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# Acidification and Atlantic salmon: critical limits for Norwegian rivers

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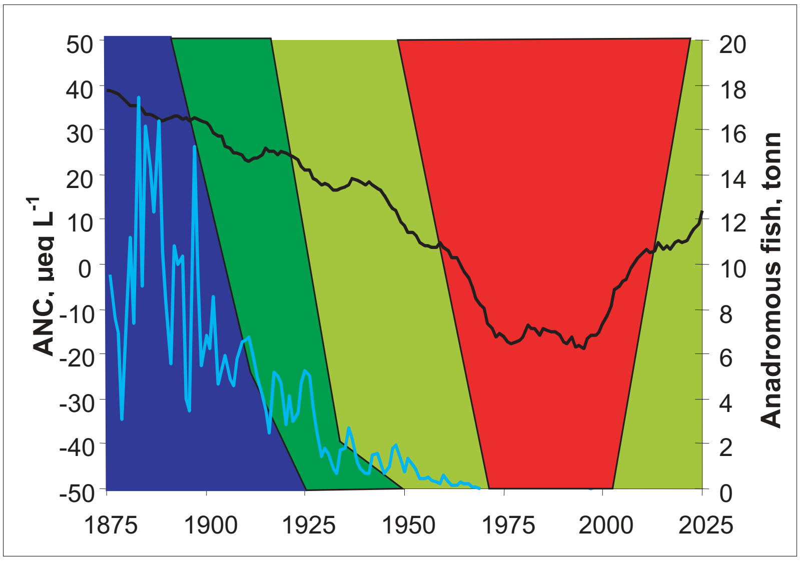

Norwegian Institute for Water Research

# REPORT

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Abstract

An analysis of water chemistry and salmon population status based on data for 1993-94 shows that of 73 salmon rivers in Norway, 23 have extinct populations and an additional 22 have affected populations. Acidification is one of several causes of damage to salmon populations. The extinct rivers have ANC below about 0 µeq $L^{-1}$, whereas the unaffected rivers have ANC above about 25 µeq $L^{-1}$. Salmon catch statistics from the late 1800's to the present indicate declining populations in many rivers, especially those on the south coast. Historical ANC reconstructed by application of the MAGIC model in 6 rivers indicates declining ANC (acidification) to levels potentially damaging to salmon. Of the rivers tested, only in Tovdal river do the salmon catch statistics and reconstructed ANC give a consistent clear-cut picture. The data indicate that the critical limit for salmon in Norway is about 30 µeq $L^{-1}$. This limit is compatible with data from laboratory and field experiments with salmon. Setting this as a limit does not necessitate revision of the critical load maps for Norway, which are based on critical limit for brown trout.

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Naturens Tålegrenser

Fagrapport nr. 111

# Acidification and Atlantic salmon: critical limits for Norwegian rivers

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# Preface

The work reported here was conducted in 2000-2001 as a contract to the Norwegian Directorate for Nature Management (DN) under the programme “Naturens tålegrenser” (Critical loads). Frode Kroglund developed the database on water chemistry and salmon population status. Carolyn Burchart compiled the data necessary for MAGIC and carried out the calibrations. Richard Wright was responsible for the MAGIC work and served as project leader. We thank Jarle Håvardstun for help with maps, and many other individuals and organisations for providing published and unpublished data on water chemistry and salmon populations. Carolyn Burchart was supported in part by the Valle Scholarship and International Exchange Program (University of Washington, Seattle, USA).

Oslo, December 2001

*Richard F. Wright*

# Contents

# Summary

An analysis of water chemistry and salmon population status based on data for 1993-94 shows that of 73 salmon rivers in Norway, 23 have extinct populations and an additional 22 have affected populations. Acidification is one of several causes of damage to salmon populations. The extinct rivers have ANC below about 0 µeq $L^{-1}$, whereas the unaffected rivers have ANC above about 25 µeq $L^{-1}$. Salmon catch statistics from the late 1800's to the present indicate declining populations in many rivers, especially those on the south coast. These statistics must be treated with caution as they are subject to many sources of uncertainty. Historical ANC reconstructed by application of the MAGIC model in 6 rivers indicates declining ANC (acidification) to levels potentially damaging to salmon. Of the rivers tested, only in Tovdal River do the salmon catch statistics and reconstructed ANC give a consistent clear-cut picture. For the other 5 rivers the weak point in the data is probably the salmon statistics, which may not give a true picture of the population status of salmon in these rivers during the past 100 years. The data together indicate that the critical limit for salmon in Norway is about 30 µeq $L^{-1}$. This limit is compatible with data from laboratory and field experiments with salmon. Setting this as a limit does not necessitate revision of the critical load maps for Norway, which are based on critical limit for brown trout.

# 1. Introduction

Decades of acid deposition have caused widespread acidification of freshwaters and damage to fish in southern Norway. Populations of Atlantic salmon (*Salmo salar* L.) have been eliminated from 7 major salmon rivers on the south coast. Numerous rivers in western Norway are regarded as affected by acidification showing reduced fry and smolt production and reduced adult returns (Leivestad et al., 1976; Sivertsen, 1989; Hesthagen and Hansen, 1991). Labile inorganic aluminium ($Al_i$) has long been recognised as the main toxic agent to salmon in Norway (Rosseland and Staurnes, 1994). $Al_i$ is mobilised from soils by strong acid anions such as sulphate and nitrate.

Atlantic salmon are more vulnerable to acidification than other fish species due to their anadromous lifestyle. Certain life stages of salmon are particularly sensitive to $Al_i$, most notably those related to smoltification (smolt) and hatching (yolk-sack fry). Regardless of which life stage is affected, the final result is recruitment failure with declining population and in severe cases, extinction of the native population.

The smoltification process represents the most vulnerable life period for Atlantic salmon. During the smoltification process the smolt become preadapted to high salinity seawater. The preadaptation includes physiological changes (increased hypoosmotic capacity), changes in behaviour (migratory- and anti-predator behaviour) and morphological changes (silvering). The smolt must leave the river during a four-week period in spring (during the smolt window). If one or more of these traits are affected by a stressor, marine survival is reduced. In this case, the cause for population effects lies in freshwater, but the population response occurs first after the fish have entered the marine environment. The preadaptation to seawater is negatively affected by aluminium at concentrations that do not cause any detectable response at the population level as long as the fish remain in freshwater (Saunders et al., 1983; Farmer et al., 1989; Staurnes, et al., 1993; Kroglund and Staurnes, 1999; Kroglund and Finstad, 2001). Based on this, the ability to maintain homeostasis in seawater is regarded as one of the most sensitive properties of Atlantic salmon and the property that is most easily affected by environmental stressors. Several controlled experiments have demonstrated that impaired hypoosmotic capacity (measured in seawater challenge tests; Clarke and Blackburn, 1977) reduces marine survival (Wedemeyer et al 1980; Staurnes et al 1993b, Staurnes et al., 1996; McCormick et al., 1998; Finstad and Jonsson, 2001; Kroglund and Finstad, 2001). As water quality declines further, population effects are also detected as reduced growth, and eventually as smolt mortality in freshwater (see e.g. Henriksen et al., 1984). Both increased marine mortality and mortality in freshwater result in reduced returns of adults. Deposition of eggs then declines to below the carrying capacity of the river, and fry production is reduced. With further deterioration of water quality, egg and fry survival decrease and cause even lower smolt production and adult returns. Ultimately the population goes extinct. Water quality limits for Atlantic salmon must take seawater survival into account. The critical question is: what are the water quality limits that cause population reductions and later extinction and how are these best presented.

