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LONG-TERM NUTRIENT LOAD MANAGEMENT AND LAKE RESTORATION: CASE OF SÄKYLÄN PYHÄJÄRVI (SW FINLAND)

by

Teija Kirkkala

TURUN YLIOPISTO
UNIVERSITY OF TURKU
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From the Department of Geography and Geology
Doctoral Programme in Biology, Geography and Geology
Faculty of Mathematics and Natural Sciences
University of Turku
Turku, Finland

Supervised by
Prof. Risto Kalliola
Department of Geography and Geology
University of Turku
Turku, Finland

Reviewed by
Research Prof. Brian Kronvang
Department of Bioscience
Aarhus University
Denmark

Prof. Ülo Mander
Department of Geography, Institute of Ecology and Earth Sciences
University of Tartu
Estonia

Examined by
Secretary General, PhD Sirpa Thessler
Finnish Partnership for Research on Natural Resources and the Environment (LYNET)
Finland

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You cannot step twice into the same rivers;
for fresh waters are ever flowing in upon you.

Herakleitos (John Burnet, 1908)

ABSTRACT

Eutrophication caused by anthropogenic nutrient pollution has become one of the most severe threats to water bodies. Nutrients enter water bodies from atmospheric precipitation, industrial and domestic wastewaters and surface runoff from agricultural and forest areas. As point pollution has been significantly reduced in developed countries in recent decades, agricultural non-point sources have been increasingly identified as the largest source of nutrient loading in water bodies. In this study, Lake Säkylän Pyhäjärvi and its catchment are studied as an example of a long-term, voluntary-based, co-operative model of lake and catchment management. Lake Pyhäjärvi is located in the centre of an intensive agricultural area in south-western Finland. More than 20 professional fishermen operate in the lake area, and the lake is used as a drinking water source and for various recreational activities. Lake Pyhäjärvi is a good example of a large and shallow lake that suffers from eutrophication and is subject to measures to improve this undesired state under changing conditions. Climate change is one of the most important challenges faced by Lake Pyhäjärvi and other water bodies.

The results show that climatic variation affects the amounts of runoff and nutrient loading and their timing during the year. The findings from the study area concerning warm winters and their influences on nutrient loading are in accordance with the IPCC scenarios of future climate change. In addition to nutrient reduction measures, the restoration of food chains (biomanipulation) is a key method in water quality management. The food-web structure in Lake Pyhäjärvi has, however, become disturbed due to mild winters, short ice cover and low fish catch. Ice cover that enables winter seining is extremely important to the water quality and ecosystem of Lake Pyhäjärvi, as the vendace stock is one of the key factors affecting the food web and the state of the lake. New methods for the reduction of nutrient loading and the treatment of runoff waters from agriculture, such as sand filters, were tested in field conditions. The results confirm that the filter technique is an applicable method for nutrient reduction, but further development is needed. The ability of sand filters to absorb nutrients can be improved with nutrient binding compounds, such as lime.

Long-term hydrological, chemical and biological research and monitoring data on Lake Pyhäjärvi and its catchment provide a basis for water protection measures and improve our understanding of the complicated physical, chemical and biological interactions between the terrestrial and aquatic realms. In addition to measurements carried out in field conditions, Lake Pyhäjärvi and its catchment were studied using various modelling methods. In the calibration and validation of models, long-term and wide-ranging time series data proved to be valuable. Collaboration between researchers, modellers and local water managers further improves the reliability and usefulness of models.

Lake Pyhäjärvi and its catchment can also be regarded as a good research laboratory from the point of view of the Baltic Sea. The main problem in both of them is eutrophication caused by excess nutrients, and nutrient loading has to be reduced – especially from agriculture. Mitigation measures are also similar in both cases.

Keywords: eutrophication, lake management, catchment management, phosphorus load, climate change

TIIVISTELMÄ

Ihmisen aiheuttamasta ravinnekuormituksesta johtuva rehevöityminen on yksi pahimmista vesistöjä uhkaavista ilmiöistä. Ravinteet kulkeutuvat vesiin ilmalaskeumana, teollisuuden ja yhdyskuntien jätevesissä sekä maatalous- ja metsäalueilta tulevissa valumavesissä. Kehittyneissä maissa pistekuormitus on merkittävästi vähentynyt viime vuosikymmeninä, ja hajakuormituksen, erityisesti maatalouden, on todettu olevan merkittävin vesistöjen ravinnekuormittaja. Tässä tutkimuksessa Säkylän Pyhäjärveä ja sen valuma-aluetta käytetään esimerkkinä pitkäjänteisestä, vapaaehtoisuuteen perustuvasta yhteistyömallista järven ja valuma-alueen vesien tilan parantamiseksi. Pyhäjärvi sijaitsee Lounais-Suomen intensiivisesti viljellyllä alueella. Järvellä toimii yli 20 ammattikalastajaa, sen vettä käytetään raakavetenä ja myös virkistyskäyttö on monipuolista ja intensiivistä. Pyhäjärvi on erinomainen esimerkki isosta, matalasta rehevöitymisen oireista kärsivästä järvestä, jonka tilaa pyritään määrätietoisesti parantamaan muuttuvissa olosuhteissa. Ilmastonmuutos on yksi suurimmista vesiensuojelun haasteista niin Pyhäjärvellä kuin muissakin vesistöissä.

Tulokset osoittavat, että ilmastollinen vaihtelu vaikuttaa valunnan ja ravinnekuormituksen määriin sekä niiden vuodenaikaisuuksiin. Havainnot tutkimusalueelta koskien lämpimien talvien vaikutusta ravinnekuormitukseen ovat linjassa IPCC:n ilmastonmuutosskenaarioiden kanssa. Paitsi ravinnekuormituksen vähentäminen, myös ravintoketjukunnostus (biomanipulaatio) on keskeinen keino veden laadun hallinnassa. Ravintoketjun rakenne on kuitenkin häiriintynyt leutojen talvien, lyhyen jääpeiteajan ja vähäisen kalansaaliin vuoksi. Talvinuottauksen mahdollistavalla jääpeitteellä ja sen pituudella on suuri merkitys Pyhäjärven veden laadun ja ekosysteemin kannalta, sillä muikkukanta on yksi ravintoketjua ja järven tilaa säätelevistä tekijöistä. Ravinnekuormituksen vähentämiseksi ja maatalouden valumavesien käsittelemiseksi kehitettyjä uusia menetelmiä, esimerkiksi hiekkasuodattimia, on testattu kenttäolosuhteissa. Suodatintekniikka osoittautui käyttökelpoiseksi menetelmäksi ravinteiden vähentämiseksi, mutta kehitystyötä on edelleen jatkettava. Hiekkasuodattimien ravinteiden poistoa voidaan tehostaa erilaisilla ravinteita sitovilla yhdisteillä, esimerkiksi kalkkipohjaisilla materiaaleilla.

Pyhäjärven ja sen valuma-alueen pitkäkestoiset hydrologiset, kemialliset ja biologiset seuranta- ja tutkimusaikasarjat ovat vesiensuojelun perusta ja niiden avulla lisätään ymmärrystä monimutkaisista järven ja valuma-alueen fysikaalisista, kemiallisista ja ekologisista vuorovaikutussuhteista. Kenttäolosuhteissa tehtyjen mittausten lisäksi Pyhäjärveä ja sen valuma-aluetta on tutkittu erilaisilla mallinnusmenetelmillä. Mallien kalibroinnissa ja validoinnissa pitkät ja monipuoliset aikasarjat osoittautuivat arvokkaiksi. Mallintajien, tutkijoiden ja käytännön vesiensuojelun toteuttajien yhteistyöllä voidaan edelleen parantaa mallien luotettavuutta ja hyödynnettävyyttä.

Pyhäjärveä valuma-alueineen voidaan tarkastella myös Itämeren kaltaisena luonnonlaboratoriona. Ylimääräisten ravinteiden aiheuttama rehevöityminen on molempien ongelma, ja ravinnekuormitusta on molemmissa tapauksissa vähennettävä - erityisesti maataloudesta. Vähentämismenetelmät ovat niin ikään samoja.

TABLE OF CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis consists of a summary and the following five articles, which are referred to by Roman numerals in the text:

I Ventelä, A.-M., Kirkkala, T., Lendasse, A., Tarvainen, M., Helminen, H. and J. Sarvala 2011. Climate-related challenges in long-term management of Säkylän Pyhäjärvi (SW Finland). *Hydrobiologia* 660: 49–58.

II Bärlund, I. and T. Kirkkala 2008. Examining a model and assessing its performance in describing nutrient and sediment transport dynamics in a catchment in southwestern Finland. *Boreal Environment Research* 13: 195–207.

III Kirkkala, T., Ventelä, A.-M. and M. Tarvainen 2012. Long-term field-scale experiment on using lime filters in an agricultural catchment. *Journal of Environmental Quality* 41: 410–419.

IV Kirkkala, T., Ventelä, A.-M. and M. Tarvainen 2012. Fosfilt filters in an agricultural catchment: a long-term field-scale experiment. *Agriculture and Food Science* 21: 237–246.

V Kirkkala, T. and A.-M. Ventelä. Pyhäjärvi restoration program – example of long-term voluntary based co-operation in lake management. Submitted to *Aquatic Ecosystem Health and Management.*

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1 INTRODUCTION

Eutrophication caused by anthropogenic nutrient pollution (phosphorus and nitrogen) has become one of the most severe threats to lakes, rivers, brackish waters and oceans globally. The problem is of particular concern for shallow lakes. If nutrient loading is excessive, the growth of phytoplankton is favoured and this has significant negative implications for the overall water quality and biodiversity of lakes: the water becomes turbid, toxic algae may develop, submerged macrophytes disappear, fish stock changes toward less desirable species and top-down control by zooplankton on phytoplankton disappears (e.g. Søndergaard et al. 2001). Eutrophication restricts the versatile use of aquatic resources and can even impact on human health and affect ecosystem services (Kernan et al. 2009, Munang et al. 2013).

Nutrients enter water bodies from atmospheric precipitation, industrial and domestic wastewaters and surface runoff from agricultural and forest areas. The importance of the catchment to lakes and rivers has been shown in many studies in the 1900s (e.g. Naumann 1919, Naumann 1929, Hynes 1975, Likens 1984). The nutrient loading rates of surface runoff from the catchment vary considerably depending on the characteristics of the catchment: geology, morphology, soil structure, vegetation, land use and human activities. As point pollution has in general been significantly reduced in developed countries, agricultural non-point sources have been increasingly identified as the largest source of phosphorus in water bodies (e.g. Kleinman et al. 2011, Kronvang et al. 2009).

Multi-faceted lake restoration projects have been initiated world-wide to circumvent this unwanted process and to achieve the desired good target state of lake ecosystems. Although some lakes respond rapidly to changes in external nutrient loading, lake recovery following a reduction of external loading is often delayed (Søndergaard et al. 2001, Gulati and van Donk 2002). In addition, global climate change may affect the recovery process negatively, but the potential effects are so far not well-known.

