IMPACT OF ACID PRECIPITATION ON FRESHWATER ECOSYSTEMS ON NORWAY[1]

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ABSTRACT

Extensive studies of precipitation chemistry during the last 20 years have clearly shown that highly polluted precipitation falls over large areas of Scandinavia, and that this pollution is increasing in severity and geographical extent. Precipitation in southern Norway, Sweden, and Finland contains large amounts of H^+, $SO_4^=$, and NO_3^- ions, along with heavy metals such as Cu, Zn, Cd, and Pb, that originate as air pollutants in the highly industrialized areas of Great Britain and central Europe and are transported over long distances to Scandinavia, where they are deposited in precipitation and dry-fallout.

In Norway the acidification of fresh waters and accompanying decline and disappearance of fish populations was first reported in the 1920's, and since then in Sørlandet (southernmost Norway) the salmon have been eliminated from several rivers and hundreds of lakes have lost their sport fisheries.

Justifiably, acid precipitation has become Norway's number-one environmental problem, and in 1972 the government launched a major research project entitled "Acid Precipitation - effects on forest and fish", (the SNSF-project). Studies of freshwater ecosystems conducted by the SNSF-project include intensive research at 10 gauged watersheds and lake basins in critical acid-areas of southern Norway, extensive surveys of the geographical extent and severity of the problem over all of Norway, and field and laboratory experiments on the effect of acid waters on the growth and physiology of a variety of organisms.

Large areas of western, southern, and eastern Norway have been adversely affected by acid precipitation. The pH of many lakes

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is below 5.0, and sulfate, rather than bicarbonate, is the major anion. Lakes in these areas are particularly vulnerable to acid precipitation because their watersheds are underlain by highly resistant bedrock with low calcium and magnesium contents.

Apart from the well-documented decline in fish populations, relatively little is known about the effects of acid precipitation on the biology of these aquatic ecosystems. Biological surveys indicate that low pH-values inhibit the decomposition of allochthonous organic matter, decrease the species number of phyto- and zooplankton and benthic invertebrates, and promote the growth of benthic mosses.

Acid precipitation is affecting larger and larger areas of Norway. The source of the pollutants is industrial Europe, and the prognosis is a continued increase in fossil-fuel consumption. The short-term effects of the increasing acidity of freshwater ecosystems involve interference at every trophic level. The long-term impact may be quite drastic indeed.

INTRODUCTION

Extensive studies of precipitation chemistry during the last 20 years have clearly shown that highly polluted precipitation falls over large areas of Scandinavia and that this pollution is increasing in severity and geographical extent (Barrett and Brodin 1955, deBary and Junge 1963, Odén 1968, Bolin et al. 1970, Ottar 1972). Precipitation in southern Norway, Sweden, and Finland contains large amounts of H^+, $SO_4^=$, and NO_3^-, ions along with heavy metals such as Cu, Zn, Cd, and Pb, that originate as air pollutants in the highly industrialized areas of Great Britain and central Europe and are transported over long distances to Scandinavia, where they are deposited in precipitation and dry-fallout (Odén 1968, Holt-Jensen 1972, Brosset 1973, OECD 1973, Rühling and Tyler 1973, Nordø 1975, Semb 1975). Only a small fraction of the H^+, $SO_4^=$, and NO_3^- deposited in southern Norway comes from local sources (Fredriksen 1973, Skogvold 1974, and Førland 1973) has firmly established that precipitation falling from air masses that have passed over industrial Europe has much higher concentrations of these ions than does precipitation from other air masses.

Because much of Norway is underlain by highly resistant granitic rocks with only a thin cover of unconsolidated glacial till and soil (Figure 1), the inland waters are characterized by low conductivities (less than 20 micromhos/cm), low concentrations of major ions, and extremely low buffer capacities. Thus large areas of Norway are quite vulnerable to inputs of pollutants from the atmosphere, and the potential damage to Norway's 300,000 lakes is indeed great.

Figure 1. Air view of a mountainous area of southern Norway showing the typical thin soil cover, sparse vegetation and many lakes.

Acidification of fresh waters and accompanying decline and disappearance of fish populations was first reported in the 1920's (Sunde 1926, Dahl 1926), and since then in Sørlandet (southernmost Norway) the salmon have been eliminated from several rivers, and hundreds of lakes have become devoid of fish (Jensen and Snekvik 1972).

Justifiably, acid precipitation has become Norway's number-one environmental problem, and in 1972 the government launched a major research project entitled "Acid precipitation - effects on forest and fish", (the SNSF-project) (Overrein and Abrahamsen 1975). Studies of freshwater ecosystems conducted by the SNSF-project include intensive research at 10 gauged watersheds and lake basins in critical acid-areas of southern Norway, extensive surveys of the geographical extent and severity of the problem over all of Norway, and field and laboratory experiments on the effect of acid waters on the growth and physiology of a variety of organisms (Table 1).

