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Environmental issues in lakes and ponds: current state and perspectives

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SUMMARY

Lakes and ponds are habitats of great human importance as they provide water for domestic, industrial and agricultural use as well as providing food. In spite of their fundamental importance to humans, freshwater systems have been severely affected by a multitude of anthropogenic disturbances, which have led to serious negative effects on the structure and function of these ecosystems. The aim of the present study is to review the current state of lake and pond ecosystems and to present a likely scenario for threats against these ecosystems for the time horizon of the year 2025. Predictions are based on a review of the current state, projections of long-term trends, for example in population and global climate, and an analysis of the trends in publications in the scientific literature during the past 25 years (1975–2000). The biodiversity of lake and pond ecosystems is currently threatened by a number of human disturbances, of which the most important include increased nutrient load, contamination, acid rain and invasion of exotic species. Analysis of trends suggests that older, well known threats to biodiversity such as eutrophication, acidification and contamination by heavy metals and organochlorines may become less of a problem in developed countries in the future. New threats such as global warming, ultraviolet radiation, endocrine disruptors and, especially, invasion by exotic species including transgenic organisms will most likely increase in importance. However, in developing countries where priorities other than environmental conservation exist, the threat of eutrophication, acidification and contamination by toxic substances is predicted to continue to increase. Although the future of biodiversity in lakes and ponds is seriously threatened, growing concern for environmental problems, implementation of new environmental strategies and administrations, and international agreements, are positive signs of changes that should improve the ability to manage old as well as new, yet undiscovered, threats.

Keywords: lakes, ponds, environmental threats, biodiversity, water quality

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INTRODUCTION

Lakes and ponds are important freshwater habitats throughout many regions of the world, although the amount of water in them constitutes only a minute fraction of the total freshwater resource on earth. A large proportion of the fresh water is stored as ice and snow at high altitudes and around the poles or as groundwater, and less than 0.5% is available for use by organisms, including humans. Water availability is a cornerstone for human civilization but increasing human populations have resulted in accelerating demands on water supplies for drinking, hygiene, industrial processes and agriculture (irrigation). Analyses of water availability and human use suggest that human withdrawal of the total available freshwater resource presently amounts to approximately 50% (Szöllosi-Nagy *et al.* 1998). The expected population increase coupled with economic development and changing lifestyles over the next 25 years will substantially increase the demand for freshwater resources, and without doubt the availability of fresh water for human consumption will be one of the great issues for humankind in the 21st century (Johnson *et al.* 2001). Further, organisms living in freshwater systems, such as fish, water plants and invertebrates, are exploited by humans for food, and in many parts of the world food products with freshwater origin make up an essential part of the diet.

In spite of the great importance to humans of access to fresh water of high quality, fresh water systems have been misused for many centuries. Small lakes and ponds have been drained or filled in to extend arable land, regulated to reduce water-level fluctuations, used as dumps for an array of anthropogenic wastes ranging from untreated sewage to synthetic substances, and many natural populations of commercially-important freshwater species have been overexploited (for reviews see Loganathan & Kannan 1994; Richter *et al.* 1997; Matthiessen & Sumpter 1998; Burkholder 2001; Lévêque 2001). Further, changes in land use, biogeochemistry and increasing international commerce have created global environmental stress expressed, for example, as climate change, depletion of the stratospheric ozone layer, acidification and invasion of exotic species (see Carpenter *et al.* 1992; Galloway 1995; Williamson 1995; Mack *et al.* 2000). All these factors will alone and in combination negatively affect the quality and availability of water for human consumption. Moreover, these anthropogenic disturbances have had, and will continue to have, serious effects on the natural systems and their biota (Sala *et al.*

2000), having far-reaching effects on ecosystem functioning and biodiversity.

In this review we will discuss the effect of anthropogenic disturbances on small lakes and ponds; Beeton (2002) discusses environmental effects on large lakes. We will mainly focus on the effects of disturbances on the biota and functioning of the natural ecosystem and not on the effects on water quality for human use (for a full treatment of these issues see Postel 2000; Johnson *et al*. 2001; URL http://watervision.org). Of course, in many cases these run in parallel; disturbances that reduce water quality for consumption also have negative effects on the biota and measures taken to improve habitat quality for freshwater biota will often result in increased water quality for human use. The objective here is to review the current state of lake and pond ecosystems, especially with regards to how biodiversity of these systems is affected by human disturbances. We begin with an introduction to the biology of small lake and pond ecosystems and discuss which factors drive changes in biodiversity in general. We then identify the most important anthropogenic disturbances and how they have affected lake and pond systems during the last 25 years, a period characterized by an increased rate of deterioration of freshwater systems, but also an increased awareness of the problem and even a start of countermeasures to restore disturbed systems. Based on this current knowledge and projections of long-term changes, for example in population and global climate, we try to predict the impact of these human disturbances on lake and pond systems to the 2025 time horizon.

Lakes and ponds as ecosystems

Both abiotic factors and biotic processes control the dynamics of lakes and ponds as natural systems (see for example Brönmark & Hansson 1998; Wetzel 2001). The abiotic conditions differ greatly between regions but also between lakes and ponds within a region. Thus, a lake provides an abiotic frame (Fig. 1) made up of all the physical and chemical characteristics of the specific lake and only organisms that have a fundamental niche that fits within this abiotic frame are able to survive and reproduce here. Important abiotic dimensions of the abiotic frame include lake morphology, sediment characteristics, nutrient concentrations, light availability, oxygen concentration, pH and temperature. Ponds may also be ephemeral habitats, i.e. some ponds are so small or shallow that they do not contain water all year, but dry out for shorter or longer periods. Naturally, organisms that inhabit such temporary ponds have to have specific adaptations to survive the dry stage or have a high ability to colonize newly water-filled habitats (Williams 1987).

The organisms able to survive and reproduce within the abiotic frame of a specific lake or pond affect each other through biotic interactions such as predation and competition for resources (Fig. 1). Competition for resources can be an important structuring force in aquatic communities and organisms that are able to gather resources faster or better will thrive at the expense of organisms with similar resource needs but with less competitive ability. Predation has been repeatedly shown to have complex effects on freshwater food chains, thereby affecting the dynamics and function of the whole system (see Kerfoot & Sih 1987; Carpenter 1988; Brönmark *et al*. 1997). Predation from the top predator level, the piscivores, may even result in a trophic cascade, i.e. not only having a direct effect on prey fish, but also indirectly affecting herbivores and primary producers, such as zooplankton and phytoplankton in pelagic food chains and snails and periphyton in benthic food chains.

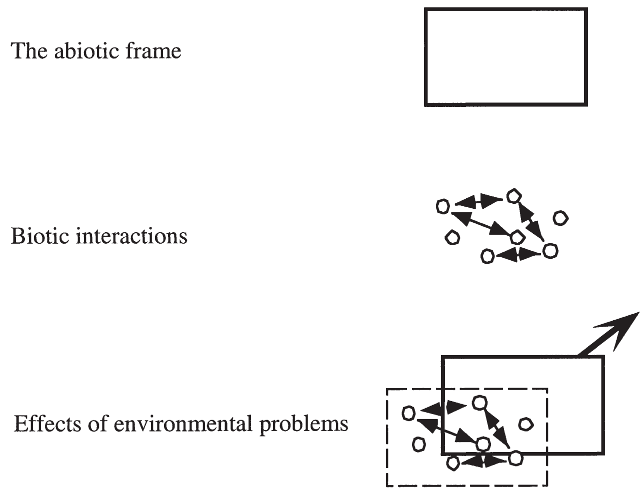

Figure 1 Schematic illustration of how lake and pond ecosystems can be viewed as consisting of an abiotic frame, including physical and chemical characteristics, defining which organism will survive and reproduce in a specific lake or pond. Within the abiotic frame biotic interactions among organisms will then further shape the community. Human impact, such as from pollution, will change the position of the abiotic frame, reducing the number of species able to survive in the system.

Anthropogenic disturbances, such as eutrophication or acidification may drastically alter the abiotic environment of a lake or pond, and thus change the position of the abiotic frame (Fig. 1). In consequence, the niche of a number of organisms will fall outside the abiotic frame and they will become extinct from that specific system. Human disturbances may have strong effects on the biodiversity of lakes and ponds and thereby affect their processes and function. Different disturbances will change the position of the frame in different directions and thereby give different compositions of the resulting pond or lake community.

Past environmental issues: identification and problem solving

Opportunities to predict the future are limited, but the future is not independent of what has happened in the past. Hence, to be able to predict events up to the year 2025 we have found it useful to review trends of environmental problems in lakes and ponds during the last 25 years, i.e. from 1975–2000. As a starting point we performed a search of the international scientific literature of the area, using the BIOSIS database (Data Star) in order to evaluate the frequency with which certain major environmental problems have been addressed scientifically during the past 25 years. From this literature survey we could identify a general pattern of how environmental problems have been dealt with over time. We also present available data on, for example, changes in actual levels of contaminants in lake and pond systems over the last 25 years.

