoplankton species.

The highest indicators Shannon-Weaver index was found at the stations Golfstream and Salmijarvi in Lake Kuetsjarvi, which might be due to mixing of different water masses. The permanent presence of nutrients along with increased mineralization (amount of all ions determined during water analysis (mg/l)) supports development of non-typical subarctic plankton communities with a large portion of green algae. The lowest species diversity was found in Ruskebukta associated with the absolute domination of *Urosolenia eriensis*.

The amount of photosynthetic pigments in phytoplankton is used in monitoring of the status, natural seasonal processes, anthropogenic impact and pollution level of water bodies in industrially developed regions of the northern Kola Peninsula (Sharov 2004). It is used as an indicator for assessment of phytoplankton productivity and biomass (Vinberg 1960).

According to chlorophyll a concentration the trophic status of the Pasvik River areas under study ranges from α-oligotrophic (Skrukkebukta) to β-mesotrophic (Kuetsjarvi, Kolosjoki) (Figure 3a). The highest concentrations of chlorophyll a in 2012 were in the eutrophied areas of Ruskebukta and Lake Kuetsjarvi; these data correlate well with the indicators of phytoplankton abundance and hydrochemical analysis results. The concentrations of phaeopigments and carotenoids were the highest in Lake Kuetsjarvi and Rajakoski, which is a sign of a higher detritus concentration in the water column or presence of aging plankton populations with a slowed-down photosynthetic activity. Ruskebukta had the lowest concentration of carotenoids, which confirms active development of phytoplankton and its high photosynthetic activity.

In 2012 the phytoplankton biomass in the Pasvik river-and-lake system varied from 0.23 (Skrukkebukta) to 2.94 g/m^3 (Lake Kuetsjarvi, Kolosjoki). The highest biomass levels were typical of Lake Kuetsjarvi and Ruskebukta and their trophic status may be regarded as α- and β-mesotrophic; the other water bodies have retained their oligotrophic status (Figure 3b). The average biomass level of phytoplankton in the study lakes did not exceed the biomass level of the Kola Peninsula lakes: 0.6–2.5 g/m^3 for the tundra and forest tundra lakes and 0.56–2.96 g/m^3 for the north taiga lakes (Letanskaya 1974, Kupetzkaya et al.1976).

Seasonal dynamics of phytoplankton

The seasonal dynamics of phytoplankton communities were studied in Lake Kuetsjarvi (station Golfstream). The phytoplankton abundance is comparatively high already in June with green algae being the most abundant, the portion of diatoms is also large and dinophytes and yellow-green algae are developing. In July the total algae abundance remains at the same level as in June but blue-green algae develop. Also the proportion of green algae increases, diatoms decrease, dinophytes virtually disappear and the abundance of yellow-green algae also decreases considerably. Later by August the total phytoplankton abundance decreases, mostly because the growth of green algae slowed down; yellow-green algae disappear entirely, the portion of blue-green algae decreas and the abundance of diatoms remained at the same level.

The seasonal dynamics of phytoplankton in Lake Kuetsjarvi are not typical for subarctic lakes due to intensive development of green algae, which start active growth already in June. At the same time, the abundance of diatoms and yellow-green algae, the typical inhabitants of subarctic, is relatively low.

Saprobity index and water quality

Saprobity index was estimated for assessment of organic pollution level for each research area. At the time of study the saprobity index of the water bodies varied within 1.2–1.89, which correlates with a relatively low pollution level (GOST 17.1.3.07-82). The lowest saprobity index was in Tjerebukta and the highest in Ruskebukta, where there was massive development of *Urosolenia eriensis*. Saprobity indices were relatively high in Lake Kuetsjarvi: at the stations Belyi kamen, Salmijarvi, and Kolosjoki the water quality class was III whereas the stations Golfstream and Shuonijoki are in the class II. This may be interpreted as another proof of different conditions within this water body.

Long-term dynamics of phytoplankton

Assessment of many-year dynamics of quantitative indicators of phytoplankton, especially biomass, is important for understanding the long-term changes in the ecosystem of the Pasvik watercourse. A grow-

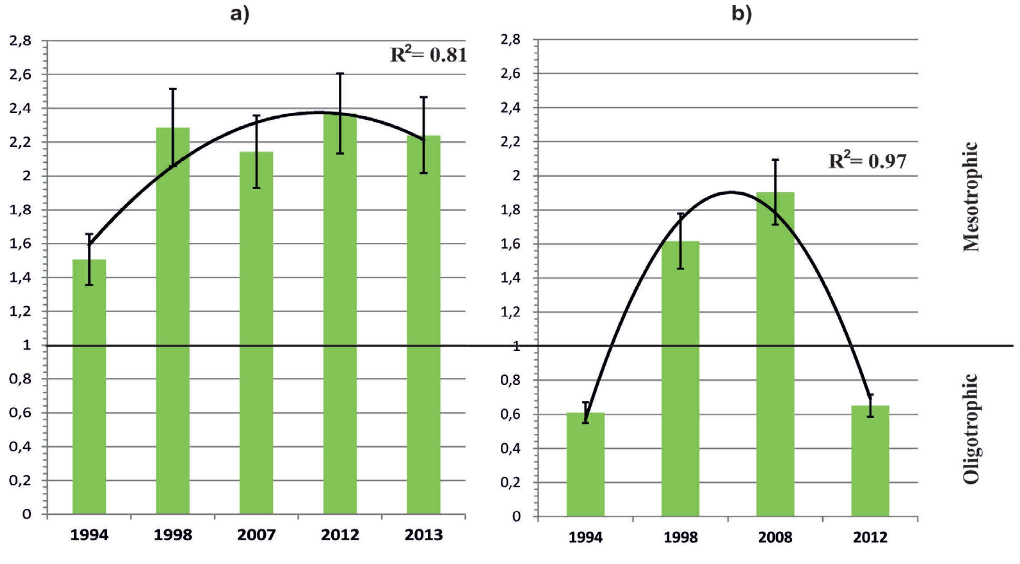

Figure 4. Long-term phytoplankton biomass dynamics (g/m^3): a) Lake Kuetsjarvi; b) Other water bodies of the Pasvik River system.

ing trend in phytoplankton biomass was observed in Lake Kuetsjarvi from 1994 to 2012 with all the values indicating mesotrophic state. In the other water bodies the maximum values were observed in 1998 and 2008 but in 2012 there was a decrease. No clear trend has been determined, which is due to the different conditions in each lake as well as to irregular sampling periods in different seasons. The average biomass values for Lake Kuetsjarvi were higher than those for the other water bodies (Figure 4). The average biomass values for the Pasvik watercourse system seem to confirm that its trophic status is changing from β-oligotrophic to β-mesotrophic.

Considerable changes have taken place in the phytoplankton species composition. In August 1994 diatoms dominated in different areas of the Pasvik River and the portion of blue-green algae was insignificant (Sharov 2004). In July 1996 several groups including green and yellow-green algae and diatoms dominated. In September 2008 the same taxa dominated in many areas but blue-green algae abundance was increased compared to the previous years, which may be associated with favorable meteorological factors, water temperatures etc. The high abundance of blue-green algae also implies a possibility of massive phytoplankton development outbreaks that may take place in favorable conditions.

In Lake Kuetsjarvi the changes in phytoplankton species composition are more prominent still. Diatoms and yellow-green algae that dominated earlier are being gradually replaced by green and blue-green algae, especially in the latest years. This may be regarded as an indicator of a warming trend in the climate change. Algae growth is also facilitated by reduction of toxic load in the latest decade.

Periphyton

Study of periphyton in the Pasvik River has not been conducted. However, in the rocky substrate in shallow waters near the Janiskoski reservoir outflow an unusual massive fouling formed of diatom *Didymosphenia geminata* (Lyngb.) Schmidt colonies was discovered. This phenomenon is known as “Brown plague: Didymo” which has been a worldwide serious problem for streaming water bodies with coldish conditions in the latest years (International…, 2013).

The structure of colonies of *D. geminata* associated with other algae, mainly with diatoms, creates firm slimy algal mats on the rocky substrate covering the river bed. Massive development of *D. geminata* does not require a large amount of nutrients or higher water temperature. The species is widespread but it is only in the latest decades that mass development outbreaks have been observed particularly in the areas where they were not common before (International… 2013). The dense colonies disrupt the natural habitats of typical arctic water fauna, including benthos and fish, and the changes affect potential spawning sites and trophic chains. Massive development of *D. geminata* definitely poses a certain threat to the Pasvik River ecosystem functioning and the occurrence could be regarded as a sign of global climate change (Lavery et al. 2014).

Zooplankton

Zooplankton is an integral component of aquatic ecosystems. In subarctic lakes the main flows of organic substances and energy from producers to higher trophic levels go through the communities of Protozoa, Rotatoria and Crustacea. Zooplankton plays an important role in the determination of the resource potential of the lakes as it holds the intermediate position between bacterioplankton, phytoplankton, benthos and fish. Prevalence of species needing higher water quality is characteristic of northern water bodies, which means higher sensitivity to industrial impact. The taxonomic structure of zooplankton community is a good indicator of the pollution degree of the water body.

Zooplankton plays a significant role in the determination of fishery productivity of the water body as it is one of the feed resources for fish. In terms of feed the most valuable organisms should be considered the crustacean genuses *Daphnia, Bosmina, Bythotrepes, Eudiaptomus, Heterocope* and *Cyclops*.

Materials and methods

Zooplankton was sampled at the same stations as phytoplankton (Introduction, Figure 1). Quantitative samples were taken with a bathometer (of 2 l and 6 l) from the surface to the bottom every other meter with distinguishing layers: surface–2 m; 2–5 m, 5–10 m, 10 m–bottom. All qualitative samples were taken with a qualitative Apstein net. Lugol’s solution was used as a fixative.

Sampling and the required calculations were performed according to standard practices of hydrobiological monitoring (Abakumov 1992). The calculation

Table 3. Structural and functional indicators of zooplankton.

Parameter	Rajakoski	Tjerebukta	Ruskebukta	Vaggatem	Skrukkebukta
Abundance (N), 10^3 ind./m^3	76.4	37.6	239.8	67.7	75.2
Biomass (B), g wet weight/m^3	0.2	0.7	1.8	0.5	0.4
$N_{Rot} : N_{Clad} : N_{Cop}$, %	93.1:2.7:4.2	63.8:28.3:8.0	85.3:10.7:4.0	85.2:12.1:2.7	92.5:3.3:4.2
$B_{Rot} : B_{Clad} : B_{Cop}$, %	18.1:58.2:21.4	22.0:64.8:8.4	14.7:62.6:22.4	24.9:70.0:0.7	27.3:16.6:53.1
B_{Crust}/B_{Rot}	4.5	3.7	5.8	3	2.6
N_{Clad}/N_{Cop}	0.6	3.5	2.6	4.5	0.7
B_3/B_2	0.2	0.2	0.3	0.1	1.7
Shannon index, bit/ind.	2.1	2.8	2.1	2.3	2.1
w=B/N, mg	0.002	0.02	0.007	0.007	0.005
Saprobity (water quality class)	1.8 (III)	1.7 (III)	2.1 (III)	1.7 (III)	1.9 (III)
Trophic state (Kitaev, 1984)	α-oligotrophic	β-oligotrophic	α-mesotrophic	α-oligotrophic	α-oligotrophic

of individual mass of organisms was based on the ratio of the length and body mass of planktonic Rotatoria and Crustacea (Ruttner-Kolisko 1977; Balushkina & Vinberg 1979). The calculations of the abundance and biomass were performed with a statistical programme package (Syarki 1996).

Saprobity index (Pantle & Bukk in Sladecek modification) was calculated proceeding from the individual characteristics of the species saprobity according to standard practices. Water quality was evaluated by hydrobiological indicators: the total number of organisms (individuals/m^3), the total number of species, the total of biomass (g/m^3), the number of the main groups (individuals/m^3), the biomass of the main groups (g/m^3), the number of species in the group, the main species and the species indicative of saprobity (description, % from the total number, saprobity).

According to the classification of lakes on the Kitaev's trophic scale (1984), the lakes with the biomass of zooplankton <0.5 g/m^3 belong to a very low trophic class (α-oligotrophic), 0.5–1 g/m^3 to low class (β-oligotrophic class), 1–2 g/m^3 to moderate type (α-mesotrophic), 2–4 g/m^3 to medium type (β-mesotrophic), 4–8 g/m^3 to the higher type (α-eutrophic), 8–16 g/m^3 to high type (β-eutrophic) and >16 g/m^3 to a very high class (hypertrophic).

Results

The species detected in the zooplankton community of the Pasvik watercourse were typical for oligotrophic, cold lakes and rivers. The majority of the zooplankton community in the sampling period was represented by rotifers. Cladoceran "fine" filtrators *Bosmina* sp. and *Daphnia* sp. were detected. Also calanoids *Eudiaptomus gracilis* Sars and *Eudiaptomus graciloides* Lilljeborg, which are sensitive to pollution and valuable in terms of fish feed, were found in all studied lakes except in Skrukkebukta. The amount of zooplankton species varied from 12 to 14; at Skrukkebukta 8 taxa of the species range were detected.

The ratio of the main taxonomic groups (Rotatoria: Cladocera: Copepoda) (Table 3) of zooplankton community shows that when taking rotifers prevail in numers but cladocerans dominate in biomass in all the stations except in Skrukkebukta where copepods dominate. Shannon species diversity index by number varied in the range of 2.1–2.8 bit/individuals and the highest value was obtained at the Tjerebukta station. The index value of the average individual zooplankter mass in the community varied within the range of 0.002 mg (Rajakoski)–0.02 mg (Tjerebukta) and the mean was 0.008 mg.

The highest abundance was noted at the Ruskebukta station (239.8 10^3 ind./m^3) where the biomass was 1.8 g wet weight/m^3. At other sites the total abundance and biomass were not high and were characteristic of the oligotrophic water bodies (37.6–76.4 10^3 ind./m^3 and 0.2–0.7 g wet weight/m^3). According to the saprobity index the water of the studied sites characterized as α-mesosaprobic and in the III water quality class. According to the Kitaev's trophic scale the lakes are α-oligotrophic type except for Ruskebukta, which is α-mesotrophic type.

Conclusions

The phytoplankton species composition in the Pasvik watercourse is characterized by high diversity and it is different in different reaches. 95 algae taxa have been found at the level one order lower than genus. Relatively high species diversity is typical of the border area conditions combining water masses different in hydrodynamic and hydrochemical properties. Diatoms, blue-green and yellow-green algae were the most abundant taxonomic groups. Abundance of green algae separates Lake Kuetsjarvi from other stations. In Ruskebukta a massive development of the diatom *Urosolenia eriensis* was observed, which is a sign of eutrophication.

The highest chlorophyll a concentrations in 2012 were detected in Ruskebukta and Lake Kuetsjarvi which correlates with indicators of phytoplankton abundance and hydrochemical analyses results. According to chlorophyll a concentration the trophic status of study areas ranges from α-oligotrophic (Skrukkebukta) to β-mesotrophic (Kuetsjarvi, Kolosjoki). The phytoplankton biomass in the Pasvik River areas in 2012 was within 0.23–2.94 g/m^3 which does not exceed the average values for the Kola Peninsula. The saprobity index calculated according to phytoplankton indicators was within 1.27–1.89, which means a relatively low water pollution level (Water quality classes II and III).

The many-year dynamics of phytoplankton biomass in Lake Kuetsjarvi show an increasing trend as a result of reduction of toxic load and anthropogenic eutrophication supported by climate warming. In other water bodies no increase in production has been found. However, analysis of the collected data is difficult because of different conditions in each station and irregular intervals in sampling in different seasons. Synchronization of sampling at each station is recommended for collection of representative data.

The species composition and structure of phytoplankton communities in the Pasvik River has undergone a number of considerable changes. The previously dominating diatoms and yellow-green algae are being replaced by green and blue-green algae which confirms climate warming and presence of eutrophication processes.

The ratio of the main taxonomic groups of zooplankton in total number reflects the prevalence of Rotatoria, and of the biomass the groups of “fine” and “coarse” filtrators, which are valuable fish feed. Shannon species diversity index by the number of zooplankton has a relatively high value, also characteristic of the oligotrophic water bodies. It should be noted that low content of taxa and high quantitative values at some stations can be explained by multifactorial impact and by the period of plankton sampling

Zooplankton can be used to evaluate the water quality. Based on the analysis of qualitative and quantitative structural and functional indicators a conclusion can be made that the sites under study of the Pasvik river-and-lake system (Rajakoski, Tjerebukta, Ruskebukta, Vaggatem, Skrukkebukta) have an oligotrophic status and average saprobity of α-mesosaprobic. The water bodies belong in the III water quality class, “slightly polluted.” They are of α-oligotrophic type except for Ruskebukta, which is α-mesotrophic type.

Bloom of blue-green algae. Photo: Juha Riihimäki

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5 Aquatic macrophytes of Lake Inarijärvi and the Pasvik River

JUHA RIIHIMÄKI, MARIT MJELDE, SEPPO HELLSTEN

Regulation of the water level of Lake Inarijärvi and the Pasvik River due to hydropower production is probably the strongest human induced pressure on aquatic ecosystem in the Pasvik River basin. The global climate change will also have several effects on hydrological cycle; changing the timing of high water levels and discharges and thus affecting the habitat conditions of aquatic organisms (see Chapter 3, Climate change impacts on hydrology and water level fluctuation). Assessment of the ecological status of Lake Inarijärvi and the Pasvik River using aquatic macrophytes as biological elements is important.

Materials and methods

Macrophyte data was collected from lakes Inarijärvi, Muddusjärvi and Nitsijärvi and the Pasvik River. Lakes Muddusjärvi and Nitsijärvi are unregulated lakes and are used as reference lakes. All lakes are classified as “large oligohumic lakes (North)” in Finnish lake typology (Aroviita et al. 2012). The lakes in the Pasvik River are classified as low alkalinity, clear lakes using Norwegian typology (Direktoratsgruppa 2013).

Field work on macrophyte sampling in the lakes Inarijärvi, Muddusjärvi and Nitsijärvi was done 31.7.–15.8.2012. Macrophyte data was gathered using the Finnish “Main belt transect method” (Kuoppala et al. 2008). Observations of macrophyte species were made along a 5 m wide transect perpendicular to shoreline. Starting point for the transects were at the upper eulittoral and extended to the outer depth limit of the macrophyte vegetation. All macrophyte species (including helophytes and bryophytes) were recorded, and frequency and abundance for each species was estimated using a continuous percentage scale.

In Lake Inarijärvi 24 transects in 5 areas were surveyed. Lakes Muddusjärvi and Nitsijärvi had 25 evenly distributed transects. Total area surveyed differs among the lakes since the length of transects are determined by the outer limit of the vegetation on transect. Total length of transects and hence also the total area was higher in Lake Nitsijärvi than in the other two lakes.

The macrophyte survey in the Pasvik River took place 27.–30. August 2013. Here, the macrophyte data was collected using both the Finnish and the Norwegian field methods. The Norwegian method (Mjelde 2013) includes only true aquatic macrophytes (i.e. isoetids, elodeids, nymphaeids, lemnids and charophytes). Helophytes, bryophytes and filamentous algae are excluded. Different habitats, from shore to maximum vegetation depth, are surveyed and the species are recorded using an aquascope and collected by dredging from a boat. Species abundance is estimated using a semi-quantitative scale (1=rare, 2=scattered, 3=common, 4=locally dominant and 5=dominant) and maximum depth distribution of vegetation is noted.

The Norwegian field method was applied also in in previous macrophyte study in the Pasvik River (Moiseenko et al. 1993) and the same study sites on the Norwegian side of the river were used in both surveys. A total of 15 sites using Norwegian method was visited. The Finnish field method was applied for 14 of those sites, with one transect on each site.

Ecological status of the lakes and the Pasvik River was assessed using macrophytes according the European Union Water Framework Directive. Assessment method for Finnish lake macrophytes was used for the lakes and both Finnish and Norwegian methods were used for the Pasvik River.

Finnish assessment method is a multimetric index combining results of three different metrics: Proportion of type specific taxa (TT50), Percent Model Affinity (PMA) and Trophic index (RI) (see Vuori et al. 2009, Aroviita et al. 2012). Observed metric values of studied lakes are divided by the average metric values of reference lakes (expected values) to calculate Ecological Quality Ratio (EQR) for each metric. EQRs are scaled to common thresholds so that scaled EQR value 0.8 is threshold for high/good status, 0,6 for good/moderate, 0.4 for moderate/poor and 0.2 for poor/bad.

Norwegian assessment method (TIc index) is based on the relationship between the number of sensitive and tolerant species in relation to eutrophication (Mjelde 2013). EQR is calculated using observed TIc index and expected TIc index value obtained from the reference lakes.

Results

Lakes Inarijärvi, Muddusjärvi and Nitsijärvi

The total number of observed macrophyte species in the studied lakes was 45, of which only 18 species were common to all three lakes, 12 species were common for two lakes and 15 species were observed only in one lake. However, the total number of observed species per lake was quite even: in Lake Inarijärvi there were 33 species, in Lake Muddusjärvi 31 and in Lake Nitsijärvi 29.

Classification of true aquatic macrophytes (helophytes and bryophytes are omitted) according to their indicator value related to sensitivity and tolerance against eutrophication (Penning 2008 a, b) showed very similar composition among the lakes. Eutrophication-tolerant species were totally missing from all of the lakes and the species pool was dominated by eutrophication-sensitive species with only few indifferent species per lake.

Ecological status of the Lake Inarijärvi was assessed using Finnish multimetric index for lake macrophytes. Macrophyte data from lakes Muddusjärvi, Nitsijärvi, Kitkajärvi and Yli-Kitka were used as reference data. Average EQR of the three metrics was 0.81, so Lake Inarijärvi was assessed to be slightly in high ecological status based on aquatic macrophytes. For each separate metrics the EQR value was also clearly above good/moderate boundary.

The Pasvik River

Total number of macrophyte species, including true aquatic macrophytes, bryophytes and helophytes, observed in the Pasvik River sites was 47. 37 of them were observed using the Finnish field method and 34 using the Norwegian field method (only true aquatic macrophytes). The number of species per site was higher using the Norwegian method in all but one site (site 4). Average number of species per site using the Finnish method and the Norwegian method were 11 and 14 and range (min–max) 5–17 and 4–22 species, respectively.

There is a clear difference in the field methods that affects the results. In the Finnish method also helophytes and bryids are observed and the number of visited sites at the Pasvik River was different. When comparing results using only common sites and common observed growth forms, the total number of observed plant species using the Finnish and Norwegian field method were 27 and 33 species, respectively.

Number of species per site is clearly higher in all sites with the Norwegian method when comparison was made using only common sites and growth forms (Figure 1). In this comparison the average number

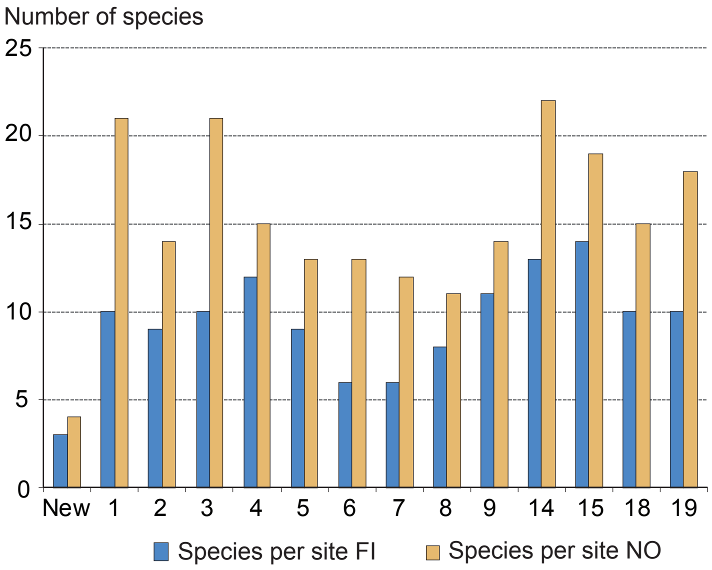

Figure 1. Number of species per the Pasvik River macrophyte study site using the Finnish field method (FI) and the Norwegian field method (NO) with common growth forms and sites.

Table 1. Ecological status assessment of the Pasvik River lakes using the Finnish and Norwegian status assessment methods. Numbers after lake names indicate site codes. The Finnish method was not applied on site 16.

Data	**RI**		**TT50SO**		**PMA**		**Total (FI)**		**TIc**	
	EQR	**Status**	**EQR**	**Status**	**EQR**	**Status**	**EQR**	**Status**	**EQR**	**Status**
The Pasvik River (all sites)	0.72	Good	0.62	Good	0.66	Good	0.67	Good	0.90	Good
Hestefoss (new)	0.60	Good	0.70	Good	0.12	Bad	0.47	Moderate	1.11	High
Fjørevatnet (1)	0.65	Good	0.47	Moderate	0.06	Bad	0.39	Poor	0.88	Goog
Vaggatem (2,3,4,5,6)	1.13	High	0.87	High	0.55	Moderate	0.85	High	0.89	Good
Langvatn (7,8)	1.00	High	0.70	Good	0.75	Good	0.82	High	0.98	High
Fuglebukta (9)	1.13	High	1.03	High	0.63	Good	0.93	High	1.00	High
Svanvatn (14, 15, 16)	0.74	Good	0.70	Good	0.61	Good	0.68	Good	0.87	Good
Björnvatn (18, 19)	1.13	High	0.70	Good	0.46	Moderate	0.76	Good	0.91	Good

of species per site using the Finnish method and the Norwegian method were 9 and 15 and range (min–max) number of species 3–14 and 4–22 species, respectively.

Ecological status assessment gave quite similar results when Finnish and Norwegian assessment methods were compared using RI index and TIc index, and all the Pasvik River lakes were classified to high or good status (Table 1). Also, when combined Finnish multimetric index was used, most of the lakes were classified to high or good status, except Hestefoss and Fjørevatnet where low number of sites made PMA index unstable and lowered status (Table 1). Results showed that relatively similar RI and TIc indices gave exactly the same results showing relatively high status of the Pasvik River lakes.

Macrophyte composition was also assessed by using a water level regulation index developed by Mjelde et al. (2012). The index showed that all lakes except Hestefoss and Langvatn were in better than moderate status. However, this index is developed for lakes regulated for hydroelectric power with (more or less) considerable winter drawdown. The lakes in the Pasvik River have different regulation regimes, with limited winter drawdown.

Aquatic macrophyte diversity of the Pasvik River is significantly higher compared to other large rivers in Norway (excluding River Glomma, which is situated in southern Norway and represents naturally higher diversity gradients).

Discussion

The ecological status of Lake Inarijärvi based on aquatic macrophytes was high. Water level regulation for hydropower production is considered to be the dominant human induced pressure to Lake Inarijärvi since nutrient loading due to human activity are estimated to be relatively low. Average water level fluctuation during the period 2000–2009 has been about 1.40 meters, which is about 0.30 meters larger than the natural water level fluctuation (Puro-Tahvanainen et. al. 2011). Water level regulation induced effects on littoral areas at Lake Inarijärvi are limited and the macrophyte communities are well adapted to the current conditions. However, it should be noted that vertical extension of sedges (*Carex* spp.) has decreased and also areas of spring-flood depended vegetation are smaller.

The macrophyte surveys in the Pasvik River lakes showed similar high-good status in almost all lakes. Despite the fact that the whole river has changed significantly and consists of cascades of hydropower reservoirs, macrophyte species composition resembles natural. It should be noted that water level of lakes is relatively stable and without significant winter drawdown. Winter drawdown is one of the most significant factors negatively affecting the status of lake macrophytes, as shown in several studies (Mjelde et al. 2013, and references herein). On the other hand, more or less stable water levels (as in the Pasvik River lakes) positively affect the abundance of several aquatic macrophyte species. However, abundance of helophytes and especially sedges is much lower than in lakes with normal spring flood reflecting decreased water level fluctuation.

The Pasvik River water quality reflects largely the outflow of Lake Inarijärvi, which in general is in good status. Therefore, the number species indicating eutrophication is low even in areas affected by the Pechenganikel.

Biological monitoring of Lake Inarijärvi and the Pasvik River using macrophytes is well established and usable in its current state. Both Finnish and Norwegian field methods and ecological status assessment show similar results regardless of the obvious disparities in the field methods. Aquatic macrophyte surveys are lacking from the Russian side of the Pasvik River basin, hence we recommend setting up comparable macrophyte monitoring and applying the status assessment system also to the Russian area of the river basin.

Macrophyte studies in the Pasvik River. Photos: Juha Riihimäki

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Taking a break in Lake Muddusjärvi. Photo: Juha Riihimäki

6 Zoobenthos of Lake Inarijärvi and the Pasvik River

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Alteration of natural water level regime due to construction of dams and reservoirs for hydropower production and flood control is one of the major anthropogenic disturbances in freshwater ecosystems (Dynesius & Nilsson 1994, Coops et al. 2003). The main effects of water level regulation are shore-line erosion caused by raised water level, changes in the annual water dynamics and changes in mean open water level (Hellsten 1998). Water level modifications are likely to be exacerbated in future by global climate change because of greater frequency of floods and droughts (Dudgeon et al. 2006). Altered variation of water level impacts especially the littoral zone of lakes where organisms, both zoobenthos and fish, can be affected directly by desiccation and indirectly by a reduction in habitat availability and food resources (e.g. Gasith & Gafny 1990).

Lake Inarijärvi belongs to the Pasvik River water system in Finnish Lapland. Inarijärvi is a subarctic oligotrophic lake which has been regulated in the Pasvik area for hydropower production since 1941, with a yearly water level fluctuation of ~1.38 m (Palomäki & Hellsten 1996, Hellsten et al. 1997). Regulation activities have caused coastal erosion and structural changes in aquatic vegetation and zoobenthic and fish communities (Hellsten et al. 1997).

This report presents the status of zoobenthic communities of rocky shores and soft bottom habitats in Lake Inarijärvi in September 2012 and in the Pasvik River 2013. Report also summarises the results from earlier monitoring of the same sites. In addition, unregulated nearby lakes Nitsijärvi and Muddusjärvi were sampled in 2012 for regional references to more accurately evaluate the status of the zoobenthic communities in the Pasvik River catchment.

Materials and methods

Zoobenthos was sampled from lakes Inarijärvi, Nitsijärvi and Muddusjärvi in 2012 and the Pasvik River in 2013 (Introduction, Figure 1). Both soft bottom and rocky shore habitats were sampled. Samples were sieved through a mesh of 0.5 mm and preserved with 70 % ethanol. Zoobenthic animals were identified to genus or species in the laboratory; Oligochaeta, Nematoda, Hydracarina and Chironomidae were counted but not identified.

This report also includes the previous decades-old data from the same sites as a baseline for temporal comparisons. Lakes Nitsijärvi and Muddusjärvi were chosen to reduce latitudinal variation in reference zoobenthic communities (Jacobsen et al. 1997, Sandin & Johnson 2000).

Structural and functional indicators of benthic communities are used as criteria for the evaluation of water quality as well as comparing the states of communities and ecosystems with industrial influences (Makrushin 1984, Balushkina 1987, Shitikov et al. 2003, Semenchenko 2011, Zinchenko 2011). Zoobenthos is used to assess of the state of aquatic ecosystems and water quality as it is the most long-lived component of community reflecting the state over a long period of time and describing its “average” regime. The most widely used indicators are the total abundance (ind./m^2), the total biomass (g/m^2), the total number of species, the proportion of widespread species in the community, the indicator species of saprobity, the abundance of the main groups (ind/m^2) and the biomass of the main groups (g/m^2). Kitaev’s trophic scale (1984) classifies types of lake ecosystems based on zoobenthic communities’ quantitative indicators (Table 1).

Goodnight and Whitley oligochaetic index is based on the accounting ratio of the number of oligochaetes and other zoobenthic animals. Woodiwiss biotic index values are determined in the biotic indices according to a special table. Both indicators are used to evaluate the water quality and to control of the environmental compartments’ pollution (Table 2).

In the Pasvik River and Lake Kuetsjarvi both soft bottom and rocky shore habitats were sampled in August–September 2012–2013. Samples were fixed with 4 % formalin or 70–80 % alcohol. The analysis of benthic samples was performed and invertebrates

Table 1. Kitaev’s trophic scale based on benthic biomass (1984).

Characteristic	**Type of lake ecosystem**						
	Oligotrophic		**Mesotrophic**		**Eutrophic**		**Hypereutrophic**
	α	**β**	**α**	**β**	**α**	**β**	
Benthic biomass, g/m^2	< 1.25	1.2–2.5	2.5-5	5-10	10-20	20-40	> 40

Table 2. Classification of water quality in ponds and streams in terms of zoobenthos (GOST 17.1.3.07-82).

Water quality class	**Degree of water pollution**	**Goodnight and Whitley oligochaetic index, %**	**Woodiwiss biotic index, scores**	**The saprobity zone**
I	Extremely clear	1 – 20	10	Oligosaprobic
II	Clear	21 – 35	7 – 9	Oligosaprobic
III	Moderately polluted	36 – 50	5 – 6	β-mesosaprobic
IV	Polluted	51 – 65	4	α-mesosaprobic
V	Extremely polluted	66 – 85	2 – 3	Polysaprobic


Isoperla sp. Photo Mira Grönroos


Micrasema gelium.
Photo Mira Grönroos


Benthic macroinvertebrate research.
Photo Mirkka Hadzic

were identified and their biomass was calculated as wet weight.

Community data is presented as total abundances (sum of individuals/site) for rocky shore habitat and as densities (individuals/m²) for soft bottoms. To summarize the variability in community structure among the last three sampling years (2003, 2008, and 2012), a Non-metric Multidimensional Scaling (NMS based on Sørensen´s distance) was performed for Lake Inari community data from both habitats. NMS was also used to summarize the variability in rocky shore community structure among regulated Lake Inarijärvi and the Pasvik River and unregulated lakes Nitsijärvi and Muddusjärvi. Indicator species analysis (Dufrene & Legendre 1997) was done to distinguish the species that best explained the possible difference between lake groupings.

The community composition was evaluated with occurrence of Type-specific Taxa (TT; Aroviita et al. 2008) and relative abundance was evaluated with the Percentage Model Affinity (PMA; Novak & Bode 1992). Data from unregulated reference lakes Nitsijärvi and Muddusjärvi were used to define the reference communities and to calculate the expected values, and to further calculate the Ecological Quality Ratio (EQR). The sampling effort of the reference lakes was standardized with Inarijärvi. Status class boundaries for each parameter were defined by using the 25th percentile of the reference lakes' EQR distribution as high-good quality class boundary. The lower quality classes good, moderate, poor and bad were then defined between the high-good class boundary and EQR = 0 at equal class widths.

Results

Taxa composition and abundance

Rocky shore communities

The number of taxa and individuals in all samples in Lake Inarijärvi was 42 and 2204 respectively. Highest taxa richness and individuals' abundance was found in Lake Muddusjärvi (Table 3). In average taxa richness per site was higher in the Pasvik River than in the lakes. After rarefaction to 71 individuals per site mean number of taxas per site was 10 in the Pasvik River, 8 in Inarijärvi, 9 in Nitsijärvi and 12 in Muddusjärvi. In the Pasvik River number of taxa varied between different river sections. Species richness was highest in Vaggatem and Svanevatn (37, 25, respectively) and lowest in Hestefossdammen and Skrukkebukta (19, both). The zoobenthos consisted mainly of Chironomidae and Oligochaeta in all sampled water bodies.

There are some differences between study years (2003, 2008, 2012) in taxa richness and individuals' abundance. Chironomidae and Oligochaeta were the most abundant groups among the invertebrate communities comprising more than 50 % of the total abundance. 17 major groups were identified in the three sampled years in rocky shores in Lake Inarijärvi. Zoobenthos abundance (individuals per 30 kicknet samples from 10 sites) was highest in 2008 and lowest in 2012.

Soft bottom communities

In 2012 32 identified taxa were collected from Lake Inarijärvi (2 m depth), with an estimated density of 1746 ind./m² and an average of 9 taxa/site (5–15). 13

Table 3. Total, average (per sites and per sample) and range (min–max) number of zoobenthic taxa and individuals of rocky shores from lakes Inarijärvi, Nitsijärvi and Muddusjärvi from September 2012.

	Total		Average site		Average sample	
Lake	**Taxa**	**Individuals**	**Taxa**	**Individuals**	**Taxa**	**Individuals**
Inarijärvi	42	2204	13 (8-24)	200 (76-435)	8 (3-13)	73 (26-177)
Nitsijärvi	22	484	17 (14-19)	161 (108-202)	8 (5-11)	54 (23-81)
Muddusjärvi	34	835	19 (14-24)	278 (221-370)	11 (4-20)	93 (24-253)
the Pasvik River	64	3450	25 (19-37)	459 (212-749)	12 (4-22)	139 (12-393)

taxa were collected from Lake Nitsijärvi, where the density was 773 ind./m² and an average of 7 taxa/site (4–19). In Muddusjärvi 19 identified taxa were found and on average density was of 925 ind./m² and 9 taxa/site. A total of 15 major groups were found. Chironomidae constituted more than 50 % of the total community. All major groups were found in Inarijärvi while Isopoda, Plecoptera, and Heteroptera were not found in any of the reference lakes. Gastropoda densities were especially lower in Inarijärvi compared to those in the reference lakes.

The temporal follow-up of Lake Inarijärvi zoobenthic communities based on all available data from literature and this study showed that the highest densities in soft bottoms were found in 1977 with 2217 ind./m². In average the lowest densities were observed 1965 and 1966 (217 ind./m²). Communities were mainly composed of chironomids and oligochaetes in all studied years. Mean densities were lower for the reference lakes. Sampling effort and method differences exist among the studies.

Community structure and status

In NMS ordination samples from the Pasvik River grouped separately from other lakes, and communities from different river sections in the Pasvik River clustered together indicating within-river variation. In Lake Nitsijärvi *Chelifera spp*. was the only significant indicator species. In Lake Muddusjärvi *Hydrachnellae, Tipula spp*. and Oligochaeta were significant indicator species whereas *Asellus aquaticus* was the only indicator species in the Pasvik River. There were no indicator species in Lake Inarijärvi.

In NMS ordination samples of the rocky shore community composition, year 2003 differed quite clearly from years 2008 and 2012. Communities in 2008 and 2012 appeared more widely distributed in the ordination space, suggesting larger differences among the sites. In the soft bottom communities none of the years clustered clearly. In some cases, regardless of the sampling year, sites closely located clustered in the graph suggesting a within lake variation in the communities associated to the location of the sites. Generally no clear trend in time for either of the habitats was observed.

Zoobenthic communities' status in Lake Inarijärvi was calculated using subarctic lakes' communities as reference. Status assessment of macroinvertebrate communities of Inarijärvi gave different results from the two parameters analysed. PMA indicates that most of the communities from rocky shore and soft bottom from different years fall into the moderate/poor class except for the rocky shore community from 2012. Results from TT showed that community status class was good or moderate in most cases. TT index indicated generally good status class, whereas PMA indicated moderate status in most cases (Table 4).

Table 4. Status of zoobenthic communities from Lake Inari based on reference data from unregulated lakes Nitsijärvi and Muddusjärvi. Lake Inarijärvi values were calculated using data from three randomly selected sites (P1, K4, and L4). Community status was classified as: high (blue), good (green), and moderate (yellow). None of the index values were found within poor or bad class.

Nitsijärvi and Muddusjärvi (n=2)						
Lake	**Habitat**	**Year**	**$TT_{0.4}$**	**PMA**	**EQRs ($TT_{0.4}$)**	**EQRs (PMA)**
Inarijärvi	Rocky shore	2003	18	0,38	🟩 0,64	🟨 0,52
	Rocky shore	2008	27	0,39	🟦 0,96	🟨 0,53
	Rocky shore	2012	21	0,45	🟩 0,75	🟩 0,61
		average			🟩 0,79	🟩 0,55
	Soft bottom	1977	7	0,37	🟨 0,44	🟨 0,49
	Soft bottom	2003	13	0,35	🟩 0,81	🟨 0,46
	Soft bottom	2008	10	0,34	🟨 0,63	🟨 0,45
	Soft bottom	2012	12	0,33	🟩 0,75	🟨 0,44
		average			🟨 0,66	🟨 0,46
Nitsijärvi	Rocky shore	2012	22	0,73	🟩 0,78	🟦 1,00
	Soft bottom	2012	12	0,75	🟩 0,81	🟦 1,00
Muddusjärvi	Rocky shore	2012	34	0,73	🟦 1,21	🟦 1,00
	Soft bottom	2012	19	0,75	🟦 1,18	🟦 1,00

Status of zoobenthos of Lake Kuetsjarvi and the Pasvik River

Zoobenthos of the rocky littoral zone of the Pasvik River was investigated at Lake Kuetsjarvi, Vaggatem and Rajakoski. Amphibiotic insects form the basis of benthic communities of all of the investigated stations, among which caddisflies and chironomids have the highest species diversity. The taxonomic diversity of benthos and the number of indicator groups increase with distance from the source of pollution.

The Shannon index (bit/ind) is 3.28 in Kuetsjarvi, 1.92 in Vaggatem and 3.35 in Rajakoski. In terms of saprobity Lake Kuetsjarvi is β-mesosaprobic whereas the other lakes are oligosaprobic. Kuetsjarvi belongs to the III water quality class, "moderately polluted", and the Woodiwiss index varies between 6–7. Vaggatem and Rajakoski belong in the II class, "clear", and the Woodiwiss index values are 7 and 8, respectively.

Variety of zoobenthos in the profundal soft bottoms of Lake Kuetsjarvi and the Pasvik River is low. 4 systematic groups of invertebrates were identified in the samples. Chironomids (predominantly *Procladius choreus gr.*) and the oligochaetes dominate in benthic communities of the Pasvik River at all stations. The other groups of zoobenthos (mainly bivalves and water mites) are rare. The quantitative indicators are low at all stations (Table 5). The maximum benthos density was observed at Ruskebukta, which is mesotrophic whereas the other stations are oligotrophic. The minimum values of numbers and biomass were observed at Skrukkebukta station, possibly due to greater depths (> 20 m).

In Lake Kuetsjarvi the profundal zone is characterized by low taxonomic diversity. Oligochaetes, chironomids and bivalves form the basis of the communities and dipterous larvae, caddisflies and water mites are met sporadically. Quantitative indicators are low. The number of benthos was on average 506.9 ind./m^2 and biomass 2.1 g/m^2 with considerable variation of both indicators in the samples and in different zones of the water body. Shannon index values are less than 1 in all sampling stations of the lake, varying between 0.79–0.98 bit/ind. Oligochaetic index was 42 %, "moderately polluted", with a variation between the samples from 20 % to 80 %. The trophic state of water is rated as oligotrophic, largely due to pollution with Pechenganikel industrial complex effluents promoting the "oligotrophysation" processes of the water body (Yakovlev 2005).

In Lake Kuetsjarvi 18 species of Chironomidae were identified. The basis of chironomid communities is formed of *Procladius, Cricotopus* and *Chironomus,* which are common in polluted lakes. 13 species are found in the deepwater zone of Lake Kuetsjarvi and three species account for > 70 % of the total number of chironomids: *Sergentia coracina*, a coldwater species widespread in the deepwater zones of various lakes of Murmansk Region, and *Chironomus cingulatus and Prodiamesa olivacea, which are* resistant to water pollution with heavy metals. 9 species of chironomids were found in the littoral zone of Lake Kuetsjarvi: the basis of communities is formed from the Orthocladiinae subfamily members *Cricotopus silvestris gr.* and *Procladius choreus gr.,* which are commonly found in polluted streams.

