JYVÄSKYLÄ STUDIES IN BIOLOGICAL AND ENVIRONMENTAL SCIENCE 141

Juhani Hynynen

Anthropogenic Changes in Finnish Lakes during the past 150 Years inferred from Benthic Invertebrates and their Sedimentary Remains

Esitetään Jyväskylän yliopiston matemaattis-luonnontieteellisen tiedekunnan suostumuksella julkisesti tarkastettavaksi yliopiston Ambiotica-rakennuksen salissa (YAA303) kesäkuun 18. päivänä 2004 kello 12.

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UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2004

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ABSTRACT

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Yhteenveto: Ihmistoiminnan aiheuttamat kuormitusmuutokset suomalaisissa järvissä viimeksi kuluneiden 150 vuoden aikana tarkasteltuina pohjaeläin-yhteisöjen avulla
Diss.

This thesis focuses on two themes concerning the anthropogenic impacts on Finnish lakes during the past 150 years. The effects of pulp mill discharges, municipal wastewaters and diffuse loading on the ecosystems of large lakes were studied from macroinvertebrate samples and from short-core paleolimnological samples. The response of benthic invertebrates to acidification and the patterns of recovery were studied from the littoral macrozoobenthos of acid-sensitive headwater lakes. The long-term responses of lacustrine chironomids to the changing degree of acidification were studied from paleolimnological samples. Based on the physical and chemical properties and biological remains in the sediment, several developmental phases were distinguished in the ecological status of the loaded lakes. These phases differed from each other on the basis of changing ecological disturbance affecting the lake ecosystems. The sediment profiles covered the time from the pre-industrial phase to the phase of severe pollution and, later on, to the phase of recovery. The lakes exposed to point loading from industrial and municipal sources revealed recent biological recovery patterns, while the lakes suffering from diffuse loading still revealed an ongoing eutrophication process. The study of acidic headwater lakes revealed many acid-sensitive benthic taxa, but also taxa tolerant of acidification. Recent chemical recovery was accompanied by a slight biological recovery in the most acidified lakes. Sedimentary chironomid assemblages of acidified lakes revealed only slight changes during the past centuries. Possible future trends and threats to the biological recovery of loaded lakes are discussed.

Key words: Acidification; benthos; Finland; lakes; pollution; pulp mill; recovery; subfossil chironomids.

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original publications, which will be referred to in the text by their Roman numerals:

I Meriläinen, J.J. & Hynynen, J. 1990. Benthic invertebrates in relation to acidity in Finnish forest lakes. In: Kauppi, P., Anttila, P. & Kenttämies, K. (eds), Acidification in Finland. Berlin, Heidelberg, New York: Springer-Verlag, 1029 - 1049.

II Hynynen, J., Palomäki, A., Veijola, H., Meriläinen, J.J., Bagge, P., Manninen, P., Ustinov, A. & Bibiceanu, S. 1999. Planktonic and zoobenthic communities in an oligotrophic, boreal lake inhabited by an endemic and endangered seal population. Boreal Env. Res. 4: 145 - 161.

III Meriläinen, J.J., Hynynen, J., Teppo, A., Palomäki, A., Granberg, K. & Reinikainen, P. 2000. Importance of diffuse nutrient loading and lake level changes to the eutrophication of an originally oligotrophic boreal lake: a palaeolimnological diatom and chironomid analysis. J. Paleolimnol. 24: 251 - 270.

IV Meriläinen, J.J., Hynynen, J., Palomäki, A., Veijola, H., Witick, A., Mäntykoski, K., Granberg, K. & Lehtinen, K. 2001. Pulp and paper mill pollution and subsequent ecosystem recovery of a large boreal lake in Finland: a palaeolimnological analysis. J. Paleolimnol. 26: 11 - 35.

V Meriläinen, J., Hynynen, J., Palomäki, A., Mäntykoski, K. & Witick, A. 2003. Environmental history of an urban lake: a palaeolimnological study of Lake Jyväsjärvi, Finland. J. Paleolimnol. 30: 387-406.

VI Hynynen, J., Palomäki, A., Meriläinen, J.J., Witick, A. & Mäntykoski, K. Pollution history and recovery of a boreal lake exposed to a heavy bleached pulping effluent load. J. Paleolimnol. (accepted).

VII Hynynen, J. & Meriläinen, J.J. Recovery from acidification in boreal lakes inferred from macroinvertebrates and subfossil chironomids. Hydrobiologia (submitted).

RESPONSIBILITIES OF JUHANI HYNYNEN IN THE ARTICLES OF THIS THESIS

Article I: The implementation of the study was carried out in cooperation with Dr. Jarmo J. Meriläinen. I was partly responsible for the field work, a comprehensive part of which was carried out by the research groups of Finnish Environment Institute. Dr. Meriläinen was mainly responsible for the identification of benthic invertebrates and I analyzed the animal material under his supervision. The article was written in cooperation.

Article II: The research team, led by Dr. Meriläinen, was responsible for the study. The majority of the members of the research group were involved in the field work. I was responsible for the identification and statistical analyses of the benthic data. Phytoplankton were identified and statistically analysed by Arja Palomäki. Zooplankton were identified by Silviu Bibiceanu and statistically analysed by Heikki Veijola. Prof. Pauli Bagge was responsible for the study of mobile macrozoobenthos. I was mainly responsible for the writing of the article. All the members of the research group provided me with the manuscripts of their research subjects.

Article III: The study was planned by the research team led by Dr. Meriläinen. I was mainly responsible for the field work. I analysed the sedimentary chironomid data from the northern basin and Anssi Teppo from the southern basin. Arja Palomäki analysed sedimentary diatom frustules. Dr. Granberg provided the team with a manuscript concerning the hydrology of L. Lappajärvi. Pasi Reinikainen performed the sediment dating. I carried out the statistical analysis together with Arja Palomäki. The article was written by Dr. Meriläinen, Juhani Hynynen and Arja Palomäki.

Article IV: The study was planned by the research team led by Dr. Meriläinen. I was mainly responsible for the field work. The sedimentary chironomids were identified and the data statistically analysed by me, and diatoms were handled by Arja Palomäki. Allan Witick and Keijo Mäntykoski were responsible for the chemical analyses. The research team co-wrote the article.

Article V: The study was planned by the research team led by Dr. Meriläinen. I was mainly responsible for the field work. Midge remains were analysed by me and diatom frustules by Arja Palomäki. We were also responsible for the statistical analysis of biological and chemical data. The team co-wrote the article.

Article VI: The study was planned by the research team led by Dr. Meriläinen. I was responsible for the field work. I analysed the chironomid remains and Arja Palomäki the diatom frustules. We also carried out the statistical analysis. Allan Witick and Keijo Mäntykoski were responsible for the chemical analysis. I was mainly responsible for writing the article with the aid of Arja Palomäki and Dr. Meriläinen.

Article VII: The study was planned by the authors and cooperating research groups. I was responsible for the field work, identification of the animal material and statistical analysis. I also wrote the article.

1 INTRODUCTION

Human activities have impacted lenthic waters in northern Europe since ancient times (Itkonen et al. 1999, Renberg et al. 2001, Bindler et al. 2002). However, the first signs of these activities in most of the lakes and rivers remained ecologically insignificant, and tracks of the biological changes can very seldom be detected (e.g. Meriläinen & Hamina 1993, Simola et al. 1996, Itkonen et al. 1999, Sandman et al. 2000). With the increasing population and establishing of new industrial plants in the 19th century, especially wood-processing paper and pulp mills, the anthropogenic changes in our watershed areas became more obvious, and the first ecological impacts on lakes began. Artificial lake level changes, which were carried out to prevent floods and to create more cultivated field area, were common in the 19th century (Anttila 1967). These activities promoted shore erosion in many lakes. But what were the ecological impacts of these changes in our lakes? This question remained for a long time unanswered, since there are only very few documents concerning the ecological state of lakes (e.g. Järnefelt 1932) from the early years of increasing human influence on waters.

The volume of industrial production, as well as agricultural activities, ditching and clear-cutting of land, increased notably after the Second World War. The ecological status of waters soon worsened in many places (e.g. Kansanen 1985), but the magnitude of the changes in water quality and biota remained unknown, because systematic water quality and biological monitoring has only been carried out in Finland since the 1960s. During the worst pollution period of Finnish waters, from the late 1960s to the early 1980s, a large number of studies focused on monitoring the prevailing biological effects of industrial effluents and municipal discharges (e.g. Särkkä 1979, Kansanen 1981, Kansanen & Aho 1981), but a little was known in those days about eutrophication and the pollution history of lakes.

Through large water protection investments a marked decrease in industrial effluent loading and municipal discharges was achieved in many parts of the country following the 1980s. However, information about the former water quality and ecological status of watersheds was lacking, so that the baselines for the prevailing and future status of recovering lakes were unknown. Fortunately, paleolimnological approaches have provided us with the possibility to reconstruct the past biological status of lake ecosystems. By means of multi-proxy studies, including assessments of the physical and chemical quality of sediment, reliable dating of the sediment and sedimentary diatom and chironomid analyses, it has been possible to estimate the recent environmental history of lakes, which has led to increasing activities in paleolimnological studies (e.g. Kansanen 1985, Meriläinen & Hamina 1993, Salonen et al. 1993, Simola et al. 1996, Itkonen et al. 1999).

Chironomid larvae leave subfossil remains of their chitinous, species-specific head capsules, which are very persistent and can be identified after being buried for thousands of years in the sediment (Smol 2002). Chironomids are relatively long-lived and they have great value in interpreting changes in the biological status of lakes. Based on the community structure of profundal chironomids with changing tolerance of organic loading and oxygen concentration, it is possible to estimate and classify the benthic quality of the sediment and trophic status of their environment (Sæther 1979, Wiederholm 1980). Chironomids have also been used in the assessment of long-term hypolimnetic oxygen changes (Quinlan et al. 1998, Little et al. 2000, Quinlan & Smol 2002).

