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ScienceDirect

Science of the Total Environment 369 (2006) 1 – 20

Science of the Total Environment
An International Journal for Scientific Research into the Environment and its Relationship with Humankind

www.elsevier.com/locate/scitotenv

Ecosystem and human health assessment to define environmental management strategies: The case of long-term human impacts on an Arctic lake

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Received 6 February 2006; received in revised form 14 June 2006; accepted 16 June 2006

Abstract

There are rich deposits of mineral and fossil natural resources in the Arctic, which make this region very attractive for extracting industries. Their operations have immediate and vast consequences for ecological systems, which are particularly vulnerable in this region. We are developing a management strategy for Arctic watersheds impacted by industrial production. The case study is Lake Imandra watershed (Murmansk oblast, Russia) that has exceptionally high levels of economic development and large numbers of people living there. We track the impacts of toxic pollution on ecosystem health and then — human health. Three periods are identified: (a) natural, pre-industrial state; (b) disturbed, under rapid economic development; and (c) partial recovery, during recent economic meltdown. The ecosystem is shown to transform into a qualitatively new state, which is still different from the original natural state, even after toxic loadings have substantially decreased. Fish disease where analyzed to produce and integral evaluation of ecosystem health. Accumulation of heavy metals in fish is correlated with etiology of many diseases. Dose–effect relationships are between integral water quality indices and ecosystem health indicators clearly demonstrates that existing water quality standards adopted in Russia are inadequate for Arctic regions. Health was also poor for people drinking water from the Lake. Transport of heavy metals from drinking water, into human organs, and their effect on liver and kidney diseases shows the close connection between ecosystem and human health. A management system is outlined that is based on feedback from indices of ecosystem and human health and control over economic production and/or the amount of toxic loading produced. We argue that prospects for implementation of such a system are quite bleak at this time, and that more likely we will see a continued depopulation of these Northern regions.

Keywords: Toxic impacts; Water quality; Metal bioaccumulation; Ecosystem health; Human health; Environmental management strategies

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doi:10.1016/j.scitotenv.2006.06.009

1. Introduction

Increasing demands of the human population require more natural resources, and push extractive industries to the previously uninhabited or sparsely inhabited areas. That is what brought them to the Arctic. That is why there are vast encroachments into the Arctic regions in many places. Arctic nature is very vulnerable to anthropogenic impacts. Slow mass- and energy exchange in ecosystems of high latitudes, makes trophic chains short, and biodiversity low, which causes rapid migration of pollutants through trophic levels, and results in fast and severe ecosystem damages.

On the other hand, the vulnerability of northern ecosystems is a limiting factor for economic development and, accordingly, the quality of life. Sustainable development assumes a balance between economic, social and environmental priorities. High economic profits conflict with ecological requirements: old technologies with no investments in environmental protection degrade the conditions of human life in the North, deplete natural capital, further decrease resilience, biodiversity, aesthetic and recreational value of the ecosystems. The alternative between permanent settlements and rotating temporary work force becomes more uncertain. Required large investments in ecological safety decrease industrial profit and, accordingly, salaries and social infrastructure. As a result there is a higher chance of population emigration, lower quality of medical services, decreasing birthrate, increasing mortality, etc. Either we need to provide effective management tools to ensure environmental safety and sustainable development. Or the large human population should be removed (or never brought back), with economic development achieved by small teams of temporary workers. In which case further and more acute degradation of natural resources is even more likely, since there will be no local controls and no sense of ownership of ecological resources by the temporary residents. It is hard to make the right decisions about the future of these regions, without understanding the specifics of human impacts on Arctic ecosystems and how the disturbed Arctic environment may affect the livelihood of human population.

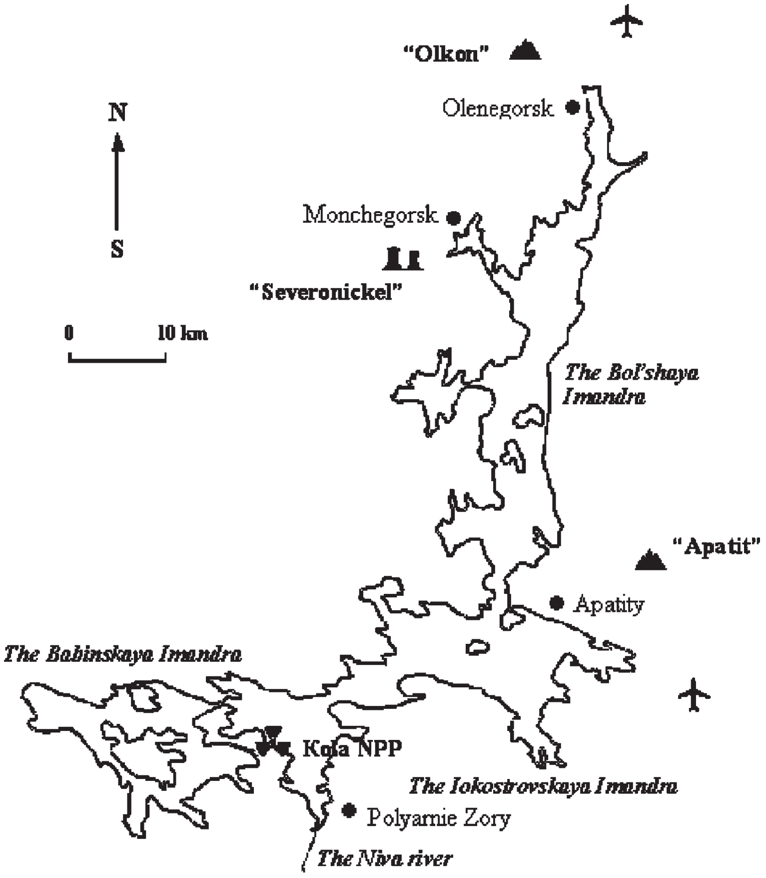

Fig. 1. Map of Lake Imandra and location of the main enterprises on its shores.

Among Arctic regions, the Russian Kola North (Murmansk region) is the most densely populated and industrially developed. The spectrum of anthropogenic impacts is wide: mining, metallurgy, refineries and chemical industries, nuclear power station, etc. A large part of these industries are in the Lake Imandra catchment basin. The population living here is about 300,000 people, or 35% of all population of Murmansk region. The watershed covers 12,300 km^2; the area of the Lake is 880 km^2. The lake consists of three parts connected by narrow straits (Fig. 1).

For more than 70 years the lake, the reservoirs, streams and rivers are used as a source of technical and drinking water supply, for recreation, tourism and fishery. Industrial development of mineral deposits close to the Lake began in the 1930–40s and reached maximum in the 1980s. The watershed can work as a model region for designing best management practices for sustainable development in the Arctic. There have been large human made changes in the ecosystems there. For sustainable development of this region it is important to define the limits for economic impacts that the environment can absorb without compromising ecosystem and human health in the watershed.

Our main objectives were as follows:

1. Understand the anthropogenic effects on water quality and the ecosystem response to development using Lake Imandra watershed as a case study.
2. Assess Lake ecosystem health, establish critical levels of water pollution, and compare them with existing levels of pollution.
3. Estimate the influence of drinking water pollution on health of local human population, and provide recommendations for water quality standards in Arctic regions.
4. Design management tools for environmental protection.

This work is based on analytical reviews of long term investigations of the authors and previous research and methods reported by Vereshagin (1930), Rikhter (1934), Poretskij et al. (1934), Voronikhin (1935), Krokhin and Semenovich (1940), Berg and Pravdin (1948) and also Galkin et al. (1966), Petrovskaya (1966), Dol'nik and Stal'makova (1975), Den'gina (1980), Moiseenko and Yakovlev (1990), Moiseenko (1999), Moiseenko et al. (1999), Yakovlev (1998), Iliaschuk (2002a,b), Vandish (2000, 2002). Unfortunately, there was no continuous monitoring of the Lake, so we had to make the best of the available information. Retrospective analysis was complemented with results of field investigations of 2003. We focused on the main parameters of water chemistry and indicators of phyto-, zooplankton, benthos and fish condition, which best reflect ecosystem change under anthropogenic impacts in relation to the reference condition, as well as the quality of drinking water and health of the local human population.

Table 1
Influx of pollutants from watershed into the Bol'shaya Imandra (numerator — in 1989 year, denominator — in 2003 year)

Rivers	Watershed area, km^2	discharge, m^3/s	SO$_4$, t/year	Ni, t/year	Cu, t/year	P, t/year	N, t/year
Nyuduaj	86.37	1.29	*39,867*	*101.7*	*4.9*	*2.8*	*69.9*
			25,548	14.2	3.9	2.8	20.1
Monche	1583.5	20.5	*23,624*	*39.7*	*47.3*	*6.2*	*75.3*
			2596	6.9	6.3	2.3	75.6
Gol'tsovka	92.3	1.84	*46*	*0.1*	*0.1*	*1.4*	–
			78	0.03	0.03	0.2	5.2
Vite	236.2	5.68	*1049*	*1.4*	*1.1*	*2.3*	*59.6*
			505	0.8	0.9	1.0	23.2
Kurkenjok	176.8	3.37	*792*	*0.9*	*0.8*	*2.6*	*50.0*
			519	0.4	0.5	0.6	13.4
B. Belaya	236.1	4.72	*4465*	*0.7*	*0.9*	*53.1*	*771.9*
			3647	0.1	0.4	54.5	332.5
Sum of inflow with rivers			*69,844*	*144.7*	*55.1*	*68.3*	*1026.8*
			32,893	22.4	12.0	61.5	470.0
Unaccounted inflow			*1509*	*2.0*	*1.6*	*4.9*	*87.7*
			882	0.9	1.1	1.4	33.4
Total inflow			*71,354*	*146.7*	*56.7*	*73.3*	*1114.6*
			33,775	23.4	13.0	62.9	503.4
Outflow			*41,683*	*31.5*	*12.2*	*32.1*	*482.3*
			32732	9.5	6.3	22.7	142.9
Accumulation			*29,671*	*115.2*	*44.6*	*41.2*	*632.3*
			1043	13.9	6.8	40.2	360.5

2. Anthropogenic loads and changes in water chemistry

Once Lake Imandra was a typical ultra-fresh and oligotrophic lake, with low concentrations of suspended material (0.7–1.0 mg/l), microelements (<1 μg/l), and nutrients. Concentration of total phosphorus was less than 2 μg/l; phosphates during the vegetation period were practically completely utilized in the production processes. Water transparency was about 8 m. The lake was characterized by high saturation of waters by oxygen (up to the bottom) due to mountain ice-free rivers falling into the lake (Rikhter, 1934; Krokhin and Semenovich, 1940). In the past the local population, mostly Saami historically living along the coasts of the lake, was very small, and before 1930 there was practically no human effect on the lake ecosystem.

