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Direct and indirect mechanisms behind successful biomanipulation

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Abstract

Lake Vesijärvi is a relatively large (length 25 km; total area 110 km^2), shallow (mean depth 6 m), but stratified lake in southern Finland. The Enonselkä basin (26 km^2), surrounded by the city of Lahti, received its sewage effluent, and changed from a clear water basin with flourishing fisheries from the 1940–50s to one of the most eutrophic lake systems in Finland thereafter. In 1976, the sewage effluent was diverted, resulting in a temporary recovery of water quality. However, in the 1980s, massive surface scums of cyanobacteria degraded the water quality and arrested the recovery of the lake. A restoration strategy providing an ecologically sound basis for the management of the lake was initiated in 1987. This strategy involved biomanipulation (mass removal of coarse fish) together with conventional pollution control measures on discharges to the lake. Biomanipulation was chosen instead of much more expensive chemical and/or technical methods, such as chemical treatment or dredging of the profundal sediment. The large-scale biomanipulation trial was carried out in the Enonselkä basin during 1989–93. Following the mass removal of coarse fish (1000 metric tons of fish; mainly roach and smelt), the biomass of cyanobacteria collapsed concomitantly with a decline of total phosphorus concentration from 45 to 35 mg P m^{-3}, and with an increase of Secchi depth from 1 m to 3.5 m. These observed improvements in the water quality were matched with a large decline in roach-mediated phosphorus movement from littoral to pelagial, from 100 mg P m^{-2} in 1989 to 15 mg P m^{-2} in 1993. Year-to-year variation within the littoral communities, and in the recruitment of fish, could in this way cause large oscillations in the whole ecosystem. The involvement of local people (fishermen, farmers etc.) in controlling non-point nutrient loading and fish stock development, is of prime importance for the long term success of lake restoration.

Introduction

Lake Vesijärvi (Figure 1) is part of the River Kymijoki catchment in southern Finland, between the extensive Salpausselkä Eskers. The lake is characterized by a long retention time and a low number of islands. The hydrological characteristics of L. Vesijärvi are shown in Table 1. Due to the shallowness of the lake, two-thirds of the sediments in the Enonselkä basin are in direct contact with epilimnetic waters (depth $<$10 m) during stratification periods (May–September).

Lake Vesijärvi (‘vesi’ means ‘water’) was originally a clear-water lake, but its eutrophication started during the first decades of this century as a consequence of increased industrial and sewage effluent discharges from its surrounding urban community, the city of Lahti (Keto & Sammalkorpi, 1988). For instance, the first incidence of cattle poisoning in Finland, by cyanobacteria-rich lakewater, was documented in L. Vesijärvi as early as 1928 (Hindersson, 1933). In the 1960s and early 1970s, the lake became known as one of the most eutrophic large lakes in Finland. *Anabaena* and *Microcystis* blooms were common, and taste and odour problems in water and in fish occurred frequently, especially in the Enonselkä basin (Figure 1). In addition, during stratification periods, oxygen deficiency below 10 m depth and a complete depletion of oxygen in the deeper hypolimnion (20–30 m), were a regular phenomena. As a result, the Enonselkä basin was unsuitable for recreation and fishing (Keto, 1982).

During the 1960s and the 1970s, the annual phosphorus loading of sewage effluent to the Enonselkä basin was 50–60 metric tons, equivalent to 1.9–2.3 g P