In addition to the eutrophication of large lakes, other environmental changes have taken place during the past decades in small forest lakes in Central and southern Finland. As a consequence of increasing airborne acid deposition since the late 1960s (Haapala 1972, Haapala et al. 1975), marked changes in the acidity of surface waters in Finnish lakes was detected in the 1970s (Kenttämies 1973) and 1980s (Mannio 2001, Vuorenmaa 2004). A comprehensive multidisciplinary research programme, HAPRO, was launched in the mid-1980s in order to survey the extent of the acidification problem in Finland. Among many other subprojects, the survey of acid-sensitive lakes and their ecosystems was carried out in ca. 140 small forest lakes.

Since the 1990s a pronounced decrease in acid deposition has been observed (Olendrzynski 1997, Mannio 2001, Posch et al. 2003, Vuorenmaa 2004), which has led to the chemical recovery of surface waters in Central and southern Finland. In 2001 a survey financed by Finnish Academy, REPRO, was launched in order to assess whether the chemical recovery of lakes during a relatively short period of declining acid deposition has been accompanied by a biological recovery.

The objectives of this work were to examine anthropogenic changes in Finnish lakes from the 19th century to the present day. The investigation of large lakes exposed to industrial effluent loading, municipal discharges and diffuse, non-point loading was mainly based on paleolimnological multi-proxy studies. The geochronology of the sediment and information obtained from sedimentary chironomid analyses were the main themes of this work (III, IV, V, VI). The ecological status of Lake Pihlajavesi was defined from data on the current pelagic and benthic communities, and also with the aid of paleolimnological investigation by Sandman et al. (2000), which was carried out in two of the basins of Lake Pihlajavesi.

The response of littoral benthic invertebrates to acidity (I) and to the chemical recovery of acid-sensitive lakes (VII) was surveyed in small forest lakes in order to assess the effects of progressive ecosystem disturbance on littoral benthic communities, as well as the significance of declining environmental stress to littoral benthos.

The results obtained from this work can be utilized in the implementation of the EU Water Framework Directive classification of lakes. The paleolimnological data provide us with the conception of the natural reference status of lakes, which can also be defined as a good ecological status, and this can be compared to the present ecological status, mainly measured by biological parameters mentioned in the WFD. The ecological distance between undisturbed and present communities provides an indication of the effectiveness of the water protection investments carried out in water systems. These results can also be utilized in defining new goals and targets for future water protection work in these lakes.

2 DESCRIPTION OF THE STUDIED LAKES

2.1 Small forest lakes

The 141 headwater forest lakes studied in the HAPRO and REPRO projects in 1984-1986 and in 2001 were mainly distributed across southern and Central Finland (Fig. 1). These lakes ranged in area from 0.01 to 2.01 km^2, and 97% of them were less than 1.0 km^2. The nutrient status of the lakes was low, the phosphorus concentration averaging 12 µg l^{-1} (2 –110 µg l^{-1}). The corresponding value for nitrogen was 403 µg l^{-1} (85–1000 µg l^{-1}), while water colour averaged 54 mg Pt l^{-1} (5– 250 mg Pt l^{-1}). Many of lakes revealed a low buffering capacity and low pH values in the mid-1980s (Fig. 1 in I), but a considerable number of them chemically recovered in the course of the 1990s because of the reduction in air pollutant emissions (Fig. 2. and Tab. 1 in VII). More information about the past and recent chemical status of these lakes is presented by Mannio (2001).

2.2 Lake Pihlajavesi

Lake Pihlajavesi is a part of the Saimaa lake complex, the main lake of the Vuoksi water system discharging into Lake Ladoga in Russia (Fig. 1). The Pihlajavesi basin is comprised of eight distinct sub-basins with maximum depths of ca. 30 m (two), 40 m (one), 50 m (three) and 65—70 m (two). Detailed hydrological and morphological data on the lake are presented in Table 1.

The northern parts of the lake formerly received untreated effluent from the town of Savonlinna and effluent from a pulp and paper mill in the town of Varkaus, some 50 km upstream. The effective wastewater treatment in the 1980s led to a rapid decrease in both industrial and municipal loading. The present nutrient status of the lake is low (Table 1 in II).

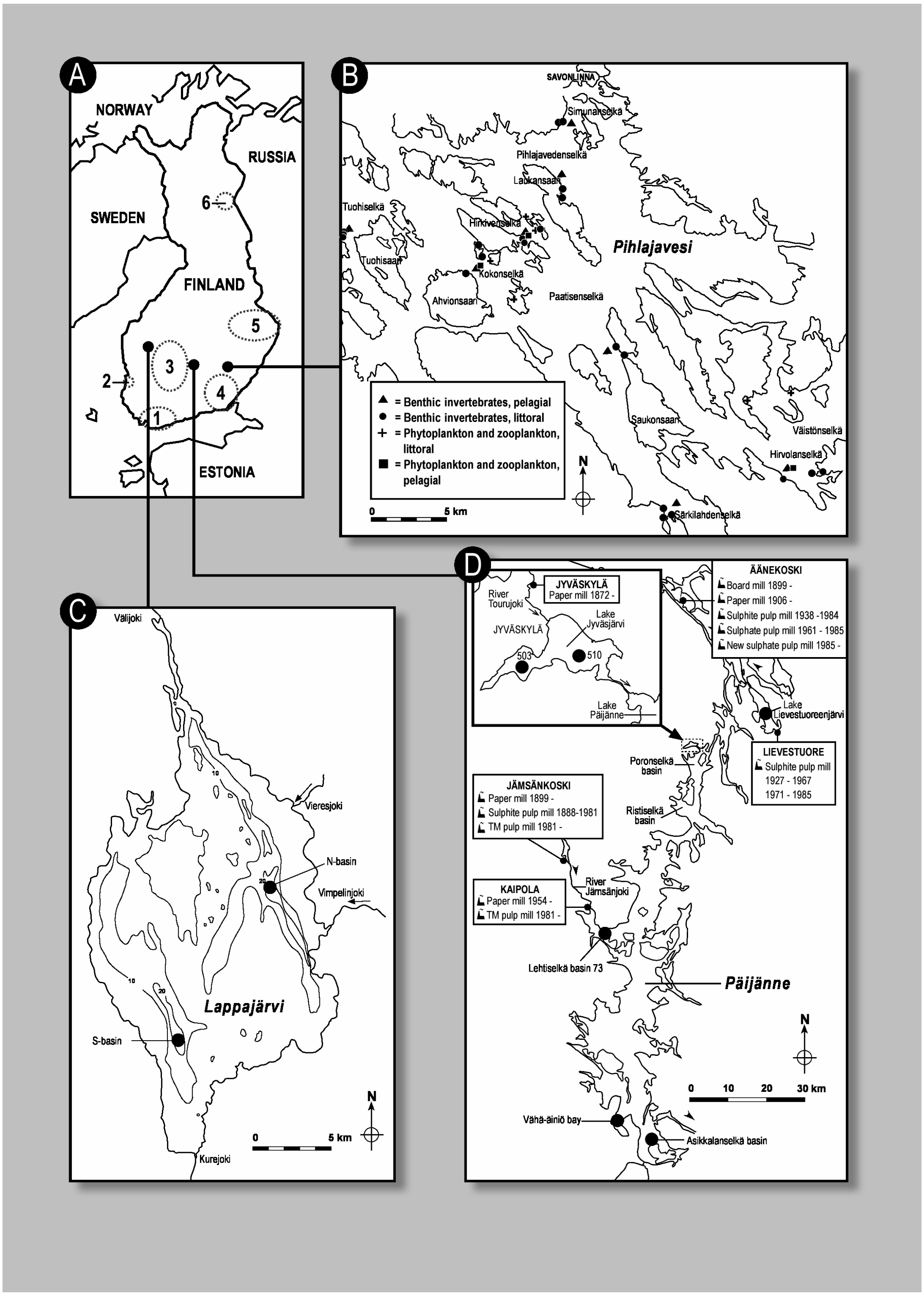

FIGURE 1 Location of study areas. A = The study of small forest lakes; (1) south-western Finland, (2) western Finland, (3) western-central Finland, (4) south-eastern Finland, (5) east-central Finland, (6) northern Finland. B = Sampling sites in Lake Pihlajavesi and location of the area in Finland. C = Sampling sites in Lake Lappajärvi and location of the lake in Finland. D = Lakes Päijänne, Jyväsjärvi and Lievestuoreenjärvi, sampling sites and location of the area in Finland.

TABLE 1 Morphological and hydrological data on lakes examined in the paleolimnological study of Finnish lakes.

	Lappa-järvi	Lehtiselkä basin	Asikkalan-selkä basin	Vähä-Äiniö bay	Jyväs-järvi	Lieves-tuoreenjärvi
Area, km^2	149	26	53	23	3.4	40.5
Mean depth, m	7.5	17.6	15.0	12.0	7.2	10.1
Max. depth, m	37.5	55	51	25	27	67
Volume, km^3	1.07	0.468	0.805	0.238	0.0239	0.422
Catchment area, km^2	1527	564	ca. 23300	ca. 100	372	235
MQ, m^{-3} s^{-1} (1960-1990)	12.7	ca. 58	213	-	3.3	3.4
Retention time, d	1022	ca. 93	44	-	81	1460

2.3 Lake Lappajärvi

Lake Lappajärvi is located in an ancient meteorite-impact crater in western Finland and is divided into two basins by an underwater ridge (Fig. 1). The hydrology and morphology of the lake are summarised in Table 1. The catchment area of the lake consists of forests (37.0%), bogs (29.2%), cultivated areas (20.3%), lakes (11.0%) and peat mining areas (1.8%). The total population in the area is low, only about 21 000.

The oxygen concentration has followed a declining since 1964 and the lake has suffered from hypolimnetic oxygen depletion almost every winter since the late 1970s (Fig. 2 in III). The phosphorus concentration of this originally oligotrophic , clear-water lake has increased during the past 25 years, consistent with the increase in COD and water colour (40 – 80 mg Pt l^{-1}), so that the lake is presently classified as meso-eutrophic.

