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Development of Water Protection of Lake Onega

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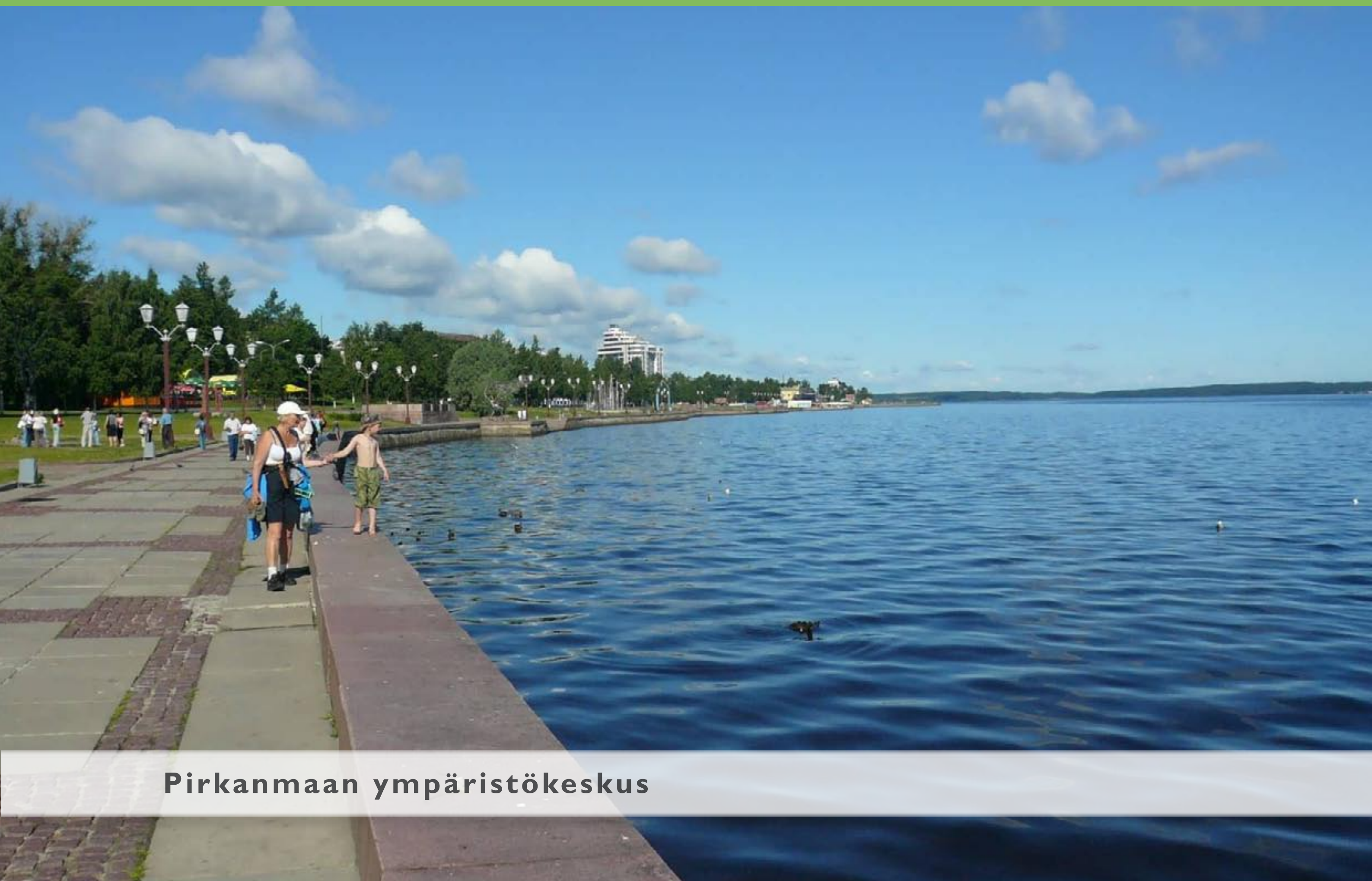

Pirkanmaan ympäristökeskus

THE FINNISH ENVIRONMENT 36 | 2009

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Final Report

Victor Podsechin, Heikki Kaipainen, Nikolai Filatov, Ämer Bilaletdin, Tom Frisk, Arto Paananen, Arkady Terzhevik, Heidi Vuoristo

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SISÄLLYS

1 Introduction

Water is one of the most essential elements required for human life. Chapter 18 of Agenda 21, adopted at the Earth Summit in Rio de Janeiro, defined the overall goal of water policy developments:

"Water is needed in all aspects of life. The general objective is to make certain that adequate supplies of water of good quality are maintained for the entire population of this planet, while preserving the hydrological, biological and chemical functions of ecosystems and adapting human activities within the capacity limits of nature and combating vectors of water related diseases". (UN 1992, p. 275)

The Water Framework Directive (WFD), Directive 2000/60/EC includes the main guidelines on organizing water management within the EU member states. It is not obligatory to non-EU countries, but experience gained during the last years of WFD implementation could also be applied to water objects in Russia (and other CIS states). In Finland, as well as in other EU countries, a lot of research and planning work has been carried out when it comes to the implementation of the WFD in different regions of Europe.

Lake Onega (sometimes name Onego is used, Onezhskoye Ozero in Russian, Äänisjärvi in Finnish) is the second largest lake in Europe after Lake Ladoga. The lake is located in the Karelian Republic, in the Leningradskaya and Vologodskaya regions of the Russian Federation. It is connected to the Baltic Sea via the river Svir (Syväri), Lake Ladoga and the Neva River and also to the White Sea via a channel. Lake position between 600 53' and 620 54' of northern latitude makes it one of the most northerly situated great lakes in the world and effects radiation and thermal regime, which, in turn, defines peculiarities of hydrochemical and ecological processes.

Northern part of the lake has a large number of elongated bays with maximum depths more than 80 m. Large towns and industrial centres are located on shores of these bays, isolated from the central part of Lake Onega. 1152 rivers bring their water to the lake but most of them are very small ones, only 52 rivers have a length of 10 and more kilometres. Three rivers: Vodla, Shuya and Suna have a total annual runoff of 9.96 km^3 or about 56% of the total river inflow (Filatov 1999).

Industrial and domestic wastewaters of Petrozavodsk, Kondopoga and Medvezhyegosrk are the main source of lake waters pollution. Wastewaters of Petrozavodsk and Kondopoga are processed with biological treatment, while Medvezheyegorsk wastewaters are withdrawn directly to Bolshaya Guba of Povenetsky Bay without purification. Petrozavodsk Bay has an intensive water exchange with open part of the lake. Kondopoga Bay is more isolated and has a longer retention time.

Lake Onega waters flow to Lake Ladoga through River Svir and finally to Gulf of Finland of Baltic Sea via Neva River. As a large water reservoir, Lake Onega is important on a European scale.

This report presents the latest investigations conducted jointly by Finnish and Russian researchers of the possible trends in ecological status of Lake Onega and its catchment area according to the recommendations of the WFD.

2 EU Water Framework Directive

2.1

General

The EU Water Framework Directive (WFD), which is widely described as the most important, far-reaching water legislation ever to emerge from the EU, was passed in December 2000 after over 10 years of development. Its timetable for implementation extends over 15 years, requiring good ecological status to be achieved by 2015. The aim of WFD is to establish a Community framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater, in order to prevent and reduce pollution, promote sustainable water use, protect the aquatic environment, improve the status of aquatic ecosystems and mitigate the effects of floods and droughts'. It updates and consolidates existing fragmented EU water legislation, whilst establishing a new, integrated approach to water protection, improvement and sustainable use. The WFD applies to all water bodies, including rivers, estuaries, coastal waters out to at least one nautical mile, and man-made water bodies, and will have implications for many different industries and activities.

The main objectives of the WFD stated in Article 1 are following:

- Prevent further deterioration, protect and enhance aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands directly depending on the aquatic ecosystems.
- Promote sustainable water use based on the long-term protection of water resources.
- Enhance protection from discharge and accidental losses of pollutants.
- Reduce groundwater pollution.
- Contribute to the mitigation of the effects of floods and droughts.
- Provide water resources for sustainable, balanced and equitable water use.
- Protect territorial and marine waters.
- Achieve the objectives of international agreements for which Member States are signatories, including those, which aim to eliminate the pollution of the marine environment.

Surface water

Central to the Water Framework Directive is the requirement that Member States must take measures to "..prevent deterioration.." and "..aim to achieve good status " of surface waters by 2015 (Article 4).

The concept of surface water status is a key to environment objectives of the Directive. There are five grades of surface water ecological status: High, Good, Moderate, Poor and Bad. Chemical status defined by EU level priority substances is either good or failing good status. The general status of surface waters is defined by poorer of its Chemical Status and Ecological Status. For a surface water body to achieve the minimum target of good status both chemical and ecological status must be at least good.

Ecological Status

The ecological status of a surface water body is defined with reference to the biological, hydro-morphological, and physico-chemical conditions found in pristine reference sites. As no absolute standards for biological quality can be set which apply across Community, because of ecological variability, the controls are specified as allowing only a slight departure from the biological community, which would be expected in conditions of minimal anthropogenic impact. Variations in characteristics of water bodies, such as geology, altitude and size, define the structure of biological communities. This must be taken into consideration when classifying the status of surface waters. Therefore the Directive requires that national typologies are developed for rivers, lakes and coastal waters. Reference conditions are then defined for each surface water type.

A set of procedures for identifying the reference conditions for a given surface water type , and establishing particular biological, physico-chemical or hydromorphological class boundaries, is provided, together with a system for ensuring that each Member State interprets the procedure in a consistent way (the so called inter-calibration procedure at EU level, to ensure comparability). The system is inevitably somewhat complicated, given the extent of ecological variability, and the large number of parameters, which must be dealt with.

Chemical Status

Good chemical status is defined in terms of compliance with all the quality standards established for harmful and hazardous chemical substances at European level. Quality standards have been defined for 53 substances or groups of substances including pesticides and industrial and household chemicals. The Directive also provides a mechanism for renewing these standards and establishing new ones by means of a prioritisation mechanism for hazardous chemicals. This will ensure at least a minimum chemical quality, particularly in relation to very toxic substances, everywhere in community.

Groundwater

The case of groundwater differs from surface water. The presumption in relation to groundwater should be that it should not be polluted at all. For ground waters there are only two categories, either good or poor. Good status is defined by the poorer of the groundwater body's quantitative and quality status. The key status indicators are defined in Annex V (2.1 & 2.3). They can be summarised as:

- Abstraction does not exceed recharge.
- Groundwater levels or chemical quality do not cause surface waters to deteriorate or fail to achieve status objectives.
- No significant damage to terrestrial ecosystems, which depend on the groundwater body.
- Abstraction will not cause saline intrusion.
- Water quality complies with standards established under other EU legislation.

One of the innovations of the Directive is that it provides a framework for integrated management of groundwater and surface water for the first time at European level.

The requirements of the WFD can be summarised as follows:

- The protection of all rivers, lakes, coastal waters and ground waters.
- The setting of ambitious objectives to ensure that all waters meet "good status" by 2015.
- Cross border cooperation between countries and all involved parties.
- The Active participation of all stakeholders, including NGO and local communities, in water management activities.
- Full environment water pricing policies and implementation of the "polluter pays" principle.

Monitoring

The Water Framework Directive also gives directions for monitoring networks. The aim is to get a comprehensive overview of all the surface and ground waters in the

Water Districts so that classification of the ecological and chemical status of surface waters and chemical and quantitative status of ground waters is possible. However, water bodies may be grouped for monitoring purposes if homogenous groups considering types and level of anthropogenic impacts can be formed. Monitoring networks shall consist of surveillance monitoring and operational monitoring. The former is designed to give an overall assessment of the general status of waters, including, e.g. sites in reference conditions and sites representing the largest and most significant surface and groundwater bodies. The operational monitoring is needed to monitor the anthropogenic impacts on waters and to monitor the efficiency of water pollution control measures.

River Basins Management Plans

The Directive proposes a single system of water management by river basin – the natural geographical and hydrological unit – instead of according to administrative or political boundaries. For each river basin district – some of which will traverse national frontiers – a "river basin management plan " will need to be established and updated every six years. The WFD is very prescriptive about the contents of the plans, which must include:

- A description of the eco-regions, characteristics, water body types and reference conditions.
- Maps showing water body status, summary of monitoring results and network details.
- Summary of significant pressures and impacts of human activity, including land use, point and non-point sources of pollution.
- Environmental objectives including justification for any derogations applied.
- Programme of measures adopted to ensure delivery of status objectives.

Member States have to until 2015 fully implement the Directive. Taking into consideration a huge amount of work to be done, the actual time scale is very tight.

The major milestones of the timetable are:

- December 2003: National and regional water laws to be adapted to implement WFD
- December 2004: Analysis of pressures and impacts on all waters has to be completed, including economic analysis.
- December 2006: Monitoring programmes have to be operational as a basis for the water management.
- December 2008: Draft River Basin Management plans published for consultation.
- December 2009: Statutory River Basin Management Plans published.
- December 2015: Water bodies to have achieved "Good Status".

