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Miljøverndepartementet

FAGRAPPORT NR. 43

Critical load exceedance and damage to fish populations

Norwegian Institute for Water Research NIVA
Norwegian Institute for Nature Research NINA

Naturens Tålegrenser

Programmet Naturens Tålegrenser ble satt igang i 1989 i regi av Miljøverndepartementet. Programmet skal blant annet gi innspill til arbeidet med Nordisk Handlingsplan mot Luftforurensninger og til pågående aktiviteter under Konvensjonen for Langtransporterte Grensoverskidende Luftforurensninger (Genevekonvensjonen). I arbeidet under Genevekonvensjonen er det vedtatt at kritiske belastningsgrenser skal legges til grunn ved utarbeidelse av nye avtaler om utslippsbegrensning av svovel, nitrogen og hydrokarboner.

En styringsgruppe i Miljøverndepartementet har det overordnete ansvar for programmet, mens ansvaret for den faglige oppfølgingen er overlatt en arbeidsgruppe bestående av representanter fra Direktoratet for naturforvaltning (DN), Norsk polarinstitutt (NP) og Statens forurensningstilsyn (SFT).

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Eva Fuglei - NP
Tor Johannessen - SFT
Else Løbersli - DN
Steinar Sandøy - DN

Styringsgruppen i Miljøverndepartementet består av representanter fra avdelingen for naturvern og kulturminner, avdelingen for vannmiljø, industri- og avfallssaker og avdelingen for internasjonalt samarbeid, luftmiljø og polarsaker.

Henvendelse vedrørende programmet kan rettes til:

Direktoratet for naturforvaltning
Tungasletta 2
7005 Trondheim
Tel: (07) 58 05 00

eller
Statens forurensningstilsyn
Postboks 8100 Dep
0032 Oslo 1
Tel: 22 57 34 00

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Arne Henriksen, Norwegian Institute for Water research (NIVA)
Trygve Hesthagen, Norwegian Institute for Nature Research (NINA)

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To examine the relationship between the *critical load exceedance* and the *damage to fish,* the data for fish damage and water chemistry for 1000 lakes in Norway was used to derive the probability of damage to fish populations as a function of the critical load exceedance. When the critical load is not exceeded there is only a small probability of damage to fish, but as soon as the critical load is exceeded, the probablity of fish damage starts to increase. Two other sets of data collected independently have also been used to examine the same relationship, the critical load exceedance map prepared for Norway and the fish damage map prepared on the basis of the *interview method.* The two sets of data showed that the exceedance of critical loads and damage to fish populations coincide geographically. Both approaches show that the critical load exceedance clearly indicate ecosystem changes that can be quantified. Therefore, prognoses carried out for given reduction scenarios can effectively assess the degree of ecosystem recovery.

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Arne Henriksen

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CRITICAL LOAD EXCEEDANCE

and damage to

FISH POPULATIONS

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Authors:
Arne Henriksen, NIVA
Trygve Hesthagen, NINA