Discussion

Variation in environmental variables caused by lakes' geographical position (latitude) generally strongly influences community structure and composition (e.g. Jacobsen et al. 1997; Sandin & Johnson 2000).

Zoobenthic communities in the unregulated subarctic lakes (Nitsijärvi and Muddusjärvi) differ from those in unregulated more southern lakes. For further biomonitoring studies subarctic unregulated reference

Table 5. Composition and quantitative indicators of deepwater zones' zoobenthos of Lake Kuetsjarvi and some stretches of the Pasvik River.

Species	Kuetsjarvi	Ruskebukta	Skrukkebukta	Vaggatem	Tjerebukta
Mean values of number, ind./m^2	506.0	1211.0	103.8	553.6	276.8
Mean values of biomass, g/m^2	2.1	4.8	0.4	2.2	1.1
Shannon index, bit/ind.	0.88	1.37	1.0	0.99	0.95
Trophic state	oligotrophic	mesotrophic	oligotrophic		

lakes should be sampled together with Lake Inarijärvi to avoid bias caused by within-year and biogeographical variability. Additionally, constant monitoring and a larger set of reference lakes would give more accurate results for assessment of community status.

In 2012 number of taxa and individuals from rocky shores from Lake Inarijärvi were on average lower than those in the unregulated lakes. Littoral zone organisms are particularly affected by water level regulation both directly by desiccation and indirectly by a decrease in habitat availability and food resources (Gasith & Gafny 1990). Previous studies (Smith et al. 1987, Aroviita & Hämäläinen 2008) have found that taxa richness decreases with increased regulation intensity and this effect might be stronger in boreal lakes due to the exposure of the regulated zone to subzero temperatures and freezing (Aroviita & Hämäläinen 2008). Temporal follow-up of zoobenthic communities from rocky shores from Lake Inarijärvi showed an increase in number of individuals from 2003 to 2008, however, numbers decreased again in 2012. The small number of sampled years together with natural variation makes it difficult to yet estimate any specific effect of water level regulation on rocky shore macroinvertebrate communities.

In soft bottom communities mean densities were higher in Lake Inarijärvi than in the unregulated lakes while average number of taxa did not differ greatly. In regulated lakes organic matter tends to accumulate immediately below the drawdown limit which in turn might increase individuals' abundance (Palomäki & Koskenniemi 1993, Furey et al. 2006). Density of soft bottom zoobenthic communities from Lake Inarijärvi showed a reduction in 2003 and 2008. The stabilization of shores and increased sedimentation of organic matter that has followed water level regulation would be expected to raise the amount of specific groups such as Diptera and Oligochaeta, but it has not been the case in 2003 and 2008. This reduction in density can be attributed to natural among-year variation in environmental conditions such as the notably dry summer of 2003.

The results from TT and PMA from rocky shores and soft bottom habitats indicate that the status of the communities in Lake Inarijärvi falls between good/moderate and poor/moderate conditions respectively. The discrepancies found between the two indices might be attributed to the small number of reference lakes which affects their accuracy. However, both indices indicate that communities are affected by water level regulation.

The Pasvik River water bodies are regarded as oligotrophic except for mesotrophic Lake Kuetsjarvi. Saprobity index indicated low pollution level, except for Lake Kuetsjarvi, which was β-mesosaprobic. Water quality classes were either II or III for the studies lakes.

Zoobenthic communities in unregulated subarctic lakes clearly differed from the regulated Pasvik River. Water level regulation and variation in environmental conditions caused by elevation may impact community structure, but the Pasvik River macroinvertebrate communities contain typical river taxas and therefore comparison to subarctic reference lakes may not be suitable.

Despite water level regulation, species richness and abundance in the Pasvik River was higher than in the reference lakes. This can be explained by the water level changes in the Pasvik River being rather moderate during the year, as in some studies of regulated lakes the benthic macroinvertebrate taxa richness decreases only beyond 2.0 m amplitude disturbance level (White et al. 2011). Abundance of the most sensitive species to water level changes (e.g. *Polycentropus flamoculatus*, *Sialis* sp. and *Caenis horaria* (Ephemeroptera)) varied between sampling sites, indicating that some parts of the Pasvik River may be more sensitive to water lever changes than others. Minimum water level fluctuation is recommended.

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Asellus aquaticus.
Photo Mira Grönroos


Rhyacophila nubila.
Photo Mira Grönroos

7 Fish communities of the Pasvik River and long-term malformation tendencies

PETR TERENTJEV, NIKOLAY KASHULIN, ELENA ZUBOVA, MIKKO TOLKKINEN

Long-term changes in the structure of the community and changes in the population and organisms were estimated taking into account the anthropogenic load intensity in different areas at different times. Data of multiyear investigations covering a long period (from the early 1990s till the present) were analyzed. The researched water bodies (lakes) were Lake Kuetsjarvi and water storage reservoirs Rajakoski (Russia), Vaggatem and Skrukkebukta (Norway). The fish fauna consists of representatives of 9 species belonging to 8 families: trout (*Salmo trutta* L.), European whitefish (*Coregonus lavaretus* L.), European vendace (*Coregonus albula* L.), European grayling (*Thymallus thymallus* L.), pike (*Esox lucius* L.), burbot (*Lota lota* L.), perch (*Perca fluviatilis* L.), Eurasian minnow (*Phoxinus phoxinus*) and nine-spined stickleback (*Pungitius pungitius*). The lakes form a gradient of anthropogenic load relative to their distance from the Pechenganikel smelter.

Malformations are found in fish living in polluted conditions and exposed to various chemical substances. Detected malformations include changes in external appearance (pigmentation of integument, depigmentation of skull), spinal curvature (i.e. scoliosis, ithykyphosis, lordosis), malformed gills (deformed, bifurcated and club-shaped rakers, irregular row or partial lack of rakers, onset of necrotic abnormalities in gill filament tips (anaemic ring)), malformed gonads (synchronic and asymmetric maturation, constriction and torsion of gonads), malformed liver (destruction of tissue, hyperaemia, focal necrosis resulting in change in color and elongation) and malformed kidneys (hyperemia, hemorrhages, progression of focal necrosis, dystrophic changes in tubule epithelium, onset of granulosis). The most common kidney disorder is development of excess connective tissue.

Material and methods

Studies of the fish communities were conducted along the Pasvik watercourse in the four main localities. Aerial pollution, sewage of the Pechenganikel enterprise and domestic sewage flow into Lake Kuetsjarvi, located ca 5 km from the Pechanganikel and downstream the Pasvik River. Skrukkebukta is located 16 km northwards of the Pechenganikel smelter. Vaggatem is located upstream from the Pechenganikel as is Rajakoski, farthest away (Introduction, Figure 1).

Sampling was done with a standard set of bottom nets. The nets were employed in the littoral zone one by one perpendicular to the coast and in the profundal zone there were ten ormore nets in line. Age of fishes was determined from the operculum, cleithrum or scales (method of Pravdin 1960,1966). The rakers on the first gill arch of the whitefishes were counted to isolate intraspecific forms (Pravdin 1966, Reshetnikov 1980, Amundsen et al. 2004, Siwertsson et al.

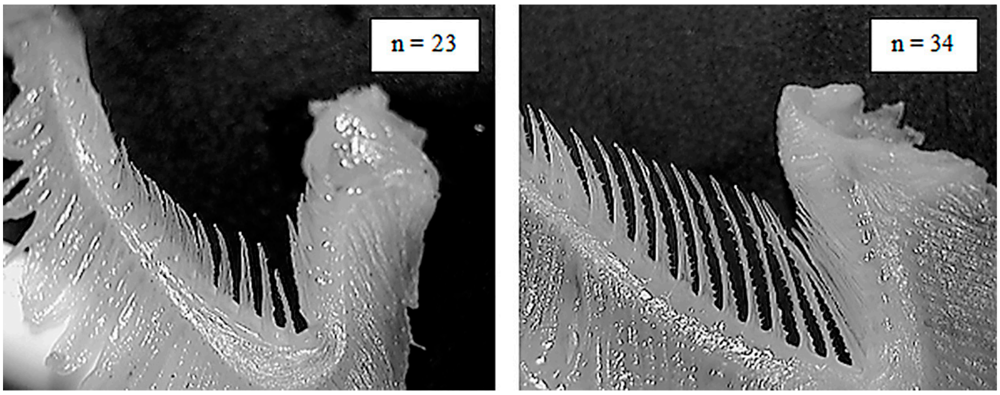

Figure 1. Rakers on the first gill arch of SR whitefish with 23 rakers (left) and DR whitefish with 34 rakers (right) in Lake Kuetsjarvi in 2012–2013.

2008) (Figure 1). Back-calculations of growth were carried out using the formula of Lee (Chugunova 1959, Bryuzgin 1969). The formula for back calculations of body length for sparsely-rakered (SR) whitefish of Lake Kuetsjarvi was: $lnL_i = 71.38 + R_i / R \times (lnL_n - 71.38)$ and for densely-rakered (DR) whitefish of Lake Kuetsjarvi: $lnL_i = ln25.64 + lnR_i / lnR \times (lnL_n - ln26.64)$. The formula for back calculations of body length for hybrid whitefish of Rajakoski: $lnL_i = ln39.15 + lnR_i / lnR \times (lnL_n - ln39.15)$. The specific growth rate was calculated using the formula of Schmalhausen-Brodie (Schmalhausen 1935, Mina & Klevezal 1976, Dgebuadze 2001).

Heavy metals in skeletal muscle tissues, liver, kidney and gills 10–15 fish individuals of the same size were analyzed. The metal concentration was expressed in mg/g dry weight.

The Pasvik River littoral fish were sampled in September 2013 by electrofishing. Sampling sites were habitats that have shelters to fish (stony littoral or macrophytes). All captured fish were identified and counted. Total length of every fish was measured and pooled individuals of each species were weighted. Presented fish densities represent the catch of one electrofishing run.

Results

Fish communities and population characteristics

Lake Kuetsjarvi

Despite the intensive industrial pollution all 9 fish species are present. The structure of fish population has not changed profoundly during the last 20 years (Figure 2). Predominant species are whitefish and perch; the rest composed less than 1 %. In the conditions of the highest anthropogenic load and toxic environment of Lake Kuetsjarvi whitefish is probably the most stable species capable of maintaining relatively high population by early maturing, change of life cycle strategy and polymorphism (Kashulin et al., 1999). The share of whitefish in the samples changed from 75 % to 96 %. The population of whitefish in Kuetsjarvi Lake was presented by two forms, sparsely rakered (SR) and densely rakered (DR), which was more numerous. Sparsely-rakered whitefish of the lake can be divided into fast-growing (large, LSR) and slow growing (small, SSR) forms. Ecological niches of these forms of whitefish do not intercross. High water body trophicity creates favorable conditions for co-existence of several forms of whitefish. The vendace of Lake Kuetsjarvi are represented by one species.

The average weight of DR whitefish during the whole period of studies varied widely (23–82 g), and the length varied from 12.1 to 18.7 cm. In some years the average values of size and weight increased, which probably was caused by large fish migrating into the water body from other parts of the Pasvik River. Maximum age of DR whitefish was eight years (Figure 7). Juvenile individuals composed 2.9 % of the community. Extremely early maturing (age 1+) of individuals was registered in both DR and SR whitefish. The share of fish ready for spawn, overall in the population in the pre-spawning period, varied from 20 % to 66 %. Minimal size of DR whitefish spawning for the first time was the weight of 6 g and the length of 9.5 cm.

The average weight and length of SR whitefish varied from 38 to 140 g and from 14.7 to 20.5 cm. Length-weight parameters did not significantly change during more than 20 years. The largest individuals of SR whitefish were aged eleven years (Figure 7). Juvenile individuals composed < 8.5 % of the community. SR whitefish reach maturity at the age 1+ with the weight 8 g and the length 9.5 cm. Overall in the population percentage of fish ready for spawning varied from 24 % to 49 %.

Growth rates of both whitefish morphs have decreased, which can be explained by persisting anthropogenic load.

Skrukkebukta

Whitefishes are predominant in the community structure and the proportion of whitefish in the selection during the whole study period varied from 64.2 to 77.5% (Figure 4). Proportions of vendace and perch were 19–28 % and the proportionst of other species varied from 0.1 to 2.4 %. The proportion of perch increased during the study.

The average weight of DR whitefish was 18–42 g and length 11.5–15.5 cm. Age composition of DR whitefish was dominated of fish of young age classes (0+–1+) (Figure 7) but in 2004 individuals aged 1+,2+ and 4+ were represented almost in equal proportion. Size of DR whitefish spawning for the first time was less than 6 g and 8.9 cm. In all age groups there was a high number of non-spawning fish.

SR whitefish were presented by individuals of small size. The average weight and length were 50–150 g and 14.8–19.5 cm. The basis of the population was

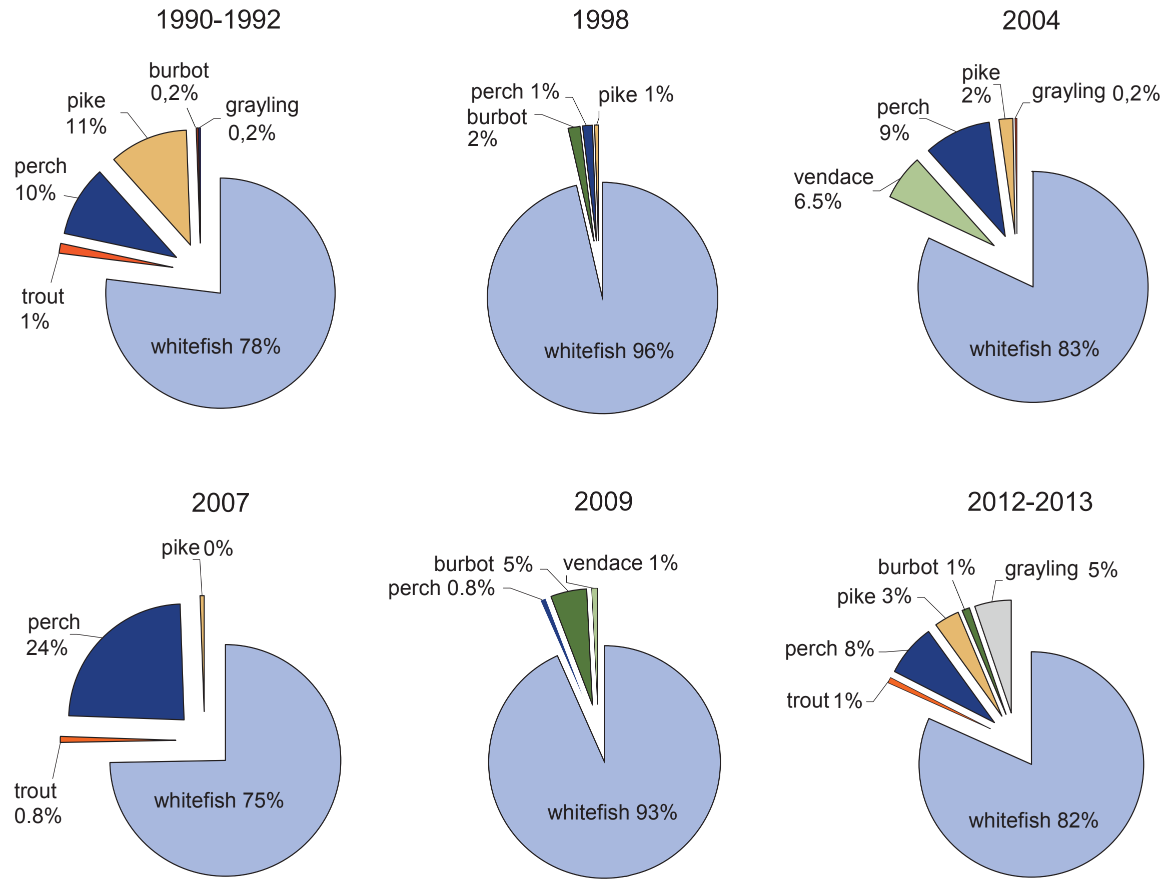

Figure 2. Proportion of fish species in Lake Kuetsjarvi in different periods of the research.

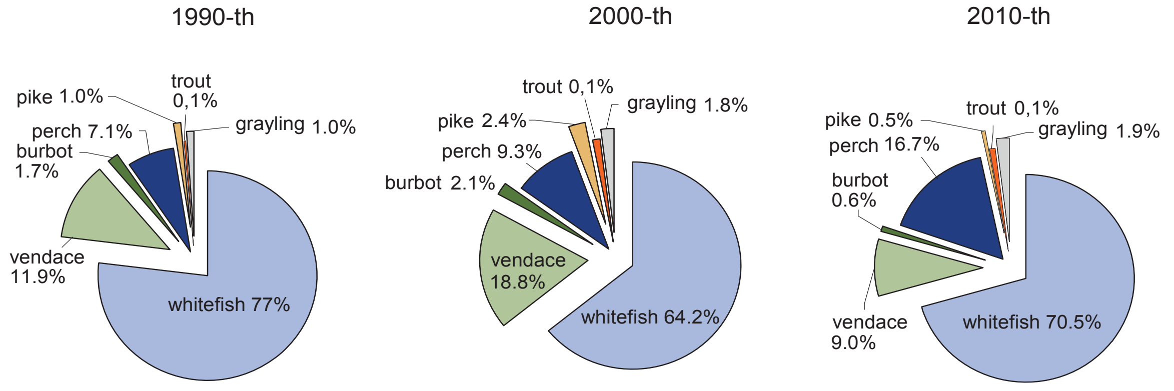

Figure 4. Proportion of fish species in Skrukkebukta in different periods of the research.

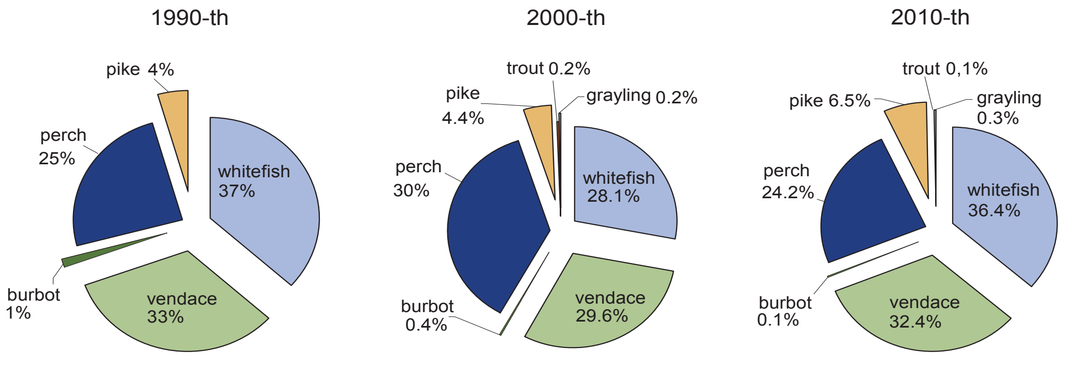

Figure 5. Propotion of fish species in Vaggatem in different periods of the research.

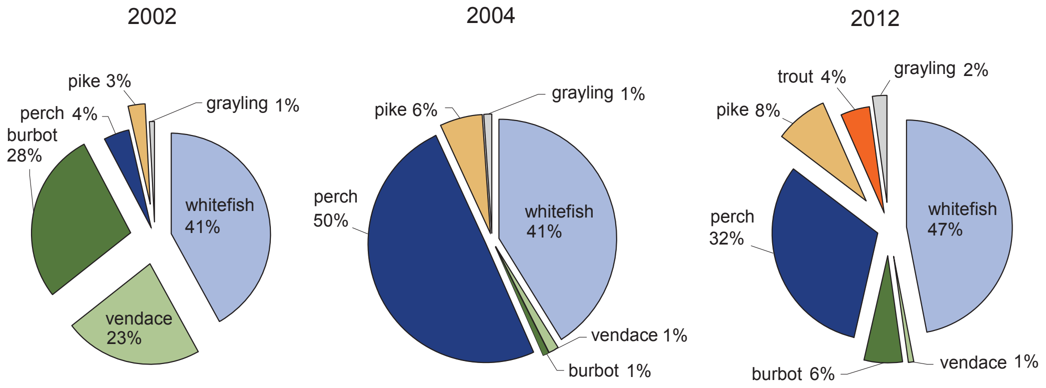

Figure 6. Proportion of fish species in Rajakoski n different periods of the research.

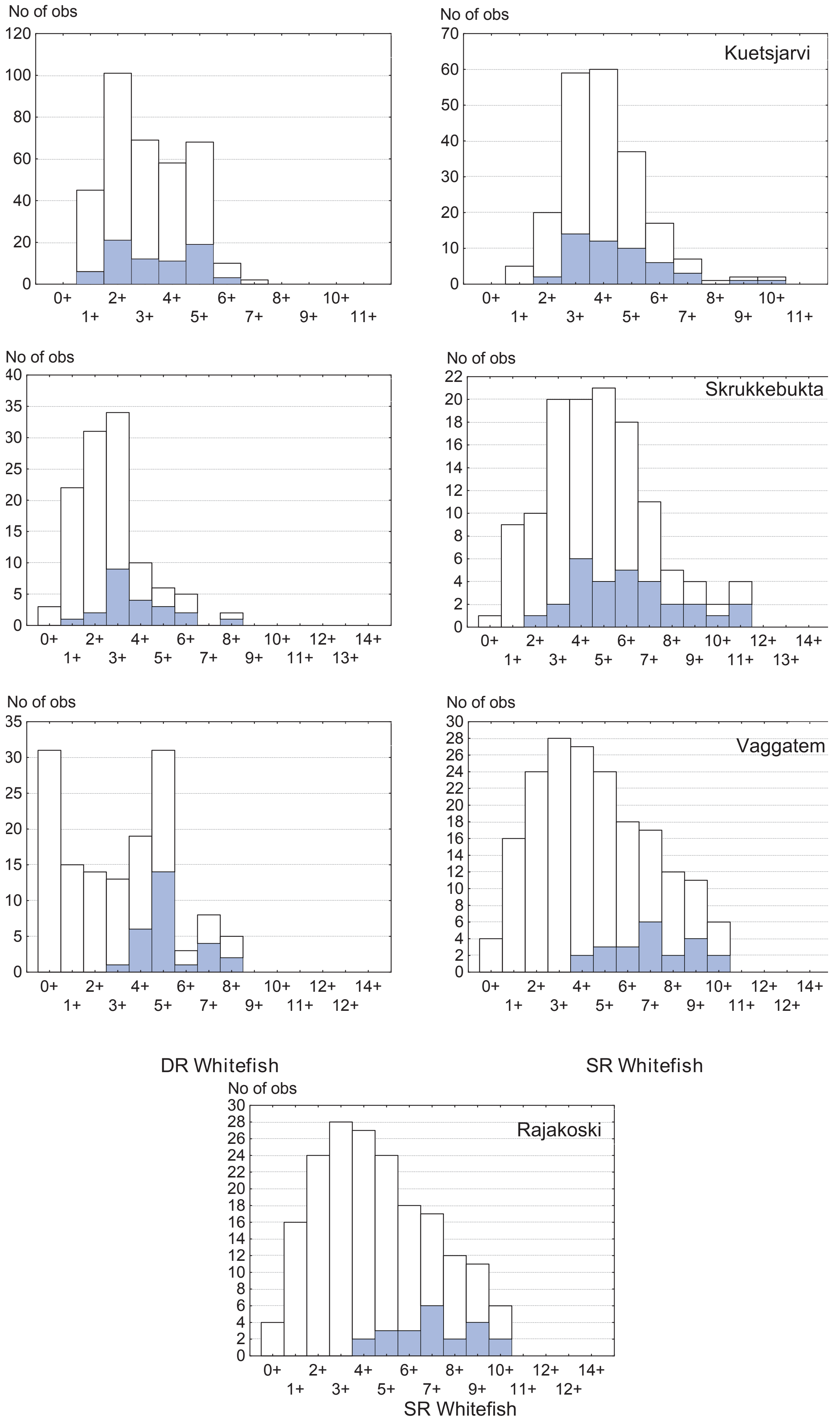

Figure 7. The present age structure of DR and SR whitefish of the investigated reservoirs (blue = fish ready to spawn).

formed by individuals of older age groups, which is more common in natural water bodies (Figure 7). It is obvious that in Skrukkebukta, despite its location in the lower reaches of the Pasvik River, influence of direct and aerial pollution is less intensive compared to Kuetsjarvi Lake. However, early maturing of fish was observed here as well.

SR whitefish aged fifteen years were encountered singly. Juvenile individuals (0+–3+) in the selection comprised from 10 % to 27.8 %. As for DR whitefish, minimal sizes of maturing fish were extremely small, the weight of 7 g and the length of 9.4 cm, and maturation age did not exceed 1+. The percentage of mature fish ready for spawn was low and varied within 13.8–32.3 % during the whole period of the study.

Analyses of size-age parameters of SR whitefish of Skrukkebukta showed that the growth rate of fish has decreased.

Vaggatem

Vaggatem is located ca 40 km upstream from the Pechenganikel. During the whole period of studies domination of whitefish was observed in the structure of the community. However, whitefish and vendace were encountered here almost in equal proportion. Perch is also of great importance and its share in samples may reach 30 % (Figure 5). The proportion of other species does not exceed 5–7 %.

The basis of DR whitefish population was formed by individuals with weight up to 100 g and length of 5–18 cm. The age structure of DR whitefish was dominated by age classes 2+– 4+ and the age of the largest fish did not exceed ten years (Figure 7). Juvenile individuals were encountered only in the samples of 2002 (8 %). Early maturing of whitefish is also distinctive of Vaggatem: individuals of the age 2+, the weight of 28 g and the length 15.4 cm can be mature. Generally percentage of fish ready for spawning comprised 46.5 % of the mature population.

The average weight of SR whitefish was 200-420 g and length 23–31 cm. There were two peaks in length distribution of fish: 15–25 cm and 30–35 cm. A generally uniform age distribution of all classes from 1+ to 10+ was seen and larger individuals of fifteen years were registered singly (Figure 7). SR whitefish begin to spawn in the age of 2+ with the weight 34 g and the length 15.3 cm. Quite high percentage (up to 67 % in 2+ or older fish) skips the spawn.

There seems to be an increasing trend in growth rate of both whitefish morphs, which is the opposite of the situation of Lake Kuetsjarvi and Skrukkebukta.

Rajakoski

Rajakoski is located ca 65 km upstream from the Pechenganikel. Whitefish dominates in the fish community and the share of vendace has significantly reduced. The proportion of perch varies but there is generally an increase (Figure 6).

During the research DR whitefish differed by size-weight parameters: variation of the weight was 7–548 g and lenght 9.2–36.0 cm. In 2002 the basis was formed by fish of age 0+ and later the number of individuals of older age still gradually reduced. There are no conditions for reproduction in Rajakoski and DR whitefish may be migrants from the upper reach of the river and from Lake Inari. Mature individuals were aged 2+ and minimal maturation weight was 36 g and length 15.8 cm.

The average weight and length of SR whitefish grew during the study: in 2002 they were 43 g and 12.4 cm, in 2004 180 g and 22.9 cm and in 2012 585 g and 35.1 cm. The age distribution of SR whitefish differed greatly between the study years. In 2002 fish aged 0+ comprised more than 65 % of the population while fish of other age classes encountered singly but later the dominating age class changed. This may be connected to migration of large individuals from the upper reach of the river as in this area there are no conditions for reproduction. The percentage of non-spawning whitefish is very high. Maturity of SR whitefish comes in the age of 2+ when the weight is 31 g and the length 14.7 cm.

Rajakoski water reservoir has the highest density of introduced vendace of all the studied water bodies. Vendace actively force DR whitefish out of the pelagic region. They are forced to look for new food items and habitats intruding the ecological niche of SR whitefish. This contributes to hybridization of SR and DR whitefish. In the early 2000's the dominance of vendace was significantly lower and segregation of the two forms of whitefish was more intense.

Fish community of the littoral zone

6 fish species were caught with electrofishing in the Pasvik River (Figure 8). Rocky shore fish densities varied between the river sections from 0 to 55 individuals/100 m^2. Minnows (*Phoxinus phoxinus*) were abundant and the only species in Skrukkebukta and Skogmo sites, which also had the highest fish density. No fish were caught in Vaggatem-Hauge and Hessefoss.

Malformations

Major malformations observed in fish of the studied lakes are shown in Figures 9–11.

Lake Kuetsjarvi

The most severe malformations are found in Lake Kuetsjarvi whitefish. The fish have specific kidney malformations described as progression of nephrolithiasis (nephrocalcinosis) in response to nickel intoxication. In some years 100 % of sampled fish had liver and kidney malformations. Despite lowering anthropogenic stress there is still no substantial improvement in the status of fish population in Lake Kuetsjarvi (Figure 12) and whitefish liver and kidney malformation frequency and rate remains at 75–86 %.

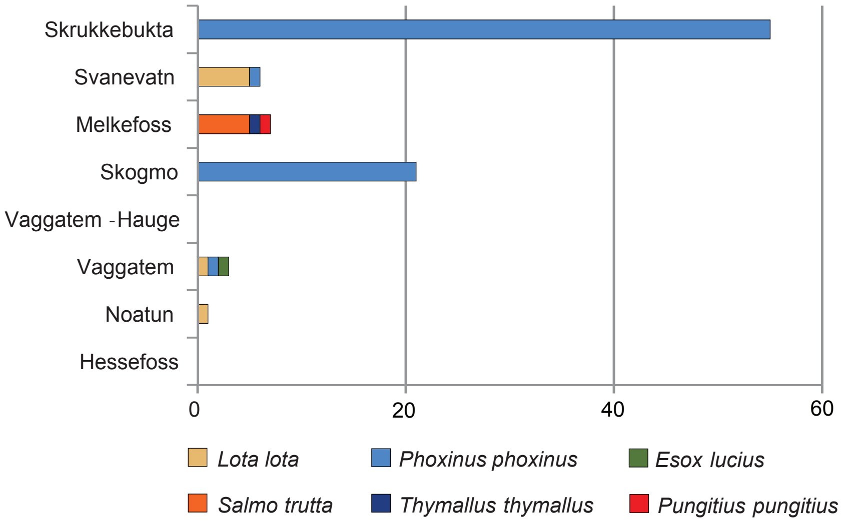

Figure 8. Rocky littoral shore electrofishing fish densities/100m^2.

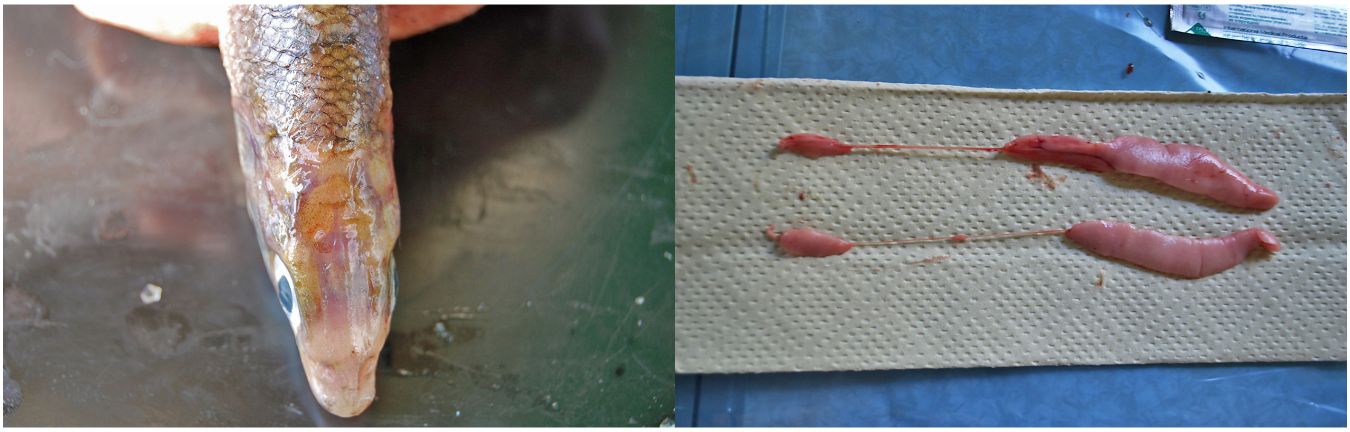

Figure 9. Depigmentation of whitefish skull (left) and segmentation of gonads of male and female whitefish due to fibrogenesis (right).

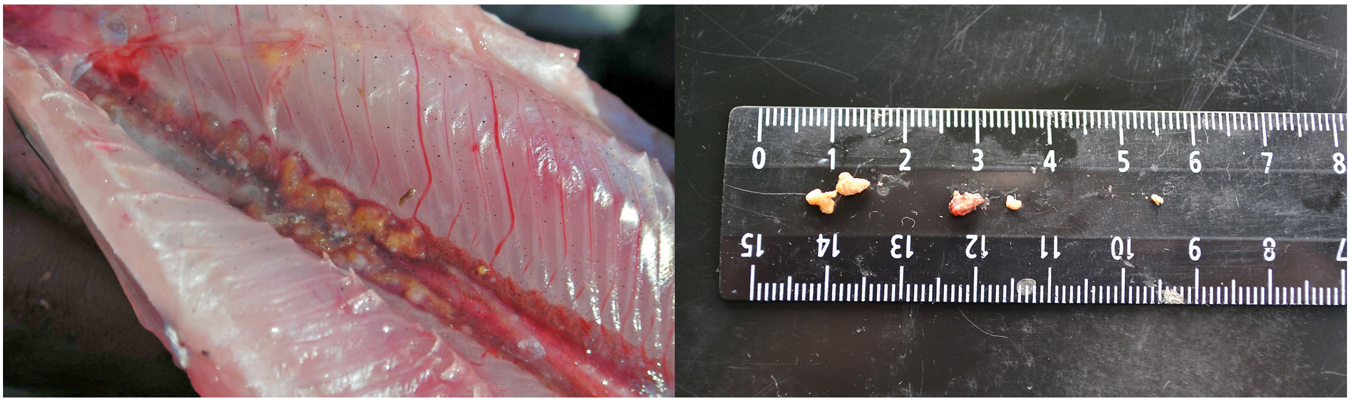

Figure 10. Terminal stage of fibrogenesis in whitefish kidney (left) and whitefish kidney stones (right).

Vaggatem and Skrukkebukta

Changes in whitefish liver structure, color and shape were the most common malformation noted in Vaggatem and other storage reservoirs in early 1990s. Kidney and gonad-related abnormalities came in second by frequency of occurrence (Kashulin et al. 1999). Later the frequency of gonad-, gill- and liver-related malformations decreased and the frequency of kidney malformations increased.

In the observation period of 2003–2005 the number of fish with affected kidneys decreased and affected liver increased in Vaggatem, and similar trends were seen in Skrukkebukta. The rate of affected gills and gonads stayed lower. The frequency of malformations in whitefish in Vaggatem and Skrukkebukta, as in Lake Kuetsjarvi, remains almost the same in 2008 as in the 90s, when intensity of stress on the waterways was at the peak level.

Rajakoski

Similar fish malformations are identified in Rajakoski, farthest from the industrial pollution source. The transformation intensity in whitefish organs and tissues was considerably less, and generally the liver and kidney malformations in whitefish are incipient in nature. However, the number of fish with such transformations has not decreased during the decade of observations (Figure 13).

Malformations in fish and anthropogenic stress

Nickel and copper are predominant contaminants of the area and the cause of high malformation rate of fish. Accumulation of nickel in organs is in direct correlation to proximity of a water body to the Pecheng-

Figure 11. Extreme degree of malformations of whitefish organs in Lake Kuetsjarvi.

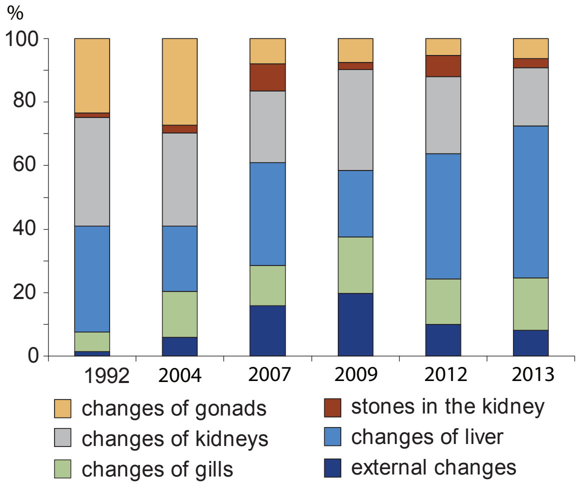

Figure 12. Long-term malformations of whitefish organs in Lake Kuetsjarvi.

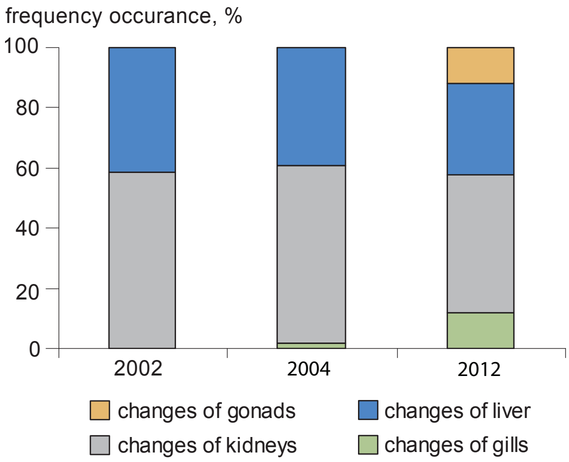

Figure 13. Long-term malformations of whitefish organs in Rajakoski.

anikel (Figure 14). Nickel and copper accumulation in the bottom sediments of the lakes correlates strongly (r=0.85–0.90) with the malformation frequency in whitefish liver and kidneys (Figure 15). Whitefish is a bottom feeder and this foraging strategy contributes to high rates of heavy metal accumulation which may have an effect on these organs. The most commonly encountered change is the enlargement of connective tissues of kidneys, which may be indicative of the persisting nickel load in the lakes.

No considerable improvement of condition of fish can be expected under the existing levels of the anthropogenic stress. Also the climate change processes may cause community-level transformations in some water bodies, which may result in a decrease in valued commercial species. This, in turn, leads to decrease of the resource potential of the ecosystem as such.

Discussion

The analysis of long-term observations of fish community of the Pasvik River basin revealed changes, which are associated with natural variability of the basic biological characteristics of fish and negative consequences of anthropogenic processes. Dominating fish community structure complexes shift from salmon-whitefish family to perch, smelt and cyprinid families due to changing climate and persisting anthropogenic stress (Kashulin et al. 2012). Such processes were identified specifically in Vaggatem, Skrukkebuk-

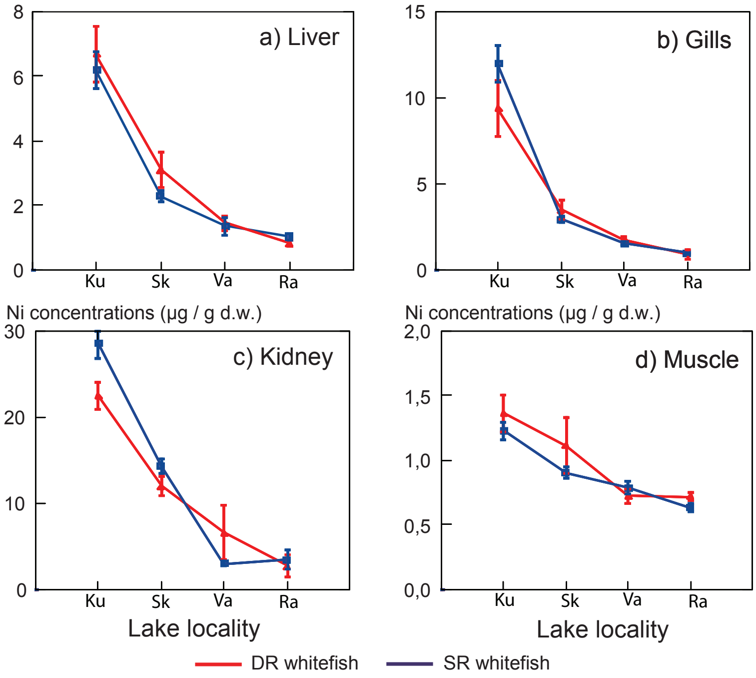

Figure 14. Nickel accumulation levels in organs of SR & DR whitefish of studied lakes.

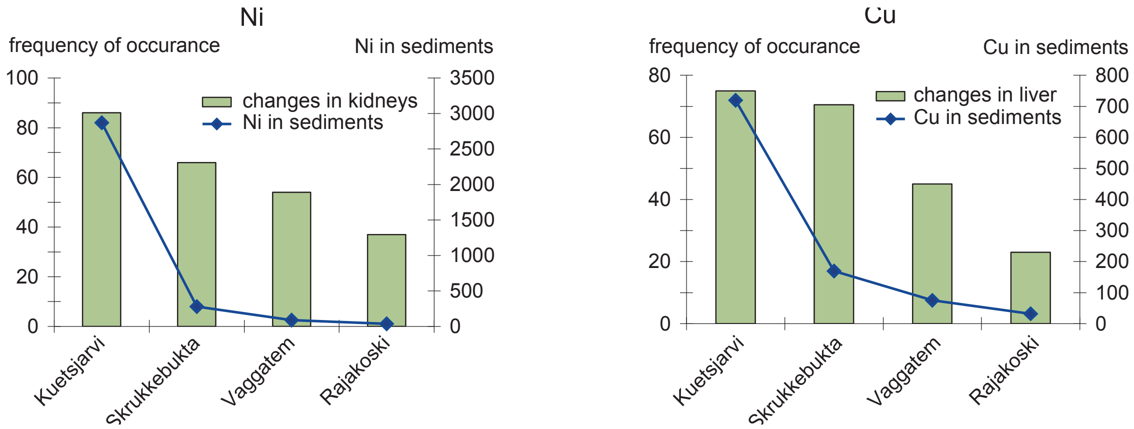

Figure 15. Correlation of whitefish liver and kidney malformation occurrence and nickel and copper accumulation in sediment beds (µg/$g_{dryweight}$) of the studied lakes.

ta and Rajakosk. Increase in the share of perch and pike was noted as well as increase in their size and the weight. At the same time in polluted Lake Kuetsjarvi there were no major changes in the fish community structure with whitefish being the most stable family, as it is able to maintain relatively high population due to early maturity, changes in life cycle strategy and polymorphism (Kashulin et al. 1999). DR and SSR forms of whitefish of Lake Kuetsjarvi have the lowest values of linear growth of all the studied reservoirs of the Pasvik River system. In these forms unique early maturing with a minimal size (at the age of 1+ with length 6–9 cm, weight 10 g) was observed, which is considered as one of adaptations to survive in heavily polluted waters.

Decrease in age, size and maturity classes of fish populations in contaminated waters may serve as a water quality criterion. In the whitefish populations missing age classes, large proportion of young fish, maturation of extremely young fish and large percentage of fish skipping the spawning season were noted. Anthropogenic stress is directly linked to fish growth processes. The average length and weight of whitefish, pike and perch seem to increase in proportion to increasing distance from the Pechenganikel.