Economic instruments

Article 5 of the Directive requires Member States to carry out an economic analysis of water use at a river basin scale. This is to help decision-makers and the public make more rational judgements about the allocation of resources and the costs / benefits of activities that impinge on the water environment e.g. the cost of pesticide removal, value of wetland amenity and so on.

Economic analysis will also inform decision-makers about the applicability of derogations.

Article 9 requires Member States to fully recover the costs of "Water Services" (the supply of water and disposal of effluent) including the cost of environmental and resource impacts.

The details of the charging scheme are left to Member States, but they must:

- Provide adequate incentives for efficient use.
- Distribute costs equitably between domestic, industrial and agricultural sectors.
- Promote the "pollute pays" principle.

Public participation

An extension of public participation is required in order to include the most appropriate measures in the river basin management plan, which involves balancing the interests of various groups. The economic analysis will put the rational basis for this, but it is essential that this process is open to the scrutiny of those who will be affected.

The second reason is enforceability. The greater the transparency in the establishment of objectives, the impositions of measures, and the reporting of standards, the greater the care Member States will take to implement the legislation in good faith, and the greater the power of citizens to influence the direction of environmental protection, whether through consultation or through the complaints procedures or courts.

2.2

Implementation in Finland

The Water Framework Directive has been implemented in the national legislation as follows:

- The Act on Water Resources Management (2004)
- The Decree on River Basin Districts (2004)
- The Decree on Water Resources Management (2006)
- The Decree on Hazardous and Harmful Substances (2006)

Five river basin districts have been delineated in mainland Finland, while two international river basin districts have also been designated covering parts of Finland, one of which is shared with Norway, and the other with Sweden. The Government of Åland is responsible for the river basin district which covers the autonomous Åland Islands province. Each river basin district has nominated one of the regional environment centres as a coordinator to lead the water management planning work.

The WFD led to major changes in the former tradition of surface water classification in Finland. The old classification system was based on the water quality and the class boundaries were set from the needs of the average suitability of the water bodies for water supply, fishing and recreation. The natural differences in lakes, rivers and coastal waters were not reflected in the classification criteria and the biological parameters were not used.

For the purposes of the WFD, 12 lake types, 11 river types and 11 coastal water types have now been defined in Finland. The lake typology is based mainly on lake size, geology of catchment area, retention time and depth, the river typology on size and geology of catchment area and the coastal water typology on duration of ice cover, salinity and openness. In addition, the geographical location is taken into consideration in all surface water types.

The type specific classification criteria have been defined and the status of waters classified. The main biological elements and physico-chemical parameters used in the ecological classification are as follows:

	Lakes	Rivers	Coastal waters
Phytoplankton	X		X
Macrophytes	X		X
Phytobenthos		X	
Macrozoobenthos	X	X	
Fish	X	X	
Total phosphorus		X	X
Total nitrogen	X	X	X
pH		X	
Transparency			X

Hydrological-morphological quality is assessed by the magnitude of water level fluctuations in regulated water, by the degree of impoundment by dams, weirs etc. and by the morphological changes at the shoreline.

In summary, the ecological quality of Finnish surface waters is mostly good or even excellent, especially in the large lakes and the northern rivers. Smaller lakes and rivers and the coastal areas of the Gulf of Finland and the Archipelago Sea are in moderate or worse status. The main problems are eutrophication in lakes and coastal areas, in the rivers also hydromorphological changes. Concentrations of harmful or hazardous substances are generally so low that chemical status of surface waters is good.

The status of ground waters is mainly good in Finland. However, there are risk areas, especially in Southern Finland. The risks are caused e.g. by traffics, polluted soils and the use of pesticides.

The monitoring programme of Finnish surface and ground waters was revised in year 2006 to meet the requirements of the WFD. The monitoring of biological parameters and harmful substances was increased. New monitoring sites were added in order to cover all surface water types.

The regional environment centres have compiled River Basin Management Plans (RBMP), which contain suggestions for water protection measures needed to achieve the good ecological and chemical status in all waters in the year 2015. The RBMPs also include maps of classification, monitoring networks and other basic information about the River Basin Districts. The RBMPs will be available for everyone to comment. They will be finalized in the year 2009 and accepted by the Council of State before reporting to the EU.

2.3

Cooperation between EU and Russian Federation in the area of water resources management and protection

Agreement on harmonisation of national legislation systems in Europe, aimed at strengthening economic cooperation, was adopted in 1994, and in 1996 it was ratified by the Russian Federation. But the practical steps towards implementation of this agreement were undertaken in Russia only starting from the end of 1999.

In 1998 the Ministry of Natural Resources of the Russian Federation asked the European Union for help and support of reforms in the area of water resources management, to share with Russian partners European experience in this field. With the help of EU TACIS programme a special project ENVRUS 9801 was executed by French consortium BCEOM-VERSeau and IOWATER in years 2000-2002 to provide the basis for the institutional reforms in the area of integrated water resources management. The test area was Oka river basin – the main tributary of River Volga (sub-basin on which the supply and effluents of Moscow depend). During project IOWATER studied the creation of information system for Russian "Basin Water Management units"(BVUs). After analysis of the present situation, it appeared that that "BVUs" have no access to a lot of data that they will need for correctly fulfilling their water planning tasks.

Within TACIS programme several international projects on Lake Ladoga were conducted in the past. Among them Development and implementation of an integrated programme for environmental monitoring of lake Ladoga: protection and sustainable use of aquatic resources (DIMPLA) 1997-2000 [Tacis Cross-Border Co-operation Small Project Facility TSP40/97], Management of aquatic resources of Lake Ladoga and its catchment (MAQREL) 2002-2004 [Tacis Cross-Border Co-operation Small Project Facility TSPF/0302/0033] coordinated by University of Joensuu, Finland (http://www.joensuu.fi/largelakes/lakeladoga_e.htm). Pirkanmaa Regional Environment Centre was actively involved in these projects and in the project "Evaluation of Human Impact on Lake Ladoga" (1991-1997), funded by Ministry of Environment, Finland, also coordinated by University of Joensuu.

This report is a result of the international cooperation between Finland and Russia funded by the Finnish Ministry of the Environment, dealing with integrated water management studies of Lake Onega and its catchment area.

3 Review of existing data and monitoring programmes

Lake Onega is the second largest lake in Europe after Lake Ladoga. The lake basin is shared by Karelian Republic, Leningradskaya and Vologodskaya regions of Russian Federation (Fig. 3.1).

The lake basin is located on two contrasting parts of the earth crust with different geological histories, viz. the Baltic shield and the Russian plate. The lake surface area is 9890 km^2, volume is 280 km^3, maximum depth is 120 m, mean depth is 30 m and mean residence time is about 14 years (Bogoslovsky & Georgievsky 1969, Kaufman 1990).

Different limnetic parts of the lake are distinguished in accordance with morphological differences and as a result in thermal conditions and duration of hydrological events. Ice cover in isolated bays appears usually in December, central part of the lake freezes in January, but it can be also ice-free through the whole winter. Ice destruction in Lake Onega starts in the beginning of May, first in Petrozavodsk and Zaonezsky Bays. Starting from May till June the spring frontal zone is generated (the thermal bar). The movement of this zone from the coast to the deep part of the lake controls the generation of direct stratification in different lake regions which lasts for about four months. Surface layers water temperature can reach 20 – 25 ^oC, bottom layers – 6 – 8 ^oC. Temperature higher than 10 ^oC at the surface is observed first in Kizhi straights. Cooling of water takes place in August – September, when temperature becomes homogeneous all over the lake (Filatov 1999).

The catchment area of Lake Onega is 51 540 km^2, with the lake itself it constitutes one quarter of Lake Ladoga catchment area. About 70% of its territory belongs to Karelian Republic where lives 480 000 people or 63% of Republic's population. Altogether there are 1152 rivers flowing into the lake, but only 52 of them have a length more than 10 km. Average volume of inflow is 17.6 km^3. The main inflows are rivers Vodla, Shuja, Suna and Andoma, with total inflow equal to 60% of the whole inflow (Filatov 1999). The only outflow is River Svir, connecting Lakes Onega and Ladoga.

After construction of White Sea-Baltic Waterway Channel (Belomorsko-Baltiyskiy Kanal) in 1933 Lake Onega became an important part of the major water transport system of Russia. It serves also as a reservoir for hydroelectric power generation (Upper Svir Hydropower Plant), is an important source of fish, freshwater of high quality and has a high recreational potential.

In 1785 the first expedition of academician N. Ya. Ozeretskovksy on Lakes Ladoga and Onega was organised by Russian Academy of Sciences (http://heninen.net/sortavala/1785/suomeksi.htm). First hydrographical survey of the lake started in 1870 under the command of Colonel Andreyev, which included detailed topographic and bathymetric studies, and was finished only in 1894. As a result 34 navigational maps of Lake Onega in Mercator projection were produced. Those studies were continued in 1940s by I. V. Molchanov from the State Hydrological Institute (GGI, then Leningrad). Detailed investigations of the lake were conducted in 1964-1967, when Onezhskaya Complex Expedition was organised. It included Water Problems Department of Karelian Research Centre of USSR Academy of Sciences (now RAS, Russian Academy of Sciences), Limnological Institute of RAS (then Leningrad), Northern Institute of Oceanography and Fisheries (SevNIORH) and Petrozavodsk Observatory. In 1970-1971 Water Problems Department studied Kondopoga Bay of Lake Onega, in 1976-1980 – Petrozavodsk and Bolshoye Onega bays jointly with Institute of Zoology RAS (then Leningrad) and Computing Centre of RAS (Moscow). In 1981-1985 the complex limnological studies were continued in different parts of the lake. In

1989–1991 a unique hydrophysical experiment "Onego" was carried out, combining in situ measurements from ships, airborne and satellite observations.

In 1991 Water Problems Department was re-organised into Northern Water Problems Institute of Karelian Research Centre of RAS, who has continued ecological monitoring till nowadays. Several monographs mainly in Russian have been prepared, where lake water balance, ecological status and influence of climate change were analysed in details (Bogoslovsky & Grigoryevsky 1969, Kaufman 1990, Filatov 1997, 1999, 2004, Rukhovets & Filatov 2010). Several publications devoted to hydrodynamic studies, numerical modelling, anthropogenic impact on Lake Onega catchment and hydrochemical studies were presented at Lake Ladoga symposiums (Terzhevik et al. 2003, Litvinenko et al. 2003, Sabylina & Martynova 2003).

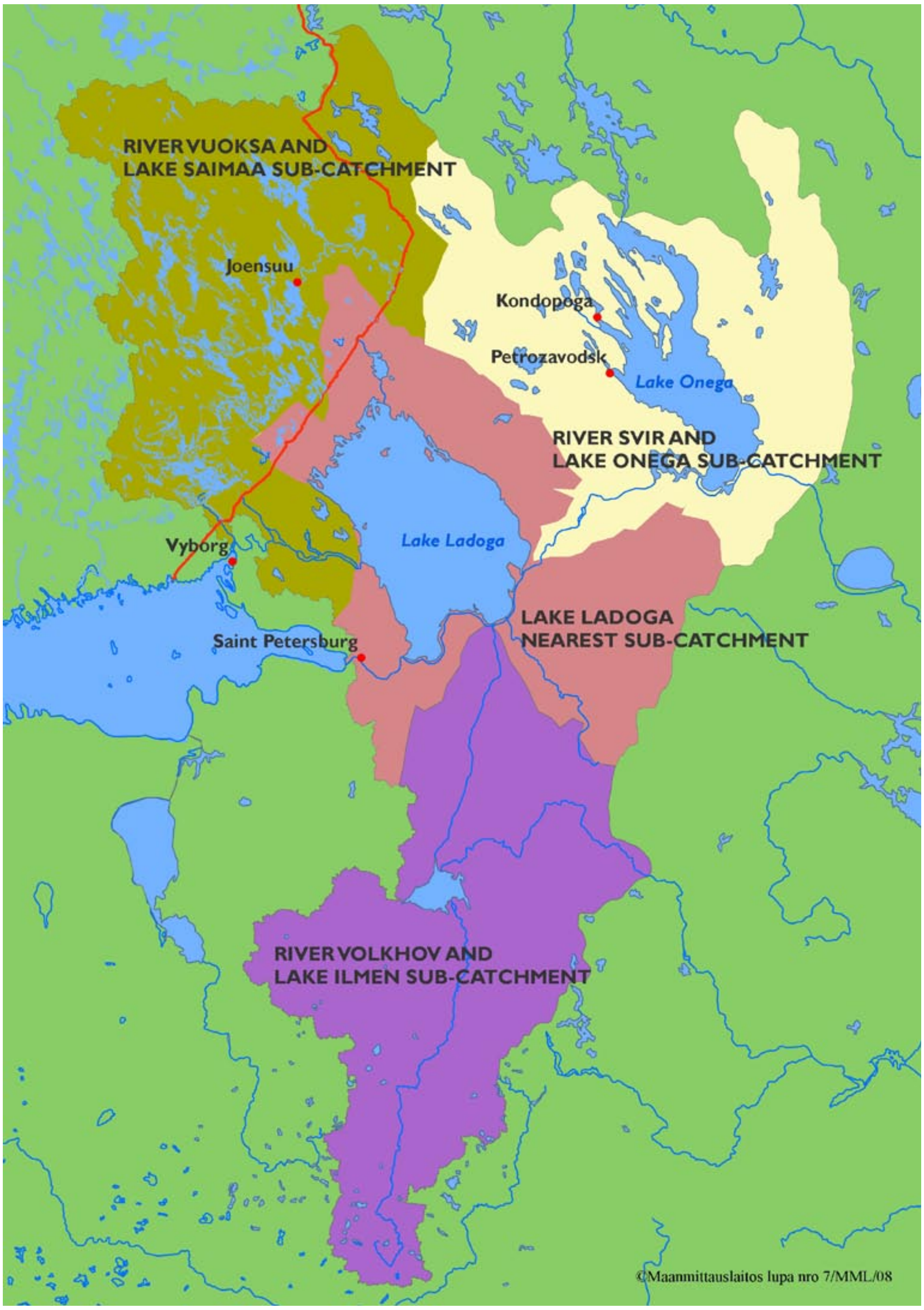

Figure 3.1. Map of Lake Ladoga catchment (1 – Lake Ladoga immediate sub-catchment, 2 – River Svir and Lake Onega sub-catchment, 3 – River Vuoksa and Lake Saimaa sub-catchment, 4 - River Volkhov and Lake Ilmen sub-catchment).