Rich mineral deposits found on the coast of the lake (apatite–nepheline, iron, manganese, copper–nickel ore) brought big mining industries. In the 1930–40s mining and enrichment of the apatite–nepheline ore began, and the “Apatit” industrial complex was built. In the 1940–50s — “Severonickel” combinat was built for nickel extraction; in the 1950–60s — Olenegorsk mining operations started producing iron–manganese ore; and in 1974 — the Kola nuclear power station started to provide local industries with energy. For map of sites of main industries see Fig. 1.

Accordingly during these periods the industries became the main factors for building of towns and cities: so the cities of Monchegorsk, Olenegorsk, Apatity, and Polyarnye Zori appeared. Now increasing human population, and industrial and household pollution were affecting the lake. Yet still, paradoxically, Lake of Imandra was and still is used as a sink of industrial and domestic wastewater, as well as a source of drinking water for several cities.

Table 1 presents the annual influx of main contaminants during two periods: intense pollution (1989) and when pollution was in decline (2003). Most of the metals were entering the lake by river Nyuduaj, nutrients — came with rivers Belaya and Monche. The lake catchment and waters were also receiving airborne pollutions, which amount was quite significant at times.

Over many years these anthropogenic loads, which started in the 1940s and reached maximum in the 1980s, caused serious changes in water chemistry: transparence decreased, salt concentrations increased, pH moved towards alkaline condition in comparison to the reference condition (Table 2). As a result of influx of salts the ionic composition of waters changed. Technogenic sulfates in ionic composition of waters have dominated over hydro-carbonates. The pollution from the metallurgical enterprise has increased the content of heavy metals and especially that of nickel, copper and zinc.

Table 2
Dynamics of water chemistry (basic ions, nutrients, trace elements) in Bol’shaya Imandra during different periods (numerator — average values, denominator — minimum and maximum values)

Parameters	Reference condition*	Periods			
		1972–1982	1983–1992	1993–1998	2003
pH	6.4–7.2	*7.2* 6.9–7.5	*7.4* 6.7–7.9	*7.2* 7.1–7.3	*7.4* 6.9–7.7
Total ion content, mg/l	20 – 30	60	87	80.5	81.3
Ca, mg/l	2 – 5	4.2	4.7	4.1	3.8
Mg, mg/l	1–2	2.2	1.6	1.1	1.2
Na, mg/l		15.0	20.1	14.8	17.4
K, mg/l		3.4	3.3	2.4	2.5
HCO_3, mg/l	13–18	20.3	20.9	20.2	22.6
SO_4, mg/l	1–3	16.1	29.7	24.2	28.5
Cl, mg/l	1–2	4.2	7.7	5.5	5.4
PO_4, μg/l	0–8	–	*11* 2–26	*9* 1–37	*3* 0–12
TP, μg/l	2–18	*124* 22–660	*27* 4–100	*38* 8–114	*26* 13–68
NH_4, μg/l	0–20	–	*48* 33–75	*36* 8–120	*21* 2–76
NO_3, μg/l	0–35	–	*23* 8–55	*24* 2–230	*20* 1–158
TN, μg/l	30–300	–	*298* 170–460	*263* 97–435	*188* 106–402
Si, mg/l	0.6–0.8	*1.1* 0.2–2.2	*1.0* 0.1–4.6	*0.9* 0.1–2.8	*0.4* 0.1–1.4
Permanganate consumption, MgO/l	3–5	*3.9* 2.0–6.1	*3.2* 1.4–4.5	*3.3* 2.5–4.5	*2.8* 2.3–3.8
Ni, μg/l	≤1	*42* 16–84	*61* 13–290	*15* 13–19	*10* 7–27
Cu, μg/l	≤1	*3* 0–5	*18* 5–28	*6* 5–8	*5.5* 4–10
Sr, μg/l	≤30	–	*66* 54–83	*69* 60–80	*59* 32–72
Al, μg/l	≤10	–	*41* 19–80	*38* 20–80	*61* 14–145
Fe, μg/l	≤15	–	*27* 13–40	*29* 16–50	*35* 9–60
Mn, μg/l	≤5	–	*9.3* 1–17	*10.4* 6–18	*13.2* 6–35
Zn, μg/l	≤2	–	*11* 2–27	*2.8* 1–6	*2.5* 1–15
Cd, μg/l		–	–	*0.3* 0.1–0.6	<0.05
Pb, μg/l		–	–	–	<0.3

Reference conditions are established based on Rikhter, 1934; Vereshagin, 1930; Krokhin and Semenovich, 1940, with corrections based on representative unpolluted lakes of the Kola North.

Anthropogenic influx of nitrogen and phosphorus to the Lake caused an increase of total contents of these elements and their mineral derivatives (in comparison to the reference condition). According to the phosphorus content, most of the lake became mesotrophic by classification of Vollenweider (1979), and Monche and Belaya Bays, where the domestic sewage is discharged, and some other warm bays became corresponding to the eutrophic status. In general, from Table 1 we can conclude that water chemistry and living conditions for all water inhabitants became different from pristine natural conditions, with a new feature now present, that is, water toxicity.

Transformation of economic conditions in Russia at the end of 1980s, beginning of 1990s brought a stop to many industrial activities and, accordingly, slowed down lake pollution. Some revival of the economy in the last decade is spurred by technology modernization and more restrictions on pollution of the lake and the atmosphere. As a result over the 14 year period the influx of nickel with river Nuduaj has dropped by more than 7 times; sulfates and copper have also decreased (see Table 1). While nitrogen pollution also decreased, phosphorus influx stayed the same. Data show that in general, in 2003 anthropogenic stress on the lake (direct pollution and airborne deposition to the catchment area) has decreased.

Calculation of balances between concentrations and flows in reaches show volumes of element accumulations by reaches (see Table 1). Nickel and copper accumulation during these years decreased in proportion to levels of lake pollution and were 13.9 and 6.8 t, respectively. If in 1998 the lake accumulated up to 90% of nickel (from total influx volume) and 75% of copper, in 2003 this percent has decreased and was about 50% for both elements. Outflow of sulfate is about the same as the inflow. However phosphorus and nitrogen accumulation in relation to their inflow has increased due to increase of biological use of the element in the trophic structure of the ecosystem.

There are no data about the number of species and biomass of phyto- and zooplankton for that period, but by analogy with non-polluted areas of this lake and other lakes of Kola Peninsula we can determine that total biomass of phytoplankton in summer was less than 1 g/m^3 and its amount was 160,000 cells/l, while the information index of the species (Shannon's index of biodiversity) during vegetation season was 3.5–4.0 in unpolluted areas. Average value of Chlorophyll-*a* in the ice-free period was 0.2–0.3 mg/m^3. The biomass of zooplankton varied from 0.2 to 1.0 g/m^3 and the number of species was from 10 to 100,000 ind/m^3; the Shannon index ranged from 2.5 to 3.0 bit/ind.

During the period of economic crisis and depopulation, metal concentrations in the water have decreased accordingly. Contents of nickel in Monche Bay became about 25 μg/l in 2003. Similar tendency is seen for copper and zinc concentrations. We can conclude that toxic properties of water have decreased. The ionic content was stable.

Total phosphorus concentrations varied substantially at different times. They were very high in the 1970s, went down in the 1980s, and in 2003 were at about the level of the 1980s. Concentrations of nitrogen fluctuated as well. However both were always higher than one would expect for an oligotrophic lake. Note that while total phosphorus remained quite high, its mineral phase, phosphates, plummeted, along with the concentration of silica (lower than natural conditions). This is likely a result of fast uptake of these elements by developing alga (mostly diatoms), and indicates that the eutrophication processes is well underway.

Our results show that water quality has worsened during the period of economic growth and associated intense pollution, and they did not recover completely during last decade despite the reduction of pollution.

3. Effects of water contamination on the lake ecosystem

In past the water inhabitants were represented mainly by Arctic cold-water species that are typical for north Fennoscandia. The analysis of phytoplankton structure has shown significant abundance and a variety of diatoms in this early period (Rylov, 1916; Poretskij et al., 1934; Voronikhin, 1935; Rodhe, 1948). In the dominant complex is presented in Table 2.

Among the macro-zoobenthos in the profundal zone of the lake there were more than 70 species and forms of invertebrates, among which by number of species and frequency of occurrence the dominant ones were the larvae of midges (Chironomidae family), bivalves *Euglesa* spp. and relict crustacean (*Monoporeia affinis* and *M. relicta*), which are found in all lakes of Fennoscandia (Gerd, 1949; Dol'nik and Stal'makova, 1975; Särkkä et al., 1990). Among Oligochaeta we noticed representatives of Lumbriculidae, Naididae and Tubificidae families. It is rather difficult to reconstruct natural parameters of zoobenthos using analogies with non-polluted areas, because of the influence of biotope character on species content and structure of zoobenthos communities. We should notice, that *M. affinis* predominates in non-polluted areas of Kola lakes (occurrence in sample up to 100%). For a pre-industrial period, exactly in 1930, average values of biomass of zoobenthos were not more than 1.1–1.4 g/m^2 (Krogius, 1930) and these values corresponded with an α-oligotrophic lake level. Values of biodiversity index of communities were up to 3.5 bit/ind (Table 3). Fishes were represented by 16 species (Berg and Pravdin, 1948). By contents of fish catches the lake was a typical whitefish-loach lake with presence of trout. In catches of 1945–1960 predominated species were species of freshwater–arctic complex, their contents in catches were: 90% — *Coregonus lavaretus* (L) — 20% and *C. albula* (L) — 50%, *Salvelinus alpinus* (L) — 7% and *Salmo trutta trutta* (L) — 3% (Galkin et al., 1966). Estimated fish productivity for lakes was 4 kg/ha.