Assessment of fish communities revealed that even though anthropogenic stress is decreasing, the condition of fish remains without considerable improvement at the level of communities, populations and individual organisms. The examined areas are located at different distances from the Pechenganikel plant and they are most representative in terms of long-term assessment of status of fish communities.

Fish species sensitive to water level regulation (minnow, *Phoxinus phoxinus*) were found only in Skrukkebukta and Skogmo sites, indicating that water level regulation may have effect on littoral fish communities of the Pasvik River. Fish densities and species richness varied between the sites indicating that effect of water level regulation may differ in different river sections depending on littoral morphological characteristics.

The Pasvik River basin monitoring programme should further focus on more comprehensive research on fish species composition and monitoring of condition of whitefish, vendace, pike and perch populations. Length, weight and age structure, growth, reproduction and feeding characteristics of fish should be the main fish population indicators. Whitefish should be used to assess the level of malformations in fish at the organism level under the anthropogenic stress: status of the kidneys (excretory system) is a critical parameter. Identification of relations between the stress intensity and negative biological responses of fish requires an integrated approach taking into account both pathology components and levels of heavy metal accumulation in fish organs and tissues and in sediments. Nickel and copper should be the main heavy metals used in determining the anthropogenic stress on the ecosystems of the border area. Observations of the status of the fish fauna of the lakes should be carried out once every three years.

Getting electrofishing equipment ready
Photo: Jukka Ylikörkkö.

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8 Long-term effects of metal contamination, water regulation, species invasion and climate change on the fish of the Pasvik River

PER-ARNE AMUNDSEN

Fish community composition

Altogether 15 different fish species have been recorded in the Pasvik watercourse, which is mainly formed of lakes and reservoirs due to hydropower stations. The most important fish species in these lacustrine systems include whitefish, vendace, perch, pike, burbot, nine-spined stickleback, brown trout and grayling.

Vendace invaded the Pasvik watercourse around 1990, after being introduced to Lake Inarijärvi in the 1960's (Amundsen et al. 1999, 2012; Præbel et al. 2013) and has now become the dominant pelagic species in the watercourse (Bøhn et al. 2008; Sandlund et al. 2013). Whitefish has been the most numerous fish species, occupying all major lake habitats in high numbers (Amundsen et al. 1999). The whitefish in the watercourse is polymorphic, consisting of three different morphs, differentiated in particular by their morphology and number of gill rakers, and referred to as small sparsely-rakered (SSR), large sparsely-rakered (LSR) and densely-rakered (DR) whitefish (Siwertsson et al. 2010). The three morphs have large ecological differences; the LSR morph predominantly residing in the littoral zone feeding on littoral zoobenthos, the DR morph in the pelagic habitat feeding on zooplankton, and the SSR morph in the profundal utilizing typical profundal prey (Kahilainen et al. 2011).

Perch is also numerous in the watercourse, mainly residing in the littoral zone and to some extent also utilizing the profundal. The diet of perch includes several ontogenetic niche shifts (Amundsen et al. 2003). Pike is typically found in the shallow littoral, but has in the latest years also more frequently been caught in the pelagic habitat. Also pike goes through ontogenetic niche shifts. Burbot is a benthic dwelling fish species, the abundance of which is low relative to e.g. perch and pike. Nine-spined stickleback has a key role in the food web of the lacustrine ecosystems in the watercourse, being a dominant prey for the small to intermediate sized predatory fishes, in particular perch and burbot (Figure 1; Amundsen et al. 2003).

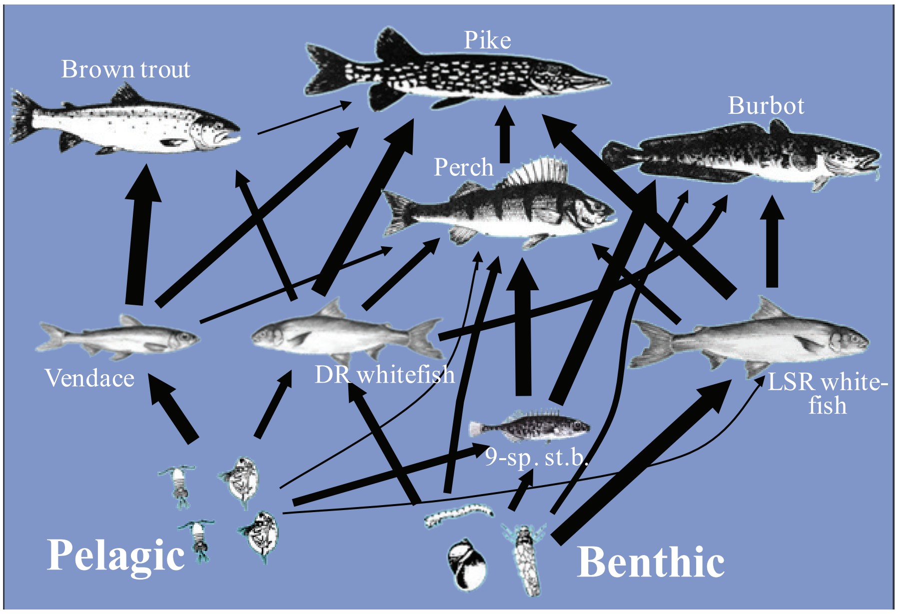

Figure 1. Summary of the basic food web structure of the lacustrine fish communities in the Pasvik watercourse (line thickness indicates the importance of the different links. Stippled lines represent unconfirmed links).

The brown trout in the Pasvik watercourse is a fast-growing, typically piscivorous form, which mainly feed on coregonid prey (vendace and DR whitefish) in the pelagic (Jensen et al. 2004, 2008). The water level regulations in the Pasvik watercourse have chiefly reduced the spawning and nursery areas for brown trout, and annual stocking of brown trout is carried out to compensate for the reduced reproduction and recruitment possibilities. Also grayling has suffered from the hydropower stations due to the loss of stretches with running water.

Food web structure and stable isotopes

The food web of the lake ecosystems in the watercourse consist of two main compartments originating from the pelagic and benthic primary production, respectively (Figure 1). In the native ecological community, the two most common whitefish morphs, DR and LSR whitefish, have central roles in each of these compartments; the DR morph utilizing the zooplankton resources and the LSR morph the benthic invertebrates mainly in the littoral zone (additionally the less abundant SSR morph is utilizing the benthic invertebrates in the profundal). Vendace has now become the key zooplankton predator and the dominant fish species in the pelagic habitat. Brown trout is the key top predator in the pelagic compartment, feeding predominantly on vendace and DR whitefish. In the benthic part of the trophic network, adult perch, burbot and pike are piscivorous species utilizing in particular nine-spined stickleback and whitefish as prey. Pike constitutes the apex predator of the whole aquatic network in the Pasvik watercourse (Figure 1). Pike, and more recently also perch and burbot, have started to include vendace in their diet, and the separation of the pelagic and benthic food-web compartments has therefore become less pronounced after the vendace invasion in the watercourse.

Stable isotope analysis provides long-term integrated information about the main nutritional sources, thereby constituting a cost-effective tool to explore the trophic ecology of freshwater organisms and the food-web structure of aquatic ecosystems (Boecklen et al. 2011, Layman et al. 2012). The carbon and nitrogen stable isotope ratios (expressed as $\delta^{13}C$ and $\delta^{15}N$, respectively) can distinguish between resources from the three principal lake habitats; littoral, pelagic and profundal (Vander Zanden & Rasmussen 1999, Syväranta et al. 2006).

A summary plot of the mean carbon and nitrogen stable isotope ratios for key taxa in the Pasvik lakes food webs reveals a distinct pattern of trophic levels and resource utilization (Figure 2), chiefly reflecting the trophic network established from habitat use and stomach contents data (Figure 1). Along the $\delta^{15}N$-axis, the invertebrates are positioned at lower values, which reflect their low positions in the trophic network. The profundal invertebrates (chironomids) show elevated $\delta^{15}N$-levels typical for them as compared to the

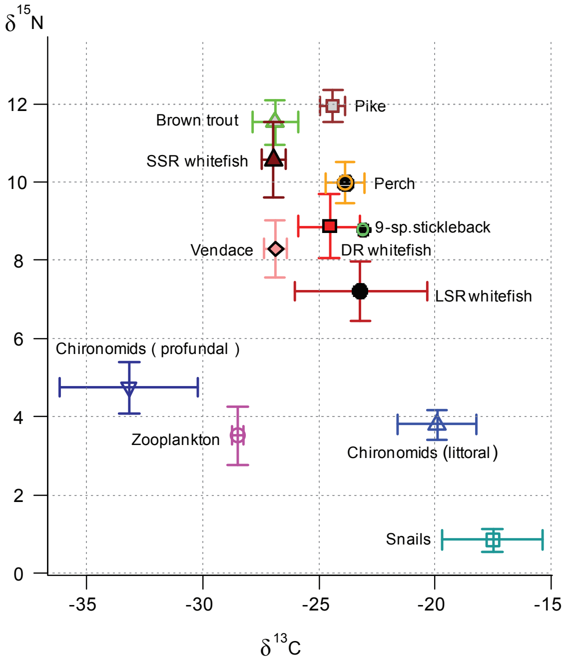

Figure 2. Mean stable isotopes ratios ($\delta^{13}C$ and $\delta^{15}N$) of important taxa in the lacustrine food webs of the Pasvik watercourse (data mainly from Vaggatem).

littoral and pelagic invertebrates, a pattern that is also reflected in the relatively high δ^{15}N-levels of the profundal dwelling, invertebrate-feeding SSR whitefish. Invertebrate-feeding fish species from the pelagic and littoral habitats dominate the intermediate δ^{15}N-levels whereas piscivorous species are positioned at the highest trophic levels as indicated by their high δ^{15}N-values (Figure 2). Perch is positioned intermediate to the coregonids and pike, reflecting their more omnivorous diet consisting both of invertebrate and fish prey. Along the δ^{13}C-axis the profundal and pelagic invertebrates have lower values than the littoral invertebrates. Similarly the coregonid species utilizing pelagic and profundal resources are positioned towards lower δ^{13}C-values than the predominantly littoral dwelling LSR whitefish. Among the top predators, brown trout, which typically feed in the pelagic habitat, had somewhat lower δ^{13}C-values than pike (Figure 2).

Anthropogenic impacts

The Pasvik watercourse suffers from a multitude of stressors that encompass chemical, physical and biological factors, in particular represented by large pollution outputs from the Pechenganikel extensive water level regulations, introduction and invasion of non-native species, compensatory fish stockings, and unregulated and unrecorded fish exploitation. Over the latest decades, global warming scenario has become an additional stressor. In relation to these extant threats and in order to enhance the general knowledge of subarctic freshwater ecosystems in this region, the fish communities of lakes in the Pasvik watercourse have been subject to extensive long-term biological studies with annual sampling since 1991.

Heavy metal contaminations in fish

Several heavy metals have been analyzed in different tissues from six fish species and at three different sites, covering four sampling periods (Period 1: 1991–1992, Period 2: 2002–2005, Period 3: 2007–2008, Period 4: 2012–2013). The studied lakes are Kuetsjarvi, Skrukkebukta and Vaggatem. Some additional samples are also available from Rajakoski (Period 2 and 4) and Lake Inarijärvi (Period 2). Studied fish species are DR and LSR whitefish, perch, pike, brown trout and vendace, and tissue samples have been retrieved from muscle, liver, gills, kidney and skeleton. Elements examined in all sampling periods include nickel (Ni), copper (Cu), cadmium (Cd), chromium (Cr), zinc (Zn) and mercury (Hg).

A temporal analysis of the Ni contents in different tissues of the DR and LSR whitefish morphs revealed no distinct variations throughout the four time periods from 1991 to 2013. A profound and significant decline in contamination levels with increasing distance from the smelters (i.e. from Kuetsjarvi to Skrukkebukta to Vaggatem) was, however, evident for all the examined time periods. This could also be seen for the Ni contents in different tissues of perch and pike. Similar patterns were also revealed for Cu and Cd. Also for the tissue contents of Cr and Zn there were no distinct variations through time. Hence, no major changes in the contamination levels of these elements in fish tissue appear to have occurred over the time period of 1991–2013.

In contrast, a distinct temporal pattern was evident for the mercury (Hg) contents in fish tissues. Both in Kuetsjarvi (Figure 3a) and Skrukkebukta & Vaggatem (Figure 3b) there was a significant increase in the Hg contents in muscle tissue of most fish species over the four sampling periods from 1991 to 2013. The inc-

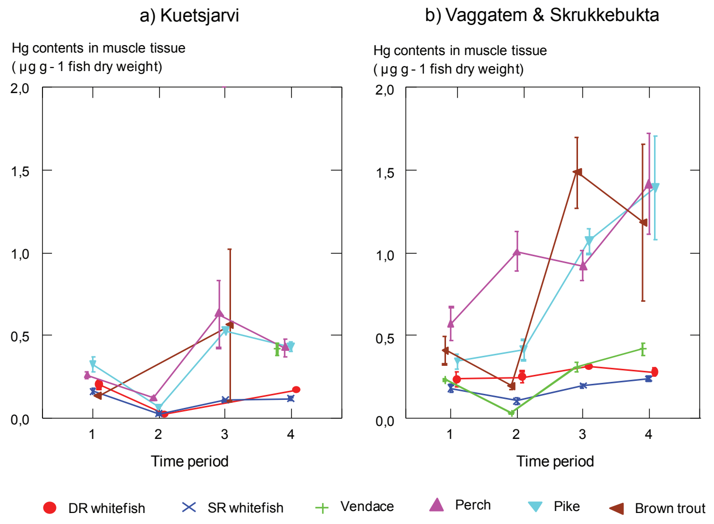

Figure 3. Temporal changes in Hg levels in muscle tissue of fish from a) Kuetsjarvi and b) Skrukkebukta & Vaggatem (samples from these two lakes were combined to strengthen the observation numbers as no large differences in Hg levels were evident between these two localities). Time periods 1: 1991–1992, 2: 2002–2005, 3: 2007–2008, 4: 2012–2013

rease in Hg contamination over the study period was particularly large for the predatory species and was most distinct in Skrukkebukta & Vaggatem. The generally higher contamination levels in predatory species than in the coregonids are to be expected as Hg is an element that accumulates in organisms and thus typically increases with increasing trophic levels within the food webs. Similarly, the Hg contents in fish also tend to increase with increasing fish size, which could be seen for brown trout, perch, pike, and LSR whitefish but was not evident for DR whitefish and vendace which have more narrow size ranges.

The observed increase in the Hg levels of the predatory fishes may be related to the recent ecological changes following the vendace invasion in the watercourse, as pelagic pathways are known to be of large importance in bioaccumulation and magnification of Hg in subarctic lake food webs. Another plausible explanation for the high levels of Hg and the distinct increase in Hg levels in fish over the latest decade is related to the ongoing global climate changes. Increased temperatures and a higher run-off due to increased precipitation have already been demonstrated for the watercourse (Chapter 1). This has likely resulted in a more extensive wash-out of pollutants from the large catchment area and into the watercourse, where biomagnification and accumulation of Hg through the food web rapidly may result in elevated contamination levels in the top predators (conf. e.g. Harris et al. 2007).

Water regulations

Following the establishment of seven hydropower stations along the Pasvik watercourse there have been large changes in the physical characteristics: large areas were flooded, previous rapids and waterfalls disappeared, and the former river system is now dominated by consecutive lakes and reservoirs. Principal spawning, nursery and feeding areas for brown trout and grayling were severely degraded and reduced due to the disappearance of the riverine stretches of the watercourse, resulting in strong declines in the abundance of these species (Kristoffersen 1984, Arnesen 1987). The large physical changes of the watercourse have benefitted typical lake-dwelling fish species like whitefish, perch and pike, especially through the development of large reservoirs. The dam constructions have resulted in a fragmentation of the watercourse, making upstream fish migration impossible and downstream migration infeasible. For the fish populations the fragmentation and migration limitations may have resulted in some genetic constraints for some of the fish populations, but this has yet not been explored.

Brown trout stocking and vendace invasion

The Pasvik brown trout recruitment potential suffers from the hydropower plants of the Pasvik River and due to this the local Norwegian hydropower company is carrying out an imposed annual stocking of 5000 large-sized trout. The stockings are important for the present brown trout population as stocked fish comprise >80 % of the total catches. From 1998 to 2008, the contribution of stocked fish in the catches has distinctly decreased, which suggests that the natural production of brown trout may have slightly improved, possibly as a result of a larger spawning population due to the contribution of stocked fish. Vendace has been the dominant prey over this time period, with an increasing dietary contribution from around 75 % in 1998 to nearly 100 % in 2008. Hence, the vendace invasion and the establishment of a high population abundance of the invader have provided a new prey source for the piscivorous trout, and may thus have increased the production potential of brown trout in the watercourse.

The strategy for the stocking programme appears good, especially in respect to the exclusive use of brood fish from the local trout population. However, artificial selection may occur during the collection of the brood stock and subsequently in the breeding and rearing facilities, potentially leading to a reduced or altered genetic diversity. Further studies of the brown trout population should therefore be implemented, including a genetic survey. Moreover, the remaining spawning and nursery areas for brown trout in tributary streams need particular attention and protection, especially since the trout has an obligate role in the lifecycle of the red-listed freshwater pearl mussel *Margaritifera margaritifera* (e.g. Aspholm 2013).

The vendace invasion started from Lake Inarijärvi, where the species was introduced in the headwaters on two occasions in the 1950s and -60s (Mutenia & Salonen 1992), and by 1995 it was apparently present along the whole watercourse (Amundsen et al. 1999). Within few years the invader became an important pelagic fish species in lakes in the Pasvik watercourse (Amundsen et al. 1999, Bøhn et al. 2004, 2008). However, the vendace population also entered a typical fluctuating ‘boom-and-bust’ development with large variations in population density (Salonen et al. 2007, Sandlund et al. 2013), resulting in a highly variable and unpredictable ecological situation in the watercourse.

In Vaggatem the vendace population rapidly increased in abundance after its arrival in 1991 and had by 1998 attained a peak density in the pelagic habitat. However, over the next couple of years there was an abrupt decline in the vendace density, which stayed low until 2003. Later, the vendace density has shown large fluctuations with mainly three years intervals between peaks.

The invasion and rapid population increase of vendace in Vaggatem had an immediate and dramatic effect on the DR whitefish population. Over the first 3-4 years the total density of DR whitefish remained at a constant level. However, only one year after the arrival of vendace a major behavioral shift occurred, where most of the DR whitefish population disappeared from the pelagic, and was relegated into the littoral and profundal habitats. This situation was maintained for a few years, but after 1995 a dramatic decline occurred in the DR whitefish abundance. Even during the period from 2000 to 2003 when the vendace density seemingly was at low levels, no apparent rebuild of the DR whitefish population occurred.

Vendace can utilize zooplankton more efficiently than DR whitefish (Bøhn & Amundsen 2001) which can be seen from the long-term changes in zooplankton density, which decreased following the vendace invasion. The zooplankton resource appears to be inaccessible as a significant dietary source for DR whitefish when vendace is present in high densities. Assumedly the differences in vendace populations between localities (Figure 4) are related to a variable resistance towards the invading species between sites and among fish communities of different structure and dynamics. In particular, the DR whitefish populations in Skrukkebukta and Kuetsjarvi consist of smaller-sized individuals and have a shorter generation time than in Vaggatem, which may make them more capable of responding to the competitive impacts of the invading vendace. In Kuetsjarvi, local adaptations of the whitefish populations to the heavy pollution may also have made it more difficult for the invading vendace to get an upper hand in competition and to establish in high densities. Furthermore, at the time of the invasion the propagule pressure was likely much larger in the upper parts of the watercourse, which may have led to an abrupt shift in competitive and numerical dominance in favor of the vendace.

Vendace and whitefish belong to the same genus (*Coregonus*) and hybridization between the two species is plausible even though it has not been documented in the Pasvik watercourse. In contrast, a breakdown of the reproductive isolation between the LSR and DR whitefish morphs is documented to have occurred following the invasion of vendace (Bhat et al. 2014). It was revealed that the frequency of hybrids had increased from 34 % in 1993 to nearly 100 % by 2008. The extensive hybridization between this morph-pair appears to reflect a situation of “speciation in reverse”, where the vendace invasion has reversed the incipient speciation process that has led to the formation of the whitefish morphs, collapsing these into a hybrid swarm and creating a situation which potentially may have large consequences for the biodiversity and functioning of these ecosystems.

Climate change impacts

Three key objectives have been addressed: 1. Are there any significant changes to be seen in the temperature regime of the watercourse; 2. Are there any evidence of temperature effects on fish growth (juve-

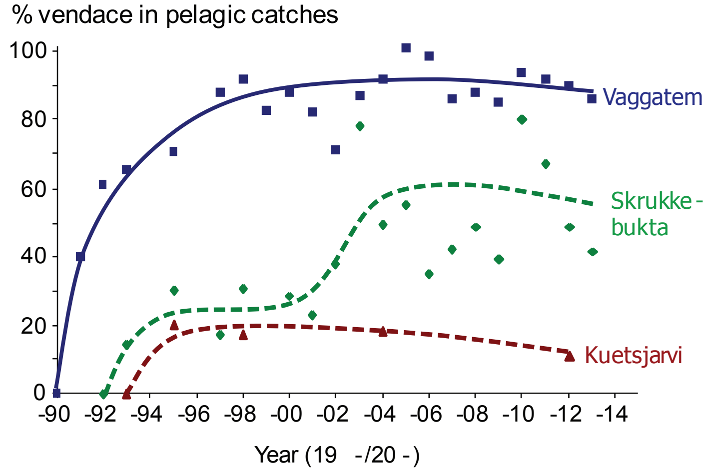

Figure 4. The contribution of vendace in pelagic fish catches in Vaggatem, Skrukkebukta and Kuetsjarvi in the period from 1991 to 2013.

nile coregonids); 3. Are there any changes in the fish community composition that can be related to temperature-induced changes in species interactions?

The water temperatures in the Pasvik watercourse have been monitored on a daily basis since 1991, and the water temperatures between 1975 and 1991 have furthermore been estimated from a modeling effort based on measured air temperatures (Gjelland et al. 2013). We found that average summer water temperature (i.e. July–September) increased significantly from 1975 to 2013 with on average 0.05 °C/year. Over the 38 years, the average summer water temperature increased from 11.89 °C to 13.84 °C, i.e. an increase of 1.95 °C for the total period, equivalent to a mean temperature increase of 0.51 °C per decade.

According to modelled temperature, precipitation and runoff predictions for the Pasvik watercourse, the water temperature and length of the ice-free season will continue to increase throughout the 21 century (Gjelland et al. 2013), as will also the annual precipitation and runoff. This sets the scene for potential large ecological changes in the watercourse.

Changes in summer water temperatures may affect the juvenile growth of the coregonids in the Pasvik watercourse. It is suggested that coregonid larval growth is primarily controlled by temperature and thereafter by food availability. Hence, a slight shift in temperature regime may potentially have a dramatic effect on growth of larval and juvenile coregonids (Eckmann and Rösch 1998; Perrier et al. 2012). To explore this, the back-calculated length at age 1+ (and thus the growth performance during the first year of life) of vendace and DR and LSR whitefish from Vaggatem and Skrukkebukta were matched to the corresponding summer water temperatures to explore possible climate and temperature effects on juvenile coregonid growth over an approx. 20 year time period. The study revealed that an increase in temperature evidently will increase larval and juvenile growth. The present temperature regime in the Pasvik watercourse may be favorable for the juvenile growth rate of the LSR whitefish morph but the expected future increase in temperatures will likely shift the favorability towards vendace. Hence, as vendace and DR whitefish compete strongly for the pelagic resources and since a further increase in water temperatures likely will be favorable for the vendace, the outcome may be an even stronger negative effect on the DR whitefish population.

Climate warming is expected to induce complex changes in fish community structure (Jeppesen et al. 2010). Whitefish is a cold-water stenothermic species with optimum growth at 18 °C (Siikavuopio et al. 2013), whereas perch is a cool-water eurythermic species with optimum growth at 23 °C (Fiogbe & Kestemont 2003). Hence, perch is considered as the species that most likely will benefit from increasing temperatures at the expense of e.g. whitefish (Graham & Harrod 2009, Hayden et al. 2014).

Our long-term data set has been analyzed in respect to the contribution of perch in the littoral habitat (Figure 5). In Vaggatem, a significant increase occurred over the first part of the study period from a contribution of ca. 20 % in 1991 to 50–60 % around 2003. In Skrukkebukta, the development pattern of the littoral fish community was very clear-cut with a distinct and significant increase in the perch contribution from 1993 to 2013, from around 5 % in the start to nearly 50 % at the end of the study period. These findings

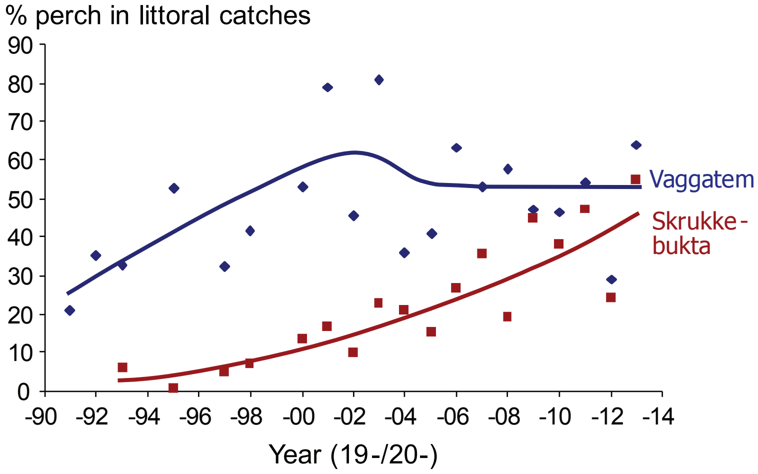

Figure 5. The contribution of perch (with fitted trend lines) in littoral samples from Vaggatem and Skrukkebukta in the time period from 1991 to 2013.

strongly suggest that perch have benefitted from the increasing temperatures.

The present findings demonstrate that climate change impacts already are in effect in the Pasvik watercourse, having induced a significant increase in the mean summer water temperatures over the last decades and seemingly also induced important ecological responses and effects. In particular, it has been demonstrated that the juvenile growth of the coregonids is significantly affected by the increased water temperatures, which potentially may affect their interspecific interactions. Furthermore, a change in the fish community composition of the littoral zone is also evident, with an increase in the contribution of perch. Additionally, the increase in the levels of Hg in fish over the latest years may suggestively be a climate change consequence related to increased precipitation and runoff. The multitude of stressors affecting the Pasvik watercourse may enhance potential climate change impacts in the watercourse, making the ecosystems less resistant and thus more vulnerable to the induced changes.

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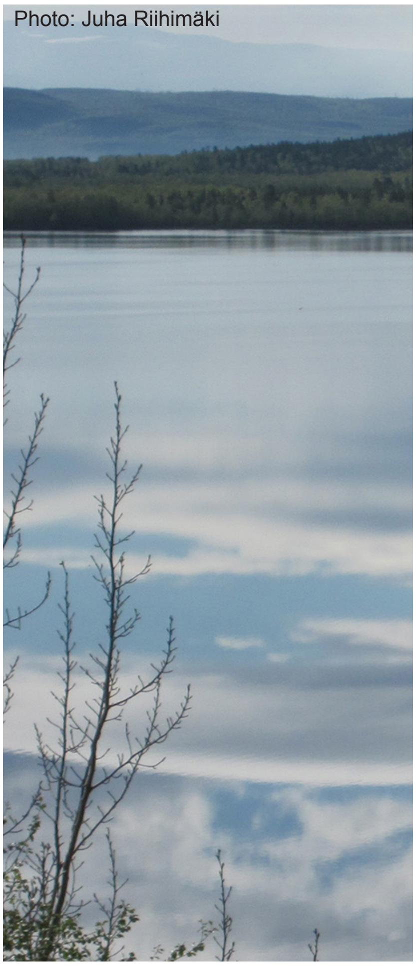


Photo: Juha Riihimäki


Taking the water temperature at fishing site. Photo: Jukka Ylikörkkö.

9 Contaminants in fish of the Pasvik River

GUTTORM N. CHRISTENSEN, HELÉN JOHANNE ANDERSEN, GEIR DAHL-HANSEN, NIKOLAY KASHULIN, PETR TERENTJEV, DMITRII DENISOV

The main contaminant sources to aquatic and terrestrial environments in the area are the Pechenganikel mining and metallurgical company's smelter in Nikel and roasting plant in Zapolyarny. In addition to this, the area is also exposed to long-range airborne pollutants. The area has been identified by the Arctic Monitoring and Assessment Programme (AMAP 2000) as a "Key monitoring area," where pollution, emissions and their effects are to be monitored.

Studies carried out in the early 1990s revealed numerous acidified and heavy metal polluted lakes in the border area (Traaen et al. 1991, 1992, Moiseenko 1994, Dauvalter and Rognerud 2001). Water quality monitoring has shown that the heavy metal concentrations in the lakes in this area have been increasing since 2004. Heavy metal levels in fish are well studied by Russian and Norwegian scientists (Amundsen et al. 1993, 1997, Arnesen et al. 1996, Kashulina & Kashulin 1997, Moiseenko et al. 1995, Lukin et al. 2003).

Previous screening of contaminants demonstrated elevated levels of persistent organic pollutants (POPs) in different fish species in the Pasvik River (Stebel et al. 2007, Christensen et al. 2007, Christensen 2008). In previous screening studies, the highest levels of POPs were found in fish from Lake Kuetsjarvi and it was a tendency of decreasing levels of POPs with increasing distance to the smelter.

The aims of this study were to follow up the findings of the previous project, "State of the environment in the Norwegian, Finnish and Russian border area" that was carried out during 2003–2006 (Stebel et al. 2007). Based on the previous studies the main contaminants in fish are mercury, polychlorinated biphenyls(PCBs), pesticides and polybrominated diphenyl ethers (PBDEs). Fish from the Pasvik River is an important food source for the people in the area. There are more than 15 species of freshwater fish in the Lake Inarijärvi and the Pasvik River watercourse. The fish community is a mixture of eastern, western and introduced species. The most important fish species for food consumption are whitefish (*Coregonus lavaretus*), trout (*Salmo trutta*), perch (*Perca fluviatilis*) and pike (*Esox lucius*). The results from this study can be used to evaluate the levels of contaminants related to food safety.

The most distinct contaminants in the area

Mercury (Hg) occurs naturally in the environment and has been used in numerous medicinal, commercial and industrial applications. Today mercury presents risks to Arctic wildlife and human populations (Arctic Monitoring and Assessment Programme, AMAP 2011). Mercury is also one of the prioritized substances under The EU Water Framework Directive (WFD) and it is included on Norway's priority list of hazardous substances. It is of particular concern that mercury levels are continuing to rise in parts of the Arctic, despite reductions in anthropogenic emissions. There are several reasons for this: increased emissions in Asia, increased riverine discharge, thawing of permafrost and local-scale climate change (AMAP 2011).

Mercury enters the Arctic environment via long-range transport from human sources at lower latitudes. The European limits for allowable levels of mercury in fish are 0.5 mg/kg ww. The documented elevated levels of mercury and especially the increasing trends of mercury in the environment are of a great concern for the Arctic countries (AMAP 2011).

Persistent organic pollutants (POPs) are a group of chemicals which persist in the environment, may bioaccumulate in human and animal tissues and are toxic. They also have the potential to be transported long distances and be deposited far away from their place of release.

Polychlorinated biphenyls (PCBs) were first manufactured in 1929 and produced in many countries. PCBs have been used extensively in a variety of industrial products and as plasticisers. In Russia, production of PCBs was terminated between 1987 and 1993 and they are listed as carcinogenic. The International Agency for Research on Cancer ranks PCBs as a probable human carcinogen. Chronic low-level exposure to PCBs can cause liver damage, reproductive abnormalities, immune suppression, neurological and endocrine system disorders, delayed infant development and stunted intellectual function.

Dichlorodiphenyltrichloroethane (DDT) was widely used as a pesticide and insecticide, but has since the early 1970s been banned in North America, Europe and the former USSR. However, it continues to be used in Asia, Africa, Central and South America (Voldner and Li 1995), resulting in a continued global source. Total DDT is the sum of the DDT structural analogs and breakdown products. DDT has been shown to be a hormone-disrupting chemical that can affect the reproductive and nervous systems.

Hexachlorobenzene (HCB) has been used as a fungicide, solvent and as a manufacturing intermediate or additive. Production and use has ceased in many countries. HCB continues to be created as a by-product in the manufacture of many chlorinated solvents and pesticides and in other chlorinated processes. It is also released in the burning of municipal waste, during incomplete combustion. In Russia, HCB was used until 1990, and was banned in 1997. HCB is toxic and can damage the liver, thyroid and kidneys, as well as the endocrine, immune, reproductive and nervous systems.

Chlordane is a versatile, broad-spectrum contact insecticide used mainly for non-agricultural purposes. Recently, the use of chlordane has been restricted in many countries, due to its toxic effects and capacity to persist and bioaccumulate. It is banned in Russia (de March et al. 1989). Chlordane exposure has been linked to liver and blood disorders, severe neurological effects and damage to the endocrine and reproductive systems.

Different mixtures of polybrominated diphenyl ethers (PBDEs) are used as additive flame retardants in plastics and textiles. (Bergman 1989). There is evidence that some PBDEs bioaccumulate and cause toxic effects at low levels. The United States Environmental Protection Agency (EPA) has classified decabromodiphenyl ether as a possible human carcinogen. PBDEs are also endocrine disrupters.

Materials and methods

Study area and sampling locations

The Pasvik River catchment area is the main freshwater system in the region, covering an area of approximately 1250 km^2. It has a catchment area of 18 404 km^{2,} of which approximately 70 % belongs to Finland, 25 % to Russia and 5 % to Norway. The watercourse constitutes a subarctic system with high biodiversity and production of fish and other aquatic organisms. The fish populations are important food resources for the locals and there is a long tradition to utilize the resources both for commercial and recreational fishing (Aspholm 2004, Aspholm 1996). Detailed descriptions of the study area are given in numerous report and publications (e.g. Arnesen et al. 1996, Moiseenko et al. 1995, Amundsen et al. 1993, 1997, Lukin et al. 2003, Stebel et al. 2007).

Sampling of fish was carried out in in September 2012 and September 2013. The following lakes in the Pasvik River were sampled: Vaggatem (Tjerebukta and Ruskebukta), Lake Kuetsjarvi and Skrukkebukta (Table 1, Chapter 3, Introduction, Figure 1).

Sampling procedure

Fish sampling was performed in the littoral (< 8 m), profundal (> 10 m) and pelagic habitats (0–6 m) using gillnets. In all studied lakes, the whitefish is represented by two different morphs, differentiated by their number and morphology of gill rakers and referred to as sparsely-rakered (SR) and densely-rakered (DR) whitefish (Amundsen et al. 2004). The two whitefish morphs exhibit distinct genetic and ecological differences (Amundsen 1988, Amundsen et al. 2004), and are treated as functional species in the analysis and presentation of the results. Fish were identified to the species level.

The following fish species were collected for contaminant analyses during 2012–2013: pike, perch, whitefish and trout.

Each fish was measured for fork length and weight, sex and stage of maturation were recorded. Otoliths were sampled from whitefish and opercula from perch for age determinations. The tissue samples (muscle and liver, weight 5–20 g) were either packed in preburned aluminium foil for POPs samples or plastic zip-lock bags for metal analysis. Samples were stored frozen (-20 °C) in the field and transported frozen to the laboratory for analyses.

Analyses

Muscle tissue from pike, perch, SR whitefish, DR whitefish and trout were selected for POPs (55 fish) and heavy metal analyses (97 fish) (Table 2).

Persistent organic pollutants analyses carried out in this project were chlorinated pesticides, polychlorinated biphenyls (PCBs), planar and non-orthosubstituted congeners of PCBs and brominated flame retardants (PBDEs).

Analysed heavy metals were mercury (Hg), arsenic (As), cadmium (Cd), lead (Pb), copper (Cu), cobolt (Co), zinc (Zn), lithium (Li), nickel (Ni), iron (Fe) and magnesium (Mn). Also lipids were analyzed.

Analyses were carried out at Typhoon analytical laboratory (Obninsk, Russia). Detailed descriptions of analytical methods used for determination of environmental contaminants, along with information on QC/QA, are given in Christensen et al. 2015.

The following persistent pollutants were determined in the biological samples:

- chlorinated pesticides and industrial organochlorines: DDT-group, HCH, hexachlorobenzene (HCB), chlordanes, mirex, endrin and dieldrin.
- ortho-substituted congeners of polychlorinated biphenyls.
- planar and non-ortho-substituted congeners of PCBs
- brominated flame-retardants

Results and discussion

The analysed material was a selection of the collected material from 2012 and 2013. The aim was to analyse the main species from the three sites, Vaggatem (Ruskebukta and Tjerebukta), Lake Kuetsjarvi and Skrukkebukta. The main fish species in all the localities analysed were pike, perch and large sparsely-rakered whitefish (LSR whitefish). In addition, also densely-rakered whitefish (DS whitefish) from Vaggatem and brown trout from Skrukkebukta were analysed.

There were some differences in the fish material regarding size of the different species from the different sites (Table 3). In general, pike, perch and LSR whitefish were larger in lake Vaggatem than in lakes Kuetsjarvi and Skrukkebukta. In average the pike, perch and LSR whitefish were smallest in Lake Kuetsjarvi.

For detailed information about this study, see Christensen et al. 2015.

Table 1. Study localities in the Pasvik River.

Lake	Country	Approx. distance from the smelters	Fish species
Vaggatem	Norway	40 km, upstream	pike, perch, SR whitefish, DR whitefish
Kuetsjarvi	Russia	5 km, downstream	pike, perch, SR whitefish
Skrukkebukta	Norway	5 km, downstream	pike,perch, SR whitefish, trout

Table 2. Analysed fish material from lakes Vaggatem, Kuetsjarvi and Skrukkebukta.

Lake	Species	Number of analysed POPs	Number of analysed metals
Vaggatem	pike	5	13
	perch	5	10
	SR whitefish	5	10
	DR whitefish	5	10
Kuetsjarvi	pike	5	5
	perch	5	9
	SR whitefish	5	10
Skrukkebukta	pike	5	5
	perch	5	10
	SR whitefish	5	10
	trout	5	5

Table 3. Summary of weight and length (max, min and std) and average concentrations of ΣPCB, ΣDDT, PBDE, Hg, Ni and Cu of the analysed fish material from Vaggatem, Kuetsjarvi and Skrukkebukta.

Component	**Pike**											
	Vaggatem (n = 10)				**Kuetsjarvi (n = 5)**				**Skrukkebukta (n = 5)**			
	Average	Max	Min	Std	Average	Max	Min	Std	Average	Max	Min	Std
weight (g)	1907	3440	823	738	590	1215	256	372	1335	3697	568	1337
length (cm)	66.7	81.4	49.9	8.79	39.8	50.8	33.0	6.61	51.2	73.5	40.9	13.5
Σ PCB (ng/g ww)	2.57	4.47	1.33	1.17	6.15	7.85	5.18	1.03	4.95	9.73	3.28	2.71
Σ DDT (ng/g ww)	0.304	0.460	0.190	0.112	1.26	1.61	0.960	0.255	0.700	1.58	0.260	0.522
PBDE (ng/kg ww)	25.6	43.4	9.33	14.9	41.0	50.6	29.1	8.51	66.2	120.2	35.4	33.5
Hg (mg/kg ww)	0.274	0.486	0.096	0.105	0.078	0.119	0.051	0.026	0.312	0.851	0.118	0.306
Ni (mg/kg ww)	0.211	0.290	0.180	0.033	0.320	0.410	0.230	0.065	0.372	0.710	0.180	0.205
Cu (mg/kg ww)	0.202	0.250	0.170	0.025	0.312	0.470	0.190	0.118	0.242	0.280	0.160	0.048

Component	**PERCH**											
	Vaggatem (n = 13)				**Kuetsjarvi (n = 9)**				**Skrukkebukta (n = 10)**			
	Average	Max	Min	Std	Average	Max	Min	Std	Average	Max	Min	Std
Weight (g)	311	409	251	49.6	192	440	104	109	251	425	144	113
Length (mm)	28.2	31.0	26.5	1.47	22.4	29.0	19.0	3.34	25.9	32.2	22.0	3.70
Σ PCB (ng/g ww)	0.342	0.680	0.020	0.304	3.95	7.65	0.140	3.50	7.48	13.1	4.97	3.36
Σ DDT (ng/g ww)	0.198	0.280	0.160	0.056	0.503	0.950	0.060	0.374	1.35	2.95	0.850	0.904
PBDE (ng/kg ww)	1.44	2.67	1.00	0.722	16.5	25.0	2.75	11.0	154	482	47.3	184
Hg (mg/kg ww)	0.144	0.21	0.102	0.033	0.068	0.126	0.038	0.027	0.438	1.49	0.076	0.436
Ni (mg/kg ww)	0.229	0.270	0.210	0.022	0.283	0.340	0.220	0.039	0.470	0.670	0.370	0.083
Cu (mg/kg ww)	0.193	0.270	0.130	0.038	0.214	0.260	0.160	0.032	0.151	0.390	0.110	0.085

Component	**LSR WHITEFISH**											
	Vaggatem (n = 10)				**Kuetsjarvi (n = 10)**				**Skrukkebukta (n = 10)**			
	Average	**Max**	**Min**	**Std**	**Average**	**Max**	**Min**	**Std**	**Average**	**Max**	**Min**	**Std**
Weight (g)	1109	1937	523	420	323	981	156	246	381	767	217	171
Length (mm)	43.0	49.8	35.3	4.81	28.2	38.5	24.2	4.38	32.0	40.3	26.7	4.05
Σ PCB (ng/g ww)	0.052	0.140	0.020	0.052	6.69	10.2	4.93	2.39	5.75	13.06	1.94	4.60
Σ DDT (ng/g ww)	0.220	0.330	0.160	0.070	1.69	2.30	0.940	0.6157	1.30	3.38	0.430	1.21
PBDE (ng/kg ww)	1.43	2.80	1.00	0.781	44.2	60.4	25.0	15.2	51.1	83.5	26.9	25.3
Hg (mg/kg ww)	0.036	0.051	0.022	0.009	0.018	0.033	0.011	0.007	0.041	0.055	0.024	0.010
Ni (mg/kg ww)	0.241	0.290	0.190	0.031	0.254	0.330	0.210	0.039	0.297	0.360	0.250	0.033
Cu (mg/kg ww)	0.185	0.270	0.140	0.044	0.300	0.370	0.240	0.045	0.210	0.240	0.190	0.016

Component	**DR WHITEFISH**			
	Vaggatem (n = 10)			
	Average	**Max**	**Min**	**Std**
Weight (g)	143.9	310.0	91.0	65.8
Length (mm)	23.1	29.6	20.3	2.8
Σ PCB (ng/g ww)	0.8	3.0	0.2	1.2
Σ DDT (ng/g ww)	0.10	0.21	0.03	0.09
PBDE (ng/kg ww)	2.58	5.49	1.00	2.07
Hg (mg/kg ww)	0.05	0.09	0.03	0.02
Ni (mg/kg ww)	0.251	0.31	0.17	0.043
Cu (mg/kg ww)	0.184	0.22	0.15	0.025

Component	**TROUT**			
	Skrukkebukta (n = 5)			
	Average	**Max**	**Min**	**Std**
Weight (g)	1544	3657	435	1464
Length (mm)	46.5	67.2	34.0	14.7
Σ PCB (ng/g ww)	10.6	14.9	5.99	3.79
Σ DDT (ng/g ww)	1.99	3.12	0.81	1.079
PBDE (ng/kg ww)	149.3	270.0	1.00	108.9
Hg (mg/kg ww)	0.161	0.273	0.099	0.071
Ni (mg/kg ww)	0.552	0.870	0.430	0.180
Cu (mg/kg ww)	0.148	0.170	0.120	0.022

Mercury

The highest average concentrations of mercury were measured in perch (0.44 mg/kg ww) and pike (0.31 mg/ww) from Skrukkebukta (Figure 1). The highest concentration measured in a single perch from Skrukkebukta was 1.49 mg/kg ww. The average levels of mercury in perch from Skrukkebukta are close to the European limits for allowable levels of mercury in fish (0.5 mg/kg ww). The levels of mercury in Kuetsjarvi were significantly lower in pike, perch and whitefish compared to Vaggatem and Skrukkebukta. However, the levels of mercury in sediments are considerably higher in Lake Kuetsjarvi compared to other sites in the Pasvik River. The reason for this is not clear but is probably both related to smaller fish (Figure 1) in Lake Kuetsjarvi and the fact that the levels of other contaminants are so high that this limits the methylation of mercury in the sediments. The levels of mercury in whitefish are, as assumed, low, compared to the predatory fish species (pike, perch and trout). The levels of mercury in this study are comparable with the results from 2008 (Christensen 2008) but the levels in Skrukkebukta and Vaggatem are higher compared to other lakes in Finnmark (Fjeld et al. 2010, Christensen et al. 2008).