Our retrospective literature search was performed on publications from 1975 to 2000, which includes two parts of the BIOSIS database, the 'BIYY' (1970–1992) and 'BIOL' (1993–present). The search terms included words in title, keywords and abstracts of published papers registered in BIOSIS (Data Star). All search terms were connected with one year at a time and either of the terms Lake$, or Freshwater, or the concept code for limnology (cc07514). The $ sign indicates that the search term is truncated; that is, all forms of that term are also included. For each year from 1975 to 2000, the number of hits of the search terms listed below was recorded and this number was then divided by the total number of publications registered in BIOSIS that year, thereby normalizing for any trend in total publication rate. The terms were:

- Eutrophication
- Acidification or acidifying or acidified
- Biodiversity or species richness
- Pollution or polluted
- Exotic or invasi$ (1993– also invasion, invasions and invasive)
- Heavy metal$ or mercury
- Global change or climate or climatic
- Ultraviolet radiation or ultraviolet or UV
- GMO or genetically modified organisms or transgenic
- Endocrine disrupt$

The scientific work regarding a specific environmental problem generally starts with a study period focusing on identification of the problem and assessment of the mechanisms behind it (Fig. 2). The initial interest in an environmental problem may be due to a sudden catastrophe that draws attention from society and media. Alternatively, the problem may be identified and discussed within the scientific community before the potential hazard becomes an environmental problem with stark headlines in the public media. The scientific penetration of a problem may initially be focused on assessments of causes, mechanisms and consequences, and in a later stage on the development of rehabilitation strategies to restore disturbed systems. This research intensive initial phase is characterized by a high publication rate in scientific journals (Fig. 2). The next phase is when the environmental problem has been addressed by the researchers and lands on the desks of politicians and administrators, a phase sometimes characterized by implementation of strategic plans to overcome the problem. During this phase the publication rate regarding the specific environmental problem is eventually decreasing. It is our belief that most environmental problems have, and will, follow this general pattern. An obvious example is acidification, which was identified as an environmental problem during the 1960s (Odén 1967) and then appeared in the scientific literature during the 1980–1990s, but which is now no longer a main issue in the scientific literature (Fig. 3). However, this does not mean that acidification is not an environmental problem anymore, only that it is no longer a main research area and has been forwarded to national and regional administrators (Fig. 2).

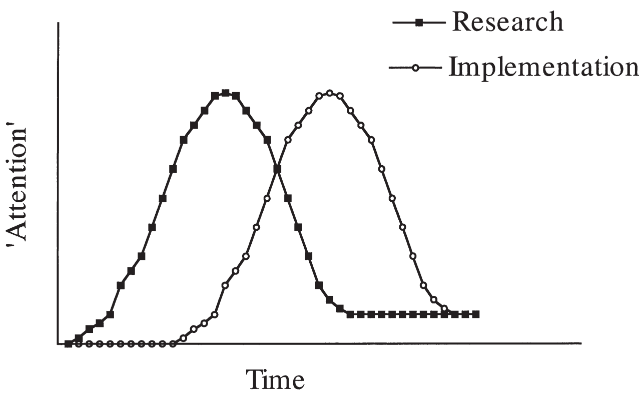

Figure 2 A schematic overview of how a new environmental threat is generally treated, starting with a research phase where the problem is identified and the causes, mechanisms and consequences are elucidated. The research phase is generally followed by a phase where rehabilitation strategies are implemented in society, i.e. a phase where the problem is dealt with mainly by administrators and decision makers. During this phase the frequency of studies of the threat in scientific journals is generally declining.

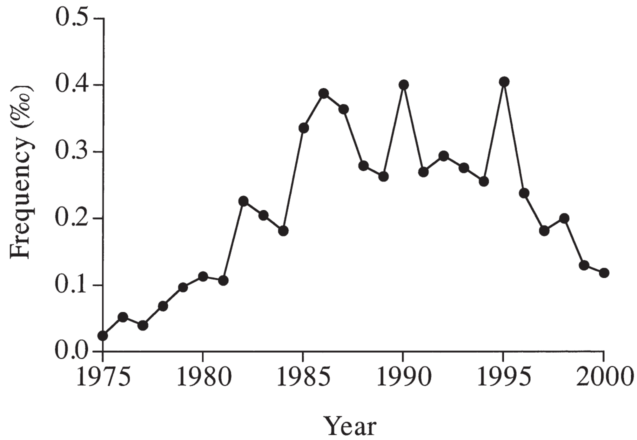

Figure 3 The frequency of the acidification problem in the international scientific literature during the 25 years from 1975 to 2000, showing an increase during the first ten years of the period and then a decline.

The advantage of using number of published scientific reports on a specific environmental issue is that instead of beliefs, impressions or memories, we are able to provide a quantitative estimate of how the importance of the issue has changed over time. Another advantage is that all issues are treated in a similar way. However, the approach also has several shortcomings, including that it may simply reflect contemporary scientific uncertanties or scientific 'bandwagons', or even the fickleness of interests as new 'bandwagons' enter the scene. Availability of funds from administrations using research to delay the expense of action may also obscure patterns. Further, the use of keywords may change over time where keywords in some fields become more specific and in others more general. Despite these potential drawbacks, we believe the approach has the potential to reveal some of the dynamics in the discovery, digestion and solution of an environmental problem. Moreover, the historic trends in scientific activity around a specific environmental problem may be used for rough predictions of what will be important issues tomorrow, and during the coming 25 years.

Below, we present the major environmental issues with regards to small lakes and ponds and their trends during the last 25 years and on this basis attempt to predict the status in 2025. However, we will first review patterns of biodiversity in ponds and lakes, which may be viewed as the ultimate response variable with which we can evaluate environmental disturbances.

BIODIVERSITY IN LAKES AND PONDS

Biodiversity may be broadly defined as the variety and variability among living organisms and the ecological complexes in which they occur. Biodiversity can be considered at different scales ranging from the gene to the ecosystem. The most commonly used meaning of biodiversity is at the level of species (organismal biodiversity) and that is also the level we will focus on here. However, it should be noted that drainage, land filling and other types of habitat destruction clearly decrease the availability of natural freshwater habitats in a region and thereby also affect biodiversity at the ecosystem level (ecosystem biodiversity).

Freshwater systems harbour a unique and diverse set of organisms. About 15% of all animal species that have been described today live in freshwater systems. More than 70 000 freshwater species from 570 families and 16 phyla have been described so far, but a similar number may remain to be detected and described as knowledge of taxonomy and distribution of freshwater organisms is poor in many parts of the world (Strayer 2001). In lakes and ponds, most animal species belong to crustaceans, rotifers, insects or oligochaetes. Planktonic and periphytic algae as well as different life forms of macrophytes are also speciose in lakes and ponds.

The global patterns of freshwater organism biodiversity are less clear than these of other habitats and in some groups latitudinal trends may even be the opposite of common patterns. For example, zooplankton are less diverse in tropical than in temperate lakes (Lévêque 2001). On a smaller spatial scale, biodiversity is determined by both abiotic and biotic factors. Abiotic factors include for example various climatic factors, water chemistry, habitat heterogeneity, habitat size and isolation. The availability of calcium, for example, determines the distribution of freshwater snails on a regional scale (Lodge *et al*. 1987). Biotic processes are important in freshwater systems; predation and competition may determine species diversity and, perhaps more importantly, species composition, and thereby the function and dynamics of the whole system. Changes in predation pressure by top predators may have complex, cascading effects down the food chain affecting the size and rates of many processes (see Carpenter 1988; Brönmark *et al*. 1997). All these factors operate at different spatial scales; for example, water chemistry may be a background environmental factor affecting the diversity of all freshwater habitats in a region, whereas at the local scale, within a pond, other factors such as habitat heterogeneity or predation may operate (Lodge *et al*. 1987; Wellborn *et al*. 1996). Also, many freshwater organisms, such as amphibians and many insects, have a complex life history where they spend some stages of the life cycle (e.g. the larval stage) in water and then metamorphose and spend the other stage (adults) in terrestrial environments. Factors affecting the growth and survival of the terrestrial stage will then affect the aquatic stage and, therefore, interactions in the terrestrial surroundings may have repercussions on freshwater biodiversity. Thus, freshwater biodiversity is affected by a number of factors, both abiotic and biotic, that operate at different spatial and temporal scales. Environmental disturbances may result in reduced biodiversity due to either direct lethal effects on organisms or due to more complex interactions between different factors.