Multiyear anthropogenic pressure on the lake caused changes to all structural components of the ecosystem. Structure of phytoplankton, zooplankton, and benthos became poor. It consists of eurybiontic species that are widespread in the Arctic, and cosmopolitans. The structure of dominating complexes has changed, their biodiversity was reduced, and the biomass was increased (Table 3).

In phytoplankton structure Green algae of genus *Scenedesmus*, *Paldorina* and some species of diatoms are dominant in polluted areas. During this period such species as *Asterionella formosa* and Tabellaria fenestratà, common for the Lake, were not observed. Species of genus *Fragilaria*, *Synedra*, *Diatoma*, *Aulacoseira*, *Stephanodiscus* were dominant. Phytoplankton biomass has increased in all the lake; in some parts it could be over 20 g/m^3 (Sharov, 2002). For algae no species-indicators of heavy metal pollution were found, and community diversity parameter is not a reliable indicator in these conditions (Moore, 1981). Increasing of biomass of chlorophyceans and cryptomonads, probably, can be an indicator of lake eutrophication.

In zooplankton of this period adult species were rare or absent for Calanoida and Cyclopoida. Also missing were predatory Cladocera (*Leptodora kindtii*, *Polyphemus pediculus*), *Collotheca* sp., *Conochilus* sp., *Holopedium gibberum* (see Table 2). Eurybiontic species (*Asplanchna priodonta*, Keratella ñochlearis, *K. quadrata*, *Notholca caudata*, *Bosmina obtusirostris*) were predominant. Note that Àsplanchna priodonta was 40–50% of their average number of species (Yakovlev, 1998; Vandish, 2000, 2002). Domination of this species in polluted waters was registered by MacIsàac et al. (1987). The total number and biomass of zooplankton increased. Index of biodiversity by number of species fluctuated in the range of 1.5–2.3 bit/ind.

The most significant degradation of macro-zoobenthos was in the 1980s. Biodiversity decreased while biomass of benthic communities increased. In the zones of copper–nickel pollution *Chironomus* spp., *Procladius* spp., Dytiscidae, Nematoda (biomass up to 20.0 g/m^2) were predominant. In the zones of mining industries and intensive eutrophication, *Chironomus*, *Tubifex tubifex*, *Limnodrilus hoffmeisteri*, *Procladius* spp. were predominant (Table 2). In general for the lake by the 1980s values of benthic biomass in polluted parts have increased 20 times, which indicates an intensive process of eutrophication alongside with toxic pollution (Moiseenko and Yakovlev, 1990). Resilience of Midges (mainly of genera *Chironomus* and *Procladius*) and Nematoda to the impact of heavy metals was notices by several authors (Nalepa, 1987; Yakovlev, 1998; Iliyaschuk, 2002b). Oligochaetes develop well when organic material and apatite–nepheline mining industry waste are accumulated at the bottom (Milbrink, 1983), while metal concentrations in water and sediments are low. Biodiversity is low in areas of high pollution from both metallurgic and apatite–nepheline industries (0.5–1.0 bit/ind). From two relict species *Monoporea relicta* and *M. affinis*, found before in Lake Imandra, only the last one is still present. The more vulnerable *M. relicta* is no longer there (Yakovlev, 1998).

In the period of maximal water pollution the amount of typical Arctic fish species – salmon trout and arctic char – has sharply decreased, due to their vulnerability to water pollution. Fish productivity decreased to less than 1 kg/ha, while there was no commercial fishing on the Lake. In catches whitefish and perch now prevail. There was a mass development of minnow, while the number of smelt has increased.

Mass diseases of whitefish were registered in 1970–1980: change of the integument colour (de-pigmentation), anal inflammation, tousling of scales, oedema gills and appearance of anaemia rims, destructive changes in liver (increase of size, change of colour and friability) and kidneys (colour, granulation, thickening of renal and presence of nephritic calculi), anomalies in gonad texture, etc. Main types of registered fish pathologies are reflected in Table 4. Together with universal attributes of organism intoxication, some specific diseases of fish appear, which are observed for this lake. A rather rare disease of whitefish, nephrocalsitosis (stones in kidney), is found. Productive areas of benthic biocenoses play a role of specific “traps”, which attract whitefish by high biomass of zoobenthos. Migrating to food-rich areas, fish becomes exposed to heavy metals (Moiseenko and Yakovlev, 1990). Diseases in fish caught in these areas were so dramatic that the lethal outcome was inevitable.

In last decades of decreased toxic pollution there was a recolonization of the Lake by Arctic inhabitants. This is seen from changing dominant complexes, and increased biodiversity index for plankton communities

Table 3
Main indicators of community conditions for key periods of Lake Bol'shaya Imandra ecosystem modification

Indicators	Reference condition	Intensive pollution and degradation	Decreasing pollution and revitalization
Phytoplankton	1)1930 and earlier	2)1994–1996 (August)	2003 (August)
Chlorophyll "a", mg/m^3	0.1 – 0.5	3.8±0.9	3.6±0.4
Biomass, g/m^3	0.3–0.5	3.6±0.5	3.4±0.3
Number, mill. cell/l	0.01–0.3	3.8±0.3	2.2±0.1
*Biodiversity H, bit/ind	3.0–3.5	2.5±0.2	3.1±0.2
%B, *Stehpanodiscus*	0.5	6±1.7	8±0.7
%B, *Cryptomonas*	0.3	17±2.5	15±1.3
%B, Bluegreen	2–4	9±1.2	11±0.5
%B, Green	5.1	21±1.9	20±0.7
Dominating complexes	1)*Aulacoseira distans*, *A. italica*, *A. islandica*, *Asterionella formosa*, *Cyclotella comta*, *Tabellaria fenestrata*, *Dinobryon divergens*, *Anabaena* sp.	2)*Aulacoseira islandica*, *Rhizosolenia*, *Eudorina elegans*, *Pandorina morum*, *Cryptomonas* sp., *Stephanodiscus* sp., *Asterionella formosa*, *Sphaerocyctis schroeteri*	9)*Cryptomonas* sp., *Stephanodiscus* sp., *A. islandica*, *Cyclotella* sp., *Synedra* sp., *Asterionella formosa*, *Pandorina morum*, *Anabaena* sp., *Limnothrix planctonica*, *Tabellaria fenestrate*
Zooplankton	3)1930 and earlier	4)1994–1996 (August)	1998–2003 (August)
Biomass, g/m^3	0.25–0.30	1.71±1.07	1.21±0.91
Number, th. ind/m^3	10–100	271.3±139.2	107.14±99.52
*Biodiversity H, bit/ind	2.5–3.0	2.3±0.5	2.53±0.36
% B, Rotatoria	10–20	44±17	20±11
Dominating complexes	3)*Kellicottia longispina*, *Conochilus unicornis*, *C. hippocerpis*, *Bosmina obtusirostris*, *Daphnia longispina v. hyalina*, *Cyclops scutifer*, *Eudiaptomus gracilis*, *Holopedium gibberum*	4)Sónchaeta pectinata, *K. cochlearis*, *Polyarthra* sp., *Ploesoma* sp., *Filinia* sp., *B. o'tusirostris*, *Daphnia* sp., *Mesocyclops* sp., *Cyclops* sp., *Eudiaptomus* sp.	9)*A. priodonta*, *P. vulgaris*, *B. hudsoni*, *K. cochlearis*, *K. quadrata*, *K. longispina*, *N. caudata*, *B. obtusirostris*, *H. gibberum*
Macro-zoobenthos	5)1930 and earlier	6)1978–1986 (October)	7)1998 (October)
Biomass, g/m^2	4)0.3–0.8	21.3–49.0	12.9±6.7
Number, th. ind/m^2	0.4–0.7	23.9–62.7	6.2±5.4
Biodiversity H, bit/ind	3.5	1–2.2	1.1
Dominating complexes	5)*Trissocladius paratatricus*, *Tanytarsus* spp., *Procladius* spp., *Monoporeia affinis*, *Limnodrilus hoffmeisteri*	6)*Limnodrilus hoffmeisteri*, *Euiliodrilus hammoniensis*, *Tubifex tubifex*, *Chironomus* spp.	7)*Monoporeia affinis*, *Tubifex tubifex*, *Chironomus* spp., *Tanytarsus* spp.
Ichthyofauna	5)1930 and earlier	6)1978–1986	1998–2003
Fish production, kg/ha	4	<1	No dates
Dominating complexes	6)*Salmo trutta* (L.), *Coregonus lavaretus* (L.), *C. albula* (L.), *Salvelinus alpinus* (L.), *Thymlus thymallus* (L.)	6)*C. lavaretus*, *C. albila*, *Esox lucius*, *Perca fluviatilis*, *Phoxinus phoxinus* (L.)	9)*Coregonus lavaretus*, *C. albula*, *Esox lucius*, *Perca fluviatilis*, *Osmerus eperlanus* (L.)

*The information index of the species (Shannon's index).
Based on data from:
1)1930 — Voronikhin (1935), Poretskij et al. (1934);
2)1981–1987 — Moiseenko and Yakovlev (1990), Sharov (2002);
3)1930 — Krokhin and Semenovich (1940);
4)1981–1987 — Moiseenko and Yakovlev (1990), Vandish (2000, 2002);
5)1930 — Krogius (1930), Krokhin and Semenovich (1940);
6)1978–1996 — Moiseenko and Yakovlev (1990), Yakovlev (1998);
7)1998 — Iliyaschuk, 2002b;
8)1930 — Krogius (1930);
9)2003 field studies by authors.