The lake level was artificially lowered in 1834 and 1905-1908 (total 1.5 m), and lake regulation was begun in 1961. The main rivers entering the lake, Kurejoki and Vimpelinjoki (Fig. 1), are both eutrophic, suffering from diffuse non-point loading with an annual average total phosphorus concentration of ca. 100 µg l^{-1} .

2.4 Lake Päijänne

Lake Päijänne is the deepest and second largest lake in Finland (Fig. 1). Hydrological and morphological data on the lake are presented in Table 1. The lake has received heavy effluent loads from four main sources: (a) pulp and paper mills in the town of Äänekoski some 40 km upstream from Lake Päijänne, (b) a sulphite pulp mill on the shore of Lake Lievestuoreenjärvi, (c) municipal waste water from a treatment plant in the town of Jyväskylä and (d) Central Lake Päijänne has received effluent loads from the pulp and paper mills in the Jämsänjoki river valley (Fig. 1).

Waste water loading into the lake peaked in the 1960s and 1970s. The organic effluent load entering the lake from the northern loading units expressed as BOD_7 (Biological Oxygen Demand) was 25 to 30 t O_2 d^{-1} in 1969-1974, and the phosphorus load exceeded 200 kg d^{-1} in 1970-1975. Respectively, the loads discharged into central Lake Päijänne since 1968 ranged from 40 to about 95 t O_2 d^{-1} for BOD in 1968-1974, and about 90 to 160 kg d^{-1} for phosphorus in 1969-1981.

A drastic decrease in loading has been detected during the past 15-20 years. The first water protection investments in the 1970s, construction of the waste water treatment plant in the town of Jyväskylä (see V), and the sulphite lye evaporation and burning plants in Jämsänkoski and Äänekoski (see IV) and beside Lake Lievestuoreenjärvi (see VI) accelerated the purification process of the lake. The improvement in water quality continued with the closure of the three old sulphite pulp mills in the 1980s and their substitution by new mills with modern waste water management systems. At present the loads entering the lake are only a fraction of the former loads (Fig. 2 and Fig. 3 in IV).

The minimum oxygen concentration at Central Päijänne began to increase in the early 1970s, but the late winter minima did not improve until much later, in the 1990s. The southern basin of the lake has never been loaded so badly as those basins in the northern and central parts of the lake. Nevertheless, the loading was also clearly visible in that basin, especially during the early years of water quality monitoring in the late 1960s (Fig. 3 in IV).

2.5 Lake Jyväsjärvi

This small city lake received municipal wastewater in an untreated form until 1977. In addition, the lake received the effluent load from a paper mill, which started to operate in 1872 on the bank of the main inflow (Fig. 1).

Hydrological and morphological data on the lake are presented in Table 1. In the early 1960s the total phosphorus (TP) concentrations at 1 m depth averaged about 200 µg l^{-1} and the total nitrogen (TN) concentration was about 1000-3000 µg l^{-1}. The TP concentrations decreased considerably after 1974 when the majority (ca. 75%) of municipal wastewater was directed to a treatment plant (V, Fig. 2). Since 1977, all the municipal wastewater has been directed to the treatment plant.

It is estimated that the TP load from municipal sources entering the lake was around 6 kg d^{-1} in the 1930s, ca. 100 kg in the 1960s, and 200 kg d^{-1} in the early 1970s. At its highest, the Biological Oxygen Demand (BOD_7), was nearly 10 t O_2 d^{-1}, half of which originated from municipal sources and half from the paper mill effluent. Hypolimnetic oxygen at that time was close to zero throughout the summer (Fig. 3 in V). As a consequence of acid paper mill effluent, pH sometimes decreased to as low as 3-4.

At present the BOD_7 is >90% lower than the highest values. The present nutrient load from the paper mill is rather low compared with the diffuse load of ca. 10 kg TP and ca. 250 kg TN d^{-1} entering the lake from its catchment area (Palomäki and Salo 2001). Hypolimnetic aeration of Lake Jyväsjärvi was started in 1979. The effectiveness of the aeration was improved in 1993 and 1998.

2.6 Lake Lievestuoreenjärvi

Lievestuoreenjärvi is a headwater lake located in the Kymijoki watershed area in Central Finland (Fig. 1). Hydrological and morphological data on the lake are presented in Table 1.

A sulphite pulp mill began operations on the lake shore in 1927 and deterioration of the water quality took place soon after this. For example, the Secchi disk transparency rapidly decreased from about 5 m to 0.5-1.2 m. The effluent discharge continued until the summer of 1967, when the mill was temporarily closed. At that time the lake was described as a huge wastewater basin with highly reduced biodiversity. The mill restarted in 1971, but was finally closed in September 1985.

Resulting from the construction of a sulphite lye evaporation and burning plant, and also changes in the pulp cooking process in the 1970s, the effluent quality improved, and especially pH began to rise in the lake. In the early 1980s the directors of the mill illegally exceeded the production and loading limits, which resulted in the destruction of the whole lake ecosystem.

The lake suffered from severe hypolimnetic oxygen depletion during the operating period of the mill, except for the years of its temporary closure. All the water quality variables indicated severe pollution of the lake up to 1985 and a marked recovery in water quality after that (Fig. 2 in VI).

3 MATERIALS AND METHODS

3.1 Sampling and laboratory analyses

3.1.1 Forest lakes

A total of 141 headwater lakes were surveyed in the HAPRO project from 1984-1986. A preliminary study was carried out in 55 of the 141 lakes in 1984 (Kenttämies et al. 1985). Only snails (Gastropoda), mayflies (Ephemeroptera), caddis flies (Trichoptera), dragonflies (Odonata) and alderflies (Megaloptera) were identified to species in that study. A more comprehensive survey of a further 86 lakes was carried out in 1985-1986. However, in 22 lakes surveyed in 1986 the species-level identification was restricted to groups regarded as key organisms in relation to lake acidification, namely snails, small mussels (Sphaeriidae) and mayflies. All the animals, excluding water mites, were identified to species or in some cases to genera in 64 lakes. Due to the lack of complete data on geomorphology and water quality, two lakes were excluded from the final results, and one lake was omitted from statistical analysis as an outlier.

Three quantitative Ekman samples (289 cm^2 each) were taken from the littoral and sublittoral area of each lake. In addition, the littoral fauna at 0.5-1.0 m was sampled with a hand net for about 1 min at a time. All the samples were sieved through a 0.5 mm mesh and preserved in 70% alcohol.

In 2001, 29 small lakes (27 HAPRO lakes and two new lakes) were surveyed in order to study possible biological recovery in recently chemically recovered headwater lakes. Some chemically non-recovered lakes were also included in the lake subset. Comparable sampling procedures were used in the mid-1980s and 2001, except that the quantitative Ekman samples were only taken in the littoral zone of the lakes in 2001.

A paleolimnological study was performed in 2001 in five acidic lakes and in one non-acidic lake from different sampling areas of the country that revealed either significant chemical recovery (four lakes) or statistically non-significant recovery (two lakes). The aim was to examine possible long-term changes in the biological status of these lakes. The sediment cores for the midge analysis were taken with a Kajak sediment corer from the main profundal area of lakes (VII).

3.1.2 Lake Pihlajavesi

In addition to phytoplankton and zooplankton, which were sampled on several occasions (Fig. 1, II), comprehensive benthic invertebrate material, including all the hypothetical depth zones usually distinguished from a lake bottom, was sampled from three basins (Pihlajavedenselkä, Kokonselkä and Väistönselkä) (Fig. 1) in May and September 2001. Only the deep profundal zone was sampled from five other basins of the lake in September.

The quantitative samples were taken with an Ekman grab (289 cm^2) and processed at the laboratory according to the Finnish standard SFS 5076. The qualitative data from the littoral zone was collected with a hand net.

Relict crustaceans and water mites were studied in sublittoral and profundal areas using vertical net (mesh size 405 µm, area 0.56 m^2) and plexiglass traps with fish bait or a yellow luminance light stick. The number of vertical net replicates in a basin ranged from six to eight.

3.1.3 Paleolimnological studies

Sediment cores from lakes Lappajärvi, Päijänne, Jyväsjärvi and Lievestuoreenjärvi were mainly collected using a Limnos sediment corer (Kansanen et al. 1991) and a dry-ice sampler (Saarnisto 1986). A Kajak-type corer was used in the study of Lake Jyväsjärvi.

The sampling procedure and the repertoire of analyses carried out in each of studied lakes are presented in Table 2. A further 29 selected elements were analysed from lakes Päijänne and Jyväsjärvi: Al, As, B, Be, Ca, Cd, Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Sc, Si, Sr, Th, V, Y and Zn. Detailed information on the different chemical laboratory analyses, diatom analyses, analysis of spherical carbonaceous particles (SCP) and dating methods of each lake are presented in the original papers (III, IV, V and VI).

Subsamples of 10-60 ml (III), 20-50 ml (IV), 20-100 ml (V) and 20-32 g (VI) wet mass were taken for chironomid analysis, deflocculated in 10% KOH solution at 30 °C for about 12 hours, and then passed through a 100 µm (V, VI) or 200 µm (III, IV) sieve. Head capsules were picked out from a grooved disc under a stereo microscope at 24 x magnification and mounted in Euparal® on glass slides for identification. The material was mainly identified according to Wiederholm (1983), but use was also made of the keys of Chernovskii (1949), Hofmann (1971), Sæther (1975) and Cranston (1982).

TABLE 2 Analysis repertoire and sampling and dating methods used in the paleolimnological studies of Finnish lakes. A cross in parentheses indicates methods carried out but not utilized in the final results. SCP=spherical carbonaceous particles.