In temperate aquatic ecosystems, ecological factors and processes are related to climate and weather conditions. It is already widely known that climate change will affect the ecological interactions in lake ecosystems (Schindler 1997, Walther et al. 2002, Feuchtmayr et al. 2009). Climate variables impact both directly via biological effects and indirectly via hydrological and nutrient cycling. Increasing temperature has a direct effect on all water organisms; usually it induces increased growth rates (Wetzel 2001). The indirect impacts are caused by higher nutrient load, wind, mixing and stratification periods, length of ice-free and ice-cover periods, any of which may change the biological interactions in the lake (e.g. Blenckner et al. 2007, Kernan et al. 2009). Catchment processes are also strongly affected by variable weather conditions.

Increasing temperature and rainfall, together with decreasing soil frost in winter, usually increase nutrient leaching (Strahler 1974, IPCC 2007, BACC 2008).

Goal-directed water protection to combat these problems started in Finland in 1961 when the first water legislation came into force. Previously, wastewater from cities and industries were fed straight into water bodies without purification. During the 1960s and 1970s, wastewater treatment plants were built and the loading from wastewater diminished considerably. Extensive water quality monitoring programmes were also started by the national and regional water authorities during the same decades (Sarvala 1992). The Finnish Water legislation did not, however, consider the diffuse loads from agriculture, forestry and scattered settlement, which are nowadays considered highly important. The nutrient load from agriculture in particular has actually increased since the 1950s when the use of artificial fertilisers started (Granstedt 2000).

Climate change may have prominent effects on nutrient processes and transport on land and in streams. Nutrient loading from land to streams is expected to increase in northern temperate coastal regions which will boost eutrophication of lakes. Predicted changes in air temperature and rainfall will also affect river flows, and increased water temperatures will change the mobility and dilution of nutrients.

The European Union’s Common Agricultural Policy (CAP) has enforced a restructuring of agriculture in Europe. The Agri-Environmental Support Scheme was introduced in Finland in 1995 when Finland joined the European Union. The programme consists of basic and additional measures and special support contracts. More than 90% of Finnish farmers are committed to the basic measures of the agri-environmental subsidy scheme (Ministry of Agriculture and Forestry 2013). The important aim of the agri-environmental support in Finland is to reduce the nutrient loads that enter water bodies from farmland runoff.

The European Commission’s Water Framework Directive (WDF) adopted in 2000 establishes further objectives for water protection (European Commission 2012). The basic principle of the WFD is water management by river basin, which is the natural geographical and hydrological unit, instead of addressing water protection measures according to administrative or political boundaries. For each river basin district, a river basin management plan must be established and updated every six years. The key objectives of all activities include the general protection of the aquatic ecology, specific protection of any unique and valuable habitats, protection of drinking water resources and protection of bathing water. A general requirement for ecological protection and a general minimum chemical standard were introduced to cover all surface waters.

In this study, the catchment of Lake Säkylän Pyhäjärvi (SW Finland) is studied as an example of a long-term, voluntary-based, co-operation model of lake and catchment management from both organisational and functional points of view. The basis of this model was created in the 1970s and the Pyhäjärvi Restoration Programme has been in its current form since 1995. Lake Säkylän Pyhäjärvi is an interesting object for this study as it is located in the centre of an intensive agricultural area in southwest Finland. The lake has also been an important fishing site and drinking water source for the local people for centuries. Today the lake is also used for various recreational activities and for a commercial fishery as well as for some local industrial processes. For all these reasons Lake Pyhäjärvi is a good example of a large and shallow lake that suffers from eutrophication and is subject to measures to improve this undesired state.

Based on the circumstances described above, three study hypotheses can be formulated:

1. Climatic variation causes both direct and indirect effects on lake eutrophication. It is possible to identify the significance of climatic variation in relation to the timing and amount of nutrient loading and to the ecological status of the lake.
2. The management of nutrient loading and lake restoration requires a wide assortment of supporting tools, e.g. research based modelling. The existing tools and practices need to be developed further. New innovative nutrient reduction methods are also needed which require experimental research in the field.
3. Long-time series provide a strong basis for lake and catchment management.

The objectives of this work are (Figure 1):

1. To analyse and evaluate the organisational and operational models and procedures of the Lake Pyhäjärvi Restoration Programme in relation to the implementation of the WFD.
2. To identify the significance of climatic variation in relation to the amount and timing of nutrient loading entering the lake and to the ecological status of the lake.
3. To evaluate the efficiency of certain innovative nutrient reduction measures for the treatment of runoff waters and to recognise the need to improve them.
4. To improve our understanding of the necessity for and methods of monitoring the state of the lake and the catchment and the efficiency and the impact of water protection measures.
5. To improve our understanding of supporting tools, like research based modelling, for water management.

In Paper I the hypothesis that winter climate would affect the water quality of the lake in the following summer was introduced and tested. The wintertime variables tested were for instance phosphorus load, air temperature and precipitation, and chlorophyll a concentration was used to measure the water quality of the lake. The tests were based on the monitoring data from 1987–2008 from the lake and its catchment. A linear model was used and a validation procedure was performed to select the best variables. It was found that the restoration work is facing new challenges: a short or almost absent ice cover period and increased wintertime nutrient load from the catchment. The results indicate linkages between climate-related catchment processes and the ecological status of the lake.

A benchmarking protocol to facilitate the dialogue between the modeller and water manager (see Hutchins et al. 2006, Kämäri et al. 2006) was created within the project coordinated by the Finnish Environment Institute "Benchmarking models for the Water Framework Directive" (2002–2004), where the whole Eurajoki basin, including Lake Pyhäjärvi and its catchment, was chosen as the Finnish test catchment. **Paper II** presents the testing of the benchmarking protocol by the modeller and the water manager during the model selection. The modeller and water manager examined the SWAT model and its suitability to describe water, sediment and nutrient transport dynamics in the Yläneenjoki catchment entering Lake Pyhäjärvi. The experiences of the dialogue between the modeller and manager were also documented.

Paper III represents the first of a series of innovative nutrient reduction measures tested in the Pyhäjärvi catchment. The structure and the nutrient removal performance of three on-site lime–sand filters established within or on the edge of the buffer zones are reported. The filters contain burnt lime (CaO) or spent lime [CaO, $Ca(OH)_2$, and $CaCO_3$] mixed with sand. The readily soluble lime produces a high pH level (>11) and leads to an efficient precipitation of soluble phosphorus (P) from the runoff. These kinds of filter and chemical amendments were previously familiar primarily from waste water treatment.

In Paper IV, the long-term nutrient removal performance of two on-site sand filters enhanced with a layer of phosphorus binding material Fosfilt-s, are reported. The aim was to test recycled amendment in filters. Fosfilt-s is a side product of the titanium dioxide production plant situated in the study region. Fosfilt-s contains SiO_2, Fe, Al, Ti, Ca and C. Another filter was located in a brook beneath the wetland and treated the runoff waters from one sub-catchment entering the river Yläneenjoki. Another filter treated runoff waters from subsurface drainage entering the river Pyhäjoki in the Pyhäjärvi catchment.

Paper V presents stages of the practical development of the Pyhäjärvi Restoration Programme and Pyhäjärvi Protection Fund. These activities were started in 1995 by local municipalities, private industries and local associations acting in collaboration with the regional environmental and agricultural authorities. The paper addresses in particular the establishment and activities of the extensive, voluntary-based, long-term co-operation arrangements in lake management, which have enabled intensive restoration activities with a variety of measures to inhibit the eutrophication progress. The objective of this paper is to document the history and progress of the Pyhäjärvi Restoration Programme whilst the actual research concerning nutrient loading, nutrient reduction measures and the status of the lake are presented in papers I–IV and in numerous other scientific publications.

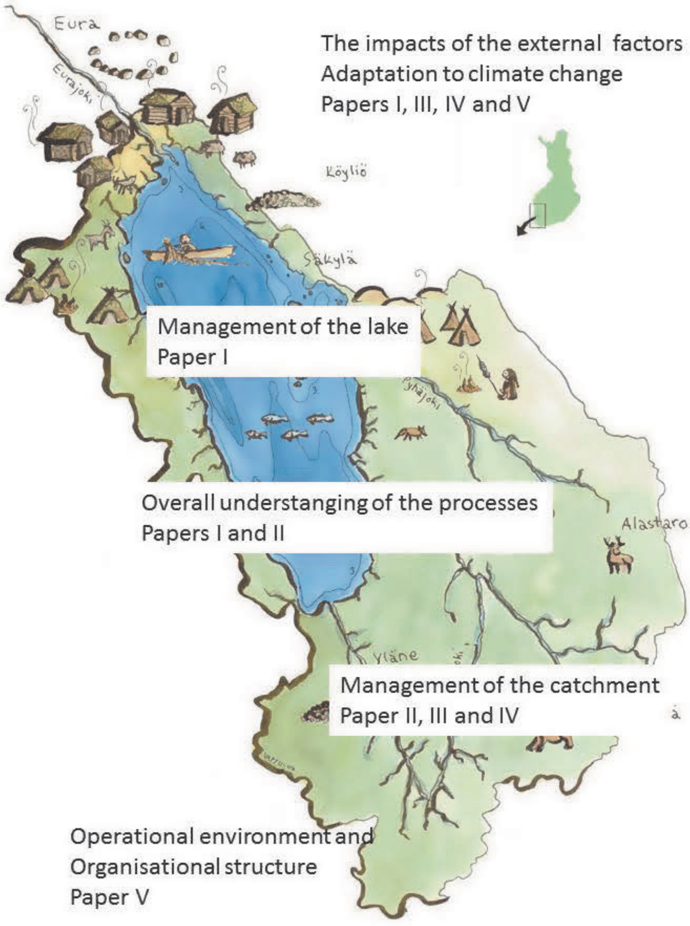

Figure 1. Schematic picture of the content and the relations between the articles of this thesis.

2 THEORETICAL BACKROUND

2.1. Eutrophication

Lakes are traditionally distinguished as eutrophic or oligotrophic according to the levels of their primary production. The words oligotrophy and eutrophy were introduced in the early 1900s by Naumann (1919) and the original definition was based on phytoplankton. Phytoplankton was scarce in oligotrophic waters and rich in eutrophic waters. Lakes can also be classified using a finer-scale trophic state distinction as follows: oligo-, meso-, eu- and hypereutrophic (e.g. Nürnberg 1996). Many different physical, chemical and biological factors influence the trophic state. The availability of nutrients, particularly phosphorus (P) and nitrogen (N), are the most important chemical factors accelerating productivity.

