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The present state of Lake Ladoga, Russia — a review

Vladislav Rumyantsev[1)], Markku Viljanen[2)] and Tatyana Slepukhina[1)]

[1)] *Institute of Limnology, Russian Academy of Sciences, Sevastyanov Street 9, 196105, St. Petersburg, Russia*
[2)] *Department of Ecology, Karelian Institute, University of Joensuu, P.O. Box 111, FIN-80101 Joensuu, Finland*

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Until the early 1960s, Lake Ladoga was oligotrophic and characterized by good water quality, but within the past 20–30 years, as a result of human impact, the ecological state seems to have deteriorated. Especially since the 1970s, its trophic state has changed to mesotrophic, with elevated nutrient concentrations and decreased transparency. Conditions at some of the worst polluted sites have actually improved in recent years, due to closing down of some sources of industrial pollution, but there are alarming signs of general eutrophication of the main body of water. The total concentration of phosphorus has increased 2–5-fold since the 1960s. During the last decades, several planktonic, benthic and fish species sensitive for eutrophication have disappeared. The present species composition and the biomass of the plankton and zoobenthos typify different trophic conditions in different parts of the lake. Primary production, phytoplankton and zooplankton biomass and species composition display mesotrophic and eutrophic conditions in the coastal regions, whereas the pelagial areas are mainly oligo-mesotrophic. The species composition of the macrobenthos and its small biomass characterize the deep central part of Lake Ladoga as oligotrophic.

Introduction

Lake Ladoga is the largest lake in Europe. Among world's freshwater lakes it ranks the 13th in the surface area and the 14th in volume (Schwoerbel 1987). Early studies on Lake Ladoga are reported by Andreev (1875) and Witting (1929). The first extensive monograph of the lake was published by Molchanov (1945). A series of subsequent publications: Malinina (1966), Semenovitch (1966), Alekin (1967), Smirnova (1968), Raspopov (1968), Kalesnik and Raspopov (1968), Petrova (1982), Petrova and Raspletina (1987) and Petrova and Terzhevik (1992) provide results of ecological investigations of the lake, particularly concerning its anthropogenic eutrophication. Recent research on Lake Ladoga has been summarized in the abstract- and proceedings-volumes of two International Lake Ladoga Symposia, arranged in 1993 and 1996 (Simola *et al.* 1995, 1996, 1997).

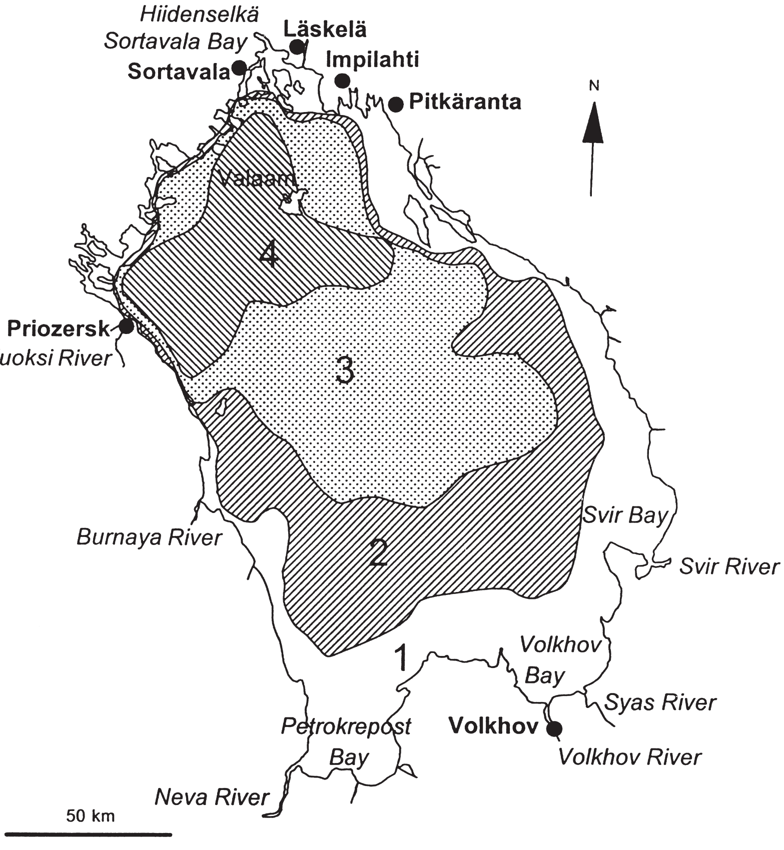

Fig. 1. Limnetic zones of Lake Ladoga and the main rivers and major population centres around the lake. Limnetic zones according to Gusakov and Terzhevik (1992): 1) nearshore (< 15 m, mean depth 9 m); 2) profundal slope (15–52 m, mean depth 30 m); 3) profundal (52–89 m, mean depth 66 m); 4) ultraprofundal (> 89 m, mean depth 113 m).

This paper is a brief summary of the joint Russian-Finnish investigations on hydrochemistry, plankton, zoobenthos, toxic substances and fish, conducted on Lake Ladoga since 1991. The results are compared with earlier data in order to evaluate the ecological state and human impact on Lake Ladoga. The Russian sampling and analysis methods are described by Alekin *et al.* (1973), Petrova and Raspletina (1987), Chernykh *et al.* (1994), Lozovik (1994), and the Finnish sampling and analysis methods by Niinioja *et al.* (1996, 1997).