	L. Lappajärvi	L. Päijänne	L. Jyväsjärvi	L. Lievestuoreen-järvi
Limnos corer	x	x	x	x
Dry ice sampler	x	x	x	x
Kajak corer	-	-	x	-
Sieve, µm	200	200	100	100
Samples, cm	0-44	0-35	0-76	0-44
Sample sectioning, cm	1	1	1	1
Water content	x	x	x	x
Loss on ignition	x	x	x	x
^{210}Pb dating	x	x	(x)	x
^{137}Cs dating	x	x	x	x
Varve counting	-	x	x	-
SCP counting	x	x	x	-
Selected elements (29)	-	x	x	-
Mercury, Hg	-	x	x	x
PCB	-	-	x	-
Resin acids	-	x	x	x

3.2 Statistical methods

Multivariate statistical methods were used in all the studies to identify possible patterns in the chironomid assemblages. The methods used were detrended correspondence analysis (DCA; Hill 1979), or principal component analysis (PCA) if the gradient length in DCA ordination was <1.5. The analyses were performed with CANOCO software (ter Braak and Šmilauer 1998). PCA was also used to explore the variation in element concentration of the sediment (V). To assess the biological differences between the former and the present macroinvertebrate communities of the acid forest lakes, the data were analysed by canonical correspondence analysis (CCA) using the water quality data and catchment features as background data (VII), and tested with the nonparametric Wilcoxon Signed Ranks Test (2-tailed) for two related samples. The trends over the different pH and labile Al gradients were calculated for the total number of species and the number of acid sensitive species by using regression models.

The Benthic Quality Index (BQI) based on the chironomid fauna (Wiederholm 1980) was used to assess the biological condition of the profundal areas. The percentage similarity (PS) for chironomids was calculated from the BQI values, since this gives a more accurate estimate of the similarity of profundal assemblages than the squared Chi-squared distance when the number of individuals in a sample is low, as it was in some chironomid samples.

4 RESULTS

4.1 Patterns of benthic recovery in acidified forest lakes

Macroinvertebrate communities studied in the mid-1980s in forest lakes revealed highly reduced benthic communities and decreased biodiversity in many acid-sensitive headwater lakes across the southern and central parts of Finland. Some indications of acid-impacted benthic assemblages were also obtained from northern Finland.

The distinct acid-induced changes were the decrease in number of species, especially among snails, mayflies and small mussels (Tables 2, 3 and 4 in I), with increasing acidity, whereas no changes were detected in the number and biomass of animals. The presence of key species was closely associated with the minimum lake pH, which usually occurred during the snow melting period (Table 1 in I). The rarefaction curves (Figs 3 and 4 in I) showed that a hand net sampling method used in the upper littoral zone is a superior method for sampling high numbers of individuals and species, and it is therefore recommended for use in future re-surveys of these acid lakes.

In the recently re-surveyed subset of lakes a significant statistical association was detected between the mean pH and labile Al concentrations (Fig. 3 in VII). The total number of species was found to correlate positively with increasing pH (Fig. 4 in VII) and decreasing labile aluminium concentration (Fig. 5 in VII).

Multivariate statistical analysis revealed the most prominent response to declining acidity in the community structures of the formerly most acidic but recently chemically recovered lakes. However, there was considerable unexplained variation in the species data. In DCA ordination, changing acidity was the most significant gradient explaining the variation in the species data.

CCA ordination revealed that increasing pH, a decreasing labile aluminium concentration and water colour were the most significant environmental variables affecting the littoral benthos of recovering lakes. The distribution of the former and the recent communities of the most acidic lakes differed greatly in the ordination diagram (Fig. 6 in VII). Of the environmental variables included, labile aluminium and pH exhibited statistically significant correlations with axis 1. Water colour and labile aluminium concentration had a significant association with axis 2 (Table 3 in VII).

The test of differences between the former (1985) and the recent (2001) littoral communities of the most acidic lakes revealed statistically significant changes in the number of acid sensitive species, the total number of species, and the number of Oligochaeta and Diptera species (Table 4 in VII).

The DCA ordination for sedimentary chironomid remains revealed separate lake clusters, where the distribution of the samples from highly acidic lakes (Orajärvi, Kakkinen) and moderately acidic and non-acidic lakes differed to some extent (Fig. 6 in VII). Although chironomid assemblages responded slightly to a change in pH, the structural similarity of the ancient and recent chironomid communities in the most acidic lakes revealed only minor changes in chironomid communities during past centuries. However, in Lake Kakkinen a weak shift was detected from a near pristine state to more acidic conditions and a slight recovery after that.

4.2 The biological status of Lake Pihlajavesi

The ecosystem study of Lake Pihlajavesi revealed planktonic and zoobenthic communities typical of boreal, oligotrophic lakes in most basins of the lake (Table 7 in II). The phytoplankton community structure was determined by the nutrient concentration and the colour of the water, and zooplankton communities revealed a distinct difference between the pelagic and littoral areas. In certain clear-water areas with a very low phosphorus concentration the phytoplankton biomass was rather high in relation to the nutrient status. This resulted from a high transparency of the water, which allows effective phytoplankton growth in the layers down to 10-12 m. Despite the low nutrient status the area is highly productive, and this increases the organic sedimentation rate in profundal areas. Consequently, the value of the chironomid-based benthic quality index was exceptionally low considering the pristine nature of the basin, as seen, for example, in the highly oligotrophic, clear-water basin Väistönselkä (Table 8 in II). The scarcity of mobile zoobenthos in clear-water areas, especially of relict crustaceans, was explained by the selective predation pressure by fish on these large-sized, actively moving invertebrates.

The water depth and bottom quality mainly controlled the structure of zoobenthic communities (Fig. 8 in II). The soft bottom communities detected in the lake were as follows: vegetated littoral (1-3 m), sublittoral (3-10 m), upper profundal (10-20 m) and deep profundal. The effluent loading entering the lake was clearly detectable in the profundal communities of the nearest basin (Simunanselkä) to the town of Savonlinna, where the benthic community indicated mesotrophy (Table 6 in II). The recovery of the profundal benthic quality of the lake was detectable in Pihlajavedenselkä (Fig. 1), where paleolimnological data

(Sandman et al. 2000) revealed a BQI value as low as 3.80 in the 1970s (Table 8 in II), whereas the present values averaged as high as 4.35 (Sandman et al. 2000, II).

4.3 Paleolimnological evidence of change in the studied lakes

4.3.1 Physical properties of the sediment and geochronology

The data obtained on the physical properties of the sediment evidenced marked changes in loss-on-ignition and water content in all of the studied lakes. However, the timing of the changes differed from case to case depending on the type of main loading source.

In Lake Päijänne and Jyväsjärvi the first distinct changes in the quality of the sediment occurred at the turn of the 19th and 20th centuries, soon after the establishment of the paper and sulphite pulp mills (Figs 5 and 6 in IV and Figs 6 and 7 in V). However, in Lake Jyväsjärvi the observed changes were also related to the increasing loading with municipal wastewaters and the intensive use of lake shores for different kinds of construction works. In Lake Päijänne, especially in the southern parts of the lake, some old (early 1800s) peaks of eroded clastic material existed, mainly derived from the expansion of agricultural ditching and the clearing of new cultivated fields, but also from the artificial lowering of Lake Päijänne in 1832-1838 and the construction of Vääksy Canal in 1868-1871 and 1909-1911.

In Lake Lievestuoreenjärvi the first changes in the physical properties of the sediment were entirely associated with the establishment of the sulphite pulp mill in 1927 (Fig. 3 in VI). Before that the lake was in a near pristine state without distinct changes in sediment quality.

In Lake Lappajärvi the physical changes observed were closely related to the growth of agriculture and forestry after World War II. The peaks of eroded material derived from ditching and the clearing of cultivated areas, as well as peaks of organic material originating from the ditching of peatlands, are visible in the sediment (Figs 5 and 7 in III). The development of hydrologically active ditching in the catchment area reached its maximum in the late 1960s and in 1970s (Fig. 14 in III).

The sediments were mainly dated by the ^{210}Pb method. Although disturbed in L. Lappajärvi and Vähä-Äiniö bay by eroded material derived from the catchment area (Fig. 3 in III and Fig. 4 in IV), this method provided reliable dating curves with the support of the ^{137}Cs concentration (from the Chernobyl accident in 1986) and analysis of spherical carbonaceous particles (SCP, Renberg & Wik (1984)). In heavily loaded Lehtiselkä basin and Lake Jyväsjärvi, ^{210}Pb dating was unreliable due to the high variation of the ^{210}Pb concentration in the sediment. The dating in these locations was based on annual lamination (varve) counting and SCP analysis. Due to undisturbed sedimentation conditions in these areas, both dating curves obtained by this method were highly reliable (Fig. 4 in IV and Figs 4 and 5 in V). In contrast to other heavily polluted areas, the ^{210}Pb dating curve for Lake Lievestuoreenjärvi was considered highly reliable (Fig. 5 in VI) and was supported by historical information on the pulp mill production volume and the chemical and physical stratigraphy of the sediment.

4.3.2 Chemical properties of the sediment

The sediment analyses of the recipients of chemical wood-processing effluent water revealed very similar chemical stratigrafies, including considerable concentrations of resin acids, mercury and certain basic elements (IV, Figs 7 and 8, V, Figs 8 and 9 and VI, Fig. 6). The most pronounced peaks of harmful substances in all recipients dated back to the time from the late 1950s to early 1980s. In all the locations studied, except the southern parts of Lake Päijänne, the maximum concentrations were many orders of magnitude higher than the background values. For example, in Lake Lievestuoreenjärvi the concentrations of Hg, used as a slimicide, drastically increased after the 1950s and peaked in the mid-1960s at 6.4 mg kg^{-1}. This value is twofold higher than in Central Päijänne and threefold higher than the maximum value in Lake Jyväsjärvi. In Central Päijänne the analysis of basic elements revealed connections to emissions from the wood-processing industry, as well as to the combustion of fossil fuels in the mills. In Lake Jyväsjärvi, PCA of the elements revealed two distinct element groups, which derived either from municipal or industrial loading or from erosion (lithophilous elements). In this city lake some elements already peaked in the early 1900s, soon after the sewage system of the town came into operation. PCB-contaminated sediments were only characteristic of Lake Jyväsjärvi, where the concentrations began to increase after the 1950s, peaked in the 1970s and decreased to zero around the beginning of the 1980s.