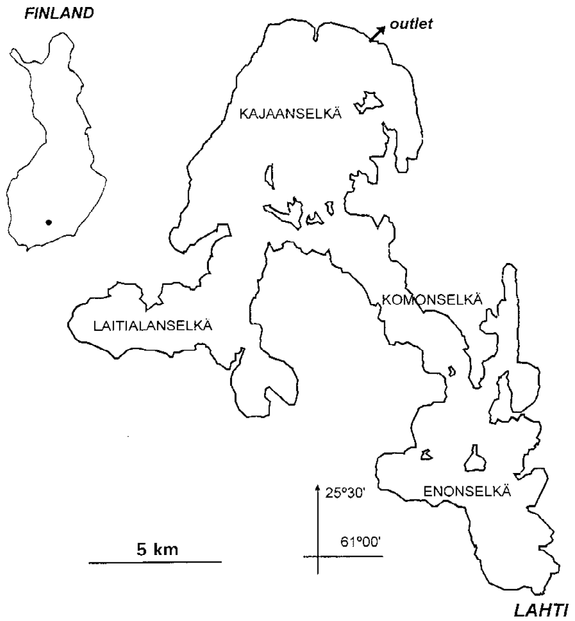

Figure 1. Map of Lake Vesijärvi representing the different lake basins, the location of the City of Lahti and the outlet of the lake.

Table 1. Hydrological properties of Lake Vesijärvi and the Enonselkä basin

Parameter	Whole lake	Enon-selkä
Drainage area, km^2	515	84
Surface area, km^2	110	26
Volume at MSL, 10^6 m^3	663	176
Theoretical retention time, yr	5.4	5.6
Maximum depth, m	42	33
Mean depth, m	6.0	6.8

m^{-2}. This nutrient loading was drastically reduced in 1976 when a new biological–chemical sewage treatment plant was opened and the effluent waters were discharged to the River Porvoonjoki instead of to the lake. After the sewage diversion, the loading of phosphorus and nitrogen dropped to 8% of pre-diversion values and the Enonselkä basin showed obvious recovery (Keto, 1982). During winter stagnation periods, artificial aeration was applied in order to prevent development of oxygen deficiency in the hypolimnion. This improved oxygen balance in winter, and consequently, within the next two years the average winter concentration of phosphorus under ice decreased from 175 μg P l^{-1} in 1975, to 50 μg P l^{-1} in 1977 (Figure 2). The aeration, however, had no influence on hypolimnetic oxygen concentrations in summer, and due to high internal loading, phosphorus concentrations regularly doubled in the course of the summer. Hence, despite the gradual improvement of the winter and spring state, the water quality in the Enonselkä basin tended to degrade as a result of massive blooms of *Microcystis* and *Aphanizomenon* cyanobacteria over the longer-term (Keto & Sammalkorpi, 1988).

Overall, the Enonselkä basin provides a typical example of the problems encountered in the restoration of large, eutrophic lakes. Cyanobacterial blooms continued throughout the late 1970s and early 1980s despite traditional restoration measures which, for example, reduced the external phosphorus loading from 2.1 g P m^{-2} ann^{-1} in 1975 to 0.15 g P m^{-2} ann^{-1} in 1978 (Keto & Sammalkorpi, 1988), clearly below the critical level of 0.3 g P m^{-2} ann^{-1} of Vollenweider (1976). Traditional lake management measures were evidently not adequate to restore the lake.

Mesocosm experiments showed that roach (*Rutilus rutilus* (L.)), which in the course of the lake's eutrophication had developed a very dense population (Keto & Sammalkorpi, 1988), had a key role in maintaining high phytoplankton biomass and productivity in the basin (Horppila & Kairesalo, 1990, 1992). Consequently, biomanipulation was started in 1989 as an additional measure in the management program, i.e. removal of roach by trawling. Between the years 1989 and 1993, more than 1000 metric tonnes of fish (nearly 400 kg ha^{-1}) were removed; roach comprised 52% and smelt (*Osmerus eperlanus* (L.)) comprised 28% of the catch. This large-scale manipulation of the fish stock was followed by collapse of cyanobac-