Natural conditions in Lake Ladoga

The lake and its drainage basin

The surface area of Lake Ladoga is 17 891 km^2, its volume 837 km^3, mean depth 46.8 m and maximum depth 230 m (Sorokin *et al.* 1996). The deepest bottom areas are in the northern parts of the lake (Fig. 1). Glacial forms of relief — rock outcrops, moraine ridges and fiords — are numerous in the northern archipelago area. Stone and gravel shores are typical for the western parts of the lake and there are extensive sandy beaches in the south and east. Aleuritic and pelitic silts, massive and varved clays occupy the deep regions of the lake. The great catchment area of Lake Ladoga (258 000 km^2, Fig. 2) includes three large sub-basins, each with a central lake: Lake Onega–Svir River (83 200 km^2), Lake Ilmen–Volkhov River (80 200 km^2) and Lake Saimaa–Vuoksi River (66 700 km^2), and several smaller riverine drainage areas (28 400 km^2) (Alekin and Smirnova 1984). The catchment area is 14.6 times the surface area of Lake Ladoga. Thus, the influence of the catchment area on the water quality of Lake Ladoga is very strong.

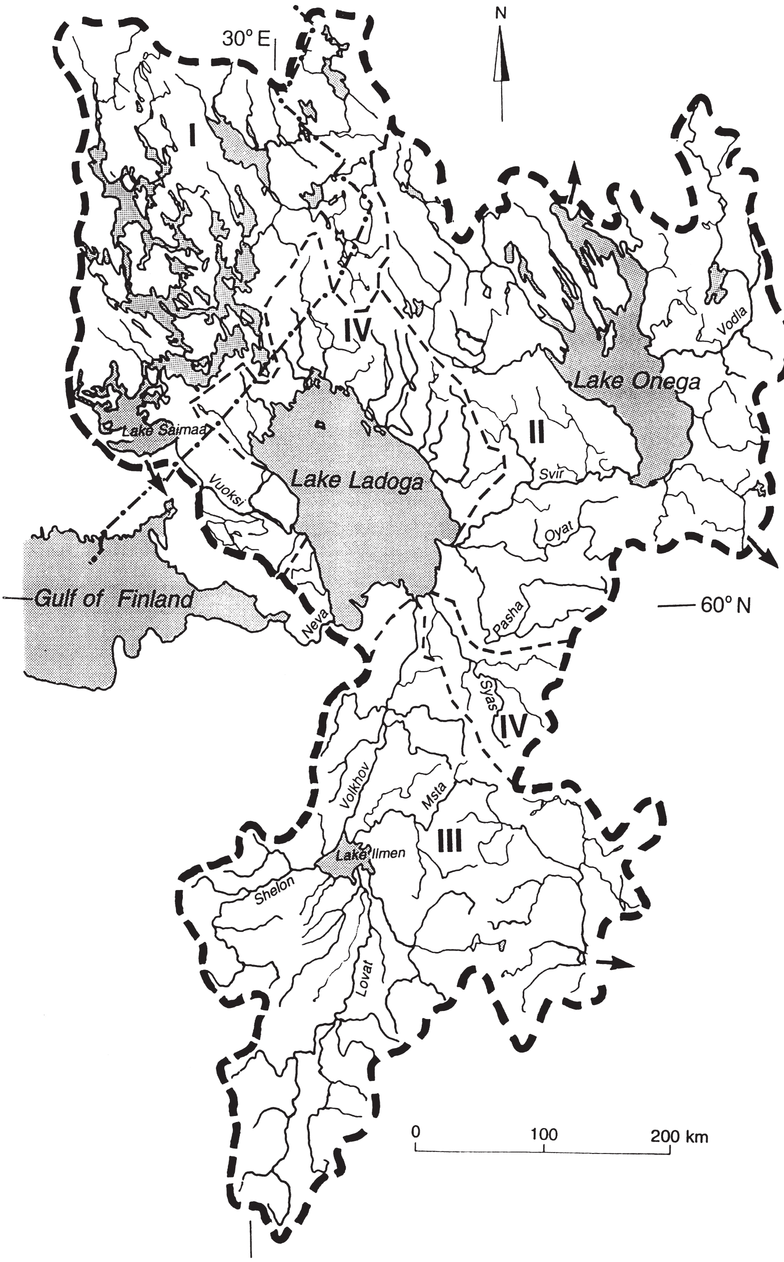

Fig. 2. The watershed basin of Lake Ladoga.

Hydrology

The theoretical water retention time in Lake Ladoga is 11 years (Naumenko *et al.* 1996), which indicates that the ecosystem is rather conservative. River discharge (86%) and atmospheric precipitation (14%) are the principal inflow components of the water balance, while water losses consist of discharge into the Neva River (92%) and evaporation (8%) (Alekin and Smirnova 1984).

Water temperature is one of the main factors determining hydrobiological processes in large

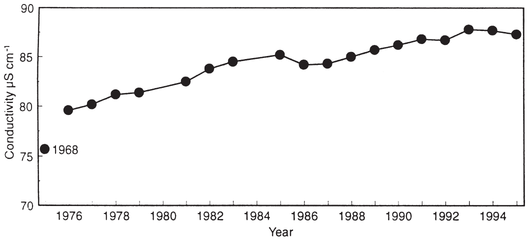

Fig. 3. Average electrical conductivity (µS cm^{-1}) in the surface water of Lake Ladoga in 1968–1995 (Petrova and Terzhevik 1992, A. M. Kruchkov, unpublished data from 1990–1995).

lakes (Naumenko *et al.* 1996). The general temporal and spatial features of the annual temperature cycle in Lake Ladoga regulate the distribution of plankton and nutrients and give rise to lake currents, especially during the warming period. The baroclinic currents of spring give rise to regular spatial temperature gradients, whereas in the cooling period, wind-induced mixing plays a primary role and barotropic currents dominate when there are smaller horizontal gradients.