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SUMMARY

In recent years large areas of Europe and eastern regions of North America have suffered from acid precipitation with resultant *acidification of surface waters*, fish mortality and other ecological changes. The concept of *critical load* has been developed on a European basis by a number of international cooperative programmes and activities under the United Nations Economic Commisission for Europe's *Convention on Long Range Transboundary Air Pollution, and a* manual for calculating critical loads/levels have been worked out. There are two major approaches for determining the critical load for surface waters: use of process-oriented models and empirical models. The empirical steady-state models based on water chemistry ignore all time dependent processes. To assess critical loads for surface waters on a regional scale, a simple steady-state method has been recommended. This method can be used to calculate critical load and the critical load exceedance, and rests on the assumption that sulphate is a completely mobile anion and the sulphur deposition can be used to indicate the acidifying effect of sulphur, and that the only acidifying effect of nitrogen deposition is the part that is leached as nitrate in runoff. To examine the relationship between the *critical load exceedance* and the *damage to fish* the data from the 1000 lake survey carried out in Norway in 1986 was used to derive the probability of damage to fish populations as a function of the critical load exceedance. Lakes with lost fish populations were given the value 1, lakes with reduced fish populations were given the value 0,5, while lakes with healthy fish populations were labelled 0. For each exceedance interval the fish indexes were summed up and divided by the number of lakes, giving values on a continuous "probability" scale from 0 to 1. A close connection between the damage to fish populations and critical load exceedance was found. When the critical load is not exceeded there is only a small probability of damage to fish, but as soon as the critical load is exceeded, the probablity of fish damage increases with increasing exceedance. Two other sets of data have also been used to compare critical load exceedance and damage to fish populations, the critical load exceedance maps prepared for Norway and the fish damage map prepared based on the *interview method.* The critical load is exceeded in about 94.000 km^2 of the land area in Southern Norway, while fish damage has been recorded in about 86.000 km^2. For 68% of the grids the two sets of independently collected data coincide. The chosen value of ANC$_{limit}$ of 20 μeq/l has been derived from an empirical relationship between ANC and fish damage based on data from the 1000 lake survey . Using this basis for deriving critical loads, we find that the exceedance of critical loads and damage to fish populations coincide geographically. In contrast, for the 1000 lake survey data the fish information and the water chemistry was compared for the same lakes. Still, from both approaches we can conclude that the critical load exceedance clearly indicate ecosystem changes that can be quantified. Also, prognoses carried out for given reduction scenarios can effectively assess the degree of ecosystem recovery.

1. INTRODUCTION

In recent years large areas of Europe and eastern regions of North America have suffered from acid precipitation with resultant *acidification of surface waters*, fish mortality and other ecological changes.

The concept of *critical load* was first put into practical use by Canada in the last part of the 70's in relation to the problem of lake acidification. It was further developed by working groups established by the the Nordic Council in 1985 and used in the Scandinavian countries as a method for quantifying the extent and spatial dimension of the acidification problem in their countries. Since then it has been developed on a European basis by a number of international cooperative programmes and activities under the United Nations Economic Commisission for Europe's *Convention on Long Range Transboundary Air Pollution,* signed in 1979. A manual for calculating critical loads/levels have been worked out (ECE 1990).

Acidic water has probably been the cause of fish mortality in Norway as far back as the turn of the century (Huitfeldt-Kaas 1922), but it was only at the end of the 50's that the link to acidic deposition was established (Dannevig 1959). Southernmost Norway receives the highest loadings of long range transported air pollutants in Norway at the present time. This area is the most severely affected with fish mortality and the elimination of fish populations (Henriksen et al. 1989, Hesthagen and Hansen 1991). The extensive losses of fish populations in Norway from the 1960's and onwards correlate in space and time with the escalation of atmospheric emissions of sulfur and nitrogen compounds in Europe (Overrein et al. 1981). The total land area now affected by acidification damage to fish populations in Norway has been estimated to be about 86.000 km^2 (Henriksen et al. 1993).

Hence, the relationship between changes in water chemistry due to acidification and fish reponse is now well documented. In this report we examine how the *critical load concept* can be applied to the responses of fish to the acidification of surface waters.

2. METHODS

2.1. Definitions

Some useful definitions used in the critical load work are:

The critical load for surface waters: "A quantitative estimate of the loading of one or more pollutants below which significant harmful effects on specified sensitive elements of the environment are not likely to occur according to present knowledge".

Acid Neutralizing Capacity (ANC): Ability of a solution to neutralize inputs of strong acid to a preselected equivalence.

Critical load: The highest load that will not lead in the long-term to harmful effects on biological systems, such as decline and disappearance of fish populations.

Receptor: An ecosystem which may potentially be affected by atmospheric inputs of sulfur and nitrogen (soil, groundwater, surface water).

Biological indicator: selected organism(s) or populations which are sensitive to chemical changes as a result of atmospheric inputs of sulfur and nitrogen (forest, fish, invertebrates).

Critical chemical value: The value of a critical chemical component or combinations of components above or below no rise to a harmful response in a biological indicator is given (pH, ANC, Al/Ca ratio).