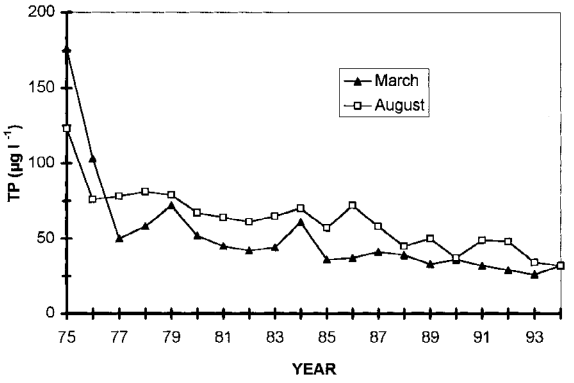

Figure 2. Volumetric mean concentrations of total phosphorus (μg P l^{-1}) during winter stagnation (under ice cover) in March, and during summer stagnation in August, in 1975–94.

terial blooms and then increased water transparency (Kairesalo et al., 1998a).

The mass removal of fish from the Enonselkä basin can be regarded as a large-scale disturbance to the ecosystem. Its execution, and subsequent developments, provide a good opportunity for monitoring and testing the dynamics of the lacustrine ecosystem, in terms of its resilience and resistance to disturbance (cf. Holling, 1973). It was clear that this disturbance exceeded the resistance of the system: the future development of water quality, however, will be a better measure of the resilience of the ecosystem. It is still not known, for instance, whether the roach stock can become dominant again to return the lake system to the ’old equilibrium’ where cyanobacteria blooms can re-appear (Horppila & Peltonen, 1994) or whether the foodweb processes involved in the pelagic fish-zooplankton interactions (Horppila, 1994a; Luokkanen, 1995), and in the enlarged submerged macrophyte beds (Scheffer et al., 1993; Kairesalo et al., 1998b), can maintain the system in its new state. The human population of the surrounding urban and rural areas with all its socio-economic feedbacks, however, will be the most prominent but also the most uncertain factor in the lake’s management. Here, local people and organizations have become more active as the rehabilitation of the lake has proceeded.

In order to evaluate the limnological changes, samples for physico-chemical analyses were taken monthly from the Enonselkä basin and those for phytoplankton 6–8 times during the growing season. Planktonic primary productivity was measured with the ^{14}C-method using illuminated (5000 lux) constant-temperature (20 °C) baths, with an exposure time of 24 hours. External nutrient loading to the Enonselkä basin was estimated from water samples taken from the major inflowing rivers and brooks during winter, spring, summer and autumn periods, and loading calculated according to nutrient concentrations and flow rates. The average drainage values of the different watersheds were then used for determining the seasonal and annual loadings. A description of the methods for zooplankton sampling and analysis is given by Luokkanen (1995). Algal biomasses given are weighted with volume.

More detailed descriptions of the eutrophication history of Lake Vesijärvi, as well as methods for analyses used, are given by Keto (1982), Keto & Sammalkorpi (1988), Liukkonen et al. (1993) and Kairesalo et al. (1998a). This paper presents the ecological basis for the present and future management of Lake Vesijärvi. Integration of ecologically sustainable measures with socio-economic activities based on regional, functional and administrational co-operation will form a central element of the holistic management plan and program.

Ecological basis for the management of Lake Vesijärvi

Generally, a reduction in the external nutrient load is always the primary restoration measure to provide a sound basis for the recovery of any eutrophic lake. Since phosphorus is most often, as in Lake Vesijärvi, the main factor controlling growth of cyanobacteria, the input reduction of this element has usually been regarded as the principal restoration measure (Sas, 1989). In the Enonselkä basin, different phases in the development of the summertime phosphorus concentration can be seen (Figure 2). At first, the phosphorus concentration responded promptly to the diversion of sewage waters but then remained at a high level, 60–70 μg l^{-1} until 1986, by which time the water mass of the Enonselkä basin had been replaced twice with inflowing waters (retention time 5.4 years). Thereafter, phosphorus concentration seemed to achieve a new ‘steady state’-level of 40–50 μg P l^{-1} between 1988–92. From 1993 onwards, there seemed to be a slight decreasing trend in phosphorus concentrations. The observed difference between the August and March concentrations indicate the contribution of summertime loading to the phosphorous concentration (Figure 2).