EFFECTS ON FRESH WATERS

The impact of acid precipitation on the chemistry and biology of Norwegian freshwaters is well illustrated by the results from a survey of 155 lakes conducted in October 1974. To obtain a statistically valid sample of lakes in southern Norway, a 10 × 10 km block was selected at random from each square of a 50 × 50 km grid covering Norway south of 63° N latitude (Figure 2). Two small lakes were chosen from each block under the conditions that they have minimal local sources of pollution and that they be large enough to permit access by light float-plane (Wright and Lysholm 1974).

Table 1. Research on aquatic ecosystems conducted by the SNSF-project in 1975.

	LAKES			RIVERS	
	regional surveys	intensive studies	sediment studies	regional surveys	intensive studies
CHEMISTRY					
major ions	+	+	+	+	+
nutrients	+	+	+		+
heavy metals	+	+	+		+
BIOLOGY					
decomposers		+	+		+
bacteria		+	+		
phytoplankton	+	+	+		
benthic algae					+
macrophytes		+			
zooplankton	+	+			
benthic fauna	+	+		+	+
fish	+	+		+	+

At each lake water samples were collected, and at 57 lakes the phyto- and zooplankton, and zoobenthos were sampled. The physiography, vegetation, and geology of the lake watersheds were described on the basis of field observations, photographs, and maps. This survey is similar to the study of 50 lakes near the smelter at Sudbury, Ontario described by Conroy et al. (1974), and to the survey of 400 lakes in southwest Sweden reported by Almer et al. (1974).

CHEMISTRY

Isopleth maps of the concentrations of various components in the surface water samples show that the chemistry of Norwegian lakes is strongly influenced by inputs from the atmosphere. The map for chloride, for example, clearly reflects its seawater source and its deposition in orographic rainfall (Figure 3). The concentrations of sulfate also reflect a seawater source for this ion (Figure 4), but the high sulfate concentrations in lakes along the south and southwest coasts are the result of an atmospheric input of sulfate in excess of that associated with the chloride (Figure 5). The source of this excess sulfate is most certainly anthropogenic. Air masses moving from industrial Europe transport sulfur compounds over long distances, and these pollutants are removed in orographic precipitation along the mountainous coastal areas of Norway (Nordø 1975).

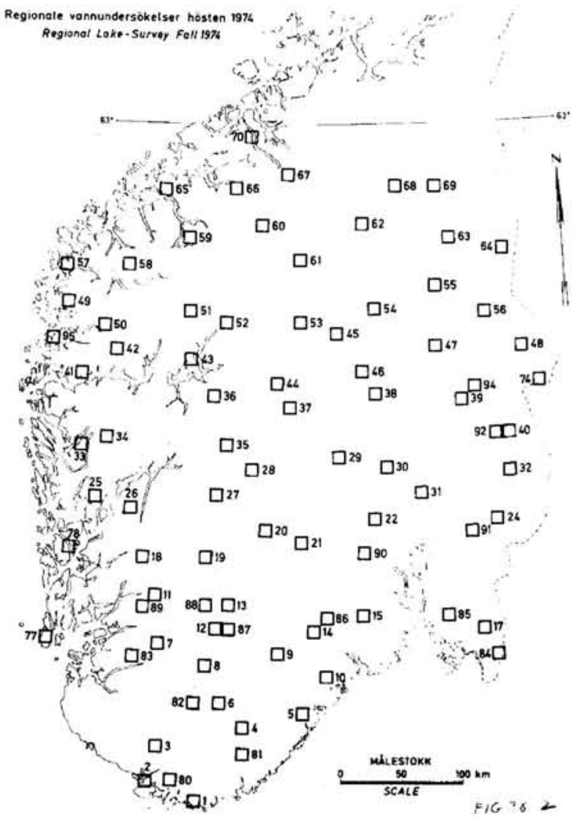

Figure 2. Location map of the 10 × 10 km blocks selected at random from each square of the 50 × 50 km grid (from Wright and Lysholm 1975).

The isopleth map of pH thus also reflects the very great impact of acid precipitation on lakes in large areas of Norway (Figure 6). Whereas unpolluted lakes in granitic basins in central Norway have pH values above 6.0 and bicarbonate is the major anion, lakes in large areas of western, southern, and eastern Norway have pH values below 5.5; many lakes in Sørlandet and southeastern Norway are below 5.0. As a result of the atmospheric loadings of sulfuric acid, sulfate has replace bicarbonate as the major anion.

The isopleth maps for other components demonstrate additional effects of acid precipitation. For example, the aluminum map (Figure 7) shows that the acidic, high-sulfate lakes also have unusually high Al concentrations. Since precipitation contains very little Al, the Al in the lake waters must be supplied from the watersheds, probably due to the washout of Al by acid precipitation. Because the solubility of Al is negligible at pH greater than 5.0 (Norton 1975), the mobilization of Al indicates that the soil pH has been depressed to levels below 5.