4.3.3 Biological changes

In all the lakes studied multivariate statistical analysis revealed several separate clusters of pelagic and benthic assemblages, which were in most cases highly similar to each other and typical of the developmental phases of the loading entering the lakes (III, Figs 12 & 13; IV, Figs 13 & 14; V, Figs 12 & 15 and VI, Figs 8 & 11). In all the studies the strongest environmental gradient distinguishing chronologically different diatom and chironomid assemblages was the change in pollution or loading status of the lake.

Despite the nature or origin of the loading, the following three environmental phases or changes in environmental disturbance were detectable in all the studied lakes: (1) a pre-industrial or natural reference state revealing slight or negligible environmental disturbance; (2) a phase of increasing pollution or loading (Lappajärvi) or eutrophication (Jyväsjärvi) revealing moderate to strong environmental disturbance; (3) a phase of severe pollution or a phase of erosion (Lappajärvi) revealing severe environmental disturbance. The names of the second and the third phases in lakes Lappajärvi and Jyväsjärvi are not identical to the other lakes, due to differences in the main loading sources. In Lake Jyväsjärvi a phase of early changes in the lake ecosystem was detected prior to increasing eutrophication (III, Table 2; IV, Tables 4, 5 & 6; V, Table 2 and VI, Table 3).

Despite the fact that chironomids and diatoms track environmental conditions in different habitats and from different trophic levels, the in-lake timing or synchronicity of the changes in pelagic and benthic assemblages were highly similar in each of the studied lakes. Depending on the type and time of onset of the environmental disturbance, inter-lake variations in the timing of environmental phases appeared, but in all the lakes the phase of severe pollution, or the phase of strong catchment erosion (Lake Lappajärvi), covered the whole of the 1970s. During the phase of severe pollution the ecosystems of pulp and paper mill recipients revealed strong ecological disturbance and biological inhibition.

As a consequence of water protection work and the closing of outdated wood-processing mills, a clear shift towards recovery in both, pelagic and benthic communities of the pulp and paper mill recipients took place in the late 1980s and early 1990s. Ecological disturbance weakened from severe to moderate during this phase. This positive trend, however, has been very slow in Lake Jyväsjärvi, or totally lacking in Lake Lappajärvi, lakes that both suffer from heavy diffuse, non-point loading. The improvements in the water quality in lakes Päijänne and Lievestuoreenjärvi, i.e. lessening inhibition and a thicker illuminated layer, were reflected in the pelagic assemblages. They resulted, for example, in an increase in diatom biovolume, i.e. a short and temporary eutrophication process. This temporary eutrophication retarded the benthic recovery, especially in Lake Lievestuoreenjärvi, where the BQI value in the early 1990s temporarily decreased to zero (VI, Fig. 10).

Despite the greatly improved water quality, the benthic assemblages in formerly heavily loaded lakes Päijänne and Lievestuoreenjärvi reveal at present meso-eutrophic profundal benthic quality, which still indicates benthic exposure to environmental disturbance and inhibition in these lakes. In Lake Jyväsjärvi the benthic communities, although recovered to some extent from the worst situation, still reveal clear eutrophication. In Lake Lappajärvi the profundal benthos at present indicates eutrophy without any distinct recovering trends during the past decades. In terms of percentage similarity the present benthic assemblages of all the studied lakes are still far from those prevailing in the pristine or near pristine state of the watersheds (Fig. 2, Table 2 in III; Tables 4, 5 & 6 in IV; Table 2 in V and Table 3 in VI).

The combined data from all the studied lakes were subjected to detrended correspondence analysis, which revealed several clusters, including samples from different environmental phases of these lakes (Fig. 3). Axis 1 represents increasing loading from left to right and axis 2 was interpreted as a pollution gradient. All the samples from oligotrophic southern Lake Päijänne and Lake Pihlajavesi, and pre-industrial samples from Central Päijänne, Lake Lievestuoreenjärvi and the northern basin of Lake Lappajärvi comprised a tight cluster on the left of the diagram, indicating similarity in the profundal benthic communities of large, pristine Finnish lakes. This structural similarity of the pre-disturbance benthic communities also revealed a highly similar natural reference status for these lakes.

Lake Jyväsjärvi and the southern basin of Lake Lappajärvi already revealed meso-eutrophic benthic communities in the natural state. The later recovery of severely polluted Central Päijänne and Lievestuoreenjärvi is discerned in the figure, while Lake Jyväsjärvi reveals only slight recovery, and Lake Lappajärvi no recovery at all.

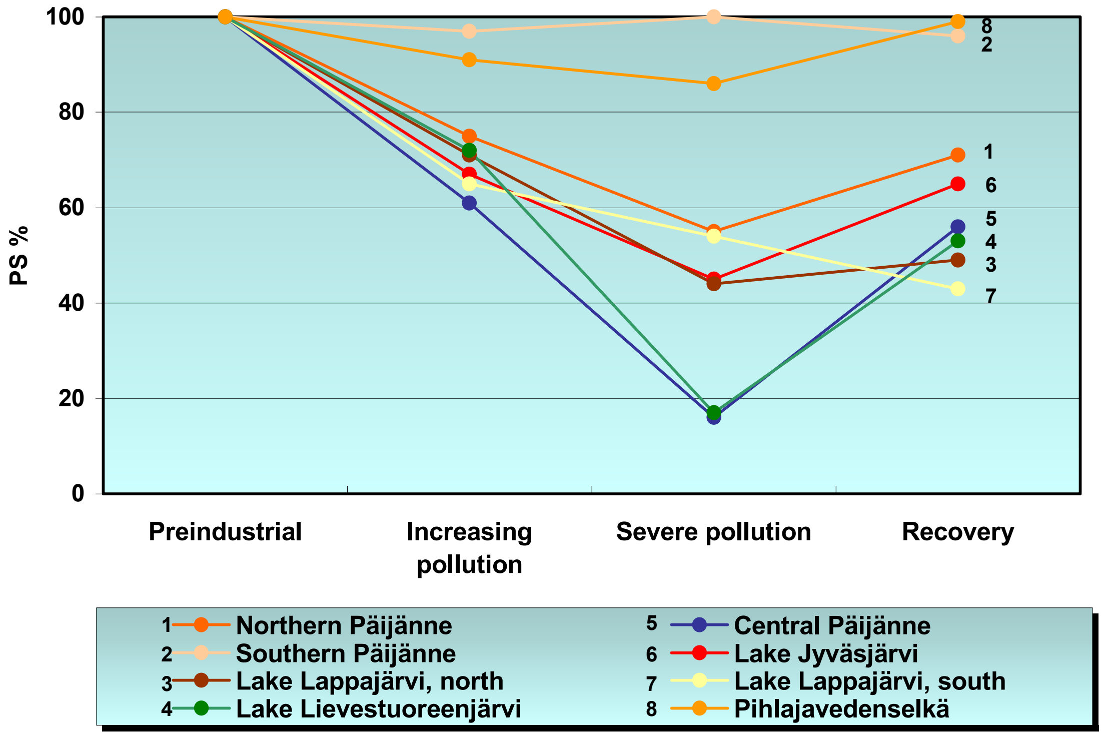

FIGURE 2 Percentage similarity of profundal benthic communities in different environmental phases of the studied lakes compared to preindustrial values. Values for northern Lake Päijänne obtained from Meriläinen & Hamina (1993).

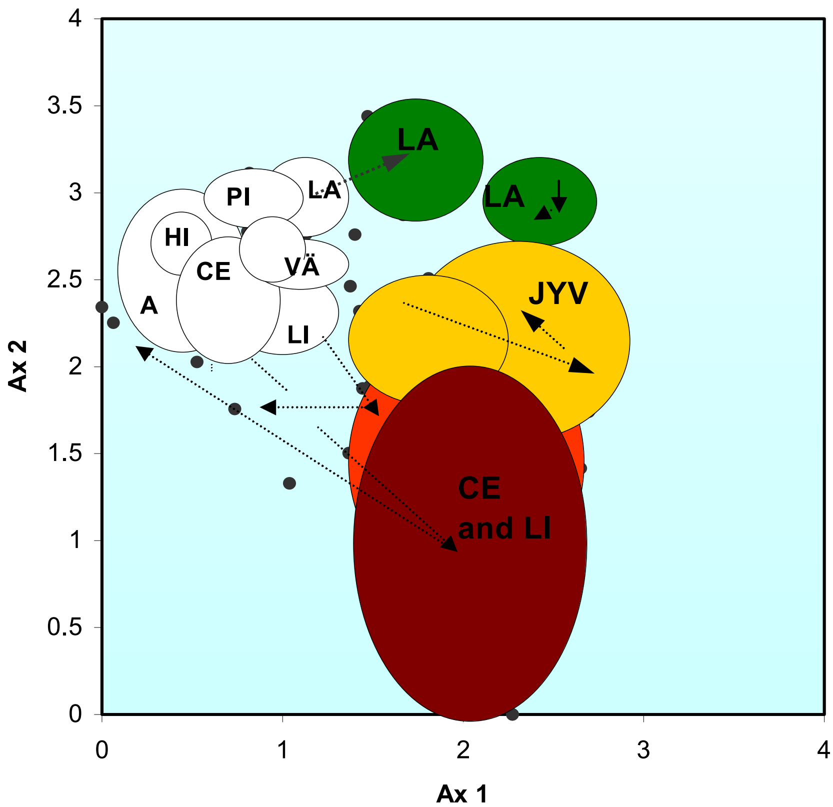

FIGURE 3 DCA ordination diagram for the paleolimnological samples of the studied lakes. A = Asikkalanselkä basin, HI = Hirvolanselkä basin (data from Sandman et al. 2000), PI = Pihlajavedenselkä basin (data from Sandman et al. 2000), LA = Lake Lappajärvi (green clusters), VÄ = Vähä-Äniö Bay, CE = Central-Päijänne (brown cluster), LI = Lake Lievestuoreenjärvi (red cluster), JYV = Lake Jyväsjärvi (yellow clusters). Axis 1 represents a loading gradient and axis 2 a pollution gradient. All the lakes, except Jyväsjärvi and the southern basin of Lappajärvi, revealed highly similar pristine benthic communities (white clusters). Central Päijänne and Lake Lievestuoreenjärvi were polluted, but recovered later (bidirectional arrows). Lake Jyväsjärvi has slightly recovered, but Lake Lappajärvi not at all.