During the last decade there has been an increasing concern about the ecological consequences of changes in biodiversity (Tilman 1999; Chapin *et al*. 2000; Loreau *et al*. 2001). Besides a direct loss of species, a reduction in biodiversity may have dramatic effects on ecosystem functioning as the number and composition of species also determine which organismal traits are present and can influence ecosystem processes. Species traits may mediate energy and material fluxes directly or indirectly through more or less complex, indirect interactions. Experimental studies have shown that plant productivity as well as dynamic variables such as variability and resilience increase with species richness (Tilman 1999). In freshwater systems the effect of species loss have so far mainly been studied using aquatic microbes as study organisms (McGrady-Steed *et al*. 1997; Naeem & Li 1997; Petchey *et al*. 1999), but recent contributions suggest that changes in biodiversity may affect freshwater ecosystem processes such as primary productivity (Lévêque 2001), detritus processing (Johnson & Malmqvist 2000) and nutrient transport at the water-sediment interface (Palmer *et al*. 1997; Mermillod-Blondin *et al*. 2002). Further, loss of species in higher trophic levels may have strong repercussion down the food chain (see Carpenter 1988, Brönmark *et al.* 1997).

Human impact on biodiversity

Extinction rates of freshwater species may be as high as for tropical rainforest systems (Riccardi & Rasmussen 1999), which are considered as being among the most stressed terrestrial systems on earth. Presently, more than 1100 freshwater invertebrates are endangered, a number that most certainly is too low as knowledge on smaller, less conspicuous or economically unimportant species is sparse and there is little or no monitoring of freshwater organisms in large parts of the world (Strayer 2001). Some groups seem to be more at risk than others. For example, 21 of the 297 North American freshwater clam and mussel species are already extinct and over 120 are threatened, and 30% of North American and 40% of European fish species are threatened. There is also a global decline in amphibian populations (e.g. Sarkar 1996; Houlahan *et al.* 2000), suggested to be caused by factors such as habitat destruction, introduction of exotic predators, acid rain, diseases and UV radiation. Many anthropogenic factors affect biodiversity in ponds and lakes and often several factors act in concert to cause the extinction of a certain species. For example, the number of threats affecting endangered freshwater species in the USA ranges from one to five per species (average 4.5; Richter *et al.* 1997). Changes in land use, atmospheric CO_2 concentration, nitrogen deposition, acid rain, climate and biotic exchanges are the most important determinants of biodiversity at the global scale (Sala *et al.* 2000). For lakes, land-use changes and invasion of exotic species will remain major drivers of biodiversity over the next century, whereas climate or deposition of nitrogen or CO_2 was predicted to have a low impact on biodiversity in the future (Sala *et al.* 2000). Agricultural non-point pollution resulting in increased nutrient loading and high concentrations of toxic contaminants, exotic species and habitat fragmentation are the three major threats to the freshwater fauna according to a North American survey (Richter *et al.* 1997). In the scientific literature, reduced biodiversity as a result of human activities has shown an increasing frequency (Fig. 4), and will most certainly continue to be a major issue during the coming 25 years.

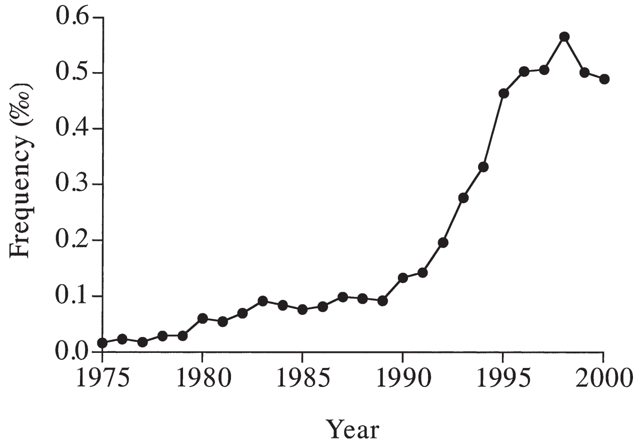

Figure 4 The frequency of biodiversity in the international scientific literature during the 25 years from 1975 to 2000.

ENVIRONMENTAL PROBLEMS AFFECTING BIODIVERSITY AND WATER QUALITY

Eutrophication

During the 1950s and 1960s many lakes in urban and agricultural areas experienced algal blooms, fish kills and disappearances of submerged macrophytes. At an early stage scientists proposed that phosphorus used in detergents was involved and research such as the pioneering whole lake experiment performed by Schindler (1974) confirmed the importance of phosphorus in the eutrophication process. Identification of the mechanisms behind eutrophication resulted in large societal resources being invested in water treatment plants, as well as restrictions on the use of fertilizers. The reduced load of nutrients to lakes and ponds in most developed countries has diminished the problem of eutrophication now, even though a number of buffering mechanisms hinder the return of freshwater systems to a pristine state. The scientific interest in eutrophication has been significant and relatively constant during the last 25 years, and has even risen in recent years (Fig. 5). This may be surprising given that both causes and mechanisms for eutrophication are known. One explanation may be that eutrophication has become a major concern in developing countries, leading to a continuously high publication rate. Despite this, we predict that eutrophication will have decreased in importance as an environmental disturbance to lake and pond systems in 2025.

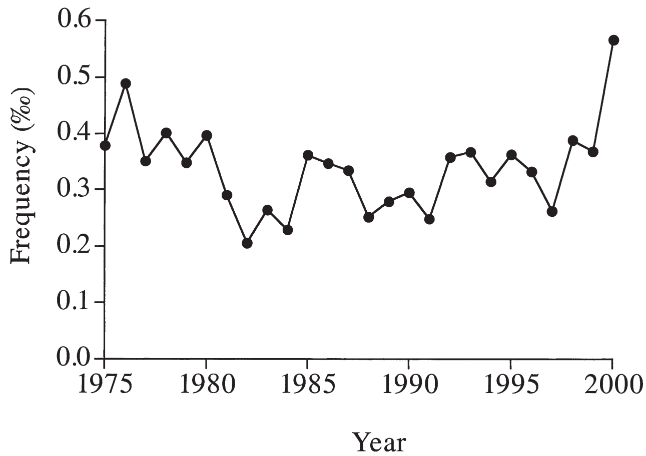

Figure 5 The frequency of the eutrophication problem in the international scientific literature during the 25 years from 1975 to 2000, showing no clear trend.

Acidification

In the industrialized part of the world, emissions of acidifying substances increased already in the late 1800s (Driscoll *et al.* 2001), but effects on biota were not documented before the 1960s (Gordon & Gorham 1963). When the pH in a lake or pond reaches values lower than 6, changes are detectable. At pH values of 5–6, the algal species diversity and biomass decrease considerably, leading to higher water transparency; a characteristic feature of acidified lakes (Stenson *et al.* 1993). The number of periphytic (attached) algal species is also reduced, resulting in dominance by a few acid tolerant genera, such as the filamentous green algae *Mougeotia*, which may cover the sediment surface completely (Lazarek 1985; Turner *et al.* 1987). Another acid tolerant group is mosses, especially *Sphagnum*, which is a genus characteristic of acidified lakes and ponds (Grahn 1985). Also the fauna becomes less diverse as acidification proceeds (Fryer, 1980; Havas *et al.* 1984; Locke 1992). Among the zooplankton, daphnids are severely affected by acidification, while the abundance of other cladocerans, such as calanoid copepods and *Bosmina*, may remain high (Stenson *et al.* 1993; Brett 1989). The species richness of fish is also severely affected by acidification, showing a clear negative relation with reduction in pH (Kretser *et al.* 1989; Rask *et al.* 1995; Driscoll *et al.* 2001).

Acidification was a major focus in the scientific literature from the middle of the 1980s to the middle of the 1990s (Fig. 3). Thereafter, research papers on acidification appeared less frequently, suggesting that the causes, mechanisms and consequences of acidification in lakes and ponds had become understood. Therefore, acidification is now mostly a political issue, as evidenced among other things by the many international treaties on reduced emissions of acidifying gases from combustion (Stoddard *et al.* 1999; Driscoll *et al.* 2001). Such agreements have led to a considerable decrease in sulphur emissions in most developed countries, as exemplified by changes in SO_2 deposits (Fig. 6; Gunn & Keller 1990; Stoddard *et al.* 1999). In contrast, the deposition of NO_x, which is mainly a result of vehicle transport, did not change during the 1980s and has only recently started to decrease (Fig. 6). In spite of the significant decrease in deposition of sulphuric acids only slight improvements of pH in lakes and ponds have been detected (Couture 1995; Forsberg *et al.* 1985; Gunn & Keller 1990; Mallory *et al.* 1998; Stoddard *et al.* 1999). Notwithstanding, we predict that the importance of acidification as a threat to lake and pond ecosystems will decrease in the future given a continued decrease in deposition rates of SO_2 and NO_x (but see Global differentiation).