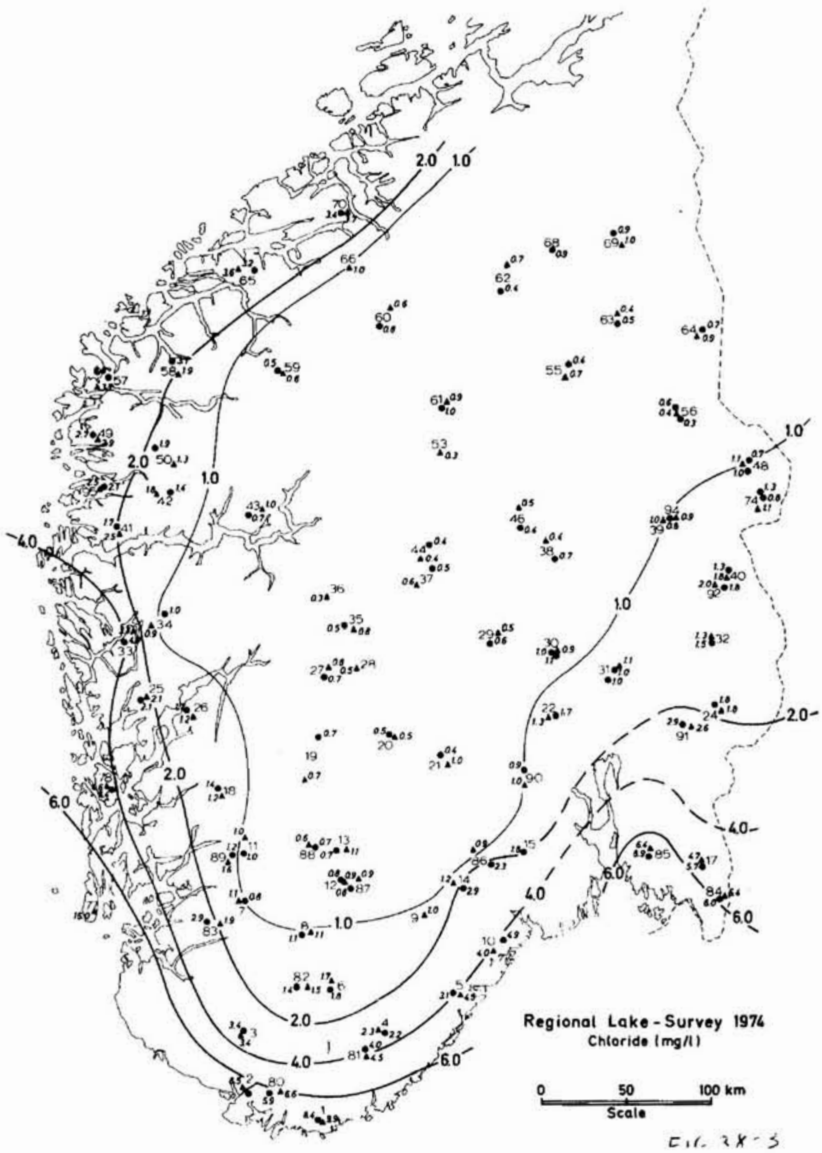

Figure 3. Isopleth map Cl (mg/l) in surface-water samples (from Wright and Lysholm 1975).

Although the washout of alkaline earths (Ca + Mg) by acid precipitation in Norway has been reported (Overrein 1972, Henriksen 1972), washout of Al represents the next, more severe stage in the alteration of soil chemistry (Malmer 1973).