The critical load concept is now used in Europe as the scientific basis for determining cost-effective strategies for emission abatements of acidifying compounds to the atmosphere (Bull et al. 2001, UN/ECE 1999). Determination of critical load involves several steps, including identification of biological indicator organism to be protected, critical chemical limit at which damage to the organism occurs, and determination of acid deposition load such that the critical limit is not exceeded (Nilsson and Grennfelt 1988).

Brown trout (*Salmo trutta* L.) has been chosen as the biological indicator organism for determining critical loads for surface waters in Norway (Henriksen et al. 1990). Brown trout is also affected by elevated concentrations of $Al_i$. The critical limit for brown trout has been determined based on empirical data for water chemistry and brown trout status in several thousand Norwegian lakes (Bulger et al. 1993). Acid neutralising capacity (ANC) is used (Henriksen et al. 1992), as it is a robust surrogate for combination of $Al_i$, pH and Ca. For brown trout the critical limit is 10 to 20 µeq/l ANC. The ANC levels from 10 to 20 can be associated with pH ranging from 5 to 6.5 and $Al_i$ ranging from 0 to 100 µg Al $L^{-1}$ based on the 1000-lake survey data (Bulger et al. 1993).

Here we use two approaches to estimate the critical limit for salmon in Norwegian rivers. First we take information on current status of salmon populations (mid-1990s) and current water chemistry (1993-94) in 74 rivers in Norway to determine empirical relationships between salmon population status and water chemistry (in particular ANC, pH, $Al_i$ and Ca) and thus identify critical chemical limits. Second we use the acidification model MAGIC (Cosby et al. 1985a; Cosby et al. 1985b) to reconstruct the acidification history in 6 salmon rivers and compare trends in water chemistry parameters with historical records of salmon catches. Together these can be used to check if the "snapshot" critical limits from the 73 rivers are consistent with the historical declines in salmon catch and reconstructed water chemistry.

# 2. Methods, data sources and site descriptions

## 2.1 Present-day salmon status and water chemistry from 74 rivers

Water quality data and fish status in this survey is based on data from 74 rivers located over all Norway (**Figure 1**). The salmon populations were categorised as extinct, affected, possibly affected and not affected, using official status evaluations (Sivertsen; 1989, Hesthagen and Hansen, 1991; Directorate for nature management; official river threat and present fish status categorisation). Some of the rivers in Sogn and Fjordane and Hordaland are categorised following Skurdal et al. (2001).

Within each category, the rivers were sorted according to pH, $Al_i$, ANC and Ca concentration, where the water chemistry data was collected from several sources (**Appendix 2)**. For the majority of the rivers, water chemistry was collected from databases maintained by the Norwegian Institute for Water Research (NIVA) or by the Norwegian Institute for Nature Research (NINA). For some west coast rivers water chemistry was obtained from salmon population studies undertaken by NIVA. Water quality data are with few exceptions annual arithmetic averages for the years 1993 and 1994. For the exceptions, water quality is based on spring samples only. For some rivers, especially rivers in northern Norway with pH >6.3, aluminium has not been measured. Based pH-$Al_i$ relationships, $Al_i$ will be low within the pH interval 6.2 to 6.7; inorganic monomeric Al ($Al_i$) is thus set to 5 µg Al $L^{-1}$ (the detection limit). In rivers with pH >6.4 and Ca concentrations exceeding 2 mg $L^{-1}$, acidification is not a reasonable cause for eventual population declines. In these cases, factors other than acidification are believed to be the cause.

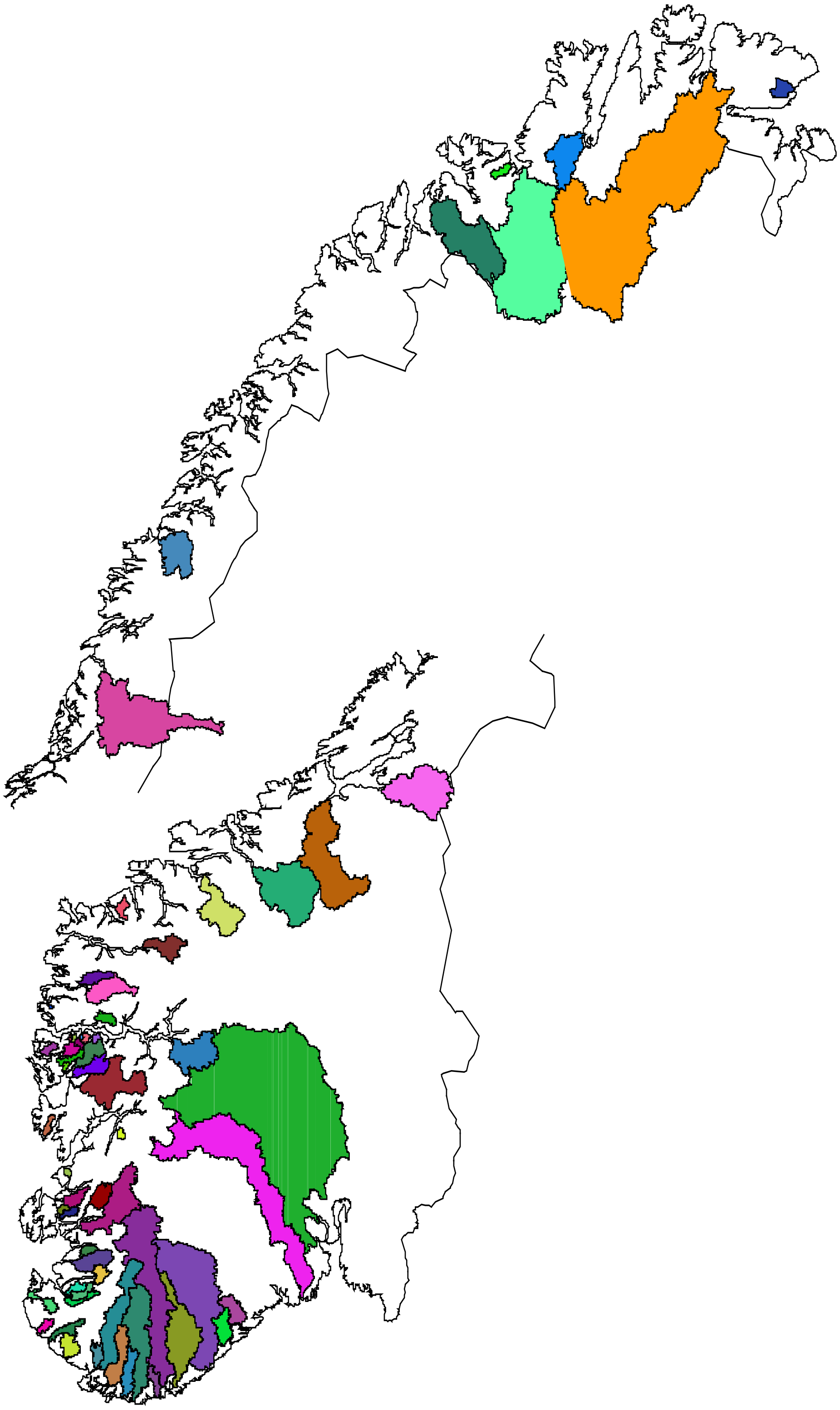


**Figure 1.** Locations of the 74 salmon rivers in Norway used to establish empirical relationships between salmon population status and water chemistry.