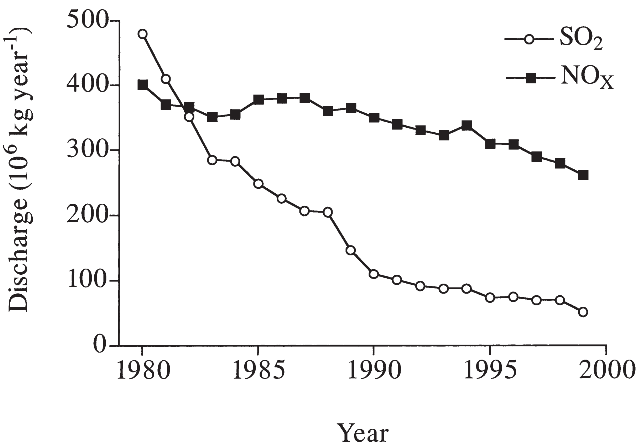

Figure 6 The discharge of SO_2 and NO_x over Sweden from 1980 to 1999, showing a clearly decreasing trend with respect to SO_2, but only a slight decrease in NO_x. (Source: Swedish Environmental Protection Agency, URL http://www.environ.se/)

Contamination

The most important contaminants in freshwater systems are heavy metals and organochlorine substances, which are both persistent pollutants, i.e. they are not broken down (metals) or take a very long time to degrade (organochlorines) (see Rand 1995; Mason 1996 for a general review of aquatic ecotoxicology). Some of these substances accumulate in the food chain with top carnivores having larger concentrations of the contaminant than organisms at lower trophic levels. They also bind to particles that fall out of the water column and become incorporated in the sediment. Sediment-dwelling organisms, such as mussels, oligochaetes and chironomids, are thus more exposed to contamination and commonly have large concentrations of heavy metals and/or organochlorines. Heavy metals and organochlorines have a number of effects on organisms, including direct toxic and longer-term effects such as carcinogenesis, neurological disorders, reduced growth, disabling of the immune system and reproductive disorders (Rand 1995; Mason 1996).

Heavy metals

Heavy metals are natural substances that enter lakes and ponds through natural weathering of rocks, volcanic activities and anthropogenic activities such as mining, smelting, different industrial processes, burning of fossil fuels and refuse incineration. Although problems with high levels of heavy metals in lakes are often the result of point source pollution, high levels of, for example, mercury in otherwise pristine lakes suggest that atmospheric transport may be important in some cases. Heavy metal concentrations in organisms are correlated with environmental variables of the lake and its watershed, such as pH, dissolved organic carbon (DOC), lake trophy, land use and temperature, and they differ in their propensity to biomagnify along the food chain (Chen *et al.* 2000). A recent study in a large number of lakes in Scandinavia and north-western Russia suggests that heavy metal pollution on the regional scale is now a minor ecological problem (Skjelkvåle *et al.* 2001), whereas on the local scale, some areas were still influenced by point source pollution from smelters. We believe that this pattern is globally representative; heavy metal pollution is a minor environmental problem in lakes and ponds at large geographical scales but may have strong adverse effects at the local scale due to point sources (see also Global differentiation later). However, methylated mercury may be an exception as it occurs at such high levels in areas with apparently pristine lakes that local authorities have been forced to enforce conservative advisories for human consumption of fish.

Organochlorines (OCs)

The chlorinated organic substances used as pesticides and in industry are hydrophobic, fat-soluble and biologically stable compounds that accumulate in the body fat of freshwater organisms. Restrictions on the use of OCs in most developed countries in the 1970s resulted in a reduced input of these contaminants from direct point-sources or from diffuse agricultural run-off. Since then there have been declining concentrations of, for instance, polychlorinated biphenyls (PCBs) and dichlorodiphenyltrichloroethane (DDT) in fish (Fig. 7), mussels and other freshwater organisms, with a more rapid decline in some substances (for example DDT) than in others (for example PCBs) (Loganathan & Kannan 1994). Today, atmospheric fall-out is the dominant input of OCs in lakes and ponds (Muir *et al.* 1990), resulting in organisms in pristine lakes in remote areas still having significant concentrations of OCs. Also, salmon migrating from the sea to spawn transport large amounts of PCB and DDT accumulated during their ocean life-stage to the spawning grounds in Alaskan lakes where it is accumulated in the food web (Ewald *et al.* 1998). In these lakes such biotransport is a more important source of persistent OCs than atmospheric fall-out. A number of factors affect the rate at which OCs accumulate in aquatic organisms, including concentrations in the surrounding medium, bioavailability, lipid content, growth rate, age and the trophic status of the lake or pond system (see Berglund *et al.* 2001).

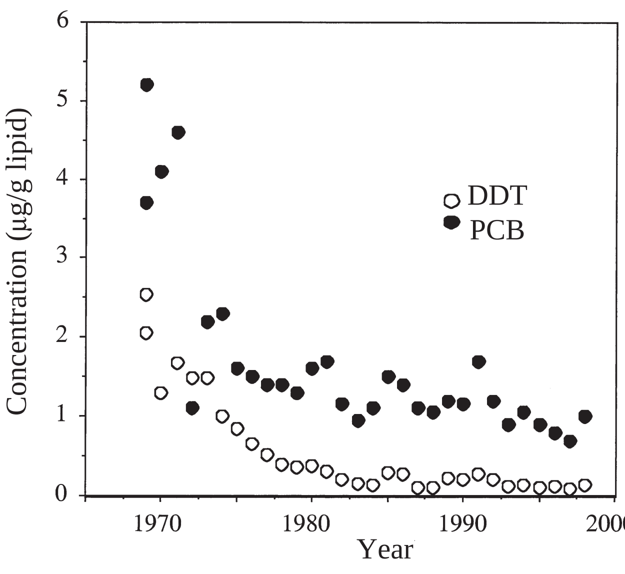

Figure 7 The concentration (μg g^{-1} lipid) of DDT and PCB in muscle tissue of northern pike (*Esox lucius*) from Lake Storvindeln, Sweden. (Source: Swedish Environmental Protection Agency, URL http://www.environ.se/)

Research on contamination, including heavy metals and OCs, is less emphasized in recent scientific literature, indicating that causes, mechanisms and risks are known, and that the problem has been forwarded to politicians and decision makers (Fig. 8). Although new types of OCs may cause problems in the future, we predict that they will be less of a problem in 25 years than they are now.

Endocrine disruptors

There has been increased interest in the importance of endocrine disruptors in aquatic systems (Fig. 9). An endocrine disruptor is a substance that changes the endocrine function and causes harmful effects on organisms or their offspring. Of particular interest are estrogenic substances that mimic steroid hormones. Aquatic organisms seem to be especially affected by endocrine disruption and it was morphologically abnormal male sexual organs in alligators, feminization of male fish and turtles and masculinization of

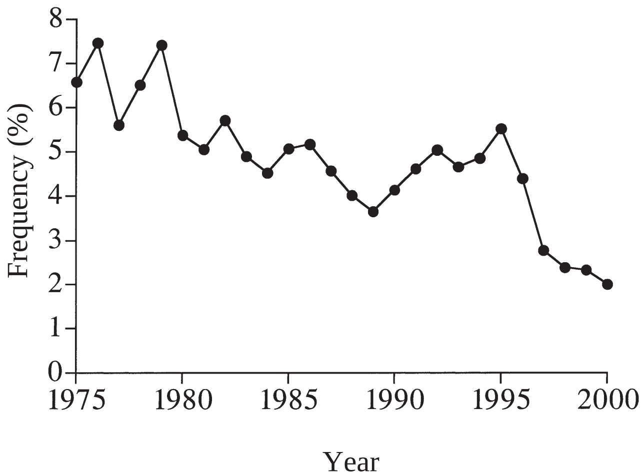

Figure 8 The frequency of the contamination problem in the international scientific literature during the 25 years from 1975 to 2000, showing a continuous decreasing trend.

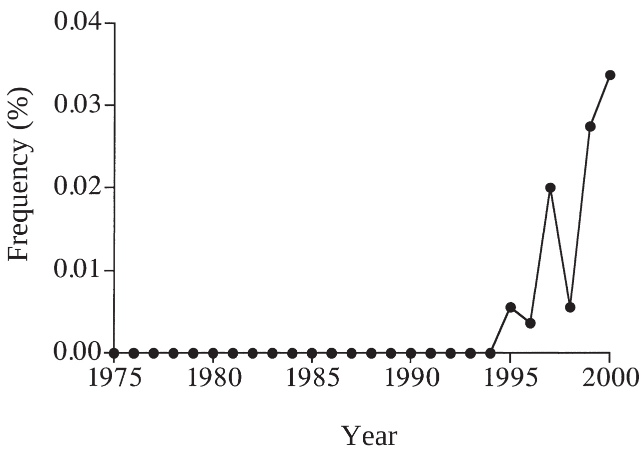

Figure 9 The frequency of endocrine disruptors in the international scientific literature during the 25 years from 1975 to 2000, showing a sudden increasing trend from the mid-1990s.

female fish in wastewater from pulp mills that first drew attention to the problem (see Mathiessen & Sumpter 1998; Kime 1998 for a review). Suggestions that endocrine disruptive compounds may be responsible for decreased sperm counts and increased testicular and breast cancers in humans have created a huge interest in the subject. Studies in England showed that male roach in water downstream from outlets of sewage treatment plants had signs of feminization, expressed as development of female sexual organs in parallel with the male organs (Jobling *et al.* 1998). The degree of feminization was related to the load of polluted water and it was suggested that remains of natural estrogenic hormones and synthetic estrogen from contraceptive pills in the effluent water were responsible. Laboratory studies have shown clear effects of these substances on different aspects of the reproductive cycle in fish (see Kime 1998). Other substances that are similar in structure to estrogen have also been shown to have endocrine disruptive effects, including substances such as chlorinated insectides and their degradation products, phtalates, dioxins, PCB and others. Further, these substances may act synergistically. However, although refined analytical methods have shown effects of endocrine disruptors in many species in a range of different aquatic habitats, it is still not clear to what degree this is a threat to their populations or whole aquatic ecosystems (Mathiessen 2000). There are presently no studies on how the dynamics of natural populations are affected by endocrine disruption.