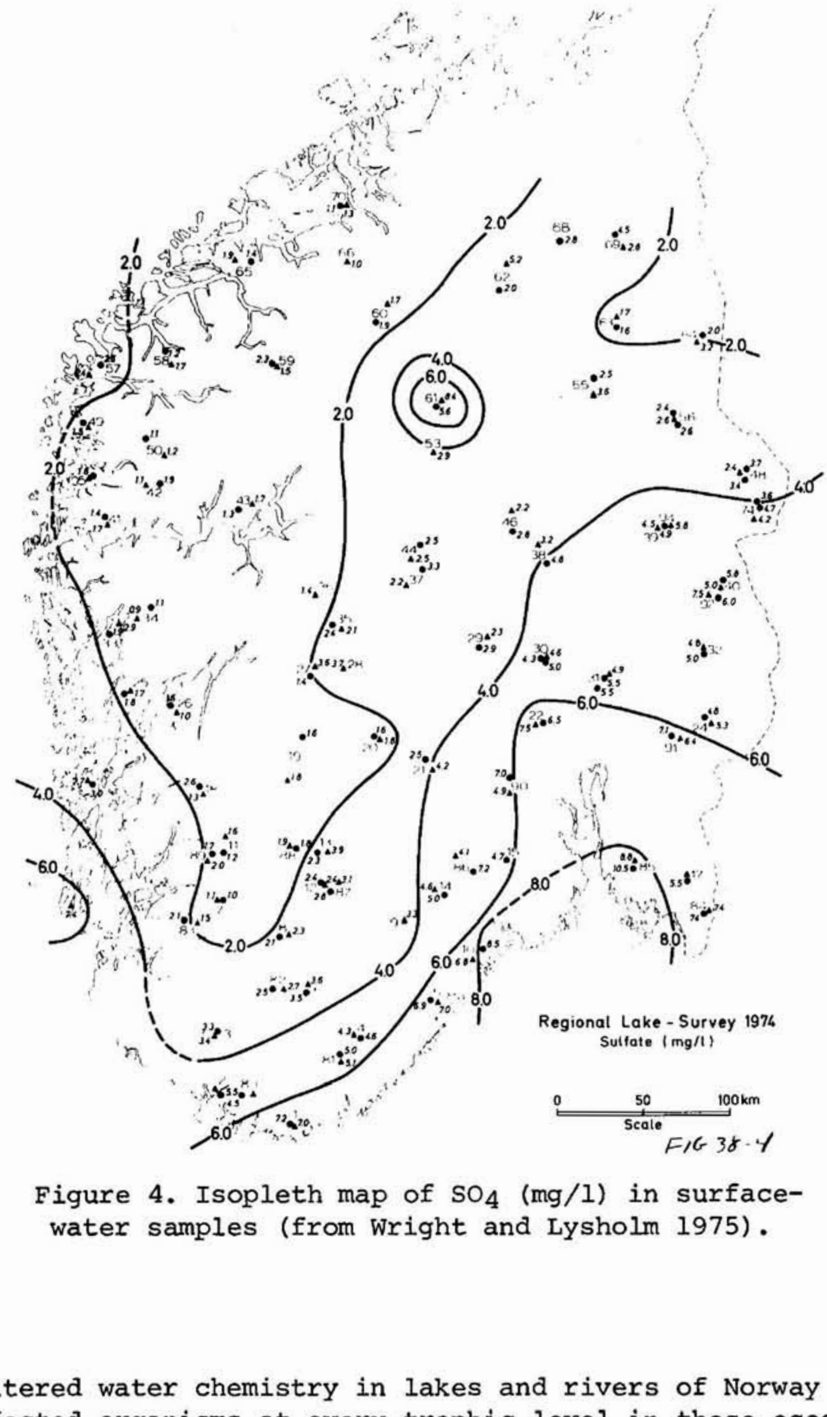

Figure 4. Isopleth map of SO_4 (mg/l) in surface-water samples (from Wright and Lysholm 1975).

BIOLOGY

The altered water chemistry in lakes and rivers of Norway appears to have affected organisms at every trophic level in these ecosystems. Experiments underway in the SNSF-project indicate that at low pH levels bacterial decomposition is retarded while fungal growth increases on aquatic sediments. The decomposition of cellulose is reduced by 50% when the pH is lowered from 7.0 to 5.2 (Traaen 1974). Inhibition of decomposition results in an increased accumulation of organic debris and a decreased rate of nutrient recycling. Organic debris and fungal mats