The collapse of cyanobacteria resulted in a new ‘equilibrium’ level of the planktonic system, as revealed by the phosphorus/chlorophyll *a* ratio (Figure 3; Kairesalo et al., 1998a). Although cyanobacteria tended to disappear as phosphorus concentrations decreased, their disappearance was not continuous, but occurred rather in stepwise fashion as observed elsewhere (Sas, 1989). In the Enonselkä basin, the collapse of cyanobacteria (roughly, from 50% to 10% of the total algal biomass) occurred with the decline of the average epilimnetic phosphorus concentration from 45 to 35 μg P l^{-1} (Figure 3), which is lower than found for shallow, unstratified *Oscillatoria*-lakes (100–50 μg P l^{-1}), but distinctly higher than that (20–10 μg P l^{-1}) found in deep, stratified European lakes (Sas, 1989). The average annual concentration, however, does not illustrate the seasonal dynamics of phosphorus, which during the stratification may be

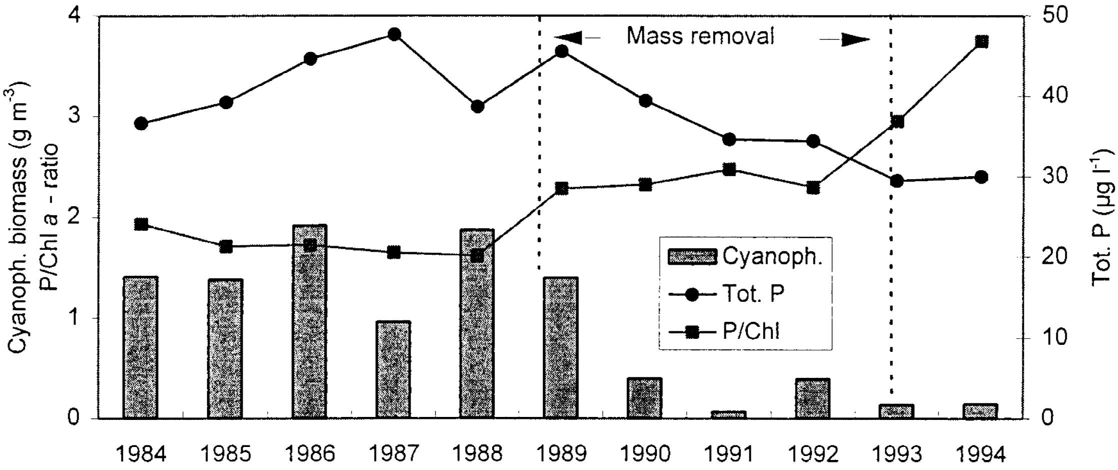

Figure 3. Summer mean concentrations of phosphorus (μg P l^{-1}, right axis); phosphorus/chlorophyll *a* ratio (left axis); and summer means of cyanobacteria biomass (g m^{-3}, left axis) in the epilimnetic water (0–5 m) in the Enonselkä basin in 1984–94.

largely steered by biotic processes and communities. In the Enonselkä basin, a stepwise increase in the epilimnetic phosphorus concentration was regularly recorded in early June during the 1980s (Figure 4), which could not be explained by the traditional means, i.e. neither by external- nor sediment-derived phosphorus inputs (Kairesalo, et al., 1995; Hartikainen et al., 1996). This phosphorus increase, however, coincided with the early-summer migration of adult roach populations from the littoral areas to the pelagic zone (Peltonen & Horppila, 1992; Horppila 1994b). During 1989–93, these migrating fish, in particular, were the target of the trawlings which led to a dramatic reduction in their biomass; from 172 kg ha^{-1} (i.e. about 100 mg P m^{-2}) in 1989 to less than 30 kg ha^{-1} (about 15 mg P m^{-2}) in 1993 (Horppila & Peltonen, 1994). Concomitantly, smaller amounts of sediment and phosphorus were re-suspended in lake water by the smaller roach populations feeding in the littoral environment (Horppila & Kairesalo, 1990, 1992). The fish phosphorus compartment in the Enonselkä basin had previously been of significant magnitude, that half of the limnetic phosphorus pool was bound to, and transported with, the fish biomass. This influenced the pelagic cycling of phosphorus and retention in algal biomass (Figure 3). Hence, the substantial decrease in the fish-mediated phosphorus input caused by the fish removal provided a reasonable explanation for the observed change and decline in the epilimnetic phosphorus concentration, which, consequently, resulted in the displacement of cyanobacteria (Kairesalo et al., 1998a). Temporal and spatial variation in the fish-P compartment may therefore be of crucial, but still poorly quantified, importance in lake phosphorus budgets.