According to recent studies Lake Onega, as a whole, preserves its oligotrophic status (Filatov 1999, Status of water objects.. 2007), but due to its high limnetic heterogeneity and very complicated shape and bathymetry (Fig. 3.2), different parts of the lake experience different levels of anthropogenic load and react variously.

Pollution by industrial and communal wastewaters started from the middle of the last century, triggered eutrophication and affected negatively especially two largest bays of the lake: Kondopoga, Petrozavodsk and Bolshaya bays (Sabylina & Martynova 2003). The annual discharge of wastewaters into the lake is about 0.12 km^3 and 83% (0.10 km^3) is discharged directly to the lake from the three main industrial centres on the western shore, namely Petrozavodsk (Petrozavodsk Bay), Kondopoga (Kondopoga Bay) and Medvezhjegorsk (Povenets Bay). The main industries are paper pulp production, wood processing, machinery, food processing.

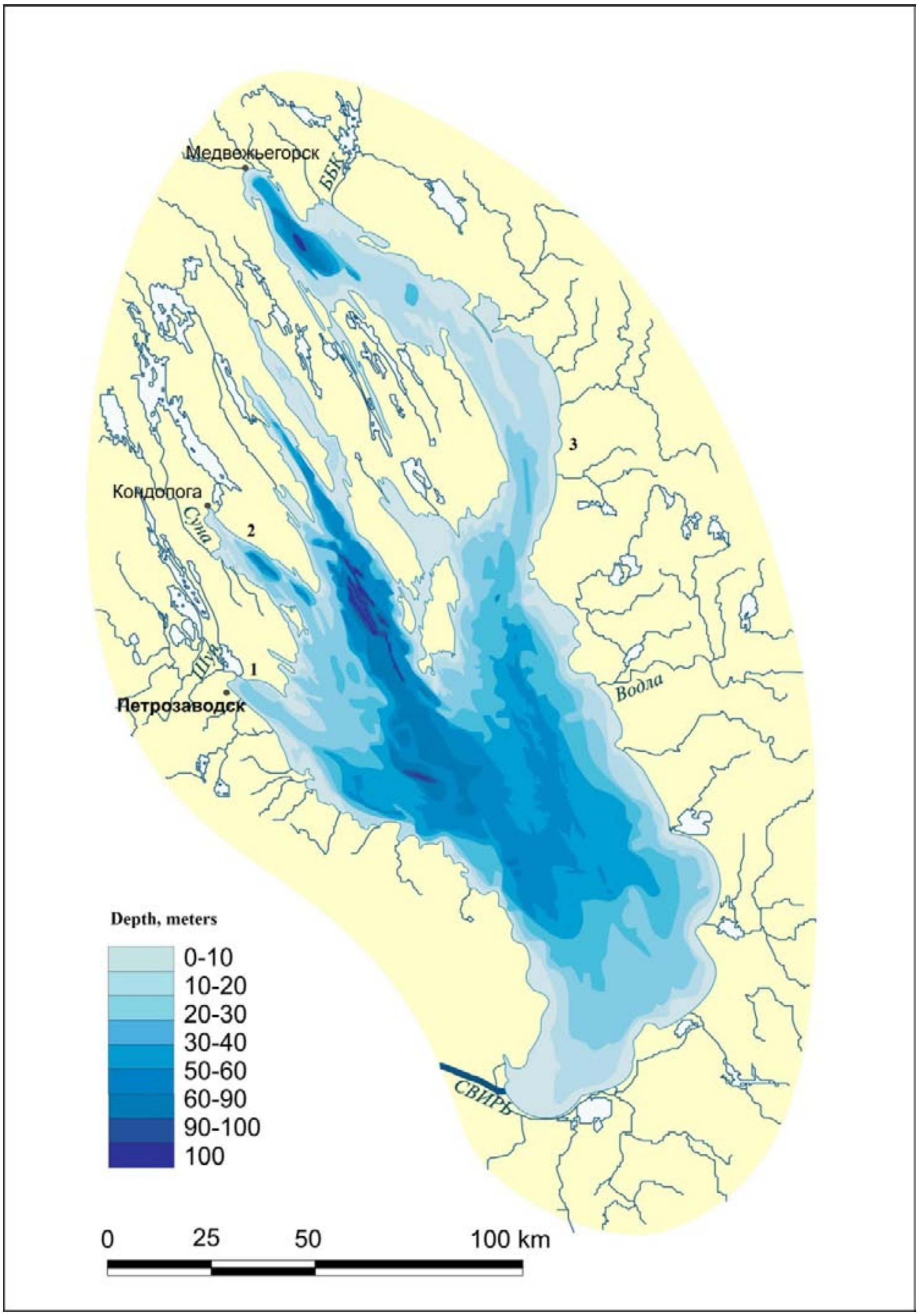

Figure 3.2. Bathymetric map of Lake Onega (source: Northern Water Problems Institute, KRC RAS, Petrozavodsk, Russia). 1 - Petrozavodsk Bay, 2 – Kondopoga Bay, 3 – Bolshaya Bay.

Agriculture is concentrated largely in the Shuja and Vodla rivers catchments. There are 15 large farms producing chickens, beef and airy products, potatoes and vegetables. The amount of water used by this sector is small compared with industry. It decreased steadily since 1990, the lowest value of 518 000 m^3 was observed in 1999. Since that the positive growth is observed, 670 000 m^3 were used by agriculture in 2001.

Economic difficulties in the 1990s and a decline of the industrial production caused the reduction of industrial water use (Litvinenko et al. 2003). During the last nine years Russian economy shows steady positive growth. The Gross National Product (GNP) in the first half of the year (2005) has increased by 5.6% (against 7.7% for the same period in 2004). Economic reforms and high oil prices create favourable conditions for further development of all economic sectors. This is already seen in the growth of industrial water use. The joint-stock company "Kondopoga", the largest enterprise and the main water consumer in Republic of Karelia used 68 million m^3 of water in 1989. In 1999 this figure was only 44 million m^3, and in 2001 it was 49.4 million m^3 (Litvinenko et al. 2003).

Water consumption by fishery disappeared after shutdown of Petrozavodsk fish hatchery in Shuja in 1991. Before that in 1990 it consumed 5% of the total water use. Nowadays with reconstruction of fishery the water use by this sector is growing, and equalled to 11 200 m^3 in 2001 or 8.9% of the total water consumption (Litvinenko et al. 2003).

At present eighty water consumers in Lake Onega basin release effluents, 56% of them are released without purification directly into the lake, and 1% into the terrain or other recipients, 10% is stated to be clean without purification. Only 12 settlements out of 57 have sewerage systems and nine have sewage treatment systems. Twenty five water consumers release effluents completely or partly non-purified. The biggest amount of non-treated waste waters is discharged by joint-stock company "Kondopoga" – 3.75 million m^3, Petrozavodsk municipal system – 1.95 million m^3 and Pudozh municipal system – 0.693 million m^3 (Litvinenko et al. 2003).

Total phosphorus income is estimated at 1003 t a^{-1} and nitrogen at 17739 t a^{-1} (Sabylina & Martynova 2003). Rivers carry 705 tons of total P and 13 167 of total N, 203 tons of P and 772 tons of total N are brought with sewage waters. The influx of total P with precipitations is 95 t a^{-1} and total N is 3800 t a^{-1}. Outflow is estimated at 298 t a^{-1} of total P and 13338 t a^{-1} of total N, i.e. 28% and 75% of the total income, respectively. In 1996 highest concentration of P_{tot} was measured in Kondopoga bay – 24 µg l^{-1}, concentration of P_{tot} was 21 µg l^{-1} in the Petrozavodsk Bay and 12 µg l^{-1} in the central part of the lake.

According to modern knowledge for the central pelagic part of the lake to stay oligotrophic P_{tot} must not exceed 15 µg l^{-1}. At the present time the average P_{tot} concentration in the lake is about 8-10 µg l^{-1}. If the influx of the total P continues to grow the eutrophication process will develop at higher rates, than, for example, in Lake Ladoga. Smaller depths and less volume of hypolimnion, compared to Lake Ladoga, provide better conditions for water column heating and development of phytoplankton.

Another aspect that should be taken into account is influence of the global climate change on the ecosystem of Lake Onega. Latest climatological data and analysis of different climate scenarios allow suggesting that global warming may develop at higher rates than it was estimated even ten years ago. Filatov et al. (2004) have shown that under future climate conditions the growth of annual air temperature is possible from 1.6 ^{o}C to 2.7 – 3.6 ^{o}C, increase of precipitation from 582 mm to 610-635 mm, and an increase of evaporation. This can lead to the fact that total runoff in the catchments of Lakes Ladoga and Onega might decrease from 319 mm in the present climate conditions to 280-290 mm in the year 2050.

There is one natural reserve “Kivach” in the catchment of Lake Onega and federal conservation area “Kizhsky” occupying islands of Lake Onega, part of peninsula Zaonezhye, where wild animals, birds, and rare species of plants are protected.

4 General description of Lake Onega and its catchment

4.1

Geography

Lake Onega catchment area is situated in the southern part of Republic of Karelia and represents Onega's sub-region of Karelia-Kolsky limnetic region (Gerd 1956, Filatov 1999, Kulikova 2007). The lake catchment is almost 300 km at its greatest breadth and about 250 km in length (Fig. 4.1). About 76% of the area are covered with forests. After the construction of Upper Svir (Verkhne-Svirsky) hydropower station on River Svir in 1953 the lake became a reservoir.

Geological history of the region shaped the complex and broken relief of the catchment. Crystalline rocks of Baltic shield mainly of Archean and Proterozoic age were smoothed by glaciers and covered with Quaternary sediments of different thickness. This feature is one of the most important physical-geographic factors determining the formation of river runoff.

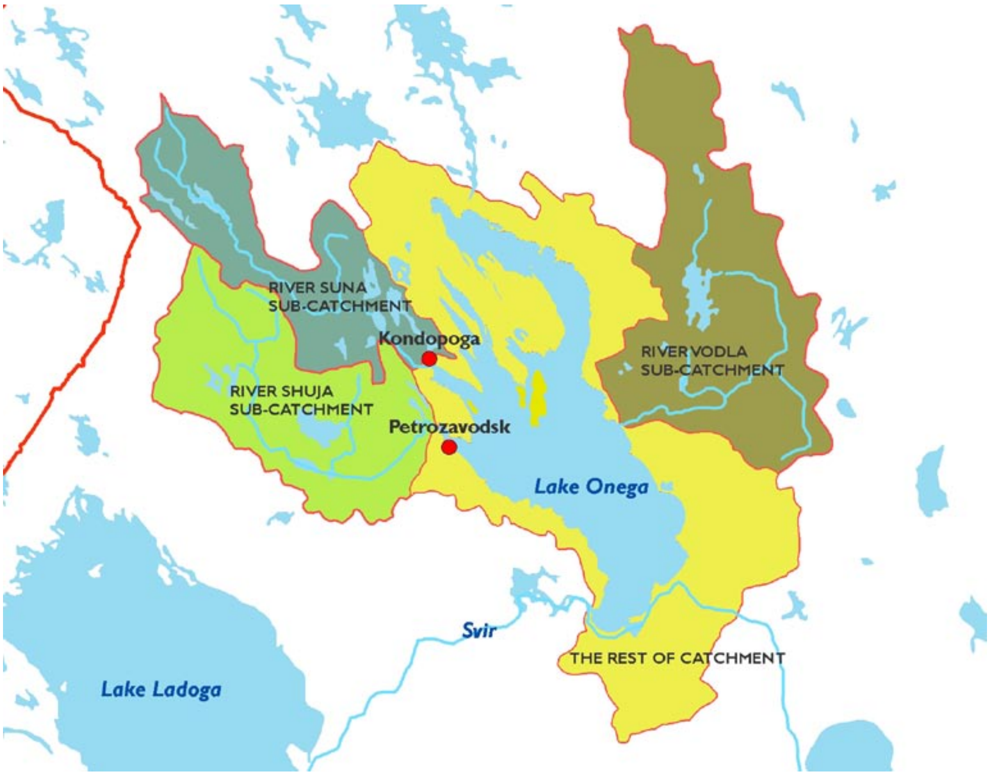

Figure 4.1. Catchment area of Lake Onega with sub-catchments.