## 2.2 Descriptions of the 6 salmon rivers modelled with MAGIC

### 2.2.1 Nausta River

The Nausta River has been classified as moderately acidified with biological effects such as reduced density of Atlantic salmon and the invertebrate *Baetis rhodani*. The water quality in Nausta has improved during the late-1990's (SFT 2000; DN 2001). Elevated concentrations of $Al_i$ and $H^+$ were measured annually prior to 1995, especially in 1989 to 1991. From 1995 to 2000, high concentrations have not been observed. River Nausta is not limed.

| | | |
|---|---|---|
| Country no. | | SF, 14 |
| Municipality no. | | Nausdal, 1433 |
| Watershed no. | | 084.7Z |
| Catchment area | $km^2$ | 281 |
| Anadromous stretch | $km^2$ | 12.4 |
| Lakes in andromous stretch | | 0 |
| Regulations | | 0 |
| Industry | | 0 |
| Other threats to salmon | | Salmon lice |
| Catch statistics | | Few reared salmon<br>Not usable prior to 1970 |
| Fish management | | Salmon ladder 1975 |

The fish statistics prior to 1975 are regarded as poor (**Figure 2**). In 1975 the anadromous stretch was increased from 2.9 to 12.4 km after the building a fish ladder. Catch data prior to 1975 are therefore omitted from further data analysis. The annual catch of anadromous fish has increased during the late 1990's, probably as a response to improved water quality (Skurdal et al. 2001). The increase cannot be explained as an effect of fewer salmon lice nor escaped fish from fish farms.

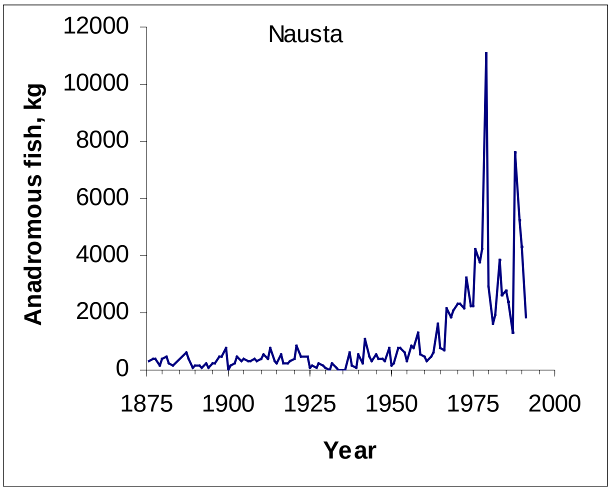


**Figure 2.** Official salmon catch statistics for River Nausta.

### 2.2.2 Vosso River

The Vosso River is affected by a hydro-electrical power plant at Evanger (build in 1963 – 1986) and a dam at the outlet of Lake Vangsvatn. The latter does not affect discharge. The power plant at Evanger has utilised water from the neighbouring River Ekso since 1973. This water is more acidic than the Vosso River main tributaries. The outlet from the power plant is in Lake Evangervatn. During winter and early spring, the water from Ekso can contribute more than 50 % of the discharge at the river mouth. The water chemistry station is located upstream Evanger and therefore is not influenced by this source of acidic water. Several tributaries between Vangsvatn and the river mouth are acidic and transport aluminium to the main river (Kroglund et al. 1998). The water quality appears to be improving, starting around 1995 (Hindar and Kroglund 2000). River Vosso has been limed since 1994 (DN 2001).

| | | |
|---|---|---|
| County no. | | Ho, 12 |
| Municipality no. | | Voss, 1235 |
| Watershed no. | | 062,Z |
| Catchment area | $km^2$ | 1499 |
| Anadromous stretch | $km^2$ | 35 |
| Lakes in anadromous stretch | | 2 |
| Regulations | | Minor - Vangsvatnet<br>Major – Evanger kraftverk |
| Industry | | 0 |
| Catch statistics | | Reared salmon |
| Other threats to salmon | | Salmon lice. Aquaculture |
| Fish management | | Fish stocking |

According to Skurdal et al. (2001) the Vosso salmon is characterised as “Storlaksstamme”. Average weight 10 kg. The annual catch declined gradually, starting in the 1970s. The decline continued up through the 1980s and all fishing efforts were stopped early in the 1990s. High proportion of escaped hatchery reared salmon from 1992 contribute to the “low” catches from 1992, making the actual reduction more intense. The salmon smolts from Vosso are also affected by salmon lice in the fjord system.

The smolt status was assessed in 1993, 1994 and 1995 (Kroglund et al. 1993; 1996ab) and yearly from 1998 to 2001 (DN-2001). The smolt quality appears to be improving, suggesting improved water quality during this period.

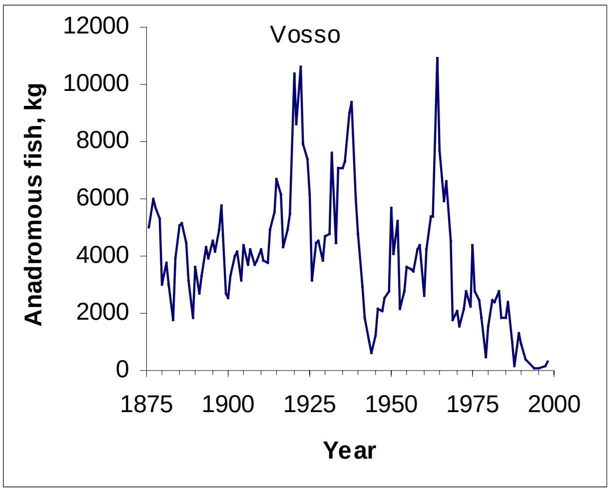


**Figure 3.** Official salmon catch statistics for River Vosso.

### 2.2.3 Vikedal River

River Vikedal has been limed since 1987. The pH target was pH 6.2 up to 1994. From then, the pH target has been elevated to 6.4 during the smoltification period. This pH increase has increased smolt production, quality and adult returns (DN 2001). Salmon from River Vikedal will be susceptible to salmon lice and escaped salmon from fish farms. In smolt surveys conducted in 1994 and 1995 in the unlimed water, smolts were very affected.

