Ambio 2021, 50:261–265
https://doi.org/10.1007/s13280-020-01441-6

EDITORIAL

Acidification of inland waters

This article belongs to Ambio's 50th Anniversary Collection. Theme: Acidification

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Published online: 8 December 2020

Acidification was one of the most recognized environmental concerns of the late twentieth century. The industrial revolution and its rapid increase in the combustion of coal and oil resulted in emissions to the atmosphere of oxides of sulfur and nitrogen, followed by deposition on land and waters. The effects are manifold. Soils get acidified and forest growth is impaired, metals are mobilized as the groundwater gets acidic; this results in increased metal concentrations in drinking water wells, corrosion is accelerated, and our cultural heritage is degraded as statues and other constructions from stones with calcium carbonate dissolve.

Being the recipients of water that runs off the surrounding landscape, inland waters—streams, rivers, and lakes—are particularly vulnerable. Lakes integrate processes in the surrounding watershed. Hence, many of the natural and anthropogenic conditions of lakes are the function of processes at much larger scales, including, e.g., natural flow with gravity of organic and inorganic matter, and agricultural fertilizers and chemicals, and they also respond to altered export of matter from their watersheds due to changing land use, temperature, and precipitation. Accordingly, lakes are not only valuable ecosystems and natural resources per se, but also sentinels of environmental change beyond their own boundaries (Williamson et al. 2008). This applies also to acidification—acids are deposited on land and water, transported downstream along with other chemical species that are mobilized from soils due to increased acidity, with subsequent consequences for aquatic life. Scandinavia and northeastern United States have in common that regional industrial areas, up to more than 1000 km away, affect the chemistry of local precipitation. Moreover, the geological conditions of these areas result in poorly buffered soils and waters, which make them vulnerable to acidification. Hence, in hindsight, it is not surprising that it is in the lakes and streams of these regions that acidification was first recognized.

Here, we highlight several influential papers published in *Ambio* that were important for the early discovery and understanding of acidification of inland waters (Almer et al. 1974; Schofield 1976; Henriksen et al. 1988). The authors of two of the pioneering *Ambio* articles give their personal views and behind the paper stories (Almer and Dickson 2021; Brakke 2021), and two other scientists who were highly influential in the recognition of acidification present their reflections on those papers and their importance (Likens 2021; Rosseland 2021). Together, these documents provide an exciting window into the history of the science of acidification of lakes and rivers.

There is currently a broad consensus on the causes and consequences of anthropogenic acidification. However, similar to other environmental issues, not the least global warming, to reach acceptance and political action in line with the scientific evidence is not trivial. Industry and governments were long reluctant to accept the facts on acidification. In their book *Merchants of Doubt*, Oreskes and Conway (2010) highlight acidification along with several other cases of politicized denial of scientific evidence, including health effects of tobacco, global warming, and ozone depletion; the two latter also subject to highly influential papers that will be recognized in forthcoming issues of the *Ambio* 50 year celebrations. The success in making governments and industry to act against acidification depended on solid scientific evidence, but also on scientists reaching out to policy makers and the public. This was very much the case during the era of acidification research highlighted here. Both authors of the original papers and those who provide the peer reflections below have acted outside of the ivory tower. An exceptional case is by Gene Likens, who played a central role in advocating the importance of combatting acidification during the Reagan administration in the USA in the 1980s (Oreskes and Conway 2010).

Today, more than half a century after the discovery of widespread acidification by fossil fuel combustion, there has been substantial progress in the reduction of emissions of acidifying sulfur and nitrogen oxides, and gradual recovery of the chemistry and biology of inland waters. Liming to restore pH and acid neutralizing capacity has been successful in protecting populations of fish and other organisms. The early reports in *Ambio* were important steps towards these successes. Importantly, it should be noted that the successful combat of acidification is not global. The emissions of sulfur and nitrogen from fossil fuel combustion are falling in Europe and North America, but the trend is opposite in the highly populated regions of Asia (Aas et al. 2019). The imminent drastic decrease in the use of fossil fuel that is crucial to address the momentous issue of global warming will also benefit recovery from acidification worldwide.