4.2

Climate

Prevailing western transfer of air masses, small amount of incoming solar radiation, especially during autumn and winter period determine climatic peculiarities of climate in Karelia. According to generation conditions it belongs to Atlantic-Arctic zone of moderate belt and can be classified as a transitional from sea climate to continental one. Air masses formed over Atlantic, define long, relatively warm winter, short, moderate summer and unstable weather regime all over the year. Long-term mean annual air temperature is 2 – 2.5 °C, mean annual temperature in July is 15.5 – 16.5 °C, in January -11 – -12 °C (Filatov 1999). The minimum air temperature during observation period was recorded on 17th January 1940 and was equal to -48.9 °C, the maximum +37.5 °C was measured in July 1972 at the meteostation Pudozh.

Wet sea air masses from Atlantic cause high humidity all over the year (70 – 90%). The number of days with relative humidity less than 30% is only 3 – 9 days a year. Annual precipitation is 600 – 650 mm, about 60 – 65% of them are in the liquid form. Total number of days with precipitation in Lake Onega region is 180-190. Active cyclonic activity over Karelia creates high cloudiness all over the year. Mean annual value is 7 – 8 points (when 10 point system is used). The highest cloudiness is observed in autumn with maximum in November (8.8 points). During winter it diminishes and during March – July the cloudiness does not exceed usually 6.5 points. Spatial distribution of clouds over lake aquatory is rather homogeneous.

The lake has a pronounced effect on climate of surrounding territories, especially in coastal areas. Lake with its huge storage of heat reduces seasonal variations of air temperature reducing summer maximums and increasing winter minimums.

4.3

Hydrography

The hydrographic network is well developed, there are totally 6 765 rivers and streams with total length of 22 471 km and 9 516 lakes with total surface area of 13 441 km^2 or 21% of the total area of the catchment. About 95% of rivers are small with the length less than 10 km and only 8 rivers have a length more than 100 km (see Table 1 from Lozovik et al., 2007). Average lake percentage of the territory is 8.4%, but for some sub-catchments this indicator can be considerably higher: in the basin of River Suna 33.5%, in the middle flow of Shuya 49.6% due to existence of large lakes – Vodlozero, Syamozero, Sandal, Pyalozero, Lizhmozero and Gimolskoye in its basin. The biggest share of water bodies (96%) are small ones with surface area less than 1 km^2, but their sum does not exceed 5%. Fifty lakes have surface area more than 10 km^2 (Filatov 1999, Kulikova 2007).

Table 1. Features of Lake Onega inflows and their catchments (Lozovik et al. 2007)

River	Runoff volume, km^3 a^{-1}	Length, km	Catchment area, thousand km^2	Lake percentage, %	Swampiness (degree of paludification), %
Vodla	4.43	406	13.7	5.6	24
Shuya	3.09	279	10.3	10.4	~20
Suna	2.36	282	7.67	12.5	19
Anduma	1.03	142	2.57	1.3	12
Megra	0.58	93	1.73	4.0	6
Vytegra	0.52	40	1.67	<1	12
Lizhma	0.23	67	0.93	19.3	9
Pyalma	0.37	72	0.91	1.7	10
Kumsa	0.22	67	0.74	8.5	7
Nemina	0.26	76	0.66	2.8	16
Tchernaya	0.13	88	0.62	<1	8

Vodlitsa	0.24	47	0.54	2	13
Oshta	0.11	39	0.37	<1	6
Unitsa	0.12	55	0.34	2.4	10
Tuba	0.23	16	0.31	3.5	5
Lososinka	0.12	25	0.30	5.7	10
Shoksha	-	23	0.12	1.2	5
Vichka	0.05	23	0.12	3	8

River runoff in the northern part of the catchment is naturally regulated by lakes. Streambeds are relatively young with steep slopes and rapids. As a result the content of mineral substance in river waters is low, but the concentration of humus and iron is high. Southern inflows are older and have well developed streambeds, lake percentage is lower and swampiness is higher. Natural concentration of substances is 2-3 times higher than in northern inflows (Lozovik et al. 2007, Sabylina & Martynova 2003).

4.4

Hydrochemistry and water quality

Water in Lake Onega has a low mineral content (in average 25 mg l^{-1}) and contains humic organic matter (colour > 40 Pt mg l^{-1}, chemical oxygen demand CODMn > 10 mg O2 l^{-1}, pH ≤ 6) (Sabylina and Martynova 2003). The natural water quality sustained at the high level due to effective ecosystem functioning and a long retention time (colour 20 Pt mg l^{-1}, CODMn 5 - 8 mg O2 l^{-1}, P_{tot} 7 – 12 µg l^{-1}). Since 1950s the effects of anthropogenic loading, like local pollution and eutrophication became visible, especially in largest bays of Lake Onega – Kondopoga, Petrozavodsk and Bolshaya bays.

Table 2. Chemical balance of main ions, biogenic elements, organic matter and suspended solids of Lake Onega in 2001 – 2002, t a^{-1} (Lozovik et al. 2007)

Balance Component	Water inflow, km^3	Σions	Corg	P_{tot}	N_{tot}	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$	Fetot	Si	Suspended solids
Income										
River inflow	15.02	549405	214098	441	8932	1384	633	11078	25356	58907
Precipitation	5.5	37400	8905	61	3700	1458	2052	150	1000	23650
Sewage waters	0.1	20000	10952	174	639	145	-	53	-	4200
Total		606805	233956	676	13271	2987	2685	11281	26356	86757
Outcome										
Outflow, River Svir	18.6	668972	144174	230	10147	5548	3630	2347	5005	36360
Residual, tons		-62167	+89782	+446	+3124	+2439	-945	+8934	+21351	+50397
Residual, % of income		10	38	66	23	82	35	79	81	58

River inflow is the main source of organic, suspended and biogenic loading. Out of 0.12 km^3 of wastewater discharged annually in the lake watershed 0.10 km^3 are discharged directly to the lake from the three industrial centres Petrozavodsk, Kondopoga and Medvezhyegorsk.

Chemical balance of main ions, organic matter calculated for the year 2001/2002 is presented in Table 2 (Lozovik et al. 2007). The total sum of ions annual income is estimated at 606.8 thousand tons, 90% of which is river inflow. Atmospheric precipitation and wastewaters contribute 6% and 3%, respectively. The outflow of mineral substances with River Svir is estimated at 669 thousand tons, the difference (10%) could be explained by neglect of supply with groundwater, inflows of small rivers and springs, calculation errors.

The total income of dissolved and suspended organic matter with river inflow, atmospheric precipitation and wastewaters equals to 491.3 thousand tons or 234 thousand tons C_{org}. Suspended organic matter in tributary waters is on the average 10% of the total organic matter. The rivers inflow gives 92% of the total income. The overall income of suspended solids is 86.8 thousand tons, the river inflow proportion is 68%. Atmospheric precipitation brings 23.6 thousand tons or 27% of the total sum.

The income of biogenic elements with river inflow, precipitation and wastewaters is by 34% higher than outflow from the lake. It implies that during transformation of substances in the lake labile elements (P, N, Si, Fe) undergo substantial changes (Sabylina & Martynova 2003). As a result of this process the sedimentation fraction of dissolved silica, iron and phosphorus is 81%, 79% and 66%, respectively.

The transition of silica from dissolved state to bottom sediments is linked with its biogenic extraction by diatoms and subsequent burial in sediments. The accumulation of iron and phosphorus in bottom sediments is connected chiefly with changes of oxidation-reduction conditions at mixing of river and lake waters. Jointly with iron the phosphorus sedimentation takes place in oxygen rich lake waters, as a sorption on iron hydroxides (Lozovik et al. 2007).

The nitrogen income with river inflow is 2.4 times higher than atmospheric influx. But the fraction of mineral nitrogen compounds in rivers waters is 23%, in precipitation 95% and in wastewaters (without N-NO3) 23%. The overall ammonium nitrogen income is 3 006 tons, which is 5.5 times more than discharge from the lake. River Svir carries out mainly mineral nitrogen in the form of nitrate nitrogen, 3 630 tons annually.

As it was mentioned earlier, water quality varies significantly in different parts of the lake. Natural conditions of the central part of the lake and Bolshaya Bay provide to certain degree the stability to eutrophication controlled by several factors: relative isolation of polluted bays, large volume of water mass and phosphorus deficit, inhibiting the phytoplankton development. Vertical temperature stratification in spring-summer time prevails supply of biogenic elements from deeper to surface layers. The ion composition and salt contents of water are stable in these parts of the lake. In all seasons of the year water can be classified as oligo-humic (water colour 20 Pt mg l^{-1}, Fe_{tot} 0.06 mg l^{-1}), oligo-mesotrophic type (P_{tot} > 10 µg l^{-1}).

Photosynthetic activity of diatoms in the epilimnion of the central part of the lake is confirmed by decline of silica concentration 2 times compared with spring concentration and 1.5 times compared with hypolimnion. Phytoplankton development is limited by low concentration of mineral phosphorus (P_{min} ≤ 1-2 µg l^{-1}). It is worth noting that in summer the concentration of P_{tot} in epilimnion is higher than in hypolimnion. This, likely can be explained by spreading of river and wastewaters from Petrozavosdk and Kondopoga industrial centres in surface layers due to thermal and density stratification. Chl-a concentration is 1.8 – 3.6 µg l^{-1}, while average value is 2.7 µg l^{-1}.

The central and southern parts of the lake and Bolshaya Bay are characterized by high quality of water. Mean annual salt content is 38 mg l^{-1}, the concentration of organic matter is low, total phosphorus concentration during open water period does not exceed 12 µg l^{-1}. But in summer when north-westerly winds blow for several days Petrozavodsk Bay waters can penetrate to the central part, when south-easterly winds blow – River Vytegra waters can reach southern parts of Lake Onega.

The shallowness of the southern part, quick spring heating, practically complete vertical mixing of water column and enrichment with organic substances create favourable conditions for eutrophication processes.

In Petrozavodsk Bay water quality is influenced by River Shuya inflow, by storm water runoff and by communal and industrial wastewaters. The joint effect depends on time of the year and hydrometeorological conditions controlling the intensity of water exchange between the bay and the open part of the lake. As a consequence water quality parameters in Petrozavodsk Bay vary in a wide range in winter time: COD_{Mn} 7 – 41 mg O l^{-1}, P_{tot} 14 – 37 µg l^{-1}, O_2 74-90%. During open water period the water mixing is more intensive: COD_{Mn} 9 – 15 mg O l^{-1}, P_{tot} 15 – 31 µg l^{-1}, O_2 87-95% (see also Table 3).

Table 3. Averaged indicators of water quality in Petrozavodsk Bay in spring, summer, autumn periods of 1998 – 1999 and 2002 – 2003 (Lozovik et al. 2007).

Part of the bay	Study year and season	Σions, mg l^{-1}	O_2, % saturation	Water colour, deg	PC, mg O l^{-1}	BOD_5, mg O l^{-1}	P_{tot}, ug l^{-1}	N_{tot}, mg l^{-1}	Fe_{tot}, mg l^{-1}
Solomenskaya river arm	Spring 1999,2003	21.2	90	96	23.0	0.81	37	0.76	0.78
	Summer 2002	26.8	89	97	18.8	2.18	48	0.81	0.84
	Autumn 2002	33.2	99	55	9.7	1.00	78	0.60	1.90
Zone of water intake	Spring 1999,2003	34.2	92	47	11.2	1.08	25	0.74	0.33
	Summer 2002	30.1	92	74	12.8	1.96	28	0.90	0.49
	Autumn 2002	38.6	88	15	6.8	1.60	15	0.52	0.12
Sewage release zone	Spring 1999,2003	35.2	88	37	8.7	0.70	26	0.86	0.23
	Summer 2002	35.6	102	45	9.3	1.74	30	0.71	0.26
Central and outer part of the bay	Spring 1999,2003	36.0	94	34	8.7	0.78	15	0.66	0.16
	Summer 2002	35.8	98	42	9.7	1.80	24	0.66	0.30
	Autumn 2002	38.5	90	15	6.6	0.98	18	0.64	0.18

Kondopoga Bay is the large and deep bay of Lake Onega. The upper part of the bay is the receiver of River Suna waters, the third tributary to Lake Onega by volume. Annually 52 x 10^6 – 53 x 10^6 m^3 of industrial and communal wastewaters of Kondopoga are withdrawn also in this part of the bay. 90% of these waters are wastewaters of Kondopoga PPM.

The modern chemical composition of Kondopoga Bay waters is the result of long-term interaction of natural and anthropogenic factors. Kondopoga PPM wastewaters are withdrawn to the lake during almost 80 years, and 40 years without any treatment. Biological productivity measured on the basis of Chl-a is 2- 3 times higher in Kondopoga Bay than in the Bolshaya Bay of Lake Onega. According to this indicator Kondopoga Bay waters have mesotrophic status.