Eutrophication refers to the process when the biological production of water body is increasing and the water body becomes more eutrophic. According to Liebig's law (Odum 1971), plant growth depends primarily on the scarcest nutrient or other resource (e.g. light, water). In terrestrial systems, phosphorus and nitrogen are usually the most critical nutrients that often limit plant growth and they influence the growth of algae and macrophytes in water bodies as well (e.g. Schindler 1974, Vollenweider 1968, Hecky and Kilham 1988). Schindler (1974) pointed out the importance of phosphorus in lakes in comparison to nitrogen and carbon (C). Vollenweider (1968) also showed that the levels of phosphorus, and to some extent nitrogen as well, are linked to accelerating eutrophication. Later studies have shown that phosphorus limitation of algal production in lakes is in general more obvious than nitrogen limitation (Schindler 1997, Hecky et al. 1993) and that phytoplankton respond mainly to changes in phosphorus concentrations (e. g. Jeppesen et al. 2005). Nitrogen has been suggested as being the main limiting factor e.g. in the Chinese Lake Taihu (Xu et al. 2010). Moss et al. (2013) suggest that co-limitation by nitrogen and phosphorus can also be usual. The most generally used estimate of the nitrogen-phosphorus ratio of algal cells is 7 (Redfield et al. 1963). If the nitrogen-phosphorus ratio is over 7, phosphorus is considered as the main limiting factor, and if under 7, nitrogen is the limiting factor. According to Hecky and others (1993) the ratio in particulate matter of freshwaters is higher and more volatile than Redfield's ratio which is based on sea data. In the case of Lake Pyhäjärvi, studies of the total nutrient ratio indicate phosphorus limitation (e.g. Ekholm et al 1997). Phosphorus has been recognised to be a primary or contributing nutrient in some coastal areas also (e.g. Howarth and Paerl 2008) such as the Baltic Sea (Granéli et al. 1990, Andersson et al. 1996, Kirkkala et al. 1998, Tamminen and Andersen 2007).

Eutrophication causes degradation of water quality such as an increase in turbidity and phytoplankton biomass. The consequences may result in losses of the ecosystem services that the water resources provide. The universal effects according to Smith (1998) and Smith et al. (1999) on lakes are:

- Increased water turbidity
- Increased biomass of phytoplankton and periphyton
- Shifts in phytoplankton species composition to taxa that may be toxic or inedible, e.g. cyanobacteria
- Elevated pH and dissolved oxygen depletion in the water column
- Changes in vascular plant production, biomass and species composition
- Decreases in aesthetic value of the water body
- Taste, odour, and water supply filtration problems
- Shifts in fish species composition towards less desirable species
- Increased fish production and harvest
- Increased probability of fish kills
- Possible health risks

The blue-green algal blooms are among the most serious and annoying consequences of eutrophication because they can be toxic and prevent many water uses. Toxin producing cyanobacteria, such as *Anabaena*, *Microcystis*, and *Planktothrix (Oscillatoria*), favour nutrient-rich freshwater systems. They survive in low nitrogen-to-phosphorus ratios, low light levels, reduced mixing, and high temperatures (Downing et al. 2001, Paerl and Huisman 2009, Paerl and Paul 2012).

Eutrophication usually results in changes in the aquatic community. The biodiversity of aquatic flora and fauna tends to regress. Jeppesen et al. (2000) observed in Danish lakes a significant decline in the species richness of zooplankton and submerged macrophytes with increasing phosphorus content, while for fish, phytoplankton and floating-leaf water plants, species richness was unimodally related to total phosphorus. The biomass of planktivorous fish (e.g. bream) is often positively correlated to nutrient levels and trophic state, but piscivorous fishes (e.g. pike) seem to dominate in more oligotrophic lakes (Jeppesen et al. 1997).

Bottom sediments may play an important role in the overall nutrient dynamics of shallow lakes (e.g. Nürnberg 1984, Rydin 2000, Ludwig et al. 2003). The internal recycling of nutrients within a lake may be so efficient that it maintains the eutrophied state even if nutrient loading is terminated. Internal P loading may develop from a pool of accumulated phosphorus in the sediments. Significant amounts of phosphorus in sediments may be bound to redox-sensitive iron compounds or fixed in more or less labile organic forms, which are potentially mobile and may eventually be released into the lake water (Søndergaard et al. 2001, Søndergaard et al. 2003). The management of these types of internal nutrient loads is even more difficult than the management of the extensive nutrient loads.

The trophic state is analysed using different quantitative parameters, for example nutrient concentrations, chlorophyll a concentrations, phytoplankton and zooplankton species and biomass, water transparency and oxygen conditions.

Management of eutrophication, in turn, requires the reduction of excessive flows of anthropogenic nutrients. In Finland, point-source pollution has been significantly reduced since the 1970s when numerous treatment plants for industrial and municipal waste waters were built. However, nutrient reduction is usually difficult and expensive to control in agricultural areas where the nutrients come from nonpoint sources. Furthermore, even though external loading of nutrients may be reduced, internal loading of nutrients from sediments may still prevent improvements in water quality (Søndergaard et al. 2003).

Many studies show that predatory top-down forces can have important implications for aquatic communities and ecosystems (e. g. Helminen and Sarvala 1997, Horppila et al. 1998). Therefore biomanipulation, the alteration of a food web to restore ecosystem health, is used to improve water quality in eutrophic lakes (Shapiro et al. 1975). The basic idea is that secondary consumers (planktivorous fishes) are removed either through the addition of tertiary consumers (piscivorous fishes) or harvesting, which allows for the dominance of large-bodied zooplankton, generalist grazers (e.g., *Daphnia*) to control phytoplankton. When planktivorous fish are abundant and they graze large-bodied zooplankton efficiently, less efficient small-bodied zooplankton grazers (e.g., rotifers and herbivorous copepods) typically dominate zooplankton communities, thus allowing for the overgrowth of phytoplankton (Perrow et al. 1997, Jeppesen et al. 2005).

Major advances in the scientific understanding and management of eutrophication have been made since the late 1960s. The diminished levels of point source phosphorus have reduced eutrophication and improved water quality in many lakes (e.g. Edmondson 1994, de Bernardi et al. 1996, Keto 1982, Smith et al. 1999). It has also proved possible to control diffuse nutrient sources relating to land use changes and urbanisation in the catchments of lakes to some extent, but this requires many years of restoration efforts. The overall understanding of eutrophication and its management have therefore evolved from the simple control of point sources to the recognition that further progress must rely on simultaneous protection and restoration of many different features both in the lake and its catchment.

2.2 Agricultural nutrient load

As shown above, the rate of phosphorus load on a lake is usually critical from the eutrophication viewpoint. For this reason water protection programmes in Finland are mainly based on the reduction of phosphorus load. The portion of agriculture is circa 50 % of the total anthropogenic phosphorus load and 60 % of the total nitrogen load. The agricultural nutrient load is particularly intensive in western and southern Finland (Nyroos et al. 2006) where abundant agricultural production occurs on erosion sensitive clayey soils. Agricultural areas are also the main sources of phosphorus entering into Lake Pyhäjärvi (Ekholm et al. 1997, Conzales-Inca et al. 2012). The Pyhäjärvi Restoration Programme thus mainly aims to reduce its levels.

According to Vollenweider (1968), the diffuse load can be distinguished into two kinds of sources:

1. Natural sources such as erosion from virgin lands.
2. Artificial and semi-artificial sources related to human activities such as fertilisers, erosion from agricultural and urban areas, and wastes and manure from animal husbandry.

Phosphorus from fertilisers and animal manure accumulates in agricultural surface soils. Regular application of fertilisers and manure in excess of crop requirements during the last six decades has led to increased soil phosphorus levels and increased runoff from agricultural soils in many agricultural areas (Granstedt 2000, Kleinman et al. 2011).

Phosphorus leaches from fields by surface erosion and runoff or via subsurface runoff. Surface runoff picks up particles of organic and mineral matter ranging in size from fine clay to coarse sand or gravel, depending on the speed of the flow, and the degree to which soil particles are bound by plant roots (Strahler 1974). Since cultivated soil is periodically exposed, rain can also seal the soil pores. Nowadays the use of heavy machinery in cultivation also results in soil compaction and reduced water infiltration which permits a much greater proportion of overland flow which picks up particles of surface soil. The steeper the slope the faster the flow and the more intense the erosion. Water transports the particles for a variable distance from the source (Strahler 1974).

The contact between the soil and dilute water induces desorption of phosphorus of soil particles which increase the content of labile phosphorus in the diluting water (e.g. Ryden 1973, Schreiber and Dowell 1985). In natural circumstances the mobilisation of phosphorus from the soil is slow, but human activities have accelerated it. In temperate areas, soil chemical processes regulate nitrogen dynamics, while phosphorus losses are mainly dependent on overland flow ways and barriers (Pärn et al. 2012). However, surface runoff is a major transport mechanism in clayey soils in southern Finland and most phosphorus in agricultural rivers consists of phosphorus bounded to eroded soil particles (e.g. Ekholm and Kallio 1996). River channel processes can also cause bank erosion. Kronvang et al. (2013) found that bank erosion was the dominant sediment source (90–94 %) in the Danish River Odense catchment during the three study years.

Nitrogen also often contributes to eutrophication. Although its significance may not be critical in many Finnish lakes, it has a profound impact in the Baltic Sea (e.g. Tamminen and Andersen 2007). The main sources of nitrogen in water bodies are atmospheric precipitation, nitrogen fixation and input from runoff. The loss of nitrogen from the soil is a result of a number of processes, all more or less controlled by physical environmental factors, such as soil humidity, soil temperature and water movement, but also by management factors, such as farming practices, fertilisation, crop rotation and cultivation. Due to this complexity and to variable weather conditions, the magnitude of leaching and its temporal distribution usually vary greatly both within and between years (Bergström et al. 1987, Johnsson and Hoffmann 1998).

Nitrogen mineralisation is a complicated process. It is defined as the transformation of nitrogen from organic into inorganic forms. Much of our knowledge derives from laboratory experiments only, and much less from field experiments, especially concerning cold (autumn, winter, and early spring) conditions. Climatic and soil conditions, type of production and tillage management influence the mineralisation conditions. Soil disturbance through cultivation also increases the rate of mineralisation (Gustafson 2012).The composition and structure of soil is of great importance, because soils including large amounts of organic material will, in the long-term, have a greater capacity for net mineralisation (Gustafson 1987, Bergström et al. 1987, Gustafson 2012). Only a part of available nitrogen is removed with the harvest and thus the losses might be high due to mineralisation of crop residues and easily decomposable organic material in the soil, especially during the autumn period. Some of the nitrogen in the surface layer is lost through denitrification, when the temperature is high enough.

The nitrate ion is the most sensitive form of nitrogen to leach out from the soil in appreciable amounts by water passing through the soil profile, because there is no significant adsorption of nitrate onto soil surfaces (Gustafson 1987, Bergström et al. 1987). Nitrates are carried downwards by rainfall or irrigation water and can be carried into groundwater and the subsurface drainage system. The water content of the soil affects the downward movement rate of nitrates.

Managing agricultural nutrient loads is a complicated issue, which requires a large variety of site-specific management practices. The most sustainable way is primarily to prevent the formation of the load (e.g. reduce the use of fertilisers), and secondarily to catch the nutrients close to the source because it is very difficult and expensive to remove nutrients from larger amounts of water. Research and development of best practices has been carried out since the 1990s, but new measures are still needed. Despite a significant reduction in the use of phosphorus fertilisers, reducing phosphorus loss from agricultural lands may still take decades.