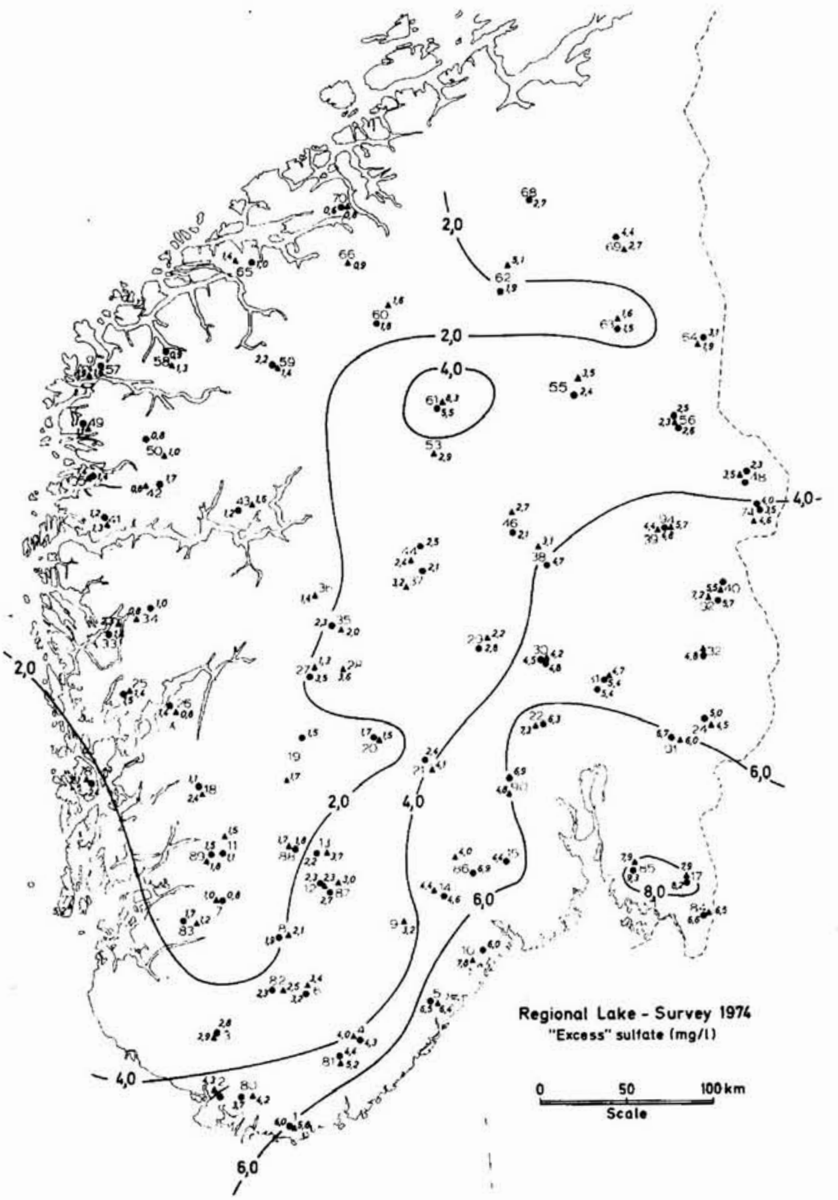

Figure 5. Isopleth map of excess-SO_4 (mg/l) in surface-water samples.

cover the lake sediments and thereby apparently inhibit nutrient exchange with the overlying water (Grahn et al. 1974). Since the nutrient recycling rate is an important control of the primary production in many lakes, reduced recycling in acid lakes would contribute to the "self-accelerating oligotrophication" proposed by Grahn et al. (1974), Hultberg (1975), and Grahn (1975).

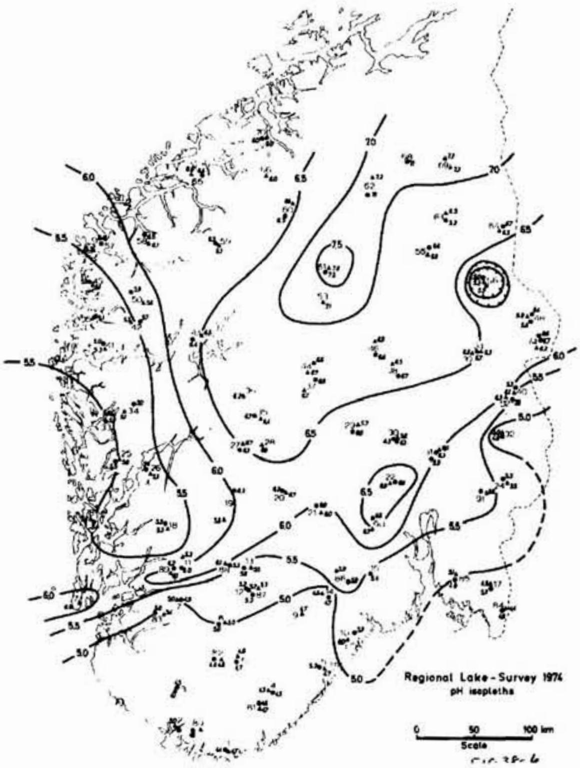

Figure 6. Isopleth map of pH in surface-water samples (from Wright and Lysholm 1975).

Acidification of lake waters alters phytoplankton species-composition and abundances. Analysis of phytoplankton samples from 57 lakes of the regional survey indicates that lakes with pH less than 6.0 have fewer species and, in particular, that the Chlorophyceae (green algae) are affected (Figure 8). Almer et al. (1974) also found decreased species numbers and altered species-compositions in a survey of 115 lakes in southwestern Sweden.

The number and type of zooplankton species also are related to pH; at a low pH fewer species are present (Figure 9). There is also evidence from investigations in Sweden that *Daphnia* species are absent in low-pH lakes (Almer et al. 1974, Hanson 1974).

Preliminary results from the regional lake-survey also indicate that the benthic fauna is sensitive to pH, with again fewer species present at pH levels below 6. Studies on the distribution of *Gammarus lacustris*, another aquatic invertebrate, indicate that this important food source for fish is rarely found in waters with pH below 6.0 (Økland 1969, 1970). Data from England show that in streams with pH below 5.7 the insect fauna is greatly impoverished (Sutcliffe and Carrick 1973).

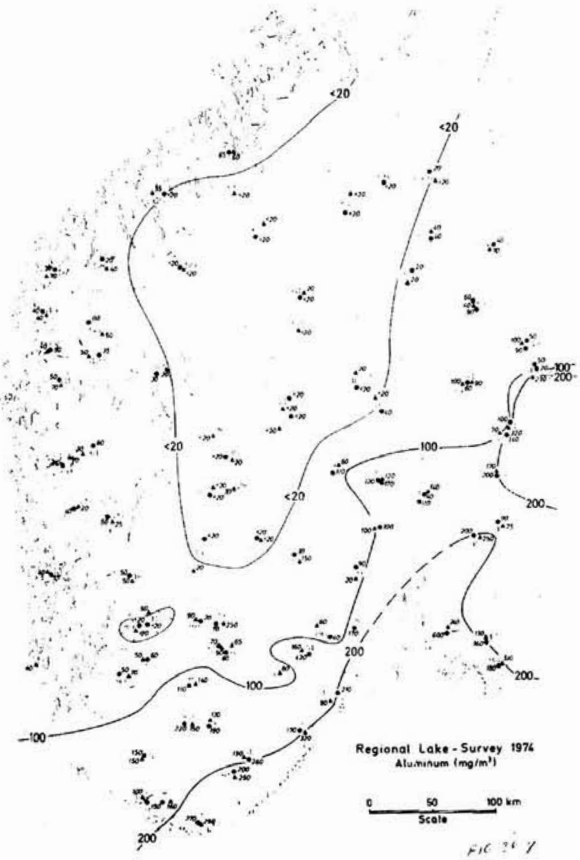

Figure 7. Isopleth map of Al (mg/m^3) in surface-water samples.