The *critical load* definition provides a framework for making numerical estimates of the loads at which adverse effects occur. Such estimates may be based upon a number of different methods, and the selection of method depends to a large extent upon the *receptor* chosen and the availability of relevant data for the calculations. The effects on sensitive *biological indicators* are used here to identify harm to freshwater systems. The methods for calculating critical loads for acidity of freshwaters all use chemical data, often making assumptions regarding the water chemistry prior to anthropogenic acidification. The *critical chemical value* is based on our knowledge of the ecological tolerance of sensitive biological species to water chemistry.

2.2. Calculation methods

There are two major approaches for determining the critical load for surface waters: use of process-oriented models and empirical models. Process-oriented models attempt to develop mathematical descriptions for the mechanisms underlying the cause-effect relationships between acidic deposition and water quality. The empirical steady-state models based on water chemistry ignore all time dependent processes. Consequently, these models can be applied with limited amount of information, and because of their simplicity estimates of critical loads for large regions have already been carried out (Henriksen et al. 1990).

For the evaluation of the results obtained there is a need for a sufficient number of observations to establish the dose-response relationships between a biological indicator and water quality variables. By using these relationships the critical load can then be derived from measured surface water quality data and be based on biological populations. To assess critical loads for surface waters on a regional scale, a simple steady-state method has been recommended (ECE 1990).

The basic equations for the Steady State Water Chemistry method are:

Critical load of acidity:

$$CL(Ac) = Q([BC]_0^* - [ANC]_{limit}) - BC_{dep}^* \qquad (1)$$

where Q is the runoff, $[BC]_0^*$ the original seasalt corrected base cation concentration, BC_{dep}^* the sea salt corrected atmospheric deposition of base cations and $[ANC]_{limit}$ is the selected critical ANC threshold (Henriksen et al. 1992). The Acid Neutralization Capacity (ANC) is used as the chemical criterion for sensitive indicator organisms (usually fish) in surface waters. ANC is defined as the difference between non-marine base cations (BC)* and strong acid anions (AN)*:

$$[ANC] = [BC]^* - [AN]^* = [HCO_3^-] + [A^-] - [H^+] - [Al^{n+}] \quad (2)$$

where $[HCO_3^-]$ is the bicarbonate concentration, $[A^-]$ is the concentration of organic anions and $[Al^{n+}]$ is the sum of all positively-charged aluminium species, and the non-marine contributions are indicated by an asterisk (*).

The present exceedance of the critical load of acidity:

$$Ex(Ac) = S_{dep}^* + N_{le} - BC_{dep}^* - CL(Ac) \qquad (3)$$

where S_{dep}^* is the total S deposition and N_{le} is the present nitrate leaching out of the catchment (as measured in the lake runoff). This equation rests on the assumption that sulphate is a completely mobile anion and the S deposition can be used to indicate the acidifying effect of S. and that the only acidifying effect of nitrogen deposition is the part that is leached as nitrate in runoff.

To calculate the critical load of acidity to surface waters a value of ANC_{limit} (eq. 1) is needed. This value can be selected from figure 1, which has been derived from the information on water chemistry and fish status obtained from the 1000 lake survey carried out in Norway in 1986 (Henriksen et al. 1988, 1989). All lake samples were analysed for all major ions, total organic carbon and aluminium species. For each lake, information about fish status was collected by the interwiev method. After checking of the fish status data and excluding limed lakes, 701 lakes remained that was considered to have acceptable fish information. The Scandinavian countries has decided to use ANC_{limit} = 20 µeq/l as the critical chemical value for fish in surface waters (Henriksen et al. 1990). Figure 1 indicate that the "probability" of damage to fish populations are small at this ANC level. One should, however, be aware of that the natural ANC in lakes can be equal or less than 20 µeq/l in areas with granitic and gneissic bedrock with thin soil cover. For such lakes the ANC_{limit} is set to the ANC-value of the lake. *Thus, the critical load for acidity will be zero for such lakes.*