Table 4
Whitefish disease, % from number of the surveyed individuals (*n*) in Lake Imandra in various years

Main symptoms of fish diseases	1981 $n=788$	1986 $n=721$	1991 $n=453$	1996 $n=462$	2003 $n=235$
Nephrocalcitoses	52	47	45	14	–
Fibroelastos	48	53	55	48	39
Lipoid degeneration of liver and cirrhosis	100	89	78	48	39
Anomalies of gonad structure	34	27	8	–	–
Scoliosis and osteoporosis	6	4	2	–	–

(see Table 3). In 2003 the total biomass of phytoplankton decreased, but a more uniform distribution was observed unlike the period of high pollution. In 1998 and 2003 the number of species in zooplankton community decreased (up to 70,000 spec/m^3); biomass also decreased. Certain zooplankton species that were usual in the lake before, but missing during the period of maximal pollution, were again found, such as the valuable forage crustacean Holopedium gibberum, *Daphnia* sp., *L. Kindtii.* However the most vulnerable to pollution *Leptodora kindtii*, *Polyphemus pediculus*, *Eudiaptomus graciloides*, and *Heterocope appendiculata* still can be found only in small quantities. Rotiferan *Bipalpus hudsoni*, *Kellicottia longispina*, *Notholca* sp. were still predominant.

Data gathered in 1998 indicate that in Bol'shaya Imandra the conditions for benthic organisms were still quite extreme (Iliaschuk, 2002a). Sediments of the lake have accumulated large amounts of metals and organic material, making it hard for the benthic communities to come back. Benthic biocenoses are still characterized by low values of biodiversity index (0.95–1.05 bit/ind). Here still most predominant are the Oligochaetae class, *T. tubifex* and *L. hoffmeisteri* (Iliaschuk, 2002a). At the same time, in recent years in the profundal zone the maximal abundance of amphipod *M. affinis* has sharply increased. In comparison with 1968 it has almost doubled: from 36 up to 60%; at the same time the influence of this crustacean on the Chiromonidae family has also increased, which is also an evidence of the ongoing eutrophication (Iliyaschuk, 2002b). These results correspond to data from Marzolf (1965).

The amount of Arctic char and salmon trout are still low, and still in the shallow Bays there are high numbers of minnows. Note that during the period of economic crisis unorganized fishing (poaching) was on the rise. This, together with eutrophication, could substantially affect the structure of fish communities, in particular, the whitefish population, which forage base has increased. That is why it is difficult to determine the main factor of

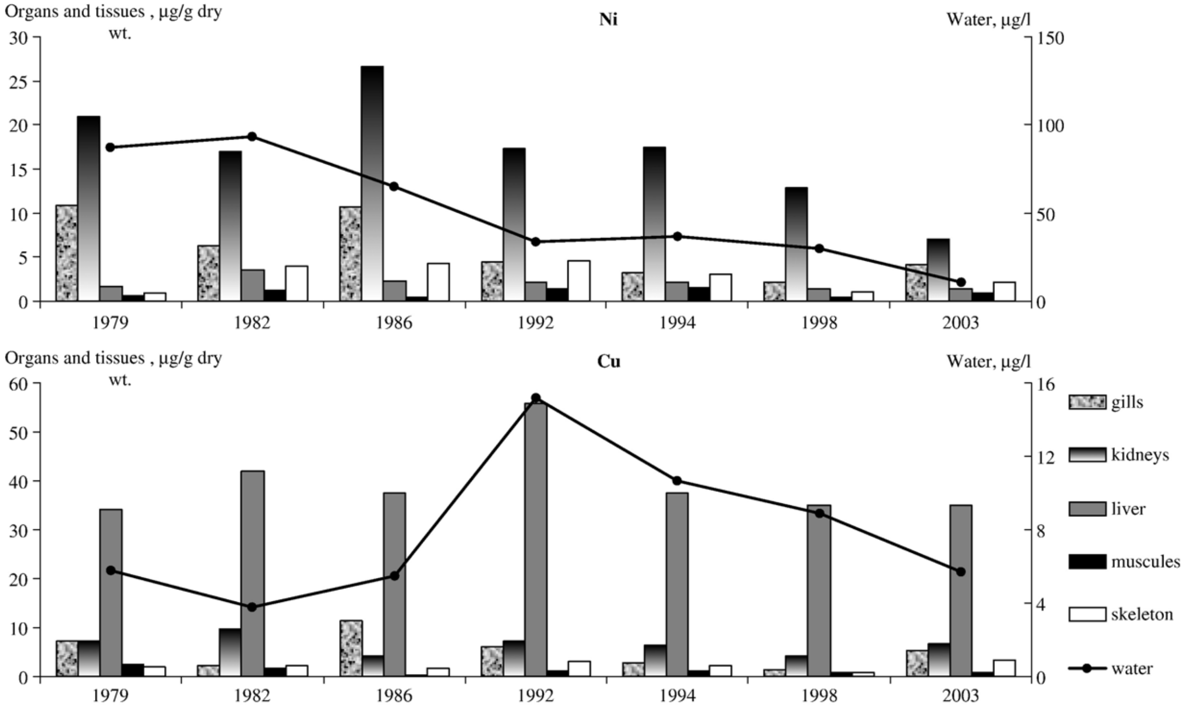

Fig. 2. Long term results for Ni and Cu accumulation in whitefish organs and tissues.

anthropogenic succession for fish: we do not have good estimates for the volumes of fish withdrawn from the lake and do not know how fishing changed the characteristics and structure of the fish population.

As the toxic impact declined, fish diseases became less prominent (Table 4). Physiological conditions have improved: there were no more fish with nephrocalcitos and scoliosis in the catches. Cases of whitefish diseases were less dramatic than in previous years, but there is evidence of chronic diseases under prolonged influence of small doses of contaminants.

4. Metals in fish as reflection of local pollution and enrichment of Northern Chemosphere

It is well known, that fish accumulate metals during their life span. In some works it was shown, that contents of metals in fish reflect levels of pollution more accurately than the indices of contaminant content in water (Forstner and Wittman, 1981a,b; Moore and Rammamoorthty, 1983; Spry and Wiener, 1991; Moiseenko and Kudryavtseva, 2002).

Nickel and copper released by the “Severonickel” enterprise belong to essential elements. These elements are functionally immanent in certain concentrations for all living organisms. However with higher concentrations in the environment they act as toxic contaminants. Fig. 2 shows the contents of nickel in water and in organisms of whitefish in Bol’shaya Imandra. Maximal nickel concentrations in whitefish were during 1978–86, when the pollution level was peaking. During this period rate of fish disease, especially nephrocalcitos was very high. Toxicity of technogenic nickel is very high — it has carcinogenic, gonadotoxic, embryotoxic and cumulative properties (Sydorenko and Itskova, 1980; Moore and Rammamoorthty, 1983). Most of Ni accumulation occurs in the kidney (Moiseenko and Kudryavtseva, 2002).

There is an exponential dependence between the concentration of nickel in water and its contents in kidneys, while bioaccumulation of Ni in the organism has a linear effect on the disease occurrence (%) (Fig. 3). Clearly the occurrence of nephrocalcitos is determined by water pollution and nickel accumulation in organisms. We can assume that accumulation of this element in kidneys from 2 up to 7 μg/g of dry weights causes disease. Currently content of nickel is lower, and cases of nephrocalcitos are not noticed. However other diseases of kidneys, fibroelastosis, are recorded for whitefish. Moiseenko and Kudryavtseva (2002) document characteristics of these diseases in detail.

Copper accumulates mainly in the liver of fish, where active biochemical processes take place (Bradley and Morris, 1986) (Fig. 2). However, no direct links with contents in water detected. Moiseenko and Kudryavtseva (2002) show that accumulation of this element is high with concentrations of the element of up to 5 mkg/l, however in conditions of high toxicity of water there is a decrease of Cu accumulation in liver due to pathological degeneration of this organ and destruction of the ferment systems. It should be noted that nickel and copper are added to water together with other trace metals. It is possible that they have a synergetic effect causing even higher occurrence of disease in fish.

Strontium pollution comes from the apatite–nepheline industry. Ions of Sr are involved in the exchange with Ca. They have a faster rate of exchange, and gradually impede normal skeleton calcification (Kovalsky, 1974, Chowdhuury et al., 2000). Absolute concentrations of Sr in water are not dangerous, however it is the interaction with calcium that causes problems. Dangerous Ratios of Sr/Ca in water that are less than 1/60 are considered hazardous. In Lake Imandra this interrelation is about 1/57. The connection

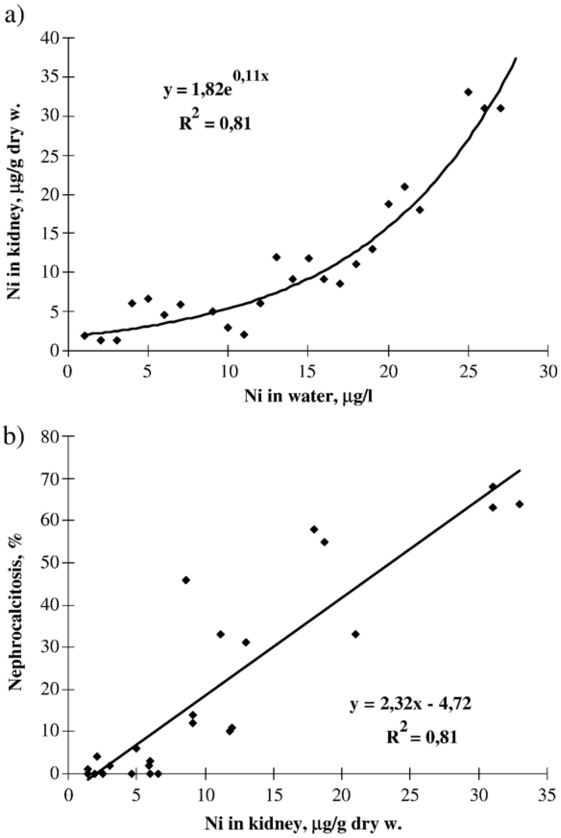

Fig. 3. Relationships between Ni accumulation in whitefish kidneys (*Coregonus lavaretus*) and (a) occurrence of nephrocalcitosis; (b) Ni concentration in water.