Information on the impact of acidification on fresh-water biology is thus mostly of a descriptive nature, and as Almer et al. (1974) points out, very little is known about the effect of low pH on the morphology, physiology, and nutrition of phyto- and zooplankton.

FISH

A great deal, however, is known about fish, primarily because of their economic and recreational value (cf. EIFAC 1968). Dahl (1926) first reported the adverse effects of acidification on fish in Norway, and in 1959 Dannevig (1959) suggested that acid precipitation was the cause of the increased acidity and adverse effects on fish.

Salmon-catch records for 79 Norwegian rivers recorded since the late 1800's show that the catch from 9 rivers in Sørlandet declined rapidly between 1885 and 1925 and was essentially zero by 1968 (Jensen and Snekvik 1972). The salmon catch for the entire country, however, shows

Mean number of Algae species against pH

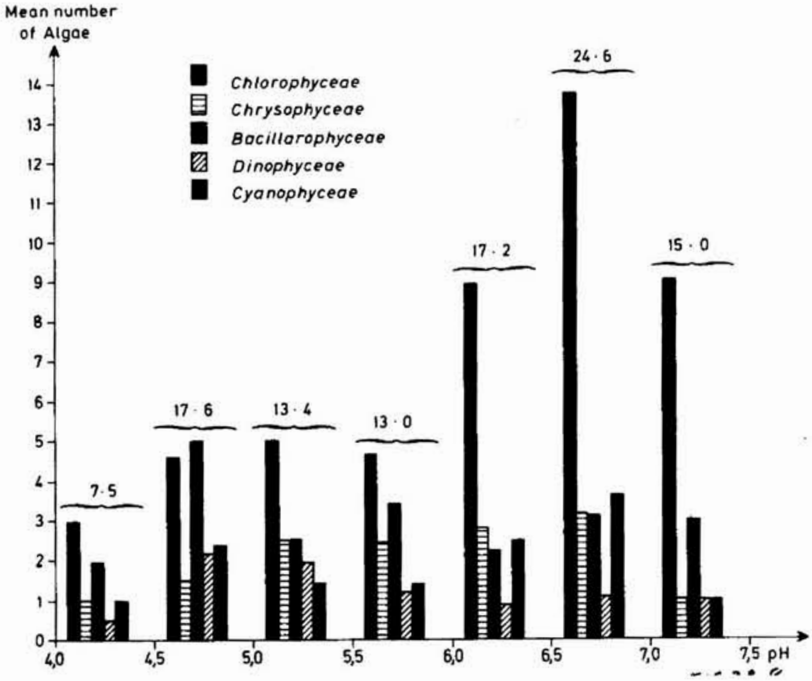

Figure 8. Mean number of algal species against pH in samples from 57 lakes of the regional lake-survey

no such decrease (Figure 10). These 9 rivers are now quite acidic (pH 4.5-5.5), and their acidity is still increasing (Henriksen 1972). There can be little doubt that acid precipitation is the cause (Hagen and Nordby 1967). The dissappearance of salmon from these rivers is not usually marked by massive fish kills (although fish kills were reported in 1911, 1921, 1948 and most recently 1975), but rather by the failure of reproduction and recruitment (Jensen and Snekvik 1972). Indeed laboratory experiments indicate that acid water first affects fish eggs and fry; the lower limit for normal reproduction is 5.0-5.5 for salmon, 4.5-5.0 for sea trout, and about 4.5 for brown trout (Jensen and Snekvik 1972).

Fish have also been disappearing from lakes in Sørlandet because of inputs of acid precipitation. Information on the fish-status of 2083 lakes in Sørlandet was gathered in 1971 by E. Snekvik and K. W. Jensen (Norwegian Directorate for Game and Fresh-Water Fish) from local fishery authorities. Of these lakes, 741 now have no fish, and 477 have become devoid of fish since 1940 (Jensen and Snekvik 1972). pH data for 516 of these lakes show clearly that at pH levels below about 5.5 the fish are either entirely absent or present only in reduced numbers (Figure 11).