Invasion by exotic species

Invasion by exotic species has in many cases resulted in loss of biodiversity and changes in community structure and ecosystem functioning (Mooney & Hobbs 2000). Aquatic habitats are particularly sensitive to invasions by exotic species because dispersal between freshwater systems is facilitated by human activities, but also because dispersal within a water system is rapid and often relies on passive transportation (Kolar & Lodge 2000)

A successful invasion of an exotic species can have dramatic effects on different organizational levels of the invaded system (Parker *et al.* 1999). At the population level, invaders may cause changes in size and age structure, distribution, density, population growth and may even drive populations to extinction causing reductions in biodiversity at the community level. In fact, more than 40% of the species listed as endangered or threatened in the USA are considered to be at risk due to competition or predation by exotic species (Pimentel *et al.* 2000). At the ecosystem level, invasion of exotic species may result in changes in nutrient dynamics, rates of resource acquisition, disturbance regimes and it may also change the physical habitat affecting biotic processes (Parker *et al.* 1999). All these changes have dramatic impacts on the biota of lakes and ponds, but invaders also cause huge economic losses including losses of goods and services as well as costs for control. Thus, identification of future invasive species and potential sites of invasion would be of great value both from an environmental and economical point of view. Successfully invading exotic species have been suggested to have certain traits in common, such as fast growth, short reproductive cycles, generalist nature with wide environmental tolerance, broad diets and mechanisms of efficient dispersal (see Riccardi & Rasmussen 1999). However, efficient control of invading species may require a more integrated approach where characteristics of both the invader and the invaded community are included (Mooney & Hobbs 2000; Kolar & Lodge 2001).

A large number of plants, invertebrates and fish have invaded lakes and ponds worldwide. Invading aquatic weeds seriously interfere with human activities, for example by hindering navigation, reducing water movement in irrigation or drainage canals and disturbing the operation of hydroelectric power plants. An extensive cover of aquatic weeds also affects other freshwater biota through, for example, increased light attenuation, reduced oxygen levels and changed nutrient cycles. There are many example of invading invertebrates, but perhaps the most spectacular example is the zebra mussel, *Dreissena polymorpha*, native to the Black and Caspian Seas (see Ludyanskiy *et al.* 1993 for a review on zebra mussel effects). The zebra mussels attach to hard surfaces and can reach densities of up to 700 000 mussels per m^2 and this has caused substantial economic losses as mussels colonize water intake pipes and other man-made hard structures. Mussels have also had strong effects on natural systems, including extinction of native unionid mussels and a redirection of carbon flow from the pelagic to the benthic habitats. The most well known example of adverse effects from invading fish species is, of course, the nile perch, *Lates niloticus*, which was introduced to the large Lake Victoria in the early 1960s to improve fisheries. However, it is clear that also in a majority of smaller lakes and ponds in the vicinity of larger human populations, the fish community has been manipulated in one way or another to increase fisheries yields or for other reasons. This also includes introduction of fish species from other lakes in the region, from other regions as well as from other continents (Rahel 2000).

The problem of organisms invading as a result of human activities is reflected in an increasing number of scientific papers published in this area (Fig. 10). Recent reviews on the threats to the biodiversity of fresh waters highlight the importance of the invasion of exotic species (Richter *et al.* 1997; Sala *et al.* 2000). Thus, reduced biodiversity in fresh waters due to invasion of exotics will most certainly be a major environmental concern during the coming 25 years.

Genetically modified organisms (GMO)

The main reasons for modifying an organism's gene sequence is to change its characteristics in a way that improves its human use, for example by improving its resistance to diseases or increasing its growth rate. Fish transgenic for growth hormone genes grow faster and become larger than non-transgenic fish (Hill *et al.* 2000). A major risk with trans-

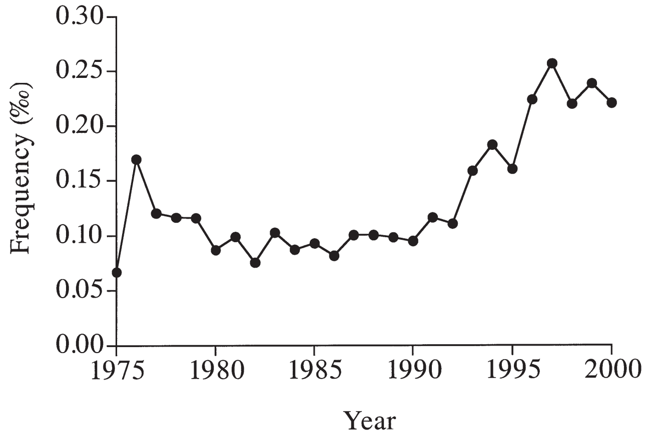

Figure 10 The frequency of exotic species in the international scientific literature during the 25 years from 1975 to 2000, showing a steady increase throughout the period.

genic fish seems to be that they escape from fish farms, interact with wild ancestors, and in this way become new actors in natural ecosystems (Reichhart 2000). For example, in many fish species larger males have a selective mating advantage and a higher reproductive success, suggesting that fast-growing transgenics may efficiently invade natural populations. Theoretical models have further suggested that if the high growth rate is combined with a viability disadvantage, population fitness is reduced and eventually results in extinction of the natural population (Hedrick 2001).

GMOs are one of the more recent potential environmental problems, which did not appear in the scientific literature until the end of the 1980s (Fig. 11). With respect to freshwater systems, they have recently received increasing attention and now show a clear increasing trend in the literature, suggesting that they will become an important future issue (Fig.11). Whether they will become a major environmental problem or not depends on policy and decision-makers, as well as on the consumer market. The

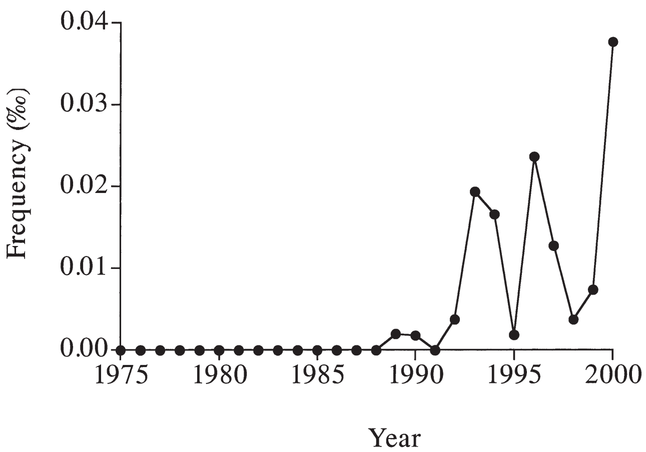

Figure 11 The frequency of genetically modified organisms in the international scientific literature during the 25 years from 1975 to 2000, showing an irregular increasing trend throughout the period.

current global resistance to consumption of genetically-modified crops such as soy beans and corn, may give a hint of a coming resistance against eating transgenic fish; a notion strengthened by the current economical problems the GMO industry is facing (Reichhart 2000).

GLOBAL CHANGE

Temperature increase

Long-term data indicate that the mean water temperature in some areas has increased (Schindler *et al.* 1996). A further increase in water temperature will most likely lead to changes in seasonal temperature patterns in lakes affecting, for example, stratification and the date of spring ice melt. Regional hydrology, such as reduction in streamflow and lake water levels, may also be affected. Moreover, changes in lake volume and thermal structure, as well as alterations in catchment inputs of detritus and nutrients and an increase in the frequency of extreme events such as droughts and floods may be expected (Sala *et al.* 2000). Hence, synergistic, and often non-intuitive, effects between a possible increase in temperature and changes in the hydrological regime of the catchment, may have profound effects on the amounts of sediment and nutrients reaching lakes and ponds.