Copper and nickel

The highest average concentration of copper and nickel in muscle tissue was measured in fish from Lake Kuetsjarvi (Figure 2). There was no clear difference between the levels in fish from Skrukkebukta and Vaggatem. The nickel levels in almost all the samples from this study are higher than in the samples from 2008 (Christensen 2008).

Polychlorinated biphenyls (PCBs)

The highest average concentrations of ∑PCB were measured in fish from lakes Kuetsjarvi and Skrukkebukta downstream from Nikel (Figure 3). The levels in Vaggatem were significantly lower for all the analysed fish species compared to lakes Kuetsjarvi and Skrukkebukta. The highest levels were measured in trout (14.9 ng/g ww) from Skrukkebukta. The levels of PCBs in fish from Skrukkebukta from the present study are higher compared to the results from the same fish species in Skrukkebukta in 2008 (Christensen 2008). The reason for this increase is not known.

The levels of PCBs in fish from lakes Kuetsjarvi and Vaggatem are elevated compared to other studies from Northern Norway (Christensen et al. 2008).

The higher levels of PCBs in the analysed samples from fish downstream from Nikel compared to upstream clearly indicate emissions of PCBs from Nikel. The PCBs' source might be related to the activity in the metallurgical smelter or in the Nikel city. PCBs have historically been used as an insulating material in electric equipment, such as transformers and capacitors, and in fluids, lubricants, paints and plasticizers. One possible source is landfills with PCB-containing products that are leaking into the environment.

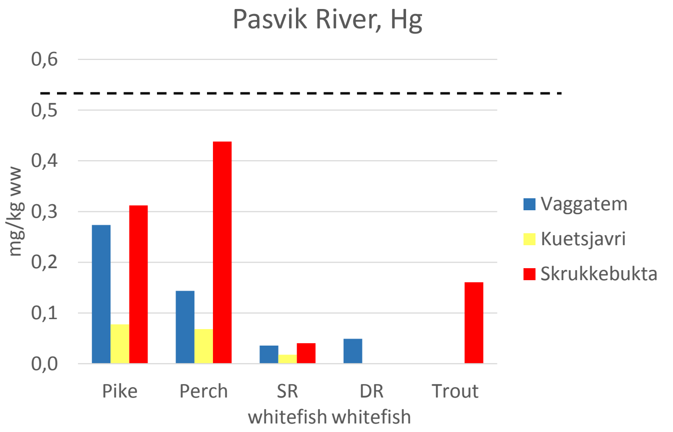
Pesticides

The results for ∑DDT were very similar to the findings for ∑PCB with the highest average concentrations in fish from lakes Kuetsjarvi and Skrukkebukta downstream from Nikel (Figure 4). The levels in Vaggatem were significantly lower for all the analysed fish species compared to lakes Kuetsjarvi and Skrukkebukta. The highest levels were measured in whitefish (3.38 ng/g ww) and trout (3.12 ng/g ww) from Skrukkebukta. The levels of DDT in fish from Skrukkebukta from the present study are higher compared to the results from the same fish species from 2004 and 2008 (Christensen et al. 2007, Christensen 2008). The reason for this increase is not known but might be related to small sample size in the previous studies. The levels of DDT in fish from lakes Kuetsjarvi and Skrukkebukta are considerably higher compared to other studies from Northern Norway, while the levels in Vaggatem are similar (Christensen et al. 2008, Skotvold et al. 1997).

The concentrations of hexachlorobenzene (HCB), hexachlorocyclohexane (HCH) and chlordanes were slightly higher in fish downstream from Nikel but the levels was comparable with other studies from Northern Norway (Christensen et al. 2008).

Polybrominated diphenyl ethers (PBDEs)

The results for PBDEs were different from the results for PCBs and DDT with the highest average concentrations for PBDEs in perch (154 ng/kg ww) and trout (149 ng/kg ww) from Skrukkebukta (Figure 5). The levels in fish from this lake were considerably higher compared to fish from Vaggatem. The levels of PBDE in perch from Skrukkebukta were 10 times higher than in Kuetsjarvi and 100 times higher than in Vaggatem. The concentration of PBDEs in fish from Skrukkebukta in the present study is higher compared to the results from the same fish species in Skrukkebukta in 2004 and 2008 (Christensen et al. 2008, Christensen 2008). The reason for this increase is not known but might be related to small sample size in the previous studies. The levels of PBDE in fish from lakes Skrukkebukta and Kuetsjarvi are higher compared to other studies from Northern Norway (Christensen et al. 2008).



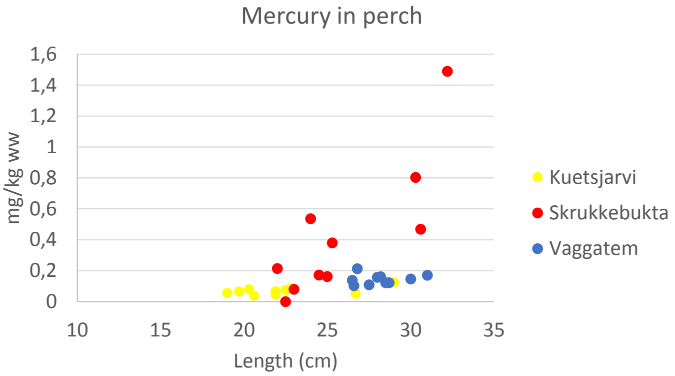


Figure 1. Upper: Levels of mercury (mg/kg ww) in fish tissue from Vaggatem (Ruskebukta and Tjerebukta, blue bars), Lake Kuetsjarvi (yellow bars) and Skrukkebukta (red bars). Lower: Levels of mercury (mg/kg ww) related to fish length (cm) in fish tissue from Vaggatem (Ruskebukta and Tjerebukta, blue dots), Lake Kuetsjarvi (yellow dots) and Skrukkebukta (red dots).

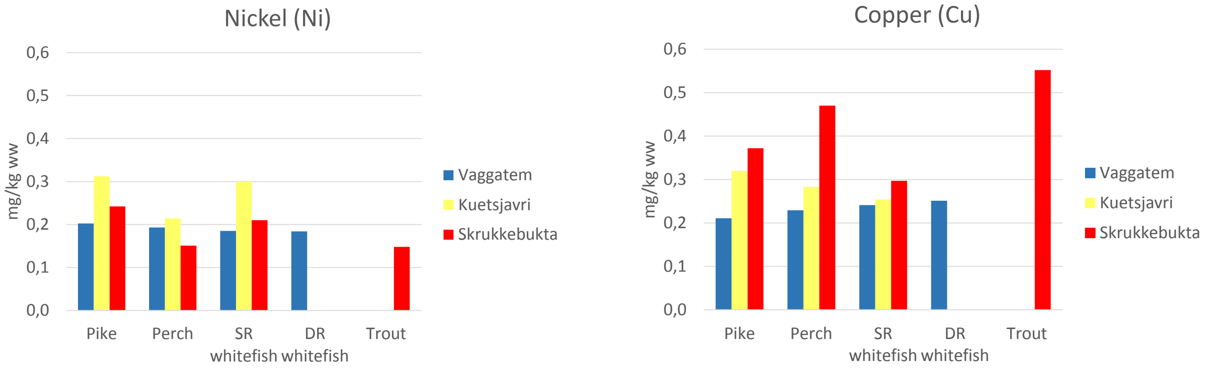


Figure 2. Levels of nickel and copper (mg/kg ww) in fish tissue from Vaggatem (Ruskebukta and Tjerebukta, blue bars), Lake Kuetsjarvi (yellow bars) and Skrukkebukta (red bars).

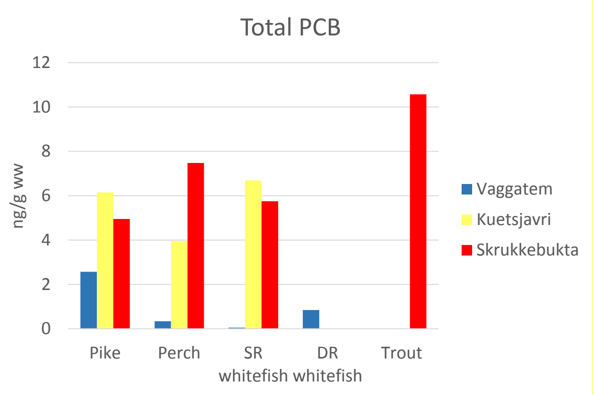


Figure 3. Levels of ∑PCB (ng/g ww) in fish tissue from Vaggatem (Ruskebukta and Tjerebukta, blue bars), Lake Kuetsjarvi (yellow bars) and Skrukkebukta (red bars).

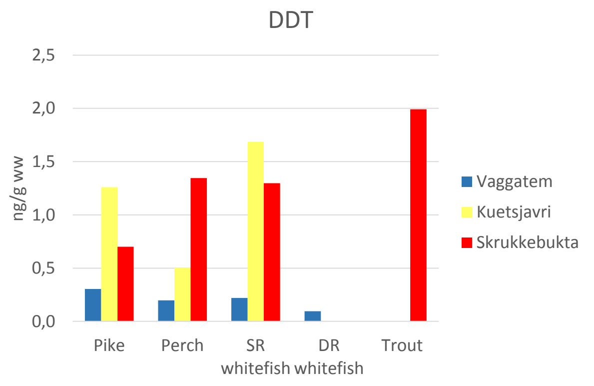


Figure 4. Levels of ∑DDT (ng/g ww) in fish tissue from Vaggatem (Ruskebukta and Tjerebukta, blue bars), Lake Kuetsjarvi (yellow bars) and Skrukkebukta (red bars).

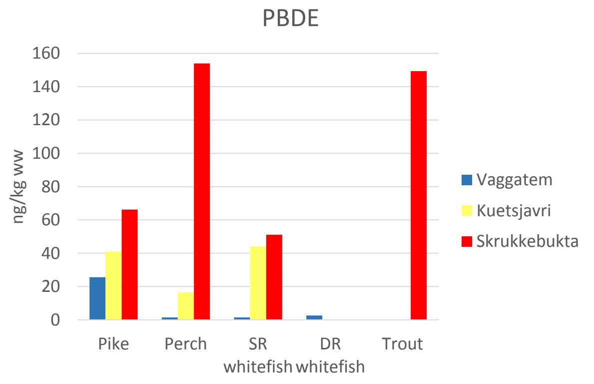


Figure 5. Levels of ∑PBDE (ng/kg ww) in fish tissue from Vaggatem (Ruskebukta and Tjerebukta, blue bars), Lake Kuetsjarvi (yellow bars) and Skrukkebukta (red bars).

Conclusions and recommendations

- The highest levels of all detected legacy POPs were found in fish downstream from the Nikel city in lakes Kuetsjarvi and Skrukkebukta.
- The highest concentrations of mercury were found in perch and pike from Skrukkebukta. The lowest levels were found in fish from Lake Kuetsjarvi.
- The levels of POPs are considered to be elevated in lakes Kuetsjarvi and Skrukkebukta compared to other lakes in the region.
- The higher levels of POPs and mercury in the analysed samples from fish downstream from Nikel compared to upstream clearly indicate emissions of these compounds from Nikel. The source might be related to the activity in the metallurgical smelter or to other activities or landfills in the Nikel city.
- There seems to be an increase in concentrations of mercury, PCB, DDT and PBDE in fish from lakes Kuetsjarvi and Skrukkebukta since the previous studies in 2008.
- It is recommended that POPs and mercury are included in a future adaptive monitoring programme for the Pasvik River.

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Chapter 4: Evaluation and development of the lake monitoring network

Photo: Helén Johanne Andersen

1 Introduction

The fifth activity dealt with the Pasvik area small lake monitoring network, first presented in Stebel et al. (2007). Water quality in the small lakes was last reported in Ylikörkkö et al. (2014). Previously regular monitoring has focused predominantly on chemical quality. For 13 selected lakes, additional biological elements are introduced here: phytoplankton, periphytic diatoms, zoobenthos and fish. Uniform and concurrent sampling between the three countries was intended. Furthermore, to increase understanding of the history of contaminations and paleolimnology of the area, also sediment was analysed.

Sediment sampling, chemical and biological monitoring was conducted in 2012–2013 and the resulting data was used in assessment of variables in terms of their reliability, cost-effectiveness and sensitivity to changes in climate and harmful substances. The Pasvik area small lakes monitoring programme was updated in the light of the new information.

In analysis of chemical and biological state the lakes were grouped into three geographical regions: Vätsäri west of Nikel in Finland, 'southern' south of Nikel in Russia and Jarfjord area in Norway. Lake Sierramjärvi west of the actual Vätsäri area was included in the biological monitoring programme. On Russian side the lakes for biological sampling lie mainly south of the Pasvik River and the Jarfjord area is north-east of Nikel.

1	Lampi 222
2	Harrijärvi
3	Pitkä-Surnujärvi
4	Sierramjärvi
5	Pikkujarvi
6	Shuonijaur
7	Ala-Nautsijarvi
8	Ilja-Nautsijarvi
9	Toartesjaur
10	Virtuovoshjaur
11	Riuttikjaure
12	Kochejaur
13	Holmvatn
14	Gardsjøen
15	Rabbvatn
16	Durvatn
17	Børsevatn
18	Rundvatn

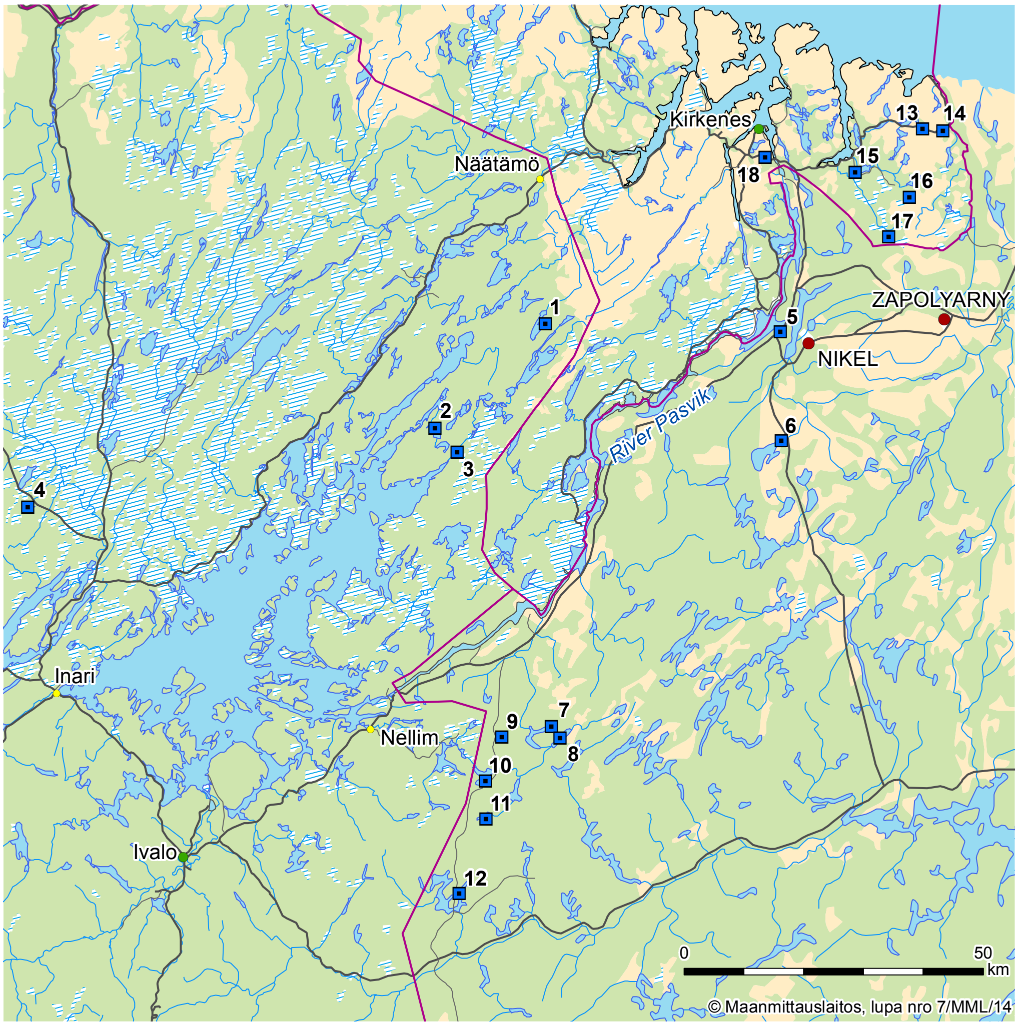

Figure 1. Location of the lakes under study (2012–2013). Lakes 1–4 are Finnish , 5–12 Russian and 13–18 Norwegian.

2 Water quality

JUKKA YLIKÖRKKÖ, GUTTORM N. CHRISTENSEN, HELÉN JOHANNE ANDERSEN

Methods

Water samples were taken between June and September in 2012 and 2013 (Table 1). The analysis of water quality served as a background for the biological variables and sediment analysis. Specific chemical analysis methods for each country are introduced in Puro-Tahvanainen et al. (2008). When available, previous data from the same area was included in analysis for more reliable interpretation. Jarfjord area samples were all from 1 meter. For the other regions, average total nutrient content (tot. N, tot. P), total organic carbon (TOC) content and alkalinity concern 1–10 m water column. Salinity balance and metal concentrations were calculated from samples from the whole water column. Values below the reliable detection limit were calculated as half of the limit value.

Table 1. Lake area (km²), altitude (masl) and number of water samples (N) during the years within the project time frame and previous data used in analysis.

	Lake	km²	masl	Years	N
Finland	Lampi 222	0.2	222	2013	3
				2012–2000	3
	Harrijärvi	1.0	127	2013	2
				2012–2000	2
	Pitkä-Surnujärvi	0.7	126	2013	2
	Sierramjärvi	1.1	254	2013	4
				2012–2000	10
Russia	Pikkujärvi				
	Shuonijaur	11.3	180	2012–2013	6
				2011–2000	4
	Ilja-Nautsijarvi				
	Ala-Nautsijarvi	3.2	133	2012	1
	Toartesjaur	0.6	195	2013	2
	Virtuovoshjaur	1.3	182	2012–2013	6
				2011–2000	3
	Riuttikjaure	0.9	190	2013	1
	Kochejaur	18.5	159	2011–2000	9
Norway	Gardsjøen	0.7	82	2013	1
				2012–1995	3
	Holmvatn	0.8	156	2013	1
				2012–2000	2
	Rabbvatn	0.4	83	2013	1
				2012–2000	2
	Durvatn	0.4	231	2013	1
				2012–1993	2
	Børsevatn	0.4	178	2013	1
	Rundvatn				

Results and discussion

Nitrogen and phosphorus

Total phosphorus was on average below the reliable detection limit (2 µg/l) or up to 3 µg/l in Vätsäri, 3–9 µg/l in the Russian lakes and 3 µg/l in Jarfjord (Figure 1). The southernmost lakes in Russia differed from others with the highest total phosphorus content.

Total nitrogen concentrations varied greatly within the areas (Figure 2). On average nitrogen concentrations were 90–170 µg/l in Vätsäri, 135–208 µg/l in the southern lakes and 94–180 µg/l in the Jarfjord lakes. Southern lakes stood out with slightly higher average nitrogen content.

The observed nutrient concentrations are typical for the lakes, considering their location. The Vätsäri and Jarfjord lakes are the poorest in nutrients. The more southern lakes lie on lower altitude, deeper in the forest zone, where there are thicker, more organic soils, resulting in typically higher trophic status in the lakes. The previous results from the lakes or regions indicate the same nutrient levels (Puro-Tahvanainen et al. 2011, Kashulin et al. 2008).

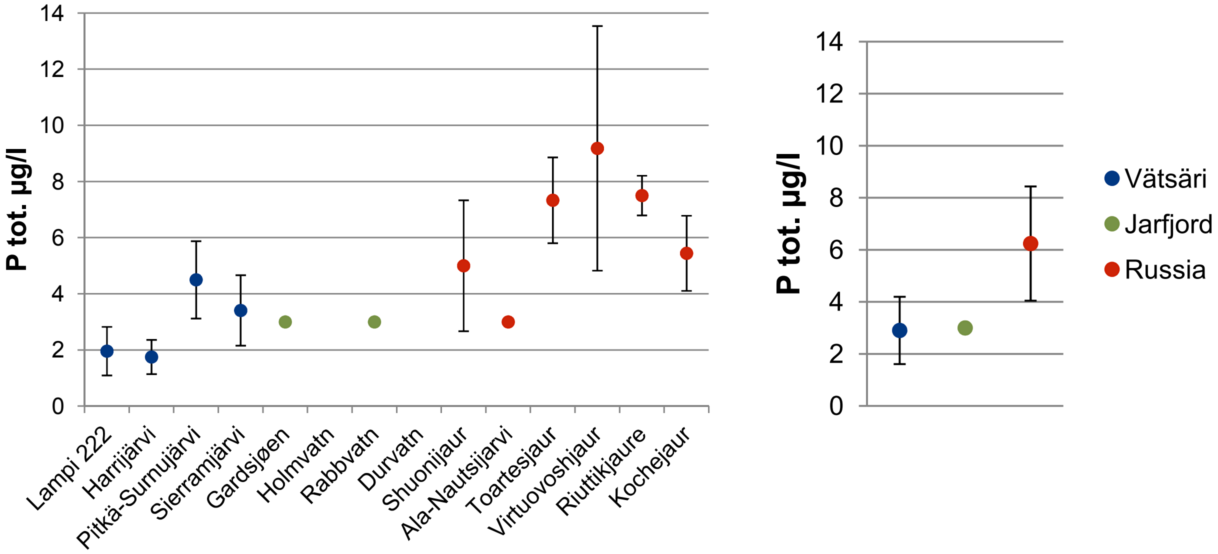

Figure 1. Average total phosphorus concentration and its standard deviation for each lake and area.

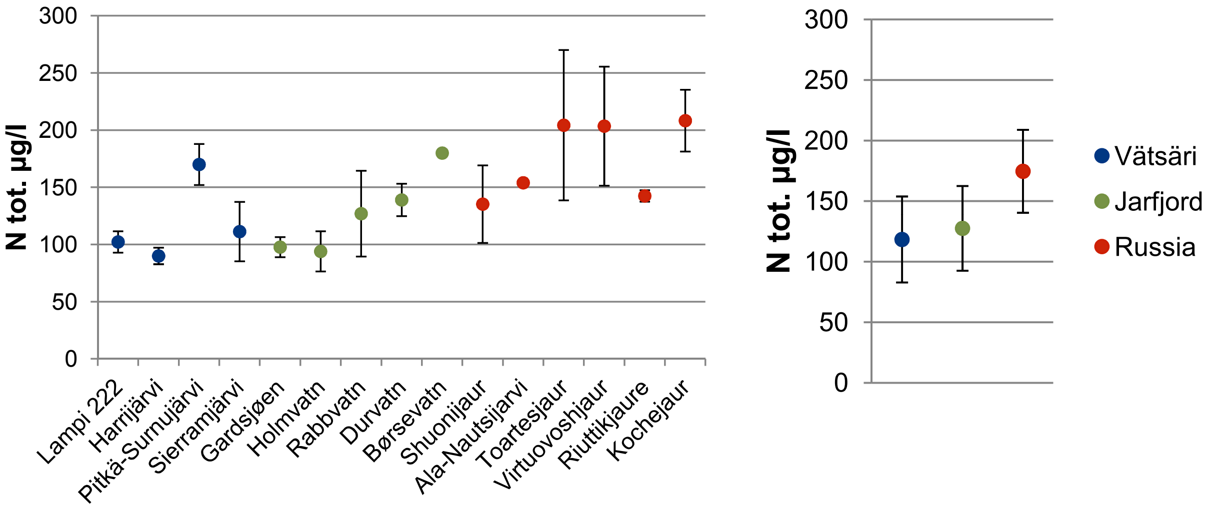

Figure 2. Average total nitrogen concentration and its standard deviation for each lake and area.

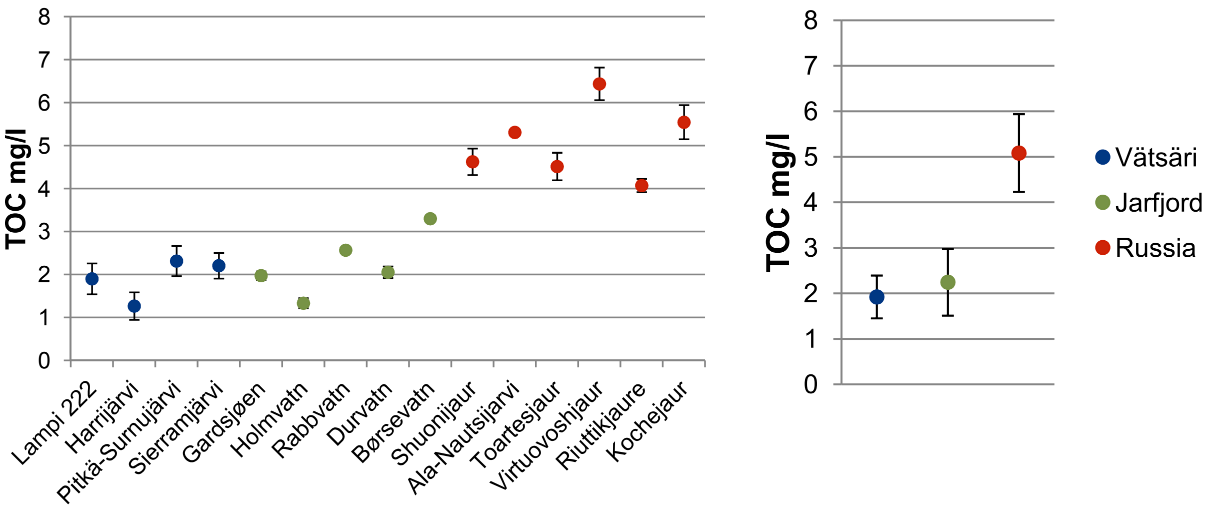

Figure 3. Average concentration and standard deviation of total organic carbon for each lake and area.

Organic matter

Total organic carbon (TOC) followed similar pattern across the regions as nutrients. It was the lowest in the Vätsäri and Jarfjord lakes: on average 1.3–2.3 mg/l and 1.3–3.3 mg/l, respectively (Figure 3). Among the Russian lakes, TOC varied widely from 4.0 to 6.4 on average, depending of the lake. TOC content in the Russian lakes was clearly higher than in the other two regions, and Lake Virtuovoshjaur stands out with the highest measured values (Figure 3).

Alkalinity and pH

Alkalinity average was the lowest 68 μeq/l in Lampi 222 in Vätsäri and the highest 217 μeq/l in Kochejaur, Russia (Figure 4). Generally the lakes in Vätsäri, excluding Sierramjärvi, were the least alkaline. The more southern lakes were slightly more alkaline.

There was little variation in the lake's pH values: the lowest 6.6 were measured in Pitkä-Surnujärvi (Vätsäri) and Holmvatn (Jarfjord) and highest 7.2 in Kochejaur in Russia (Figure 5). On regional level Vätsäri and Jarfjord had average pH just below 6.8, only slightly lower than southern region (Figure 5).

Alkalinity and pH were within the same range as reported earlier for Vätsäri (Puro-Tahvanainen et al. 2011) and some of the Russian lakes (Kashulin et al. 2008). The selected Jarfjord lakes appeared to have more neutral water compared to some other small lakes in the area described in Puro-Tahvanainen et al. (2011). No clear indication of acidification was observed in water samples of the studied lakes. All the regions have rather low alkalinity naturally.

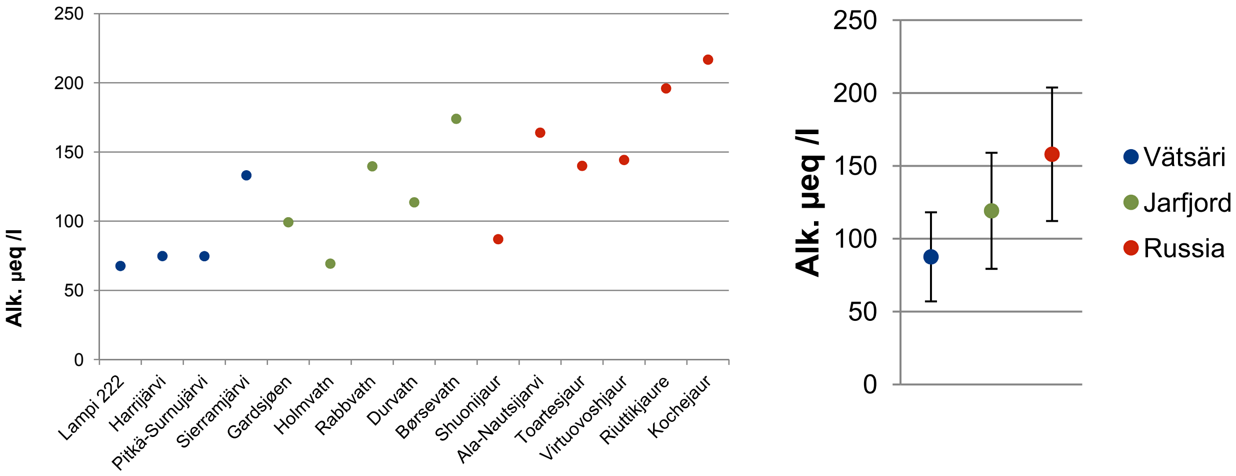

Figure 4. Average alkalinity for each lake and for each area with standard deviation.

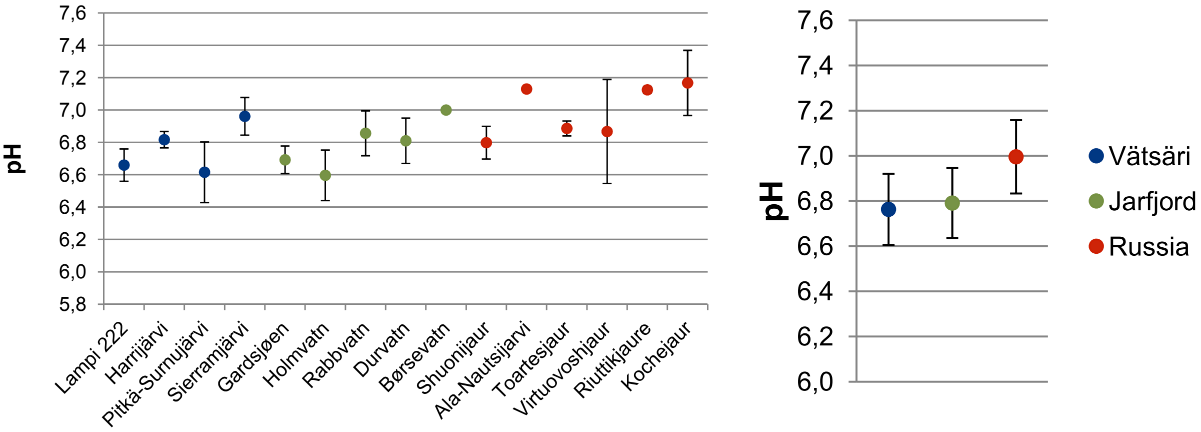

Figure 5. Average pH and its standard deviation for each lake and area.

Salinity balance

Cation content tended to be low in the Vätsäri lakes (Table 2, Figure 6). Lake Shuonijaur, in the vicinity of Nikel, stands out with higher calcium (2.0 mg/l) and magnesium (0.8 mg/l) concentrations. The southern lakes in Russia had mostly higher cation contents and greater variance between the lakes. Jarfjord lakes were roughly on the same level with calcium (Ca), magnesium (Mg) and potassium (K), but sodium (Na) content was much higher.

Average sulphate ranged 1.9–2.1 mg/l in Vätsäri, 1.8–3.3 in the Russian lakes, and on notably higher level 2.1–4.7 in Jarfjord (Figure 7). The greatest difference was between Vätsäri and Jarfjord lake sulphate levels. Chloride content did not differ much between Vätsäri (0.8–1.4 mg/l) and the Russian lakes (0.9–1.7 mg/l) (Figure 8). Chloride was much higher in Jarfjord compared to the other two regions.

Being closest to the ocean, the Jarfjord lakes receive more marine salts, which shows in higher sodium and chloride contents in the area. Sulphate concentrations in Jarfjord are elevated also by sulphur deposition from the Pechenganikel. These ions contribute to salinity, and due to more salts the conductivity is notably higher in the Jarfjord region (Figure 9).

Table 2. Average range and regional means for main cations (mg/l) in the lakes of three regions.

	Ca (mg/l)		Na (mg/l)		Mg (mg/l)		K (mg/l)	
	range	mean	range	mean	range	mean	range	mean
Vätsäri	1.2–2.0	1.4	1.4–1.5	1.5	0.3–0.8	0.5	0.2–0.3	0.2
South	1.8–3.1	2.3	1.2–1.5	1.4	0.9–1.1	0.9	0.4–0.6	0.5
Jarfjord	1.6–2.7	2.0	2.8–3.9	3.3	0.8–1.1	0.9	0.3–0.4	0.4

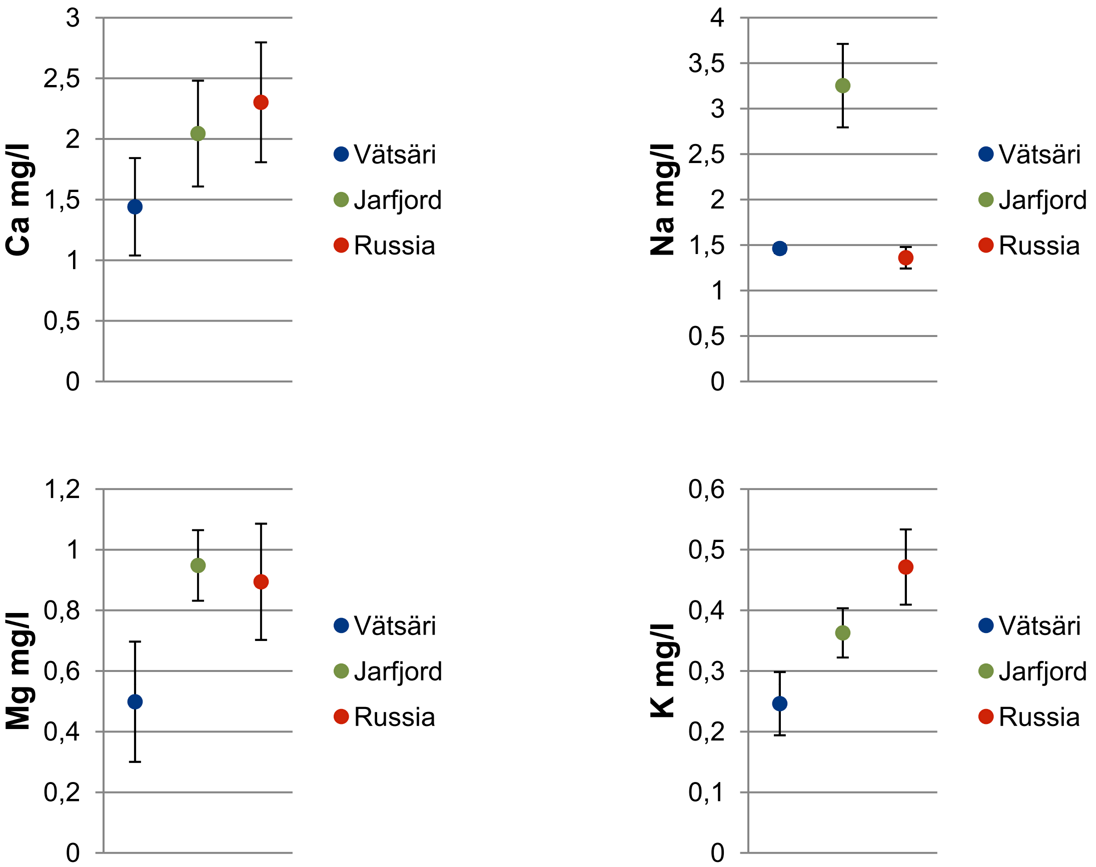

Figure 6. Regional average values and standard deviations for calcium (Ca), sodium (Na), magnesium (Mg) and potassium (K).

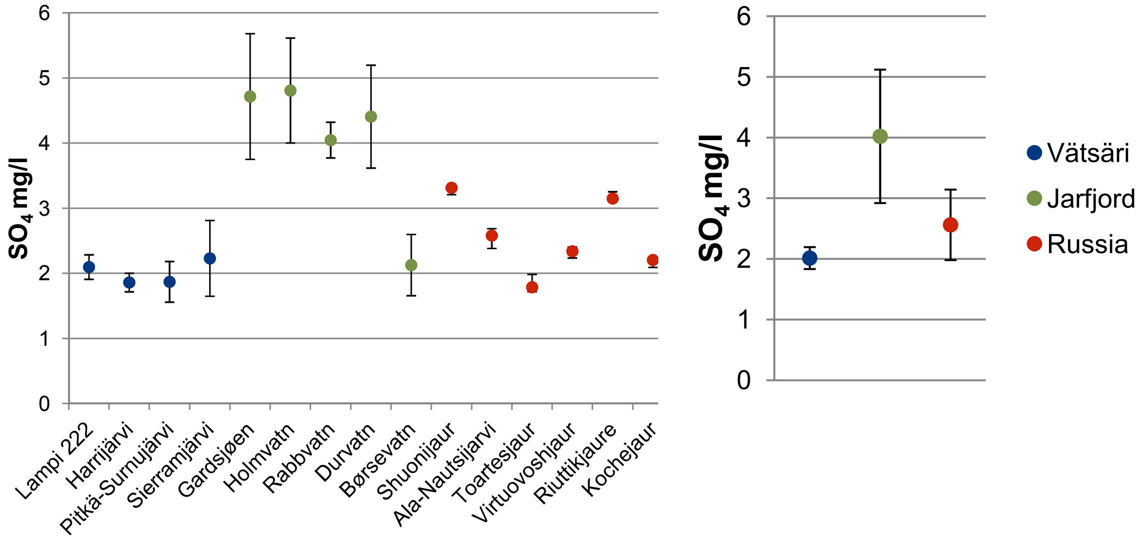

Figure 7. Average concentration and standard deviation of sulphate for each lake and area.

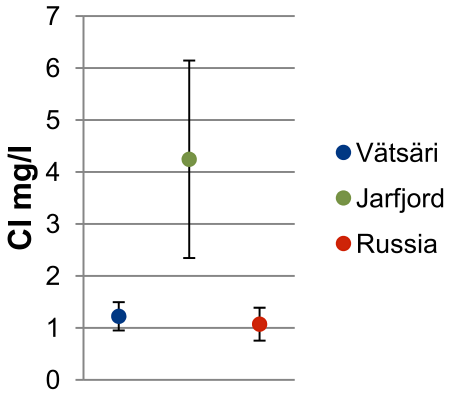

Figure 8. Regional average values and standard deviations for chloride

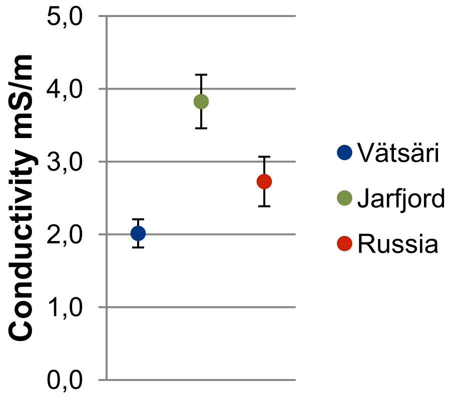

Figure 9. Regional average values and standard deviations for conductivity.

Metals

Average nickel concentration was the lowest in Vätsäri: 0.4–1 µg/l (Figure 10). In the Russian lakes it was roughly on the same level (0.5–1 µg/l), excluding Lake Shuonijaur close to Nikel, where average nickel concentration was 8.8 µg/l. Jarfjord region had the highest nickel concentrations varying (4.9–16.7 µg/l).

Copper concentrations followed a similar pattern (Figure 11). Average copper in Vätsäri and the Russian lakes varied 0.5–1.3 µg/l, excluding Shuonijaur (4.9 µg/l). Also the copper levels were the highest in the Jarfjord lakes: 2.5–9.2 µg/l.

Copper and nickel deposition from the Pechenganikel show in Shuonijaur close to Nikel, and in the Jarfjord lakes directly downwind from the smelter. Both metals have notably elevated concentrations in these lakes. Metal pollution is on the same level in these Jarfjord lakes as reported for other lakes earlier in Puro-Tahvanainen et al. (2011). First time sampled Børsevatn appears to be the most polluted of all the lakes.

Cadmium concentrations were low in all the lakes. In Vätsäri area measured cadmium was below the reliable detection limit 0.01 µg/l and on the same level in Jarfjord lakes, excluding Rabbvatn (0.02 µg/). Average cadmium in the Russian southern lakes was only slightly more: 0.03–0.05 µg/l.

Lead concentrations in Vätsäri lakes varied between 0.02–0.04 µg/l, on average. The other regions had significantly higher lead content: in Jarfjord the corresponding range was 0.02–0.52 µg/l, and in the southern lakes 0.13–0.23 µg/l.

Average iron concentrations varied widely: 4–11 µg/l in Vätsäri, 12–284 µg/l in the southern lakes and 10–49 in Jarfjord. Relative to the average, the measured iron contents varied highly within the sampling period.