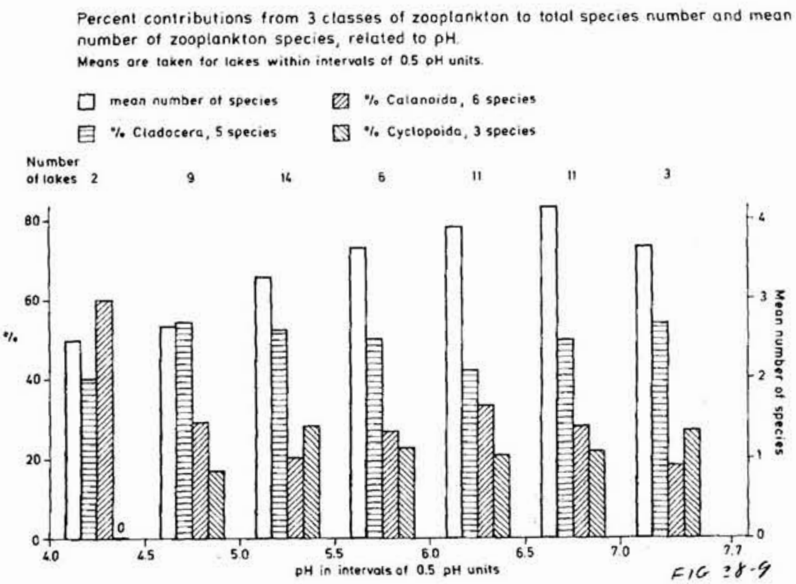

Figure 9. Percent contributions from 3 classes of zooplankton to total species number and mean number of zooplankton species, related to pH. Data from 57 lakes of the 1974 regional lake-survey.

Acid precipitation has resulted in the decline and loss of fish populations in other areas of Norway as well. A preliminary survey of the fish status for lakes over all of southern Norway was conducted during 1974 as part of the SNSF-project. Lakes with no fish or only sparse populations occur over large areas of western and east-central Norway as shown in Figure 12, and these lakes are acid, generally below pH 5.5 (Muniz 1975).

The disappearance of fish from lakes as pH decreases often follows a characteristic pattern. Long-term increases in acidity apparently first interfere with reproduction and spawning such that the remaining adult fish increase in size and age until the only fish left are large and old. This pattern has been described in Norway (Jensen and Snekvik 1972), in Sweden (Hultberg and Stenson 1970, Almer et al. 1974, Andersson et al. 1971, Almer 1972 a, Almer 1972 b), in Canada (Beamish 1975), and in the United States (Schofield 1975).

Another mode of fish mortality is caused by large, rapid changes in pH. Sudden drops in pH cause severe physiological stress that may produce fish kills at pH levels *above* those normally toxic to adult fish. Resistance to such shocks is also species dependent. Sudden drops in pH are often observed in the early spring when the pollutants accumulated in the snowpack are released in high concentrations during the first phases of melting (Hagen and Langeland 1973, Hultberg 1975).

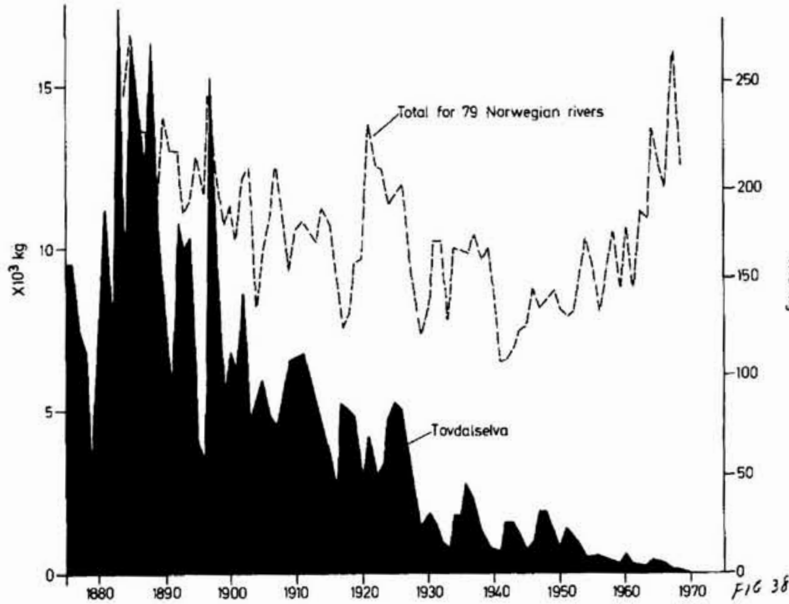

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Figure 10. Salmon-catch statistics for 79 Norwegian rivers and for Tovdalselva, an acidic river in Sørlandet, over the period 1880-1970 (data from Sndkvik 1970).

SUMMARY

The precipitation over much of southern Scandinavia contains large amounts of H^+, $SO_4^=$, NO_3^- that originate as air pollutants in the highly industrialized areas of Great Britain and central Europe. Because much of Norway is underlain by highly resistant granitic rocks with only a thin cover of unconsolidated glacial till and soil, the inland waters have extremely low buffer capacities and are thus quite vulnerable to inputs of atmospheric pollutants.

The continually growing inputs of acidic pollutants have resulted in major changes in the chemistry of lakes and rivers in southern Norway. Regression analysis on 10 years of data from several rivers in Sørlandet (southernmost Norway) show significant decreases in pH and increases in conductivity and total hardness, the latter due to the washout of Ca and Mg from the watersheds. The inputs of sulfate have resulted in the replacement of bicarbonate by sulfate as the major anion in many lakes.