In winter time wastewaters influence can be traced along the main transect of the bay. These waters are released through diffuse outfalls in the middle layer of water column. The differentiation of the flow is seen already at a distance of 10 km from the outlet and especially in the central deepwater part of the bay. Measurements in winter 1998 showed that concentration of P_{tot} at a depth of 30 m is 51 µg l^{-1} or 2 – 3 times larger than in surface and near bottom layers. During ice-free period wind-induced circulation affect essentially the distribution of wastewaters in the bay. Under northwesterly winds the transport of wastewaters to the open part of the lake is intensified, whilst south-easterly winds "lock" them in the bay. As a result water quality is very low in the upper part of Kondopoga Bay (Table 4).

Table 4. Chemical indicators reflecting pollution of Kondopoga Bay with sewage waters of Kondopoga PPM in summer 1999.

Indicator	Upper part	Middle part	Central part	Outer part	Sewage waters
PC, mg O l^{-1}	9.8 – 15.7	9.1 – 10.2	9.1 – 9.6	8.3	631,6
BOD5, mg O l^{-1}	1.88 – 3.56	0.64 – 2.45	0.30 – 1.18	0.28	80.0
O_2, % saturation	93 – 111	89 – 105	96 – 102	1	0
P_{min}, ug l^{-1}	3 – 10	0 – 1	0 – 1	0.4	413
P_{tot}, ug l^{-1}	31 – 70	15 – 39	15 – 17	9	967
Suspended solids, mg l^{-1}	2.6 – 6.0	1.9 – 2.5	2.0 – 2.1	1.4	113.5
Phenols, ug l^{-1}	5.4 – 26.9	3,5 – 5.5	3.5 – 5.3	0.5	Not measured
Phurphurol, mg l^{-1}	0.01 – 0.04	Not found	0.01 – 0.02	Not found	Not measured
Oil products, mg l^{-1}	0.05 – 0.13	Not found	Not found	Not found	Not measured
Sulphide, mg l^{-1}	0.02	Not found	Not found	Not found	0.10
Tiosulphate, mg l^{-1}	0.04 -0.05	0.04 – 0.05	0.04	0.04	0.05
Sulphite, mg l^{-1}	0.01	Not found	Not found	Not found	0.07
Sulphate, mg l^{-1}	2.4 – 4.0	3.7 – 4.1	3.4 – 4.2	3.8 – 3.9	63.8
Lignosulphonate, mg l^{-1}	2.0 – 3.2	0.7 – 2.6	0.7 – 2.6	0.2 – 2.0	200

Nowadays, despite the reduction of pollutants income during the last 20 years, the eutrophication processes in the bay have intensified (Sabylina & Martynova 2003, Lozovik et al. 2007). In accordance with observations performed in 1998 – 2004 the mean annual concentration of P_{tot} is 32 µg l^{-1} (in the upper part up to 40 µg l^{-1}). The income of total phosphorus equals to 120 t a^{-1}, total nitrogen 1646 t a^{-1}.

In summary it should be pointed out that Kondopoga Bay is characterized by increased level of pollution and eutrophication caused by wastewaters of Kondopoga industrial centre. The area of the polluted zone depends also on specific meteorological conditions, but in contrary to Petrozavodsk Bay this zone is localized. The significant pollution in the upper part of the bay is observed through the whole year.

4.5

Identification of pressures

Water resources of Lake Onega and its catchment are used for different purposes since people settled around the lake after the end of the last glacial period, known as Weichsel glaciation in Scandinavia and northern Europe, about 10 – 9 millennium BCE. But only during last hundred years the growth of population and their activities increased the anthropogenic pressure on the lake ecosystem nearly exponentially. The anthropogenic loading on the lake grew considerably from the beginning of 50th in the last century. Lake Onega catchment is one of the most intensively used in Republic of Karelia, especially its southern and western parts, where pulp and paper production, machine construction and metal processing, building materials production, food processing, printing, fisheries, transport, water supply and other branches of the economy are developed.

Litvinenko et al. (2003) divided catchment area into three zones according to the degree of the ecological influence on Lake Onega. Wastewaters from the first coastal zone (width two kilometres) enter the lake without any transformation. Here lives

81% of the population of whole lake watershed and 88% of water consumption and discharge is concentrated in this zone (Figs. 4.2 and 4.3). Three main industrial centres – Petrozavodsk, Kondopoga and Medvezhyegorsk are located in this area, where lives about 91% of the coastal zone population. The upper boundary of next adjacent zone (2 – 30 km wide) is selected using the 3-day run-up time, which is considered to be enough for neutralization of main pollutants by auto-purification processes (Litvinenko et al. 2003). The rest part of the lake catchment is grouped into the third zone. As it can be seen from these figures the main consumers in 2001 were industry (44.5%) and communes (46%), while fishery used only 8.8% and agriculture 0.7%.

From 1980 through 2001 the decline of industry share in the total consumption was clearly observed (Fig. 4.4). It was compensated partially by the steady growth of domestic use, but still the total consumption decreased by 26% in 2001 compared to maximum value of 149 478 x 10^6 m^3 in 1990. Pulp and paper production is the largest water consumer in industry, accounting for 88% of the total industrial water use in the cathcment of Lake Onega. It should be noted that during last years the fishery has been restored completely and even exceeded the level of 1980th. According to latest estimates about 90% of salmon production in Russia is concentrated in Lake Onega area.

The total discharge, consisting mainly of domestic, industrial and agricultural wastewaters proportional to their water uses has decreased gradually from 1989 through 2001 (Fig. 4.5). As pointed by Litvinenko et al. (2003) the main reason is a decline in production, not the technological improvements. Last eight years the growing tendency is observed again, following the increase in water consumption.

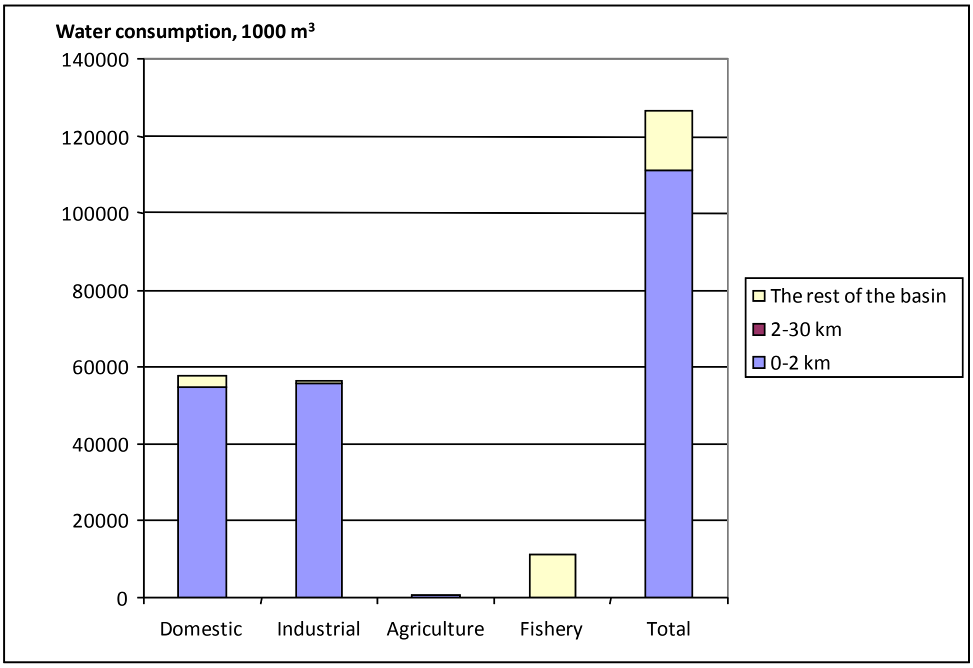

Figure 4.2. The territorial allocation of water consumption within the drainage basin of Lake Onega in 2001 (Litvinenko et al. 2003).

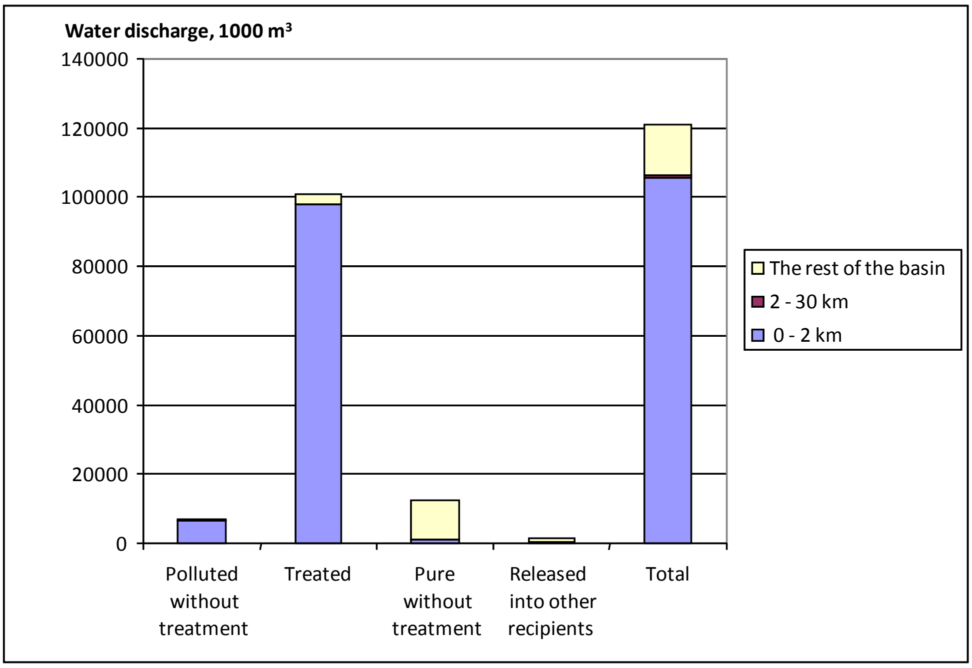

Figure 4.3. The territorial allocation of water discharges within the zones of Lake Onega catchment in 2001 (Litvinenko et al. 2003).

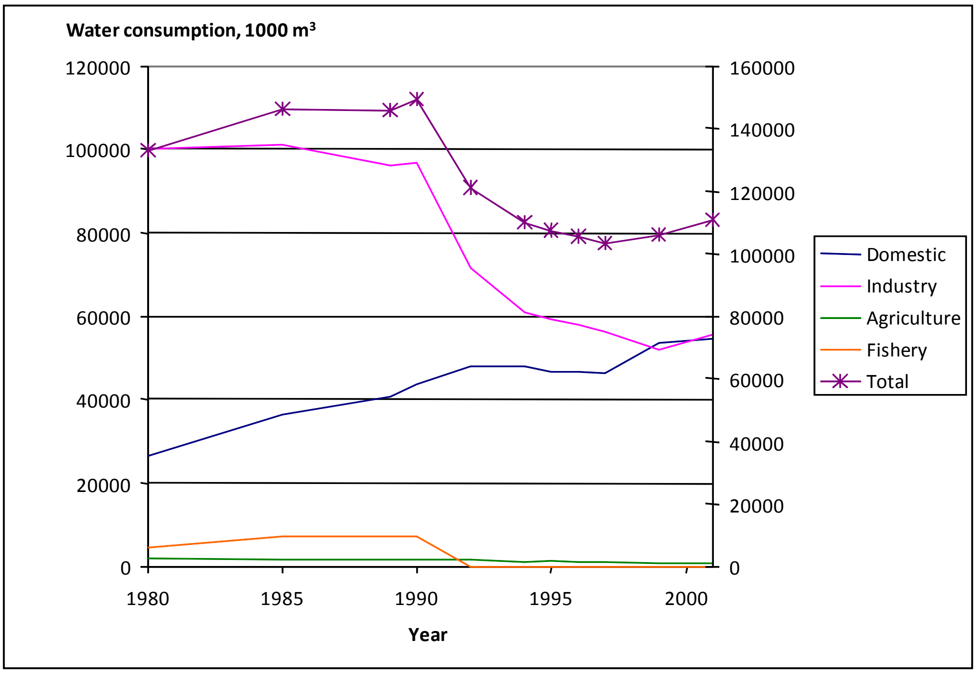

Figure 4.4. Water consumption (1000 m^3) within Lake Onega catchment in 1980 – 2001 (left axis -solid lines, right axis -solid line with symbol marks) (Litvinenko et al. 2003).