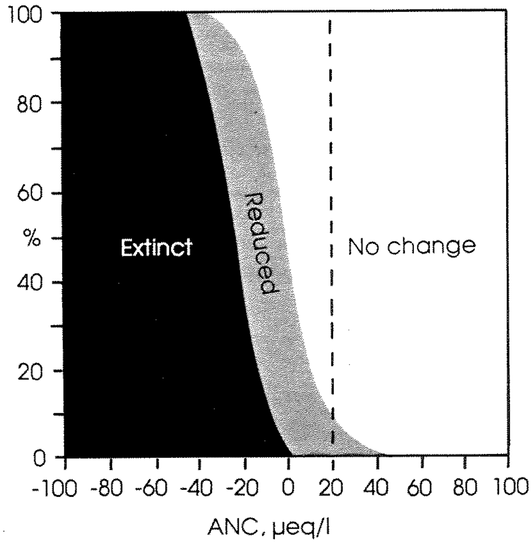


Figure 1. There is a close connenction between the ANC-concentration of a lake and damage to fish populations. Of the fish species studied ,salmon, brown trout snd roach were the most sensitive, and perch the least sensitive. The probability of damage to fish is low at an ANC > 20 µeq/l (after Lien et al. 1992).

Once the ANC_{limit} is set and the sulphur deposition and the nitrate concentration of the lake is known, the critical load and the present critical load exceedance of sulphur and nitrogen can be calculated according to eq. 3.

3. RESULTS AND DISCUSSION

To examine the relationship between the *critical load exceedance* and the *damage to fish* the data from the 1000 lake survey can again be used. Figure 2 illustrate the probability of damage to fish populations as a function of the critical load exceedance. For each exceedance interval (10 µeq/l) the fish damage index (see figure text) was calculated. Here, the data based on the status for all fish species in the lake were used. (Using only the status of brown trout in the lakes a very similar curve was obtained, because the brown trout is fish species the most abundant one in Norway).