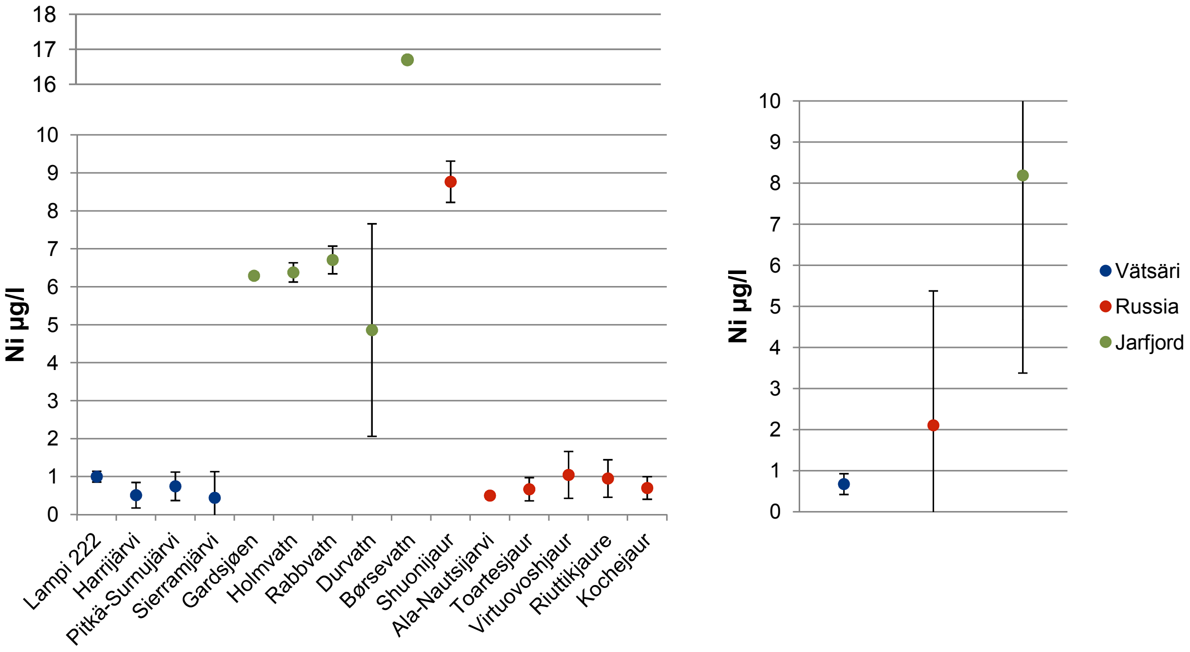

Figure 10. Average nickel concentration and standard deviation for each lake and area.

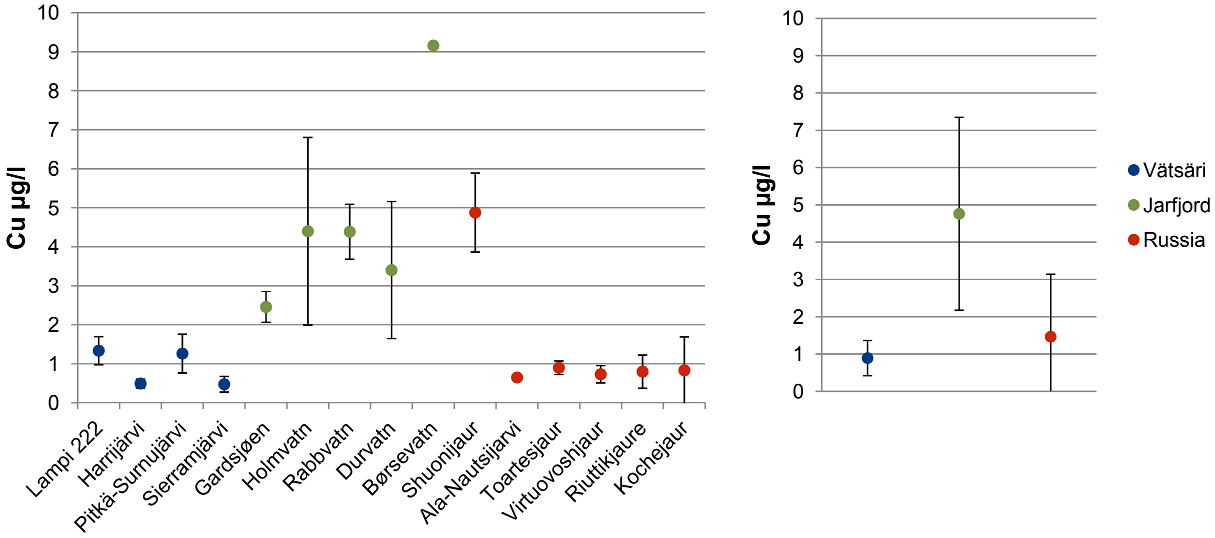

Figure 11. Average copper concentration and standard deviation for each lake and area.

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Jarfjord mountain. Photo:Helén Andersen

Going to sampling in Vätsäri. Photo: Jouni Satokangas

3 Sediments and paleolimnology

VLADIMIR DAUVALTER, DMITRII DENISOV

The border area between Russia, Norway, and Finland is exposed to serious industrial impact. Lake Kuetsjarvi and the lower watercourse of the Pasvik River receive wastewater from smelting and by-processes of the Pechenganikel Company. The river, as well as lakes and rivers of this area not part the Pasvik watercourse, is also exposed to pollution via atmospheric deposition. The major pollutants include sulfur compounds and heavy metals (Ni, Cu, Cd, Cr, Zn, As, Hg, etc.), polycyclic aromatic hydrocarbons (PAHs), and persistant organic pollutants (POPs). Sulfur dioxide emissions cause acidification and pollution of the surface water due to intensification of rock weathering processes. Dust, nitrogen oxides and carbon dioxides are also part of the emissions from the Pechenganikel.

The history of ecosystems' development and the range of natural fluctuation of biological parameters are needed to identify the reasons for various current changes in the Pasvik watercourse. Information about specific past environmental features allows identification of the role of climate change in the ecosystems' transformations, which is especially important in the analysis of industrial impact on the northern areas. In this context the small lakes of glacial origin in the river's catchment area are most suitable for obtaining paleoecological information for reconstruction of the historical dynamics of the environment and climate.

Layer-by-layer analysis of sediments provides data on global and local climate changes, fluxes of various substances into the environment etc., which can be interrelated with absolute time scale. Paleoecological research and restoring of water ecosystems' development history is impossible without correct estimation of sedimentation rate allowing to determine the age of studied sediments. Radionuclides are widely used for determination of sedimentation rate in natural water reservoirs. ^{210}Pb is applicable for studies of contemporary sedimentation rates (from 100 to 150 years) which in turn can be used to estimate the age of sediments. ^{210}Pb-dating is often used for chronological reconstructions of anthropogenic pollution by radionuclides, heavy metals and organochlorides.

Materials and methods

Sediment cores from the deepest areas were sampled from the 16 lakes (Introduction, Figure 1). Heavy metal concentrations of the sediments were analyzed and the level of industrial load on the lakes' ecosystems was determined according to the estimated pollution factor (C_f) for each of the priority heavy metal contaminant (method of Håkanson, 1980). The contamination degree (C_d) of the bottom sediment was determined by the sum of all C_f values for eight main heavy metals in a particular lake.

Three lakes were selected for the study of diatom complexes of bottom sediments (Harrijärvi, Finland, Rabbvatnet, Norway, and Shuonijaur, Russia) (Introduction, Figure 1). The selected lakes are characterized by depths sufficient for formation of uninterrupted sequence of layers of bottom sediments.

Diatom analysis was carried out according to the standard generally accepted method (Zhuze et al. 1949, Davydova 1985, Denisov et al. 2006). All diatom valves were identified, if possible, to intraspecific taxonomic categories (Krammer & Lange-Bertalot 1988–2003). Further analysis included investigation of taxonomic structure of diatom complexes, dynamics of relative abundance (%) of the predominant species and estimation of the total amount of valves in the sediment. Species diversity was estimated according to Shannon-Weaver index (H' bit/ex.). The total amount of valves was counted in each investigated layer (mln. ex./g).

Tolerance analysis in relation to pH was made for the discovered taxa and integral pH value for each layer was calculated using the equation (Moiseenko & Razumovsky 2009): $\text{pH} = \sum ph_i k / \sum k$, where ph_i is the individual numerocal value of each indicator taxon and k is the relative abundance of this taxon.

In relation to pH values the following plankton groups were identified: neutrofilic with developmental optimum at pH 7.0, indifferent capable of developing in a relatively wide range of pH around 7, alkalifilic preferring pH> 7.0, alkalibiont preferring pH 7.6 and above, acidofilic preferring pH< 7.0 and acidobiont developing at relatively low pH 6.4 and below.

Ecological groups of diatoms and their proportions in each sediment layer were analyzed to reconstruct the conditions in each lake. According to preferred habitat phytoplakton was divided into planktic, benthic and plankto-benthic forms. The relation to water salinity (chloride concentration) was also considered: halophob (growth is inhibited by salinity), indifferent (tolerates different salinities), oligohalob (tolerates some salinity), halofilic (growth is stimulated by salinity) and mesohalob (grows in water with medium salinity, for example in brackish water) groups were identified. Last ecological group was formed according to biogeographical association (cosmopolitan, arctic-alpine, boreal, holarctic).

Saprobity index (S) was calculated for each analyzed layer as an indicator of presence of nutrients and also as an indirect indicator of the lakes' trophic status (Sladecek 1967, Barinova et al. 2006). Data of ecology of specific algae taxa, individual saprobity indicators and reaction to pH from the updated database on algae ecology (Barinova et al. 1996, 2006) were used in the analysis.

Results and discussion

Sediments

Lead-based method of sedimentation rate determination

Sediment cores' ages were determined according to ^{210}Pb chronology and the sedimentation rates (Table 1). The average rate of sedimentation in the latest hundred and fifty years in the lakes was fairly stable, within 0.3–0.6 mm/year. The lowest sedimentation rates are typical for the oligotrophic lakes Rabbvatnet, Virtuovoshjaur and Shuonijaur. Rabbvatnet had the longest sediment column and oldest sediment, which allows the study of environmental and climate changes prior to active industry in the catchment area of the Pasvik River.

Background concentrations of elements in bottom sediments

Background heavy metal concentrations are found in the deepest layers of the sediment cores (usually >20 cm) which were formed over two hundred years ago, i.e. before industrial development of North Fennoscandia (Norton et al. 1992, 1996, Rognerud et al. 1993). The background heavy metal concentrations reflect the geochemical peculiarities of the catchment and provide quantitative information of water bodies' pollution degree and help determine anomalies in search of mineral resources (Tenhola & Lummaa 1979).

The maximum background heavy metal concentrations in sediment were found in different lakes: Cu and Hg in Lake Lampi 222, Zn and Cd in Lake Ala-Nautsijarvi, Co in Lake Ilja-Nautsijarvi, Ni in Lake Pikkujarvi, Pb in Lake Holmvatnet, and As in Lake Gardsjøen. Factor analysis was used to identify the factors having the greatest impact on the chemical composition of the lakes' sediment. Analysis confirmed the influence of geochemical composition of bedrock on the formation of the sediment background layers' chemical composition.

Cluster analysis identified three groups of water bodies: the first group includes the Finnish lakes (Pitkä-Surnujärvi and Sierramjärvi) and a similar Russian lake Ilja-Nautsijarvi, the second group includes the Russian lakes Shuonijaur and Virtuovoshjaur and the Norwegian lake Rabbvatnet, and the third group includes the Russian lakes Toartesjaur, Kochejaur and Riuttikjaure. The lakes in the groups are believed to be similar in terms of the natural conditions of sediment chemistry formation. A large number of lakes not belonging to any of the three groups shows the large diversity of these conditions, which is reflected by a considerable range of background concentrations in

Table 1. The lengths of sediment cores, sedimentation rates and the ages of the bottom sediments of some lakes.

Lake	core length (cm)	sedimentation rate (mm/year)	Approx. age of bottom sediment (years)
Rabbvatnet	44	0.65	687
Harrijarvi	30	1.3	240
Shuonijaur	14	0.7	210
Ala-Nautsijarvi	17,5	1.6	106
Virtuovoshjaur	18	0.7	257
Kochejaur	16	1.5	106

sediments. It was also established that the average background concentrations in sediments are similar to average concentrations of chemical elements in the crust of earth (percentage abundance) and in the rocks and soils.

Changes of elements' concentration in sediments over time

Increased concentrations and sedimentation rates of Ni, Cu, and Co in the sediments dated back to 20th century were observed in the Norwegian lakes (Norton et al. 1992, 1996, Rognerud et al. 1993). Higher concentrations of Pb in the sediments, generally, are not related to the Pechenganikel's emissions since they date back to the time too early to be related to any industrial activities in this area. Ni, Cu, Co and other heavy metals enter the atmosphere from the Pechenganikel but growth of the concentrations and accumulation rates dates back one decade prior to the beginning of the industrial activities.

Vertical distribution of heavy metal concentrations in the sediments was studyied to find out the anthropogenic load intensity of lakes located at different distances from smelters. The most polluted with Cu and Ni are the Russian lakes (Pikkujarvi, Shuonijaur), located close to the emission source as well as all Norwegian lakes of Jarfjord, exposed to intensive atmospheric pollution of the integrated plant (Figure1). Growth of Cu and Ni content in the surface layers of sediment was also recorded in lakes Ilja-Nautsijarvi and Virtuovoshjaur, located 80 and 90 km from the smelters respectively.

Increasing Cu and Ni content in sediment cores was recorded mainly near the integrated plant (Shuonijaur). In the Norwegian lake Rabbvatnet the first noticeable growth of Cu and Ni content was observed in the middle of the 17th century, which is probably associated with the beginning of the industrial revolution in Europe and increase of heavy metal emissions into the environment and their air transport in the direction of the Arctic (Figure 2).

The next noticeable growth of Cu content was observed in the 19th century, which may be attributed to the industrialization. Since then the Cu concentration has kept growing and the intensive growth of Cu content is associated with the beginning of copper and nickel production in the Pechenga area. In the last two decades the production dropped after the collapse of the USSR, but the concentrations of Cu in the sediment of Lake Rabbvatnet (as well as in Russian lakes Shuonijaur and Virtuovoshjaur) have only been growing, which can be explained by heavy metal accumulation in the catchment of the lakes (Dauvalter et al. 2012).

No increase of Zn concentrations have been noted in the surface layers except for Lake Pikkujarvi. In the majority of the lakes there is a tendency of Zn decrease.Chalcophile high-toxic heavy metals Cd and Pb have been considered a global pollution element by many ecologists in the last decades (for example Pacyna & Pacyna 2001). Significant growth of Cd and Pb concentrations in the dated sediment was recorded in the beginning of the 20th century associated with the intensive industrial development after World War II, metallurgical production at the Pechenganikel and the growing use of leaded petrol in case of Pb. In the majority of the lakes there is a tendency to both Cd and Pb content growth towards the sediment surface, and at the same time a decrease occurs in the very top layer in about half of the lakes. Cd and Pb content reduction in the surface layer dated to one-two decades may be associated with the the collapse of the USSR or with the reduction of global emission of Cd over the last decades. Possibly the main reason for decrease of Pb in the latest decades is the prohibition of leaded petrol. However, in some lakes maximum heavy metal contents are noted in the surface layer.

In majority of the lakes growth of chalcophile high-toxic As and Hg content is noted towards their surface. Especially noticeable growth of As and Hg occurred in the middle of the latest century associated with the industrial development after World War II, growing use of As and coal high in Hg in metallurgy including at the Pechenganikel Company. In the very top layer of sediment (1–3 cm) of a few lakes a reduction of As and Hg occurs, which is suggestive of the consequences of the global emission reduction. The reduction may be associated with the collapse of the USSR and reductions of the global emissions in the latest decades due to use prohibitions and increase in recycling.

Growth of Co concentrations was found in the surface layers of all Norwegian lakes, Russian lakes located close to Pechenganikel (Pikkujarvi and Shuonijaur) and Finnish Lake Lampi 222, which is the closest to the Pechenganikel among all the Finnish lakes. Other studied lakes show the tendency of Co content reduction towards the sediment surface. Co concentrations reached maximum values in the beginning of the 21st century and then they drop towards the sediment surface probably due to the reduction of production of heavy metals.

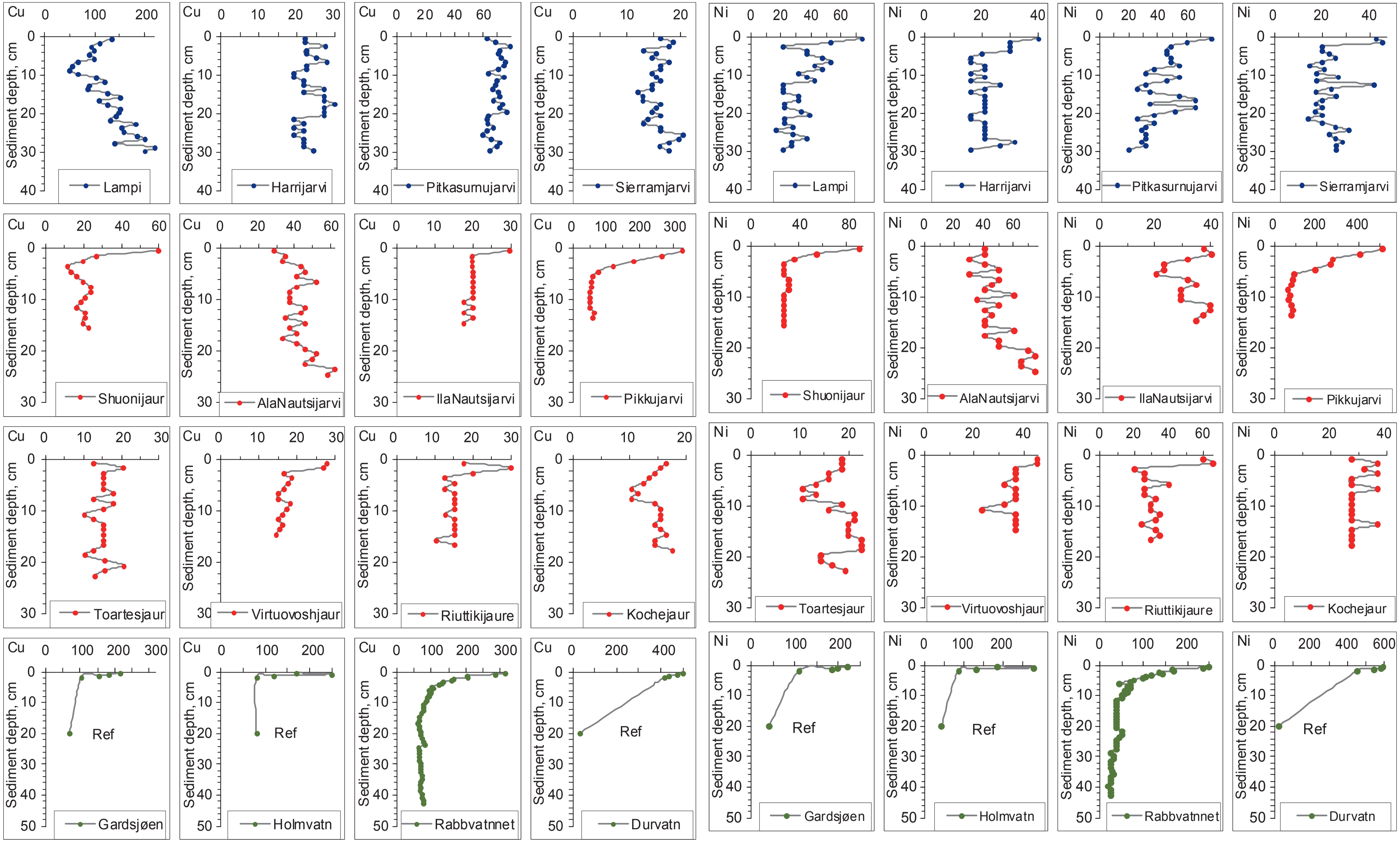


Figure 1. Vertical distribution of Cu and Ni concentrations (μg/g of dry weight) in the sediments of the studied lakes. In this and in further figures the Finnish lakes are colored in blue, the Russian lakes in red and the Norwegian lakes in green.

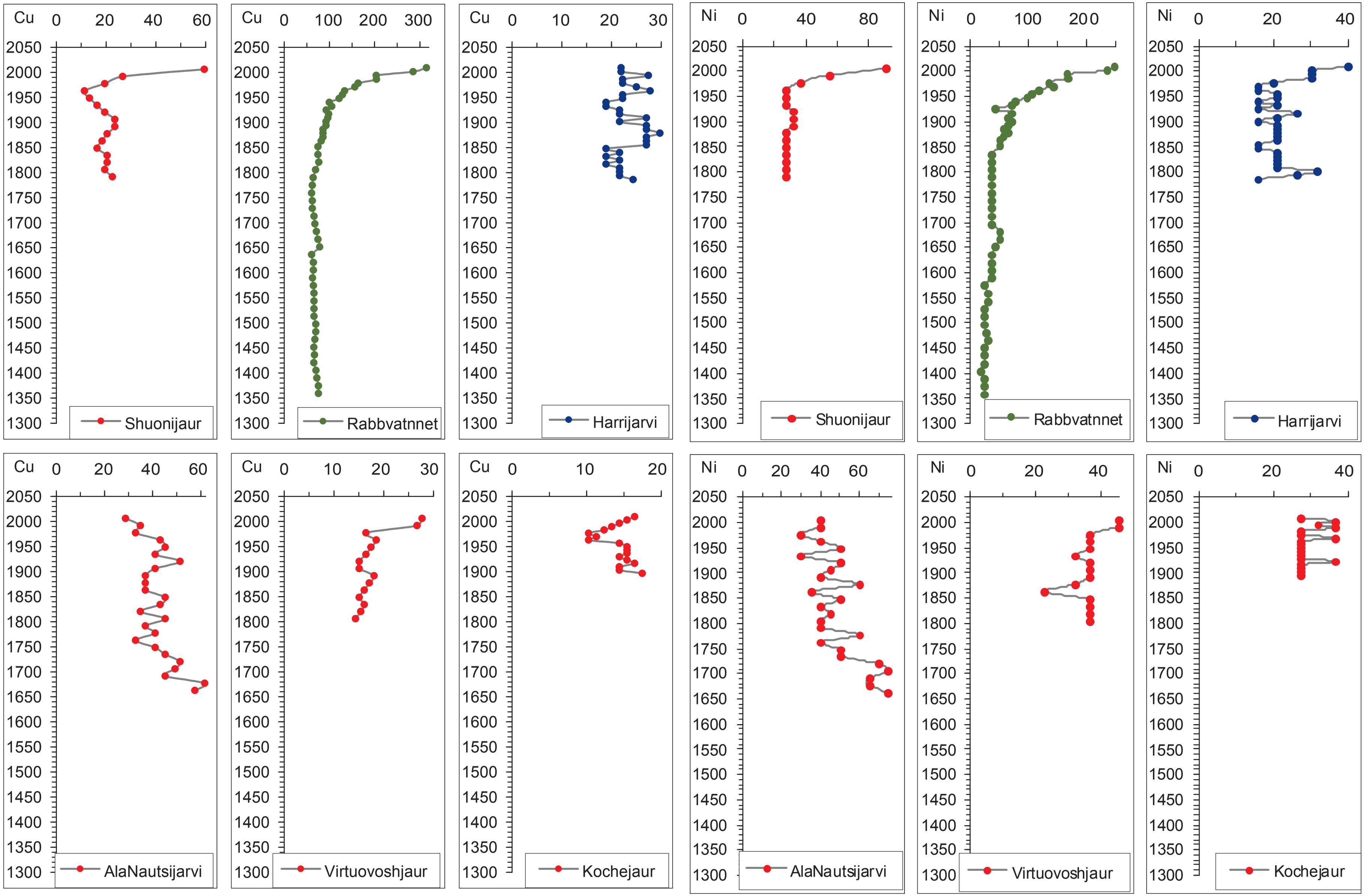


Figure 2. Vertical distribution of Cu and Ni concentrations (μg/g of dry weight) in the dated sediment of the studied lakes.

Territorial distribution of elements in the surface of the bottom sediments

Long-term anthropogenic load on the catchments of the lakes has led to alteration of natural conditions of the formation of sediment chemical composition and to growth of heavy metal concentrations in the surface sediment layers. The main reason for high concentrations of heavy metals (Ni, Cu, Co) in the surface layers are the atmospheric emissions from the smelters of the Pechenganikel especially near the integrated plant. The majority of heavy metals from the emissions and waste water are tied to and stay in the sediments.

The most polluted lakes are located in the immediate proximity of the smelters and in Jarfjord inside 20–40 km zone from the Pechenganikel. The highest concentrations of Ni, Cu and Co, exceeding background values by 5–25 times, were noted in the lakes at a distance up to 40 –50 km from the integrated plant (Figure 3). Further away at 60–100 km the reduction of concentrations (first of all of Ni and Cu) is noted. A similar pattern is observed in the distribution of Cd, As, and Hg: the same area up to 50 km is polluted most intensively (concentrations exceed background values by 2–8 times) and at distance of >50 km the concentrations are reduced to 1–3 times of the background values. However, pollution with chalcophile elements (especially Pb) is quite serious there.

The contents of Zn in the sediments exceed the background values insignificantly (up to 1.4 times in Lake Pikkujarvi); therefore this element can be regarded as non-polluting. In the distribution of Pb no increasing tendency in the surface layers was noted approaching the Pechenganikel (the largest Pb concentrations were recorded in the Norwegian territory), which testifies that the Pechenganikel is not the major source of Pb pollution.

A close relationship between the content of alkaline and alkaline-earth metals (first of all K, Na and Mg) in the sediment surface and the distance from the source of pollution was also noted: concentrations grow clos to the Pechenganikel. This means that along with the emissions of heavy metals, the integrated plant also releases into the atmosphere alkaline and alkaline-earth metals, which are in the ore-hosting and stripping rocks containing minerals with large content of these elements.

Factor analysis confirmed the contribution of the Pechenganikel in the emissions of Cu, Ni, chalcophile elements and alkaline and alkaline-earth metals that greatly influence the chemical composition of the sediments. Chalcophile elements are delivered also via atmospheric transboundary transport. Physical and chemical conditions of the lakes also influence the sediments as does the water level in lakes above sea level.

Cluster analysis clearly identified three groups of water bodies: lakes Harrijärvi, Ilja-Nautsijarvi and Virtuovoshjaur with relatively small contents of priority pollutant heavy metals (Ni, Cu), lakes Shuonijaur and Rabbvatnet with relatively high concentrations of Ni and Cu and other heavy metals and Russian lakes Toartesjaur, Riuttikjaure and Kochejaur, located close to each other and far from the Pechenganikel integrated plant (>80 km) and characterized by relatively small contents of Ni and Cu as well as other heavy metals, except for Pb and Hg in Lake Riuttikjaure. Probably these clusters are similar by natural and anthropogenic conditions of the sediments' chemical composition formation. The unclustered lakes suggest a great variety of these conditions, which in itself reflects the wide range of the elements' contents in the sediment surface of the studied lakes.

Factor and degree of contamination

To assess the geoecological condition of the surface waters the factor and degree of contamination were determined with the method of Håkanson (1980). The contamination factor (C_f^i) was calculated as the quotient by divisiding the element (or compound) concentration in the surface 1 centimeter layer by the background value. The contamination degree (C_d) was determined as the sum of the pollution factors for all eight investigated pollution elements.

The following classification of contamination factor was used: $C_f^i<1$: low, $1\leq C_f^i<3$: moderate, $3\leq C_f^i<6$: significant, $C_f^i\geq 6$: high. In characterizing the contamination degree the classification was based on the sum of the contamination factors for 8 elements (Ni, Cu, Co, Zn, Cd, Pb, As, Hg): $C_d<8$: low, $8\leq C_d<16$: moderate, $16\leq C_d<32$: significant, $C_d\geq 32$: high pollution degree, testifying of serious pollution (Håkanson 1980).

Very high values of C_d were noted in Norwegian lakes at a distance ≤40 km from the pollution sources, and significant values at ≤60 km. The lakes located to the north-west from the Pechenganikel (prevailing wind direction) have larger C_d values. The largest values of the pollution factor (C_f) were noted for Ni and Cu (27 and 16 respectively) in Norwegian Lake Durvatn 30 km from the integrated plant. The largest value of the pollution factor for Co (4.5: significant) was noted in the Norwegian Lake Holmvatnet. The largest

C_f value for Cd (3.1 – 'significant') was noted in Lake Durvatn. The largest C_f values for Pb were also noted in Norwegian lakes Rabbvatnet and Durvatn (14.3 and 13.0, respectively). Maximum C_f values for As and Hg were recorded in lakes Sierramjärvi and Durvatn, respectively (9.6 and 8.3). The pollution factors for Pb, As and Hg refer to high degree of pollution. In general the high pollution factors for Ni and Cu are observed near the Pechenganikel smelters. Chalcophile Pb, As and Hg are also recorded at a significant distance from the smelters, which confirms the conclusions regarding the global nature of pollution with these high-toxic elements.

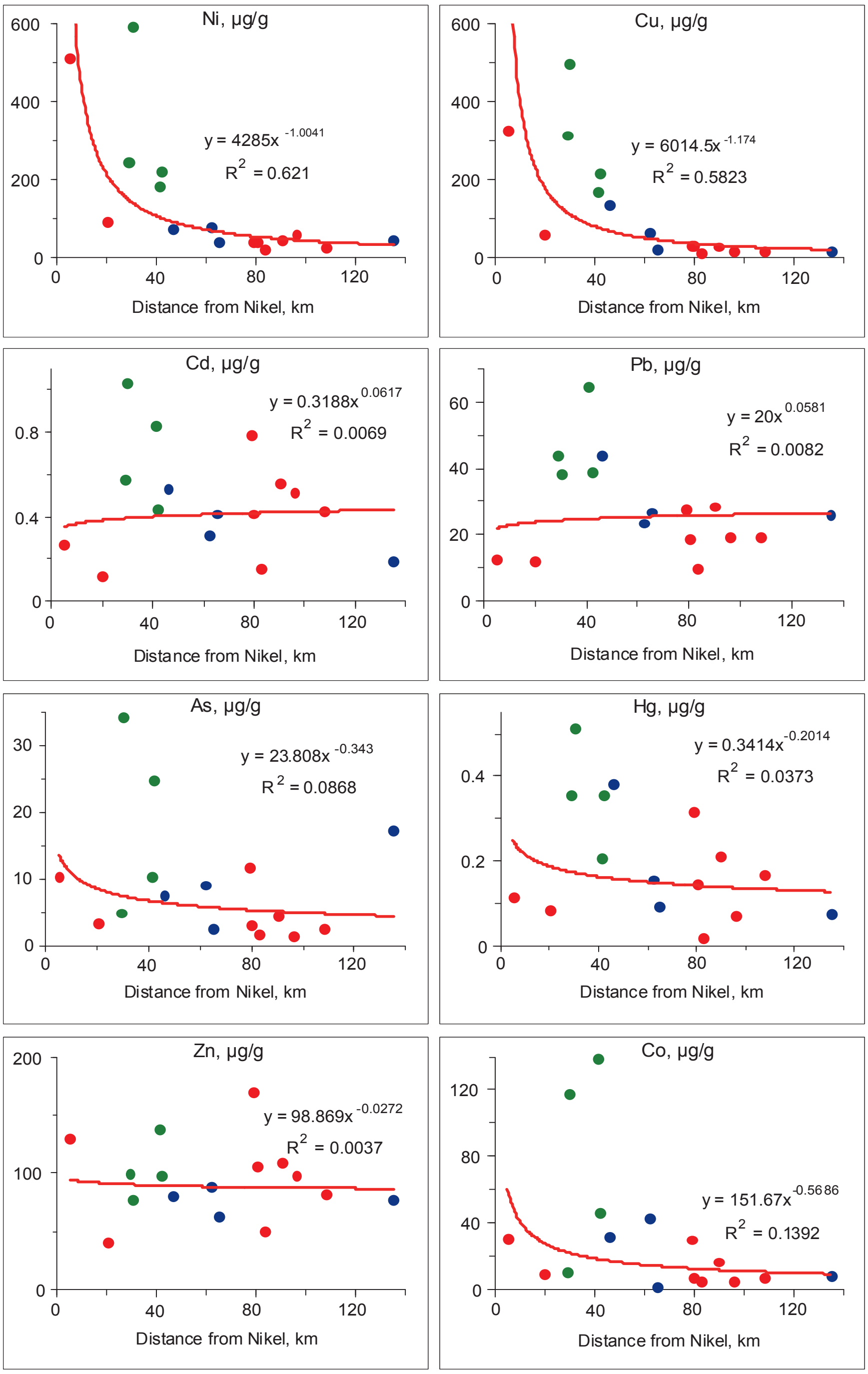
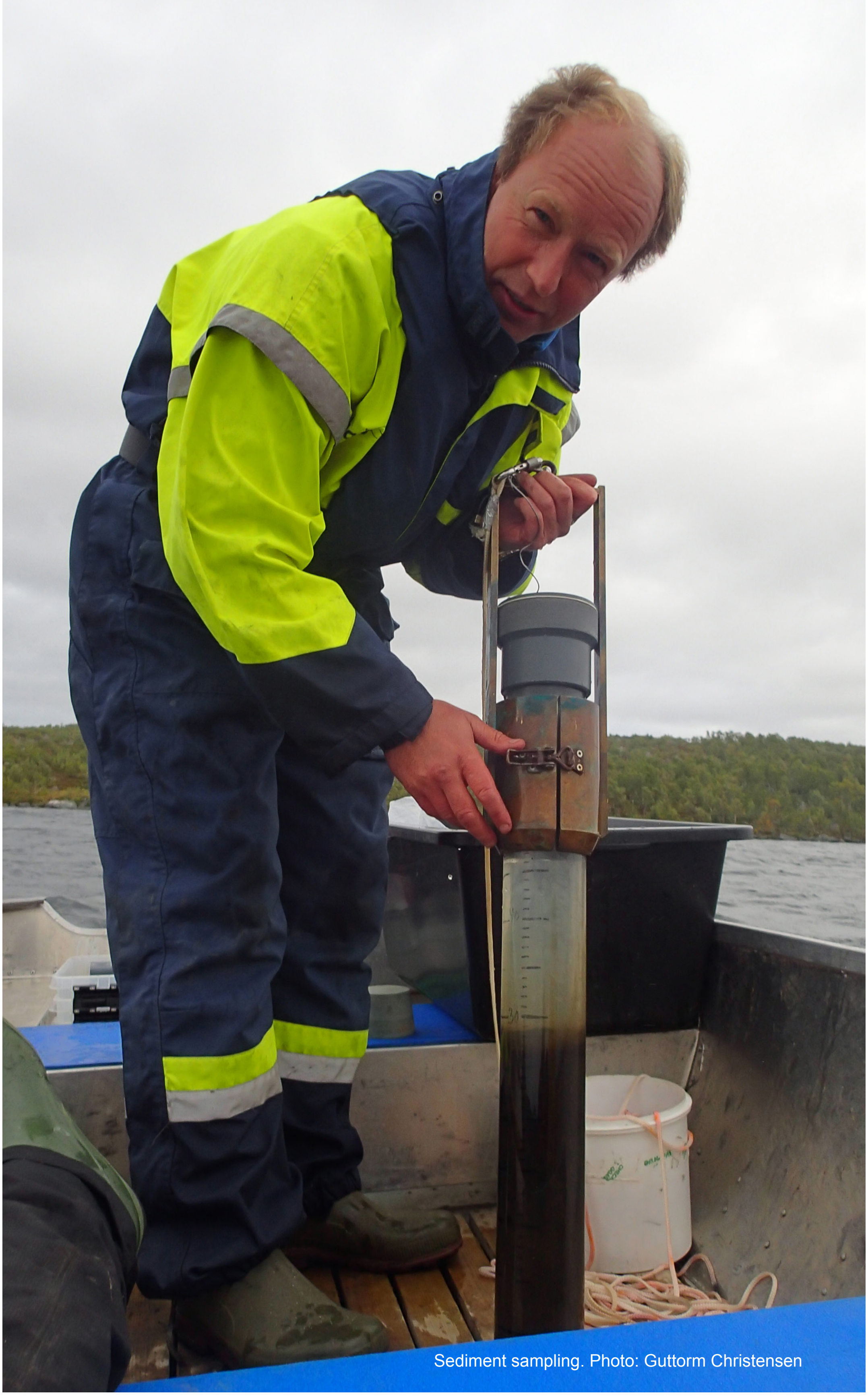


Figure 3. Distribution of the concentrations of key pollution elements (µg/g) in the surface layer (0–1 cm) of the sediment of the studiedlakes depending on the distance from the Pechenganikel integrated plant.



Sediment sampling. Photo: Guttorm Christensen

Paleolimnology

Lake Shuonijaur

In Lake Shuonijaur the diatom complexes in the top layer of sediments (interval 0.5–1 cm) and in the bottom part of the column (13–14 cm) were analyzed. Top layer reflects the present-day status of the lake ecosystem and the bottom layer the status before the intensive industrial transformations (ca. 200 years ago). Lake Shuonijaur is a subarctic lake with low salinity and oligotrophic status. Diatom periphyton is found on the numerous shallow-water areas on littoral rocks and rocky bottom down to 2.5–3 m depth, which illustrates high transparency of the water.

In the present-day plankton the typical species are *Aulacoseira alpigena* (Grun.) Kramm., *A. distans* (Ehrb.) Simons., *Cyclotella schumannii* (Grun.) Håk., *C. rossii* Håk. and *Tabellaria flocculosa* (Roth) Kütz and the same diatoms were found in the top layer. In the bottom layer the same species are complemented by *Cyclotella michiganiana* Skvortzov 1937, *C. bodanica var. lemanica* (O. Müll. ex Schröter) Bachm. and *Pseudostaurosira brevistriata* (Grun.) D.M. Williams & Round. The presence of *P. brevistriata* is a sign of previously more favorable trophic conditions for algae development. The ratios between the biogeographic groups have not changed much over the latest 200 years. The increase of the boreal and holarctic species may be regarded as an indirect indicator of a certain climate change towards warming (Figure 5d); at the same time the portion of arctic-alpine species remains the same.

The present typical subarctic conditions are similar to those that existed 200 years ago and no radical changes have taken place in the lake over this period. A certain increase of the total abundance of diatoms in the modern sediments along with a decrease of the species diversity was observed and it may have resulted from climate change toward warming. The modern conditions are also characterized by lower values of pH and saprobity (Figure 4). The decrease in saprobity index is a consequence of a certain shift of the lake's trophic status towards oligotrophy.

There have been no significant changes in ecological conditions (Figure 5). The proportions of diatoms tolerating different pH-values have not changed except for some decrease of the alkalifilic diatoms. Salinity also remained at the same level and the halophobs and oligohalob-indifferents dominate, which is typical of low-mineralized waters. The water level and volume have not changed significantly as the proportions of planktic forms have remained at the same level. Decrease in the amount of plankto-benthic diatoms along with increase of benthic diatoms may be a sign of changes in the shoreline or development of new type of bottom and substrate, which supports the development of richer benthic communities.

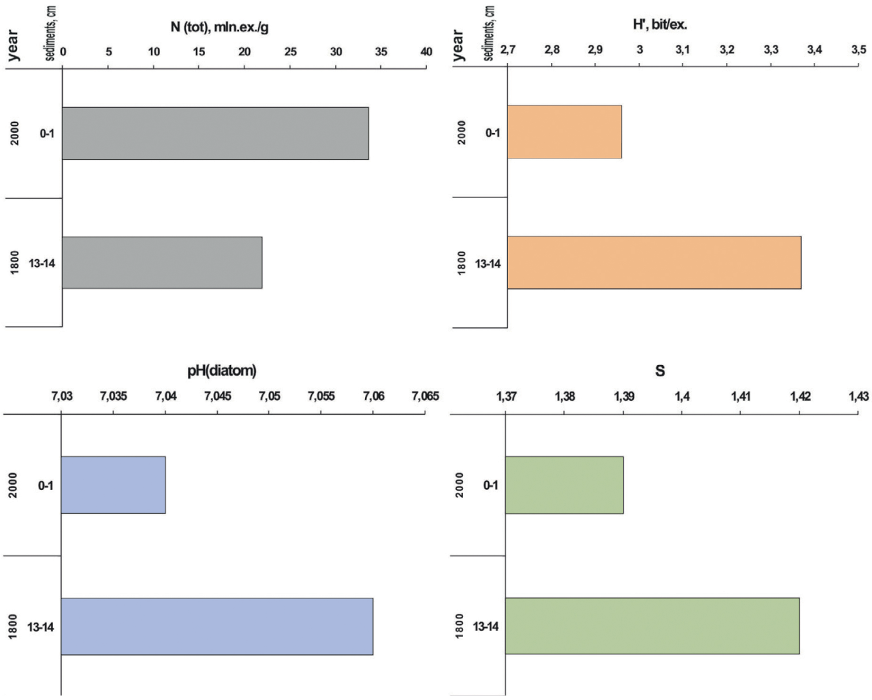


Figure 4. Diatom complexes of Lake Shuonijaur: total abundance (N(tot), mln.ex./g), species diversity (H', bit/ex.), pH recontructed from diatoms (pH(diatom)) and saprobe index (S).

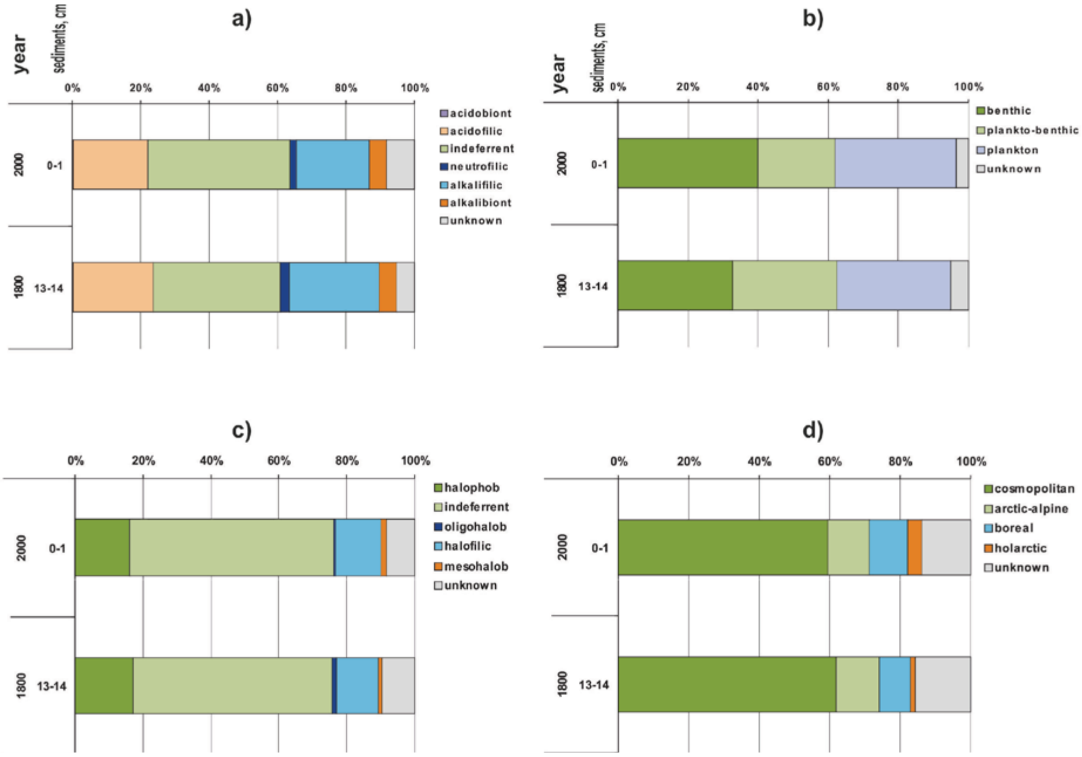


Figure 5. Ecological characteristics of the diatom complexes in Lake Shuonijaur: a) pH-tolerance groups; b) habitat groups; c) salinity groups; d) biogeographic groups.