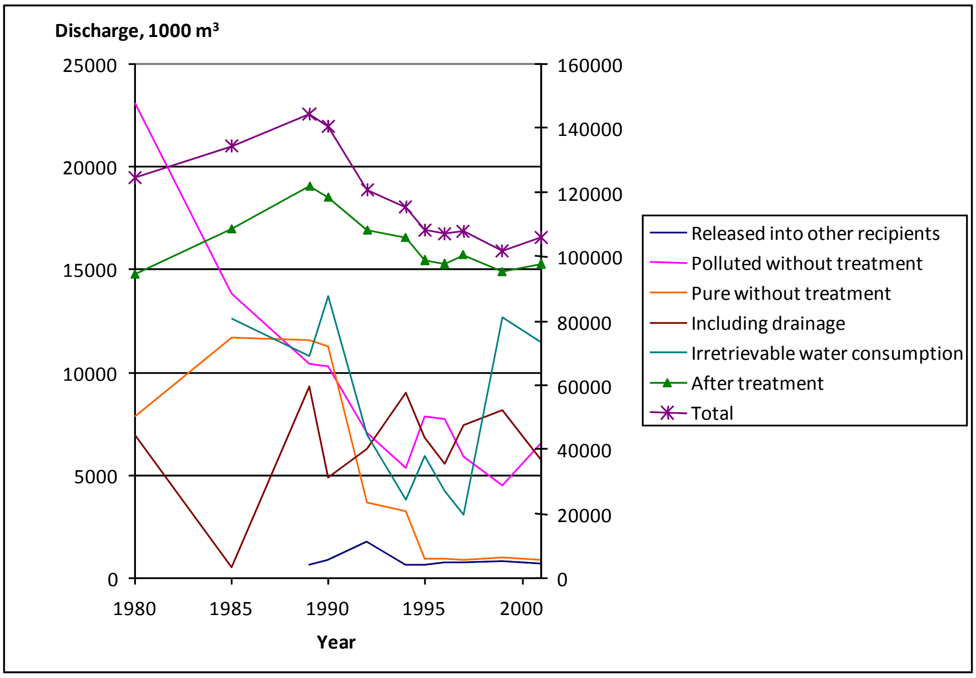

Figure 4.5. Water release (1000 m^3) from the Lake Onega catchment in 1980 – 2001 (left axis -solid lines, right axis -solid lines with symbol marks) (Litvinenko et al. 2003).

4.6
Detailed examination of "hot spots" - Petrozavodsk Bay and Kondopoga Bay

Petrozavodsk Bay - current environmental conditions

Petrozavodsk and Kondopoga industrial centres discharge almost equal volumes of wastewaters but Petrozavodsk Bay receives 1.6 times more of total phosphorus and 5 times more of total nitrogen than Kondopoga Bay (Table 5).

Table 5. Mean annual indicators of water withdrawal and washout of chemical substances with sewage waters of Petrozavodsk, Kondopoga and Medvezhyegorsk industrial and commune centres (Lozovik et al. 2007).

Indicator	Petrozavodsk	Kondopoga	Medvezhyegorsk
Water withdrawal, million m^3	49	54	0.91
Suspended solids, thousand t a^{-1}	1.2	3,0	0.21
Dry weight, thousand t a^{-1}	9.1	37	0.47
BOD_{tot}, thousand t a^{-1}	0,5	2.8	0.24
P_{tot}, t a^{-1}	104	66	4,8
N_{tot}, t a^{-1}	543	93	18
$N_{ammonium}$, t a^{-1}	59	70	16

Drainage and storm waters coming from territories of large cities Petrozavodsk, Kondopoga and Medvezhyegorsk have local influence on water quality in bays, which is most pronounced during spring and autumn floods.

PETVK water supply system extracts water from Petrozavodsk Bay on Lake Onega. The extraction site is located not far from the city's harbour front and only 8 km from the discharge point of the biological wastewater treatment plant. Under unfavourable hydro-meteorological conditions, municipal wastewater can reach the inlet of the water supply system. Eutrophication and humus rich waters from River Shuya also affect Petrozavodsk Bay, with the corresponding decrease in water quality. Raw water is treated by sand filtration and disinfected by chlorine. The existing water treatment system does not ensure drinking water quality of satisfactory quality, including bacterial pollution, according to the national standards. The water quality even deteriorates in the distribution system. The poor tap water quality increases the population morbidity (Nefco/Amap 1995).

Biologically treated wastewater is being discharged into Petrozavodsk Bay. The treated wastewater causes noticeable pollution of the Petrozavodsk Bay. Due to increased nutrient loading, intensive development of blue green algae (up to 1 million cells l^{-1}, with the BODs of 0.4 g m^{-3}) has in recent years been observed during the summer months in Petrozavodsk Bay.

The dewatered wastewater sludge is transported to a dumping site which has been constructed to an old gravel pit. The sludge has not been stabilized and is contaminated with heavy metals and cannot thus be utilized in agriculture. The sludge also causes environmental contamination of the general environment and the ground water resources in the vicinity of the dumping site.

The most significant result will be the reduction of phosphorus emissions to Lake Onega which will be halved from the present situation due to the new biological removal process. The project is expected to bring environmental, as well as health, benefits because:

- Rehabilitation and improved operation and maintenance of the water treatment plants will assure better drinking water quality, reduction in the use of chemicals and better handling of water treatment residuals;
- Rehabilitation of parts of the water supply network will reduce water losses and decrease the volume of water intake;
- Rehabilitation and improved operation and maintenance of the wastewater treatment plants will reduce the risk of spillage of sewage, and assure improved quality of wastewater released after treatment and better handling of solid and liquid waste.
- Improvement in operations will contribute to a better day-to-day environmental management (treatment plants waste management, handling of chemicals and toxic substance, improvement in the operation and maintenance of the sewerage network, including improved emergency response; more efficient use of information from the existing water quality monitoring networks; better compliance with environmental regulations).
- Water conservation through demand management is expected to eliminate the need for the construction of new capacity for years to come.

Pollution of Lake Onega with communal waste waters of Petrozavodsk and high nutrient load promote strong eutrophication in the bay. Poorly treated effluents are discharged into the Petrozavodsk Bay that is the source of potable water supply.

Kondopoga Bay

Kondopoga Bay is deep and large bay with the length along the main axis equal to 33 km, surface area 243 km^2 (2.5% of the lake area), water volume 4.3 km^3 (1.5% of the lake volume), mean depth 21 m and maximum depth 82 m.

Town of Kondopoga has total population about 36 000 people. The main industrial enterprise is Kondopoga PPM, largest producer of paper in Russia. It processes about

1.5 million m^3 of wood annually and produces 550 thousand tons of paper, or 31% of the whole paper production in Russia. It was built in 1929 and during first six months of operation 5 thousand tons of paper were produced. The mechanical wastewater treatment facilities were built in 1977, biological treatment started in 1986.

Since 1994 about 900 millions roubles was spent to solve problems of air cleaning, plus 1 766 millions roubles were used to improve water purification systems. Wastewaters of the main technological processes go through mechanical treatment first, where settling of suspended solids in radial sedimentation tanks takes place. Clarified waters are pumped to the two-stage biological treatment facilities and after that are released through deep diffuser to Kondopoga Bay of Lake Onega. The productivity of the biological treatment of industrial wastewaters is 195 thousand m^3 per day. The effectiveness of the treatment is 95% according to BOD5 test and 77% for suspended solids.

In 1999 the contract with Swedish company ANOX was signed and the first stage of reconstruction was completed already next year, when moving bed biofilm reactors Natrix in aeration tanks were installed. The renovation of the equipment continues also today. Using leading Swedish "know-how" of biological treatment with moving bed biofilm reactors the main goal was reached - reduced the increase of excessive sludge and removed it from the purification system to the modern high-effective dewatering equipment.

The goal of the renovation is burning of the sludge in the boiling layer of the utilization boiler. This will be achieved in coming years. Now the tuning of the process of excessive sludge dewatering composed with fibre and alkaline sediments and selection of the optimal dose of flocculants is carried out. Advancement is that wastewaters of the yeast production are biologically treated nowadays; there is no more release of these waters to the lake.

Figure 4.6. A view from the wastewater treatment plant of Petrozavodsk.

5 Classification of surface waters

Surface waters in Republic of Karelia have in general low mineralization (average value is 22 mg l^{-1}), prevailing of hydro carbonates and calcium in ion composition and relatively high content of humus substances (Filatov et al. 2006). Lake Onega waters are also characterized by a low mineral content equal to 25 mg l^{-1} (averaged over the lake volume). Detailed description of the classification of Karelian waters using two approaches: first method developed by experts of Northern Water Problems Institute and the second one - Finnish classification scheme used before the adoption of the Water Framework Directive, and their comparison can be found in the chapter 2.2 "Quality of surface waters" of the Russian- Finnish monograph (Filatov et al. 2006, pp. 75 – 87).

The problem of multivariate classification is a challenging scientific task and no general mathematical solution was found yet. The method developed by Russian researchers (Filatov et al. 2006) takes into consideration the following indicators of water quality: value of pH, water colour (concentration of organic substances), iron, total phosphorus, chlorophyll-a and oxygen. Several groups are distinguished: with high water quality, good, satisfactory, low (or bad), and a separate group of polluted waters is recognised.

The pre-WFD classification method used in Finland is based on the following indicators: chlorophyll-a, total phosphorus, transparency of water, turbidity, water colour, oxygen, coli-index, Hg content in predator fish, As, Cr, Pb, total cyanide, damage caused by algae and changes of fish organoleptic properties. As it can be seen the value of pH or acidity of water is not taken into account. The other difference comes from the fact that NWPI method classifies water with high water colour (> 120 mg Pt l^{-1}) as satisfactory or bad, whilst according to Finnish method natural waters rich with humic substances (colour up to 200 mg Pt l^{-1}) can be considered as good.

According to the NWPI classification waters of the central part of Lake Onega belong to the class of excellent water quality, water in the southern part of the lake has a good status. In some bays, like Kondopoga and Petrozavodsk, where the pollution by industrial and commune waters is essential, water quality is satisfactory or even low, depending on weather conditions, time of the year etc. Similar conclusions were deducted when Finnish methodology was applied.

The new classification method developed in Finland after the adaptation of the European Water Framework Directive takes into account the size of water body, water colour and concentrations of total phosphorus and total nitrogen. In accordance with this scheme Lake Onega belongs to the class of great slightly humic lakes with good or moderate ecological status of water (surface area is more than 40 km^2 and colour is mainly less than 30 mg Pt l^{-1}). Table 6 shows the example of the new classification for the great slightly humic lake. At the same time, like in previous classification schemes some parts of the lake, like Kondopoga or Petrozavodsk Bay may fall into the category of moderate or even poor status in certain periods of time within a year cycle.

Table 6. Limit nutrients concentrations of the new Finnish classification scheme for the large slightly humic lake.

Ecological status	Excellent	Good	Moderate	Poor	Bad
Total phosphorus concentration, µg l^{-1}	< 10	10 - 18	18 - 35	35 - 70	> 70
Total nitrogen concentration, µg l^{-1}	< 400	400 - 500	500 - 700	700 - 900	> 900

Figure 5.1. The Finnish classification of Lake Onega.

In addition to the physico-chemical characteristics, the ecological quality of lakes should also be assessed with biological elements. In Finland the following biological metrics and class boundaries for the large slightly humic lakes (Lake Onega and its bays would belong to this lake type, if the Finnish typification were applied) have been defined (Table 7):

Table 7. Biological metrics and class boundaries for the large slightly humic lake (new Finnish classification scheme)

Biological metric	Unit	Sampling period	Reference value	Class boundaries			
				Excellent/ Good	Good/Moderate	Moderate/ Poor	Poor/Bad
Phytoplankton							
Biomass	mg l^{-1}	June-August	0.4	0.5	0.9	1.9	3.8
Chlorophyll-a	µg l^{-1}	June-September	3.0	3.6	7.0	13	26
Macrozoobenthos							
BQI-index[1)]	Index value	Autumn	A	75% of A	60% of A	30% of A	10% of A
PMA-index[2)]	Index value	Autumn	0.477	0.420	0.315	0.210	0.105
Fish							
Biomass (eutrophication)	g/gillnet night	July-August	890	990	1200	1600	2400
Biomass (toxic effects)	g/gillnet night	July-August	890	610	460	310	150
Number of fishes (eutroph)	number/ gillnet night	July-August	39	48	60	82	130
Number of fishes (tox)	number/ gillnet night	July-August	39	24	18	12	6
% of cyprinids	%	July-August	40	46	53	63	77
% of predatory fish	%		39	36	27	18	9
Indicator species		All observations		Artic char, white fish, minnow, stone loach, fourhorned sculpin	Burbot, trout, vendace, grayling, bullhead, alpine bullhead, nine-spined stickleback	Pike, perch, roach, normal population composition	Pike, perch, roach, abnormal population composition

A= value to be calculated for each sampling site, depends on the depth of the site:
BQI-1=1.53+(0.178*mean depth (m)
1) BQI= Biological Quality Index (Wiederholm 1980)
2) PMA=Percent Model Affinity (Novak & Bode 1992)

The Finnish classification system gives class boundaries for phytoplankton biomass in summer time (June-August). If those classification criteria were applied to the average summer time values in the lake Onega (Fig. 5.1), the central parts of the lake would be in high class. In some of the bay areas the classification would be lower, but still good. In the most eutrophicated bay areas the average phytoplankton biomass values can exceed the good/moderate class boundary.

In the Finnish ecological classification system, there are also tentative class boundaries for e.g. percentage of cyanobacteria in the phytoplankton and for some macrophyte indices. However, these have been used and tested only in limited cases and need further development.