During spring, when the temperature is rising, and during autumn, when it is falling, the thermal structure of Lake Ladoga is especially complicated. A vertical barrier of water at its maximal density (+4 °C), the thermal bar (Tikhomirov 1981), is formed during these periods. In spring the thermal bar divides the nearshore thermally active region, where the temperature is rising, from the offshore thermally inert one, where the temperature is lower than +4 °C. Effluent and sewage load entering the lake in spring tends to be accumulated within the regions confined by the thermal bar. Surface heating in spring moves the thermal bar along the bottom slope to a greater depth. In autumn, the reverse process occurs. The water masses of the thermally active and inert regions differ strongly in their physical and chemical properties and as regards dwelling conditions for aquatic organisms.

Hydrochemistry

Until the early 1960s Lake Ladoga was oligotrophic, but within the past 20–30 years its trophic state has changed to mesotrophic, with elevated nutrient concentrations and decreased transparency (Petrova 1982, Drabkova *et al.* 1996). The concentration of dissolved oxygen in the open water area in surface water has been reported to fluctuate from 9 to 15 mg l^{-1} (90%–120% saturation), electrical conductivity from 75 to 87 µS cm^{-1} (Fig. 3) and water transparency (Secchi disk depth) from 1.8 m to 3.9 m. The relatively low transparency in comparison with other large lakes is related to the water colour of Lake Ladoga (average 23–59 mg l^{-1} Pt) and to the condition of the lake (Drabkova *et al.* 1996). In the 1990s the water transparency in the open water area (August) has fluctuated, on average, from 1.8 to 3.5 m (Petrova and Terzhevik 1992, Drabkova *et al.* 1996, Niinioja *et al.* 1996, 1997) and the water colour from 25 to 35 mg l^{-1} Pt. The increase in electrical conductivity during the last 30 years (Kruchkov 1997) and the marked decrease in water transparency, which in the years 1899–1902 was 5–6 m (Witting 1929), indicate eutrophication of the lake.

The earliest accounts of nutrient concentrations give very low values: in 1959–1962 the concentration of mineral phosphorus was reported to be about 1–3 µg l^{-1}, whereas the values for 1976–1979 are 12–15 µg l^{-1} (Raspletina 1982, Petrova and Terzhevik 1992). Corresponding range for nitrate concentration was from 0.1 to 1.2 mg l^{-1} and for ammonium (NH_4) from 0.04 to 0.24 mg l^{-1} (Raspletina 1982, Petrova and Terzhevik 1992). In 1976–1995 the mean total phosphorus concentration in summer was 21 µg l^{-1} in the pelagial zone and 32 µg l^{-1} in the littoral area (Fig. 4). In 1993–1995 the concentrations of total phosphorous ranged from 26 to 34 µg l^{-1} in the coastal zone and from 15 to 24 µg l^{-1} in the open-water zones (Niinioja *et al.* 1997). The mean total nitrogen values for the water column were from 592 to 660 µg l^{-1} in the coastal zone and from 520 to 690 µg l^{-1} in the pelagial zones. The N:P ratio varied from 19 to 23 in the coastal zone and in other zones from 26 to 39. Considerable variation in water quality is characteristic of Lake Ladoga. The concentration of phosphorous indicates mesotrophic or even eutrophic conditions in the lake. The eutrophication process is most evident in the loaded bays and littoral areas (Petrova and Terzhevik 1992, Andronikova 1996, Holopainen *et al.* 1996, Kapustina 1996, Holopainen and Letanskaya 1997, Niinioja *et al.* 1997). Phosphorus seems to be the limiting nutrient for bacteria and algae.

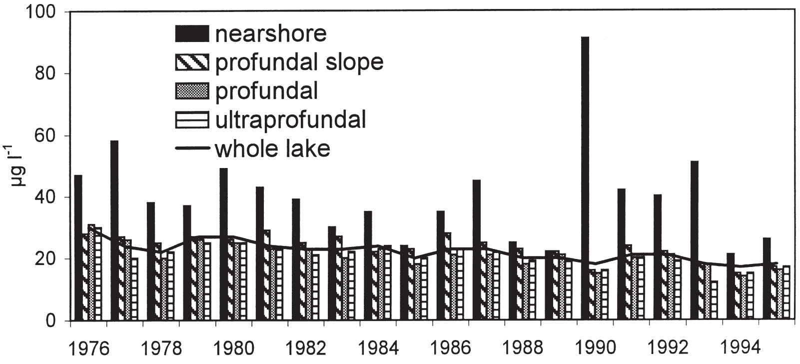

Fig. 4. Total phosphorus concentrations (µg l^{-1}) in Lake Ladoga: volume weighted average values for the different depth zones and the whole lake in 1976–1995 (Raspletina 1992, 1996, Chernykh *et al.* 1994, Niinioja *et al.* 1997).

Phytoplankton

In the 1950s–1960s the phytoplankton of Lake Ladoga consisted of 380 species, subspecies, forms and varieties: 45.5% Bacillariophyta, 33.2% Chlorophyta, 20% Cyanophyta, 3.7% Chrysophyta, 1% Pyrrophyta, 0.8% Xanthophyta and 0.8% Euglenophyta (Kalesnik and Raspopov 1968). Only 25 taxa sometimes reached mass development — more than 25 000 cells or 10 000 colonies per litre. The most abundant were the diatoms *Aulacoseira italica* (Ehr.) Simonsen (maximum 6×10^6 cells l^{-1}), *Aulacoseira islandica* ssp. *helvetica* (O. Müller) Simonsen and *Asterionella formosa* Hassall (> 1×10^6 cells l^{-1}). There were 69.2% cosmopolitan taxa, 18.6% boreal taxa and 12.2% northern alpine taxa. The composition and proportional abundance of algae characterized the planktonic flora of Lake Ladoga as cold water pelagic community, typical for a large oligotrophic lake.