Nutrient reduction measures are also needed in subsurface drainage, in ditches and brooks, and in rivers, to hinder accelerating eutrophication. Sedimentation ponds, wetlands, buffer zones, filters, chemical treatment and other measures are widely developed, implemented, and researched (e.g. Uusi-Kämppä et al. 2000, Jeppesen et al. 2007, Mander and Mitsch 2009, Falk Øgaard 2010, Kjaergaard 2010, Vohla et al. 2011, Qin 2013, Uusitalo et al. 2013). The possibility of a changing climate brings further challenges to nutrient reduction and water protection. Recent climatic variation has already affected the timing of the annual external nutrient load in south-western Finland and the need for new load reduction solutions has arisen.

2.3 Climate change

In recent decades, anthropogenic global climate change has become a serious concern. IPCC (the Intergovernmental Panel on Climate Change) defines climate change as any change in climate over time whether due to natural variability or as a result of human activity. Recent anthropogenic climate change is mainly related to elevated greenhouse gas concentrations and to increasing air temperatures (IPCC 2007). The detection and interpretation of systematic changes is difficult, because weather conditions are variable.

Climate change scenarios have been used as a tool in climate research. IPCC (2007) published emission scenarios as "Special Report on Emissions Scenarios" based on greenhouse gas and aerosol emissions and on changing land use. The scenarios are:

- A1. Rapid economic growth and rapid introduction of new and more efficient technology.
- A2. Heterogeneous economic and technological development, emphasis on family values and local traditions.
- B1. Environmental sustainability, clean technology.
- B2. Emphasis on local solutions to economic and ecological sustainability.

It has already been observed that the mean temperatures have increased (e.g. Tuomenvirta 2004), that the permanent snow and ice cover has melted in large regions and that the surface levels of the oceans have risen. There are also changes in the amounts and timing of rains and winds. An important aspect in adaptation to climate change is to cope with extreme weather conditions, such as heavy rains and thunderstorms, which have become increasingly common (IPCC 2007). The likelihood of record-breaking amounts of precipitation has also increased in Finland (Jylhä et al. 2009).

Generally, the northern hemisphere is predicted to become warmer; winters will get wetter and summers drier (IPCC 2007, BACC 2008). These trends correlate partly with the North Atlantic Ocean Index (NAO) within the region of the Baltic Sea and its catchment (BACC 2008). The NAO-index is comparable with the strength of westerly winds in Northern Atlantic Ocean and describes annual weather variation around the Northern Atlantic Ocean. The positive NAO-index means more rain and mild winters with less or no snow in Northern Europe. Correlations between climate-induced factors of water bodies and the NAO-index can be used in evaluating/forecasting the effects of climate change (e. g. Hänninen et al. 2000). Dippner et al. (2012) suggest that the new multivariate Baltic Sea Environmental BSE index shows better performance than any other climate index. It is defined on the basis of the Arctic Oscillation index, salinity between 120 and 200 m in the Gotland Sea, the integrated river runoff of all rivers draining into the Baltic Sea, and the relative vorticity of geostrophic wind over the Baltic Sea area.

According to scenario-based forecasts, temperatures will increase during every season but most dramatically in winter (IPCC 2007). The forecasts also suggest that the consequences are most significant in the regions with a mean winter temperature warmer than -5 degrees Celsius (Jylhä et al. 2009), such as western Finland including the Satakunta region where this study was conducted. The thickness and durability of the snow cover is expected to decrease but the wintertime total rainfall will increase. The intensity of rains will also increase and rainstorms will become more common.

It can be expected that the symptoms of eutrophication will intensify through such climatic changes (Jeppesen et al. 2010, Moss et al. 2013). Changing rainfall patterns and warming soils will increase erosion and nutrient leaching especially during wintertime (Jeppesen et al. 2011) when the vegetation cover may be missing. Higher water temperatures also affect chemical and biological processes. Due to higher nutrient loads and altered chemistry and ecology, eutrophication may accelerate. Both climate change and eutrophication should therefore be seen as the largest threats to lake ecosystems during this century (Elliott et al. 2010).

On the other hand, water bodies could also be used for climate change regulation. Mander et al. (2013) analysed about 150 publications to estimate the roles of free water surfaces and constructed wetlands or riverine wetlands in climate regulation. They found that a pulsing water regime and support for macrophyte growth would help to minimise both methane and nitrous-oxide emissions.

3 MATERIAL AND METHODS

3.1 Study area

Lake Säkylän Pyhäjärvi is located in the boreal temperate zone (cool climate type) in south-western Finland (Fig. 2). It was separated from the Litorina Sea 5 600 BP due to land uplift (Eronen et al. 1982). The bottom of the lake was ground flat due to the movement and weight of the continental glacier. The lake's development is transgressive: land uplift is proceeding faster in the northern part of the lake than in southern part. Therefore the lake is sloping southwards and flooded peat areas are found on its bottom at the south-eastern end (Tikkanen 2002).

Lake Pyhäjärvi's water area is 155.2 km^2 and the catchment area (including the lake) is 615 km^2. The mean depth of the lake is 5.4 m and the deepest point is 26 m. The water level was lowered almost two meters in 1852 and the lake has been regulated since the 1930s. It was decreed that the highest level is N_{43} +45.12 and the lowest N_{43} +44.54 (Kuusisto 1975). The main rivers entering the lake are River Yläneenjoki (catchment area 234.0 km^2) from the south and River Pyhäjoki (catchment area 77.5 km^2) from the east. Together, these two rivers cover 68 % of the total catchment area. The dominant land cover in the catchment area (22%) is made by cultivated fields, the rest comprising forests, peat lands and built-up areas. The outflow of the lake is at the northern end where the River Eurajoki starts and flows to the Bothnian Sea.

Pyhäjärvi is located on the Satakunta sandstone formation. In the eastern part of the lake, Svekofennidic metamorphic gneiss and Precambrian igneous rocks are found and the western rocky shore is dominated by Finnish Rapakivi granite. The diabase dyke goes through sandstone and Rapakivi granite areas in the northern and western part of the lake (Fig. 3). The lake is some 45 metres above sea level, and the main part of the catchment is 50–100 metres above sea level (Kuusisto 1975).

The soils of the Pyhäjärvi catchment are clay, silt, till and peat (Fig. 4). The soils in the Yläneenjoki river valley and catchment are mainly clay, silt and till. The soils in the Pyhäjoki river valley and catchment differ from Yläneenjoki being mainly fine sand, sand and till. The land use in the whole catchment is distributed between agriculture (22% of the area), forest (50%) and peat land (20%).

Figure 2. Lake Pyhäjärvi and its catchment

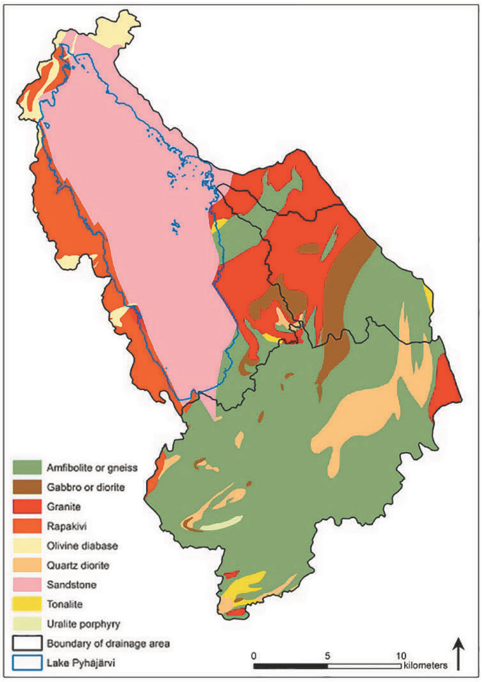

Figure 3. The bedrock of the Lake Pyhäjärvi catchment (source: GTK, Finland).

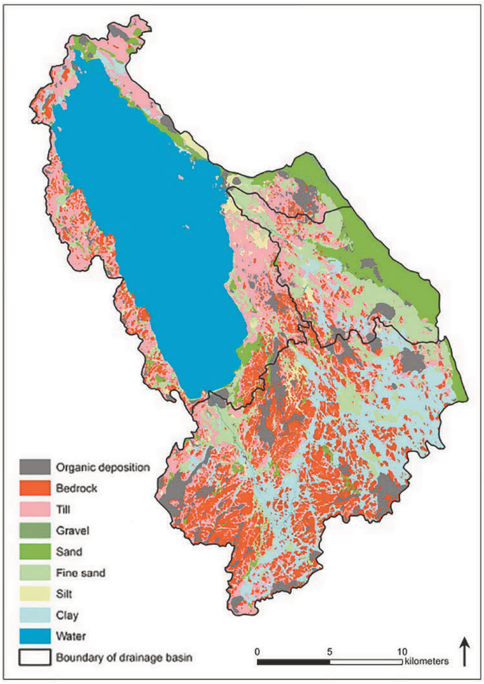

Figure 4. The soils of the Lake Pyhäjärvi catchment (source: GTK, Finland).

The annual mean temperature in the study area was +4.8ºC during the period 1970–2000 (Paper I). The wintertime mean air temperature in the area is -2.1ºC and the lake is ice covered for 140 days on average. Long-term (1959–2009) average annual precipitation in this area is 590 mm. The long-term (1979–2008) average monthly temperature for the period October–March is -2.0ºC, varying between -5.4 and +1.9ºC. The warmest month is generally July, when the average temperature is 16.5ºC (1980–2009). The catchment is normally covered by snow in winter. The average annual temperatures and precipitation during 2001–2012 are presented in Fig. 5.

Field cultivation and animal husbandry comprise 55% and 39% of the external phosphorus and nitrogen inputs to Lake Pyhäjärvi, respectively (Paper II). Of the lake's phosphorus load, 54% originates from the river Yläneenjoki catchment, 10% from the air, 24% from smaller ditches, and 12% from the river Pyhäjoki (Ventelä et al. 2007). The phosphorus load from agriculture is accentuated in areas with clay soils and sloping fields. In such cases, most of the phosphorus is transported in surface runoff due to the low infiltration capacity of the soil. Phosphorus is mainly removed by eroded soil; slopes in excess of 2 to 3 degrees are vulnerable to erosion. Some 20 to 30% of the phosphorus load is in soluble form, called algal-available phosphorus (Ekholm 1998, Ekholm et al. 1997). Since the catchment area is relatively small compared to the lake's surface area, atmospheric deposition also accounts for a large portion of nutrient input: some 10% for phosphorus and 33% of nitrogen (Ventelä et al. 2007).