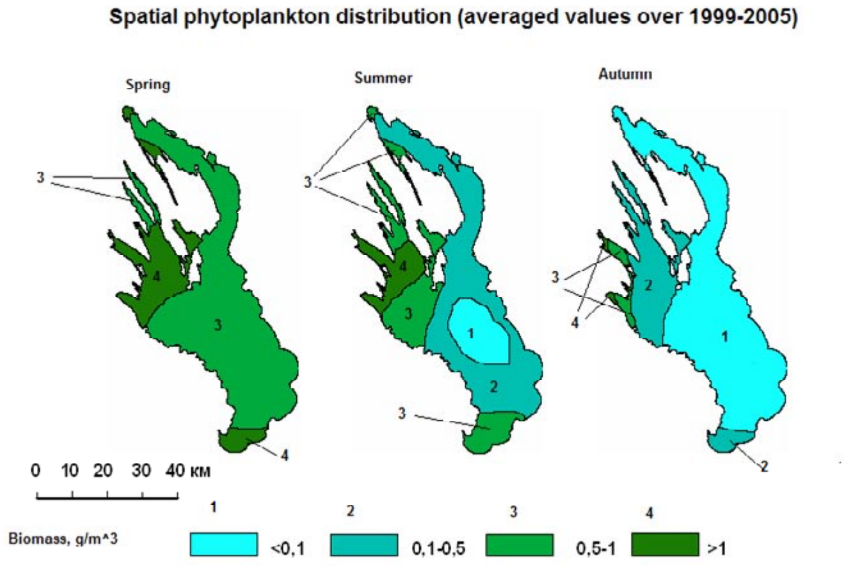

Figure 5.2. Phytoplankton distribution in Lake Onega in different seasons averaged over 1999 – 2005 (source: Northern Water Problems Institute KRC RAS)

The WFD also stipulates that quality standards for certain harmful substances shall be set. These substances include heavy metals, industrial and household chemicals and pesticides. For instance, following quality standards have been set on EU-level for heavy metals (in soluble form, background concentrations can be subtracted):

Table 8. EU quality standards for heavy metals

Substance	Annual average AA-EQS ($\mu g\ l^{-1}$)	Maximum allowable concentration MAC-EQS ($\mu g\ l^{-1}$)
Cadmium Cd	≤ 0.08 [1)]	≤ 0.45 [1)]
Mercury Hg	0.05	0.07
Lead Pb	7.2	NA
Nickel Ni	20	NA

[1)] if $CaO_3 < 40\ mg\ l^{-1}$, higher values for waters with CaCO3 concentrations.
NA= not applicable

6 Scenarios of reducing loading

According to modern knowledge the main source of eutrophication in lakes worldwide and in Lake Onega particularly (Chapra 1997, Filatov 1999, Astrakhantsev et al. 2003, Radcliffe & Cabrera 2007) is anthropogenic loading. To establish links between future development of lake ecosystem and economical development in water body watershed the detailed socio-economic analysis of the region development and prevailing trends in economy, ecology should be performed. This is a very difficult task which requires very detailed and accurate statistical data at different levels from regional down to enterprise level. Official statistics in Russia is in a transition to the system of national estimates (Druzhinin et al. 2005) and frequent changes of methods and errors in the process of filling blanks at enterprises resulted in essential bias estimates. Another aspect is that there is no desire to report accurately at the enterprise level and in the case of small and medium business the indicators are frequently flawed intentionally. High inflation level in the beginning of 90th created a complex problem to reconstruct comparable data time series (Druzhinin et al. 2005).

For Petrozavodsk wastewater treatment plant the only estimates of possible future loading scenarios are found in the Russian Federation Municipal Water and Wastewater Project., Environmental Assessment of the Project (EA), prepared by the World Bank in 2000. According to this report the estimated reduction of phosphorus output could be reduced almost twofold from 127 t a^{-1} to less than 61 t a^{-1} in 2010, provided that reconstruction of the wastewater treatment plant will be done according to the proposed plan.

7 Mass balance calculations (steady-state)

7.1

Description of the method

Eutrophication is one of the main problems of lakes worldwide. By definition, eutrophication in lakes is the increase of ecosystem's primary productivity, i.e. excessive plants growth and decay, caused by excessive nutrients loading. The main limiting factor for freshwater ecosystem is phosphorus, therefore, phosphorus balance models are often used to understand better the mechanism and dynamics of the system. The data available is not very comprehensive and a steady state mass balance model was considered to be suitable.

Steady state mass balance models for phosphorus have long been successfully applied in describing the average degree of eutrophy in lakes (e.g. Vollenweider 1969, Lappalainen 1974, 1977, Dillon & Rigler 1974, Frisk et al. 1981). This kind of models are practical in strategic planning when the effects of different loading scenarios on the average status of the lake are predicted. However, temporal variations of water quality cannot be described by means of these models, even though changes between successive steady states can be calculated (transient models).

As the basic model in this study, the model of Vollenweider (1969) was used. In the model, input, output and net sedimentation of phosphorus are considered. Input is the same as the total loading of phosphorus. Completely Stirred Tank Reactor (CSTR) hydraulics is applied and therefore output can be calculated as the product of discharge and phosphorus concentration in the lake. Net sedimentation represents the difference between gross sedimentation and release from the sediment. It is described as a first order loss reaction. The basic mass balance equation can be written as follows:

$$\frac{dc}{dt} = \frac{I}{V} - \frac{Q}{V}c - \sigma c \qquad (1)$$

where
c = total phosphorus concentration ($M\ L^{-3}$)
t = time (T)
I = total phosphorus input ($M\ T^{-1}$)
V = volume of the lake (L^3)
Q = discharge of the lake ($L^3\ T^{-1}$)
σ = first order net sedimentation coefficient of phosphorus (T^{-1}).

Dimension symbols: M = mass, L = length, T = time.

The steady state solution of Eq. (1) can be obtained by setting the derivative of the left-hand side as zero. Thus:

$$c_{ss} = \frac{I}{Q + \sigma V} \qquad (2)$$

where c_{ss} = steady state total phosphorus concentration ($M\ L^{-3}$).

For the application of the model, the catchment of the lake was divided into sub-catchments. Phosphorus loadings were calculated for each sub-catchments. The steady state calculations were made for the Lake Onega and two hot spot areas Kondopoga Bay and Petrozavodsk Bay separately. The sedimentation coefficients (σ) were determined using equation (2) and observed long term average concentrations of the Lake Onega, Kondopoga Bay and Petrozavodsk Bay.

7.2
Phosphorus input to the Lake Onega

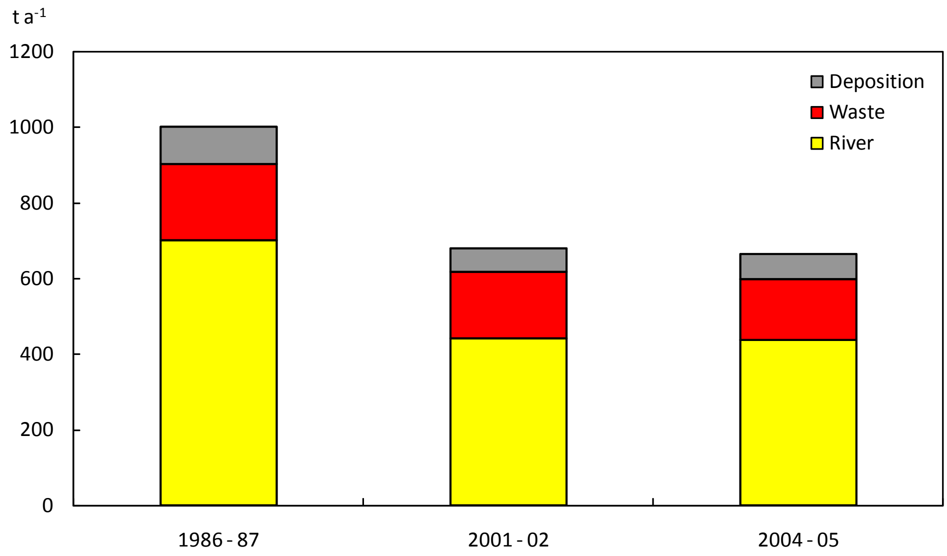

Figure 7.1. Temporal development of total phosphorus loading to Lake Onega.

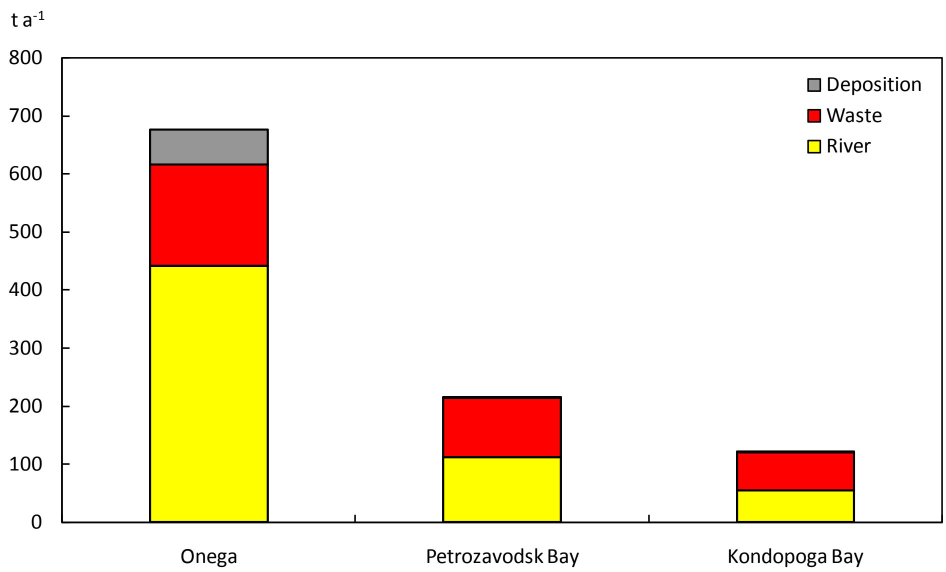

Figure 7.2. Present total phosphorus loading to Lake Onega and to two hotspot areas Petrozavodsk Bay and Kondopoga Bay.

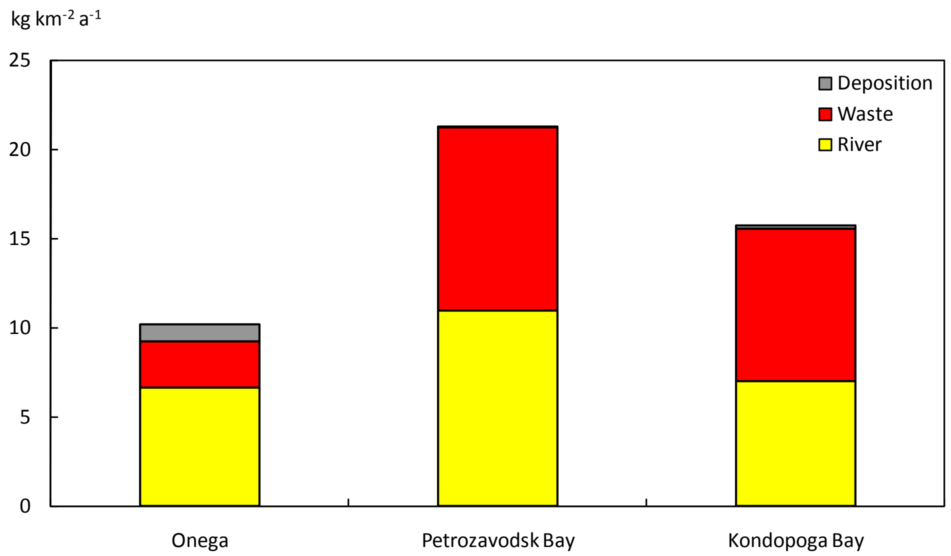

Figure 7.3. Present relative total phosphorus loading to Lake Onega and to two hot spot areas Petrozavodsk Bay and Kondopoga Bay.

7.3
Modelling results

The model was applied to estimate the effects of changes in two major point source loadings Petrozavodsk waste water treatment plant and Kondopoga pulp and paper mill.

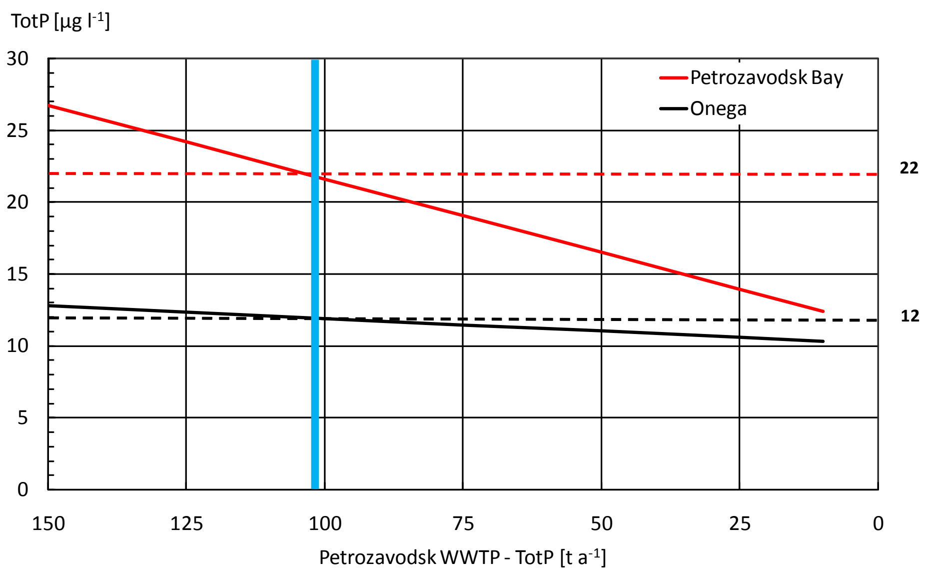

Figure 7.4. The relationship between Petrozavodsk WWTP phosphorus loading and the average phosphorus concentration of the Lake Onega (black line) and the Petrozavodsk Bay (red line). The vertical blue line represents the present loading.