Changes in the abiotic frame of lakes and ponds induced by global warming, such as changes in nutrient input and heat loading may have strong effects on the biota, altering the species composition of phytoplankton, zooplankton, benthic invertebrates and fish (Magnusson *et al.* 1997). Temperature is of fundamental importance for the life history of aquatic organisms affecting, for example, metabolic and development rates. Hence, an increase in temperature may affect the hatching date with far reaching effects on for example size at hatching, food availability and over-winter survival (see Chen & Folt 1996). Bioenergetic modelling of lake trout in arctic lakes indicate that increased temperatures and associated higher metabolic rates would result in higher food requirements for juvenile trout to reach the size needed for over-winter survival (McDonald *et al.* 1996). With present resource availability young-of-the-year trout would not survive their first winter and the concomitant change in predation pressure from trout would alter the structure and dynamics of the whole system. Such changes in ecosystem structure due to global warming will make the system more vulnerable to invasions by exotic species (Kolar & Lodge 2000) and, in addition, indigenous species may change their distribution pattern in response to temperature increase with an expansion of warm water species to higher latitudes (Shuter & Post 1990).

Increasing temperature has also been predicted to result in changed distribution of vector-borne diseases, such as malaria (caused by *Plasmodium falciparum* carried by mosquitoes) with an expansion into regions that at present are too cool for their persistence (Martin & Lefebvre 1995). Recent models predict, however, that the distribution of

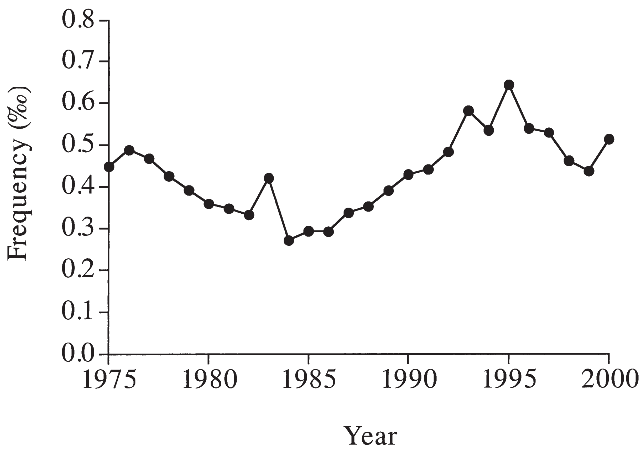

Figure 12 The frequency of climate in the international scientific literature during the 25 years from 1975 to 2000, showing no clear trend.

Table 1 Predictions of the importance of some major threats to lakes and ponds in 2025 divided into developed and developing countries. In developed countries we predict a decrease in the importance of eutrophication, acidification, heavy metals and organochlorines, whereas all other threats may become more of a problem in 25 years than they are at present. With respect to developing countries, all the major environmental threats may increase in magnitude during the coming 25 years. The ultimate response variable, biodiversity, is predicted to decline both in developed and developing countries.

Threats	*Trends 2025*	
	Developed countries	*Developing countries*
Eutrophication	Decreasing importance	Increasing significantly in importance
Acidification	Decreasing importance	Increasing significantly in importance
Heavy metals	Decreasing importance	Increasing significantly in importance
Organochlorines	Decreasing importance	Increasing significantly in importance
Endocrine disruptors	Increasing importance	Increasing importance
Exotic species	Increasing significantly in importance	Increasing significantly in importance
GMO	Increasing importance	Increasing importance
Climate change	Increasing significantly in importance	Increasing significantly in importance
UV	Increasing significantly in importance	Increasing significantly in importance
To biodiversity	Increasing significantly in importance	Increasing significantly in importance

malaria will change only insignificantly despite temperature increase (Rogers & Randolph 2000). The argument for the latter scenario is that the interactions between host and vector are complex and that the predictive models have included insufficient variables in their calculations so far. Hence, at present the main issue regarding future developments of vector-borne diseases may be to sort out differences in approaches and predictions from several modelling approaches.

Published research on climate was relatively frequent already 25 years ago and the increase since then has been surprisingly slow regarding freshwater ecosystems, given the enormous focus this problem has received in the media (Fig. 12). However, since the effects of climatic changes, albeit documented, have not yet affected human everyday life, an increase in significance of this environmental problem may be predicted during the coming 25 years (Table 1).

Ultraviolet radiation (UV)

Use of chlorofluorocarbons (CFCs) has caused the ozone concentration in the upper atmosphere to decline, with the consequence that 'holes' are formed in the ozone layer and higher amounts of UV radiation are reaching earth's surface, especially at high latitudes (see Madronich 1994). Large amounts of UV radiation are very harmful to organisms and affect many of the fundamental cell processes, including DNA replication and cell metabolism. UV-B radiation (280–320 nm) has been shown to damage DNA of freshwater organisms ranging from bacteria to fish (Karentz *et al*. 1994; Siebeck *et al*. 1994).

The UV radiation attenuates rapidly through the water column (Williamson *et al*. 1996), and only a small proportion of the most harmful part that reaches the surface of the earth, namely UV–B radiation, penetrates deeper than 8 m in clear water. In humic lakes, where the amount of DOC is high, it may only reach a depth of a few centimetres (Williamson 1995; Schindler *et al*. 1996). However, exposure to UV-B radiation may result in a breakdown of recalcitrant DOC to smaller molecules that can be used by bacteria and thus result in a higher bacterial production (Williamson 1995; Lindell *et al*. 1995). However, the reaction between UV and DOC may also result in the formation of harmful substances, such as hydroxide radicals and hydrogen peroxide (H_2O_2), which may inhibit bacterial production (Xenopoulos & Bird 1997).

The sensitivity to UV radiation differs among organisms, for example biomass of benthic algae was reduced when exposed to high levels of UV radiation, but in the presence of benthic grazers (chironomid larvae), the patterns were reversed with benthic algae having greater biomass at the higher UV radiation (Bothwell *et al*. 1994). The likely explanation for these results is that although the benthic algae were negatively affected by UV radiation, their grazers (the chironomids) were even more sensitive. In this way, UV radiation and other environmental hazards may indirectly affect the equilibria between different groups of organisms, such as consumers and producers. Another notable example of some organisms being better adapted to UV radiation is that certain zooplankton groups have pigments protecting them from harmful radiation; in *Daphnia*, the pigment melanin functions as a sun screen (Hill 1992). Copepods, on the other

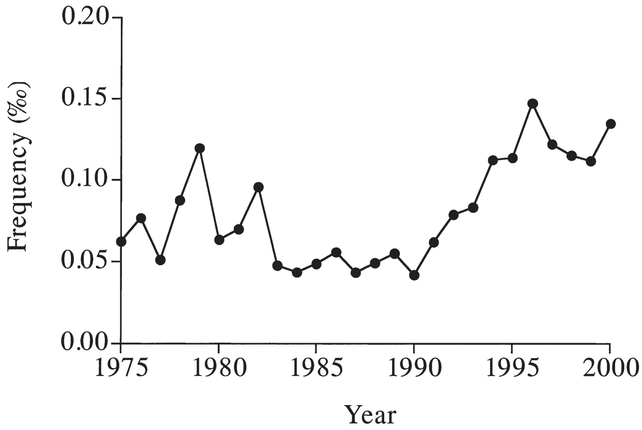

Figure 13 The frequency of ultraviolet radiation in the international scientific literature during the 25 years from 1975 to 2000, showing an increasing trend from about 1990.

hand, have the red pigment astaxanthin which functions as an antioxidant by neutralizing carcinogenic substances induced by UV radiation. Interestingly, copepods seem to adjust their level of pigmentation in relation to the prevailing risk; being highly pigmented but vulnerable to predators, or being transparent but unprotected against UV radiation (Hansson 2000). Hence, some aquatic organisms seem to be better adapted than others to a possibly increasing UV influx, and such organisms may be predicted to play a more important role in future ecosystems. Increase in UV radiation may therefore lead to considerable alterations in the composition of aquatic communities, especially in shallow, clear-water lakes and ponds. However, effects of increasing UV radiation will most probably be less catastrophic in aquatic than in terrestrial systems, since the water surrounding the organisms absorbs much of the UV radiation.

The frequency of UV-related papers in the literature has shown an increasing trend suggesting that causes, mechanisms and consequences are still incompletely known (Fig. 13). This suggests that problems related to UV also will be a major issue in the literature in the future.

Synergistic effects

The influence of each of the global environmental hazards on ecosystem processes is considerable. Less easily realized are the effects of combined environmental problems, which have already been shown to lead to non-intuitive synergistic responses in aquatic ecosystems (Schindler 1998). One such example is that the increase in temperature has led to a drier climate, a reduced stream flow and, thereby, a reduction in the export of DOC from terrestrial habitats to lakes and ponds (Schindler *et al.* 1996). The lower DOC input has resulted in clearer lakes where the UV radiation penetrates deeper. This is exactly what happens during the acidification process; the effect of global warming accelerates the increase in transparency of the water in lakes and ponds subject to acidification, which in turn increases UV penetration through the water column.