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Report

Effects of Acidification on Swedish Lakes

By B Almer, Institute of Freshwater Research Drottningholm, Fack, S-170 11 Drottningholm; W Dickson, C Ekström and E Hörnström, National Environment Protection Board, Research Laboratory, Fack, S-170 11 Drottningholm; and U Miller, Geological Survey of Sweden, Fack, S-104 05 Stockholm, Sweden

This report describes the acidification of lakes in the Swedish west coast region. Some 3,000 lakes are located in an area within 80 km from the coast. Investigations were made in nearly 400 of these in 1970–1972. Half of the lakes investigated had pH values below 6.0. In the autumn and spring 36–22 percent of the lakes had pH values even lower than 5.0. This would correspond to 1,100–700 lakes in this area. The acidification has accelerated the last two or three decades. In some lakes the pH was lowered by as much as 1.8 pH units. In addition, the sulfate content has increased in proportion to observed increased depositions.

The pH decrease has caused great changes in the lakes. Among the phytoplankton, most of the diatoms and green algae species disappear below 5.8; and among the zooplankton, most of the daphnians disappear below 6.0. Low pH values will wipe out many fish species as well. Thus roach, minnow, arctic char and trout have disappeared from acidified waters. Their reproduction is affected below pH 5.5. Somewhat less sensitive fish, such as perch and pike, are also strongly influenced.

The acidification can be followed further east and north in Sweden. If the acidification trend continues, thousands of the Swedish lakes will harbor a very strange aquatic life in the future.

Many rivers and lakes in Scandinavia show a decrease in pH (1). Low values are known to cause negative biological effects. In southernmost Norway valuable fish from a great number of lakes have been wiped out during the last 20–30 years (2).

In Sweden, the corresponding area, the west coast region, is the most exposed. The proximity to the sea causes a high precipitation, 750–900 mm per year, a humid climate, and a high runoff. The bedrock in the area as a whole consists of low-weathering granites and gneisses often covered with just a thin podsol layer. Because of this the lake waters have a low ionic composition, especially low alkalinity, and are very sensitive to external influences. The present deposition of excess acid in this region is of the order of 20–30 milliequivalents of hydrogen ions per m^2 and year, compared to 0–10 milliequivalents in the 1950's (1). The yearly mean pH in precipitation has been 4.3–4.4 (1969–1972).

Around three thousand lakes are located in the area within eight Swedish miles (50 English miles) from the coast. Alarming reports of low pH values in lakes in this area led to an initiative from the County Administrations of the west coast areas, the National Board of Fisheries and the National Environment Protection Board to examine almost 400 of these lakes in this region during 1970–1972.

This report will discuss these investigations, particularly the acidification of the lakes, and summarize the effects observed on phytoplankton, zooplankton, and fish.

The individual lakes were chosen, with respect to their surroundings, size, and height above sea level, to be representative for the area (Figure 1). About half of them were analyzed for phytoplankton. The zooplankton and fish fauna were studied in 50 lakes that covered the whole pH range. The sediment from one lake was analyzed for diatoms.

CHEMISTRY

Most of the lakes were examined at least twice. pH was measured both in the field and in the laboratory. In the autumn and spring the water samples were taken from the outflow, and during the summer the samples were taken from the surface of the free water.

Half of the lakes studied had pH values lower than 6 (Table 1). Extrapolated to the total number of lakes in the area, around 3,000, this corresponds to 1,500 lakes with pH lower than 6. In the autumn of 1970 36 percent of the lakes had pH values lower than 5, which for the area as a whole would correspond to a total number of 1,100 lakes with pH lower than 5. The winter of 1970–71 was very poor in snow, which probably caused the less extreme conditions of the following spring, when only 22 percent of the lakes had pH below 5. In the summertime the values are usually somewhat higher, due to the biological activity and a low water flow. Acidified lakes are located in forests and are found throughout the region. The most acid lakes, however, are located near the industrialized and urbanized areas.