| | | |
|---|---|---|
| County no. | | RO, 11 |
| Municipality no. | | Vindafjord, 1154 |
| Watershed no. | | 038,Z |
| Catchment area | $km^2$ | 118.4 |
| Anadromous stretch | $km^2$ | 10 |
| Lakes in anadromous stretch | | 0 |
| Regulations | | 0 |
| Industry | | 0 |
| Other threats to salmon | | Salmon lice. Aquaculture |
| Catch statistics | | poor |
| Fish management | | none |

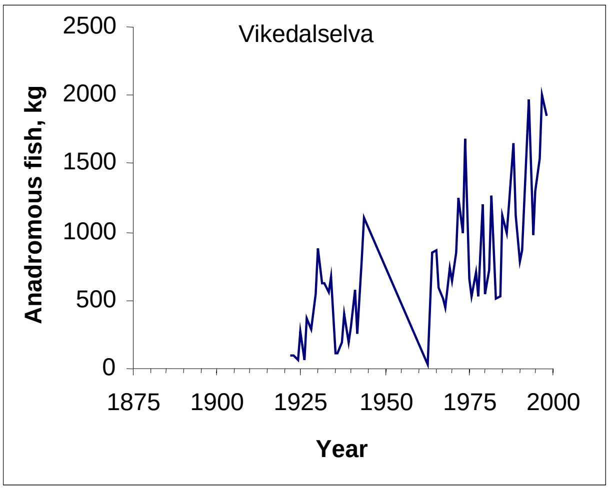


**Figure 4.** Official salmon catch statistics for River Vikedal.

### 2.2.4 Bjerkreim River

The river has been limed since 1995.

| | | |
|---|---|---|
| County no. | | Ro, 11 |
| Municipality no. | | Eigersund, 1101 |
| Watershed no. | | 027 |
| Catchment area | $km^2$ | 705.8 |
| Anadromous stretch | $km^2$ | >40 |
| Lakes in anadromous stretch | | several |
| Regulations | | sparse |
| Industry | | sparse |
| Other threats to salmon | | Salmon lice. Aquaculture |
| Catch statistics | | poor |
| Fish management | | stocking |

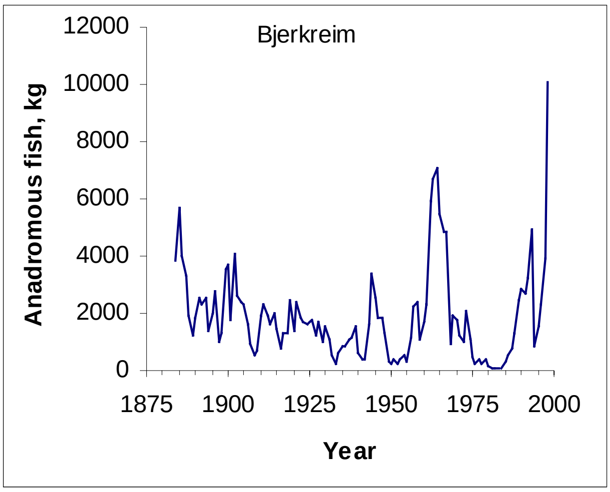


**Figure 5.** Official salmon catch statistics for River Bjerkreim.

### 2.2.5 Tovdal River

The river has been limed since late 1996.

| | | |
|---|---|---|
| County no. | | VA, 10 |
| Municipality no. | | Kristiansand, 1001 |
| Watershed no. | | 020 |
| Catchment area | km$^2$ | 1885 |
| Anadromous stretch | km$^2$ | 35 |
| Lakes in anadromous stretch | | 1 |
| Regulations | | sparse |
| Industry | | sparse |
| Other threats to salmon | | none |
| Catch statistics | | |
| Fish management | | egg stocking from 1999 |

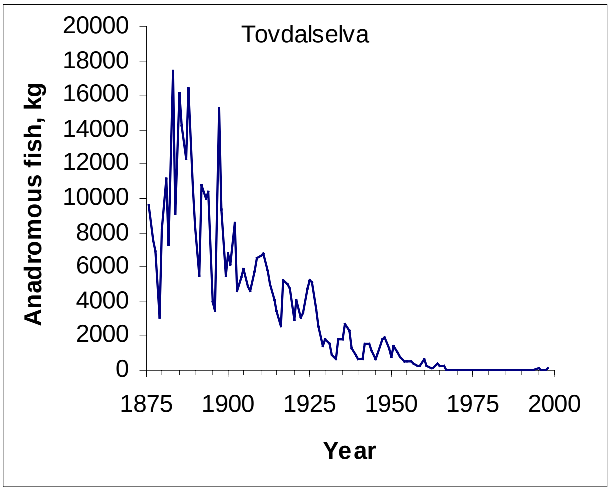


**Figure 6.** Official salmon catch statistics for River Tovdal.

### 2.2.6 Gjerstad River

A dam at the mouth of the river constructed in the early 1900's effectively stopped migration of salmon and sea trout in this river. Catches in recent years follow the construction of a salmon ladder. There has been liming in many parts of the catchment beginning in the late 1980's.

| | | |
|---|---|---|
| County no. | | AA, 09 |
| Municipality no. | | Risør, 0901 |
| Watershed no. | | 018 |
| Catchment area | $km^2$ | 380 |
| Anadromous stretch | $km^2$ | |
| Lakes in anadromous stretch | | several |
| Regulations | | sparse |
| Industry | | none |
| Other threats to salmon | | dam at river mouth; seal |
| Catch statistics | | poor |
| Fish management | | none |

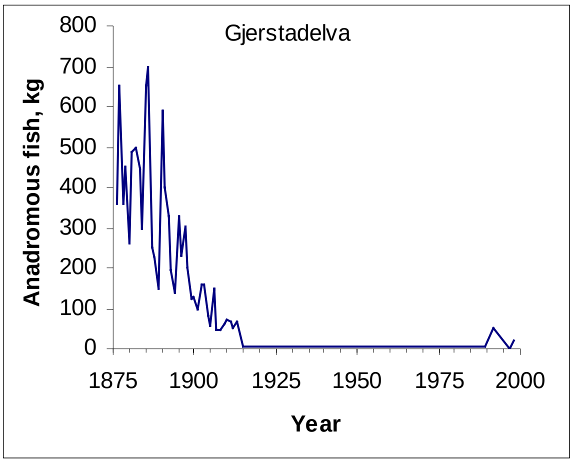


**Figure 7.** Official salmon catch statistics for River Gjerstad.

## 2.3 MAGIC model

### 2.3.1 Description of model

MAGIC is a lumped-parameter model of intermediate complexity, developed to predict the long-term effects of acidic deposition on surface water chemistry (Cosby et al. 1985b, Cosby et al. 1985a). The model simulates soil solution and surface water chemistry to predict average concentrations of the major ions. Time step is month or year. MAGIC calculates for each time step the concentrations of major ions under the assumption of simultaneous reactions involving sulphate adsorption, cation exchange, dissolution-precipitation- speciation of aluminium and dissolution-speciation of inorganic carbon. MAGIC accounts for the mass balance of major ions in the soil by book-keeping the fluxes from atmospheric inputs, chemical weathering, net uptake in biomass and loss to runoff.