Lake Harrijärvi

In Lake Harrijärvi the top layer of sediments (interval 0–1 cm) and different parts of the column (intervals 5–6, 11–12, 15–16, 18–19 and 29–30 cm), which have formed in different periods, were analyzed. The age of bottom sediments was 240 years. Lake Harrijarvi is a typical subarctic lake with low salinity and an oligotrophic status

Brachysira brebissonii Ross, *B. vitrea* (Grun.) Rossin Hartley and *Frustulia saxonica* Rabenh form a large proportion of the present-day periphyton. Typical species in the top sediment layers were the same supplemented with *Cyclotella comensis* Grunow in van Heurck 1882. In the older layers the diatom complexes also included *C. kuetzingiana* Thwaites and *A. alpigena*. No dramatic differences were found in the species composition for the different periods.

Total abundance (N) increases gradually from the lower sediment layers and reaches the maximal values in the sediment layer 15–16 cm, which is 130 years old (Figure 6). Benthic species preferring pH<7.0 were especially abundant then as well as some planktic and the plankto-benthic species. This is likely to be linked with pH decrease due to acidification with humic acids from the catchment. Change of environmental conditions early in the 19th century due to climate warming is confirmed by the dynamics of the proportions of biogeographic groups of diatoms as some reduction of the arctic-alpine portion along with increase of boreal forms occurred. Early in the 20th century change of climate during transition from Little Ice Age to warming led to growth of pH and some increase of water volume in the lake, confirmed by the reduction of benthic diatoms. The maximum value of the saprobity index (1.41) is the evidence of temperature rise in this period.

From the beginning of the 20th century the general abundance of diatoms reduced (Figure 7). Probably this was primarily a result of pollution by the emissions from the Pechenganikel. Deposition of acidifying compounds in the catchment area resulted in pH reduction and transformation of diatom communities. At present the diatom complexes are characterized by some increase of total abundance, species diversity and pH compared to the middle of the 20th century (Figure 6) which is probably a consequence of some reduction of the emissions from the Pechenganikel. The saprobity index also testifies of more favorable conditions for algae development.

There have been no fundamental changes of diatom complexes (Figure 7). Reduction of the proportion of acidobionts and increase of alkalifilic diatoms was noted at the turn of the 20th century as a result of warming and increasing quantity of water in the lake. Increased water quantity and water level also caused some reduction of benthic forms, which otherwise dominated throughout the times due to shallow depths and high transparency. Salinity practically has not changed during the study period: halophobs, oligohalobs and indifferents form a significant portion of diatom complexes (up to 40 %), which is characteristic of subarctic lakes.

Present day diatom complexes from the top layers of sediments are evidence of the reduction of pollution. No obvious consequences of the current climate warming were detected. Warming of early 20th century was more significant for the ecosystem of Lake Harrijarvi.

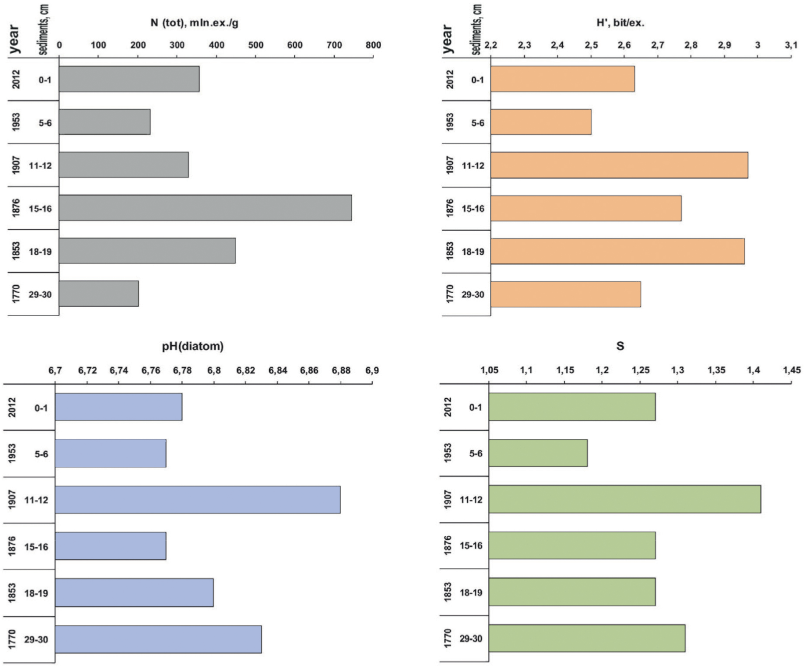


Figure 6. Diatom complexes of Lake Harrijarvi: total abundance (N(tot), mln.ex./g), species diversity (H', bit/ex.), pH recontructed from diatoms (pH(diatom)) and saprobe index (S).

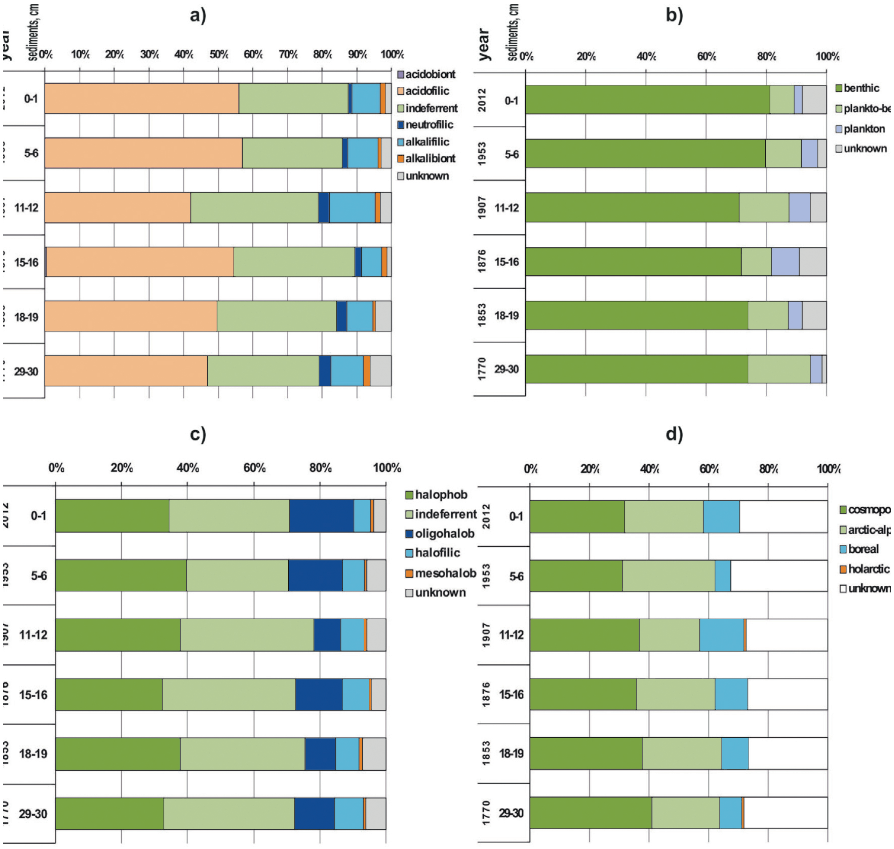


Figure 7. Ecological characteristics of the diatom complexes in Lake Harrijarvi: a) pH-tolerance groups; b) habitat groups; c) salinity groups; d) biogeographic groups.

Lake Rabbvatnet

In Lake Rabbvatnet the diatom complexes were analyzed in the top layer of sediments (interval 0–1 cm) and in different parts of the column (intervals 1–1.5, 4–4.5, 6–6.5, 10–11, 20–21, 30–31, 42–43, and 43–44 cm). The total age of the sediments is 680 years. Lake Rabbvatnet is a typical subarctic lake with an oligotrophic status.

Typically subarctic diatom flora dominated in the lake phytoplankton throughout the whole study period: arctic-alpine phytoplankton formed a significant portion (up to 18 %) while the boreal portion was insignificant. The typical diatoms in the top layer were *A. alpigena, P. brevistriata, Cyclotella ocellata* Pant., *C. bodanica* Eulenstein. and *Staurosira construens* Ehrb. In the middle part of the column the main species were *T. flocculosa*, *Denticula tenuis var. tenuis* Kütz., *C. rossii*, *C. bodanica var. lemanica* and *C. schumannii*. In the oldest layers *Fragilariforma virescens* (Ralfs) D.M.Williams & Round and *C. michiganiana* were the most abundant species.

Diatom complexes are characterized by significant changes both in the quantitative characteristics and in the dynamics of the ecological structure. The total abundance (N) is characterized by gradual growth as time passes and it grows almost by 10 times (Figure 8). The primary productivity of the lake has also gradually grown. Two maximums in abundance can be seen: 4–6.5 cm (70–100 years old) and in the present-day layer 0–0.5 cm. The turn of the 20th century was the time for the most significant changes in the lake ecosystem and many ecological indicators are characterized by extreme values. Presumably some transformation of the trophic structure of the communities occurred, which caused the maximum value of the saprobity index in 1900 (Figure 8). The same was also observed in Lake Harrijarvi (Figure 6).

The species diversity of diatoms has also changed: there is a gradual increase of the Shannon-Weaver species diversity index (H') starting from the ancient layers up to 10-11 cm (1830's) where the maximum diversity was observed. This process is probably the due to ending of the Little Ice Age. Further warming early in the 20th century led to reduction of species diversity along with increase of abundance (Figure 9). The species diversity grows again towards present due to climatic changes towards warming along with industrial impact.

Reconstruction of pH from diatom complexes showed that throughout the whole period the lake water was characterized by near-neutral values and fluctuations were insignificant. No fundamental changes were detected in the main pH tolerance groups' proportions. In the 14th century the lake was characterized by more acidic conditions with pH< 7.0, which was caused by the influence of the Little Ice Age. Closer to the 16th century pH grew and since then it has never dropped below 7.0. The maximum values were characteristic of the early 20th century and the present. These particular periods are also described as the warmest. Reduction of pH in the middle of the 20th century is a direct consequence of deposition of acidifying compounds from the Pechenganikel though this reduction does not exceed natural fluctuations of pH (Figure 8). Reduced pH allowed development of diatoms preferring more acidic water.

Changes were also noted in the ecological structure of the diatom complexes (Figure 9). Changes in water salinity were insignificant: only the proportion of indifferent diatoms increased and the halofilous diatoms decreased. Presumably the ratio of these groups reflects primarily the intensiveness of erosion processes in the lake's catchment area. The salinity was highest in the Little Ice Age when catchment was minimal. Throughout the whole time typical halophob diatoms characteristic of arctic and subarctic freshwater ecosystems were present in the lake.

Gradual reduction of planktic forms in the period from the 14th century through late 18th century illustrates reduction of the water quantity in the lake during the Little Ice Age. At the same time the proportion of benthic and plankto-benthic algae grows which is a sign that the lake has become shallow. Climate warming early in the 20th century again caused increase of water level and development of planktonic diatoms. Evidently in the 1930's the lake had more water than today.

The present-day diatom complexes confirm the reduction of pollution as well as the more favorable climatic conditions for development of diatoms, which shows in a dramatic increase of quantitative parameters.

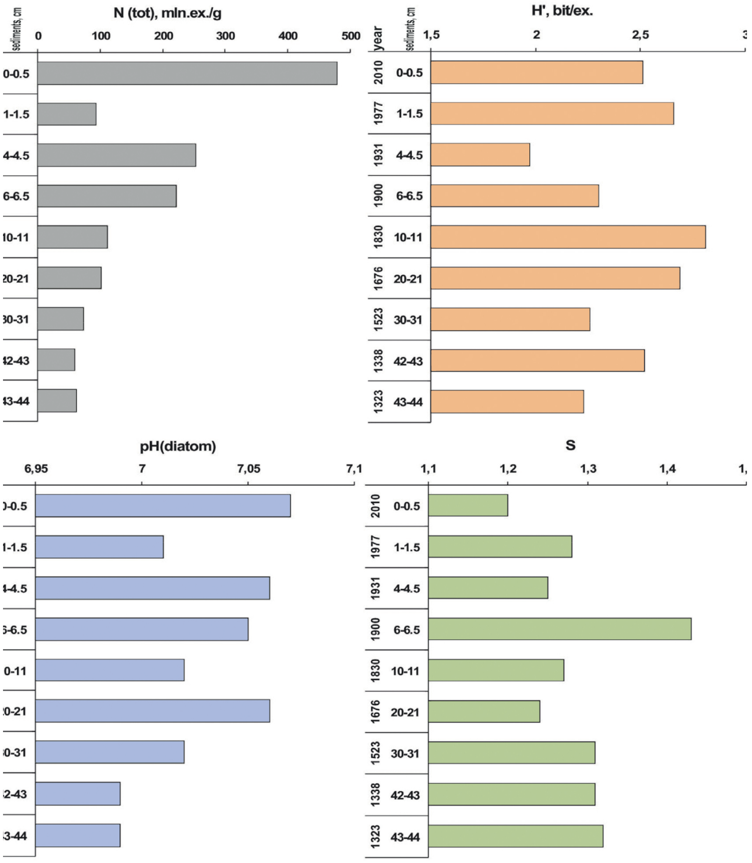


Figure 8. Diatom complexes of Lake Rabbvatnet: total abundance (N(tot), mln.ex./g), species diversity (H', bit/ex.), pH recontructed from diatoms (pH(diatom)) and saprobe index (S).

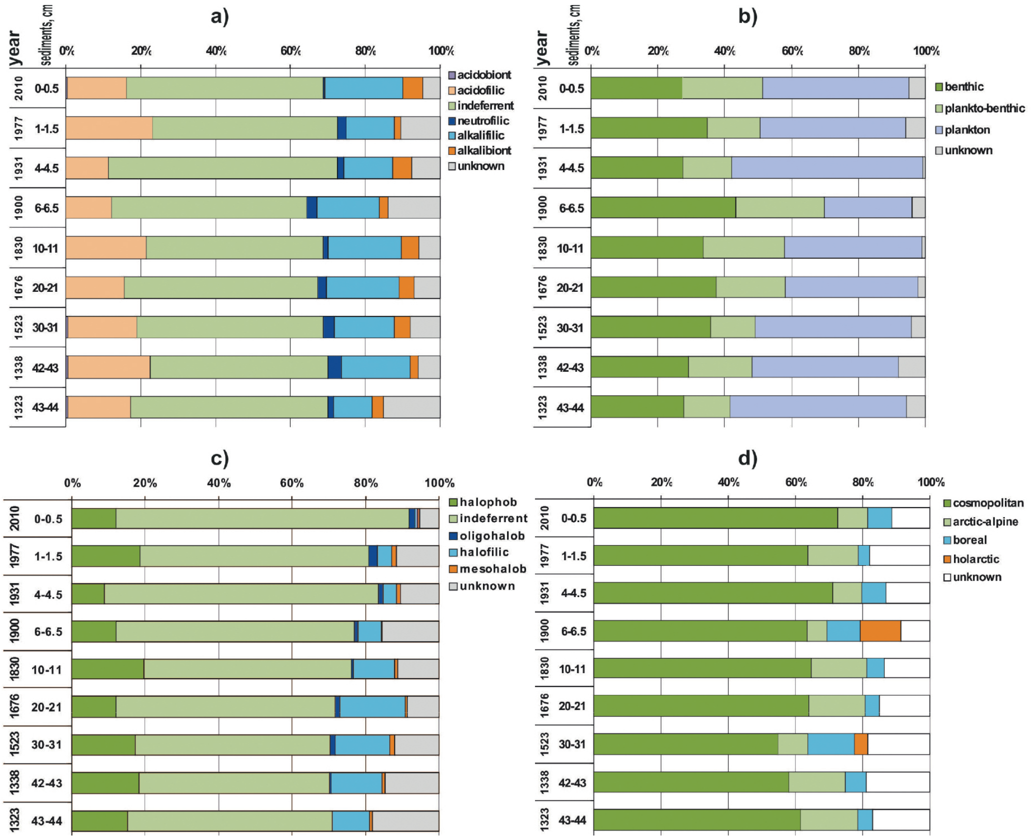


Figure 9. Ecological characteristics of the diatom complexes in Lake Rabbvatnet: a) pH-tolerance groups; b) habitat groups; c) salinity groups; d) biogeographic groups.

Conclusions

The accumulation and distribution of elements, including heavy metals, in the bottom sediments of lakes were thoroughly assessed. Four aspects were reviewed: 1) background contents, 2) vertical distribution of elements, 3) concentrations in the surface layers of sediments, 4) determination of anthropogenic load intensity by the factor and the degree of pollution, caused by the heavy metals accumulated in the sediments.

It was established that the largest background concentrations of heavy metals in bottom sediments were noted in different lakes, which is caused by geochemical and morphometric peculiarities of the catchment territory and of the lake itself. Growth of Ni, Cu and Co content in the sediments dates back to the 1920s and 1930s and maximum values are reached in the 1970s–1980s as a result of metallurgical activities.

Emissions into the atmosphere from the Pechenganikel are the major source of high concentrations of Ni, Cu and Co at the distance up to 40–50 km. Similar pattern is observed in the distribution of alkaline and alkaline-earth metals. In the more distant lakes the main pollution elements are the chalcophile Pb, Hg and As, which in the latest decades have obtained the status of global pollution elements. The area up to 50 km is the most intensively polluted.

Diatom complexes of all the lakes testify of the changes occurring in their ecosystems over the studied historical periods. The impact of natural processes associated with the dynamics of the climatic system and industrial processes associated with the Pechenganikel have been detected. However no fundamental changes in the ecosystems of the lakes have been detected; they all correspond to typical subarctic oligotrophic lakes with low salinity.

The most important climatic events in the development of lakes were 1) the Little Ice Age (14th–19th centuries) when low temperatures contributed to acidification, reduction of water quantity and decrease of production and 2) warming in the 20th century, the maximums of which fell on the period 1900s through 1930s and on the two latest decades (Figure 10). In between these events the ecosystems of the lakes were affected by industrial load, primarily by acidification caused by deposition from the Pechenganikel. At present the consequences of production decrease are showing. It is impossible to draw a decisive conclusion regarding the dramatic climate changes in the latest decades; warming in the early 20th century turned out to be more significant for the studied lakes. At the same time, the remaining level of industrial load evidently impedes the analysis of the consequences of climatic changes.

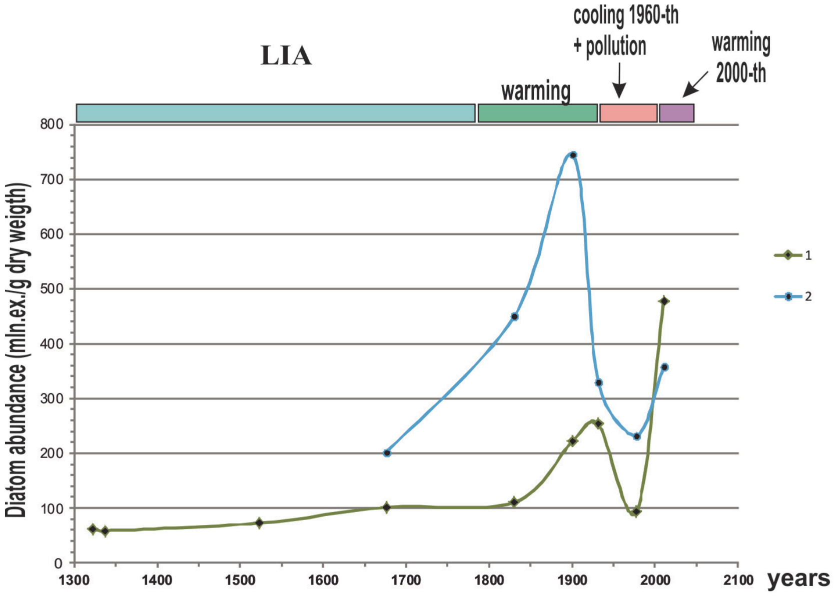


Figure 10. The diatom abundance reaction on the cooling-warming periods: 1. Lake Rabbvatnet and 2. Lake Harrijarvi. LIA=Little Ice Age.

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4 Biology

DMITRII DENISOV, SVETLANA VALKOVA, JUKKA YLIKÖRKKÖ

4.1 Phytoplankton

Phytoplankton are used to monitor nutrient enrichment. Phytoplankton biomass and water chlorophyll content are proven to correlate with concentrations of nutrients, especially phosphorus, in lakes (eg. Schindler 1978). Phytoplankton quality also indicates the lake trophic level. The amount of cyanobacteria (blue-green algae) in the assemblage is scarce in oligotrophic lakes but tends to grow with increasing phosphorus content, especially in relation to nitrogen (eg. Smith 1983). Climatic factors affect plankton assemblage directly as temperature and through various indirect ways through nutrient flux.

Toxicity of copper to freshwater phytoplankton varies widely depending on taxa sensitivity and specific water chemistry. The bioavailable fraction of metals present depends on the amount of dissolved organic carbon, among other factors. Photosynthesis and growth of sensitive green algae may be inhibited roughly at >10 µg Cu/l (USEPA 2007). Algae appears rather resilient to nickel (USEPA 1980) and at the measured levels of nickel no growth-inhibition should be evident.

In an earlier study in the Jarfjord and Pechenga regions phytoplankton density was found to be the lowest in the most acidified lake (Nøst et al. 1997).

Materials and methods

16 lakes were selected for phytoplankton sampling and analysis in the project area (Introduction, Figure 1). Small lakes previously included in international projects were studied, as well as new potential lakes for the future monitoring network. On the Russian side, attentoin was paid not only to typical small lakes but also to relatively large water bodies (lakes Ilja-Nautsijarvi and Ala-Nautsijarvi), which gives a better understanding of the Pasvik River catchment area.

Phytoplankton sampling in the field followed national standards. Samples were collected monthly during June–September. All lakes were sampled at least in August. Tube sampler was used to collect integrated samples. Samples were taken from 0–2 m column in Finland, from 0–2 m, 2–5 m and 5–10 m columns in Russia and from 0–10 m column in Norway. Russian and Norwegian samples were filtered through 20 μm plankton net. Finnish and Norwegian integrated samples were taken from composite that represents the average phytoplankton density of sampled depths. All samples were preserved in Lugol's solution.

Laboratory procedures included identification and enumeration of phytoplankton taxa. Taxa densities were estimated.

Floristic analysis based on similarity coefficient (Sørensen 1948, Czekanowski 1909) was performed to classify the lakes according to their phytoplankton species structure. Sørensen's similarity coefficient:

$$K_s = 2c / a+b$$

where *a* is number of taxa of the one site, *b* is number of taxa of another site and *c* is number of taxa common to both sites. Sørensen-Czekanowski's similarity coefficient (considering the quantitative values):

$$K_s = \frac{\sum_{i=1}^{N} \min(A_i, B_i)}{\sum_{i=1}^{N} A_i + \sum_{i=1}^{N} B_i}$$

where A_i and B_i are abundance values of species *i* in lakes *A* and *B,* and *N* is the total number of species.

The analysis was performed with the help of software module Graphs (Novakovsky 2004).

Results and discussion

Total of 117 taxa of algae on species or variety level from seven systematic groups were found: Cyanophyceae 22, Chlorophyta 22, Charophyceae 19, Chrysophyceae 5, Dinophyta 6, Bacillariophyceae 42 and Cryptophyceae 1 taxon. The number of species in each lake is shown in Figure 1.

The highest species diversity was found in Lake Virtuovoshjaur. This is likely because there are favo-

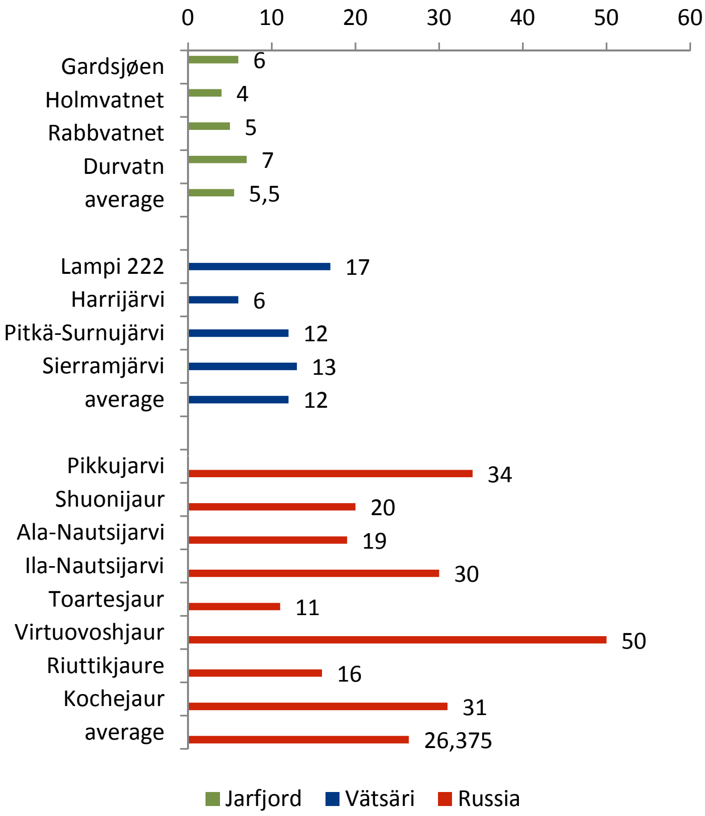

Figure 1. The number of phytoplankton taxa in the monitored lakes.

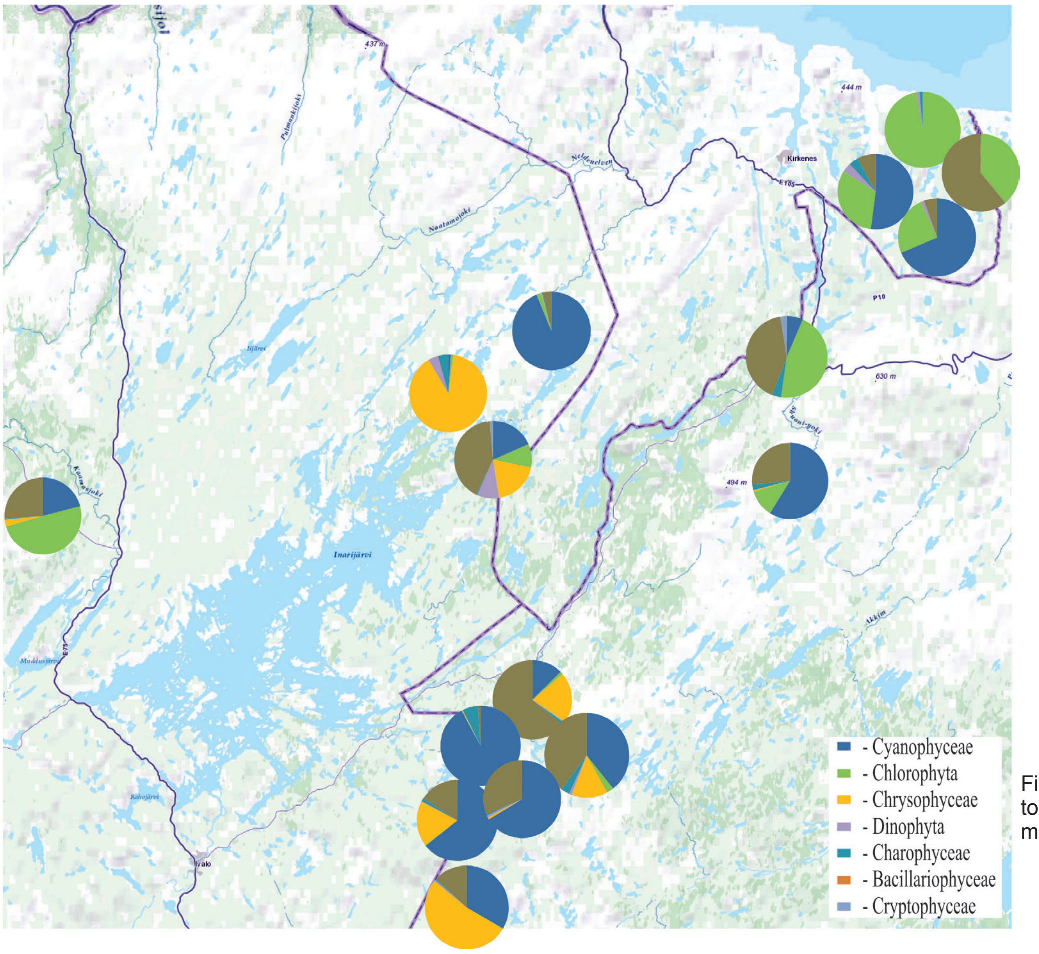

Figure 2. Phytoplankton communities of the monitored lakes

Figure 3. Lakes' classification by floristic analysis based on Sørensen's similarity coefficient.

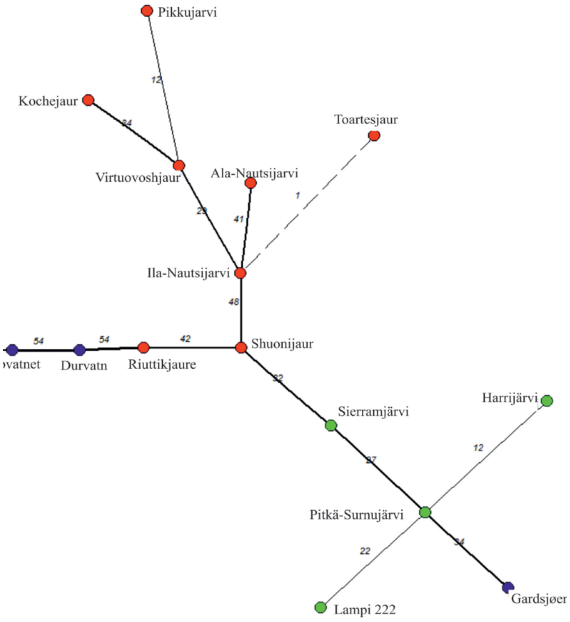

Figure 4. Lakes' classification by floristic analysis based on Sørensen-Czekanowski's similarity coefficient.

rable conditions for algal growth especially in terms of nutrients (see Chapter 4, Water Quality). The lakes in Jarfjord area were found to have the lowest diversity, a difference which was not statistically significant (see Chapter 2). The Jarfjord lakes have higher sulphate, nickel and copper concentrations. However, the catchment areas in Jarfjord tend to be smaller and soil layer thinner compared to the other regions, which also might explain the result.

The phytoplankton species composition and the dominating taxa were variable within regions and lake types (Figure 2). The most abundant phytoplankton groups were diatoms (Bacillariophyceae, at most 64 %), blue-green (Cyanophyceae, 94 %), yellow-green (Chrysophyceae, 89 %) and green algae (Chlorophyta, 97 %). Dinophytes (at most 9 %) and Charophytes (<6 %) were the least abundant at all of the stations.

In floristic analysis by the species richness and number of shared taxa between the lakes (Figure 3), three large groups of lakes were identified, mostly coinciding with geographic areas (countries). The first group included lakes on the Russian side where phytoplankton communities in the southern part of the Pasvik catchment basin and Lake Shuonijaur were found similar in species composition. In this group, lakes Pikkujarvi and Toartesjaur had the largest differences in the species composition.

The second group comprised the lakes of Finland, with Lakes Pitkä-Surnujärvi and Lampi 222 being the closest in terms of phytoplankton communities and species composition. Lake Shuonijaur from the first group was the closest in phytoplankton composition.

The third group comprised the lakes in Jarfjord (Norway) which turned out to be closer to the Finnish lakes rather than Russian, in terms of phytoplankton composition. Lake Gardsjøen was the most different from all the groups.

The results of floristic analysis based on Sørensen-Chekanovskii's similarity coefficient considering the abundance of the discovered species in the communities demonstrate similar results (Figure 4). In phytoplankton species composition and community structures the lakes in Jarfjord were found closer to the Russian lakes in the southern part of the Pasvik catchment area except for Lake Gardsjøen which is closer to the composition and abundance parameters of the Finnish lakes. Lakes Pikkujarvi and Harrijärvi, as well as Toartesjaur, were the most different from all the groups. This is due to divergent domination structures: in Lake Pikkujarvi the portion of green algae is the largest among all the Russian lakes, and cryptophytes were found (2.1 %), which were not present in the other lakes. In Lake Harrijärvi yellow-green algae were abundant (89 %), and in Lake Toartesjaur the same was true for blue-green algae (92 %).

The classification of the lakes according to the main floristic relations principle based on Sørensen similarity coefficient singled out two large groups (Figure 5). One of the groups included all the Russian lakes in the southern part of the Pasvik catchment basin; the other group comprised the Finnish and Norwegian lakes. Lakes Pikkujarvi and Gardsjøen were found to be the most different. This can be explained by the high pollution of Lake Pikkujarvi, closest to the Pechenganikel, and also by the nutrients it receives from agricultural lands on its shores. Lake Gardsjøen differs from the other lakes because it has species not found in them: for example, green-algae *Raphidocelis subcapitata* and diatom *Amphora ovalis*. According to the hydrochemical analysis, the lakes of Jarfjord are the most polluted with heavy metals. Copper and nickel concentrations in the bottom sediment are also high. Industrial pollution and a short distance to the sea are the possible reasons for communities with a large proportion of green algae which is not common in subarctic. At the same time, the most specific plankton develops in Lake Gardsjøen, which may result from the peculiarities of morphometry, nutrition regime and other local factors.

Identifying groups by phytoplankton species composition is to describe the regional characteristics and lake conditions. The division of the lakes into groups was primarily defined by the hydrochemical conditions. The largest differences were found in the water bodies exposed to industrial impact. Jarfjord lakes deviated with higher contents of suphates, certain metals of industrial origin and more marine chlorides. The Russian lakes were rich in nutrients, which was reflected in the phytoplankton composition.

Chlorophyll a content in the Vätsäri lakes were low, all less than 2 µg/l, which indicates oligotrophic status. Assessment of photosynthetic pigments and biomass for the Russian lakes to evaluate their trophic status is presented in Figure 6. The highest concentration of chlorophyll a and the highest phytoplankton biomass was found in Lake Pikkujarvi, which is exposed to anthropogenic eutrophication and the trophic status of which is eutrophic. The other lakes were classified as oligotrophic, based on chlorophyll a and phytoplankton biomass (Kitaev 1984). Among the oligotrophic lakes, the highest concentrations of chlorophyll a were found in lakes Toartesjaur and Ilja-Nautsijarvi, which is probably associated with intensive development of blue-green algae: *Anabaena* sp., *Dolichospermum lemmermannii* and *Chroococcus dispersus*. In favorable conditions these species may cause algal blooms. In the same lakes carotenoid concentrations were relatively high: this is an indirect indicator of detritus in the water column, as well as of "aging" groups of phytoplankton. The blue-green algae in the samples were often associated with detritus.

In all of the study lakes, except in Lake Pikkujarvi, the average plankton biomass during the study period (2012–2013) did not exceed the average of the Kola Peninsula lakes: 0.6–2.5 g/m^3 in the tundra and forest tundra lakes and 0.56–2.96 g/m^3 in the north taiga lakes (Letanskaya, 1974, Kupetzkaya et al. 1976).

Principal component analysis was performed in the single factor space combining hydrochemical parameters and certain functional characteristics of phytop-

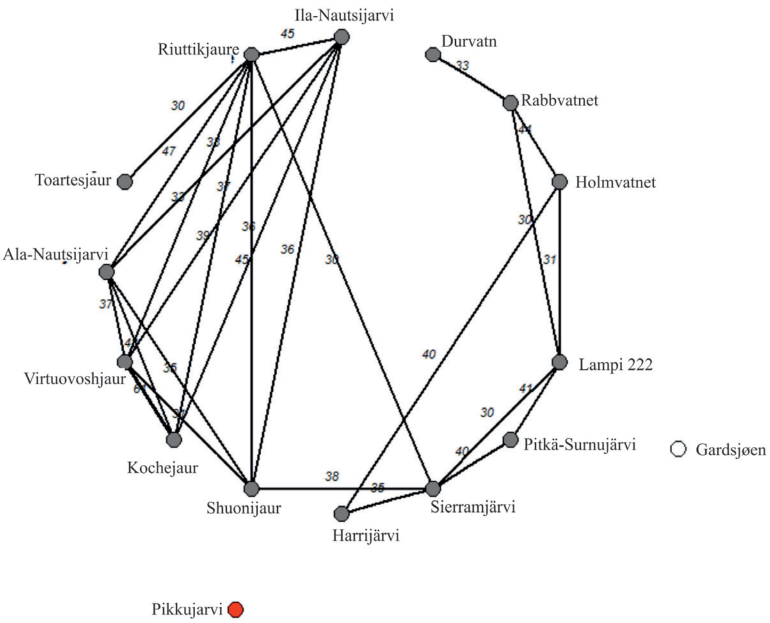

Figure 5. Lakes classification: association by the strongest relations based on Sørensen similarity coefficient.

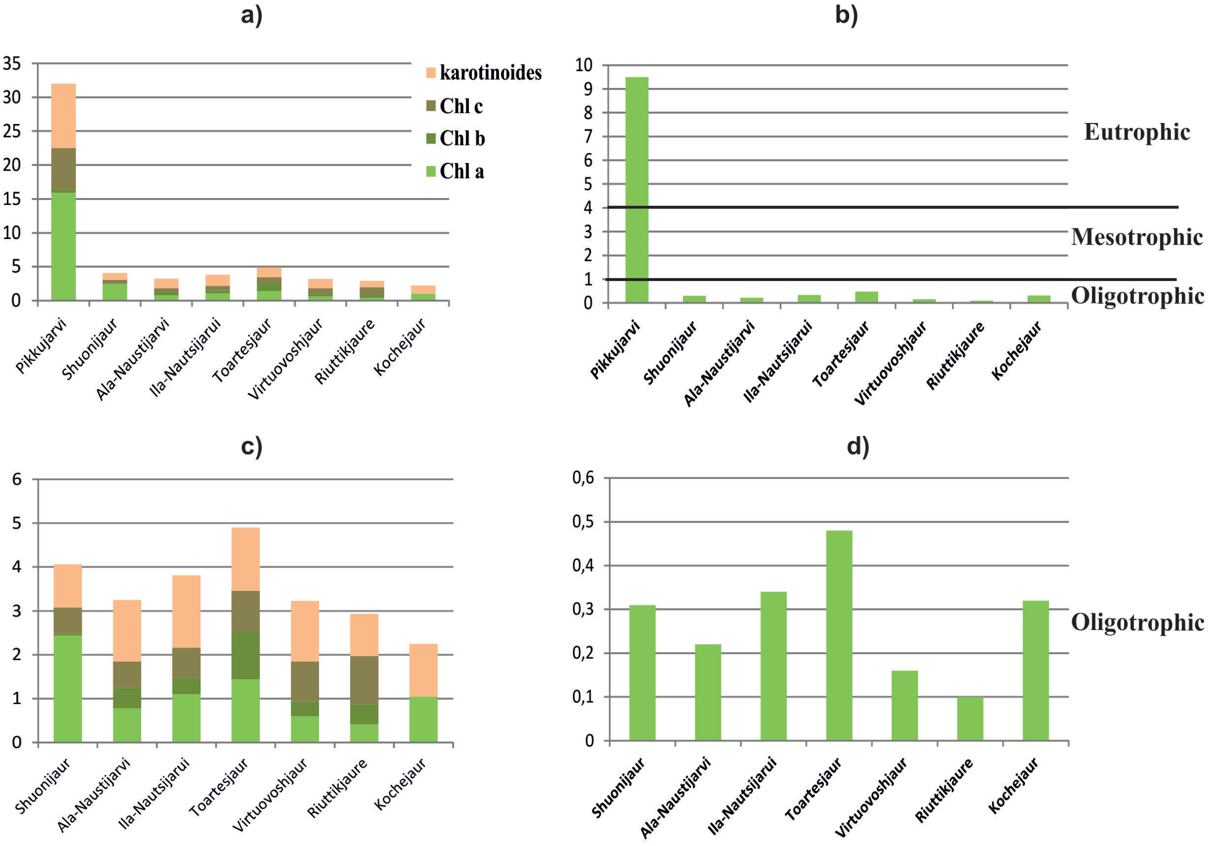

Figure 6. Photosynthetic pigment content, total biomass and trophic state of the phytoplankton (Russian lakes): a) photosynthetic pigments (mg/m^3), b) biomass (g/m^3), c) photosynthetic pigments (mg/m^3) excluding Lake Pikkujarvi, d) biomass (g/m^3) excluding Lake Pikkujarvi

lankton to assess the factors of phytoplankton development conditions. Nutrients, in particular nitrates and phosphates, do not seem play an important role in phytoplankton development in the study lakes, i.e. a large part of the assemblages are consistent with oligotrophic status and there are species that do not require large amounts of nutrition.

Salinity and water color were found to be the most important hydrochemical factors that have a positive impact on phytoplankton development. This is confirmed by positive relation of chlorophyll a and plankton biomass. Possibly, in the conditions of relatively low salinity, mineral components and humic acids coming from the catchment area become important for the plankton. The results indicate that organic compounds in water are associated with plankton vitality. There is a positive relation between phytoplankton biomass and copper and nickel, which confirms the absence of their negative impact; in the current concentrations these elements only contribute to general salinity.

Similar groups in terms of phytoplankton communities and hydrochemical indicators were identified. Lake Pikkujarvi differed most from the other lakes: specific hydrochemical conditions are formed there because of eutrophication and pollution resulting from the proximity of the Pechenganikel. This has an impact on phytoplankton development characterized by the largest quantitative parameters (biomass and chlorophyll a concentration) among the studied lakes. Lake Pikkujarvi is the most transformed by human activities, which makes it an interesting lake for the integrated environmental monitoring network.

Also Lake Toartesjaur was different from the other lakes: the phytoplankton communities are characterized by high concentration of chlorophyll b. Lake Toartesjaur has a higher concentration of zinc than the other lakes which may have had a stimulating effect on development of algae containing this pigment.

The other lakes reflect background conditions of water quality and plankton assemblages. In this group the most accessible lakes, Shuonijaur and Vuirtuovoshjaur, may be selected for future monitoring. It would be reasonable to sample phytoplankton in the other lakes less frequently.

Conclusions

The phytoplankton assemblages in the project area lakes were found to be variable, showing no regional concordance. In general the Russian lakes, which were larger and more southern, had the highest species diversity and the Jarfjord lakes the lowest.