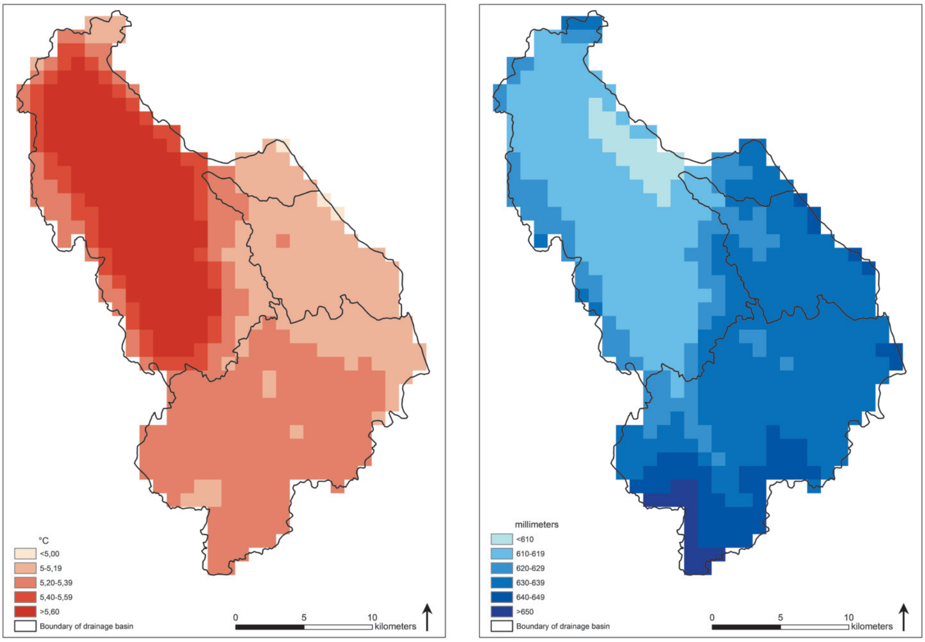

Figure 5. Average temperatures and precipitation (source: FMI).

3.2 Methods

3.2.1 Sampling and analysis

In this study (Papers I, II, III and IV), investigation of the state and nutrient loading of the lake, the efficiency and effects of water protection measures and the factors that affect them are based on extensive physical, chemical and biological data. These data have been collected partly during different research and development projects where the author of this thesis has coordinated or taken an active part, and partly through national and regional programmes of environmental monitoring.

The water chemistry and hydrology of Lake Pyhäjärvi and rivers Yläneenjoki and Pyhäjoki have been monitored since the 1960s as part of a national monitoring programme by water and environmental authorities (Paper I). Since 1971 hydrological monitoring has been more intensive, including the use of automatic meters to continuously measure river flows (Ekholm et al. 1997). The monitoring of water quality has been more intensive since 1980, first as part of statutory monitoring

(Sarvala & Jumppanen 1988) and then by regional authorities. Water samples from the lake for chemical analyses are taken from surface to bottom from one sampling point situated in the deepest area of the lake. In the present study, only values for the open-water season (May–October) and for the water layer from 0 to 5 metres are used. This layer represents 80% of the total lake volume.

The nutrient concentrations in the water of Lake Pyhäjärvi and the main rivers Yläneenjoki and Pyhäjoki have been monitored since 1980 at intervals of approximately 2 or 3 weeks during the open water season. The P loads from the major rivers were calculated, based on P concentrations (samples taken at intervals of 2 or 3 weeks) and stream flow data (continuous measurement), both annually (year x) and for the different seasons: winter (January–March), spring (April), summer (May–September) and autumn (October–December). In addition, loading outside the growing season was calculated separately using the values of October, November and December from year x - 1 and the values of January, February and March from year x.

The analytical methods used follow Finnish standard laboratory procedures (Ekholm et al. 1997) which are accepted by FINAS (Finnish Accreditation Service). The water chemistry and hydrology data were collected for this study from the Finnish Environment Institute's Oiva data service (www.ymparisto.fi/oiva) and from the Pyhäjärvi Institute's own data archives. Nutrient loads from the major rivers are calculated on the basis of the respective phosphorus and nitrogen concentrations and stream flow data.

For phytoplankton analyses, composite samples were collected from 0 to 5 m depth 6 to 24 times during May–October each year from 1980 to 2008. Two sites were sampled in the 1980s, and since the early 1990s, eight other sampling locations have also been included and sub-samples from all 10 sites were combined. Also additional phytoplankton data, collected as part of a national monitoring programme, were available from several years in the period 1963–1979. Phytoplankton was counted using the Utermöhl technique (von Utermöhl 1931), and the biomass was estimated separately for each cell using standard methodology (Rocha and Duncan 1985). Zooplankton has been sampled weekly or at 2 or 3 week intervals between May and October since 1987. Samples were taken from 0–5 m at 10 locations, selected with a stratified random design (Cochran 1977). Samples were concentrated with a 50 µm mesh sieve and combined in the laboratory to form one composite sample for each date. In the laboratory, subsamples were enumerated until 50–200 individuals of each dominant crustacean species were counted and measured.

The efficiency of water protection measures (e.g. filters) were studied by taking water samples from the inflow and outflow of each site in different hydrological situations. The aim was to concentrate sampling during high-flow periods, but samples were also taken during low-flow periods. The outflow rate (flow L s^{-1}) was measured every time water samples were taken. On the basis of the flow rates and the nutrient and suspended solid concentrations, the masses of inflowing and outflowing phosphorus, nitrogen and suspended solids and their reduction rates were calculated. The mean of the measured inflow and reduction was used to roughly estimate the phosphorus mass removal by the filter material (g kg^{-1} lime).

3.2.2 Modelling

In this thesis, modelling was used to better understand the diverse factors affecting the lake water quality (Paper I) and to simulate water and nutrient cycles in the catchment (Paper II).

Linear modelling was used to investigate the effects of abiotic and biotic variables on lake water quality, described by chlorophyll a. The 16 possible explanatory variables consisting of annual means of the open water period over 22 years were used. The linear model was also used to investigate the effects of selected climatic variables (winter NAO, winter air temperature and winter precipitation) on river runoff, wintertime (October–March) and annual phosphorus loads, length of ice cover and ice out date.

The SWAT model (Soil and Water Assessment Tool) was used to simulate water and nutrient cycles in the catchment of the River Yläneenjoki (Paper II). SWAT is a process based temporal model operating in river basin scale, and it also includes empirical relationships between the different considered variables (Arnold et al. 1998, Neitsch et al. 2001). The catchment is generally partitioned into a number of sub-basins where the smallest unit of discretisation is a hydrologic response unit (HRU). The model's suitability and applicability to investigate water and nutrient transport was tested in collaboration between the water manager and modeller. A benchmarking protocol for the dialogue between the water manager and modeller in model selection, developed in BMW (Benchmark Models for the Framework Directive) Project, was also tested in Paper II.

3.2.3 Organising local water management

The history and implementation of the Lake Pyhäjärvi protection efforts as well as the collaboration related to it are described in Paper V. The actions, data and experiences of the restoration work were collected from reports and articles (Kirkkala 2001, Mattila et al. 2001, Ventelä and Lathrop 2005, Ventelä et al. 2007) and the annual reports of the Pyhäjärvi Institute and Pyhäjärvi Restoration Programme. The information on nutrient reduction measures (filters, wetlands, sedimentation ponds, buffer zones) was gathered from GIS and other databases of the Pyhäjärvi Institute and the Centre for Economic Development, Transport and the Environment of Southwest Finland.

4 RESULTS AND DISCUSSION

4.1 Climatic variables affect runoff and nutrient loss patterns

The seasonality of flow patterns and nutrient transfer was studied in the rivers Pyhäjoki and Yläneenjoki that run into Lake Pyhäjärvi (Papers I, II and V). Runoff patterns in the catchment of Lake Pyhäjärvi changed during the study period (1971–2008). Since 1989, the wintertime flows (January–March) in both of these rivers has clearly been higher than previously: in River Yläneenjoki it was three times higher in the period 1989–2008 than in the winter period 1971–1988, and in River Pyhäjoki twice as high (Fig. 6). During the spring (April) and summer (May–September) seasons, the mean flow was diminished.

The wintertime phosphorus load on Lake Pyhäjärvi was exceptionally high during the mild winters in the early 2000s (Paper I). The mean winter temperatures are normally below zero in the Pyhäjärvi region, and the ground is frozen and covered with snow in normal winters. Since the 1990s, freezing periods have often alternated with melting periods during the winters of several consecutive years, causing high runoff and high phosphorus loads. The climatic variables (winter NAO, winter air temperature and winter precipitation) explained 47% of the wintertime phosphorus load variation and a significant linear relationship was found between the winter NAO and the winter phosphorus load for the period 1980–2009. When testing the hypothesis that climate-related wintertime variables would affect the water quality of the lake in the following summer, some linkages were found, but the indications were not very strong (Paper I). However, in the long term, increased phosphorus input accelerates eutrophication. These results support Puustinen et al. (2007) who report that agricultural erosion and phosphorus loading of surface waters in Finland mainly occur outside the growing season. The majority of annual runoff at the catchment scale seems to occur in autumn and spring, but a considerable proportion also occurs in winter (Paper I). During the growing season nutrients are used for plant growth, and vegetation cover furthermore prevents soil erosion.

In all, hydrological and weather circumstances (precipitation, intensity and duration of a rain event, runoff volume, and degree of soil frost) strongly affect the occurrence of erosion and thus also phosphorus loss (e.g. Rekolainen and Posch 1993, Strahler 1974). According to Puustinen et al. (2007), the effect is particularly high in steep slopes under intensive cultivation or without vegetation cover. The combination of a rainy autumn and a warm winter causes considerably higher erosion and particulate phosphorus loading compared to a dry autumn and a snowy winter (Paper I). Vegetation cover decreases erosion in all situations. Puustinen et al. (2007) also found that the intensity and timing of tillage affected erosion and phosphorus loss. Reduced or totally abandoned autumnal tillage (stubble in winter) resulted in decreased erosion and phosphorus load.

Similar trends to those found in the rivers Yläneenjoki and Pyhäjoki have also been observed in other rivers in south-western Finland. The seasonal mean flows (Jan–March, April, May–Sept, Oct–Dec) for three south-western rivers, the rivers Eurajoki (including the rivers Pyhäjoki and Yläneenjoki), Kokemäenjoki and Loimijoki, were calculated in the project "Changing Baltic Sea" where hydrological scenarios were also considered (Hakala 2011). During the most recent years, wintertime flows (Jan–March) have increased and spring and summer flows decreased in all of these rivers.

Veijalainen (2012) estimated climate change impacts on the hydrology and floods in Finland with hydrological modelling (Watershed Simulation and Forecasting System, WSFS) and several climate scenarios. The results showed that the seasonality of river discharges would change: winter discharges are expected to increase and spring snowmelt discharge to decrease. The watershed simulation and forecasting system (WSFS) that was also used for the rivers Eurajoki, Kokemäenjoki and Loimijoki, and the scenario calculations, indicate that winter flows of these rivers will be clearly higher in the period 2010–39 than in the reference period 1971–2000 (Hakala 2011). All the scenarios indicate that the flows will increase particularly at the end of the year. In short, all these calculations indicate that the seasonality of the river flows will clearly change in the future, and this will also affect the levels of nutrient loading (Kirkkala et al., unpublished).