At the end of the 1970s and during 1980s the mean phytoplankton biomass was growing rapidly compared to the values found at the beginning of the 1960s (Petrova and Terzhevik 1992). The mean quantities of algae (1 000 cells l^{-1}) in pelagial area during summer in 1960–1962 varied from 78 to 161, in 1976–1980 from 703 to 1190, and in 1984–1989 from 834 to 1364. The structure and species composition of phytoplankton have also changed. Earlier diatoms dominated in summer, now Cyanophyta and Cryptophyta. The concentrations of some algae associated with eutrophy, e.g. *Diatoma elongatum* var. *elongatum* (Lyngb.) C. A. Agardh, *Oscillatoria* and *Microcystis,* have increased. On the other hand, some oligotrophic species, e.g. *Asterionella formosa* and *Tabellaria fenestrata* (Lyngb.) Kuetz. have decreased in numbers. The formerly frequent *Attheya zachariasii* Brun, *Rhizosolenia eriensis* H. L. Smith var. *morsa* and *Dinobryon* spp. have almost entirely disappeared.

The annual primary production of Lake Ladoga is reported to have increased in the pelagial area from 14.7 g m^{-2} C in 1976 to 139.5 g m^{-2} C in 1985, (Petrova 1982, Petrova and Terzhevik 1992). The values for maximal daily production of phytoplankton 1.11 and 1.03 g m^{-2} C in 1986 and 1989, respectively, characterize Lake Ladoga as mesotrophic. Coastal regions are mesotrophic or eutrophic. At the end of the 1980s the maximal biomass began to decrease again. In 1993 the biomass of phytoplankton varied from 0.4 to 6.6 g m^{-3}, the mean value being 1.38 g m^{-3} (Letanskaya and Protopopova 1994, Holopainen and Letanskaya 1997). However, according to phytoplankton biomass and chlorophyll *a* concentrations, Lake Ladoga may, in general, still be classified as mesotrophic. During the period 1976–1983, mean summer concentrations of chlorophyll *a* reached 2.6–2.8 µg l^{-1} and maximum values 6.4–47.0 µg l^{-1}, compared with 1.6–2.0 µg l^{-1} and 3.2–14.5 µg l^{-1} in 1984–1989 (Petrova and Terzhevik 1992). Eutrophied areas are found in the northern archipelago of the lake and in the areas influenced by large rivers (Letanskaya and Hindák 1992, Letanskaya and Protopopova 1994, Holopainen *et al.* 1996, Holopainen and Letanskaya 1997). Regional differences in phytoplankton biomass are considerable: values in the northern archipelago have been found to be more than 10 times higher than those in some pelagial areas (Fig. 5).

The observed tendency towards increasing numbers and activity of bacterioplankton in re-

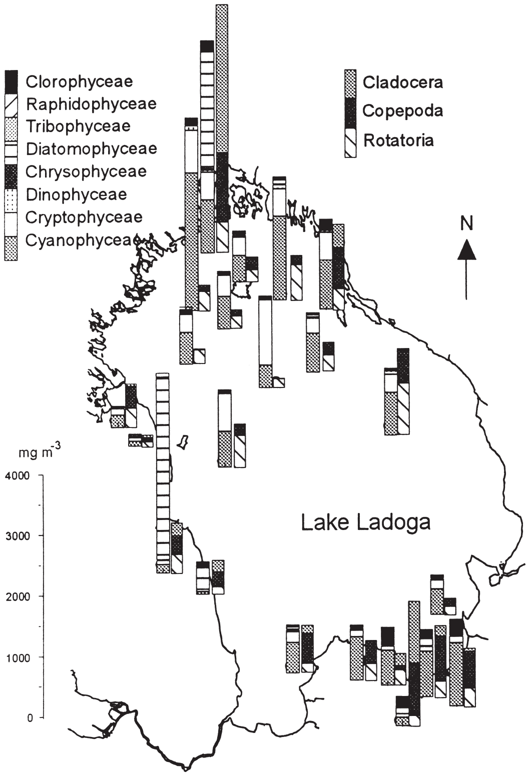

Fig. 5. Phytoplankton and zooplankton biomasses (mg m^{-3}, fresh mass) and their composition on August 8–13, 1993 in the surface water (0–5 m) of Lake Ladoga (Rahkola *et al.* 1994, and unpublished data).

cent years in the open lake also reflects the ongoing eutrophication of the offshore regions of Lake Ladoga, even though there has been a small decrease in the concentrations of total phosphorus (Kapustina 1996).

Zooplankton

According to Dengina and Sokolova (1968), the list of recorded species included 327 planktonic taxa, of which 221 Rotatoria, 72 Cladocera and 34 Copepoda. Since then, a further 39 taxa of the littoral zone have been added to the list (Raspopov *et al.* 1996, Telesh 1996). There is a very long record of pelagic summer zooplankton observations, spanning the period 1948–1994. According to these data, the zooplankton community of the pelagic zone shows great stability throughout the entire monitoring period (Table 1). The biomass of zooplankton is rather low, and there are no definite trends in the monitoring data collected over the four decades. Copepoda have been prevalent in the community throughout the period, which is typical for bodies of water with low productivity.