Diatoms, blue-green, green, and yellow-green algae formed the most abundant algal groups. Green algae were found to increase from south to north and to be the highest in the lakes of Jarfjord, as well as in lakes Pikkujarvi (Russia) and Sierramjärvi (Finland). The Pechenganikel seems to have an impact on the species composition, as the results are consistent with the data on Lake Kuetsjarvi, which is exposed to direct pollution with copper and nickel production process discharge, and where the portion of green algae is also large.

The floristic analysis divided the lakes into three groups, mainly according to geographic territorial areas. Lakes Pikkujarvi and Harrijärvi, as well as Lake Toartesjaur, were found to be the most different from the others, because of specific local conditions and hydrochemical parameters. The largest differences were found in the lakes under anthropogenic impact, which is to some extent consistent with the hydrochemical data: the Russian lakes are rich in nutrients and the lakes of Jarfjord are dramatically different because of high concentration of marine ions as well as sulfates and metals originating from the Pechanganikel. The lakes also have different-sized catchments: generally the largest in Russia and smallest in Jarfjord.

Among the Russian lakes Lake Pikkujarvi is notably higher in phytoplankton biomass and photosynthetic pigments because of anthropogenic eutrophication. The other lakes are regarded as oligotrophic according to their chlorophyll a concentration and phytoplankton biomass, which both represent typical levels for the region.

The principal component analysis of the Russian lakes established that water salinity and color are the most important hydrochemical factors having a positive impact on phytoplankton development. Mineral components and humic acids are important for the algae in the conditions of relatively low salinity. No significant impact by contaminants, copper and nickel in particular, on phytoplankton quantitative parameters was found. Lake Pikkujarvi exposed to eutrophication and pollution was found to be the most different from the other lakes.

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4.2 Periphyton

Epilithic diatoms on stone substrate are studied here as periphyton. In terms of chemical factors, the diatom communities are primarily a result of water trophic state, organic matter and acidity. The growth substrate quality affects the periphyton especially in lake habitats. Diatom communities are used in assessing several environment variables.

According to Soininen et al. (2004) phosphorus content is one of the major environmental factor affecting diatom communities. The lakes studied in the project are oligo- or mesotrophic. As all biota in nutrient-poor habitat, periphyton can be expected to react to even small changes in available mineral nutrients. Diatom communities in water courses have been observed to react to nutrient increase by increasing numbers of eutrophy-associated species, such as those in *Nitzschia*-genus (Eloranta et al. 2007). Epilithic diatoms take in all nutrients from the water and therefore express the prevailing nutrient status well.

Traditionally diatom communities are also used in assessing the organic pollution (the saprobic level) (e.g. Sladecek 1973).

Similar to other biota, acidity generally decreases diatom species richness: sensitive species disappear and few tolerant species increase (Patrick 1977). Diatom taxa can be categorized by their tolerance to acidity (Van Dam et al. 2004). However, many species tolerate changes in pH rather well and acidofil taxa is found also in neutral water, but in less extent compared to acidified waters (Eloranta 1990).

There is some experimental data regarding diatom responses to heavy metals. According to USEPA (2007) freshwater *Nitzschia palea* growth is inhibited at copper concentration of 5 µg/l. This gives a rough reference to possible pollution-related effects in the most sensitive diatom taxa. There is less accurate information about nickel compounds' toxicity to diatoms. Patrick et al. (1975) reported nickel to cause dominance of green and blue-green algae over diatoms.

Materials and methods

Samples were collected by scraping rocks (roughly fist-sized) from c. 20 cm depth in littoral zone of the lakes. Detached periphyton was collected and preserved in ethanol in Finland, formaldehyde in Norway and Lugol's solution in Russia. In Finland samples were collected from 5 stones in 2–3 different littoral stations in September; in Russia and Norway 10 rocks from one location in August 2013.

Diatom slides for the microscope analyses were prepared using standard traditional methods (Zhuze et al. 1949, Davydova 1985, Denisov 2007). The organic matter was eliminated by hydrogen peroxide, then diatom valves were separated from other mineral components by the difference in sedimentation velocity. All diatoms have been identified, if possible, to intraspecific taxa (Krammer & Lange-Bertalot 1986-1991). Diatom taxa identification and enumeration followed principles in standard EN 14407:2004.

A nutrient status analysis was done using the Diatom Assessment of Lake Ecological Status (DALES), which is based on average score per taxon method (UKTAG 2008).

The diatom-inferred value of the pH has been calculated according to method of Moiseenko & Razumovsky (2009) with the following formula:

$$pH = \Sigma phi \cdot k / \Sigma k,$$

where phi – individual numeric value of the each taxa-indicator; k – abundance value (quantity).

Periphyton groups were determined according to their preferred pH: neutrophils with pH-optimum at pH 7.0, circumneutrophils with a range of pH close to neutral, indifferent capable of developing at a relatively wide range of pH, alkaliphils preferring pH > 7.0, alkalibionts preferring pH 7.6 and above, acidophiles preferring pH <7.0 and acidobionts developing at relatively low values of pH 6.4 and below.

Saprobe index (S) (Sladecek 1973, Pantle & Buck 1955) was calculated for each site. This indicates the nutrient supply and is an indirect indicator of the trophic status of the lake (Barinova et al. 2006). The analysis used data on the ecology of individual taxa and relation to saprobity and pH from the updated database of the algae ecology (Barinova et al. 2006).

Results and discussion

Sampled lakes had diatom communities typical of nutrient-poor north boreal lakes. There were differences in the number of species and species composition between the areas (Figure 9). The diatom communities reflected the lakes' humic and nutrient content. DALES indicated low nutrient status for all and saprobic index oligosaprobia for most of the lakes (Table 3). *Tabellaria flocculosa* is considered acidophilous, mainly occurring at pH less than 7 (Van Dam et al. 1994). It is a common species in the research areas, which are naturally low alkaline. pH estimated through diatom communities was quite neutral and corresponded to the measured pH values.

Vätsäri area had the highest species diversity: on average 59 littoral diatom species. The lakes were dominated mainly by *Brachysira vitraea*, *Tabellaria flocculosa* and *Frustulia rhomboides*. These taxa are associated with low nutrient concentrations (UKTAG 2008, Kelly et al. 2001), and also considered sensitive to organic pollution (Cemagref 1982). Diatom communities were oligosaprobic.

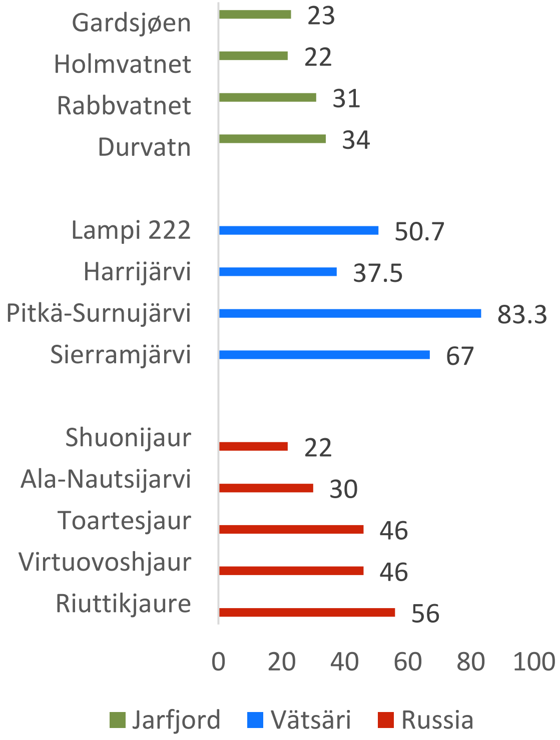

Figure 9. The number of periphytic diatom species in each lake. Vätsäri values are averages from 3 sub-samples.

Table 3. DALES index values and their respective ecological quality ratios (EQR) (all values represent high status class EQR ≥ 0.8), the diatom-inferred saprobe index (S) and saprobe zone and the diatom-inferred and measured pH of the investigated lakes.

	DALES	Class (EQR)	S	Saprobe zone	pH (diatom)	pH (measured)
Vätsäri						
Lampi 222	14	high (>1)	1.16	α-oligosaprobic	6.8	6.7
Harrijärvi	6	high (>1)	1.25	α-oligosaprobic	6.7	6.7
Pitkä-Surnujärvi	20	high (1.0)	1.22	α-oligosaprobic	6.9	6.7
Sierramjärvi	26	high (0.9)	1.44	α-oligosaprobic	7.0	6.8
Russia						
Shuonijaur	26	high (0.9)	1.63	β-mesosaprobic	6.8	6.8
Ala-Nautsijarvi	27	high (0.9)	1.57	α-oligosaprobic	7.3	7.0
Toartesjaur	28	high (0.9)	1.46	α-oligosaprobic	7.0	6.9
Virtuovoshjaur	21	high (1.0)	1.39	α-oligosaprobic	7.0	6.9
Riuttikjaure	36	high (0.8)	1.42	α-oligosaprobic	7.2	7.1
Jarfjord						
Gardsjøen	20	high (1.0)	1.55	α-oligosaprobic	6.9	6.8
Holmvatnet	12	high (>1)	1.34	α-oligosaprobic	6.9	6.8
Rabbvatnet	19	high (>1)	1.45	α-oligosaprobic	7.0	7.0
Durvatn	23	high (0.9)	1.22	α-oligosaprobic	7.0	7.0

In the southern lakes in Russia, there were, on average, 40 species in a lake. *Tabellaria flocculosa* was also dominating in these lakes. Taxa of slightly higher nutrient level is more common there, such as *Denticula tenuis* in Ala-Nautsijarvi. In Riuttikjaure the dominating species was *Epithemia sorex*, which is considered taxa of moderate nutrient level (UKTAG 2008) and tolerant to mild organic pollution (Cemagref 1982). Saprobic index indicated oligosaprobia for the lakes, excluding Shuonijaur that was on mesosaprobic level. The number of diatom species in Shuonijaur was low, 22 species, which was similar to Jarfjord. Shuonijaur copper concentration has, at times, exceeded the potentially toxic levels to diatom growth.

Jarfjord lakes had the lowest species diversity: on average 27 species. The difference in species diversity in relation to Vätsäri is statistically significant (see Chapter 2). *Tabellaria flocculosa* or similarly oligotrophic *Brachysira styriaca* dominated in Jarfjord lakes. All the lakes were oligosaprobic by saprobic index. The Jarfjord lakes all had elevated sulphate levels (see Chapter 4, Water quality). This indicates that the lakes might have experienced some degree of acidification in the past. As a result diatom community would have suffered a loss of species. Moreover, all the lakes had copper and nickel concentrations higher than in the other regions. Biological impact is the combined effect of both metal pollution and acid deposition.

It should be noted that catchment structure or soil quality was not controlled in the study. Sampling differences, catchment size and soil quality and thickness may also explain species diversity. In addition, the Jarfjord lakes are slightly more north compared to Vätsäri, which could also contribute to the result.

Conclusions

There were fewer species in Jarfjord lakes compared to the other two regions. The main chemical differences to other lakes are elevated levels of sulphate and heavy metals. Chemical quality in Jarfjord does not imply acidification, but heavy metal pollution and past changes in alkalinity may explain the difference. Similarly Lake Shuonijaur in the vicinity of Nikel has notably low diatom species diversity and elevated levels of copper and nickel.

Periphytic diatoms are quick and straightforward to sample. It is found to be a relatively effective monitoring target for the current environmental impacts and therefore recommended for future monitoring.

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Photo: Helén Andersen

4.3 Zoobenthos

Zoobenthos, or benthic macroinvertebrates, were studied in littoral and profundal zones. Littoral zoobenthos responds to multiple environmental pressures due its community's diverse feeding adaptations and life cycles. North boreal streams are much studied and they have been reported to sustain lower species richness and abundance relative to south boreal region (eg. Sandin & Johnson 2000). This is expected to be true also for lake habitats. Indicator taxa for eutrophication, organic pollution (saproby) and acidification may be recognized in zoobenthos communities. Environmental changes are reflected to species diversity, abundance and community composition. The profundal zoobenthos is most of all prone to oxygen depletion, which is similarly studied through community metrics.

The effect of sulphate on invertebrate biota depends on the compound it is bound to. Water alkalinity and chloride content alleviate sulphate toxicity (Meays & Nordin 2013). The level of sulphate measured in project lakes is not high enough to necessarily cause direct effects in zoobenthos but it may indirectly alter the communities through acidification.

Invertebrate sensitivity to heavy metals is specific to each group and life-stage. The nickel and copper concentrations that can directly affect invertebrate viability are higher than what was measured in the study lakes (USEPA 2007, 1980). The bioavailable fraction of a metal in nature depends primarily on the dissolved organic carbon content. In a previous study in the project area (Nøst et al. 1997) sensitive Ephemeroptera, Trichoptera and Plecoptera species were fewer or altogether missing in the most acidified and heavily polluted lakes (Nøst et al. 1997).

Materials and methods

Littoral zoobenthos was collected using a kick-net on rocky bottom substrate ca. 20–40 cm deep. Kick-net samples were sieved with 0.5 mm mesh. Each lake was sampled once between August and October in 2012 and 2013. Sampling procedures are summarized in Table 5. The Finnish method is described in detail in Meissner et al. (2013, in Finnish) and Russian method in state standard (GOST 17.1.3.07-82). Norwegian sampling time is 20 seconds per 1 m and the net is emptied after 1 min sampling time. Total kicking time is 3 min, during which a total of 9 m is moved.

Profundal zoobenthos was collected using a standard Ekman grab from the deepest basin in each lake. Samples were sieved with 0.5 mm mesh. Profundal sampling was conducted at the same time with littoral sampling. Sampling procedures are summarized in Table 6.

Table 5. Littoral zoobenthos sampling month and the number of sampled stations and replicates.

	Month	Sampling time (s.)	Stations	Replicates
Finland	September-October	20	3*	2
Russia	August	10-15	3	1
Norway	September-November	20	3	2

* Harrijärvi has 2 stations and 3 replicates.

Table 6. Profundal zoobenthos sampling time and the number of replicate Ekman grab samples.

	Month	Replicates
Finland	September-October	6
Russia	August	2
Norway	August	6

Results and discussion

Littoral community

The observed littoral macrozoobenthos represented typical taxa for nutrient-poor, clear-watered lakes in cold climate.

In the Russian lakes there were altogether 34 species. In Vätsäri and Jarfjord lakes were total of 36 and 23 species, respectively. Chironomid species were the most numerous in all of the regions. The number of all the recorded families was consistently lower in Jarfjord (Figure 10). The difference between Jarfjord lakes' number of families in contrast to the other two regions was found statistically significant (See Chapter 2).

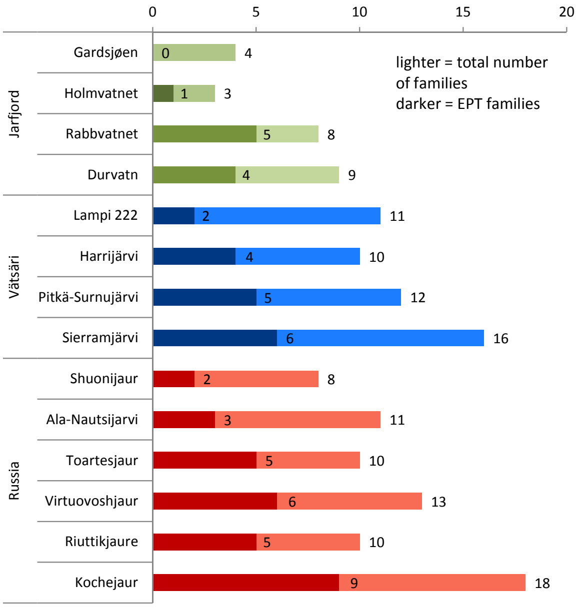

Figure 10. The number of littoral zoobenthic families (lighter color) and the number Ephemeroptera, Plecoptera and Trichoptera families (darker color) in each lake and region.

Table 7. The number of species, Woodiwiss biotic index and Shannon diversity index values for the Russian, Vätsäri and Jarfjord lake's littoral zoobenthos communities. The consequent ecological state is assessed by the Russian state standard limit values.

Lake	Number of species	Woodiwiss index	Shannon index	Ecological state
Russia				
Virtuovoshjaur	22	10	3.81	clean
Kochejaur	25	10	4.01	clean
Ilja-Nautsijarvi	19	8	3.55	clean
Shuonijaur	12	7	2.54	clean
Ala-Nautsijarvi	14	8	3.34	clean
Toartesjaur	13	8	3.21	clean
Pikkujärvi	17	7	3.31	clean
Riuttikjaure	16	8	3.40	clean
Vätsäri				
Pitkä-Surnujärvi	24	9	2.61	clean
Sierramjärvi	23	9	2.64	clean
Harrijärvi	17	9	2.84	clean
Lampi 222	13	9	2.86	clean
Jarfjord				
Holmvatn	3	4	1.50	polluted
Durvatn	10	6	2.04	moderately polluted
Gardsjøen	7	3	0.60	dirty
Rabbvatn	14	8	2.16	clean

The Ephemeroptera, Plecoptera and Trichoptera (so called ‘EPT’) families are considered pollution-sensitive and therefore specifically the number of their families is used as an indicator of environmental status. The EPT families were again fewer in Jarfjord lakes, but the difference was not significant at 95 % confidence level.

Analysis of ecological state using Woodiwiss biotic index for organic pollution and Shannon diversity index against the Russian state limit values (GOST 17.1.3.07-82) is summarized in Table 7. All the Russian and Vätsäri littoral zoobenthos communities yield clean water status. Three Jarfjord lakes classify as polluted at some degree. The three polluted lakes have notably few taxa of zoobenthos. No chemical factor separates the three from other lakes in Jarfjord.

It is assumable that the combined effect of industrial pollution, namely sulphate, copper and nickel, play a role in shaping the Jarfjord littoral zoobenthic communities and lower their diversity. In comparison to Vätsäri the lakes have the same trophic state and thus should not express significant differences. However, the latitude and catchment characteristics were not controlled in the study: the Jarfjord lakes are generally more north and tend to have smaller catchments with thinner soils, both of which could have negative impact on diversity.

Profundal community

Profundal macrozoobenthos densities and biomasses were found to be low. In the Russian lakes there was high variance from no zoobenthos (Virtuovoshjaur, Kochejaur) to 1938 individuals/m^2 (Toartesjaur) (Table 8). The lakes in Vätsäri and Jarfjord had lower densities of zoobenthos: 0–329 ind./m^2 and 52–456 ind./m^2, respectively (Table 8). The cause of empty samples is probably the naturally sparse distribution of the individuals. Chironomidae and Oligochaeta comprise majority of the lake profundal taxa.

The Russian profundal zoobenthos communities mainly indicate oligotrophy or mesotrophy on Kitaev’s (2007) trophic scale based on zoobenthos biomass. Lake Toartesjaur classified as eutrophic because more than 70 % of the community was composed of eutrophy indicator chironomid *Limnochironomus gr. tritomus*.

Vätsäri communities indicate oligotrophy. Jarfjord communities indicate oligotrophy, apart from Lake Durvatn, where the benthos made up mostly by *Mic-*

Table 8. The mean values of number and biomass, Shannon diversity index values, trophic states according to Kitaev (2007) and status of the community based on Finnish national zoobenthos metrics (PMA, PICM) for the Russian, Vätsäri and Jarfjord lake’s profundal zoobenthos communities. Some lakes could not be classified due to low abundance of invertebrates.

Lake	**Mean values of number (ind./m^2)**	**Mean values of biomass (g/m^2)**	**Shannon index**	**Trophic state**	**Community status (PMA, PICM)**
Russia					
Virtuovoshjaur	-	-	-	-	-
Kochejaur	-	-	-	-	-
Ilja-Nautsijarvi	190.1	1.0	1.87	oligotrophy	-
Shuonijaur	576.7	2.9	2.76	mesotrophy	high
Ala-Nautsijarvi	415.2	2.1	2.42	oligotrophy	high
Toartesjaur	1937.6	9.7	1.12	eutrophy	high
Pikkujärvi	622.8	3.1	3.08	mesotrophy	-
Riuttikjaure	692.0	3.5	2.50	mesotrophy	high
Vätsäri					
Pitkä-Surnujärvi	155.7	1.3	2.60	oligotrophy	good
Sierramjärvi	328.7	2.7	1.50	oligotrophy	high
Harrijärvi	196.1	1.6	3.00	oligotrophy	good
Lampi 222	-	-	-	-	-
Jarfjord					
Holmvatn	103.8	0.9	3.09	oligotrophy	-
Durvatn	455.6	3.8	1.93	mesotrophy	-
Gardsjøen	184.5	1.5	1.92	oligotrophy	high
Rabbvatn	51.9	0.4	1.89	oligotrophy	high

rasema sp. (Trichoptera) and mussel *Pisidium (Euglesa)* sp.

The Finnish community metrics faced difficulties with low abundance of invertebrates. Some lakes had so few taxa that PMA (Percent Model Affinity) would have been 0, which is not a useful result. Profundal Invertebrate Community Metric (PICM) requires certain indicator Chironomidae and Oligochaeta on species level to assess benthos status. Lakes that were possible to classify, gained at least good status class. The presence of relatively sensitive *Sergentia* and *Cladotanytarsus* resulted in mostly high status class for PICM. PMA gave variable results from poor to high. The index reacted to low invertebrate density, which is considered natural in the nutrient-poor, cold lakes. Final profundal status was classified as good or high.

Dendrogram analysis

In relatively deep water bodies (e.g. Shuonijaur, 15-20 m) the psychrophilic, oligo-mesotrophic larvae of *Sergentia coracina* (Chironominae) dominate in the structure of the profundal communities and cold water oligotrophic *Arctopelopia* sp. (Tanypodinae) dominate in the littoral area. Chironomidae *Procladius choreus gr.* (Tanypodinae), widely spread in the Palearctic, are encountered everywhere. The portion of *Cricotopus silvestris gr.* (Orthocladiinae) is increased in shallow, quickly warming water bodies with well developed aquatic vegetation and periphyton cover. Increase of anthropogenic impact leads to the reduction of relative density of oligotrophic species and to the increase of eurybiontic larvae of *Chironomus* spp.

Four isolated groups were distinguished by similarity in the profundal macrozoobenthos. Eutrophic Lake Toartesjaur is separate from the others, as is Lake Riuttikjaure, where Oligochaeta dominate in the benthos fauna. Lakes Virtuovoshjaur and Kochejaur, characterized by the lowest diversity indicators and zoobenthos density, form a group of their own. A separate cluster unites lakes Gardsjøen, Shuonijaur, Sierramjärvi and Durvatn: the common feature is the domination of one group of invertebrates in the profundal zoobenthos composition: for example, larvae of *Micrasema* genus (Trichoptera) dominate in Lake Durvatn whereas in Lake Shuonijaur Chironomidae were the most abundant.

For the littoral macrozoobenthos the clusters were somewhat different (Figure 11). Lakes Harrijarvi, Sierramjarvi and Pitkä-Surnujärvi, where various species of Chironomidae dominate in the macrozoobenthos, form one cluster and Holmvatn and Durvatn other cluster. Other water bodies are positioned on the dendrogram in the order of increasing biodiversity of littoral macrozoobenthos.

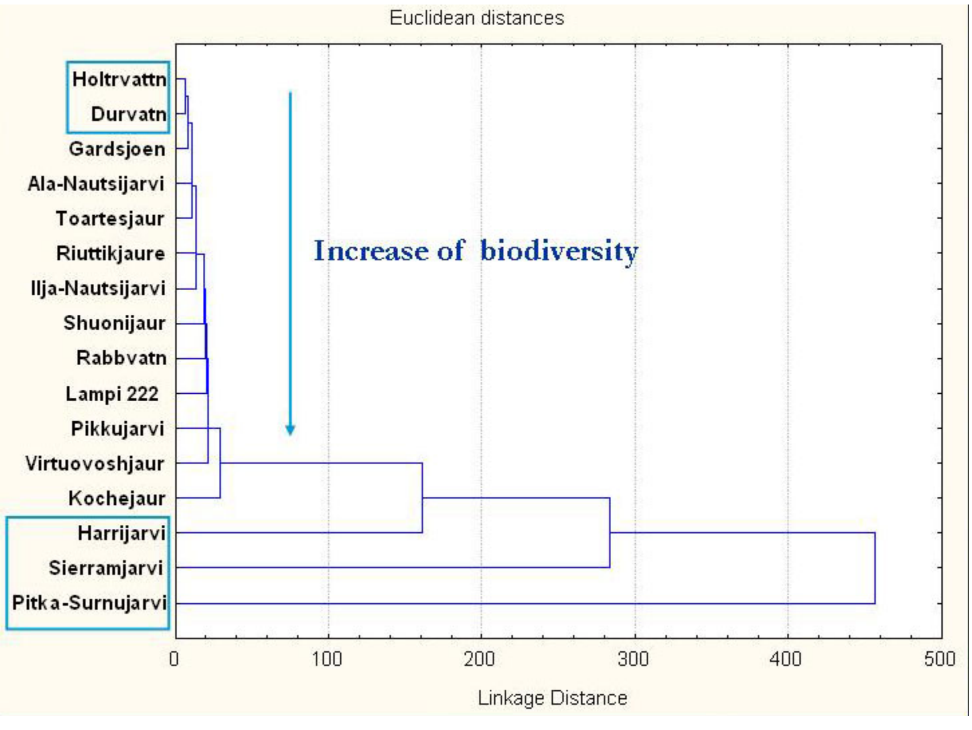

Figure 11. The dendrogram of the similarity of the macrozoobenthos of the studied lakes. (littoral benthic communities, method: Single Linkage, Euclidean distance).

Conclusions

The results from macrozoobenthos littoral communities indicate mostly natural ecological status with sensitive taxa present in Russia and Vätsäri, Finland. However, certain lakes in Jarfjord indicate pollution of moderate or high degree. In addition there were differences in biodiversity between the areas so that Jarfjord lakes expressed consistently the lowest diversity.

The profundal communities had low density of individuals but the community indices gave normal results when there were zoobenthos in the samples.

Littoral zoobenthos is recommended for future monitoring due to long history of monitoring and feasibility as pollution indicator. Profundal benthic community assessment was troubled by empty samples and naturally very low densities and therefore profundal monitoring should not be placed high priority in the future.

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Kick-net sampling of zoobenthos. Photo: Jukka Ylikörkkö

4.4 Fish

PETR TERENTJEV, HELÉN ANDERSEN, GUTTORM CHRISTENSEN, GEIR DAHL-HANSEN, KATJA MÄÄTTÄNEN, MARTTI RASK, JUKKA RUUHIJÄRVI, SAMULI SAIRANEN, ERNO SALONEN, ARI SAVIKKO

Fish communities of small border area lakes in Finland, Russia and Norway were studied in 2013 and 2014 and the ecological status was evaluated based on fish community variables. The final aim was to evaluate the usefulness of fish community variables (community structure, growth rate, maturation age, longevity) in assessment of impacts of climate change and hazardous substance deposition and possible effects of acidification on fish communities of survey lakes.

There are several possible methods for collecting information for doing a classification depending on type of the river or lake system. The main methods for lakes are interviews with locals, historical data, gillnet fishing, mapping by echo sounding or electrofishing. The lakes in the border region all potentially influenced by acidification. Gillnet fishing was carried out according EU standards in order to evaluate the status of the fish populations in the lakes

Finnish lakes Harrijärvi and Pitkä Surnujärvi were test fished in summer 2013. Russian lakes Shuonijaur, Ilja-Nautsijarvi, Virtuovoshjaur, Riuttikjaure and Toartesjaur were also test fished in summer 2013 but also additional, older data from previous years was used in the case of some lakes to determine changes in fish community structure. Also some results from Lake Kochejaur, which has been a subject of fish community research for decades, are included here. The Norwegian lakes Durvatn, Gardsjøen, Holmvatn and Rabbvatn were test fished in August 2013 and Rundvatn in August 2014.

Materials and methods

Test fishing was carried out with using a stratified random sampling method in the littoral, sub-littoral and profundal zones (Kurkilahti 1999, CEN 2005). The sampling was carried out by using standard NORDIC multimesh gillnets (30 x 1.5 m) with 12 different mesh size between 5–55 mm (mesh sizes 5, 6.25, 8, 10, 12.5, 15.5, 19.5, 24, 29, 35, 43 and 55 mm). The NORDIC multimesh gillnet is the standard method in the EU Water Framework Directive. The number of gillnets that are recommended according to EU standards in the survey depends on size and depth of the lake (Table 1). The lake size varied from 0.4 km^2 to 8.5 km^2 and the depth from 10 to 25 meters which lead to different numbers of gillnets used (Table 2).

The nets were set in the evening and hauled the next morning after a catching period of 12–15 hours. All lakes were sampled during one night. The catch of each net was handled separately by mesh size and sorted by species, counted and weighted.

Total catches, catches of species groups and catches of each fish species were calculated as catch per unit effort (CPUE, g/net and CPUE, number/net). The catch of each net was handled separately and by mesh size. Each catch was sorted by species and then counted and weighed. For size distributions, the total length of every fish was measured at 1 cm accuracy in Finland and Russia and in Norway the fork length was measured at 1 mm accuracy. Also the total number and weight of potentially piscivorous perch (*Perca fluviatilis*) (≥ 15 cm) was calculated separately for the proportion of predatory fishes.

Hectares	I	II	III	IV
< 20	6	10	16	24
21–50	10	16	25	37
51–100	15	21	30	42
101–250	20	26	35	47
251–500	24	30	39	51
501–1000	28	36	48	64
> 1000	32	40	52	68

Table 1. Recommended number of gillnets according to size and depth of the lake. Depth is divided into four categories (I–IV). Category I includes lakes with a maximum depth of 3 m and one depth zone (0–3 m). category II includes lakes with a maximum depth of 10 m and two depth zones (0–3 m, 3–10 m), category III includes lakes with a maximum depth of 20 m and three depth zones (0–3 m, 3–10 m, 10–20 m) and category IV includes lakes with a maximum depth of > 20 m and four depth zones (0–3 m, 3–10 m, 10–20 m, > 20 m).

Table 2. Lake area (km²), depth (m) and number of gillnets used in the test fishing.

	Lake	Area (km²)	Depth (m)	Number of gillnets
Finland	Harrijärvi	0.96	11	21
	Pitkä Surnujärvi	0.69	11.3	22
Norway	Durvatn	0.37	16	16
	Gardsjøen	0.67	25	21
	Holmvatn	0.80	>20	21
	Rabbvatn	0.40	23	16
	Rundvatn	0.45	15	23
Russia	Shuonijaur	8.5	10	40
	Ilja-Nautsijarvi	3.5		30
	Virtuovoshjaur	1.16	13	26
	Riuttikjaure	0.9		21
	Toartesjaur	0.6		21

Table 3. Determination of ecological status for trout in acidified lakes based on the catch per unit effort (CPUE, number of fish per 100 m²) and quality of the spawning and feeding habitat (OR) (Sandlund et al. 2013).

		CPUE, number of fish per 100 m²				
Gillnet type	**OR**	**Very good**	**Good**	**Moderate**	**Bad**	**Very Bad**
NORDIC	≥ 50	> 20	20–5	15–10	< 10	< 5
NORDIC	25–50	> 15	15–10	10–5	5–2	< 2
NORDIC	≤ 25	> 10	10–5	5–2	< 2	0

Age determination was based on operculum (perch), otoliths (trout and char in Norway), cleithrum (pike in Russia) or scales (others). For the Finnish lakes the back-calculation of growth is based on the formula of Monastyrsky (Bagenal & Tesch 1978). For the Russian lakes the growth of perch and pike was back-calculated with the Lea formula and the growth of whitefish was back-calculated with the Lee formula (Chugunova 1959, Bryuzgin 1969).

For the Finnish lakes the ecological status was evaluated by using the Finnish EQR4 index (Tammi et al. 2006, Olin et al. 2013). Fish community variables used in evaluating the ecological status were biomass (CPUE, g/net), number (CPUE, number/net) and appearance of indicator species. Ecological quality ratio (EQR) was calculated by dividing the observed value of each variable with lake type specific reference value. Average from the EQR values of each variable describes the fish community based on evaluated ecological status of the lake.

For the Norwegian lakes the ecological status of trout populations was evaluated based on a classification system that takes into account the quality of the available spawning and feeding habitats (OR = oppvekstratio) and the ratio between their surface areas (m²) and the lake's surface area (ha). In this study the quality of spawning and feeding habitat was evaluated from satellite pictures. Ecological status is evaluation also dependent on catch per unit effort (CPUE, as number of fish per 100 m²) (Table 3). The classification system describes the fish community on a five step scale: Very good, Good, Moderate, Bad and Very Bad. Quality of trout and char was also evaluated based on muscle colour, presence of parasites and condition factor.

For Russian lakes the ecological status was evaluated based on expert assesment method in which the studied lakes were compared to reference ecosystems. Also the frequency of malformations in fish and heavy metal accumulation in fish tissues was studied.

Results and discussion

Community structure

The community structures of the studied lakes were quite similar in Finland and Russia (Figure 1). The dominant fish groups overall were salmonids and percids. The common salmonids were whitefish (sparsely-rakered (SR) form in Russia, form was not determined in Finland) and grayling, some of the lakes also had trout and char. The only percid present was perch. Pike, cyprinids, minnow and burbot were caught in some of the lakes but the numbers were low. In the Norwegian lakes that were sampled in 2013 trout and char were the main species (Figure 1) but also the presence of stickleback was suspected in most lakes. However, after the first field work in 2013 it was decided to include one more lake in the survey, in order to compare community structure of perch across borders. An additional “perch lake” was therefore chosen in Norway.

The fish communities in the lakes are different between Russia, Finland and Norway due to the historical immigration of fish after the previous ice age (Økland 1966). After the ice age (8 000 years ago) the big Ancylus lake was established. This lake covered the Baltic Sea and parts of Finland and Sweden. Fish species like perch, pike and whitefish emigrated from the Ancylus Lake into rivers and lakes in the inland part of Finnmark, Northern Finland, Sweden and Northwest Russia. Trout and char immigrated to the coastal lakes and rivers along the Norwegian coast.

CPUE in Finland

The total CPUEs as g/net and number/net of each study lake were evaluated (Table 4, Figure 2 and Figure 3). Lake Harrijärvi had a higher g/net CPUE of the Finnish lakes and Lake Pitkä Surnujärvi had more individuals per net. Fish community of Lake Harrijärvi consisted mainly of large-sized individuals of grayling. Domination of salmonids is typical of the oligotrophic lakes in the northern Finland. In Lake Pitkä Surnujärvi the biomass was dominated by perch, but in numbers more salmonids were caught. Fish community of Lake Pitkä Surnujärvi mainly consisted of large perches and small whitefish.

CPUE in Norway

Most of the Norwegian lakes had CPUEs similar to Finnish lakes and the catch consisted of trout and Arctic char. The highest CPUEs of all study lakes were in Lake Rundvatn (3846 g/net and 38.3 individuals/net) (Table 5, Figure 2 and Figure 3). The catch in Lake Rundvatn was clearly dominated by perch. The quality of the trout in Rundvatn was very good with a condition rate of 1.1 and the color of the muscle tissue is mainly red or pink. Trout larger than 25 cm are considered as piscivorous and therefore have plenty of small perch to feed upon. There are only small tributaries to Lake Rundvatn and the spawning possibilities for trout are considered as poor. The perch population is very dense but the fish still grow to lengths of > 15 cm.

CPUE in Russia

The CPUEs of Russian lakes were similar to, or lower than in the Finnish and Norwegian lakes (Table 6, Figure 2 and Figure 3). Lake Shuonijaur had low CPUEs. Percids dominated in the catch but in a previous test fishing in 2005 trout and Arctic char were the main species. This kind of change is typical of the water reservoirs in the Murmansk Region. The ratio of mature and immature Arctic char specimens in different age groups testifies of a significant number missing spawning. It is evident that in Lake Shuonijaur effective reproduction of char is impeded by anthropogenic load, lack of favorable food reserves and competition from perch.

In lakes Ilja-Nautsijarvi, Virtuovoshjaur and Toartesjaur percids dominated in the catch of 2013. However, earlier test fishings in Virtuovoshjaur in 1992 and 2005 indicated that whitefish was the dominant species. Present whitefish population in Virtuovoshjaur consists mainly of younger age groups for which early maturity is common.

In Virtuovoshjaur the average weight of perch was 100–150 g and length 18–24 cm In Ilja-Nautsijarvi perch were of a smaller size (up to 100 g and 10–15 cm). In Lake Toartesjaur there were quite a lot of juvenile perch but also mature fish of all size classes were caught. In Lake Riuttikjaure the biomass was dominated of salmonids but small-sized percids were more abundant in numbers.

CPUE values for most of the study lakes can be deemed low. A high proportion of predatory fish was also noted in the structure of Russian fish populations. The biomass of predators in some lakes reached 64 % (Virtuovoshjaur), 84 % (Ilja-Nautsijarvi) and even 92 % (Toartesjaur).

In Lake Kochejaur in Russia the fish community has been studied in the period from 1989 to 2010. The proportion of perch was small in 1989 and whitefish has historically been the dominant species. New studies revealed an elevated proportion of perch. In

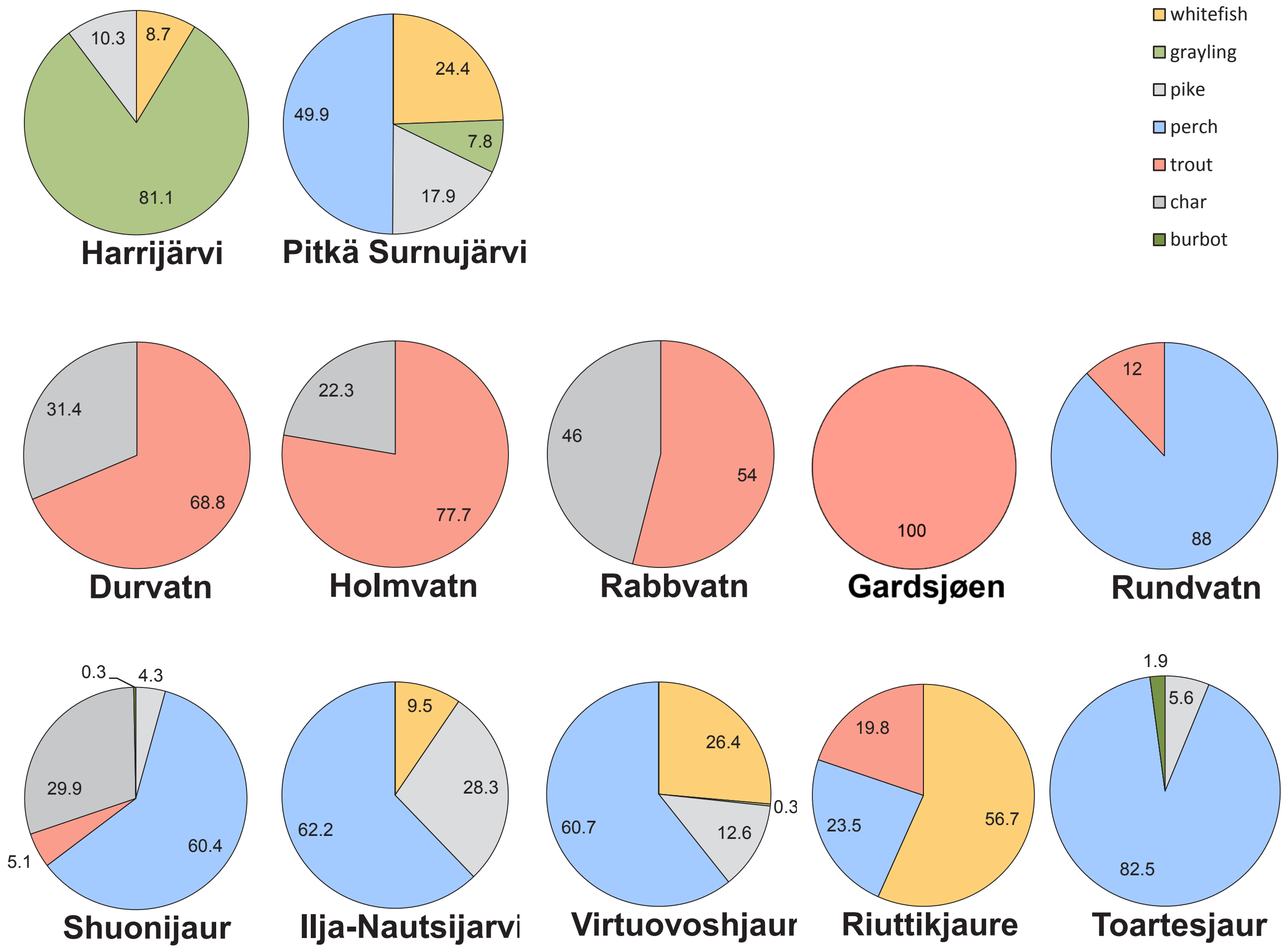


Figure 1. The proportions (biomass %) of different fish species in the studied lakes. Minnows were caught in lakes Pitkä-Surnujärvi and Ilja-Nautsijarvi, but their biomass proportions were so low that they rounded to zero.

Table 4. Summary of the results from the gillnet fishing in the Finnish lakes.

Lake	Fish species	Total catch (number)	Number %	Total catch (g)	Biomass %	CPUE g/net	CPUE number/net	CPUE (per 100 m²)
Harrijärvi	Pike	9	12	2699	10.3	128.5	0.4	0.9
	Whitefish	28	40.6	2285	8.7	108.8	1.3	2.9
	Grayling	32	46,4	21352	81.1	1016.8	1.5	3.3
	Total	**69**	**100**	**26336**	**100**	**1254.1**	**3.2**	**9.8**
Pitkä Surnujärvi	Perch	50	41.3	6936	49.9	315.3	2.3	5.1
	Pike	9	7.4	2494	17.9	113.4	0.4	09
	Whitefish	55	45.5	3390	24.4	154.1	2.5	4.9
	Grayling	6	5.0	1084	7.8	49.3	0.3	0.7
	Minnow	1	0.8	3	0.0	0.1	0.1	0.2
	Total	**121**	**100**	**13907**	**100**	**632.2**	**5.6**	**11.8**

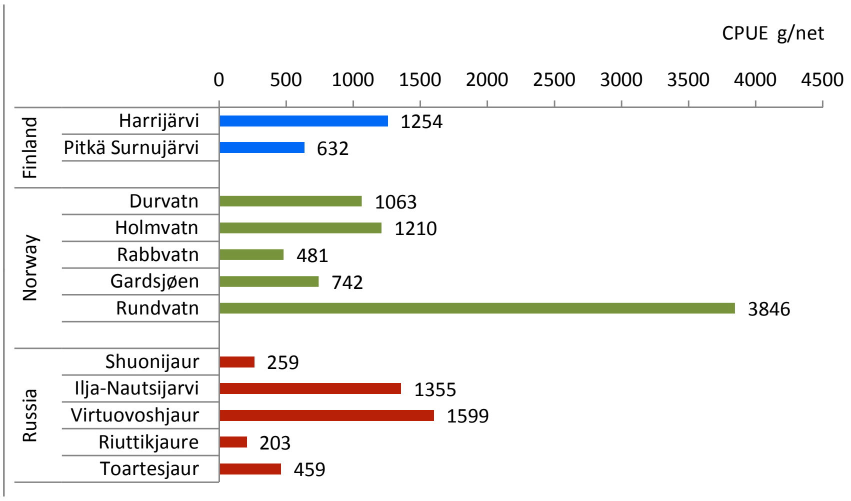


Figure 3. The total CPUE g/net in the study lakes.