The findings of this study concerning warm winters and their influences on nutrient transport (Paper I) are in accordance with the IPCC scenarios of future climate change (IPCC 2007). The challenges are huge, especially regarding agricultural nutrient loss in boreal areas. Many nutrient reduction measures for the treatment of runoff waters, such as wetlands, buffer strips and filter systems, work insufficiently in winter flood situations. Cultivation practices will have to be further developed to hinder erosion and nutrient losses from fields.

Figure 6. Mild and rainy winters increase nutrient transport.

4.2 Weather and climatic variation challenges lake ecosystem management

In this study, chlorophyll *a* concentrations and phytoplankton biomasses are used to indicate levels of eutrophication (Paper I). According to the time series analysed, phosphorus concentrations increased in the period 1980–2001, then decreased in the period 2001–2004, and then increased again until 2008. Chlorophyll *a* and phytoplankton biomasses followed a similar pattern to some extent, but the variations were larger. According to linear modelling (Paper I), the concentration of total phosphorus was ranked high as an explanatory variable explaining the concentrations of chlorophyll *a* in Lake Pyhäjärvi. However, the correlation between the wintertime phosphorus load and the lake phosphorus concentration was not high. Increased external phosphorus load will in any case result in increasing phosphorus concentrations in the lake, enhancing primary production and eutrophication.

A reduced zooplankton grazing effect on phytoplankton was observed through the 1990s, while phosphorus concentrations increased as well (Paper I, Ventelä et al. 2007). In the period 2002–2004, the intensive biomanipulation that was implemented resulted in an efficient grazing effect and lower chlorophyll *a* concentrations and phytoplankton biomasses. The winters 2006/2007 and 2008/2009 were exceptionally warm and caused not only a high external nutrient load on the lake but also a poor and short ice cover period, which hindered seine fishing and left planktivorous fish stocks strong. The planktivory index was high and cladoceran biomasses were low due to reduced winter catches of vendace (Paper I). Sarvala and others (1998) studied relations of nutrients, phytoplankton and zooplankton and found that both total phosphorus concentrations and late summer cladoceran zooplankton biomass explained late summer chlorophyll *a* concentrations to a similar level of approximation. The cladoceran biomass is dependent on planktivorous fish abundance. The vendace is known to be the main planktivore in Pyhäjärvi causing cascading effects in the food web (Helminen and Sarvala 1997).

Biomanipulation has been shown to be a very important method of managing the water quality in Lake Pyhäjärvi (e.g. Ventelä et al. 2007). Professional fishermen carry out harvesting in winter (Fig. 7), and the annual catch covers the total production of vendace (Sarvala et al. 1998). Fishing is also the only way to remove phosphorus from the lake: 25% of the annual phosphorus input is removed by the fish catch (Ventelä et al. 2007). The food-web structure in Lake Pyhäjärvi has however become disturbed due to mild winters, short ice cover and low fish catch. An ice cover that enables winter seining is extremely important to the water quality and ecosystem of Pyhäjärvi, as the vendace stock is one of the key factors affecting the food web and phosphorus removal (Paper I).

It is obvious that climatic variation and weather circumstances affect a shallow lake ecosystem in many ways, both directly and indirectly. Both monitoring and modelling studies of European lakes have shown that increasing air temperatures lead to increasing surface water temperatures. The warming of water has a direct effect, enhancing primary production, and an indirect effect, resulting in longer stratification periods (Blenckner et al. 2004, Jeppesen et al. 2012). Both wintertime (March) and summertime (July) surface water temperatures have increased in Pyhäjärvi (Hakala 2011). A similar trend can be observed in the maximum temperatures (Jeppesen et al. 2012). The shallow Lake Pyhäjärvi is usually non-stratified and summertime anoxia is unlikely. The small-scale trench in the western part of the lake enables short-term stratification. The significance of possible remineralisation of nutrients is slight because of the small area of the trench. Climate warming may, however, lead to more frequent stratification, enhancing anoxia and nutrient release from sediments.

The long-term management of Lake Pyhäjärvi is currently facing new climate-related challenges (Papers I and V). The consequences of warming and changed runoff patterns seem to be parallel and enhance primary production and eutrophication. The interactions within the food web are complicated and partly unknown. Climate change may also induce unpredictable changes in species composition, such as changes in fish assemblage composition, abundance and size structure. Increased mortality and recruitment of vendace and overall population decline have been suggested to be climate induced changes in Pyhäjärvi, as well as declining whitefish catches and strong year classes of perch (Jeppesen et al. 2012). The overall impact of various changes in the structure and processes on water ecosystems is unpredictable.

Figure 7. Professional fishermen carry out biomanipulation in Lake Pyhäjärvi through winter seining.

4.3 Field-scale filters supplement the selection of nutrient reduction measures

Experimental work to develop and test innovative methods of catching nutrients from agricultural runoff waters is necessary in changing circumstances (Papers III and IV). Diffuse nutrient load from fields and forests is the main source of nutrient loading to Lake Pyhäjärvi and other water bodies in Finland. Since 1995, nearly all farmers in the catchment of Lake Pyhäjärvi have committed to the Finnish agri-environmental programme to implement basic water protection measures (Kirkkala 2001). In addition, catchment management practices, such as buffer zones, sedimentation ponds and wetlands, have been introduced. The efficiency of buffer zones and wetlands is largely based on microbial and biological processes, which are weak in the boreal temperate zone in winter. According to the IPCC (2007) scenarios and forecasts, climate change is expected to increase the wintertime nutrient load in particular. Therefore, innovative nutrient catching methods are needed. The new methods have to be tested in field experiments because real-world circumstances may yield outcomes different from those produced in laboratory studies. The experimental sand-filters tested in the Pyhäjärvi catchment (Fig. 8) are an excellent example of this (Papers IV and V). Their evaluation, however, requires high quality monitoring data so as to be able to determine the usability and the life span of these measures.

Sand filters are primarily known and studied in the area of municipal wastewater treatment. Treatment mechanisms in a sand filter include physical filtering of solids, ion exchange, and decomposition of organic substances by soil-dwelling bacteria.

Different reactive materials have been tested and studied to intensify nutrient removal, for example, iron or other metals containing side products (Dobbie et al. 2009, Penn and Bryant 2006, Shilton et al. 2006). In the Pyhäjärvi catchment several techniques using sand filters have been experimented with in the removal of nutrients from runoff waters. Sand filtration ditches, filter fields and ditch bottom filtration systems were built as early as in the 1990s. Lime and Fosfilt-s were used as reactive materials. In this study, the results of lime and Fosfilt-s filter fields are presented (Papers III and IV).

Figure 8. Experimental sand-filters of different structures and sizes are tested in the Pyhäjärvi catchment.

The results of this study confirm that the sand filter technique is applicable in situations where diffuse pollution, especially phosphorus load, has to be reduced (Papers III and IV). The ability of sand filters to absorb phosphorus can be improved with nutrient binding compounds, such as lime. The sand filter studies also showed that the method is highly efficient in decreasing the amounts of suspended solids and total and soluble phosphorus. This result is in accordance with results from some previous studies in other areas (Renman 2008). The lime filters that were tested removed 60–82% of the incoming total phosphorus and 16–28% of the nitrogen load (Paper III). The Fosfilt-s filters studied removed 0.5–37% of phosphorus and 4–32% of nitrogen (Paper IV). It is noteworthy that also the levels of nitrogen removal varied considerably. The efficiency and the lifetime of the filters depend on the inflow rate and the water quality. In the filters, structural changes and new internal preferential water flow routes decreased the ability to remove phosphorus.

Potential problems were also detected (Papers III and IV). As preferential flow paths developed, incoming water was not evenly distributed in the filter. This may be caused by a gradual loss of the porous structure and by clogging of the filter material. The high suspended solid content of the water may clog filters, as was also found by Dobbie et al. (2009) in their iron ochre-based filters. In our study, the Fosfilt-s filter in particular seemed to be sensitive to clogging if the inflowing water included fine-coarse suspended sediment, resulting in low nutrient reduction capacity. However, the experiment with clear drainage waters was successful. To prevent clogging, the suspended solids should be allowed to settle before the water reaches the filter. The granule composition should be optimal for water percolation and for water to be distributed evenly within the filter. Based on our earlier results from other test sites (Kirkkala, unpublished data), it seems that the clogging of filters can be avoided by installing sedimentation ponds or a wetland upstream of the filter.

There is also a risk of releasing precipitated phosphorus when the filters age. In lime filters this is related to a decreasing pH in consequence of diminishing concentration of calcium (Diaz et al. 1994). It is also probable that in a temperate boreal climate, the filter medium freezes in winter, leading to anoxic conditions, which stimulate the release of phosphorus. Further monitoring is needed in order to establish both the lifetime and the removal capacity of such filters. It is also very important to know the chemical composition and properties of the reactive materials used sufficiently well in order to avoid any negative environmental consequences. For example, lime in the filters increases the pH of water which makes the filtered water alkaline (Paper III).

The investment costs of sand filter beds are high. However, as the lifetime of field-scale filters is unknown, the cost-effectiveness of this technique cannot yet be assessed. Furthermore, the criteria for dimensioning the filters are not fully understood, for which reason it is difficult to ensure the sufficient retention time in varying weather and field conditions. Yet the filters are suitable for the treatment of phosphorus-rich waters when the inflow rate is controllable.

Wintertime phosphorus loads are likely to remain at high levels in the future (IPCC 2007). For this reason, long-term ecosystem consequences will presumably also appear at some point. The challenges seem to be huge, especially concerning agricultural nutrient loading. Most water protection measures (wetlands, buffer zones, filter systems) work insufficiently in winter flood situations. Thus, new solutions should be developed for both flood management and nutrient removal in winter.

Economically and ecologically, probably the most sustainable way to diminish agricultural nutrient loading is to prevent nutrient loss through promoting those farming practices that ensure that the crop uses the nutrients available in the soil. The emphasis in farming should be placed on conditions of the field, hydrology, soil structure, including porosity, and chemical and microbial composition.

4.4 Long-term time series needed to identify the effects of water management

The realisation of the present study depended on the availability of long-term hydrological, chemical and biological research and monitoring data, which were used to create an understanding of the complicated physical, chemical and biological interactions between the terrestrial and aquatic realms (Papers I, II, III, IV and V).

In Paper I, versatile long-term data from the catchment and the lake were used to test the hypothesis that climate-related wintertime factors would affect the water quality of the lake in the following summer. The availability of long-term time series data on air temperature, precipitation, ice conditions, hydrology, chemistry and ecology made it possible to analyse and select the variables that had the best ability to explain the phenomena examined using linear modelling and the Leave-one-out validation procedure.

In Paper II, a long-term time series of hydrological and chemical data from the River Yläneenjoki was used for the calibration and validation of a catchment scale SWAT model. After calibration, the validation was started against the data of the lowest monitoring point on the river. The second validation was performed for four different points along the same river. In the final validation test, water quality data from 12 sub-channels running into the River Yläneenjoki were used. Although the water quality data from the river's catchment is exceptionally extensive and frequent, the data was found to be too sparse for a perfect judgement of the model performance. The data from the catchment was also used in a GIS analysis (e.g. Kirkkala 2001, Conzales-Inca et al. 2012) which helps to choose and allocate water protection measures both spatially and temporally.