When the pH values are compared with earlier measurements, a sharp decrease in many lakes can be recorded. Since the 1930's decreases of up to 1.8 pH units have been reported when sum-

Acid Precipitation:
Effects on Fish

BY CARL L SCHOFIELD

Rapid extinction rates of fish populations inhabiting acidified waters have been observed over the past few decades in the Scandinavian countries and in parts of eastern North America. Extinction is often a result of chronic reproductive failure due to acidification induced effects during sensitive stages of the life-cycle.

The focal point of concern for the acidification of extensive freshwater areas by acid precipitation in both Scandinavia and eastern North America is the devastating effect this phenomenon has had on fish populations. In addition to the obvious economic and social impacts related to the loss of irreplaceable fish stocks exploited by man, the widespread extinction of fish populations has far reaching ecological implications as well. Reductions in fish species affect aquatic ecosystem structure and function, and diminished intra-specific genetic diversity is of ultimate concern for the maintenance of species integrity.

Although biological effects of acidification by acid precipitation have been observed and reported for several aquatic taxa at virtually all trophic levels, the effects on fish have been most thoroughly investigated and documented in the literature. In addition to descriptive information derived from long-term assessment of fish stock changes resulting from acidification, recent experimental investigations and physiological studies have contributed greatly to our understanding of the specific mechanisms involved in the extinction of fish populations and to identification of the relative sensitivity and critical life history stages of many species in relation to acidification. This article represents a summary of information derived from these studies, most of which have come from Norway and Sweden where the problem is particularly severe and has been intensively researched.

EXTENT AND TRENDS OF FISH DEPLETION

Declining fish populations in dilute lakes and streams exposed to acid precipitation inputs have been reported in Norway (1), Sweden (2), Canada (3), and the United States (4). In all cases, the affected waters are characterized by inherently low acid neutralizing capacity and the drainage systems are situated in areas of crystalline or metamorphic bedrock with shallow, acid soils of low buffer capacity. These conditions are prevalent in the southern regions of Norway and Sweden, the mountainous areas of the northeastern USA, and the pre-Cambrian shield in eastern Canada. The fish fauna inhabiting these waters vary considerably in species composition; however, the communities are ecologically similar and are usually dominated by a salmonid-coregonid species complex in undisturbed states.

Norway. The earliest indication of acidification-induced mortality in salmonid fish populations was reported in the early 1900s in southernmost Norway (Sørlandet) (5). Annual catch statistics from 75 major salmon *(Salmo salar)* rivers in Norway reveal a negative trend in yield from about 1910 to 1975 for seven rivers in the southern counties, which is not evident for the remaining 68 rivers from other areas of Norway (1). In the southern rivers the current annual catch is practically nil and the levels of acidity are above those known to be critical for successful salmon reproduction. In addition, water chemistry data for the past ten years indicates a significant trend of increasing hydrogen ion concentration (6). Massive fish kills of adult salmon and trout *(Salmo trutta)* have been periodically reported in these river systems, usually in association with spring snow melt or heavy autumn rains (7). However, recruitment failure due to acid-induced mortality of younger age groups (primarily age 0) appears to be the major force driving these populations to extinction (8). Extensive surveys of water chemistry and fish population status in southern Norway indicate that trout have become extinct in thousands of lakes currently exhibiting low pH (9). Norwegian fishery scientists estimate that fish populations are affected by high acidity in 20 percent of the area south of 63° N (1).

Sweden. As in Norway, extensive areas of southern Sweden have been subject to severe acidification and loss of fish populations. The west coast region of Sweden is the most sensitive and it is estimated that 50 percent of the lakes in this area currently have pH values < 6 and further that pH has decreased by up to 1.8 pH units since the 1930s. For the whole of Sweden, the number of lakes acidified to less than pH 6 is about ten thousand (10). In addition to the extinction of salmonid populations (principally char, *Salvelinus alpinus)* on the west coast, fish communities consisting of roach *(Rutilus rutilus),* perch *(Perca fluviatilus)* and pike *(Esox lucius)* have been seriously affected in central and eastern Sweden (11) as well.