5 DISCUSSION

5.1 Pre-industrial stage – only slight changes in lake ecosystems

Finland is a land of lakes, the total number being ca. 188 000. Although the country is relatively sparsely populated, the population has in many places concentrated on riverbanks or lakeshores so that many lakes have already been exposed to anthropogenic impacts for a long time. Anthropogenic trophic signals have thus also been present in the sediment geochemical properties of lakes in Finland for a long time, and in Lake Päijänne, for example, since the Iron Age (Itkonen et al. 1999). Studies in Scandinavia have revealed sedimentary evidence of early eutrophication and heavy metal pollution as well as atmospheric pollution on acid-sensitive lakes since Medieval times (Renberg et al. 2001, Bindler et al. 2002). In general, however, these changes have become distinct during the last 200 years. The first clear signs of human impact on lakes – small scaled clearings or burned-over clearings of land – were minor and biologically almost undetectable.

In many lake sediments the first distinct signs of increasing human impact are the peaks of inorganic matter derived from shore erosion following the artificial lowering of lake levels, which was carried out to prevent flooding and to create more land for cultivation (III, IV, Itkonen et al. 1999). These water level changes did not seriously affect the ecosystems of large lakes, although they increased the availability of nutrients for production, for example in Lake Päijänne (carried out in 1832-1838), for around 100 years (Itkonen et al. 1999). In smaller lakes such as Lake Lappajärvi (carried out in 1834 and 1905-1908), the water level lowerings are thought to have decreased the resistance of the lake to loading by reducing the hypolimnion volume by at least 200 million cubic metres, and thus decreasing the hypolimnetic oxygen supply (III). In contrast to large lakes, the artificial lowering of the water level of shallow and small-sized lakes may disturb and weaken the nutrient balance so badly that this event can be considered as a distinct impetus behind the later eutrophication process of a lake. This is, for example, the case in Lake Enäjärvi, south western Finland, which was lowered in 1928 (Salonen et al. 1993).

The first small paper and sulphite mills were established in the late 1800s and early 1900s on the shores of large watersheds of the southern and central parts of the country: Lake Päijänne, Lake Saimaa and Lake Vanajavesi. However, during the first decades of operation the production of these factories was so marginal that the ecological effects of loading in the recipients remained low, and are hardly detectable in pelagic and benthic assemblages (Kansanen 1985, Meriläinen & Hamina 1993, Simola et al. 1996, IV).

At the turn of 19th and 20th centuries the agricultural productivity in Finland was very low compared to the present situation due to poor tillage methods and a lack of artificial fertilizers. Diffuse loading entering lakes from non-point sources that time therefore evidently remained low. Lakes situated in the middle of rural areas, without any sources of industrial loading, revealed no distinct environmental disturbances in the late 1800s and early 1900s (III, VI).

Most of the Finnish towns or villages were small at the beginning of the 20th century, with only some hundreds or thousands of inhabitants. Sewage systems were constructed in many towns in the late 19th or early 20th century (Katko 2000), but wastewater treatment plants were only built in some bigger towns in the early 20th century. At that time the majority of towns directed their wastewater straight into adjacent watersheds. In Lake Jyväsjärvi a large number of wastewater elements began to increase in concentration in 1910, just after the sewage system of the town of Jyväskylä came into operation. This result can probably be generalized to many other lakes receiving municipal wastewater discharge from nearby towns; the same kind of stratigraphy of wastewater elements would be found in many of these recipients.

5.2 Eutrophication, pollution and airborne acidification of lakes

5.2.1 Effluent loading from the wood-processing industry

The period from the first decades of the 20th century up to the Second World War revealed a pronounced increase in the production volume of the wood processing industry, and first signs of eutrophication appeared in Lake Vanajavesi (Kansanen 1985), Central Päijänne (IV) and Lake Lievestuoreenjärvi (VI). In northern Päijänne these signs appeared somewhat later, around the beginning of the 1940s (Meriläinen & Hamina 1993), and in Lake Saimaa after the 1950s (Simola et al. 1996). Pulp mills, common throughout boreal regions, discharged effluents with high BOD, nutrients, resin acids and chlorinated compounds. In addition to northern Europe, many watersheds in Canada and USA were also exposed to pulp and paper mill effluent loading already in the first decades of the 20th century (Northern River Basin Study 1996).

In Lievestuoreenjärvi the pulp mill effluents already seriously disturbed the whole lake ecosystem during the early years of operation of the pulp mill, and the time lag between the establishment of the mill and collapse of pelagic and benthic assemblages was exceptionally short (Järnefelt 1932, VI). The observed sensitivity of organisms to highly toxic chlorine and organic chlorine compounds has also been detected in other studies (Fukushima & Kanada 1999, Suominen et al. 1999, Wei & Wang 2001, IV). Although the use of elemental chlorine in modern bleaching processes was banned in 1993, toxins and genotoxins from past discharges still persist in old sediment layers with a high content of bound organic chlorine compounds (Schindler 1998, Suominen et al. 1999), which may disturb the recovery process of pulp mill recipients. In Central Päijänne the effluent loading was not so considerable with respect to the hydrological and morphological features of the recipient, and marked changes in the lake ecosystem therefore occurred later than in L. Lievestuoreenjärvi.

After World War II a rapid increase in the volume of the wood-processing industry took place in Finland (Karessuo 1999), and the biological condition of all pulp mill recipients was worsened by the increasing pulp and paper production. As a consequence of increased loading the ecological status of Lievestuoreenjärvi and Central Päijänne quickly became bad and northern Päijänne eutrophicated in the course of the 1960s (Särkkä 1979, Meriläinen & Hamina 1993).

Our observations on acute and chronic community disturbance associated with effluent-induced strong acidity (VI, V) indicate distinct impacts on pelagic communities but less pronounced impacts on benthic ones, because chironomids are, as a group, highly acid-tolerant (e.g. Meriläinen & Hynynen 1990, Mousavi 2002, Olander 2002). However, the acidic effluents seriously disturbed the littoral benthic communities, so that a highly reduced snail and mussel fauna has been detected in all of the basins that formerly received acidic industrial effluents (Hynynen 1987). As stated by Tolonen et al. (2001) and Tolonen et al. (2003), the littoral benthic communities are highly important in the evaluation and monitoring of the ecological status of lakes, and they should also be monitored in these recipients when future assessment of the biological recovery of these lakes is carried out.

The deposition of many harmful toxic substances such as mercury, chlorine compounds and resin acids (IV, VI) and their biological derivatives, especially retene (Leppänen & Oikari 2001), still occurs in high concentrations in the sediments of these recipients. At least the collapse of the population of *Chaoborus flavicans* (Meigen) Lievestuoreenjärvi concurrently with increasing concentrations of resin acids (VI) indicated the inhibitive role of these substances during the worst phases of loading. This agrees with the results of Dubé & Culp (1997), according to whom chironomid growth was stimulated at low concentrations of treated bleached kraft pulp mill effluent (BKPME), but inhibited at higher concentrations, most probably due to the wood extracts.

The benthic communities of these recipients were exposed to direct toxic effects, but also to increased organic loading and a subsequent temporal hypolimnetic oxygen deficit during the early eutrophication and pollution processes. Later on, in the course of the severe pollution phase, the hypolimnetic anoxia was continuous, covering whole of the stagnation periods, especially in Lake Lievestuoreenjärvi, and no stationary life existed in the deep profundal of the lake. The observed shifts from oligotrophic communities dominated by sensitive species, *Heterotrissocladius subpilosus* (K.), *Micropsectra* spp. and *Paracladopelma nigritula* gr., towards eutrophic communities dominated by *Chironomus* species was typical of these basins during the early eutrophication process. Our results were consistent with the observations of Sibley et al. (2001), who in the study of nearshore benthic communities of Lake Superior, Canada, found that *Chironomus* tolerates pulp mill effluent loading well and was even found at the most impacted areas in the recipient. *Chironomus* larvae are well adapted to variations in their habitat due to their ability to survive for long periods without oxygen (Nagell & Landahl 1978). The larvae are inactive in the absence of oxygen, but grow and mature in the periods with better oxygen availability (Jonasson 1972). The changes in benthic communities reflecting alteration in the trophic status of a lake are well documented in the literature (e.g. Sæther 1979, Wiederholm 1980, Quinlan et al. 1998, Little et al. 2000, Quinlan & Smol 2002).

5.2.2 Municipal waste water discharge and diffuse loading

In contrast to Päijänne and Lievestuoreenjärvi, Lake Pihlajavesi and Lake Jyväsjärvi have received industrial effluents and a heavy load of municipal sewage waters and diffuse loading from non-point sources. Lake Lappajärvi has received treated effluent from the food processing industry, but a major part of the loading derives from forestry, agriculture and peat mining areas.

In Lake Pihlajavesi the observed changes in pelagic and benthic communities were very slight compared to other basins. The present indications of effluent load are restricted to the vicinity of the town of Savonlinna (II). At present most of the sub-basins in Lake Pihlajavesi reveal a biological state close to their natural character. These results agree with the observations of Sandman et al. (2000), according to which environmental changes have been small in this area during the past two centuries. However, in the 1960s and 1970s the biological state of Pihlajavedenselkä (Fig. 1) was affected to some extent by industrial and municipal effluent water, which could only be distinguished in sedimentary chironomid assemblages, while diatom community structure and stratigraphy indicated a near pristine state of the pelagic and littoral zones.