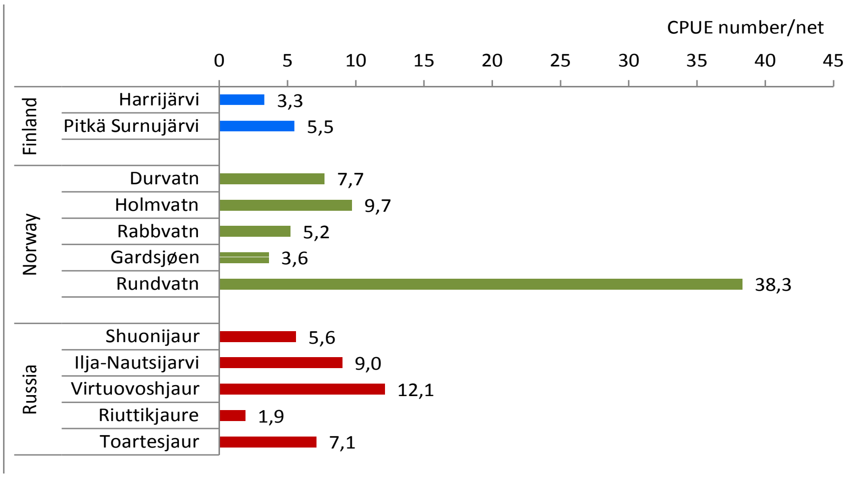


Figure 2. The total CPUE number/net in the study lakes.

Table 5. Summary of the results from the gillnet fishing in the Norwegian lakes.

Lake	**Fish species**	**Total catch (number)**	**Number %**	**Total catch (g)**	**Biomass %**	**CPUE g/net**	**CPUE number/net**	**CPUE (per 100 m^2)**
Durvatn	Trout	90	73.2	11666	68.6	729	5.6	12.5
	Arctic char	33	26.8	5340	31.4	334	2.1	4.6
	Total	**123**	**100**	**17006**	**100.0**	**1063**	**7.7**	**17.1**
Holmvatn	Trout	126	61.8	19725	77.7	939	6.0	13.3
	Arctic char	78	38.2	5678	22.3	270	3.7	8.2
	Total	**204**	**100**	**25403**	**100**	**1210**	**9.7**	**21.6**
Rabbvatn	Trout	34	41.0	4151	54.0	259	2.1	4.7
	Arctic char	49	59.0	3542	46.0	221	3.1	6.8
	Total	**83**	**100**	**7693**	**100**	**481**	**5.2**	**11.5**
Gardsjøen	Trout	76	100	15590	100	742	3.6	8.0
	Total	**76**	**100**	**15590**	**100**	**742**	**3.6**	**8.0**
Rundvatn	Trout	30	3.8	9100	12.0	446	1.5	3.3
	Perch	750	96.2	69000	88.0	3400	36.8	81.8
	Total	**780**	**100**	**78100**	**100**	**3846**	**38.3**	**95.1**

Table 6. Summary of the results from the gillnet fishing in the Russian lakes.

Lake	Fish species	Total catch (number)	Number %	Total catch (g)	Biomass %	CPUE g/net	CPUE number/net	CPUE (per 100 m²)
Shuonijaur	Trout	3	1.3	525	5.1	13.1	0.1	0.2
	Perch	208	88.9	6256	60.4	156	5.2	11.6
	Arctic char	20	8.5	3096	29.9	77.4	0.5	1.2
	Pike	1	0.4	441	4.3	11	0.03	0.1
	Burbot	2	0.9	32	0.3	0,8	0.1	0.2
	Total	**234**	**100**	**10350**	**100**	**259**	**5.93**	**13.3**
Ilja-Nautsijarvi	Perch	231	85.5	25293	62.2	843	7.7	17.1
	Whitefish	25	9.3	3859	9.5	129	0.8	1.8
	Pike	12	4.4	11495	28.3	383	0.4	0.9
	Minnow	2	0.7	3	0.0	0.1	0.1	0.2
	Total	**270**	**100**	**40650**	**100**	**1355**	**9**	**20**
Virtuovoshjaur	Perch	205	65.1	25228	60.7	970	7.9	17..5
	Whitefish	103	32.7	10963	264	422	4.0	8.9
	Pike	6	1.9	5241	126	202	0.2	0.4
	Grayling	1	0.3	130	0.3	5.0	0.04	0.1
	Total	**315**	**100**	**41562**	**100**	**1599**	**12.14**	**26.9**
Riuttkijaure	Perch	31	795	1001	23.5	47.7	1.5	3.3
	Whitefish	6	15.4	2415	56.7	115	0.3	0.7
	Trout	2	5.1	843	19.8	40.1	0.1	0.2
	Total	**39**	**100**	**4259**	**100**	**203**	**1.9**	**4.2**
Toartesjaur	Perch	145	97.3	8578	82.5	409	6.9	15.2
	Pike	3	2.0	582	5.6	27.7	0.1	0.2
	Burbot	1	0.7	1235	11.9	58.8	0.05	0.1
	Total	**149**	**100**	**10395**	**100**	**495**	**7.15**	**15.5**

the last test fishing perch formed the majority of the fish population. The whitefish population had only single specimens of younger age groups. The majority was 4–7 year old fish, which is associated with a high degree of fish migration from other water reservoirs, using Lake Kochejaur mainly as a feeding area. Absence of juvenile specimens is caused by silting up of the water reservoir and absence of spawning grounds.

Growth rate

Finland

The growth of grayling in Lake Harrijärvi was quite fast (on average, the total length of 30 cm was exceeded during the fourth growing season) whereas in Lake Pitkä Surnujärvi 30 cm length was not exceeded before the age of six. The growth rate seemed to be quite constant in Lake Harrijärvi and in Pitkä Surnujärvi during the first four growing seasons, but seemed to slow down after the individuals exceeded the length of 25 cm.

The growth of whitefish in Lake Harrijärvi was quite fast as the total length of 30 cm was exceeded on average during the third growing season but in Lake Pitkä Surnujärvi the growth was fairly slow. The growth rate in Harrijärvi was quite constant during the first three growing seasons but seemed to slow down after fish exceeded the length of 30 cm, whereas in Pitkä Surnujärvi the growth rate seemed to stay the same during all growing seasons.

The growth of perch in Lake Pitkä Surnujärvi was moderate when compared to other northern lakes (Sairanen et al. 2007) as the total length of 20 cm was exceeded during the sixth or seventh growing season, on average.

Norway

The growth rates for trout and Arctic char were relatively good the first 4–5 years in Lake Durvatn and Lake Gardsjøen. In lakes Rabbvatn and Holmvatn the growth rate for trout and Arctic char was lower compared to lakes Durvatn and Gardsjøen. In all the lakes the growth slowed considerably when the fish matured, which is normal. The age for maturity varied between the different lakes but both trout and Arctic char population in all the lakes started to mature at the age of four or five years old.

Russia

In the small Russian lakes short lifetime and early maturity of fish was noted despite their apparent remoteness from industrial pollution (Chapter 4, Introduction, Figure 1). Fish older than seven years are encountered in single specimens. The growth rates have decreased compared to earlier research in most lakes. In Lake Shuonijaur perch has higher growth rate than char. The growth rate of perch is high until the length of 20 cm but is then reduced, which can be explained by the transition to the combined and predatory type of feeding. The growth rate of char seemed to be quite constant at all ages. In Lake Ilja-Nautsijarvi the growth rates of all the fish species are low, for example the whitefish reach the size of 30 cm only at the age of 7–8 years. In Lake Virtuovoshjaur and Lake Riuttkijaure the growth rates of whitefish and perch are even somewhat lower than in Lake Ilja-Nautsijarvi.

In all of the Russian study lakes the whitefish (SR) grows fastest during the first year of life and the growth decreases when they reach the age of 2+. Whitefish of lakes Virtuovoshjaur and Ilja-Nautsijarvi have periods of even slower growth at the age of 7+ which accords with literature (Reshetnikov, 1966, 1980). The growth rate of the perch was noted to slow at the age of nine. In Lake Toartesjaur the growth rate of perch is average until the age of four and then it drops until the age of seven when it seems to start growing again.

Ecological status

According to test fishing results 2013 the fish community based ecological status of Lake Harrijärvi was good and Lake Pitkä Surnujärvi high. In the case of Lake Harrijärvi the number catch and indicator species indicated high ecological status whereas the biomass catch indicated only moderate ecological status. The high biomass catch compared to lake type (Finnish lake type Vh = Small and medium sized clear water lakes) specific reference value resulted from too high biomass catch of grayling that lead only to good overall ecological status. However, because grayling is one of the indicator species, Lake Harrijärvi should also be considered in the highest class (Table 7).

The ecological status of trout populations in the Norwegian lakes was classified as good in Durvatn, Holmvatn and Gardsjøen and moderate in Rabbvatn and Rundvatn. In Norway a method for ecological classification of fish communities other than trout has not been developed yet.

The method of lake ecological status classification based on the fish communities' condition is not developed in Russia. However, long-time experience of the researchers (INEP) made possible to assess the status of the studied Russian lakes based on comparisons with "reference water ecosystems". According to this expert assessment method, the ecological status of Lake Virtuovoshjaur was high and Lake Ilja-Nautsijarvi good. The other lakes´ status was classified as moderate.

Table 7. Ecological status of the fish populations in lakes in the border region according to national standards.

Country	Lake	Ecological status
Finland	Harrijärvi	High (very good)
	Pitkä Surnujärvi	High (very good)
Russia	Shuonijaur	Moderate
	Ilja-Nautsijarvi	Good
	Virtuovoshjaur	High (very good)
	Riuttikjaure	Moderate
	Toartesjaur	Moderate
Norway	Durvatn	Good
	Gardsjøen	Good
	Holmvatn	Good
	Rabbvatn	Moderate
	Rundvatn	Moderate

Malformations in fish and assessment of anthropogenic load

Malformations due to environmental pollution were noted in different species of fish in all the Russian lakes, as fish muscle, liver, kidneys and gills were analyzed for copper, nickel, mercury and zinc. The main affected organs were liver and kidneys but also changes in gonads and gills were detected. The common changes included pale color of liver (fatty degenerations), formation of excess connective tissue in kidneys and gonads, segmented structure and asynchronous maturity of reproductive products and distortion of gill rakers in whitefish. In general, the frequency of occurrence and intensiveness of fish pathologies stay on the same level with insignificant changes throughout the whole term of observations (Figure 4). The malformations are caused by toxic impact of heavy metals.

Copper concentrations have either grown in the last decades (more common) or stayed at the same level. Concentrations are highest in whitefish, especially in the bottom-feeding sparsely-rakered type, and in all studied species it accumulates most in the liver and kidneys. Nickel, in difference to copper, demonstrates a reduction of accumulation in fish over the last years. The differences between species and organs are not as clear as with copper but it seems that whitefish is the most affected species and kidneys and gills the most accumulating organs.

Mercury tends to accumulate more in the liver and kidneys than in the muscle and highest contents of mercury were naturally recorded in predatory fish. Exceeded maximum allowable concentrations of mercury were noted in muscle tissue of perch and pike throughout the whole observation period in the most distant lakes Kochejaur and Virtuovoshjaur (Figure 5).

Zinc enhances the toxicity of many other metals. Its concentrations did not exhibit time trends or interspecies trends in any of the water reservoirs and there is also a significant variability of zinc accumulation in fish organs within each species.

High variability of the heavy metal content within one species was recorded practically in all the water reservoirs. For some specimens the levels of copper, nickel and zinc accumulation were comparable to and exceeded the maximum values of metals' concentrations in the fish of Lake Kuetsjarvi, which is regarded as the most polluted water body of the Pasvik watercourse. This can testify of the retaining airborne anthropogenic load in the border area and impact of the secondary pollution from bottom sediments.

Malformations were not studied in Finnish and Norwegian lakes' fish. Norwegian lakes have suffered from acidification quite recently but the situation has improved. The quality of trout and char was evaluated based on the color of muscle and presence of parasites. The quality was good in Holmvatn and Rundvatn, moderate in Gardsjøen and relatively poor in Rabbvatn.

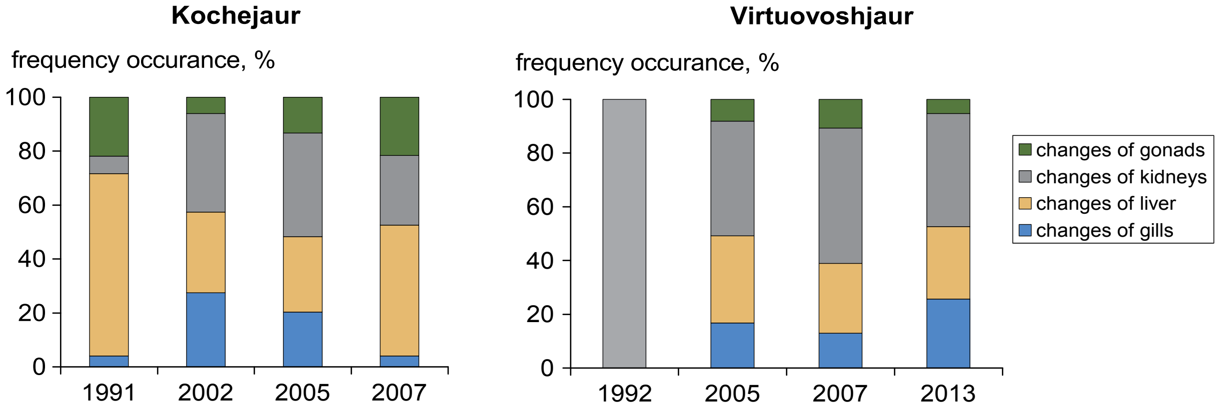
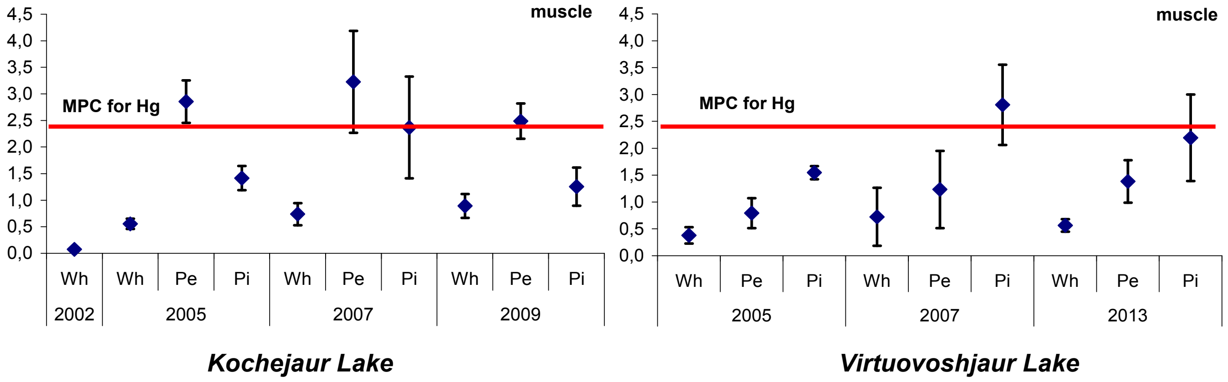


Figure 4. Frequency of malformations of whitefish in lakes Kochejaur and Virtuovoshjaur.



Kochejaur Lake

Virtuovoshjaur Lake

Figure 5. Mercury in fish muscle in lakes Kochejaur and Virtuovoshjaur over various periods of research ($\mu g/g_{\text{dry weight}}$/ppm). MPC = maximum permissible concentration, Wh = whitefish, Pe = perch, Pi = pike.

Summary and findings

Fish communities of small border area lakes in Finland, Russia and Norway were studied in 2013 and 2014 and the ecological status was evaluated based on fish community variables. The final aim was to evaluate the usefulness of fish community variables (community structure, growth rate, maturation age, longevity) in assessment of environmental impacts.

Based on earlier studies carried out in small lakes in the border area, several new variables were included in order to assess impacts of climate change, hazardous substance deposition and possible effects of acidification. One of the main reasons to conduct fish community studies was to carry out a baseline study using the methods required in the EU Water Framework Directive.

Fish community studies give information on how the community structure changes over time. Fish community variables measured in this study give a clear indication of how fish communities change across borders and over a long time period.

Lakes of Arctic and subarctic latitudes, as a rule, do not have a variety of fish species as species richness decreases as latitude increases (Hillebrand 2004). Arctic char, trout, whitefish and perch are the most common species in the border area of Finland, Russia and Norway.

Community structure

Finnish and Norwegian lakes are highly oligotrophic clear water lakes and their water quality is generally high. The fish communities represent the typical fish community of small sized lakes in northern areas where the number of species is low and salmonid fishes are dominant. No signs of environmental degradation were detected and occurrence of several year-classes of most species indicated no signs of failure in reproduction. No harmful effects of acidification on the fish communities of surveyed lakes were observed. Minnow, which is highly sensitive to acidification, existed in Lake Pitkä Surnujärvi For further monitoring, electrofishing of stony shores could be included to obtain a more reliable figure of minnow population.

The studied Russian lakes are all oligotrophic and the composition of fish community is typical for such arctic lakes even though the predominant species are changing from coregonids and other salmonids to perch. A fast restructuring of fish community of water reservoirs of the Murmansk Region in the last decade was noted: perch and cyprinids often replace salmonids. The number of perch in the lakes over the last decade has a constant tendency to grow, and in a number of lakes its proportion can reach over 90 %. This change in the fish community is evident in Norway, in the Pasvik River lakes, where an increase of perch most likely is related to observed temperature increases (Chapter 3, Long-term effects of metal contaminations, water regulations, species invasions and climate change on the fish community of the Pasvik River). In addition to climate change, also high level of loading from the indusrty, the catchments and bottom sediments may influence this change in species communities (Kashulin et al. 2012, Terentjev & Kashulin 2012).

Growth rate and maturation age

In the Finnish lakes the growth rates were quit fast and constant in both lakes. The growth rates in most lakes in Russia have decreased compared to earlier studies. In Norway the growth rate of trout was normal. The growth rate and maturation age varied for fish in the Norwegian lakes. In all the lakes the growth rate slowed considerably when the fish became mature at the age of four to six years. There seems to be a good correlation between growth rate, population density and lake morphology.

The studied Russian lakes are all oligotrophic and the composition of fish community is typical for such arctic lakes even though the predominant species are changing from coregonids and other salmonids to perch. The levels of priority toxicants copper, nickel, zinc and mercury are all elevated, which shows especially in whitefish through changes in life cycle and multiple malformations.

For future studies of the fish communities of small border area lakes it is recommended that monitoring should be continued with the NORDIC nets and same methods. Monitoring should be conducted at a three-year interval. Electrofishing of stony shores could be included to obtain a more reliable figure of minnow population and other species or size classes living in the shoreline in all of the study lakes. Monitoring of heavy metal levels and especially mercury in fish is recommended. The evaluation of the ecological status of the lakes based on fish communities should be done in an as uniform way as possible.

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Photos: Helén Johanne Andersen

Chapter 5: Influence of pollution and climate variation in small rivers indicated by freshwater pearl mussels

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Freshwater pearl mussels. Photo: Helén Johanne Andersen.

1 Freshwater pearl mussel – The environmental storyteller

The objectives of this investigation are to establish a method of revealing the influence of climate parameters and heavy metal pollutants in rivers using shells of freshwater pearl mussels for long time series. The effects of climate change on the hydrological regime of the rivers and further on the ecological status of the EU Water Framework Directive bioindicator and flagship species *Margaritifera margaritifera* have been evaluated from three rivers in two different climatic zones in Sør-Varanger County in Norway.

The freshwater pearl mussel (*Margaritifera margaritifera*) is a long-lived aquatic organism, which may reach an age up to 150–200 years (Bauer 1992, Ziuganov et al. 2000, Schöne et al. 2004, Helama & Valovirta 2008). It occurs in clear, flowing streams and rivers throughout northern Europe (Skinner et al. 2003). Overall abundances and populations have declined dramatically over the past century due to harvesting (for the shell and pearls) and habitat degradation (Bauer 1986, 1988), and the mussel is currently listed on the IUCN red list as severely threatened.

The hard parts of aquatic organisms (e.g. coral skeletons, shells of clams, fish otoliths) are deposited sequentially as the organism grows (Morrongiello et al. 2012). Consequently, the sequential deposition of hard parts by an animal records a biological and environmental chronology during its life, and the study of this record, sclerochronology, has been fundamental in reconstructing past environments (Hudson et al. 1976, Wanamaker et al. 2012).

The freshwater pearl mussel shell grows through sequential accretion of calcium carbonate material deposited at the shell margin (Mutvei et al. 1994, Dunca 1999). Seasonal changes in growth result in annual growth increments in the shell structure (similar to tree-rings). The size of the annual rings is affected by nutrients, pH, availability of food, availability of calcium and climatic and environmental factors such as water temperature and turbidity. This allows us to use the growth of the mussel as a proxy for different environmental conditions (Mutvei et al. 1996, Dunca et al. 2005, Black et al. 2010). The shells are excellent archive indicators of environmental changes, as they have solid and impermeable shells that retain incorporated elements from the ambient water without spatial relocation. This allows reconstruction the history of impacts like climate and pollution experienced over lifespans that can be well in excess of 100 years (Westermark et al. 1996), predating instrumental records in the area. The analysis of shell increments makes it possible to establish long-term growth chronologies and assess environmental conditions in different years (Jones et al. 1989, Schöne et al. 2003, Ambrose et al. 2006).

The freshwater pearl mussel is a key species in northern Norwegian rivers, especially in those containing Atlantic salmon and brown trout. The mussels are natural biological filters and one mussel can filter up to 50 liters of water per day (Hendelberg 1961). This reduces organic matter in the system, and hence helps to maintain oxygen levels in the interstitial water, which would be reduced through bacterial degradation of excess organic material on the bottom. Therefore, M. margaritifera is an effective indicator of the temporal variation in local pollution levels (Mutvei et al. 1996, Mutvei & Westermark 2001).

High levels of bioaccumulated metals have been found in the shells of *M. margaritifera* from several European countries, and toxic heavy metals (copper (Cu), lead (Pb), arsenic (As), nickel (Ni), and chromium (Cr)) are regarded to have contributed to the decline of freshwater pearl mussel populations. The same applies to the essential metals iron (Fe), manganese (Mn), and zinc (Zn). Cadmium (Cd) and Cu are predominantly found in the viscera; Mn, Ni, Pb, Mg, and Zn are mainly found in the combined other tissues, while Fe, As and Cr are evenly distributed between both fractions. Cu is a toxic metal to all aquatic organisms and is bioaccumulated to a rather high degree. Cu, Fe, Pb, Mg and As all interfere with calcium metabolism by different mechanisms. These heavy metals are also stored in the shell as it is secreted. Hence, simultaneously analyzing shell metal concentrations and growth patterns can lead to better constraints on the temporal history of metal inputs to the environment and ecosystem (Carroll et al. 2009).

Methods and key findings

30 living mussels were collected in 2012–2013 from each of the three rivers; Karpelva, Skjellbekken and Spruvbekken. The rivers are located in different climatic zones, enabling a comparison of growth of the mussel under variable climatic conditions. The *M. margaritifera* populations occur at various distances and directions from the Nikel combine at the Kola Peninsula in Russia. The freshwater pearl mussel is currently listed by the IUCN red list as severely threatened and it is therefore a challenge to collect mussels for investigation. However, this study has also taken into consideration the use dead shells to reveal new knowledge about pollution and climate variations.

The bivalve shells were sectioned dorso-ventrally along the axis of minimum growth starting at the hinge point of the shell. Then these cross sections were imaged and advanced imaging microscopy software was used to enumerate growth lines for growth rates in order to identify placement of sample sites for mineral, including heavy metal, analysis (Figure 1). Growth and age were calculated from the growth rings, and contaminant levels can be related to the increments, providing an absolute time marker. Shells exhibited annual growth distinguished from distinct lines signifying the winter period of little or no growth (Figure 1). This study determined that individuals from Karpelva (N=30) ranged in age from 60 to 220 years. Preliminary growth chronology was developed, which exhibits a variable shell growth pattern among years (Figure 2). The role of different environmental factors regulating these growth patterns (e.g. river temperature, air temperature, precipitation, wind etc.) will be studied further.

Tissue was dissected from shells and frozen for analysis of contaminants and stable isotopes.

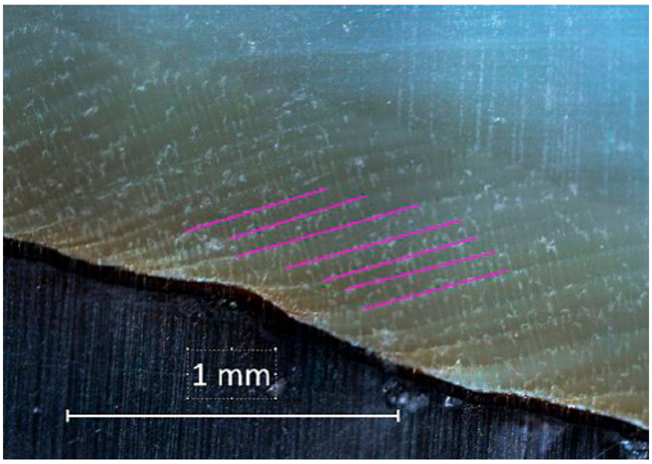


Figure 1. The growth increments of the *M. margaritifera*, which are produced with an annual cycle. These increments form the temporal basis of the chronology.

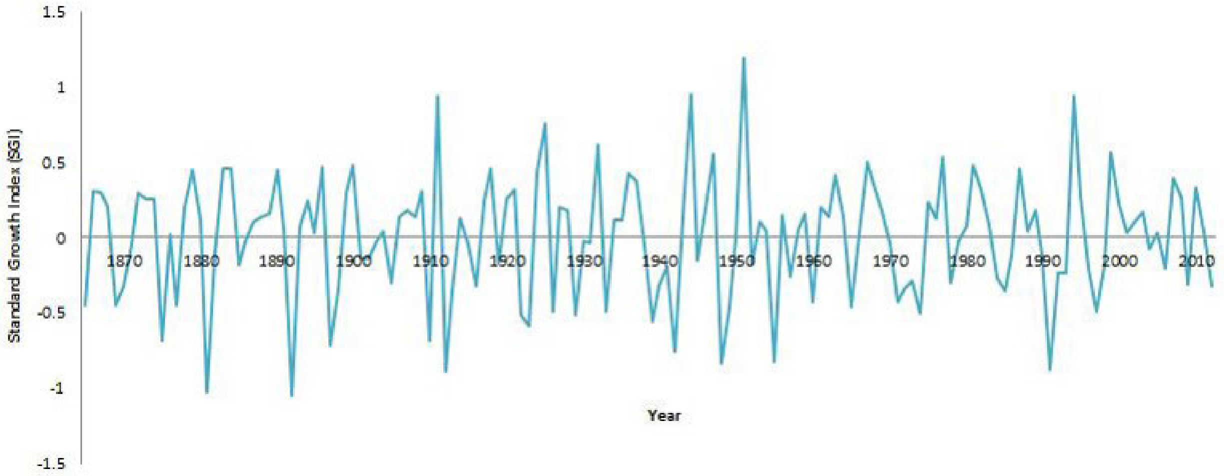


Figure 2. Growth chronology of the freshwater pearl mussels from the collection point in 2012 back to 1860, spanning some 150 years. Oscillatory periods of higher and lower growth are evident.

Shell and tissue isotopic ratios ($\delta^{18}O$, $\delta^{13}C$ and $\delta^{15}N$) can be proxies for water temperatures and food sources, respectively. Heavy metal concentrations in tissues and shells varied among individuals (Figure 3), but overall exhibited higher levels at Karpelva compared to other river systems farther afield from the Nikel plant (Figure 4).

Thin (1 mm) sections of the shell were prepared for geochemical analysis, followed by measurement of elemental ratios within the prismatic layer (Figure 5). The heavy metal concentrations in the shell material varied among time-periods with elevated concentrations of some elements after the Nikel plant came into operation (in the 1930s), compared with earlier (Figure 6). Iron and manganese particularly have trends of increased concentrations in growtn increments formed during the plant operation compared to before.

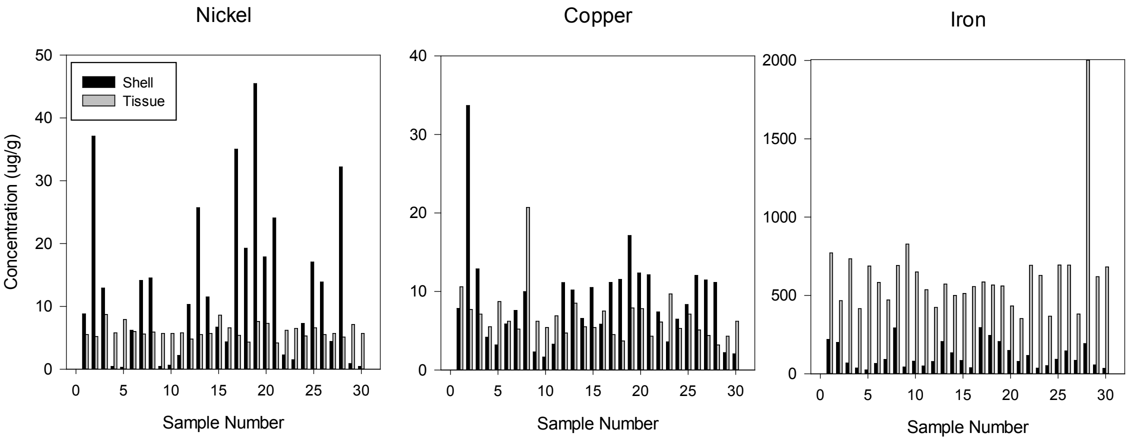


Figure 3. Heavy metal concentrations (Ni, Cu, Fe) in bulk shell and tissues from Karpelva.

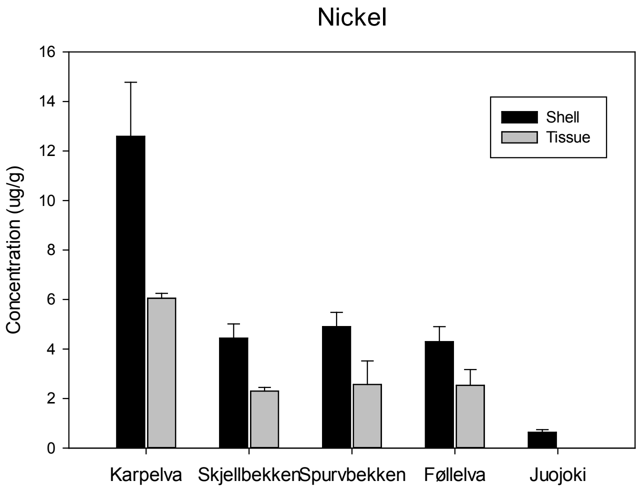


Figure 4. Comparison of nickel concentration (mean +SErr) in bulk shell and tissues from Karpelva and other river systems.

Conclusions

The results from this study show that the freshwater pearl mussel (*Margaritifera margaritifera*) can be used to investigate climate parameters and heavy metal pollutants for long time series in rivers. However, more investigation is needed to harmonize and calibrate the annual growth chronology and to relate growth differences among years to local climate and large-scale climate indices.

The project has also evaluated the possibilities to use mussels that have died of natural causes for monitoring of contaminants and climatic variations. It is possible, but it is beneficial that the mussels are relatively fresh and that the approximate time of death is known.

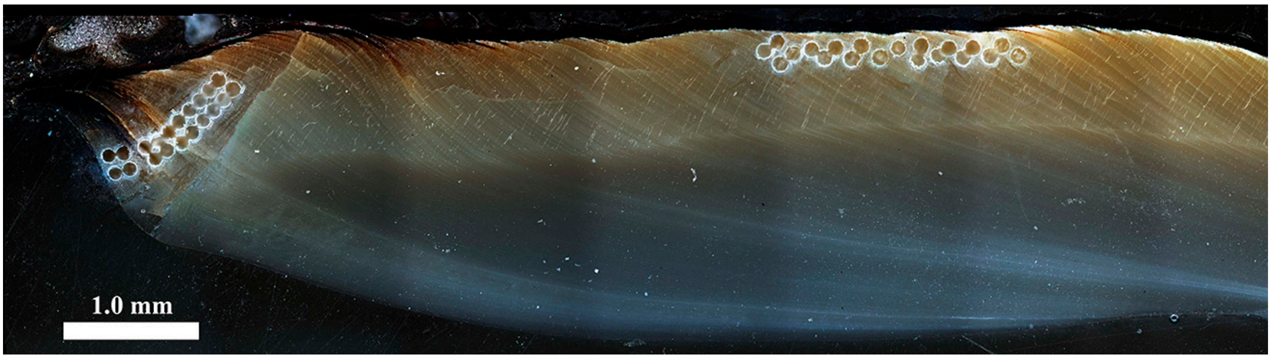
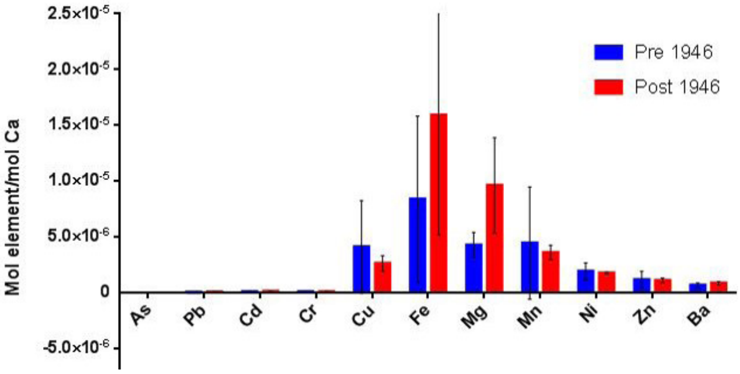


Figure 5. Image of the shell margin area of a freshwater pearl mussel after laboratory processing (sectioning and polishing). (Image: W. Locke)



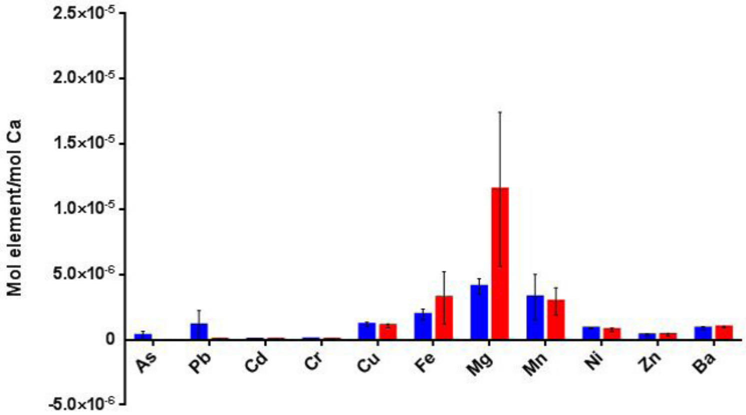


Figure 6. Concentration of various metals in the *M. margaritifera* shells from Karpelva (site 1 = upper figure, site 2 = lower figure), separated in periods before and after the beginning of operation of the Nikel plant in Russia in 1946.

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Freshwater pearl mussel investigations. Photos: Helén Johanne Andersen.

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Environmental Challenges in the Joint Border Area of Norway, Finland and Russia

Abstract

This report examines the human impact on the subarctic environment of the joint border area of Norway, Finland and Russia. The aim is to present the current state and recent changes that have taken place in the region.

The main threat to the environment is the Pechenganikel mining and metallurgical industrial combine in the towns of Nikel and Zapolyarny in the Kola Peninsula. Emissions from this complex include high levels of heavy metals, persistent organic pollutants and sulfur dioxide. Pollution, along with climate change, water level regulation and other anthropogenic effects, has affected the aquatic ecosystems in the joint border area.

The main heavy metals in the area are copper and nickel, the highest concentrations of which are measured near the combine. Direct discharge of sewage into the river continues and airborne heavy metal particles are also deposited to areas farther away. Climate change-induced increase in temperature and precipitation in the Kola Peninsula is evident. Water level regulation with seven hydropower plants in the Pasvik River have changed it into a series of lakes and lake-like reservoirs.

This report discusses modelling, which was enabled to estimate the effect of climate change on Lake Inarijärvi and the Pasvik River hydrology, water level fluctuation and ecology and to follow the sulfur dioxide emissions emitted from the Pechenganikel. Effects of pollution on the nature and concentrations of the main pollutants were studied and climate change in the border area and its effects on the ecology were estimated. Also the effects of water level regulation on the ecological status of the aquatic ecosystems were addressed.

Keywords
Environment, monitoring, air quality, climate change, water quality, aquatic, ecosystems, the Pasvik River, heavy metals, POPs

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Environmental Challenges in the Joint Border Area of Norway, Finland and Russia
(Ympäristöhaasteet Norjan, Suomen ja Venäjän yhteisellä raja-alueella)

Tiivistelmä

Tässä raportissa tarkastellaan ihmisten aiheuttamia haittoja Norjan, Suomen ja Venäjän yhteisellä, subarktisella raja-alueella. Raportissa esitetään ympäristön nykytila ja alueella tapahtuneet viime-aikaiset muutokset.

Suurin uhka ympäristölle on Nikkelissä ja Zapolyarnyissa Kuolan niemimaalla sijaitseva Petsenganikelin kaivos- ja metalliteollisuuskombinaatti. Laitoksesta leviää ympäristöön suuria määriä raskasmetalleja, pysyviä orgaanisia yhdisteitä ja rikkidioksidia. Saasteet, yhdessä ilmastonmuutoksen, säännöstelyn ja muiden ihmisvaikutusten kanssa, ovat vaikuttaneet yhteisen raja-alueen vesiekosysteemeihin.

Alueen tärkeimmät raskasmetallit ovat kupari ja nikkeli, joiden ptioisuudet ovat korkeimmillaan kombinaatin lähellä. Suorat jätevesipäästöt jokeen jatkuvat ja raskasmetallihiukkaset kulkeutuvat ilman mukana myös kaukaisemmille alueille. Kuolan niemimaalla on havaittavissa ilmastonmuutoksen aiheuttama lämpötilan ja sademäärän nousu. Paatsjoen säännöstely seitsemällä vesivoimalalla on muuttanut joen järvien ja järvimäisten patoaltaiden jatkumoksi.

Tässä raportissa käsitellään mallitusta, jolla arvioitiin ilmastonmuutoksen vaikutuksia Inarijärven ja Paatsjoen hydrologiaan ja veden pinnankorkeuden vaihteluihin ja seurattiin Petsenganikelin rikkidioksidipäästöjen leviämistä. Saasteiden vaikutuksia luontoon ja päähaitta-aineiden pitoisuuksia tutkittiin ja ilmastonmuutosta raja-alueella ja sen vaikutuksia ekologiaan arvioitiin. Lisäksi havainnoitiin vedenkorkeuden säännöstelyn vaikutuksia vesiekosysteemien ekologiseen tilaan.

Asiasanat (YSA:n mukaan)
Ympäristö, seuranta, ilmanlaatu, ilmastonmuutokset, vedenlaatu, vesiekosysteemi, raskasmetallit, pysyvät orgaaniset yhdisteet

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Environmental Challenges in the Joint Border Area of Norway, Finland and Russia
(Экологические проблемы общей приграничной территории Норвегии, Финляндии и России)

Резюме

Данный отчёт является обзором настоящего состояния окружающей среды и произошедших за последние годы изменений в приграничном районе Норвегии, Финляндии и России. Основное внимание уделяется антропогенному воздействию на водную среду.

Горно-металлургический комбинат ”Печенганикель”, расположенный на северо-западе Мурманской области, является одним из самых крупных объектов, влияющих на состояние природной среды в приграничном районе. Выбросы комбината содержат высокие концентрации тяжелых металлов, стойких органических загрязняющих веществ и диоксида серы. Загрязнение в сочетании с климатическими изменениями, регулирование уровня воды и другие антропогенные факторы оказывают негативное воздействие на водные экосистемы общей приграничной территории.

Из тяжелых металлов наиболее значимыми загрязнителями в этом районе являются медь и никель, самые высокие концентрации которых наблюдаются вблизи комбината. Продолжаются сбросы токсических веществ в притоки реки Паз. Свой вклад в загрязнение региона привносит и трансграничный перенос поллютантов. В связи с климатическими изменениями отмечается рост температуры и количества осадков на Кольском полуострове. Семь ГЭС на реке Паз превратили ее в цепь озер и водохранилищ озерного типа.

В публикации помещена информация о моделировании, позволяющем проследить за перемещениями выбросов диоксида серы и оценить воздействие климатических изменений на гидрологический режим, колебание уровня воды озера Инари и реки Паз, на их экологическое состояние. Продолжается изучение влияния регулирования на состояние водных экосистем в условиях изменения климата.

Ключевые слова
Окружающая среда, мониторинг, качество воздуха, климатические изменения, качество воды, водный, экосистемы, река Паз, тяжёлые металлы, СОЗ

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Environmental Challenges in the Joint Border Area of Norway, Finland and Russia
(Miljøutfordringer i grenseområdet mellom Norge, Finland og Russland)

Sammendrag

Denne rapporten tar for seg miljøtilstanden i grenseområdet mellom Norge, Finland og Russland, på bakgrunn av industriell aktivitet i området. Målet er å slå fast den nåværende miljøtilstanden og eventuelle nylige endringer.

Den største trusselen mot miljøet er gruve- og fabrikkanleggene i Nikel og Zapoljarnij. De forurensede utslippene fra smelteverkene er tungmetaller, persistente organiske forbindelser (POPs), og svoveldioksid (SO_2). Forurensning, klimaendringer, vannregulering, og andre menneskeskapte påvirkninger har konsekvenser for det akvatiske økosystemet i grenseområdet.

Kobber og nikel er de mest framtredende tungmetallene som slippes ut fra smelteverkene, hvor de høyeste nivåene er målt nærmest smelteverket. Smelteverket slipper ut avløpsvann til nærliggende elver og tungmetaller til luft som kan langtransporters i atmosfæren. Det er tydelige tegn til klimaendringer, høyere temperaturer og mer nedbør på Kolahalvøya. Vannstanden i Pasvikelva blir regulert med syv vannkraftverk, dette har resultert i at elva har fått et innsjøliknende preg.

Denne rapporten tar også for seg modellering for å kunne anslå effektene av klimaendringer i Enaresjøen og Pasvikelva. Modelleringen vil også kunne anslå i hvilken grad endringer i vannstanden, økologi og SO_2 sluppet ut fra Penchenganikel har på miljøet i regionen. På bakgrunn av en rekke miljøundersøkelser er konsekvensene av forurensede utslipp og klimaendringer estimert. Hvilke konsekvenser vannregulering har på miljøtilstanden og det akvatiske miljøet er også blitt undersøkt.

Emneord
Miljø, overvåkning, luftkvalitet, klimaendringer, vannkvalitet, akvatisk, økosystem, Pasvikelva, tungmetaller, POPs

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