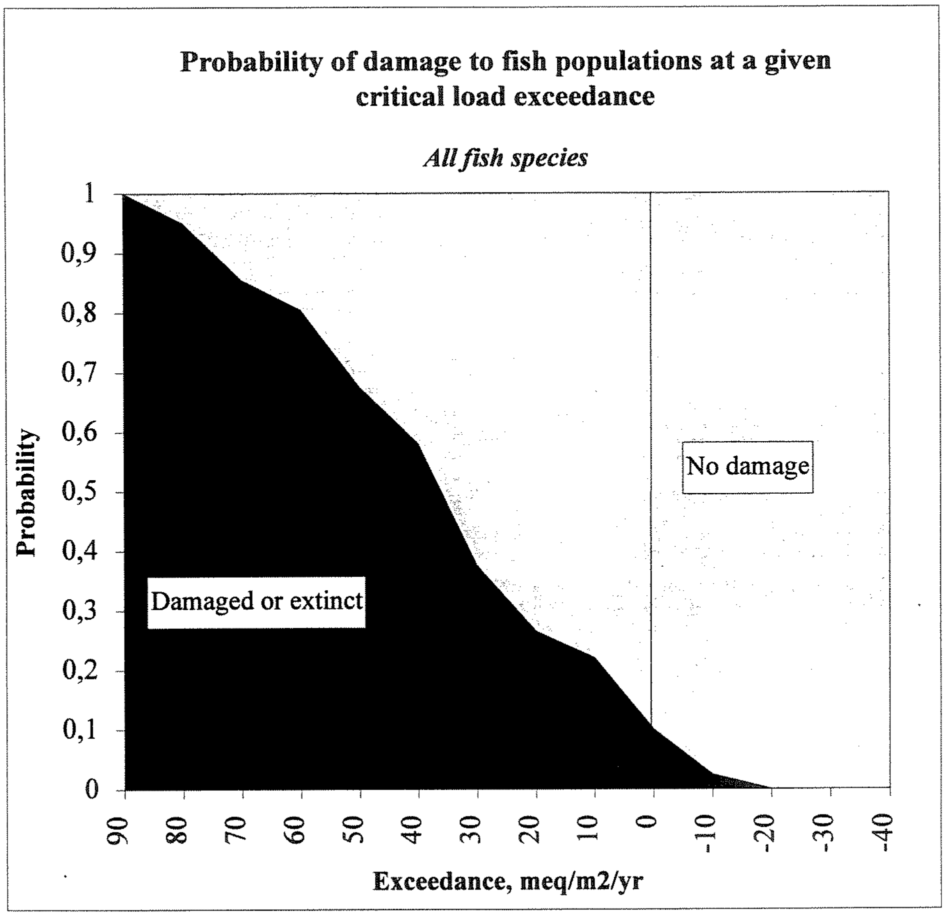


Figure 2. There is a close connection between the damage to fish populations at a given critical load exceedance. Data are from the 1000-lake survey 1986 (Henriksen et al. 1988, 1989). The fish damage index was recalculated as suggested by Berger et al. (1992): Lakes with lost fish populations were given the value 1, lakes with reduced fish populations were given the value 0,5, while lakes with healthy fish populations were labelled 0. For each exceedance interval the fish indexes were summed up and divided by the number of lakes, giving values on a continuous scale from 0 to 1. This scale can be considered as a probability scale for fish damage to a lake at a given critical load exceedance.

Figure 2 indicate that there is a very good relationship between the *exceedance* of critical load and the response of the *biological indicator* (fish). When the critical load is not exceeded there is only a small probability of damage to fish, but as soon as the critical load is exceeded, the probablity of fish damage starts to increase. At high exceedances, however, there are still lakes that are not affected. There are several reasons for this:

1). Some of the lakes have high content of humic substances (highly coloured waters), and it is known that some fish species, especially perch, can tolerate higher acidity (or negative values for ANC) in coloured waters.
2) The fish information collected can be older than the water chemistry data, especially can this be the case for more remote lakes rarely visited.
3) The time lap from a lake reaches a critical chemical condition and until the effects become evident in reduced and lost fish populations can be considerable, maybe decades (Hesthagen et al. 1993).

4) The fish information can be unreliable.

Everything considered, however, the relationship shown in figure 2 indicate strongly that assessing the critical load exceedance will establish the ecosystem damage in a reliable way, and indicate strongly a clear relationship between a *critical chemical value* (ANC) and a *biological indicator* (fish). Prognoses carried out for given reduction scenarios can thus effectively assess the degree of recovery of water quality so that the lakes again can sustain fish populations.

3.1. The critical load data base for Norway

The Steady State Water Chemistry method was used to calculate and to produce maps of critical loads of acidity and critical load exceedance for sulphur and for present exceedance for sulphur and nitrogen (Henriksen et al. 1992).

GRID SIZE: Each 1^{o} longitude by 0.5^{o} latitude grid was divided into 16 subgrids, each covering about 12 x 12 km in southern Norway, and with decreasing grid width at higher latitudes. The land area covered by each grid (N=2315) has been calculated.

DATA SOURCES: National regional lake surveys and monitoring programs.

Precipitation: A weighted average total deposition value for each NILU-grid (a 3 by 3 subdivision of an EMEP-grid) has been calculated from ambient air concentrations and wet deposition taking land use data (coverage of different receptors) into account. Data for the period 1983-1987 were used. The deposition values for each of the surface water grids (see above) was estimated from the NILU-grid data base.

Water: The chemistry of surface water within a subgrid was estimated by comparing available water chemistry data for lakes and rivers within each grid. The chemistry of the lake that was judged to be the most typical was chosen to represent the grid. If there were wide variations within a subgrid, the most sensitive area was selected, if it amounted to more than 25% of the total grid area. Sensitivity was evaluated on the basis of water chemistry, topography and bedrock geology. Geology was determined from the geological map of Norway (1:1,000,000) prepared by the Norwegian Geological Survey. Mean annual runoff data are derived from maps prepared by the Norwegian Water and Energy Works.

The present exceedance of critical loads of sulphur and nitrogen is shown in figure 3.

3.2. Damage to fish populations in Southern Norway

Damage to fish populations due to acidification of lakes and rivers have been assessed by *the interview method* (Sevaldrud et al. 1980, Henriksen et al. 1989, Berger et al. 1992,) from the mid 1970's, and the validity of the method has been confirmed by extensive test fishing (Hesthagen et al. 1993). The interview method gives a good, but conservative estimate of the situation. in Norwegian lakes. Today, information for most of southern Norway has been collected, largely as part of the Norwegian Monitoring Program for Long Range Transported Air Pollutant and Precipitation under the Norwegian State Pollution Control Authority (SFT) (Berger et al .1992). The information has been presented in a geographic grid system based on the UTM coordinates and is thus somewhat different from the one applied to the critical load assessments. The fish index for each grid was calculated as discribed above. The information was converted to the same grid system as as the one used for the critical load assessment. The resulting map is shown in figure 3 together with the critical load exceedance map.