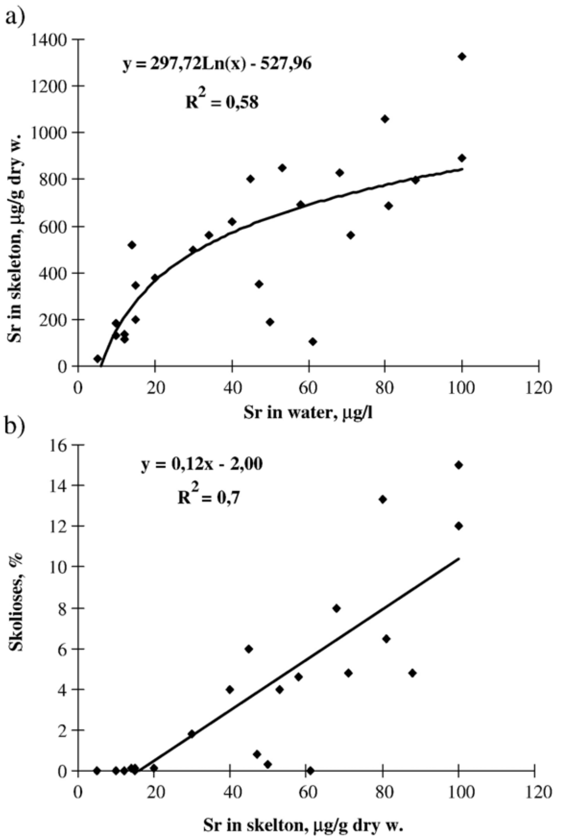

Fig. 4. Relationships between (a) scoliosis occurrence and Sr accumulation in skeleton; and (b) Sr accumulation in skeleton of whitefish (*Coregonus lavaretus*) and Sr concentrations in water.

between Sr contents in water and its accumulation in the skeleton of whitefish is detected, as well as cases of pathologies of skeleton tissue (Scoliosis, Osteoporosis) (Fig. 4).

In the last years scientists pay more attention to investigation of pollution by non-essential elements (Pb, Cd, Hg). Norton et al. (1990) give convincing data about increasing lead contents in sediments of northern lakes as a result of globally increasing concentrations of Pb in the environment. For Imandra, Cd, Pb, and Hg contents in systems of whitefish organisms were measured in 2001 (Fig. 5). Comparison of contents of Cd in liver and muscles of Imandra whitefish with data about whitefish of Taimyr Lake (Allen-Gil et al., 2003) show that average values are close, but maximal values in Imandra are higher. Cd like Ni is mostly accumulated in kidneys, but we have no literature data about Cd concentrations in this organ. Contents of Hg in liver and muscles of whitefish of Imandra are comparable to those in lake Taimyr. Thus, Pb, Cd, and Hg contents in fish of Lake Imandra reflect global trends of pollution in northern waters.

5. Ecosystems health and critical levels of toxic multicontaminats

The term *“ecosystem health”* is increasingly used in scientific literature of the recent decade (Adam and Ryon, 1994; Wong and Dixon, 1995; Attrill and Depledge, 1997). Various methods are available to investigate the pollution effects and water quality change. Aquatic ecosystems are stressed in all levels, ranging from individual and up to the population and community levels. Each method has limitations and advantages, and the type of method used influences the interpretation of stressor effects on ecosystem health. Community- and population-level measurements integrate the responses to a variety of environmental conditions and therefore may be less reflective of

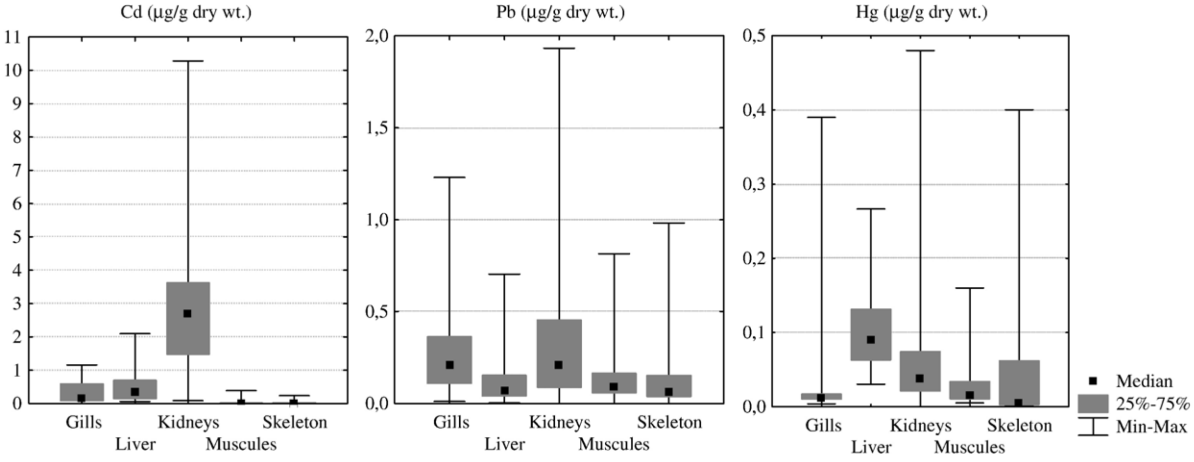

Fig. 5. Cd, Pb and Hg accumulation in whitefish (*Coregonus lavaretus*) organs and tissues.

contaminant-induced stress. Many organism groups can be used as indicators of environmental and ecological change (Cash, 1995; Whitfield and Elliott, 2002).

Numerous publications attest that fish (*in situ*) is a good indicator of environmental change and ecosystem health, especially in case of toxic water pollution (Adam and Ryon, 1994; Wong and Dixon, 1995; Simon, 2000). Fish occupy the upper level in the trophic system of aquatic ecosystems. Pathologic changes in fish organisms allow the determination of the degree of the aquatic environment toxicity and give an idea of the potential hazard presented by different substances finding their way to this water body, as well as of the cumulative effect of the substances in question on organisms during their lifetime. It is very important to reveal unfavorable water quality, based on studying fish organisms, because many physiological systems of fishes are similar to those of hematothermal animals, which allows us to predict the consequences of toxic substances occurrence in the aquatic environment for human organism as well.

Our results show that water quality and conditions for water inhabitants have worsened in the period of intense pollution and they did not recover with decreasing inflows of contaminants. The main question for environmental management is to which level must pollution loads be decreased to achieve reference conditions and to preserve ecosystem health?

To answer this question, we need to accomplish three tasks:

1. Assign criteria of estimation of ecosystem health, which could reflect effects of impact more informatively;
2. Determinate the method of hydro-chemical information compression to a unified parameter of water quality, which could reflect real impacts of the dose taking into account contaminant complexes (multi-pollution);
3. Determine critical levels of water pollution and required level of its reduction based on this dose–effect relationship.

Below is how we addressed these problems for Lake Imandra.

Criteria of fish condition assessment. Table 4 documents data about fish morbidity in different periods of Lake Imandra pollution. During the period of intensive stress the situation was quite dramatic and gave a clear signal about a need to decrease the toxic pollution.

Diagnostics of fish health requires system studies, which combine extensive data with making exact diagnoses. A diagnostic system for fish state, suitable for practical monitoring, is presented elsewhere (Moiseenko, 1999, 2005). The *macro-level* examination of individuals involves diagnosing of diseases on the basis of a visual examination of numerous organisms. At this level, a preliminary diagnosis is made based on clinical and postmortem symptoms of intoxication. The *micro-level* diagnostics include hemathologic, histologic, biochemical, instrumental, and other methods. These are labor-intensive and cannot be used widely used, however they are essential to refine the diagnosis and estimate the consequences of pathologic changes in fish organisms.

The determination of the degree of disturbance in an individual organism is very important to diagnose the damage to fish organisms in the contaminated zone. For instance, up to 70% of individuals in the zones of contamination may be in the state close to the lethal threshold. If the concentration of toxic substances is not high, the percentage of affected individuals can be the same, but disturbances in fish organisms can be inconsiderable and will not be life threatening. In order to estimate the state of fish organism using the data of clinical and postmortem examination, experts suggest using different rating point systems. In the process of macro-diagnostics, three stages of the disease can be singled out (0 denotes healthy individuals):

(1) Low disturbances, not threatening the life of the fish;
(2) Medium-level disturbances, causing a critical state of the organism;
(3) Distinct intoxication symptoms leading to inevitable death of the organism.

The overall index of morbidity in fish in the given zone of contamination can be presented as:

$$Z = (N_1 + 2N_2 + 3N_3)/N_{\text{tot}}.$$

Here Z is the morbidity index for fish, $O \le Z \le 3$; N_1, N_2, and N_3 are the number of fishes in the first, second, and third stages of the disease, respectively; N_{tot} is the total number of the examined fishes in the local contamination zone, including healthy individuals. If all the fishes in the given water body do not demonstrate any intoxication symptoms, then $Z=0$. The value of Z will increase with an increase in both the number of sick fishes and the severeness of their diseases.

Histopathological analyses of liver, kidney and gills alteration are used for the final diagnosis. Histological analysis of diseased liver of whitefish of Lake Imandra shows lipoid degeneration of liver cells, signs of necrosis and atrophy caused by the destruction of liver cells and connective tissue expansions. The histological sections of gills show evidence of hyperemia and necrosis of epithelial cells. Nephrocalcitos and fibroelastosis of kidney may be related to specific diseases whose etiology is associated with water pollution by heavy metals (see Fig. 3).

The hemogenesis system of fish is sensitive to any environmental changes and changes in the physiological state of the fish organism. The changes revealed in hemathologic parameters of the examined fishes confirm the development of toxicoses in fishes inhabiting Lake Imandra. For whitefish, the concentration of hemoglobin under environmentally optimal conditions varies from 80 to 130 g/l, average — 110 g/l (Moiseenko and Yakovlev, 1990). A decrease in hemoglobin concentration more then 80% is a signal of disease, which can be caused by toxic agents.