Papers III and IV are based on a large database on the efficiency of nutrient reduction measures (sedimentation ponds, wetlands, filters) in the Lake Pyhäjärvi catchment. Water flow and quality are measured from the inflow and outflow of the objects in different hydrological situations. The sampling periods varied, but were several years. On the basis of these data, nutrient reduction rates could be calculated, and the evaluation of efficiencies and applicabilities was possible. Calculations like these are necessary for identifying the measures to be applied and techniques for further development.

The long-term monitoring of Lake Windermere in the English Lake District since the 1930s also shows that continuation of research is important in efforts to validate models and to forecast future responses (Maberly and Elliott 2012). These scientific necessities interact synergistically to help us understand the whole ecosystem. However, long-term monitoring is often threatened at times of economic austerity. There is also a risk in Finland that future monitoring of waters will be carried out according to the minimum requirements set out in the Acts and Decrees due to diminishing economic resources.

The best and most reliable way to verify the changes and effects of climate-related phenomena in water bodies is to use continuous and long-term monitoring data. The monitoring data is strengthened when it is combined with cross-disciplinary other research data (Maberly and Elliot 2012), as in the case of Lake Pyhäjärvi (Papers I–V). Globally, there is an urgent need for applicable climate information based on reliable scientific facts. Predictive, accepted and understandable data, analyses and forecasts are needed, and they should be turned into information to support decision-making (Kerr 2011).

Experimental situations have shown that, even with a known stressor, responses can be delayed, indirect, and complex, and causality can be difficult to ascertain. However, sufficient data resources permit the identification of alternate models and trends that, in turn, facilitate insightful mechanistic inference and consideration of useful management options (Stow et al. 1998).

The aim of the Finnish Act on Water Resources Management (1299/2004), based on the EU's Water Framework Directive, is to ensure that the status of surface waters and groundwaters does not fall below the classification level "good". According to the Act, bodies of surface water must be protected, improved and restored so as to enable the ecological status "good" to be achieved by 2015 at the latest. The Act stipulates that the monitoring of waters is to be organised in such way that a consistent and diverse overall picture is gained of their status. The Finnish Government Decree on Water Resources Management (1040/2006) defines the criteria for surface water monitoring points, variables and frequency.

Surveillance monitoring shall be carried out on the status of surface waters and groundwaters to assess the impacts of human activities, to draw up monitoring programmes, and to assess natural conditions and the long-term impacts of human activity. The Decree also defines operational monitoring which has to be implemented if there is a risk of failing to meet environmental objectives. Investigative monitoring shall be implemented when the reason for failing to meet environmental objectives is unknown or due to a sudden cause, to investigate the degree of deterioration and to draw up water management plans. The criteria for monitoring points are vague. According to the Decree, monitoring points shall preferably be located on 1) large rivers where the catchment area is greater than 2,500 km^2 and the rate of flow is significant; and 2) on large lakes and reservoirs where the volume of water is significant within the water management region.

Surveillance monitoring is arranged for a minimum period of one year during each period of the water management plan (six years). For parameters indicative of biological and hydromorphological quality elements, monitoring shall be carried out at least once. Physico-chemical quality parameters shall be monitored four times per year in the main, unless technical knowledge and expert judgement indicates otherwise.

As Lake Pyhäjärvi and its catchment have been thoroughly monitored and studied for decades, this allows an analysis of climate-related impacts on the catchment processes and lake ecosystem (Paper I). The wide monitoring and research database includes wide-ranging results and information of the lake's ecology, catchment characteristics and processes, and nutrient reduction techniques and practices. The long-term time series have helped researchers and water managers to create an understanding of the complicated interactions and processes of the lake ecosystem. The time series from the catchment, combined with GIS (Geographical Information System) data, have provided the basis for identifying the most critical nutrient loss areas and allocating nutrient reduction activities (Paper I, Paper II, Kuusela 1999, Kirkkala 2001, Bärlund et al. 2007, Ventelä et al. 2007, Conzales-Inca et al. 2012). The research data on the efficiency and impact of several, nutrient reduction measures, including experimental measures, are valuable, because innovative measures are needed due to climatic variation. Although the frequency of monitoring in Lake Pyhäjärvi and its catchment (main channels and sub-channels) has been high, it remains challenging to identify the reasons for and the impacts of the processes and changes (Papers I, II, III and IV).

The time series data of water quality in the national monitoring programs include some uncertainties. Sampling frequency has varied over time, being scarce in the 1970s, but more frequent and regular since the 1980s. The monitoring data has also been complemented by several different research projects. However, river flow data has been collected with continuous automatic measurement techniques since 1971, which makes it reliable and frequent enough and to enable the calculation of daily mean discharges. More frequent water quality measurements would naturally improve the reliability of nutrient load calculations.

Automatic continuous measurement techniques are increasingly used for environmental monitoring as they provide temporally accurate and real-time data. These techniques have also been tested in Lake Pyhäjärvi and its catchment (Lepistö et al. 2008, Lepistö et al. 2010). In the SoilWeather project, a river basin scale wireless sensor network for agriculture and water monitoring was implemented (Kotamäki et al. 2009). The results show that the SoilWeather network was relatively reliable, great benefits were therefore seen, but they also showed that maintenance and data quality assurance require a lot of effort (i.e. calibration samples). The experiences gained from the Pyhäjärvi area are similar. The automatic techniques still require further development. For example, the parameter assortment for natural waters is still incomplete.

4.5 Catchment-based water management requires versatile tools

In this study, the SWAT model was applied in the River Yläneenjoki catchment to describe the hydrology and the temporal and spatial dynamics of sediment and nutrient transfer, and to test the model for evaluating the effects of nutrient reduction measures (Paper II, Bärlund et al. 2007). The aim was also to test the criteria established in the project by the Finnish Environment Institute entitled "Benchmark models for the Water Framework Directive" for the dialogue between the modeller and water manager (Hutchins et al. 2006, Bärlund et al. 2007). The SWAT model was chosen due to its process and GIS–based characteristics. The modelling work consisted of several calibration and validation steps and an intensive dialogue between the modeller and water manager.

Calibration of the model was made against discharge, sediment and nutrient concentrations and daily loads at the Vanhakartano monitoring station for the period 1991–1994. In Paper II, the emphasis was on nutrients, since hydrological calibration is described by Bärlund et al. (2007). Altogether, 28 parameters were used for calibration. The best calibration results were obtained for discharge and nutrient loads.

During the calibration process, certain problems were also detected. A discrepancy was found between the measured and simulated peak values during snow melt periods, and the low summer flow was also usually underestimated. This has a considerable impact on simulated nutrient concentrations and loading. It was also very difficult to estimate the correct unit loading from scattered settlement. It was also found that not all of the 300 parameters of the model were relevant, yet some elements, such as ponds and wetlands, were still missing.

The first step of validation was implemented at the Vanhakartano monitoring point. The validation performance was poorer than the calibration result for other parameters except suspended sediment concentration and load. The underestimation of flow peaks and the lack of in-stream denitrification led to the overestimation of nitrate concentrations. A second validation was made for total nutrient concentrations at four monitoring points along the main river channel. According to the monitoring data, nutrient concentrations rose from the lowest monitoring point to the agriculturally intensive upper parts of the catchment, but the model results showed quite the opposite. This may indicate that in the present model setup, in-stream processes constitute the most important factor affecting the simulation result, and not the loading from land. In addition, studies should be made to see whether the model overestimates the loading from forested areas. The third validation test was performed for average nutrient and sediment concentrations from 12 sub-channels running to the River Yläneenjoki. Concentrations were compared to the proportion of agricultural land. The average nitrate concentration and suspended sediment concentration measured showed a strong linear correlation with the proportion of agricultural land. Paper II concludes that the validation tests indicate that the concentrations in the main channel are not only explained by the transport from land but also by the channel processes themselves which are not very well understood.

A model benchmarking process (Hutchins et al. 2006) was tested in Paper II for the joint model selection by the modeller and water manager. It was discovered that the SWAT model was applicable from the management point of view to the River Yläneenjoki. The previous exercise with buffer strips showed that the model could be used in water management planning and decision-making (Bärlund et al. 2007). However, it is still uncertain whether there is sufficient confidence in the performance of the model. All in all, the dialogue and the collaboration in the modelling process were found to be very fruitful.

Lake Pyhäjärvi and its catchment have been studied using a modelling approach in many different research projects (e. g. Malve et al. 2006, Bärlund et al. 2007, Lepistö et al. 2008, Mäkynen 2009). This is partly due to the fact that the area is optimal for such studies as there are plenty of available monitoring and research data as well as interested actors in environmental protection. In other areas, the modeller often has to work a lot in initial model calibration and validation without the expertise, views, visions and wishes of the water manager. In addition, the lack of accurate spatial data often hampers empirical modelling. The usability of models may therefore remain low, particularly if the water managers are not familiar with them. Collaboration and discussion between researchers, modellers and local water managers in turn improves the reliability and usefulness of models. From the point of view of Lake Pyhäjärvi, the models have often been found to be too simple and limited from the perspective of their practical implications. The considerable and wide-ranging data on Lake Pyhäjärvi and its catchment provides a wider perspective to lake management than the models as these often lack important parameters.

The catchment-scale SWAT model appears promising in water management but the assessment of the model’s performance is laborious and time-consuming. Our exercise showed that the SWAT model can be calibrated to match discharges and nutrient loadings using a limited set of circa 30 parameters. Further calibration would be needed for nutrient concentrations. Although the River Yläneenjoki catchment is intensively studied and the amount of existing data is wider than is often the case, many real parameter values from the area were unavailable and the model’s default values had to be used.

4.6 Continual focus on lake restoration yields good results

The Pyhäjärvi Protection Fund and the Pyhäjärvi Institute have planned and implemented the Pyhäjärvi Restoration Programme during three periods: 1995–1999, 2000–2006 and 2007–2013. The five main themes of actions are: 1) Management of the catchment: external load reduction; 2) Management of the lake: biomanipulation; 3) Education and information services; 4) Research and monitoring; and 5) Networking.

Regional co-operation for the protection of this lake started already in the 1970s in order to oppose the plans of the City of Turku to take raw water from Pyhäjärvi. After the plan was rejected by the local municipalities, private entrepreneurs and local associations founded the Pyhäjärvi Protection Fund (PPF) in 1995, aiming to guarantee the necessary funds for long-term restoration (Paper V). The success of its efforts is evidenced by the halted eutrophication of Lake Pyhäjärvi: its water quality has remained at a good ecological level during the last ten years (Papers I and V). Signs of continued eutrophication were still observed during the early stage of the work when the lake restoration was started, before the water became unmanageable. Annual mean phosphorus concentrations increased during the 1980s and the 1990s, but since 1996 the increasing trend seems to have stabilised, although annual variations are high (see Fig. 7, Paper V). Mean annual nitrogen concentrations increased during the 1980s, but nitrogen levels have now stabilised. In the most recent years, the users of the lake have also given positive feedback on the improved water quality, and the ecological status has recently been classified as good (Ministry of the Environment et al. 2013). Without the activities of the Pyhäjärvi Protection Fund the state of the lake could be clearly worse.