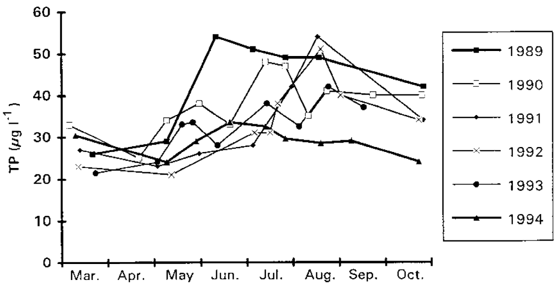

Figure 4. Seasonal variation in the total phosphorus concentration (μg P l^{-1}) in the epilimnion of the Enonselkä basin in 1989–1994.

Planktonic primary productivity declined gradually after 1989 when it reached 1100 mg C m^{-3} d^{-1}, both in early July and in September (Figure 5). In 1993, the highest measured primary productivity was 460 mg C m^{-3} d^{-1} in late July, and in 1994, only 280 mg C m^{-3} d^{-1} in late June, very low values compared to the earlier years.

Despite the decline in the density of planktivorous fish there were no significant changes in the pelagic cladoceran community in the years 1991–1994 (Luokkanen, 1995; unpublished). The summer maximum biomass declined from more than 150 μg C l^{-1} to less than 100 μg C l^{-1} in 1994, but the change is largely due to the decline in the epilimnetic *Bosmina crassicornis* population. The biomass peak of this bosminid alone has declined from over 80 μg C l^{-1} in 1991 to less than 30 μg C l^{-1} in 1994. The

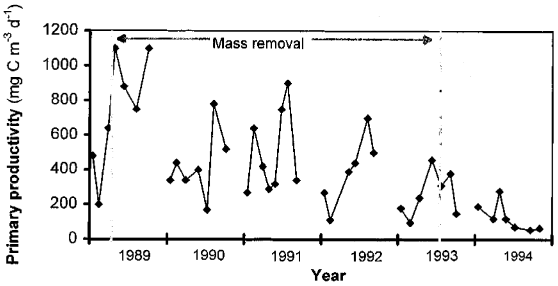

Figure 5. Summertime fluctuation and development of planktonic primary productivity in the Enonselkä basin in 1989–94.

daphnids, *Daphnia cucullata, D. longiremis* and *D. cristata* remained at the same level both in numbers and in biomass, and no increase in their average size was recorded. Thus the disappearance of cyanobacteria cannot be explained by any increased grazing by cladocerans.

The management imperative is now to maintain the improvements in water quality. In practice, this requires the mobilization and action of local people and organizations for the rehabilitation of the lake to achieve two ends – control of external nutrient loading, and maintenance of the fish stock with a balanced prey-predator ratio.

Present management of Lake Vesijärvi

Since the diversion of point-source sewage effluent in the late 1970s, measures for reducing the external nutrient loading into the lake have been focused on diffuse sources of nutrients from the surrounding agricultural areas. Accordingly, during 1991–1994, management plans for reducing the use of fertilizers have been made individually for each of the 321 farms on the drainage area. These management programs have been supported financially from several regional and local funding sources.