Another example of synergistic effects initiated by human activities is that an increased temperature will lead to an increased evaporation and reduced precipitation, and thereby a reduced water flow through streams and lakes. Since the influx of UV radiation is increasing, organisms in shallow water may be strongly affected by UV radiation. This notion may be especially valid for ponds and shallow parts of lakes, and may be crucial if the water level is further reduced due to an increase in temperature. An example of such synergies between climate-induced drought and increased UV radiation is that reduced water level at oviposition sites caused an increased embryo mortality in amphibians due to greater exposure to UV radiation, followed by infections by the fungus *Saprolegnia ferax* (Kiesecker *et al.* 2001). Hence, higher temperature led to lower water levels, exposing the amphibian embryos to an increasing intensity of UV radiation, which, in turn, reduced resistance to fungal infection.

Thus, environmental hazards may act together to strengthen an effect, but may also lead to completely unexpected consequences. There are, unfortunately, reasons to believe that the future will bring additional unexpected events caused by such synergistic effects among environmental problems; effects that are almost impossible to predict.

DEVELOPMENT OF REHABILITATION STRATEGIES

Restoration of degraded freshwater systems

Disturbances caused by such large-scale processes as climate change may not be reversible, but in many other situations it is possible to restore or, at least, rehabilitate, degraded lakes or ponds that have been subject to environmental disturbances such as eutrophication or acidification. Since water is such an important resource for human populations, large efforts have been made to restore disturbed freshwater systems to more pristine conditions. Moss (2000) suggested that the approach used to conserve biodiversity in terrestrial habitats with an emphasis on conserving charismatic species, should not be applied to freshwater systems. Instead, the functional value of the system should be in focus in conservation and restoration projects in fresh waters. Maintenance of particular species is not that important as species could be substituted without losing the functional value (Moss 2000).

A multitude of restoration methods have been developed for degraded aquatic ecosystems and we will provide only two examples of methods that have been used frequently and with varying success. The first example deals with measures against lake eutrophication. After it was realized that the eutrophication process was caused by an excess of nutrients (Schindler 1974), a number of measures was taken to reduce nutrient input to lakes, including extension of water treatment plants and restrictions of fertilizer use in agriculture.

However, even though nutrient input was reduced, many eutrophicated lakes remained in the disturbed state with algal blooms and fish kills (Kitchell1992; Hansson *et al.* 1998; Scheffer 1998; Hansson & Bergman 1999). Research showed that lakes could exist in two alternative states under similar nutrient loads, one dominated by phytoplankton resulting in turbid water and the other dominated by submerged macrophytes and clear water (Timms & Moss 1984; Scheffer 1990). Both states are stable and buffered by a number of mechanisms and, thus, a lot of effort is needed to shift the system to the clear-water state. In aquatic systems, one method to 'push' the system is called 'biomanipulation' and refers to the manipulation of biota, usually fish, in order to change the state of the lake (Shapiro *et al.* 1975; Shapiro & Wright 1984). Biomanipulations are generally performed by reducing the abundance of zooplanktivorous fish (usually cyprinids), either by addition of piscivorous fish, or by manually removing undesired fish, for example by trawling. The idea is that if the amount of planktivorous fish is sufficiently reduced, the predation pressure on large zooplankters will decrease and the grazing rate on algae will increase. In this way the likelihood of algal blooms will decrease and the water transparency increase (Benndorf 1990; Hansson *et al.* 1998).

One of the few ways of making an acidified lake return to its former pH is to add lime (calcium carbonate, $CaCO_3$). Liming leads to rapid increases in pH and alkalinity, and reductions in transparency and metal concentrations. Generally there is also an increase in species diversity and biomass of most organisms (Eriksson *et al.* 1983; Stenson *et al.* 1993). These improvements are partly the result of increasing pH, and partly a result of lower metal concentrations, allowing metal-sensitive organisms, such as fish, to recolonize the system (Stenson *et al.* 1993). Although liming may improve the conditions in specific lakes and ponds, and the SO_2 discharge has been reduced, it certainly does not solve the acidification problem. Discharge of nitrous oxides is still high and acid rain continues to fall on the ground, on the sea, and on lakes and ponds. The causes of acid rain are already known; no more research is needed, only political courage to redress the problem.

IMPLEMENTATION OF STRATEGIC PLANS

Global, regional and national political efforts

Although restoration of degraded systems on a local scale is one way to reduce the effects of environmental problems caused by human activities, pollution as such has no county, federation or national borders, but is in many cases spread globally by wind and water. Hence, one of the most important actions that can be taken against environmental problems is international agreements. Although such agreements may seem inefficient and slow, it may be the only way to reach a sustainable use of resources and an acceptable level of emissions on the international scale. With respect to water resources, this statement may be even clearer when it is realised that the world population has tripled during the 20th century, whereas the water use by humans has increased sixfold! Hence, there is no doubt that the demand for water resources of good quality is increasing, especially in coastal areas and in developing countries. This rapidly increasing demand has forced national, regional and local administrations to improve the planning and protection of water resources. For example, the European Commission has passed the 'Water Framework Directive' (URL http://europa.eu.int/comm/environment/water/), which is a strategic plan agreed upon by all member states with the ultimate aim of completely stopping pollution of freshwater resources by dangerous substances. The Directive is based upon two important strategies, namely that the management of water resources should be based on catchment areas where all water resources should be monitored and classified according to an ecological quality gradient stating if the water is of 'high', 'good' or 'bad' quality. Moreover, the principle that 'the polluter pays' should be applied, which means that if someone wants to use and pollute water resources, this user should pay for any damage caused to the common water resource (see also Johnson *et al.* 2001). Several other important international agreements have been signed, including Agenda 21 (URL http://www.igc.org/habitat/agenda21/) and several initiatives from the United Nations. One such recent initiative regarding freshwater resources is the UNESCO World Water Assessment Programme (URL http://www.unesco.org/water/wwap/) aimed at making the use of fresh waters more sustainable and reducing the number of people not having access to clean water.

Diversified use of water resources and 'the tragedy of the commons'

In some countries, lakes, ponds and rivers are common resources available to all citizens; that is, nobody owns the water. This is a positive way of administrating a resource that everyone needs. However, since the resource has no formal owner nobody takes care of it, and, even worse, a main opinion is that a common resource can be used without responsibility for the consequences; surface fresh waters are still used as recipients of waste substances from human activities, including industrial, urban and agricultural runoff. This means that one of the resources most urgently needed for maintaining life is managed in a non-sustainable way, leading to deterioration of drinking water resources, and reduced quality of the resource with respect to for instance recreation, fishing and tourism. This 'tragedy of the commons' (Hardin 1968) has also lead to the common attitude among decision makers and local authorities that lakes, wetlands and running waters are problems that have to be 'restored', instead of being resources for society. Surface waters are seldom viewed as resources, whereas it is self-evident that agricultural land and forests are of great importance for society; they are resources that we cultivate and manage. Time may be ripe for a change of attitude, to start viewing lakes and ponds as systems of the same importance as forests and agricultural land to be used, provided they are managed and cultivated in a sustainable way. The benefit of such a change of attitude is that if it pays to use water, then the users will also manage the resource in a sustainable way, leading to an improved water quality. Of course, not all surface waters within a catchment are suitable for all types of use. Some lakes and wetlands may, for example, be assigned for 'production' of biodiversity or for protection of some rare plant or animal species. Others may be more fit for delivering drinking water, whereas wetlands close to urban areas may be used for wastewater treatment. Some lakes, and their surroundings, may be used for recreation purposes such as swimming and boating. Finally, eutrophicated lakes may be suitable for large-scale fish farming. Such 'diversified use' of water resources in a catchment area may improve the overall water quality considerably, since all potential 'products' require a good water quality. To be able to use and manage water resources in this way, a plan for all water bodies in the catchment has to be made. Diversified use and planning of water resources within a catchment area may thus entail several positive results, including overall improved water quality, improved economy within the region, reduced costs for drinking water retrieval, and improved recreational conditions for citizens, as well as motivated and engaged users of water resources.

GLOBAL DIFFERENTIATION

Much of the above, for example effects of contaminants on lake and pond systems, has been based on patterns found in developed countries where industrialization caused many environmental problems, but where large efforts have been made to reduce the effects of at least point-source pollution. Developing countries, especially in the tropics, are facing problems at a completely different scale. Urbanization has resulted in strong pressure on freshwater systems for human consumption, while, simultaneously, untreated effluents from the same urban areas increasingly pollute these water sources. At the same time resources harvested from freshwater systems, such as plants, invertebrates and fish, constitute important parts of the diet in many developing countries. Water in these areas is thus, and will increasingly become, a limiting resource for human development and the importance of lakes and ponds as habitats for a diverse, natural biota will be secondary to the management of these systems for human needs.