At the heart of MAGIC is the size of the pool of exchangeable base cations in the soil. As the fluxes to and from this pool change over time owing to changes in atmospheric deposition, the chemical equilibria between soil and soil solution shift to give changes in surface water chemistry. The degree and rate of change of surface water acidity thus depend both on flux factors and the inherent characteristics of the affected soils.

Data inputs required for calibration of MAGIC comprise soil chemical and physical characteristics, input and output fluxes for water and major ions, and net uptake fluxes for vegetation.

**Table 1.** Overview of the data sources used to calibrate MAGIC.

| River | Nausta | Vosso | Vikedal | Bjerkreim | | Tovdal | | Gjerstad |
|---|---|---|---|---|---|---|---|---|
| **Precipitation chemistry** | | | | | | | | |
| NILU station | Nausta | Voss | Vikedal II | average of Ualand and Skreådalen | | average of Treungen and Birkenes | | Treungen |
| | | | | Ualand | Skreåd. | Treungen | Birkenes | |
| latitude | 61°34' | 60°36' | 59°32' | 58°31' | 58°49' | 59°01' | 58°23' | 59°01' |
| longitude | 5°53' | 6°32' | 5°58' | 6°23' | 6°43' | 8°32' | 8°15' | 8°32' |
| **Discharge** | | | | | | | | |
| NVE station | Hovefoss | | Holmen | Gjedlakleiv | | Flaksvatn | | Gjerstad |
| code | 84.11.0 | | 38.1.0 | 27.25.0 | | 20.3.0 | | 18.10.0 |
| area | 274 km$^2$ | | 117.7 km$^2$ | 643 km$^2$ | | 1794 km$^2$ | | 235 km$^2$ |
| **Water chemistry** | | | | | | | | |
| NIVA station | 34.1<br>Nausta | 9<br>Bolstad | 32.9<br>Låkafoss | 19.1<br>Tengs | | 7.1 Boen Bruk | | 3.1<br>Gjerstad |
| UTM-EW | 3367 | | 3291 | 3269 | | 4492 | | 5047 |
| UTM-NS | 68312 | | 66030 | 64616 | | 64557 | | 65141 |
| R | 32 | | 32 | 32 | | 32 | | 32 |
| **Soil chemistry** | | | | | | | | |
| samples | sites in catchment | sites in catchment | sites in catchment | sites in and near catchment | | Birkenes and Storgama | | Storgama and Gjerstad forest liming project |
| no. sites | 4 | 7 | 4 | 9 | | 4 | 4 | 6 |
| sampled by | NISK | NIVA | NISK | NIJOS | | NISK | NISK | NISK |
| analysed by | NISK | NISK | NISK | NISK | | NISK | NISK | NISK |
| sampling year | 1987 | 2000 | 1985 | 1998 | | 1984 | 1982 | 1994 |
| reference for aggregation | Reuss 1990 | this report | Reuss 1990 | this report | | Reuss 1990 | Reuss 1990 | Hindar et al. 1999 |
| reference for soil data | SFT 1988 | Wright, unpubl. | SFT 1986 | Wright and Henriksen 1999 | | SFT 1985 | SFT 1983 | Hindar et al. 1999 |

### 2.3.2 Soils data

Soil data come from various research projects and monitoring programmes (**Table 1**). In all cases the data were aggregated to obtain a single set of values for each river basin (**Table 2**). First the data from the soil horizons in individual soil profiles were aggregated by mass weighting, and then the data from the several soil profiles within the catchment were aggregated as arithmetic averages.

**Table 2.** Soil data used to calibrate MAGIC. Date refers to sampling year(s).

| Parameters | units | Nausta 1985-88 | Vosso 2000 | Vikedal 1985 | Bjerkreim 1998 | Tovdal 1984-88 | Gjerstad 1994 |
|---|---|---|---|---|---|---|---|
| Soil depth | m | 0.75 | 0.23 | 0.75 | 0.4 | 0.36 | 0.36 |
| Porosity | % | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Bulk Density | kg $m^{-3}$ | 800 | 743 | 1037 | 632 | 717 | 592 |
| CEC | meq $kg^{-1}$ | 62 | 77 | 23 | 111 | 84 | 103 |
| Exchangeable Ca | % | 7.9 | 4.7 | 3.8 | 11.8 | 6.2 | 9.0 |
| Exchangeable Mg | % | 3.6 | 3.9 | 2.6 | 8.2 | 3.4 | 3.0 |
| Exchangeable Na | % | 4.4 | 1.4 | 2 | 3.1 | 1.2 | 0.7 |
| Exchangeable K | % | 2.4 | 3.0 | 2.2 | 3.6 | 1.7 | 2.9 |
| Base Saturation | % | 18.4 | 12.9 | 10.6 | 26.8 | 12.3 | 15.6 |

### 2.3.3 Deposition data

Deposition data are from SFT's monitoring programme operated by NILU. The data are based on samples of bulk deposition collected daily or weekly. The data are reported annually (Aas et al. 2000).

These deposition values, however, do not give representative deposition for the catchment as a whole. Dry deposition of both seasalts and acid pollutants are not included. Both precipitation volume and chemical concentrations vary with distance from the coast and elevation, due to among other things orographic effects. The measured annual bulk precipitation fluxes were thus adjusted in three ways to obtain estimates for catchment-representative deposition.

The measured runoff discharge and the measured arithmetic average chemical concentrations in the river were assumed to be exactly correct. First the annual flux of chloride (Cl) was calculated by multiplying the arithmetic average concentration by the annual discharge. Next the annual measured Cl fluxes in deposition were multiplied by a factor such that the flux of Cl in deposition matched the flux of Cl in runoff for the whole period for which data are available (**Table 3**). This estimate assumes that all Cl in runoff comes in atmospheric deposition, and that there are no sources or sinks for Cl in the catchment. Next the inputs of the marine fractions of Ca, Mg, Na, K, and $SO_4$ were increased by the same factor (assumes ratio to Cl is same as in seawater) (**Table 3**).

Next the inputs of acid pollutants were adjusted such that the flux of sulphate in deposition matched the flux in runoff for a 2-3 year period. Annual fluxes in deposition of non-marine sulphate ($SO_4^*$) were multiplied by a second factor (**Table 3**). This procedure assumes that for the selected time period, all $SO_4$ in runoff came in atmospheric deposition, thus there are no sources or sinks for $SO_4$ in the catchment. In fact there are soil processes operating on time scales of years-to-decades which retain and release $SO_4$, but these are assumed to be negligible (or at steady-state) for the selected time period.