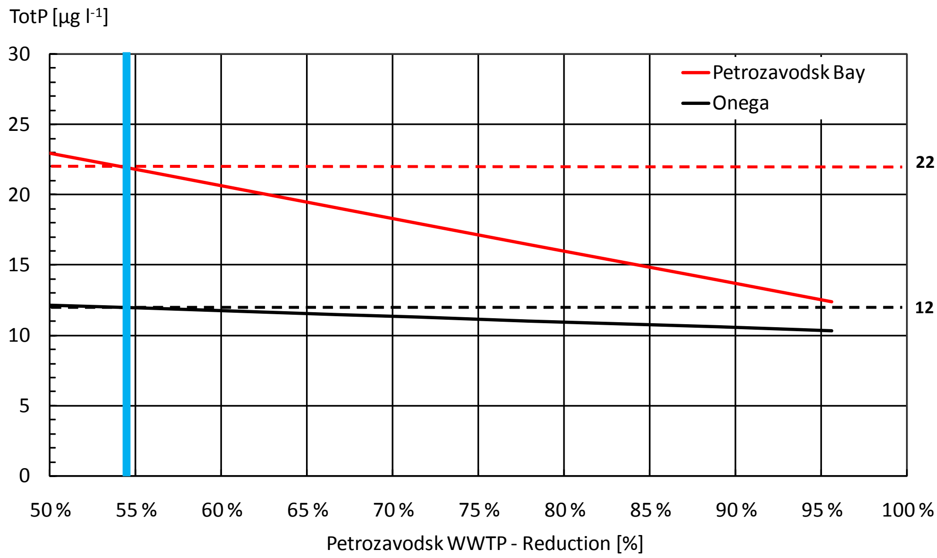

Figure 7.5. The relationship between Petrozavodsk WWTP phosphorus removal efficiency and the average phosphorus concentration of the Lake Onega (black line) and the Petrozavodsk Bay (red line). The vertical blue line represents the present loading.

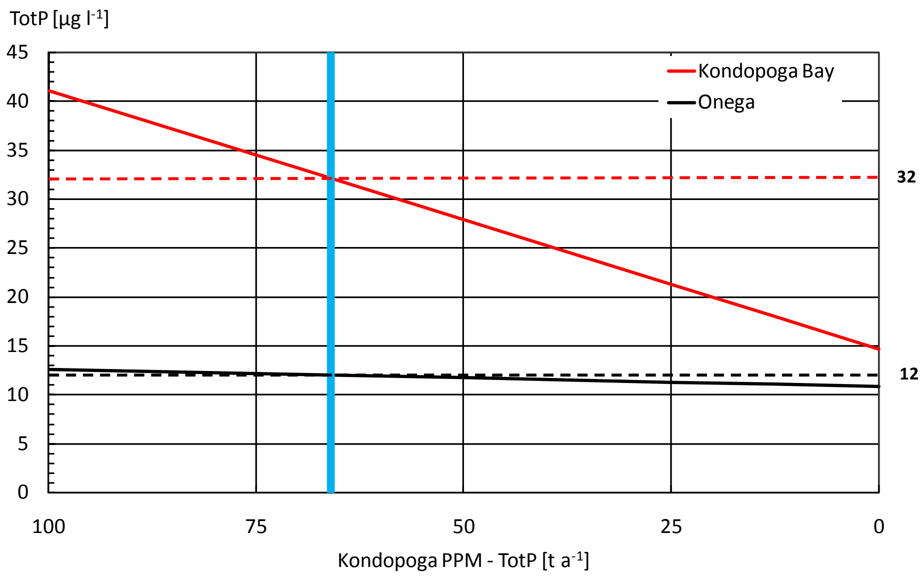

Figure 7.6. The relationship between Kondopoga PPM phosphorus loading and the average phosphorus concentration of the Lake Onega (black line) and the Kondopoga Bay (red line). The vertical blue line represents the present loading.

It can be seen that if the phosphorus removal efficiency of the Petrozavodsk WWTP would be 95 % the average phosphorus concentration of the Petrozavodsk Bay would be 13 µg l^{-1} which is 9 µg l^{-1} less than in present situation (Fig 7.4). Accurate estimations of the effectiveness of waste water treatment at Kondopoga PPM were unavailable but reduction of phosphorus loading would have significant effect of the average phosphorus concentration of the Kondopoga Bay (Fig 7.6).

8 Water quality modelling under dynamic loading

8.1

Estimation of long-term changes of phosphorus concentration in lakes

Excessive use of nutrients, phosphorus in particular in agriculture and forestry has detrimental effects on freshwater ecosystems. It can accelerate eutrophication processes in water bodies, trigger harmful algal bloom outbreaks and affect negatively human health. The need for model tools to estimate the phosphorus concentration in lakes has been recognised long time ago and many approaches have been developed since 1960s starting from simple mass balance models (Chapra 1997) to three-dimensional coupled hydrodynamic and ecosystem models (Astrakhantsev et al. 2003). High-dimensional models can provide deep insight on functioning of lake ecosystem under different scenarios but they require detailed information on forcing and input loadings and are very computationally demanding. As more efficient and feasible means much more simple one-dimensional or even zero-dimensional in space (so called box models) having one independent variable – time, are used widely. The main goal of this approach is to evaluate effects of different management alternatives aimed at reducing phosphorus loading from watersheds on phosphorus concentration in lakes.

Lake Ladoga catchment loading data for the period 1990 – 2005 were presented by Kondratyev (2007) and Lyskova (2007). It was possible to extract phosphorus loading data from different sources for Lake Onega catchment being the sub-catchment of Lake Ladoga (Table. 5). As it can be seen from these data and Figure 8.1 there is a steady decline both in diffuse and point-source phosphorus loading from Lake Onega watershed during the last fifteen years, attributed to economical difficulties, reduction of agricultural production and use of fertilizers. There was not enough data on atmospheric and internal loading, so the constant values for the whole period, suggested by Kondratyev (2007), were used.

The mass balance equation (1) was solved numerically using explicit and implicit integration schemes. The net sedimentation coefficient in this equation was approximated with the statistical equation of Canfield and Bachmann (1981). Their equation is based on a large data set and it has found to give good results in most lakes. The model can be written as follows:

$$\sigma = 0.162\left(\frac{I}{V}\right)^{0.458} \qquad (3)$$

Phosphorus input (I) must be given in mg a^{-1} and volume in m^3. Equation (3) gives σ in a^{-1}.

Calculations of the lake averaged total phosphorus concentration using Vollenweider-Canfield-Bachmann model (1), (3) with one year integration time step gives values (Fig.8.2) close to the estimates obtained from observations (Lozovik et al 2007, Sabylina & Martynova 2003).

Table 5. Components of total P balance in Lake Onega, t/a (Lyskova 2007, Kondratyev 2007).

Year	L_Diffuse	L_Point	L_atmosp	L_Internal	Total income
1990	600	220	95	197	1112
1991	600	220	95	197	1112
1992	500	210	95	197	1002
1993	420	210	95	197	922
1994	400	210	95	197	902
1995	470	200	95	197	962
1996	400	180	95	197	872
1997	380	180	95	197	852
1998	350	180	95	197	822
1999	350	190	95	197	832
2000	330	170	95	197	792
2001	300	200	95	197	792
2002	250	180	95	197	722
2003	210	190	95	197	692
2004	190	100	95	197	582
2005	190	100	95	197	582

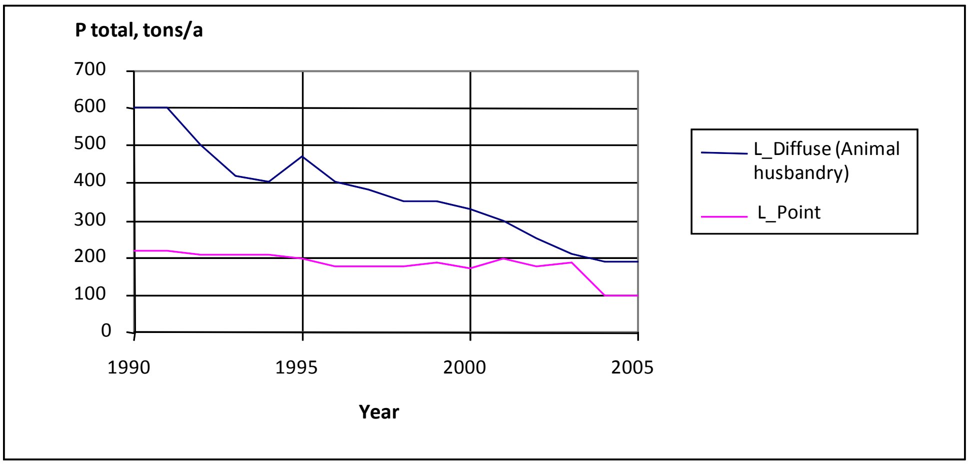

Fig. 8.1. Dynamics of diffuse and point source loading from the catchment of Lake Onega according to data by Lyskova (2007) and Kondratyev (2007).

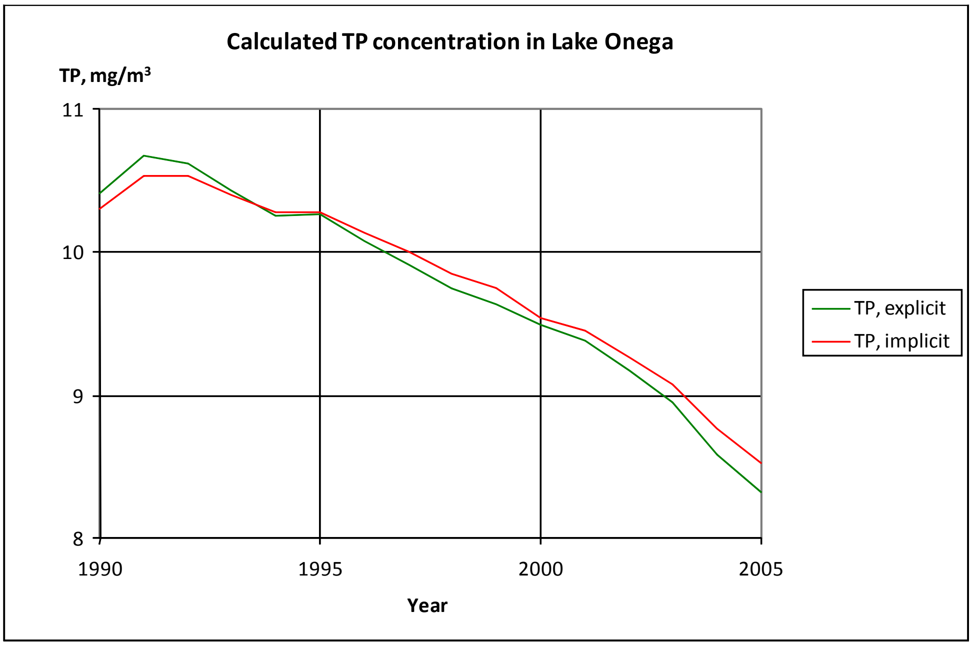

Fig. 8.2. Calculated mean total phosphorus concentration in Lake Onega under dynamic loading for the period 1990 – 2005.

In order to estimate changes of phosphorus concentration in lakes under possible future scenarios or when data on loading from watershed are not available the only way is to simulate these processes. Usually for these purposes hydrological runoff models of various complexities combined with nutrients transport sub-models are used (Radcliffe & Cabrera 2007). A simple statistical method was suggested recently by Håkanson and Boulion (2002) to estimate total phosphorus load from lake catchment within a frame of the integrated lake ecosystem model LakeWeb. The required driving parameters are latitude, altitude, mean annual river discharge and mean concentration of total phosphorus in tributary water (the default value is 30 mg m^{-3}). According to the authors the model gives good prediction of monthly mean discharges for rivers with mean annual discharge in the range of 1 – 500 $m^3 s^{-1}$. This range is wide enough to include most of European rivers (Håkanson et al. 2003). The inflow of total phosphorus in gram TP per week is calculated using the following formula

$$F_{in} = Y_Q \cdot Q \cdot C_{in} \cdot 3600 \cdot 24 \cdot 7 \qquad (4)$$

where Q is the mean annual discharge, m^3 s^{-1}, C_{in} is the mean concentration of total phosphorus in tributary water, Y_Q=f(L_x, L_i, Q_x, Q_i, A_x, A_i) is the seasonal moderator, describing mean weekly variations in surface runoff with statistical parameters tabulated using wide range of data (88 of 114 rivers in the calibration and 90 of 119 in the validation data sets).

Examples of calculations for four main rivers in the cathcment of Lake Onega are shown in Fig. 8.3.