It has been estimated that without an active exploitation policy the roach stock would double within 3 years (Horppila & Peltonen, 1994). Former manifestations of eutrophication, driven by roach-mediated nutrient reallocation, could then return. In order to prevent this, the roach population was modelled at different levels of simulated natural and fishing mortalities (Horppila & Peltonen, 1994). This has led to a policy of removal by local fishermen (and other people) of about 50 metric tonnes of roach each year from the Enonselkä basin, using large pound nets and fykes (made by the fishermen).

An alternative method of controlling the ‘unwanted’ fish stocks is to increase the stocks of predatory fish, formerly weak in this lake. Before biomanipulation, the only predatory fish inhabiting the pelagic zone was perch (*Perca fluviatilis* L.). Over 1 million fingerling pikeperch (*Stizostedion lucioperca* (L.)) were stocked during years 1984–1991, with the intention of increasing predation pressure on roach and smelt. The minor goal was to increase the value of the fishery. The restocking proved successful, as in 1992 natural spawning took place. The growth of stocked pikeperch was also rapid compared to other lakes in Finland (Ruuhijärvi, unpublished), indicating that a dense pikeperch stock can consume a large fraction of the planktivorous fish production. Diet studies showed that small pikeperch fed mainly on smelt, whereas the diet of large ones also comprised perch and roach (Peltonen et al., 1996).

The stocking was a victim of its own success however, because the species rapidly became the most valuable in the gill-net fishery, particularly in the Enonselkä basin. The fishing regulations were very liberal, neither mesh size limits, nor a limit to the number of fishermen, were applied. The minimum size limit for catchable pikeperch (370–400 mm) had no effect in practice because more than 95% of catch was captured with gill nets (Ruuhijärvi, unpublished), providing no chance for released fish to survive. Intense competition between fishermen forced the mesh sizes used, down to 80 mm (stretched mesh) and the catch then consisted mostly of pikeperch in the age groups 3–4 years. This led to a serious risk of overfishing because most female pikeperch in Lake Vesijärvi mature at 5 years old (Ruuhijärvi, unpublished). It was also very likely that, under such pressure, the food consumption by pikeperch was only a fraction of its maximum value (Peltonen, unpublished data). The situation was also undesirable for the fishery itself, as according to other studies in Finland, the recruitment age producing the maximum total yield is 5–7 years (Lehtonen, 1987; Lehtonen & Miina, 1988).

In Finland, water areas are mostly privately owned and decison-making process in fishery management is very complicated, and hence often ineffective. Thus, although the need for an increase in legal minimum mesh size was obvious, no restrictions were applied before 1996, when the classical Y/R analysis was performed with the growth data from Lake Vesijärvi, and the problem was presented in the form of a simple model. Such analyses were not done earlier because data were available only on the growth of pikeperch. However, the Y/R model showed that the conclusions were valid on a wide range of natural mortalities, selection curves and growth speeds. On the basis of this very simple modelling (Figure 6), a decision to set the minimum legal mesh size at 100 mm (stretched mesh) was finally made by the local fishery authorities in April 1996. This is perhaps only a small step towards the optimum mesh size but it is hoped that it will at least protect the stock from extinction.

This mesh size limit will be applied only in the Enonselkä basin. In other areas, especially in the Kajaanselkä basin (Figure 1), the gill-net fishery of whitefish (*Coregonus lavaretus* (L.)) and perch is also important, and the increase of mesh size would perhaps lead to large declines in the yield of these species. Finding an appropriate management strategy for mixed gill-net fisheries is a general problem in Finland where gill nets are also widely used in recreational and 'household' fishing, in contrast to many other countries. The objectives of these fisheries are totally different from those of a commercial fishery.

Future management of Lake Vesijärvi

The future management of Lake Vesijärvi will be based on the integration of ecologically sustainable measures with the participation of local people. The Department of Ecological and Environmental Sciences of University of Helsinki has started a project to study and develop this kind of integration. The project is co-financed by the European Union Life Programme and the City of Lahti. People in the areas surrounding Lake Vesijärvi had already been educated about the problems of lake rehabilitation during the period of mass removal of fish in 1989–93. For the present and future management of the lake, it is even more important to inform the public and thus gain essential support for efforts to maintain the lake in its rehabilitated state. However, mere education is not enough. For efficient and sustainable lake management, increased ecological awareness must be combined with a more intensive participation of the local population.