Thus, the following biological parameters were used as criteria of fish and ecosystem health: (a) the percentage of fishes in which the second or third stages of diseases were diagnosed; (b) the *Z*-index defined above; (c) the percentage of fish with hemoglobin concentration not reaching 80 g/l.

An integrated impact dose. In nature, aquatic organisms are exposed to the influence of the combined dose of all metals. It is important an estimate a uniform numerical parameter adequately describing the total metal impact on biota. An integrated impact dose of metals is determined by the number of metals, their concentration and toxic properties for each of them.

The values of Guideline Concentrations (GC) or Maximum Permeation Concentrations (MPC) largely differ by country, in spite of the fact that experimental research techniques to establish the MPCs are universal (Can. Water Qual. Guidelines, 1994; Env. Quality Obj., 2001; Bioassay meth. aquatic org., 1985; Methodological recommendations, 1998). For example, in Russia, the MPC values for Cu, V, Mn and some other elements are unreasonably underestimated, whereas the MPCs for Cd, As, Pb, and Al are overestimated (Moiseenko, 2005).

Although accepted in Russia, as well as in other countries, water quality standards for metals in water do not take into account the integrated impact dose. Using data about toxicological properties of each metal based on guidelines concentrations (GC), we can define the integrated impact dose by summing the excess of real concentration for each of metals to their GC or known threshold of impact as follows:

$$I_{\text{tox}-1} = \sum (C_{\text{i}}/\text{GC}_{\text{i}-\text{aq.l.}}).$$

Where $I_{\text{tox-1}}$ is the integrated toxicity index, $O \leq I_{\text{tox-1}} \leq 1$; C_{i} are concentrations registered in water; $\text{GC}_{\text{i-aq.l}}$. Guideline Concentration for metals accepted in Russia for aquatic life. Note that for ecosystem health measures we used the GC for aquatic life, which are more stringent than those for drinking water.

Despite of critical GC analysis and taking into account that Imandra is situated on the territory of Russia, for the assessment of metals toxicity in surface water for fisheries and aquatic life the following concentrations, legislatively accepted in Russia, are used (μg/l): Cd = 5, Ni = 10, Cu = 1, Pb = 10, Zn = 10,

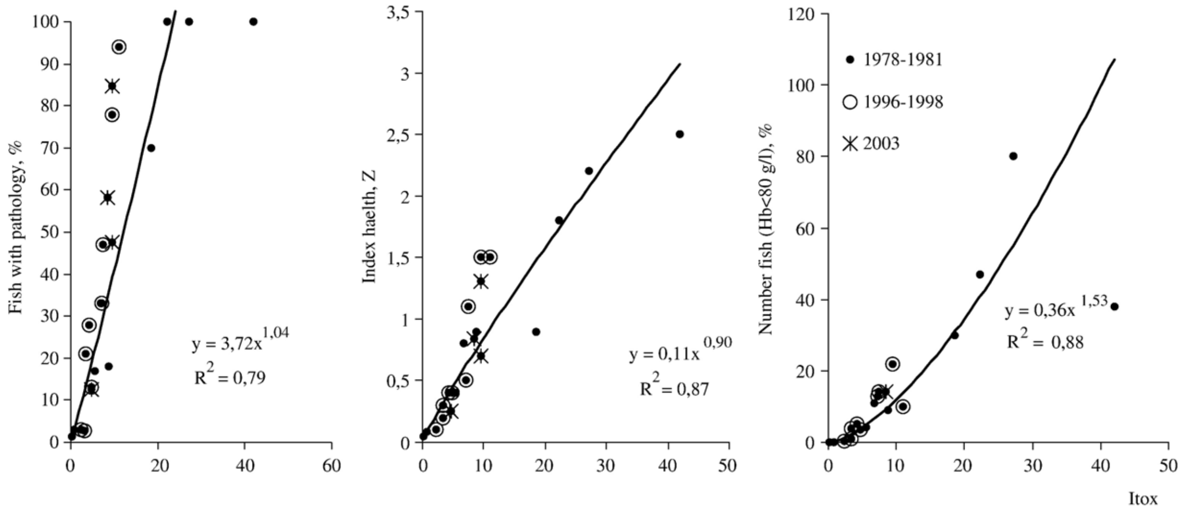

Fig. 6. Measuring ecosystem health: dependence between an integrated parameter of toxic loading ($I_{\text{tox}} = \sum (C_{\text{i}}/\text{GC}_{\text{i}})$ and indicators of fish diseases (% of fish with deviances, % of fish with anemia (decrease of hemoglobin in blood lower than critical 80% level).

Table 5
Statistical data on occurrence of major diseases in adult population in cities and Murmansk oblast as a whole

Disease of organs of digestion

Location	1997	1998	1999	2000	2001
Apatity	0.1	0.5	0.6	0.4	0.1
Monchegorsk	2.1	0.5	0.4	0.3	0.3
Olenegorsk	0.4	0.6	0.1	0.1	0.2
Polarni Zori	0.3	0.2	0.6	0.5	0.3
Murmansk oblast	0.5	0.5	0.3	0.3	0.3
Russia	0.3	0.3	0.3	0.3	

Diseases of genitourinary system

The Regions	1997	1998	1999	2000	2001
Apatity	41.3	50.1	62.4	55.7	59.8
Monchegorsk	33.7	43.6	53.8	32.9	53.1
Olenegorsk	23.9	25.2	65.2	29.9	24.3
Polarni Zori	26.2	45	60.8	34.6	37.5
Murmansk oblast	44.9	47.8	50.3	47.3	49.8
Russia	35.6	37.5	40.3	41.8	

Urolithiasis

The Regions	1997	1998	1999	2000	2001
Apatity	1.1	0.8	2.5	2.4	2.4
Monchegorsk	1.3	1.4	1.6	1.5	1.8
Olenegorsk	0.7	1.1	7.6	3.1	2.4
Lovozerskiy	2.1	1.6	0.7	1	1.7
Polarni Zori	2.9	1.3	2.6	3.2	4.5
Murmansk oblast	1	1	1.7	1.6	1.7
Russia	1.1	1.1	1.4	1.4	

Neoplasms

The Regions	1997	1998	1999	2000	2001
Apatity	13.4	13.9	14.7	16.3	13.9
Monchegorsk	9.9	10.6	14.1	16.3	14.1
Olenegorsk	6.5	7.5	21.1	9.6	7.2
Polarni Zori	13.8	15.1	15.2	15	14.6
Murmansk oblast	10.9	11.7	13	13	12.8
Russia	8.7	9.4	10.0	10.3	

Occurrence measured as number of first diagnosed per 1000 population.

As=50; Cd=5. (List of Fishery-Related Standards..., 1999). Water quality may be considered good if $I_{\text{tox-1}}$ is no more than one.

Dose–effect dependencies and critical levels of water pollution. Three dependencies were plotted for the integral parameter of toxic water pollution and rate of fish disease: % of fish with physiological deviances from norm, Z — the morbidity index (index health); % of fish with anemia (decrease of hemoglobin in blood below critical level — 80% (Fig. 6). Analysis of these dose–effect dependencies shows that if the integrated toxicity index of water is close to 1, pathologies and dysfunctions start to appear in fish organisms.

6. Effects of drinking water contamination on human health

From the above we can see that decrease of anthropogenic load on the lake is not sufficient for recovery of ecosystem health. Let us now consider the effect of contaminated drinking water on the health of people living around the lake. The analysis of statistical data on human morbidity in cities on the Imandra shores, have shown that it is higher if compared to the rest of Murmansk oblast and the rest of Russia (Table 5). This leads to a hypothesis that human disease is connected to toxic pollution of drinking water in Lake Imandra and its watershed. We may assume that accumulation of metals in human body will cause pathological changes in human organisms. Drinking water for Apatity and Polyarnye Zori comes from the Lake Imandra, for Monchegorsk town – from Lake Moncha and for Olenegorsk town – from the Permus Lake. These towns are located in the area that is severely polluted by airborne heavy metals from Severonickel smelters. Below we report the results of our systemic studies in 2003–05 that tracked the following components and pathways: metals in water — their bioaccumulation — histopathology — diagnosis of human pathologies.

The methods of investigations are described in detail in the works of Megorsky (2003).

The properties of drinking water. The drinking water quality was examined for samples from urban water supply. Concentrations of heavy metals in drinking water (as from the tap) for the towns and settlements are presented in Table 6. The analysis of the data above

Table 6
Concentrations of metals in drinking water (μg/l) for cities in Murmansk oblast

Cities	Ni	Cu	Co	Cr	Sr	Cd	Pb	$\sum C_i/\mathrm{GC}_{i\text{-d.w}}$
Apatity	4.9±0.6	3.6±2.5	0.3±0.2	0.13±0.07	88±13	0.12±0.07	0.6±0.2	0.21
Monchegorsk	13.9±11.4	12.0±8.5	0.3±0.2	0.15±0.07	17±3	0.19±0.11	0.4±0.1	0.30
Kovdor	0.5±0.3	0.5±0.4	0.2±0.0	0.28±0.16	38±9	0.09±0.05	0.5±0.1	0.10
Olenegorsk	0.8±0.1	1.3±0.4	0.2±0.0	0.25±0.25	32±5	0.15±0.02	0.4±0.2	0.11

According to State Standards the water is clean since $\sum C_i/\mathrm{GC}_{i\text{-d.w}}$ is consistently less than one.

shows that drinking water in Monchegorsk and Apatity is polluted by heavy metal at the highest level. Drinking water after being processed in technological cycles of water treatment is only slightly better in comparison to the water from the lake. This shows that even after water treatment people get elevated concentrations of heavy metal, indicating that water treatment technologies are clearly inadequate. However comparing these heavy metal concentrations with the standards accepted in Russia (Bespamyantnov and Krotov, 1985) we find that none of these standards are in violation.

It should be noted that waters contaminated by heavy metals are even more active in soft waters, Lake Imandra, with low content of calcium, and this increases their penetrating ability into the human organism (Forstner and Wittman, 1981a,b).