This procedure resulted in a matrix of deposition fluxes for each year of measurements and each of the seven major ions. This became the file used to drive MAGIC during the measurement years (.dep file). For the years prior to onset of measurements (from about 1860 to about 1980) the average of these measured and corrected annual fluxes were used for the ions Ca, Mg, Na, K, Cl, and $SO_4^*$ (asterisk denotes non-marine fraction) (**Table 4**). For non-marine $SO_4$ the historical deposition was scaled to the estimated deposition history for the EMEP square in southernmost Norway (the Birkenes square) as given by Mylona (1996). Similarly the historical deposition of $NO_3$ and $NH_4$ was scaled to the estimated deposition history for Europe given by Simpson et al. (1997). The scale factors for these 3 pollutant ions relative to 1995 are given in **Table 5**.

**Table 3.** Scaling factors for Cl and $SO_4^*$ used for the deposition input from measured data. The factors vary widely from river basin to river basin due to the locations of the precipitation stations relative to the river sampling station at the mouth of the river. See text for details.

| River | Nausta | Vosso | Vikedal | Bjerkreim | Tovdal | Gjerstad |
|---|---|---|---|---|---|---|
| Period used for Cl | 1985-99 | 1994-99 | 1986-99 | 1980-99 | 1980-96 | 1981-99 |
| Cl factor | 0.88 | 3.02 | 1.09 | 1.72 | 1.42 | 3.88 |
| Period used for $SO_4^*$ | 1993-95 | 1995-97 | 1986-88 | 1980-82 | 1980-82 | 1981-83 |
| $SO_4^*$ factor | 1.05 | 3.91 | 1.28 | 1.44 | 1.28 | 1.79 |

**Table 4.** Mean deposition parameters for seasalt ions (top section) and pollutant ions (bottom section) used as default for period 1860 to beginning of measurements (about 1980). Units meq $m^{-2}$ $yr^{-1}$.

| Parameter | Units | Nausta 1985-99 | Vosso 1994-99 | Vikedal 1986-99 | Bjerkreim 1980-99 | Tovdal 1980-99 | Gjerstad 1981-99 |
|---|---|---|---|---|---|---|---|
| Ca | meq $m^{-2}$ $yr^{-1}$ | 7 | 7 | 13 | 15 | 9 | 3 |
| Mg | meq $m^{-2}$ $yr^{-1}$ | 36 | 37 | 68 | 82 | 16 | 17 |
| Na | meq $m^{-2}$ $yr^{-1}$ | 156 | 161 | 296 | 356 | 70 | 74 |
| K | meq $m^{-2}$ $yr^{-1}$ | 3 | 3 | 6 | 8 | 4 | 2 |
| Cl | meq $m^{-2}$ $yr^{-1}$ | 183 | 188 | 346 | 416 | 82 | 86 |

| Parameter | Units | Nausta 1995-97 | Vosso 1995-97 | Vikedal 1986-88 | Bjerkreim 1995-97 | Tovdal 1993-95 | Gjerstad 1995-97 |
|---|---|---|---|---|---|---|---|
| $NH_4$ | meq $m^{-2}$ $yr^{-1}$ | 21 | 44 | 68 | 55 | 44 | 30 |
| $SO_4$ | meq $m^{-2}$ $yr^{-1}$ | 50 | 80 | 117 | 120 | 55 | 81 |
| $NO_3$ | meq $m^{-2}$ $yr^{-1}$ | 19 | 56 | 67 | 52 | 50 | 25 |

**Table 5.** Scaling factors relative to 1995 for historical deposition of pollutant ions in Norway, as used in MAGIC modelling. Source: sulphur from Mylona 1996); nitrogen from Simpson et al. 1997). Values for year 2000 are estimated from measured deposition at 7 stations in southern Norway (Aas et al. 2000).

| Year | non-marine $SO_4$ factor | N factor |
|---|---|---|
| 1860 | 0.00 | 0 |
| 1915 | 0.73 | |
| 1925 | 0.76 | |
| 1940 | 0.93 | |
| 1955 | 1.42 | |
| 1960 | 1.48 | 0.76 |
| 1965 | 1.75 | |
| 1970 | 1.76 | |
| 1975 | | 1.14 |
| 1980 | 1.57 | |
| 1990 | 1.29 | 1.19 |
| 1995 | 1.00 | 1.00 |
| 2000 | 0.73 | 1.00 |

### 2.3.4 Runoff and water chemistry data

Discharge data come from gauging stations located near the mouth of each river, operated by NVE (Norwegian Electricity and Water Resources Board) (**Table 1**). Annual mean runoff for the observed years at each site is given in **Table 6**. Mean runoff for the years of measurement of chemistry was used in MAGIC for the period 1860 to beginning of measurement

**Table 6.** Mean annual discharge (m $yr^{-1}$) used in calibration of MAGIC.

| Units | Nausta 1985-99 | Vosso 1994-99 | Vikedal 1986-99 | Bjerkreim 1980-99 | Tovdal 1980-96 | Gjerstad 1981-99 |
|---|---|---|---|---|---|---|
| m $yr^{-1}$ | 2.315 | 3.155 | 3.083 | 2.397 | 1.057 | 1.009 |

Samples for chemical composition of river water are collected generally monthly in the lower (salmon carrying) stretch of each river (**Table 1**), and for most of the rivers the data are reported annually as part of the Norwegian monitoring programme (SFT 2000). The average concentrations for the selected time period used in calibration are given in **Table 7**.

**Table 7.** Arithmetic average concentrations (µeq $L^{-1}$) of major ions in river water for the time periods used in calibration of MAGIC.

| Parameters | Units | Nausta | Vosso | Vikedal | Bjerkreim | Tovdal | Gjerstad |
|---|---|---|---|---|---|---|---|
| Years | | 1994-96 | 1994-97 | 1986-88 | 1980-82 | 1993-95 | 1981-83 |
| Ca | µeq $L^{-1}$ | 30 | 49 | 36 | 50 | 50 | 107 |
| Mg | µeq $L^{-1}$ | 21 | 20 | 29 | 48 | 25 | 44 |
| Na | µeq $L^{-1}$ | 69 | 51 | 86 | 146 | 89 | 85 |
| K | µeq $L^{-1}$ | 8 | 8 | 6 | 10 | 7 | 11 |
| $SO_4$ | µeq $L^{-1}$ | 25 | 30 | 49 | 67 | 66 | 113 |
| Cl | µeq $L^{-1}$ | 76 | 62 | 89 | 167 | 92 | 80 |
| $NO_3$ | µeq $L^{-1}$ | 6 | 11 | 12 | 25 | 12 | 20 |
| SBC | µeq $L^{-1}$ | 128 | 128 | 157 | 252 | 171 | 247 |
| SSA | µeq $L^{-1}$ | 107 | 103 | 160 | 260 | 170 | 213 |
| ANC | µeq $L^{-1}$ | 21 | 25 | -3 | -8 | 1 | 34 |
| $H^+$ | µeq $L^{-1}$ | 1 | 1 | 4 | 3 | 7 | 2 |
| $Al^{n+}$ | µeq $L^{-1}$ | 1 | 0 | 3 | 3 | 8 | 2 |
| $A^-$ | µeq $L^{-1}$ | 5 | 0 | 0 | -12 | 12 | 11 |