In a recent Finnish-Russian investigation (Andronikova and Avinski 1994, Rahkola *et al.* 1994), three different areas were distinguished according to zooplankton composition: the northern archipelago, the deep pelagial area, and the shallow Volkhov Bay (Fig. 5). These areas also differed in their physical characteristics and water quality. The effect of nutrient loads on the plankton community can be observed along the Bay of Sortavala (Karjalainen *et al.* 1999). However, wind-induced currents from the pelagial zone to the eutrophied bays can change the structure of the plankton community. In the Volkhov Bay, high discharge and turbidity as well as the content of the waste waters seem to lower phyto- and zooplankton biomass compared to the biomass in the

Table 1. Numbers (N), biomass (B, wet mass) and percentages of taxonomic groups of summer zooplankton according to long-term investigations in the pelagic zone of Lake Ladoga, stations 55 and 82, weighted means for 0–70 m of the water column (mean and range for the early observations, ± SE for the later decadal values) (for sources of data and original references, *see* Andronikova 1996).

Characteristics	1948–1963	1970s	1980s	1990s
N, ind. × 10^3 m^{-3}	11.1 (10.3–12.0)	12.6 ± 3.6	16.4 ± 3.1	13.3 ± 2.2
B, mg m^{-3}	214 (132–348)	291 ± 58	224 ± 36	268 ± 88
Rotatoria, N	43	16	36	38
B	23	6	11	10
Cladocera, N	7	25	12	13
B	22	29	16	16
Copepoda, N	50	59	52	49
B	55	65	73	74

Sortavala Bay (Karjalainen *et al.* 1999).

On average, between the surface and deep layers the differences in numbers of individuals are 100-fold and the differences in biomass 10-fold. However, zooplankton distribution is not regulated only by physical factors; these organisms can actively swim both vertically and horizontally (Siebeck 1980). Changes in the abundance, development and composition of zooplankton along the nearshore-offshore gradient may also reflect the effects of habitat and planktivory on the community (Johansson *et al.* 1991). During the observed period there has been a slight increase in the average values of several eutrophy-indication parameters in the pelagial area: the densities have increased from 550 (1970s) to 920 (1990s) ind. m^{-3}, the biomass from 64 to 112 mg m^{-3}, and the Cyclopoid:Calanoid biomass ratio (B_{cycl}:B_{cal}) from 1.5 (1970s) to 2.3 (1990s) (Andronikova 1996).

Zooplankton data for the Petrokrepost Bay show that during the last decade both the quantitative characteristics and taxonomic structure of the community have changed significantly. The relative numbers of Copepoda and Calanoida have decreased: the number of *Eudiaptomus gracilis* (Sars) decreased from 17% to 7% and the formerly dominant *Eurytemora lacustris* Poppe has virtually disappeared from the samples (Andronikova 1996). *Bosmina longispina* Leydig has become the dominant species instead of *Daphnia cristata* Sars.

Analysis of data for 1990–1995 allows us to reach a conclusion about the stable condition of pelagic zooplankton at this period (Avinski 1996). The average density and biomass of pelagic zooplankton for the layer 0–50 m were 19 100 ind. m^{-3} (range 11 100–27 100 ind. m^{-3}) and 406 mg m^{-3} (300–576 mg m^{-3}), respectively. The data confirm that the pelagic zooplankton community has remained rather stable for the last 25 years.

Macrophytes and periphyton

Intensive water dynamics and the great depth of the lake are unfavourable factors for macrophyte development. In the archipelago region with sheltered biotopes and in the southern shallow bays, macrophyte stands occupy larger areas than in the steeper, exposed shores along the western and eastern sides of the lake. A total of 87 species of higher aquatic plants have been recorded in the macrophyte stands that cover 1 460 hectares in the archipelago region and 8 170 hectares in the southern shallow bays, whereas macrophyte stands, with 58 recorded species, occupy only 242 hectares along the western shore and 342 hectares on the eastern shore (Kalesnik and Raspopov 1968). The total area of macrophyte associations is slightly over 10 000 hectares, or 0.5% of the lake surface area.

In the periphyton, 350 species and forms have been recorded (Rychkova 1995): 47% of the taxa belong to the Bacillariophyta (including 10 species and forms of *Achnanthes*, 16 *Cyclotella*, 16 *Cymbella*, *16 Eunotia*, 12 *Fragilaria*, 17 *Gomphonema*, 13 *Navicula* and 78 *Nitzschia*), 37% to the Chlorophyta (including 6 taxa of *Closterium*, 11 *Cosmarium*, 8 *Pediastrum*, 14 *Scenedesmus* and 7 *Staurastrum*), 14% to the Cyanophyta and 2% to the Xanthophyta and Chrysophyta. The most important factor determining the development of periphyton associations are the stable substrates: rocks, stones and macrophytes. Periphyton on macrophytes in sheltered places is rather abundant; its production was sometimes comparable to the production of higher aquatic plants.

On the stones along the open shores, some diatoms (*Cymbella*, *Achnanthes*, *Stephanodiscus*) are rather abundant; near the mouths of rivers *Oedogonium* and *Cladophora* appear to be predominant. On the rocks, the most widespread alga is the filamentous *Ulothrix zonata* (Web. et Mohr.) Kütz. (max. density 3×10^6 cells m^{-2}, max. biomass 400 mg m^{-2} of substrate).

Periphyton is abundant only down to a depth of 5 m, so its role in such a deep lake is relatively small, as the proportion of the 0–5 m depth zone is less than 10% of total lake area. Changes in periphyton development and distribution are caused mainly by succession of macrophytes and fluctuations in water dynamics (Rychkova 1995).