Canada. The first reports in North America linking lake acidification and the extinction of fish populations to acid precipitation were derived from studies of lakes in the vicinity of Sudbury, Ontario (12—16). Populations of lake trout *(Salvelinus namaycush),* lake herring *(Coregonus artedii),* white suckers *(Catostomus commersoni)* and other species disappeared rapidly during the 1960s from a group of remote lakes in the LaCloche Mountain region, some 65 km distant from Sudbury (12). The rapid acidification and fish population extinction in this sensitive region was attributed to the spread of acid deposition from the metal smelters in Sudbury, which were emitting 2.4 million metric tonnes of sulfur dioxide annually and had recently increased stack height significantly. Increases in acidity of more than one hundredfold in the past decade were observed in some lakes and of 150 lakes surveyed, 33 were classified as "critically acidic" (pH less than 4.5) and 37 were described as "endangered" (pH 4.5—5.5). Subsequent consideration of the pH levels observed to affect fish reproduction in the lakes of this region indicated that even lower acidity levels should be ascribed to these categories for the maintenance of successful reproduction of the most sensitive species (13).

United States. Although there are numerous areas of poorly buffered surface waters in the northeastern United States which are potentially susceptible to acidification from acid precipitation, there have been no comprehensive inventories of water quality and fish population status for the north-east region as a whole. Intensive studies of acid precipitation effects on fish populations have been conducted in the Adirondack Mountains of New York State, which is one of the major dilute lake districts in the eastern United States (17—22). A recently completed survey of the higher elevation lakes in this region (217 lakes greater than 610 meters elevation) revealed that 51 percent had pH values less than 5 and 90 percent

Lake Acidification in Norway— Present and Predicted Chemical Status

Report

By Arne Henriksen, Leif Lien, Tor S. Traaen, Iver S. Sevaldrud and David F. Brakke

The Thousand Lake Survey was conducted in Norway in the fall of 1986 to determine the chemical status of lakes in areas sensitive to acidic deposition. The survey was also designed to detect possible changes in water quality as a follow-up to extensive regional surveys which were conducted in 1974/75. In large areas of southern Norway receiving acidic precipitation thousands of lakes and streams are acidic (ANC <0). Large areas elsewhere in Norway contain lakes with low concentrations of base cations. These areas would also be expected to contain acidic lakes if they receive acidic loadings equivalent to those in southernmost Norway. The pH of lakes in southern Norway has changed little from 1974/75 to 1986. Sulfate concentrations are significantly lower today in the most affected lakes in southernmost and eastern Norway, corresponding to reductions in emissions, but are still elevated. Nitrate concentrations in most of the lakes in Sørlandet have, however, doubled on average over the same period, while no significant changes have occurred in the rest of southern Norway. In the lakes with higher concentrations of nitrate in 1986, aluminum concentrations are also higher. At present, about 70 percent of the lakes sampled in southern Norway have lost all of their bicarbonate buffering capacity. With a 30-percent reduction from present levels of SO_4 in lakes, this percentage should decline to about 55 percent and with a 50-percent reduction about 45 percent of the lakes will be without bicarbonate buffering.