## 2.3.5 Calibration procedure

The model was calibrated using measured inputs and outputs for the control catchment at each location. The calibrations were based on data for soil, deposition and runoff considered to be characteristic for the entire catchment for the periods of observation (selected time period). The calibrations at each site proceeded by sequential steps:

(1) The model was set up for one soil layer.
(2) Cl and $SO_4$ deposition to each catchment were set such that inputs equalled output as described above
(3) Uptake rates of nitrate and ammonium in the catchments were set such that modelled N output (mostly as $NO_3$) matched measured for the calibration period. It is assumed that the percent retention of nitrogen is constant.
(4) Sulphate maximum absorption capacity in soil was adjusted such that the slope of modelled changes in stream sulphate concentrations over the entire period of measurements matched the observed.
(5) Once these anions were calibrated the sum of strong acid anions (SSA) equalled the measured SSA. A trail and error process is used to adjust the weathering rates of Ca, Mg, Na, and K and initial soil exchange pools of these 4 cations until modelled concentrations of base cations in the streamwater and modelled pools of base cations in the soil matched the observed for the calibration period. At this point the modelled sum of base cations (SBC) equalled the measured SBC for the calibration period. Further the modelled and measured ANC (SBC-SSA) also agreed.
(6) Surface water aluminium solubility constant was adjusted such that matched the observed for the calibration period.

(7) Surface water DOC was adjusted such that the modelled concentration of organic anions and pH in streamwater pH matched the observed for the calibration period.

**Table 8.** Calibrated parameters obtained from MAGIC.

| *Cation exchange selectivity coefficients* | units | Nausta | Vosso | Vikedal | Bjerkreim | Tovdal | Gjerstad |
|---|---|---|---|---|---|---|---|
| Al-Ca | log 10 | -2.0 | -0.5 | -0.9 | -2.0 | -2.8 | -0.46 |
| Al-Mg | log 10 | -1.4 | -1.4 | -0.7 | -1.6 | -2.7 | -0.1 |
| Al-Na | log 10 | -3.9 | -2.6 | -2.5 | -2.5 | -3.8 | -1.1 |
| Al-K | log 10 | -5.6 | -6.0 | -6.2 | -6.1 | -6.1 | -5.7 |
| *Weathering rates* | | | | | | | |
| Ca | meq $m^{-2} yr^{-1}$ | 60 | 147 | 100 | 108 | 25 | 80 |
| Mg | meq $m^{-2} yr^{-1}$ | 10 | 25 | 25 | 32 | 3 | 20 |
| Na | meq $m^{-2} yr^{-1}$ | 0 | 0 | 0 | 13 | 2 | 12 |
| K | meq $m^{-2} yr^{-1}$ | 18 | 23 | 12 | 17 | 3 | 6 |
| Sum BC | meq $m^{-2} yr^{-1}$ | 88 | 295 | 137 | 170 | 33 | 118 |
| *Initial base saturation* | | | | | | | |
| Ca | % | 8.8 | 6.1 | 5.3 | 17.7 | 19.0 | 19.7 |
| Mg | % | 4.1 | 5.0 | 3.7 | 12.8 | 9.8 | 6.9 |
| Na | % | 4.8 | 1.6 | 2.5 | 4.1 | 4.7 | 1.2 |
| K | % | 2.5 | 3.4 | 2.6 | 4.3 | 2.7 | 3.7 |
| Sum BS | % | 20.2 | 16.1 | 14.1 | 38.9 | 36.2 | 31.5 |
| *Nitrogen retention* | | | | | | | |
| $NH_4 + NO_3$ | % | 66 | 65 | 75 | 66 | 86 | 70 |

### 2.3.6 Fixed parameters

The fixed parameters that were measured or estimated at each site include annual discharge, soil aluminium solubility, soil and water temperature, soil and water carbon dioxide, soil and water organic acid equilibrium constants, depth, porosity, bulk density, soil DOC, cation exchange capacity, and sulphate half-saturation constant (**Table 9**).

**Table 9.** Fixed parameters (measured, estimated or calibrated) used in calibration of MAGIC.

| ***Runoff parameters*** | units | Nausta | Vosso | Vikedal | Bjerkreim | Tovdal | Gjerstad |
|---|---|---|---|---|---|---|---|
| Discharge annual | m | 2.315 | 3.155 | 3.083 | 2.397 | 1.086 | 1.009 |
| Solubility $Al(OH)_3$ | $\log_{10}$ | 9.3 | 10.1 | 10.1 | 9.7 | 9.3 | 10.1 |
| Temperature | °C | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| $CO_2$ partial pressure | atm | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| Total organic acid | mmol $m^{-3}$ | 4 | 3 | 0 | 1 | 4 | 8 |
| pK1 | $-\log_{10}$ | 3.04 | 3.04 | 3.04 | 3.04 | 3.04 | 3.04 |
| pK2 | $-\log_{10}$ | 4.51 | 4.51 | 4.51 | 4.51 | 4.51 | 4.51 |
| pK3 | $-\log_{10}$ | 6.46 | 6.46 | 6.46 | 6.46 | 6.46 | 6.46 |
| ***Soil parameters*** | | | | | | | |
| SO4 ads. Half-sat. | meq $m^{-3}$ | 50 | 100 | 50 | 100 | 80 | 100 |
| SO4 ads. Max-capacity | meq $kg^{-1}$ | 1.0 | 1.0 | 2.0 | 1.0 | 1.0 | 8.0 |
| solubility $Al(OH)_3$ | $\log_{10}$ | 8.1 | 8.1 | 8.1 | 8.1 | 8.1 | 8.1 |
| Temperature | °C | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| $CO_2$ partial pressure | % atm | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 |
| Total organic acid | mmol $m^{-3}$ | 100 | 100 | 100 | 100 | 100 | 100 |
| pK1 | $-\log_{10}$ | 3.04 | 3.04 | 3.04 | 3.04 | 3.04 | 3.04 |
| pK2 | $-\log_{10}$ | 4.51 | 4.51 | 4.51 | 4.51 | 4.51 | 4.51 |
| pK3 | $-\log_{10}$ | 6.46 | 6.46 | 6.46 | 6.46 | 6.46 | 6.46 |

# 3. Results

## 3.1 Salmon status and water chemistry in 73 rivers in the 1990's

Water quality and salmon status in 73 rivers from various written sources were assessed and classified as not affected, possibly affected, affected, and extinct (Appendix A).