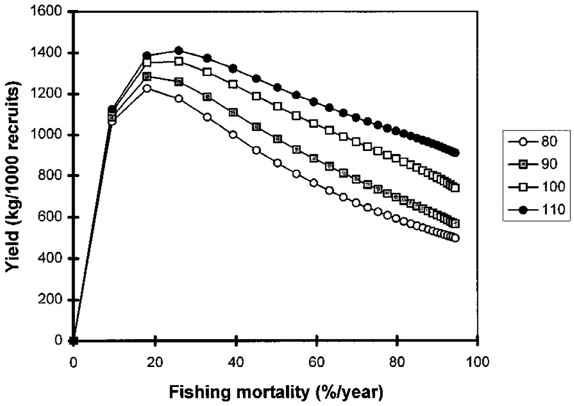

Figure 6. The yield per 1000 recruits as a function of fishing mortality with four minimum mesh sizes. The current mesh size is 80–90 mm (stretched mesh) and fishing mortality very high (more than 80%), new allowable minimum mesh size is 100 mm.

Since the rehabilitation of the lake has improved opportunities for recreation and fishing, the future of Lake Vesijärvi is strongly dependent on the commitment of lake users to the ecologically sustainable management. Commitment of people makes the regulatory measures of authorities less necessary and the rehabilitation thus becomes a continuous process.

Local people will be involved in lake management by means of participatory planning. Mere consultation of the people is no longer considered sufficient. People and their organizations need to be involved throughout the project cycle, from design stage to monitoring and evaluation. The opportunity to participate effectively in the different phases presupposes flexibility in planning and organization of the project. The mode of action most suitable for this is that of action research, conducted as a learning process for all involved (Schneider & Libercier, 1995).

Participatory action research is a cyclical inquiry process that includes a diagnosis of the problem, plans for action, implementation and evaluation of outcomes. The approach aims to help people develop a higher degree of self-determination and self-development capability, so that learning continues after researchers leave the system (Elden & Chisholm, 1993). A careful and often lengthy process of observation, analysis and consultation forms the initial phase of the project. It offers opportunities for the population to put forward its views of problems and priorities. Of importance are differences in the positions and power constellations of the various groups, or categories of the population and the possible conflicts of interest between them (Schneider & Libercier, 1995). Participatory action research emerges over time as a process; it does not appear fully at the outset in most situations. Each case starts as an attempt to solve a particular kind of problem and gradually opens up into a much broader and deeper research process (Greenwood et al., 1993).

The holistic management project of Lake Vesijärvi will start with ascertaining the goals and preferences of fishermen. Fishermen are considered to have a central position in the process of encouraging local people to take responsibility for ecological lake management. Lake Vesijärvi serves an urban population base of 150 000 and there is thus a large pool of potential fishermen who can choose to fish on the lake when fishing conditions are good. Representatives of fishermen will participate in personal computer-aided interviews. The interviews are performed by using the HIPRE 3+ software (Hämäläinen & Lauri, 1993). The decision analyst conducts the interviews, operates the computer and familiarises the stakeholder with the decision analysis methods used. When the objectives of various groups of fishermen – such as anglers and net fishermen – have been defined, the utility outcomes of different management strategies can be computed by ecological modelling. However, because of the stochastic nature of many processes in the ecosystem, these outcomes are uncertain. The uncertainty is modelled with Bayesian decision analysis, which, especially the approach using influence diagrams, has been shown to be a useful tool for analyzing environmental management problems (Varis et al., 1990; Varis & Kuikka, 1990; Varis, 1995). In an influence diagram, controllable (decisions) and uncontrollable (probabilistic or deterministic) variables are connected with one-directional links (Figure 7). The approach is based on the Bayes' theorem, which makes it possible to calculate the probable distribution of the outcomes of different management options.