Zoobenthos

At least 385 species and forms of bottom-dwelling macroinvertebrates were known from Lake Ladoga in the 1950s–1960s; 85% of these were found in the littoral zone, and the distribution of zoobenthos was mainly dictated by water depth and type of bottom deposits (Stalmakova 1968). At that time only oligosaprobic species, e.g. oligochaetes, were found in the deep profundal areas, whereas nowadays in some localities in the ultraprofundal zone, at depths reaching 200 m, species typical of *a*-mesosaprobic conditions (*Potamothrix hammoniensis* (Mich.), *Limnodrilus*) have been recorded (Slepukhina and Belyakova 1994, Slepukhina *et al.* 1996).

At depths exceeding 90 m, the ultraprofundal zone, the fauna is extremely poor: typically, only 3–4 species are encountered with a total wet weight biomass (WM) of less than 0.5 g m^{-2}. Maximal densities and biomasses in the open lake are recorded at depths of 20–30 m on silty sands (max. WM up to 11 g m^{-2}) and also in some shallow bays among macrophytes (max. WM 20 g m^{-2}). In polluted localities (e.g. the river mouths of the Volkhov and Syas rivers and near Sortavala) not only higher densities and biomasses are recorded, but changes are also observed in the species composition from species typical of oligotrophic lakes to species characterizing eutrophic waters (Slepukhina and Belyakova 1994, Slepukhina *et al.* 1996).

Among the benthic invertebrates of Lake Ladoga, some glacial relicts occur: *Saduria (Mesidotea) entomon* (L.), *Gammaracanthus loricatus* Sars, *Pallasea quadrispinosa* Sars and *Monoporeia (Pontoporeia) affinis* (Lindstöm). Lake Ladoga is the only freshwater lake where *Saduria* is known to occur as a relict species. *Monoporeia* is the most widespread benthic organism in the lake (Slepukhina 1990).

Species composition and certain taxonomic indices of the benthic meiofauna communities indicate the geographic pattern of polluted and unpolluted conditions in Lake Ladoga (Särkkä 1996). The high proportions of Oligochaeta, Tubificidae and resting Cyclopoida indicate eutrophy or organic load, but high proportions of Aeolosomatidae and Harpacticoida indicate oligothrophy. The most polluted sites are near Sortavala and Pitkäranta, and at the mouths of the rivers Burnaya and Volkhov (Kurashov and Gorichensky 1992, Kurashov 1994, Särkkä 1996). The pollution tolerance of the meiofauna in a very large lake such as Lake Ladoga evidently is high, presumably due to effective mixing of water masses (Särkkä 1996).

Fish

Lake Ladoga is characterized by a rich fish fauna. Altogether 48 species and forms of fish have been encountered in the lake. Of these, 25 have commercial importance and 11 are mass commercial fish; the salmonids, coregonids and pikeperch (*Stizostedion lucioperca* (L.)) are the most valuable commercial species (Kudersky *et al.* 1996). The construction of hydroelectric dams in rivers, timber floating, fishery and other factors have reduced the abundance of some fish species. Atlantic sturgeon (*Acipenser sturio* L.) and Volkhov whitefish (*Coregonus lavaretus baeri* Kessler) are considered to be taxa that are facing extinction, and have thus been included in the 'Red Data Book' of endangered species of Russia (Kudersky *et al.* 1996).

Lake Ladoga fish can be grouped into northern species, southern species and ubiquitous species. The northern species are the most common in the lake. As a rule they are stenobionts, requiring low water temperatures, high oxygen concentrations and good water quality. This group e.g. salmonids, coregonids, grayling and charr, in particular, has suffered from eutrophication and pollution. Thus the abundance and commercial catches of some of them have decreased (Kudersky *et al.* 1996).

The post-war fishery of Lake Ladoga can be divided according to catch level into four periods. In the years 1945–1954 the total annual catch increased (Rumyantsev *et al.* 1994), and reached a level of 4 000 tonnes (Fig. 6). In this period the fish stocks that had increased during the war years were intensively exploited. During the period 1955–1963, however, this fishery was not in balance with the stocks. As a consequence, the catch decreased drastically, down to less than 2 000 tonnes in some years (Kudersky *et al.*1996).

Control of fishing restored the abundance of whitefish and pikeperch (Fig. 7), increasing the total annual catch to about 5 500 tonnes in 1964–1989 (Kudersky *et al.* 1996). However, the fishery control measures have not been sufficient to achieve the conservation of salmon (*Salmo salar* m. *sebago* Girard), brown trout (*Salmo trutta* L.), and the migratory whitefish stocks in the lake.

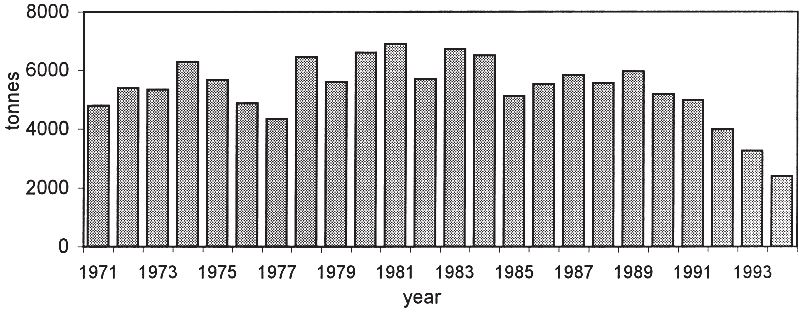

Fig. 6. Annual total fish catches (tonnes) in Lake Ladoga in 1971–1994 (Kudersky *et al.* 1996, L. K. Kudersky, unpublished data).