The study of urban Lake Jyväsjärvi revealed considerable, long-lasting ecological disturbance in the lake ecosystem associated with acidic industrial effluent loading, municipal waste water discharge, diffuse non-point nutrient and organic loading and internal nutrient loading from the sediment. The observed differences between lacustrine diatom and profundal chironomid assemblages in response to wastewater loading were considerable in this lake, although both assemblages reflect the environmental disturbance. The early changes, caused mainly by acid industrial effluent, could only be distinguished from the diatom assemblages (see also IV and VI). Later, from the 1950s up to the late 1980s, the municipal wastewater entering to lake exceeded the effects of acid effluents, which accelerated the eutrophication process of the lake.

Pronounced changes in profundal chironomid communities started about 80 years later than those in diatom communities, but subsequent changes in chironomid assemblages were greater than those in diatoms. Lake Jyväsjärvi is one of those small-sized lakes having a small profundal area and low hypolimnetic volume, which often results in hypolimnetic oxygen deficit even when the lake is in an undisturbed state (cf. Tolonen et al. 2003, VI). Under these circumstances the profundal benthic community structure has never been diverse, but indicated meso-eutrophic conditions before the exposure to extensive loading. Succession from a meso–eutrophic *Sergentia coracina* (Zett.)–*Chironomus thummi* gr. community to *C. thummi* gr.–*C. plumosus* L. community was detected in the course of the eutrophication. In the black decade, the 1970s, severe and permanent hypolimnetic anoxia led to the disappearance of the stationary profundal fauna. These observations of the succession of species associated with eutrophication agree with the results obtained from pulp mill recipients (Kansanen 1985, Meriläinen & Hamina 1993, IV, VI) and also those from lakes suffering from oxygen deficit and anoxia due to increased nutrient and organic loading from the catchment (Quinlan et al. 1998, Francis 2001, III).

The indication of increased erosion input into the lake was evidenced by increases in the sediment concentrations of certain lithophilous elements, for example aluminium, which is consistent with the observations of Eilers et al. (in press) from hypereutrophic Upper Kalamath Lake, Oregon, USA receiving increased erosional input from the catchment area.

The loading entering Lake Lappajärvi is at present almost entirely derived from non-point sources without the deposition of toxic substances. In addition to high organic enrichment, the estimated phosphorus loading entering the lake from the catchment area is at present very high, even 185 kg P d^{-1} (Malve et al. 1991). The observed dystrophication and eutrophication and increased input of eroded material accelerated after the 1950s and led to repeated hypolimnetic oxygen deficit and a subsequent shift to simple profundal benthic communities, dominated by *Chironomus* species (III).

The study carried out in 1999-2001 in Lappajärvi (Hynynen & Meriläinen 2003) revealed profundal benthic biomasses as high as ca. 30 g m^{-2}, which indicates strong organic enrichment in the profundal sediment. The benthic biomass was comprised mainly of *Chironomus* larvae and oligochaetes *Limnodrilus hoffmeisteri* Clap. and *Tubifex tubifex* (O.F. Müller). The study of small streams and rivers entering the lake (Hynynen 2003) revealed highly reduced stream invertebrate communities throughout the area. The factors explaining the ecological disturbance in stream invertebrate communities were the silting of river beds, a lack of water moss cover, acidity derived from peat mining areas and high concentrations of nutrients. Our observations indicate that large-scale problems currently exist in the lake itself and also in the catchment area. First of all, significant effort will be needed to decrease the external loading to the lake, which is the necessary to reduce the internal loading in the lake.

Multiproxy paleolimnological approaches, with the analyses of sediment chemistry and diatom and chironomid remains, provided a satisfactory description of the degree of ecological disturbance and timing of the environmental change in these lakes exposed to several types of loading. However, to obtain more accurate information on the eutrophication process, future development of diatom-based and chironomid-based training sets and transfer functions would be very useful for reconstructions of historical lake water total phosphorus concentrations and long-term hypolimnetic changes. The transfer functions for phosphorus reconstructions in eutrophicated boreal lakes have provided encouraging results (Kauppila et al. 2002, Kauppila & Valpola 2003), and chironomid-based functions for the assessment of hypolimnetic oxygen changes have been used successfully in studies on eutrophicated Ontario (Canada) shield lakes (Quinlan & Smol 2002). The measurement of stable isotopes of nitrogen, $\delta^{15}N$, is a promising and practicable method for the indication of long-term anthropogenic activities and system-level changes in watersheds, especially caused by human wastewater and extensive land use (e.g. Lake et al. 2001).

5.2.3 Acidification of small lakes

The first observations of increased sulphur deposition in Finland were made in the early 1970s by Haapala (1972), and the first acid episodes were detected in lakes in the 1970s (Kenttämies 1973, Haapala et al. 1975). Base cations exhibited a slight decline throughout the 1970s and 1980s, and without a corresponding decrease in sulphate this increased the acidifying potential of the deposition (Vuorenmaa 2004).

In the 1980s and 1990s, an effective sulphur emission control programme was launched, and in Europe the emissions of sulphur and nitrogen compounds declined by 34% (SO_2), 14% (NO_2) and 18% (NH_3), respectively, between 1988-1995 (Olendrzynski, 1997). In Finland, sulphate deposition has decreased 30% in northern and 60% in southern parts of the country since the late 1980s (Vuorenmaa 2004). N deposition has also decreased, but less than S deposition. Because of the changes in the quality of deposition the chemical recovery in acidified small forest lakes has been detected since the early 1990s (Mannio 2001, Vuorenmaa 2004). The SMART dynamic acidification model for 36 acid-sensitive Finnish headwater lakes (Posch et al. 2003) predicts that between 2010-2030 all lakes will reach a positive acid neutralization capacity (ANC), which is considered as a pre-requisite for the recovery of fish populations and acid-sensitive macroinvertebrates.

Thus far, observations have revealed only slight changes in the benthic communities of acidified lakes. That the recovery of acid-sensitive species (VII) was only slight was not surprising considering the large number of factors that may retard the recovery of invertebrates. The isolation of lakes from potential re-colonizing sources and the poor dispersal ability animals of such as snails and mussels may hinder the re-colonization of habitats (Power 1999, Keller et al. 1999, Yan et al. 2003). Regularly and frequently occurring acid peaks probably still exist in these lakes, especially in spring, and this may seriously disturb the benthic communities (Bradley & Ormerod 2001, Lepori et al. 2003). Demographic factors and problems of small populations (Yan et al. 2003) may also retard the recovery process. Although fish populations revealed marked recovery in these lakes (Tammi et al., in press), there is still considerable bias in the fish populations, which may induce the expansion of key insect predator populations such as

Odonata and Megaloptera, and thus prevent the recovery of benthic communities.

Finally, there are many questions and theoretical considerations (NIVA 2002) that must be addressed when we are trying to assess the benthic recovery in seriously disturbed lake ecosystems. Is acidification and recovery unique in each lake? Will biological recovery occur in irregular steps? Will the recovered state be the same as the pre-acidified condition? Will functionality be the only aspect that is restored? These questions remained unanswered in this study, which was carried out on a small subset of lakes.

The paleolimnological approach evidenced and supported the assumption that chironomids are tolerant of acidification (I, Wiederholm and Eriksson 1977, Mossberg and Nyberg 1979, Raddum and Saether 1981, Schnell 2001, Halvorsen et al. 2001, Olander 2002), and no major changes have occurred in the chironomid communities of acidic lakes during the past decades or centuries.

6 CONCLUSIONS

1 Sedimentary chironomid communities revealed a pristine or near pristine status up to the 1920s in lakes Lievestuoreenjärvi and Central Päijänne. In Lake Jyväsjärvi the chemical contamination of the sediment increased in the 1910s, but changes in benthic communities did not take place until the 1940s. In Lake Lappajärvi the eutrophication accelerated after ca. 1935, and in Lake Pihlajavesi slight and temporary eutrophication occurred in the 1970s to 1980s.

2 When the further goals of water protection activities are defined with a view to reaching a good ecological status in affected watercourses, the data from undisturbed benthic communities can be utilized in defining the reference status for these lakes.

3 Eutrophication and pollution accelerated after World War II, especially in lakes exposed to industrial effluent loading and municipal discharges. The diffuse loading and erosion from agriculture and forestry also highly increased after the war years.

4 In lakes exposed to industrial and municipal wastewater, the ecological disturbance reached its maximum in the 1960s-1970s, whereas ongoing eutrophication can still be detected in lakes suffering from diffuse loading.

5 Because of the increasing acid deposition, a large number of small, acid-sensitive headwater lakes in Central and South Finland acidified after the 1960s, and this resulted in highly reduced macroinvertebrate communities and disturbed lake ecosystems.

7 A pronounced recovery occurred in the 1980s and 1990s in lake ecosystems exposed to loading from point sources. In contrast, no such recovery was observed in lakes heavily impacted by diffuse loading. A slight recovery of benthic communities in acid-sensitive forest lakes has accompanied the chemical recovery of acidified lakes since the 1990s.

8 Pulp mill recipients that have shown a recovering trend are still threatened due to persistent, harmful substances in the sediment and the high oxygen demand of industrial sediments. Measurement of the percentage similarity of communities revealed great differences between undisturbed and present benthic communities, even in the recovered lakes. In acidified lakes that have chemically recovered, biological recovery is threatened by habitat limitations, demographic factors and existing obstacles for re-colonization. The recovering benthic communities may not necessarily revert to their original, pre-disturbance state, but may be characteristic for a region.

9 Paleolimnological multi-proxy studies are highly useful and recommended in the future Water Framework Directive classification of lakes. The littoral benthos has great value in detecting biological changes in acidified lakes.