Metal accumulation and patho-physiology in urban population. To study heavy metal accumulation in tissues of human body we have sampled pathology in anatomical material from people living for no less than 10 years in the settlements of interest, and who have never worked at factories or other places with elevated health risks. For these analyses tissues from liver and kidneys were taken. When evaluating metal bioaccumulation, similar tissues from premature and non-viable fetus were taken as control, reference sample, as a "norm" for the microelement content in organs. It was thought that trans-placenta barrier prevents metal penetration into the organism of growing fetus.

Simultaneously pathology-anatomical samples were taken for histological examination and pathology-anatomical postmortem examinations were evaluated to understand the consequences of chronic effects of subtoxic doses of metals and their accumulation for human health. Clinical, histological and laboratory data was analyzed for 110 postmortem records. The clinical components included data from health histories, results of clinical examination and pathology-anatomical findings. In case of chronic alcoholism or virus hepatitis the subjects were excluded from analysis. The main objective was to find out the forms of illnesses related to liver and kidney disturbances, i.e. the reasons which were not found out in present medical histories. We hypothesized that for those illnesses etiology and pathogenesis was caused by chronic intoxication of the organism by metals.

Metal content in livers and kidneys of the examined patients are presented in Fig. 7. In comparison with the "norms" the highest metals concentrations are typical for people who died in Monchegorsk. Here, the heavy metals content is 2 to 10 times higher than the "norms", especially for Ni, Cu, Cr, Cd and Pb. In kidneys Cr and Cd concentrations exceed the "norms" by 10–50 times.

In organisms of the people who died in Apatity region, in their livers the highest concentration of Cu, Cr, Cd is observed, in livers of those who died in Olenegorsk region — Cu, Cd and Pb is highly concentrated, in Lovozero region — Cu and Cd, and in Allakurti — Cu and Pb are of highest content.

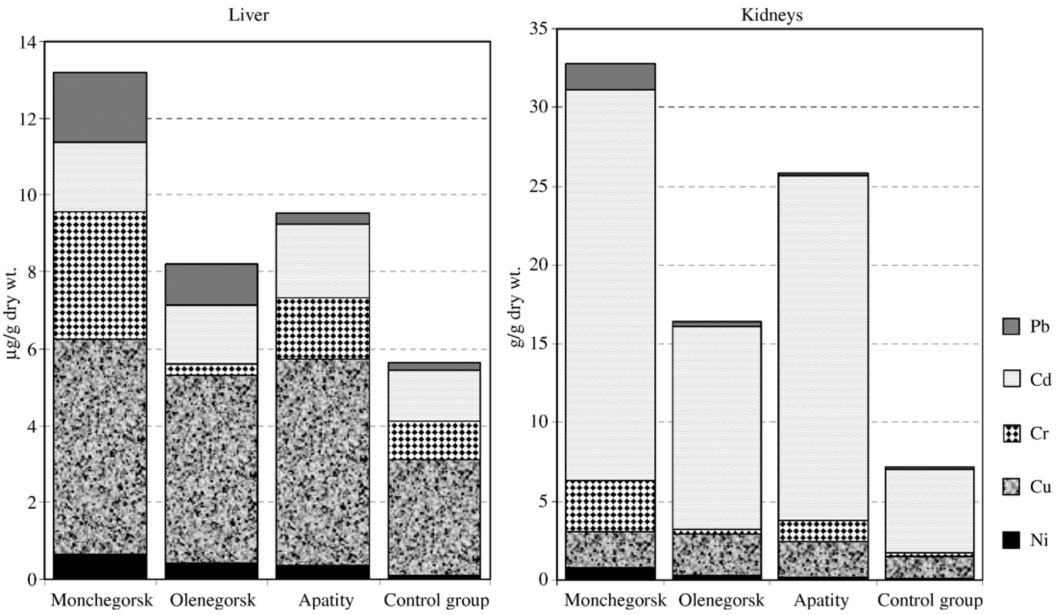

Fig. 7. Metal content in liver and kidneys of the examined patients in cities and settlements located on Lake Imandra shores.

In terms of the data mentioned above, despite the fact that drinking water is mainly contaminated by Ni and Cu, Cd has the strongest accumulative ability in the human body, and that turns out to be the biggest danger in terms of migration of elements within the region.

Lake Moncha that is the source of the Monchegorsk water supply is located in the zone of the most intensive acid depositions. By the level of complex accumulation of heavy metals in liver and kidneys of people the cities can be ordered as Monchegorsk, Apatity, and Olenegorsk. This order correlates with the decreasing degree of heavy metals concentration in drinking water in the urban supply.

The analysis of canonic correlations can illustrate the differences in the microelement content in the main human organs in the cities with different content of heavy metals in drinking water. Fig. 8 presents the graphics of diversity in projections 1 and 2 of the function roots, which make the best discrimination between the groups of examined patients under different control in different cities. The patients examined in Monchegorsk are most different in heavy metal content from the control group. Slight overlapping of the indices of metal accumulations in humans in Monchegorsk and Apatity indicates that the latter is also effected by metal pollution in drinking water.

Histological analysis of 100 samples of liver and kidney produced 24 cases with some pathological processes, which have not been diagnosed before. Histological picture of pathogenesis in liver is often seen in fat dystrophy hepatocyte cells, their singular necrosis; in some cases it is the hemociderosis, in 5 cases — it was the toxic destruction, and in 10 cases — fat dystrophy of liver. Histological picture of kidney patho-genesis is also clear: in 5 cases we had nephrosclerosis at its initial stage, in 5 cases — glomerulonephrite and in 1 case — amiloidosis (Megorsky, 2003). All these cases are not in the level of disease; they are only of polyetiological character, which does not exclude toxic pathogenesis influenced by heavy metals.

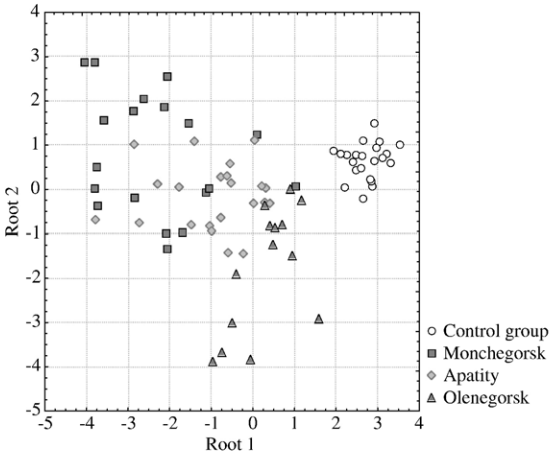

Fig. 8. Graphs of diversity in projections 1 and 2 for function roots, which make the best discrimination between the groups of examined patients under different control in different towns.

It has been determined that in addition to inflammatory changes there are original focal diastrophic and necrobiotical changes in vessels — capillary, precapillary, and small veins. Morphological changes are characterized by breaks of small veins, high penetrating ability, which leads to edema of tissue and cirrhosis or cirrhosis hemorrhage inflammation in tissues of Korcovogo and cerebral matter. Besides, we found 36 cases with bladder stones previously not diagnosed, which accounts for 12% from a total number of examined material (Megorsky, 2003). These investigations are consistent with the statistical data on bladder-stone morbidity growth.

These cases of pathological toxic etiology, which have progressing latency, may lead to poor health, developing sickness and growth of mortality.

High correlation between human morbidity in the cities and vicinities, and the quality of drinking water and bioaccumulation of metals have proved the assumption about the effect of drinking water contamination by metals upon human health (Table 7). Evidently, the pathology of kidneys is closely connected to concentrations of such elements as Cd, Cr, and Pb. Ni and Cu concentrations in human liver and kidneys was lower than for Cd. Cadmium turns out to be very hazardous for the Arctic. There are reliable relationships between the index of urinogenital system and high accumulation of Cd, Cr, and Pb in tissues, which is especially high for people living in Monchegorsk, and Cd, Cr for Apatity. The pathology in gepathosis has direct correlation with Pb, Cd, and Ni accumulation in Monchegorsk, Apatity and Olenegorsk.

A similar integrated toxicity index $I_{\text{tox-2}}$ was inserted into the correlation matrix to estimate the total effect of metals in drinking water on human health. In this case we used the GC for drinking water: $I_{\text{tox-2}} = \sum(C_i/\text{GC}_{\text{i-d.w}})$ (see Table 6). There is significant correlation between $I_{\text{tox-2}}$ and human health, which makes us assume that direct sub-toxic concentrations of metals in drinking water have a stronger negative effect on human health than on the cumulative function. However, the stomach-intestinal illnesses have stronger connection to both the metal content in water and the accumulation in human body tissues.

Table 7
Significant ñorrelation coefficients ($p \geq 0.01$) between diseases and pathology of the systems and organs (% of the surveyed patients) of the population city Kola Peninsula from concentration trace element in drinking water, as well as from level of their accumulation in liver and kidney (crossed out section — not significant)

Trace elements		Renal disease	Liver disease	Disease of bodies of digestion	Disease of blood and hemopoietic tissues	Disease of circulation system
Concentration in water, μg/l	Ni	–	0.63	0.89	–	0.73
	Cu	–	0.64	0.91	0.67	0.77
	Co	0.93	0.75	0.85	0.90	0.91
	Cr	–	–	–	0.76	0.70
	Sr	–	–	–	–	–
	Cd	0.87	0.76	0.87	0.77	0.83
	Pb	0.97	–	–	0.69	0.70
	Zn	–	–	0.81	0.61	0.68
$I_{\text{tox-2}}$	$\sum C_i/GC_{\text{i-d.w}}$	0.76	0.77	0.95	0.79	0.86
Accumulation in liver, μ/g dry weight	Ni	0.70	–	0.79	–	0.76
	Cu	0.94	0.65	0.84	0.80	0.90
	Co	–	–	0.85	–	0.88
	Cr	–	–	0.71	–	–
	Sr	–	–	–	–	–
	Cd	–	–	–	–	–
	Pb	–	–	0.76	–	0.72
Accumulation in kidney, μ/g dry weight	Ni	–	–	0.82	–	0.71
	Cu	0.77	–	–	0.81	0.75
	Co	–	–	0.80	–	0.80
	Cr	–	–	0.88	–	0.72
	Sr	–	–	–	–	–
	Cd	–	–	0.81	–	0.78
	Pb	0.36	0.59	0.82	0.53	0.64

The analysis of data on drinking water quality, human morbidity, metal accumulation in kidneys and liver from the postmortem examination, and their pathogenesis suggest a direct relationship between growth of mortality and the index of drinking water quality, and a strong correlation between disease etiology and the sub-toxic prolonged effect of metals on the human organism.