Altogether 128.526 km^2 (about 40%) of Norway's total land area has been mapped for both critical loads and for fish status index (figure 3). The critical load is exceeded in about 94.000 km^2, while fish damage has been recorded in about 86.000 km^2. For 68% of the grids the two sets of information coincide. For those grids with contradictive information both databases will be checked, but some of the discrepancy is due to the choice of ANC_{limit}. In unimpacted and slightly impacted areas healthy fish populations may survive at ANC concentrations down to 0 µeq/l.

4. CONCLUSIONS

The first approach was based on the 1000 lake survey carried out in 1986 and compared data for fish damage and water chemistry for the same lakes, and the results indicate strongly a clear relationship between a *critical chemical value* (ANC) and a *biological indicator* (fish). The second approach, however, used two sets of data collected independently. The latter data indicate that exceedance of critical loads and damage to fish populations coincide geographically. Both approaches leads to the conclusion that the critical load exceedance strongly indicate ecosystem changes that can be quantified. Prognoses carried out for given reduction scenarios can thus effectively assess the degree of ecosystem recovery.

The responses of fish to changes in water chemistry are fairly well documented, while the responses of trees to changes in soil chemistry are poorly understood. Factors that affect the health and growth of trees are less well known compared to those affecting the health and growth of fish. A major factor is variation in climate. Forests are subject to large variations in climate, i.e. air temperature and humidity of the soil, and it is difficult to distinguish effects of the natural variations in ecosystems from the effects of external inputs. Fish, hovewer, exist in a more stable system not underoing dramatic changes due to climate variations, even in small waterbodies and streams. The major factor that inflicts damage to fish is external inputs that change their chemical surroundings.

Text to Figure 3 (next page):

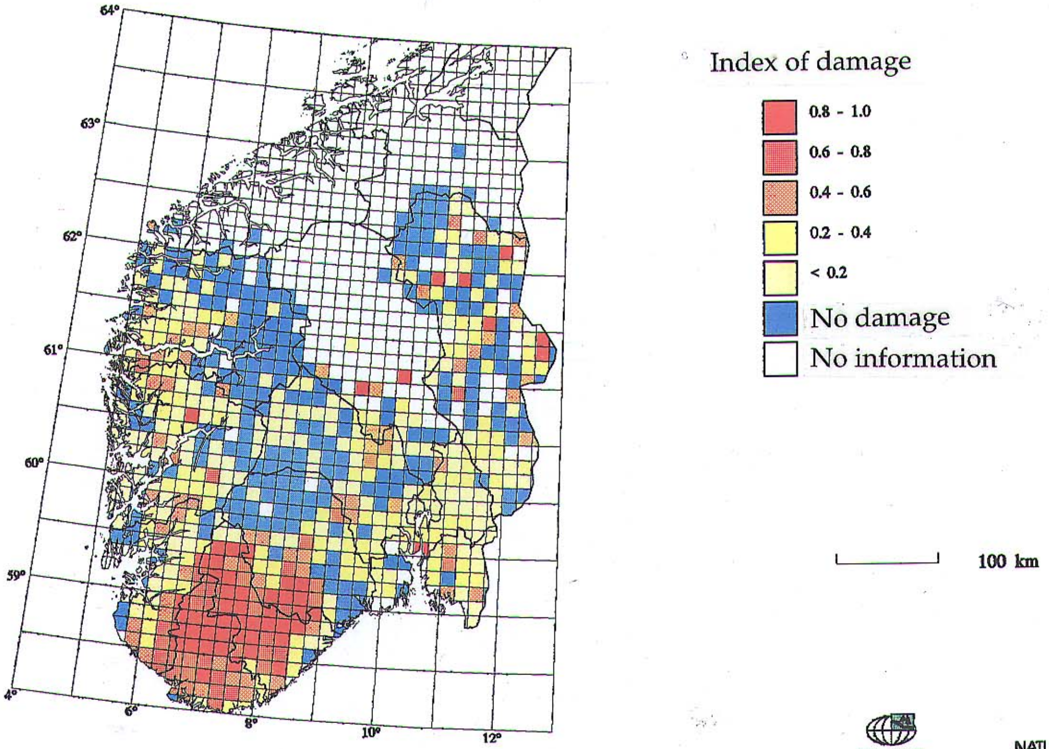
a) Present exceedance of critical load has been calculated by deducting present sulphur deposition to and present nitrate leaching from the lake. The ANC_{limit} was set to 20 µeq/l (Henriksen et al. 1993).