This study has undeniably revealed the value of versatile and extensive co-operation and the engagement of different parties and stakeholders in the context of successful water management (Paper V). Well-established and trust-based co-operation is in contrast with management regimes that are executed as projects that have limited goals, funding and duration. This is important also from the perspective of the EU's Water Framework Directive (WFD) (2000/60/EC) which establishes the objectives for water protection in Europe. For each river basin district a "river basin management plan" will need to be established and updated every six years. The aim is to engage all parties involved in water management. Based on the WFD, the Finnish Act on Water Resources Management (1299/2004) obliges each regional environment centre (nowadays the Centres for Economic Development, Transport and the Environment i.e. ELY Centres) to arrange a sufficient level of co-operation and interaction with the different authorities and other parties at every stage of preparation of the water resources management plan. Every centre must have at least one cooperation group, but groups may also be set up for each river basin. An adequate number of representatives shall be invited to the cooperation group from the key government and municipal authorities that influence the use, protection and status of waters, from entrepreneurs, organisations, owners of water regions and water users (Government Decree on Water Resources Management Regions (1303/2004).

As both the advisory board and the member delegation of the Pyhäjärvi Restoration Programme consist of a wide variety of professionals (see Paper V), the Programme's basic work is closely linked to local, regional and national administrations, decision-making, entrepreneurs and the scientific community. The implementation of the Pyhäjärvi Restoration Programme is essentially carried out in co-operation with a large group of stakeholders, including the advisory board and the delegate members. Broad-based co-operation with local inhabitants, farmers, land-owners, summer cottage owners and entrepreneurs has been very important and fruitful. Thus, it effectively implements the principles of the WFD and the Finnish Acts and Decrees on water management. The Pyhäjärvi Protection Fund also offers basic funding for the Pyhäjärvi Restoration Programme, which is managed by a local non-profit foundation, the Pyhäjärvi Institute, which implements several projects, co-funded by EU funds, Finnish national funds, local municipalities and other organisations.

When the Pyhäjärvi Protection Fund started in 1995, this kind of fund with voluntary but strong long-term participation of municipalities and entrepreneurs was unique. The combination of this type of fund and a non-profit foundation has proved to be a successful. Similar voluntary-based water management organisations or funds were also established elsewhere in Finland later in the 2000s: the Lake Vesijärvi Foundation was established in 2007 (www.puhdasvesijarvi.fi/en/) and the Vanajavesi Foundation in 2012 (www.vanajavesi.fi). The Pyhäjärvi Institute and the Pyhäjärvi Restoration Programme have been used as a model in the establishment processes of these two foundations.

An important operational concept of the Pyhäjärvi Restoration Programme is its close co-operation with local residents and stakeholders (Paper V, Kirkkala 2001). The local residents are invited to prepare their own village plans, and this has been found to be a successful form of co-operation. The aim is to encourage residents to participate in the development and planning of their environment, and especially to draw their attention to water and environmental management. Water protection issues are included in the plans and they result in concrete new and innovative ideas for phosphorus removal and collective action. The strength of the Pyhäjärvi Restoration Programme therefore also lies in its success in combining practical views with scientific knowledge. The water management planning activities are based on the latest international scientific research, and the management actions and experiments are always connected with extensive monitoring and research (Papers I, III and IV).

Eutrophication caused by excessive nutrient input from anthropogenic activities is also regarded as the most acute environmental problem in the Baltic Sea (e.g. HELCOM 2012). In 2006, the total waterborne input of nitrogen to the Baltic Sea was 637,000 tonnes and the total waterborne input of phosphorus was 28,400 tonnes. The main pathway for nutrients was riverine load (79% of phosphorus and 60% of nitrogen). The partitioning of anthropogenic diffuse sources performed for selected countries indicates that agriculture contributed on average about 60–70% of the reported total diffuse loads (HELCOM 2012). Nutrient loading from Finland to the Baltic Sea was circa 4,100 tonnes of phosphorus and 74,000 tonnes of nitrogen. The proportion of natural runoff, independent of human activity, is circa 28% for phosphorus and 38% for nitrogen. Agriculture is nowadays the most important anthropogenic nutrient source in Finland too, accounting for approximately 31% of the phosphorus load and 27% of the nitrogen load entering the Baltic Sea (www.itameriportaali.fi).

In most countries in the Baltic Sea catchment, the total nutrient loads on inland waters are higher than the total waterborne input to the Baltic Sea due to retention. Soil and inland processes in the catchment can retain, transform and release nutrients (HELCOM 2012). In the period 2000-2005, the annual nutrient input to Lake Pyhäjärvi was 14.1 tonnes of phosphorus. The nutrient balance calculations show that on average, 26% of the annual phosphorus input is removed from the lake with fish catch and 56% of phosphorus remains in the lake. Only 18% of the phosphorus input flows out from the lake into the river Eurajoki running to the Baltic Sea. The most important way to improve the state of the Baltic Sea is to diminish the riverine nutrient input which requires activities in the catchment. As regards agricultural loads, field- and farm-scale nutrient mitigation measures are the basis for restoration of both inland waters and the Baltic Sea. Protection and improvement of the quality of inland waters, such as Lake Pyhäjärvi, will also secure the status “good” for the Baltic Sea.

5 CONCLUSIONS AND IMPLICATIONS

This research shows linkages between climatic variation, catchment processes and the ecological status of the lake studied. The climate models suggest an increase in temperatures, warmer and wetter winters and drier summers for the northern hemisphere (IPCC 2007). The management of agricultural nutrient loss will be even more challenging in the future than today. Most of the known and studied runoff treatment measures, such as wetlands and filters, are not efficient enough in nutrient reduction in winter when temperatures are still too low for efficient chemical and biological processes. New runoff treatment methods are needed, and cultivation practices, in particular, have to be developed. The main emphasis should be put on the nutrient balances of fields. It is both an economic and ecological advantage that crops use the nutrients available in the soil efficiently and that the nutrients do not leach away. The hydrology and the physical and chemical structure of the field are often a more sensible way to increase crop yield than increased use of fertilisers (Salo and Turtola 2006).

The most important aim of the Finnish Agri-Environmental Support Scheme is to diminish agricultural nutrient losses to water bodies. The scheme has been criticised for inefficiency because nutrient losses have not been reduced as quickly as desired. In the long term, reducing the use of fertilisers in particular will diminish soil nutrient concentrations and nutrient leaching, but the lag can be long. In south-western Finland, the majority of agriculture is based on contracts between farmers and food processors. There are already some processors who require farmers to follow certain environmentally friendly cultivation practices as many consumers appreciate this. The education of consumers would increase the pressure for more environmentally friendly cultivation practices.

The anticipated climate change may endanger winter seine fishing in northern areas. In Lake Pyhäjärvi, wintertime fishing has been the most productive and cost-efficient fishing method, and the local fishermen's equipment has been developed for winter seining. If winter seining becomes impossible in the future, the fishermen will have to adapt to open water fishing methods and invest in new equipment. This is very important from both the economic perspective and the water management perspective. Secondly, the structure of the fish community may change due to labile spring weather conditions. The changing climate may have an unfavourable effect on coregonid recruitment (Jeppesen et al. 2012). Since preventing climate change through local activities is impossible, fishermen will have to adapt, not only to find new fishing methods, but also by preparing themselves for changes in catch species.

The Pyhäjärvi Restoration Programme has developed and implemented dozens of different agricultural runoff treatment measures, including numerous experimental and innovative site-specific solutions, such as different kinds of filter, to reduce phosphorus loss efficiently. The results vary, depending on the flow rate and the quality of incoming water, the weather conditions, the structure of the measures taken and the materials and processes used. The sand filters with phosphorus binding compounds tested were found to supplement the selection of treatment methods for runoff waters, but the method should be further developed. The dimensioning criteria and the recommended texture and composition of the filter medium need to be studied further, and the results obtained need to be collated. More field experiments on nutrient removal by sand filters from runoff waters should be carried out, and their long-term effects should be monitored.

Lake Pyhäjärvi and its catchment have been the object of exceptionally long-term, wide-ranging and intensive research and monitoring for decades. The extensive data set has helped to interpret and understand the processes and interactions of the complicated ecosystem. It has also provided the basis for the planning of water management measures in the catchment and the lake. Research and monitoring are also needed to identify and verify the consequences of water management measures. However, although the research and monitoring data in the case of Lake Pyhäjärvi is better and more comprehensive than for most other water bodies, it is not always very easy to identify the impacts of different measures. The usability of mathematical models has often been found to be low due to their simplicity and the lack of interaction between the modeller and water manager. Models can be useful tools if the monitoring data is adequate and local knowledge and research results are included in the model, and interaction between the modeller and water manager is intensive.

The resident-, stakeholder- and livelihood-oriented concept of the Pyhäjärvi Restoration Programme and the Pyhäjärvi Institute has successfully promoted water management and supported water-related business, such as professional fishing. The co-operative approach applied has enabled the implementation of an exceptionally high number of water protection measures in the catchment. An independent and non-profit body, such as the Pyhäjärvi Institute Foundation, has proved to be a successful contributor to local voluntary action. The partners of the Institute and the Pyhäjärvi Protection Fund also see the model as economically beneficial, as the basic funding has been multiplied by funding for numerous projects.

Eutrophication caused by an anthropogenic source of nutrients is also the most severe problem affecting the Baltic Sea. Point source pollution has diminished, but problems still exist. The riverine nutrient input accounts for most of the annual nutrient load, and a significant portion of the annual nutrient load originates from agriculture practiced in the areas around the Baltic Sea. The most important way to improve the state of the Baltic Sea is to diminish the riverine nutrient input which requires activities in the catchment. As regards agricultural loads, field- and farm-scale nutrient mitigation measures are the basis for restoration of both inland waters and the Baltic Sea. The protection and improvement of the quality of inland waters will also secure the status “good” for the Baltic Sea.

Lake Pyhäjärvi and its catchment can be regarded as a good research laboratory from the point of view of the Baltic Sea. The main problem in them both is eutrophication caused by excess riverine nutrient load, i.e. nitrogen and phosphorus, loads. Reducing nutrient losses, especially from agriculture, is the basis for restoration of both these water bodies nowadays, since waste water effluents have significantly diminished. Mitigation measures are also similar in both cases. Biomanipulation has been found to be an efficient restoration method in some lakes, especially in Lake Pyhäjärvi. The development of biomanipulation in the coastal areas of the Baltic Sea has also started, but the sea area is very challenging to manage. However, every measure that reduces nutrient loading and improves the status of Lake Pyhäjärvi also benefits the Baltic Sea.

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