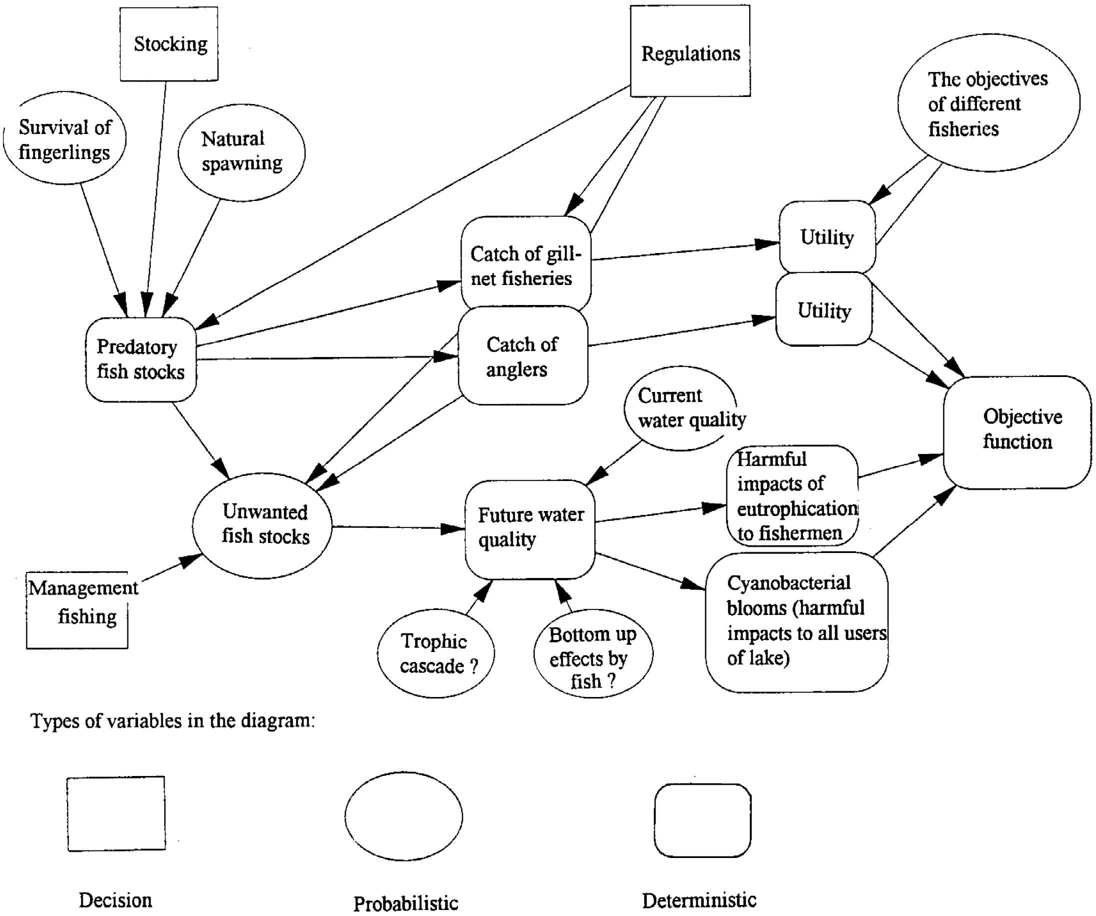

Figure 7. A prior Bayesian influence diagram about the management problem of Lake Vesijärvi. The costs of management options are not presented here.

An important advantage of the interactive method is that by active participation the commitment of stakeholders to the chosen alternative can be increased. The computer-supported interactive decision analysis is a practical and an efficient way of dealing with conflicting opinions and improving citizens' participation in environmental project planning and evaluation (Marttunen & Hämäläinen, 1995).

Acknowledgements

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