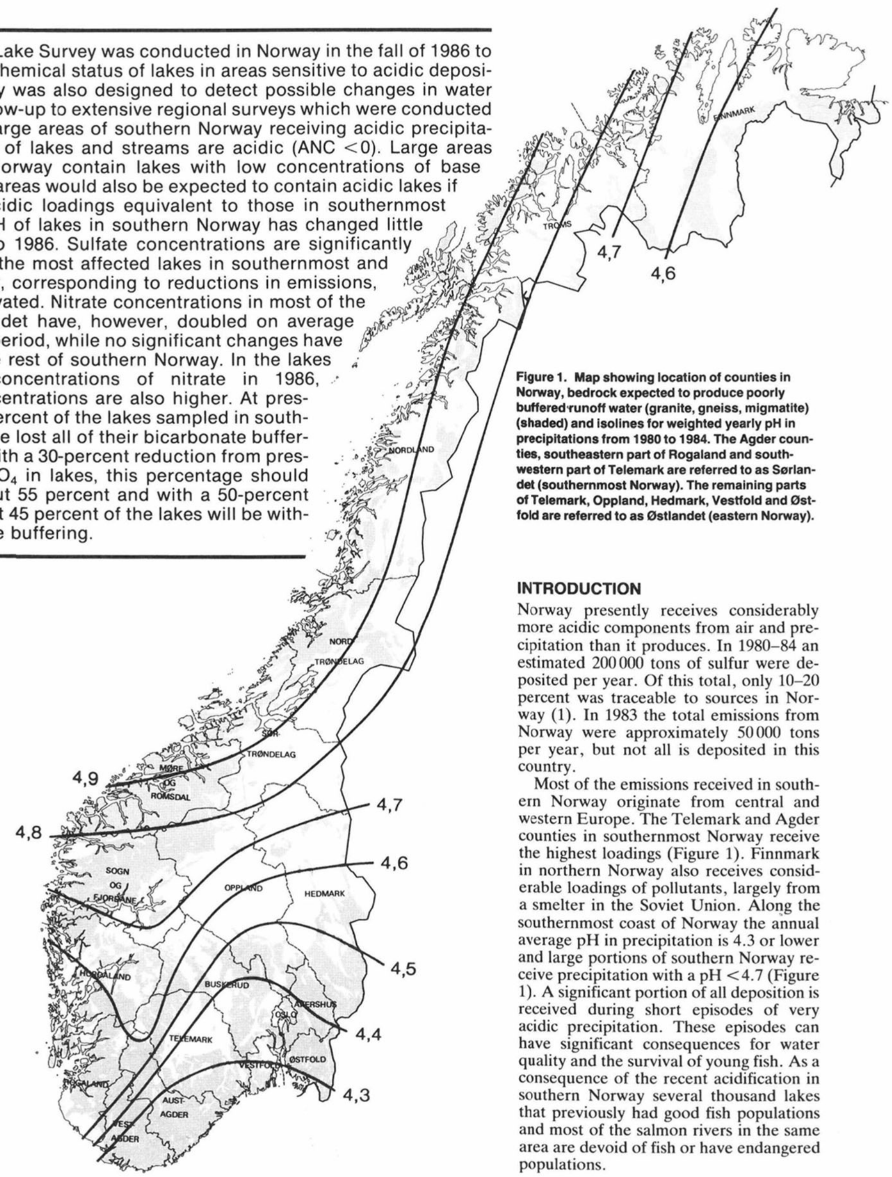

Figure 1. Map showing location of counties in Norway, bedrock expected to produce poorly buffered runoff water (granite, gneiss, migmatite) (shaded) and isolines for weighted yearly pH in precipitations from 1980 to 1984. The Agder counties, southeastern part of Rogaland and southwestern part of Telemark are referred to as Sørlandet (southernmost Norway). The remaining parts of Telemark, Oppland, Hedmark, Vestfold and Østfold are referred to as Østlandet (eastern Norway).

INTRODUCTION

Norway presently receives considerably more acidic components from air and precipitation than it produces. In 1980–84 an estimated 200 000 tons of sulfur were deposited per year. Of this total, only 10–20 percent was traceable to sources in Norway (1). In 1983 the total emissions from Norway were approximately 50 000 tons per year, but not all is deposited in this country.

Most of the emissions received in southern Norway originate from central and western Europe. The Telemark and Agder counties in southernmost Norway receive the highest loadings (Figure 1). Finnmark in northern Norway also receives considerable loadings of pollutants, largely from a smelter in the Soviet Union. Along the southernmost coast of Norway the annual average pH in precipitation is 4.3 or lower and large portions of southern Norway receive precipitation with a pH <4.7 (Figure 1). A significant portion of all deposition is received during short episodes of very acidic precipitation. These episodes can have significant consequences for water quality and the survival of young fish. As a consequence of the recent acidification in southern Norway several thousand lakes that previously had good fish populations and most of the salmon rivers in the same area are devoid of fish or have endangered populations.