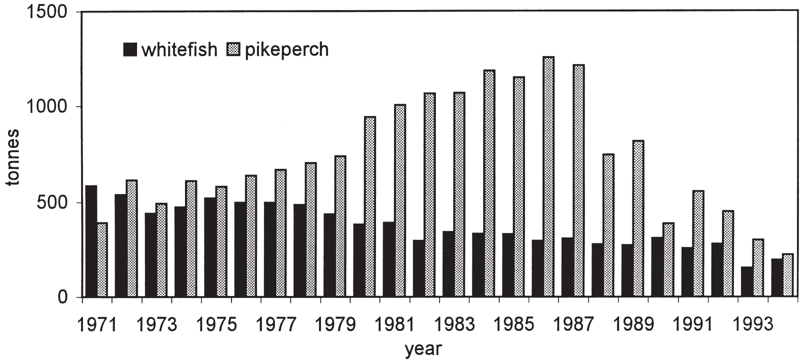

Fig. 7. Annual catches of whitefish (*Coregonus lavaretus*) and pikeperch (*Stizostedion lucioperca*) in Lake Ladoga in 1971–1994 (Kudersky 1996, L. K. Kudersky, unpublished data).

The Ladoga ringed seal

Lake Ladoga is inhabited by a subspecies of ringed seal (*Phoca hispida ladogensis* Nordq.), which has the same origin as two other ringed-seal subspecies that live in nearby bodies of water, the Baltic ringed seal and the Saimaa ringed seal (Sipilä *et al.* 1996). Differentiation of these subspecies began 11 000 years ago after the last glacial epoch when the Baltic ringed-seal stock was isolated from the Arctic ringed seal (Sauramo 1958).

In comparison with the Baltic ringed seal, and especially with the Saimaa seal, the population status of the Ladoga ringed seal is good. The population probably includes over 5 000 animals (Sipilä *et al.* 1996). The main part of the population lives in the southern part of the lake where the main breeding areas lie on open shores. During summer in northern Ladoga, the Ladoga ringed seal forms haul-out herds of more than 50 animals (Antoniuk 1975, Sipilä *et al.* 1996). Concentrations of mercury in the liver and kidney of the Ladoga seal are clearly elevated, but levels of the other environmental toxicants analysed (Cd, Pb, PCB) are comparatively low (Sipilä *et al.* 1996).

The results of recent studies confirm that the Ladoga seal population is not endangered, even though 200–400 seals die in fishing gear annually (Sipilä 1993).

Present state of the environment

Anthropogenic eutrophication is revealed differently in different parts of the lake (Petrova and Raspletina 1987, Petrova and Terzhevik 1992, Viljanen and Drabkova 1992, Viljanen *et al.* 1994, 1996, Simola *et al.* 1995, 1996, 1997, Holopainen *et al.* 1996). Eutrophication processes, indicated by increased nutrient levels, high algal densities and abundance of blue greens, are obvious in some isolated bays and in areas influenced by the large rivers. There are definite signs of increased nutrient content even in the pelagial areas.

Extensive blooms of blue-green algae in late summer have been observed within the whole lake area (Petrova and Raspletina 1987, Rahkola *et al.* 1994, Holopainen *et al.* 1996). In Ladoga, as well as in other large and deep lakes, there may appear a discrepancy between trophic level classification based on different ecological groups. For example, in the 1970s the phytoplankton production in July–August in the northern region of Ladoga was three times that in the southern part of the lake (Petrova and Terzehevik 1992), while the biomass of benthos in the southern region was twice that of the northern region. In deep lakes only a small amount of organic detritus reaches the bottom serving as a source of food for benthic invertebrates. Therefore, the deeper the body of the lake, the higher must be the level of primary production to affect trophic conditions in the deep profundal (Saether 1980).

Recent studies of zoobenthos confirm the anthropogenic eutrophication of the lake as a whole (Slepukhina and Belyakova 1994). Changes in density, biomass and species composition have been recorded. Most parts of the deep archipelago and the deep northern region and central parts of the lake are oligotrophic, the southern region and Volkhov Bay are mesotrophic, and Impilahti and Sortavala bays are eutrophic.

Zooplankton in the coastal regions displays features of mesotrophic and eutrophic lakes, but in pelagial areas the species composition and biomass of zooplankton characterize Lake Ladoga as oligo-mesotrophic, with only a slight trend towards eutrophication. Thus, the lake as a whole does not belong to one definite trophic type (Andronikova and Avinski 1994, Andronikova 1996). The highest values of phyto- and zooplankton have been recorded in coastal regions, especially near polluted tributaries (Rahkola *et al.* 1994).

In recent years, toxic contamination has become one of the most urgent problems for Lake Ladoga (Frumin 1993, Krylenkova *et al.* 1995, Drabkova *et al.* 1996). In water samples from all parts of the lake the presence of organochlorine compounds and heavy metals have been recorded. Concentrations of copper commonly exceed the permissible values allowed in Russia ($0.1 \mu g l^{-1}$); near the mouth of the Svir River this excess was 18 times the permitted limit and in the Shchuchiy Bay near Priozersk it was 19 times the limit (Anon. 1992). In some areas the concentration of zinc has been three times higher than the permissible value ($10 \mu g l^{-1}$). Concentrations of phenol and oil products have been high and often very close to the permissible levels ($1 \mu g l^{-1}$ and $50 \mu g l^{-1}$, respectively), especially near the points of pollution and at the mouths of the rivers. According to the amount of toxic chemicals and the toxicity of the sediments, the state of the lake is not critical, although some toxic responses have been seen (Pellinen *et al.* 1994). Reliable signs of strong toxic pollution are deformities which are exhibited by some invertebrates, mainly chironomids larvae (Warwick 1990) and oligochaetes (Milbrink 1983). Such deformities have been registered in polluted areas of Lake Ladoga, in the Sortavala archipelago, near Läskelä, in the Shchuchiy Bay, near Pitkäranta, and in the Volkhov Bay (Slepukhina 1994).