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YHTEENVETO (Résumé in Finnish)

Ihmistoiminnan aiheuttamat kuormitusmuutokset suomalaisissa järvissä viimeksi kuluneiden 150 vuoden aikana tarkasteltuina pohjaeläinyhteisöjen avulla.

Olen väitöskirjassani tutkinut ihmistoiminnan aiheuttamia kuormitusmuutoksia ja niiden vaikutuksia järviemme biologiseen tilaan 150 vuoden aikana, noin 1800-luvun puolivälistä nykypäivään. Tutkimukseni perustui pääosin paleolimnologisiin tutkimusmetodeihin, joilla selvitettiin puunjalostusteollisuuden, yhdyskuntien jätevesien sekä hajakuormituksen vaikutuksia suurten järvien biologisen tilan kehitykseen. Tätä voidaan myös kutsua järvien ympäristöhistorian tutkimiseksi. Kohteina olivat Etelä- ja Keski-Päijänne, Lievestuoreenjärvi, Jyväsjärvi, Lappajärvi ja Saimaan Pihlajavesi. Pihlajavedellä tutkimus perustui sekä paleolimnologisiin näytteisiin että ranta-alueen ja syvänteiden pohjaeläimistön tutkimiseen. Paleolimnologisella tutkimuksella tarkoitetaan vesistöjen pohjasedimenttiin hautautuneiden eliöjäänteiden, kuten esimerkiksi surviaissääskijäänteiden, eliöiden yhteisömuutosten sekä sedimentin fysikaalisten ja kemiallisten ominaisuuksien selvittämistä sekä niiden perusteella tehtäviä johtopäätöksiä järvien kuormituksesta ja biologisen tilan muutoksesta.

Työn toinen keskeinen teema oli pienten, happamoitumiselle herkkien metsäjärvien happamoitumiskehityksen sekä 1990-luvulta alkaneen palautumisen tutkiminen rantojen pohjaeläinyhteisöjen avulla. Työ toteutettiin kahdessa vaiheessa. Ensimmäinen tutkimus tehtiin 1980-luvulla, etenevän happamoitumiskehityksen aikana, ja toinen vaihe ajoittui vuoteen 2001, jolloin happaman laskeuman vähenemisestä johtuva järvien kemiallinen palautuminen oli jatkunut Suomessa noin kymmenen vuoden ajan.

Ihmistoiminnan vaikutukset vesistöissämme olivat vähäisiä 1800-luvun alkupuolelle saakka, ja tutkitut vesistöt olivat käytännöllisesti katsoen luonnontilaisia 1800-luvulle saakka. 1800-luvulla ja 1900-luvun alussa ihmistoiminnan vaikutukset alkoivat näkyä vesistöissä yhä enenevissä määrin. Järviä laskettiin tulvasuojelun vuoksi ja viljelysmaan hankkimiseksi. Järvenlaskuista esimerkiksi Etelä-Päijänteen ja Lappajärven pohjasedimenttiin jäivät selkeät jäljet, lähinnä rantaeroosiosta aiheutuvasta epäorgaanisen aineksen huuhtoutumisesta johtuen. Samalla järviin huuhtoutui ravinteita levätuotannon käyttöön ja niiden alusveden tilavuus pieneni, mikä nopeutti esimerkiksi Lappajärven myöhempää syvänteen happitilanteen huononemista. Ensimmäiset puunjalostustehtaat Päijänteen rannoilla, Jyväsjärven valuma-alueella ja Lievestuoreenjärven rannalla aloittivat toimintansa. Myös kaupunkien viemäriverkostoja alettiin rakentaa ja jätevesiä johtaa vesistöihin, mikä näkyi esimerkiksi Jyväsjärvessä jätevesien sisältämien metallien ja muiden alkuaineiden rikastumisena pohjasedimenttiin 1900-luvun alusta alkaen. Järvien biologinen tila säilyi kuitenkin lähes muuttumattomana 1900-luvun alkupuolelle saakka.

1900-luvun ensimmäiset vuosikymmenet olivat puunjalostusteollisuuden tuotannon voimakkaan kasvun aikaa, ja jätevesien vaikutukset vesistöissä alkoivat

nopeasti näkyä biologisen tilan heikkenemisenä. Keski-Päijänteen ja Lievestuoreenjärven kunto heikkeni voimakkaasti 1930-luvulle tultaessa, ja myös Jyväsjärven kunto alkoi heiketä kasvavan teollisuuden jätevesikuormituksen sekä yhdyskuntajäteveden järveen johtamisen seurauksena. Lappajärven biologinen tila alkoi heiketä 1930-luvulla maa- ja metsätalouden hajakuormituksen sekä turvemaiden ojituksesta johtuvan kuormituksen seurauksena. Teollisuuden kuormittamien vesistöjen eliöstöön kohdistui myrkkyvaikutuksia mm. klooriyhdisteiden ja hartsihappojen päästöjen kasvaessa ja järvien happamuus lisääntyi puunjalostusteollisuuden jätevesistä johtuen. Yhdyskuntajätevesien vuoksi Jyväsjärven hygieeninen tila heikkeni ja orgaanisen aineksen kuormituksen kasvu vaikutti syvänteen happitilannetta huonontavasti sekä Lappajärvessä että Jyväsjärvessä.

Varsinainen vesistöjen pilaantuminen kiihtyi sotien jälkeen, 1950-luvulta alkaen. Teollisuustuotannon voimakas kasvu, tehomaa- ja –metsätalouden alkaminen, turvesoiden ojitus ja yhdyskuntajätevesien sisältämät myrkyt, kuten PCB, huononsivat nopeasti järvien biologista tilaa. Myös Saimaan alueella Pihlajaveden kunto alkoi tuolloin huonontua. Teollisuuden kuormittamat Keski-Päijänne ja Lievestuoreenjärvi sekä moniongelmainen Jyväsjärvi olivat tuolloin jo erittäin huonossa kunnossa. Kuormituksen vaikutukset näkyivät tuolloin myös Etelä-Päijänteen eliöstössä. Lappajärven tila heikkeni nopeasti massiivisen hajakuormituksen vuoksi. Jätevesien myrkkyvaikutukset ja pitkäkestoiset hapettomat jaksot järvisyvänteissä huononsivat dramaattisesti pohjasedimentin biologista kuntoa, ja 1970-luvulle tultaessa biodiversiteetti oli romahtanut Lievestuoreenjärvessä, Keski-Päijänteellä ja Jyväsjärvessä. Myös Pihlajavedellä kuormitus oli huipussaan 1970-luvulla, ja Lappajärven tilaa huononsi ratkaisevasti jatkuva ravinteiden ja eroosioaineksen hajakuormitus valuma-alueelta. Kaikissa tutkituissa vesistöissä järviekosysteemien tila oli huonoimmillaan 1970-luvulla ja 1980-luvun alussa.

Pienten, happamuudelle herkkien latvajärvien happamoituminen kiihtyi 1970-luvulla, ja Suomessa havaittiin tuolloin ensimmäiset selkeät merkit pienvesien happamoitumisesta. 1980-luvulle tultaessa monet etelä- ja keskisuomalaiset metsäjärvet olivat happaman laskeuman voimakkaasti pilaamia ja niiden eliöstö oli happamoitumisen seurauksena erittäin yksipuolinen. Monet normaaliin järvifaunaan tyypillisesti kuuluvat pohjaeläimet olivat kadonneet järvien eläimistöstä pitkäkestoisesta happamuudesta johtuen. Happamuudesta kärsivät eniten kalkkikuoriset kotilot ja simpukat sekä hyönteistoukista päivänkorennot. Tämän vuoksi näitä eläinryhmiä kutsutaan happamuuden indikaattoreiksi.

1980-luvun puolivälistä alkaen aktiiviset vesiensuojelutoimet, jätevesien tehokkaampi puhdistaminen, vanhentuneiden tehtaiden lopettaminen ja kansainväliset ilmansuojelusopimukset johtivat vesistöjen kemiallisen ja biologisen tilan palautumisen alkamiseen. Päijänteen, Lievestuoreenjärven, Pihlajaveden sekä monien happamoituneiden metsäjärvien veden laatu on parantunut, ja sen seurauksena myös järvien eliöstö on alkanut palautua. Palautumiskehityksestä huolimatta järvien pohjaeläinyhteisöt ovat laskettujen rakenneindeksien perusteella edelleenkin melko kaukana luonnontilaisista yhteisöistä. Moniongelmaisen Jyväsjärven palautuminen on ollut erittäin hidasta, ja hajakuormitetussa Lappajärvessä palautumista ei havaittu, vaan rehevöitymiskehitys on edelleenkin jatkunut.

Järvien palautumiskehityksen uhkana ovat metsäteollisuuden jätevesistä peräisin olevat toksiset yhdisteet, joita tutkittujen järvien sedimenteissä on runsaasti. Näiden ravinteikkaiden sedimenttien hapenkulutus on myös voimakasta, mikä häiritsee vielä pitkään pohjaeläinyhteisöjen palautumista. Happamuudesta toipuvien latvajärvien eläinyhteisöjen palautumista voivat häiritä eläinten leviämisesteet, habitaattien rajoitukset ja pieniin, palautuviin populaatioihin liittyvät demografiset ongelmat. Tutkimus osoitti, että vesistöjen biologinen palautuminen kuormituksen loputtua voi olla monimutkainen prosessi, ja tulokset antoivat viitteitä siitä, että palautumiskehitys ei välttämättä aina johda alkuperäisen, ennen kuormituksen alkua vallinneen biologisen tilan palautumiseen eikä alkuperäisiin eliöyhteisöihin.

Tutkimuksen tuloksia voidaan hyödyntää näiden kuormituksesta toipuvien vesistöjen alkuperäisen biologisen vertailutilan määrittämisessä sekä EU:n vesipuitedirektiivin tarkoittamassa vesistöjen tulevassa luokittelussa.

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