b) Index of damage to fish populations in Southern Norway based on information for 13.000 fish populations (Berger et al. 1992).

For both maps a grid system was constructed by dividing each 1^{o} longitude by 0.5^{o} latitude grid into 16 subgrids, each covering about 12 x 12 km in southern Norway, and with decreasing grid width at higher latitudes. The land area covered by each grid (N=2315) has been calculated.

Index of damage to fish

(Brown Trout, Arctic Char and Perch)



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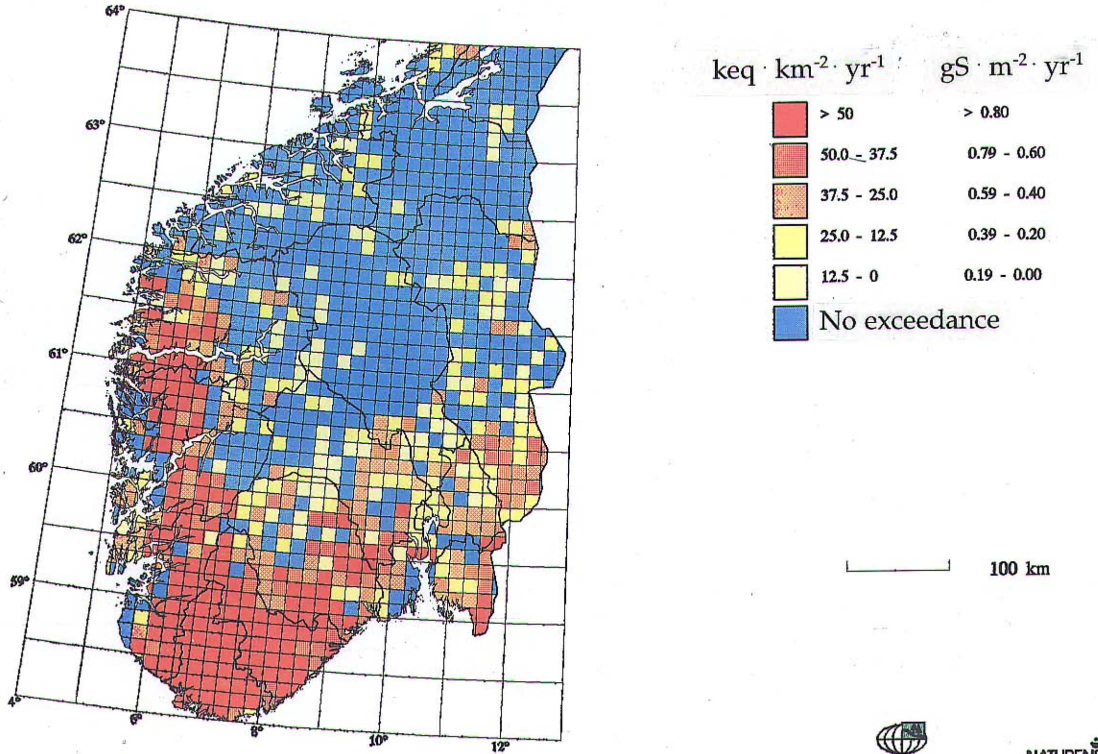
Exceedance of Critical Loads - Surface water

Amounts of sulphur and nitrogen. $ANC_{limit} = 20\ \mu eq/l$



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Norwegian Institute for Water Research NIVA

P.O.Box 69, Korsvoll N-0808 Oslo, Norway
Phone: + 47 22 18 51 00   Fax: + 47 22 18 52 00

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