High concentrations of aluminum in acid lakes in southernmost Norway suggest that pH levels in the watershed soils have dropped below 5, resulting in the mobilization and washout of Al.

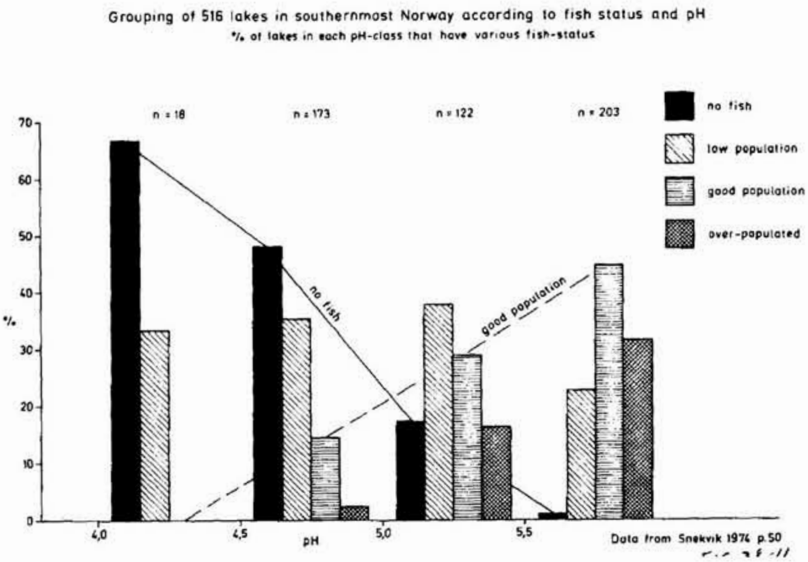

Figure 11. Grouping of 516 lakes in southernmost Norway according to fish status and pH. Percent of lakes in each pH-class that have various fish-status (data from Snekvik 1974).

Information from the survey of 57 lakes in southern Norway indicates that increasing acidity results in a decline in the number of phytoplankton species, and in particular, a decrease in the abundance of green algae. The composition of zooplankton and zoobenthos species are similarily affected. These decreases begin to occur at about pH 6.0.

Data on the annual salmon catch, pH, and success of fish hatching indicate that acidic precipitation began affecting fish as early as the 1920's. Since then the salmon have been eliminated from many major rivers, and thousands of lakes have become devoid of fish (Jensen and Snekvik 1972). Fish are eliminated from lakes and rivers because of gradual increases in acidity that cause interference with reproduction and spawning. Sudden drops in pH, especially during snowmelt cause severe physiological stress and often death in fish. The tolerance of fish to both long-term and short-term changes in acidity is species dependent.

Acid precipitation has affected large areas of Norway. These adverse effects are occuring over greater geographical areas with both increasing frequency and severity. The source of the pollutants is industrial Europe, and since the prognosis is for a continued increase in fossil-fuel combustion, the situation will continue to deteriorate. The short-term effects of the increasing acidity of freshwater ecosystems involve interference at every trophic level. The long-term impacts may be quite drastic indeed.

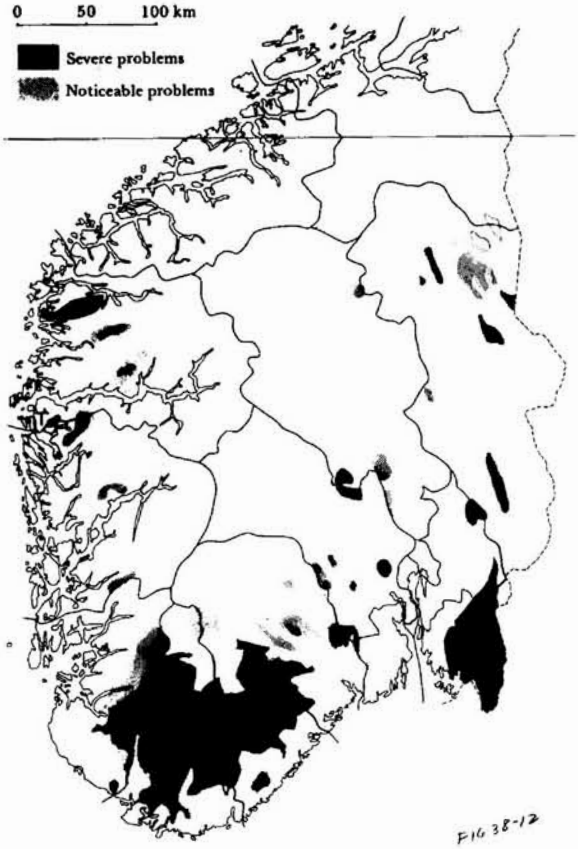

Figure 12. Fisheries status in lakes of southern Norway showing areas that have been moderately and severely affected by acid precipitation (from Muniz 1975).

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