7. Discussion and conclusions

Once Lake Imandra was an oligotrophic water body with ultra-fresh water. The aquatic community consisted of cryophilic stenobiotic species, which are characteristic for the Paleoarctic. For more than 60 years the lake served as a sink of toxic pollution accompanied by nutrients, which were dumped into the lake with untreated domestic sewage and industrial waste. From the stable pristine state the ecosystem has transformed into a new developing phase, in which the number of typical Paleoarctic species, vulnerable to contaminants, is decreasing while the number of eurybiontic species is increasing. This transition is enhanced by high concentrations of nutrients and weaker competition with typical Arctic species. As a result, the community structure is simplified, as well as the trophic chains. In benthic communities the toxic pollution is resulting in high numbers of midges (Chironomidae family) that are resistant to heavy metal pollution. In some areas, where eutrophication is prominent, the massive growth of Tubificidae was observed.

As toxic pollution started to decrease during the recent years, there was a re-colonization by native Arctic inhabitants. Dominant complexes started to change, increasing the biodiversity index of plankton communities. Accumulated nutrients are still involved in the biological cycle in the ecosystem, as seen from the ratio of total P to mineral P (orthophosphate) (8.7 in 2003 vs. 2.6 in 1983). The number of predators in the structure of the zooplankton and benthic, and, apparently, fish communities has increased. Algal biomass did not decrease in the last years. Unfortunately, we do not have exact data about fish production over this period. However, interviews show that unorganized fish catches (poaching) have increased. At the same time biomass of zooplankton and benthos is decreasing, which can be explained by two factors: (i) increasing dominance of predatory forms in these communities; (ii) uptake by fish in conditions of lower toxic pollution and its higher survivability. Benthic communities are more inert to restoration, since their biodiversity is low. Such inhabitants as the amphipod *M. affinis*, are advantageous in conditions of decreasing toxic pressure and favorable trophic conditions.

The overall trend of Lake Imandra recovery is very similar to the processes recorded by Gunn et al. (1995) around Sudbury (Canada). Attributes of ecosystem recovery observed in this work, show an increasing role of higher trophic levels, affected by ecosystem succession (Odum, 1981) and developing toward a more stable (climax) modification that is nevertheless different from its original natural structure.

Parameters of fish physiological conditions are even more directly related to ecosystem health. During the period of severe pollution there were mass fish diseases (nephrocalcitos, lipid liver degeneration, cirrhosis, anemia, scoliosis and others). Nephrocalñitos of fish was an endemic disease in Lake Imandra, its etiology determined by accumulation of heavy metals and their toxic impact. Based on integral estimates of ecosystem health and rate of fish intoxication symptoms, we can conclude that ecosystem conditions are getting better, but it is still far from recovery. Low calcium concentrations in the Arctic lakes make organisms more vulnerable to toxins. To preserve health of Arctic ecosystems maximal allowed concentrations accepted in Russia for fisheries require revision. The dose–effect dependencies clearly show that heavy metal pollution must be significantly decreased. At the same time, for healthy ecosystem revitalization water pollution (integral parameter $I_{\text{tox-aq.l}}$) must be decreased at least 5 times, first of all for nickel, which determines many water properties.

Our results show that while concentrations of metals in drinking water are quite low according to the standards accepted in Russia, they are still a cause of high rates of diseases in the human population. Neoformations and kidney pathology are abundant in the population living near Lake Imandra. We should take into account that human population in the Arctic is also exposed to climatic stress, as well as to relatively high air deposition rates for metals, which get incorporated into the food cycle. Besides, the population living around Lake Imandra acts as a top predator consuming most significant doses of elements accumulated in fish tissues. Clearly, the high rate of diseases indicates that the quality of drinking water does not meet the requirements for human health preservation.

This conclusion is in line with the needs of ecosystem health recovery, and confirms that water quality standards for fishery and drinking water supply adopted in Russia for Arctic regions are unacceptable. Total flux of sewages and airborne contaminants coming into reservoir must be considerably reduced. However, human health also depends on economical and social factors. The livelihood and sustainability in the Arctic is dependent both on economic development and high quality of drinking water, ecosystem health, biodiversity, and esthetic and recreational capacity — all the components that are accounting for the natural capital in the area. The health of the nation is equally dependent on all these indicators.

The obvious next challenge is to relate the observed health indices with watershed management practices as shown in Fig. 9. We have clearly demonstrated that human activity causes environmental damage, which translates into impaired ecosystem health. This is prominently seen from the poor state of the fish population in the lake, increased fish mortality and overall disease level. Furthermore we see how environmental conditions impact the human population living around the Lake. Through drinking water heavy metals pass on into human organisms, resulting in all sorts of disease and decreased life expectancy (the feed-forward chain in Fig. 9a). The question is how to create feedback in this system, and how

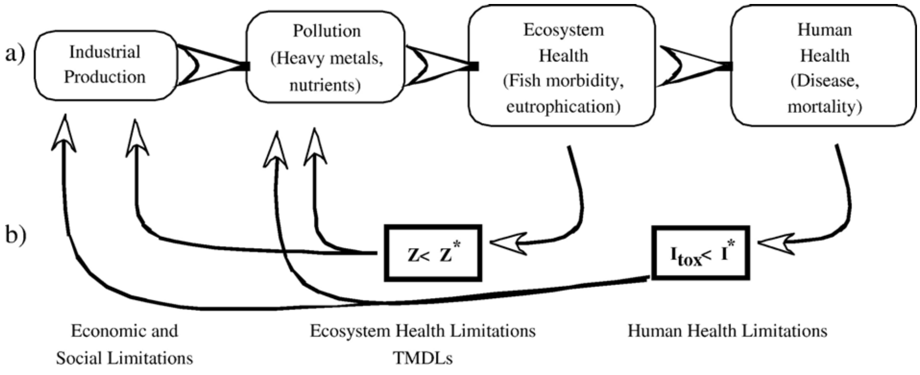

Fig. 9. The (a) feed-forward and (b) feed-back components of an integrated system of ecosystem management for Lake Imandra watershed.

to communicate the information about ecosystem and human health back into the economic and social systems, which could help design adequate control and management practices (the feed-back chain in Fig. 9b).

At first glance this may seem simple, and one could assume that once the maximal loads for heavy metals and nutrients are identified, the appropriate regulatory and institutional mechanisms will follow. However, this is not a straightforward process in the West (Voinov et al., 2004a), and it is way more difficult to implement in conditions of the transitional economy in Russia.

The Lake Imandra watershed is somewhat unusual for the Arctic for an extremely high permanent population. The strategies for the development of the North adopted in the USSR, especially in the 1920s–50s have been primarily based on permanent settlements providing the entire infrastructure necessary to support livelihoods of significant numbers of workers and their families. This was a simple task under the centrally controlled economy, when large subsidies were always available when necessary, and certain data were never released to the public. This made it easier to keep the population where needed at low overhead and little need to invest in environmental conservation and restoration.

At the same time, with a more open society, awareness about health risks may further increase the emigration from the region. Such uncontrolled emigration has already started in the Imandra area during the economic meltdown period (Voinov et al., 2004a). At present it has been almost stopped and industrial production is starting to grow again. However there is still very little concern among the population about ecosystem health and the connections to the human health. In many cases we are dealing with a population living in cities monopolized by the industry. The easiest way for the enterprises to avoid sufficient investment in environmental restoration is to relate these investments with the salaries that people are paid. People would rather live in polluted areas than take cuts in their paychecks, especially as long as the alternatives for migrants are few or none.

Therefore it may be wishful thinking to assume that market economy will help solve these questions. Most of the production in the watershed is still very labor intensive and from the market stand point it is cheaper to keep the poorly informed population in place, rather than invest in new technology and deal with social problems associated with emigration.

From the strictly ecological viewpoint one may assume that keeping the population in place may be beneficial for the environment, because certain probably still sufficiently high standards of environmental control are more likely to stay in place to make sure that the population can still live in these areas. Switching to temporary rotating work shifts may only result in further degradation of ecological conditions, if the economic profits only are to be maximized. On the other hand the impact of the human settlements, the city infrastructure, including transportation, heating, etc. — is only adding to the loads that the ecosystems need to sustain.

In the short term we could easily design control measures that would at least protect human health. One obvious solution is to switch to underground, still unpolluted water supplies in cities. Fishing advisories and information on toxicity of fish may reduce consumption of Lake fish. Apparently the younger generation is less involved in fishing, which remains a favorite hobby of the older people. However these measures will still require investment, and will not solve the problem of air pollution and decaying ecosystem health.

In the long term mass exodus (or rather slow die-off due to non-replacement) of people living in the Kola North is very likely, especially taking into account the projections for skyrocketing fuel prices and climate change that may actually make it colder in the Kola. At this time in most cases it is only the lack of opportunity (jobs, housing) in the South that forces people to stick to their current job in the Imandra watershed cities.

Ideally, we could easily envision a system that would dictate limits on loading (dose) based on monitoring the state of human and ecosystem health (effect). As shown above all the necessary components of such a system are already in place and it would not be a problem to tie them together with some modeling tools such as other existing models used to predict and understand watershed dynamics (e.g., Voinov et al., 1999, 2004b; Voinov and Costanza, 1999). However so far we do not see any demand for such management system and it is not clear how to implement the recommendations that a system like this would generate. Perhaps we need to wait until the economic transition will settle down to a new quasi-steady state condition, in which the new governing mechanisms and drivers will start operating.

Acknowledgments

The work was supported by grants from the NSF Office of Polar Programs OPP 0095196, 0354298, and Russian Fund for Fundamental Investigation (Grant 04-05-64523).

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