Deforestation and increasing agricultural expansion directly affect lake and pond systems in developing countries through habitat destruction, including land filling, sedimentation, and water-level reductions after irrigation, but indirect effects are also increasing in importance. The economy in developing countries is mainly based on agriculture and depends on intensive use of pesticides to improve productivity, creating a major problem of contamination of freshwater habitats (Lacher & Goldstein 1997). The use of pesticides in developing countries approaches that of, or is even higher than in, developed countries. At the same time legislation against organochlorine pesticides is less restrictive and safety measures to prohibit environmental effects are frequently not applied. Compounds that are banned in developed countries or new compounds not registered in their country of origin are exported for use in developing countries. Recent outbreaks of malaria have, for example, led to reintroduction of DDT in some areas. Further, although knowledge on the effects of contaminants in lakes in northern latitudes is incomplete, understanding of how they operate in tropical environments is negligible (Lacher & Goldstein 1997; Castillo *et al.* 1997). Freshwater habitats in the tropics differ from those in temperate zones in physical, chemical and biological attributes and, for example, toxicity of contaminants may be higher in the tropics due to temperature effects on solubility, uptake and bioconcentration.

The use of organochlorines in the tropics is not just of concern for countries in this region. Organochlorines are atmospherically transported from tropical regions, where pollutants are volatilized on the ground, towards the polar regions of the globe where the vapours are condensed and washed out. The 'condensation point' differs among organochlorine substances resulting in a global fractionation or distillation (Wania & Mackay 1993). DDT and PCB congeners, for example, which are considered 'semivolatile', are expected to deposit in temperate regions and potentially result in higher concentrations of these contaminants in the biota in deposition areas than in source areas (Larsson *et al.* 1995).

Increasing rates of waste disposal in lakes in developing countries will cause eutrophication problems. Industrialization in developing regions will also increase the emission of sulphur and although sulphur emissions are declining in Europe and North America they are rising in many developing countries around the world (Galloway 1995). Freshwater habitats in many areas of the world hitherto unaffected by acidic rain are at serious risk of acidification, as sulphur emissions exceed critical loads (Kuylenstierna *et al.* 2001). Further, as noted above, many of the examples of exotic species that have had the greatest impacts on lake and pond systems come from the tropics and there is no reason to believe that this will change in the future.

In an optimistic scenario, the developing countries will not make the same environmental mistakes as the developed countries, errors that are now costly to remedy. Policy makers and decision makers in developing countries may draw conclusions based on experiences from temperate systems when choosing among developmental pathways and thereby avoid errors made during the industrial era in Europe and North America. However, as pointed out above, tropical freshwater systems do not necessarily react to disturbances in the same way as temperate systems, and more research is needed. Economic aid from developed countries that is directed towards environmental conservation is also crucial for the future.

More pessimistically, it must be noted that in countries where the population increase results in a doubling of populations every 25–35 years, all aspects of the infrastructure need to increase at the same rate just to maintain present-day standards (Lacher & Goldstein 1997). Thus, the pressure on environmental values, especially water resources, will be tremendous and Lacher and Goldstein (1997) predict that environmental quality is doomed to decline in developing countries in foreseeable time.

POTENTIAL STATES OF PONDS AND LAKES IN 2025

Our review of the scientific literature on environmental threats to lakes and ponds suggests that research on an environmental threat follows a certain pattern starting with a period when the problem is identified (Fig. 2). Then follows a period of intense research activity mirrored in an increasing number of published papers in the area. When the mechanisms behind the problem have been identified more work can be focused on strategies to reduce the threat and possible ways to restore the disturbed systems. The environmental problem is then no longer the researchers' main responsibility, but instead the problem is taken over by politicians and administrators, resulting eventually in a decreasing production of scientific papers related to the problem. Thus, an analysis of the pattern of past scientific citations may be a tool for making predictions regarding the future importance of an environmental problem. Major threats to lakes and ponds as a resource for humans and as natural ecosystems include well-known problems like eutrophication, acidification and contamination, for which causes, mechanisms and consequences are known. In most cases, these problems have left the researchers' desks and will, during the coming 25 years, mainly be dealt with by environmental administrators and decision makers. Hence, we predict that the threats arising from these factors will be lower in 2025 than they are at present (Table 1). This conclusion should encourage continued efforts, as it illustrates that the hard work with environmental issues is not in vain. However, in developing countries, where priorities other than environmental conservation are fundamental, we predict that eutrophication, acidification and contamination by toxic substances will increase as threats to freshwater resources and ecosystems (Table 1).

Unfortunately, as the mechanisms of environmental treats are identified and we learn how to minimize their effects on natural systems, new environmental threats arise. With respect to large-scale climatic changes and increased UV radiation there are reasons to believe that they will become increasing threats to all freshwater systems (Table 1). Further, due to increased spread of organisms throughout the world, a higher frequency of successful invaders into lake and pond ecosystems is expected and we predict that this threat will be more severe in 2025 than at present. There are also recently discovered threats that will require more attention in the future. The use of complex chemicals that are similar in structure to hormones has resulted in reproductive disturbances in several groups of organisms. These substances occur in low concentrations, but they are disposed in wastewater and will finally end up in aquatic ecosystems. Aquatic organisms are predicted to be more severely affected by these endocrine disruptors than terrestrial organisms. Moreover, the development and use of GMOs will probably increase in the future, although there are yet no reports of whether GMOs may act as environmental threats to lake and pond ecosystems. The importance of these potential environmental threats in the year 2025 is difficult to predict, as their effects are still not fully understood. However, since the use of hormone-like substances, as well as the commercial interest in manipulating genomes, is increasing, we may predict that both endocrine disruptors and GMOs will have increased in importance as environmental threats by the year 2025 (Table 1). So far, we have made predictions for each environmental threat individually, but naturally lake and pond systems will be exposed to several threats at any one time creating massive potential for synergistic effects. Which threats will be involved, which synergistic effects they will have and how strong these effects will be is impossible to predict, but it is clear that some of the environmental problems act synergistically.

With respect to biodiversity, our forecast is mostly pessimistic, despite the large efforts made to restore habitats for threatened organisms. We therefore predict that biodiversity in fresh waters will in most places have decreased considerably by the year 2025. This will also have effects on the properties and functioning of pond and lake ecosystems. Recent studies suggest that species are not lost randomly from disturbed communities, but that species in the upper trophic levels may have a higher probability of extinction (Petchey *et al.* 1999). If this is true also for other compartments of pond and lake ecosystems we may expect strong

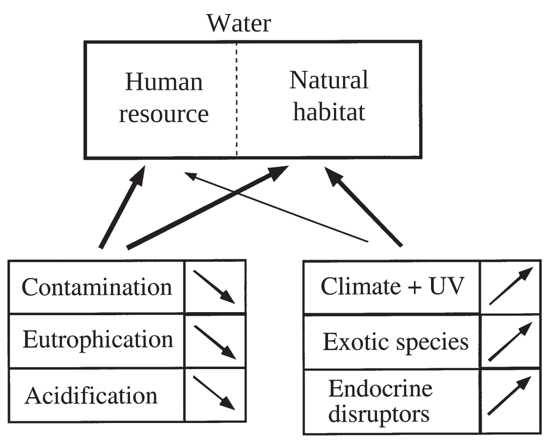

Figure 14 Water as a human resource and as a natural ecosystem in relation to 'old', well known environmental threats (for example, contamination, eutrophication and acidification) and 'new' threats (for example different aspects of global change, invasion of exotic species and pollution by endocrine disruptors)

effects of species loss through changes in the strength and direction of indirect interactions emanating from higher trophic levels. Such changes in interaction pathways should have strong effects on lake and pond ecosystem properties and processes, such as turbidity, productivity, nutrient turnover, and decomposition rates, and thereby affect the systems as habitats for freshwater organisms, as well as their potential as resources for human use.

Our review on environmental threats to lakes and ponds suggests that 'old' problems such as eutrophication, acidification and contamination, may become less of a problem in the future, whereas 'new' threats such as global warming, UV radiation, exotic species, and endocrine disruptors most likely will increase in importance (Fig. 14). Interestingly, the old problems severely affect freshwater systems both as human resources and as natural ecosystems. The new threats, however, are primarily affecting fresh waters as natural habitats, whereas the direct effects on water as a human resource are less pronounced (Fig. 14). This may indicate that the incentive for politicians and decision makers to instigate measures against the new threats will be lower than for the old ones.

This overview of environmental threats does not give an entirely optimistic view of the status of lake and pond ecosystems in 2025. However, it clearly points out some positive trends showing that the work on environmental issues has been fruitful. Although our use of databases in the survey of historical scientific literature can help us identify trends for existing environmental threats, it cannot identify future, yet unknown, problems. Hence, we will most probably see new threats making headlines in the media in the future. However, the growing concern for environmental problems in most developed countries, implementation of new environmental strategies and administrations, as well as interest in international agreements, are other positive signs of changes that will improve our possibilities to handle new threats.

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