Eutrophication and pollution as a whole have a great negative influence on the biota. During recent decades the most sensitive planktonic and benthic species have disappeared, while species tolerant to organic and even toxic contamination have become widespread. The glacial relicts *Gammaracanthus loricatus* and *Pallasea quadrispinosa* used to be widespread in the lake. Now *Pallasea* is very rare and *Gammaracanthus* has not been registered for the last 20 years (Slepukhina *et al.* 1996).

The most heavily polluted areas of Lake Ladoga are characterized by a 'lifeless bottom', where no invertebrates are found. Until 1986 such areas existed in the Shchuchiy Bay and until 1991 in the Hiidenselkä Bay near Läskelä and in the vicinity of Pitkäranta (Slepukhina and Belyakova 1994, Slepukhina *et al.* 1996). After the pulp and paper mills were closed at the first two locations and the place for outflow of effluents was changed in the third area, ecological conditions have improved and the benthic communities have revived. The speed of the restoration depends on many factors and to a large extent on water depth and water dynamics at the site.

Investigations of macrozoobenthos in the Shchuchiy Bay during the 10 years from 1986 to 1996 showed that invertebrate communities are being formed rather quickly due to the exposed location and intensive water dynamics. The first group to appear in samples the year after the pulp and paper mill was closed in 1986 was chironomids. The next year oligochates and in 1988 also amphipods were found; near the shore the quantity of amphipods reached up to 100 g m^{-2} (WM) (Slepukhina *et al.* 1993).

As compared with the Shchuchiy Bay, the restoration of life in the Hiidenselkä Bay near Läskelä has been slow, due to the thick layer of wood fibre on the bottom and restricted exchange of water. The first invertebrates appeared on the bottom only two years after the pulp and paper mill was closed, but during the winter of 1992 all of these perished under the ice. In winter samples there were only dead invertebrates (Slepukhina and Belyakova 1994).

'Lifeless bottom' areas still exist in the Volkhov Bay, near the effluent inflow of the Syas pulp and paper mill, and within the Valaam archipelago in the Monastery Bay, where there is much wood debris on the bottom (Slepukhina *et al.* 1996). On the periphery of the 'lifeless zones' one can observe polysaprobic areas, where only 1–2 species can survive; these sometimes with a mass development.

After intentional introduction, an amphipod crustacean, *Gmelinoides fasciatus* Stebb., which is endemic to Lake Baikal, invaded Lake Ladoga in 1988 and has become well established in the littoral communities throughout its northern parts (Panov 1996). The highest abundances are over 50 000 ind. m^{-2}, and negative impacts on native species have been observed.

Human activities also affect fish, especially the anadromous species. Many fish also suffer from toxicoses (Arshanitza 1988): in Volkhov Bay this proportion is 70%–80%, and 20%–60% of the fish have a smell of oil products. In the Svir Bay, 50%–60% of the fish have toxicoses, near the Vidlitza 60%.

Great loads of untreated sewage effluents have enhanced the production of pathogenic bacteria in water and bottom deposits: the most dangerous situation is near Priozersk and Petrokrepost (Rumyantsev *et al.* 1994, Vorobieva *et al.* 1996). Epidemiological studies have revealed high levels of morbidity and mortality among human populations using Lake Ladoga water in areas close to pulp and paper mills, due to diseases that have a potential connection with water quality, i.e. diseases of the digestive organs and urogenital system; from 1960 to 1985 the incidence of intestinal tumours was observed to have increased 7-fold among people living near pulp and paper mills (Vorobieva *et al.* 1996).

Future prospects

It is evident that the ecological situation of Lake Ladoga has deteriorated during the last decades, and in some parts it is critical. The present environmental situation, in combination with problems associated with regional economic development heralds the indissoluble relationship and interdependence of social, economic and environmental processes. To change the existing environmental situation, new approaches, principles and types of activity are essential. The natural processes of self-purification are not sufficient to counteract the intensive human impact.

The main problems of Lake Ladoga are eutrophication and toxic contamination, which affect the water quality and influence the structure and processes of the ecosystem. Blooms of blue-green algae have become common in summer; toxic substances and heavy metals accumulate in water and sediments; the unique biota, including fish, is in danger; and people living in the vicinity of polluted areas suffer from contamination. If the eutrophication process is allowed to continue, the water quality may soon become unsatisfactory for recreation or as a supply of drinking water. The quality of water in St. Petersburg is loosing its high standards. Therefore it is urgent to solve the problems connected with the water pollution control of Lake Ladoga in a way that sustains its high ecological and economic value.

Lake Ladoga is a body of water of international importance because its drainage basin is located on the territory of Russia and Finland and the quality of its water has considerable influence on the Baltic Sea. Therefore, formulation of a policy and strategy of sustainable development for this region must be an integral part of the corresponding strategies which are now being developed, especially for the circumbaltic countries.

Lake Ladoga is a unique natural complex of great national value in Russia, and it must be protected and guarded. The vast drainage basin of Ladoga belongs to Russia and Finland; the southern margin of the drainage area even reaches Byelorussia. Therefore, it will be necessary to have a special federal law that can regulate all the interests of different regions, administrative bodies, industries and other involved parties, including the international concern. This law must include ecological zonation of the drainage basin territory and foresee the various requirements for environmental loads in the different zones.

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