Acidification is not regarded as a potential threat in 26 rivers, most of which are in northern and central Norway, regions that do not receive significant amounts of acid deposition and thus do have significant problems with acidification. These rivers have an average pH of 7.0, <5 µg $Al_i$, 150 µeq $L^{-1}$ ANC and 4.0 mg Ca $L^{-1}$.
In 7 rivers the populations are classified as threatened, but the cause for this threat is under debate. The cause for population declines has been attributed to hydropower plants and salmon lice. Acidification in tributaries is also proposed. Several of these have acid tributaries entering the anadromous stretch of the river, but the water quality of the main river does not suggest acidification. In all but Oseelv, aluminium accumulation onto the gill surface has been documented. These rivers have an average pH of 6.0, 11 µg $Al_i$, 26 µeq $L^{-1}$ ANC and 1.1 mg Ca $L^{-1}$.

In 7 rivers in western Norway acidification has been proposed as a possible threat (Kroglund et al. 1993; Kroglund et al. 1994; Kroglund et al. 1996ab; Kroglund et al. 1998; Hindar et al. 1997; Hindar et al. 2000). Indications include elevated concentrations of Al on gills. Other possible explanations for declining or low salmon populations include presence of parasites such as sealice and changes in marine conditions due to climate.

Reduced population densities have been recorded in 17 rivers in western and southwestern Norway. In some of these rivers, fish kills have been observed, but liming was initiated before the native population went extinct. Because of the liming the native salmon population cannot be classified as extinct, but in many cases would most likely have become extinct provided water quality had remained poor. These rivers have an average pH of 5.7, 21 µg $Al_i$, 4 µeq $L^{-1}$ ANC and 0.9 mg Ca $L^{-1}$.

The salmon catch and fry density is low in 25 rivers, most of which lie in southernmost or southwesten Norway. These rivers have an average pH of 5.2, 60 µg $Al_i$, -9 µeq $L^{-1}$ ANC and 1 mg Ca $L^{-1}$.

A total of 22 rivers are categorised as having an extinct salmon population. Many of these are now limed and salmon has been reintroduced, thus the official salmon statistics show non-zero catches. These rivers had pH from 4.5 to 5.8, $Al_i$ concentrations from 19 to 127 µg Al $L^{-1}$ and ANC values ranging from –22 to 7 µeq $L^{-1}$ as annual mean values.

**Table 10.** Water quality (annual average) for rivers with salmon populations classed into 4 categories.

| | **Extinct**<br>**Category 0** | **Affected**<br>**Category 1a** | **Possibly affected**<br>**Category 1b** | **Not affected**<br>**Category 2** |
|---|---|---|---|---|
| pH | < 5.7 | 5.2 - 6.1 | 5.6 - 6.2 | > 6.0 |
| $Al_i$ (µg Al $L^{-1}$) | > 20 | 5 - 50 | 3 - 25 | < 10 |
| ANC (µeq $L^{-1}$) | < 8 | -5 - 15 | 10 - 36 | > 20 |
| Ca (mg $L^{-1}$) | < 2.6 | 0.4 – 2.2 | 0.6 – 1.9 | > 1.1 |

The data indicate clear thresholds between categories (**Table 10**, **Figure 8**, **Figure 9**). All rivers with extinct salmon populations had pH lower than 5.5. All rivers with unaffected populations had pH higher than 6.0. River with extinct populations had $Al_i$ concentrations above 20 $\mu eq\ L^{-1}$, whereas most rivers supporting healthy salmon populations had $Al_i$ concentrations below 5 $\mu g\ L^{-1}$. ANC was < 10 $\mu eq\ L^{-1}$ in all rivers with extinct salmon populations, and >20 $\mu eq\ L^{-1}$ in rivers not affected.

An ANC value of 20 $\mu eq\ L^{-1}$ separates extinct and possibly affected from not affected. The category possibly affected is found at ANC levels overlapping the not affected. An $Al_i$ of 8 $\mu g\ L^{-1}$ separates possibly affected and extinct from not affected. A pH of 6.0 separates possibly affected and extinct from not affected.

The rivers that based on these values could overlap possibly affected with not affected are few. The rivers can be identified as rivers having acidic tributaries along the lower portions of the watershed.

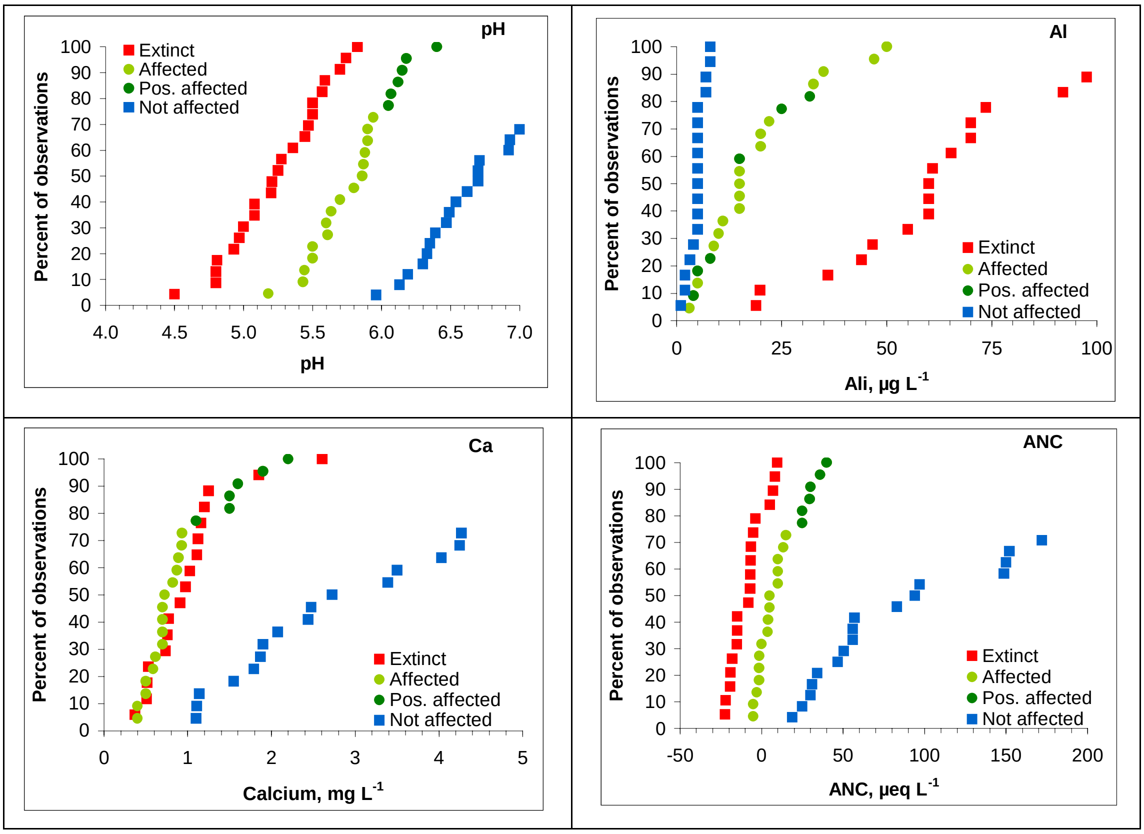


**Figure 8.** Cumulative frequency diagrams of 4 key water chemistry variables for the 73 rivers grouped into categories of salmon population status.

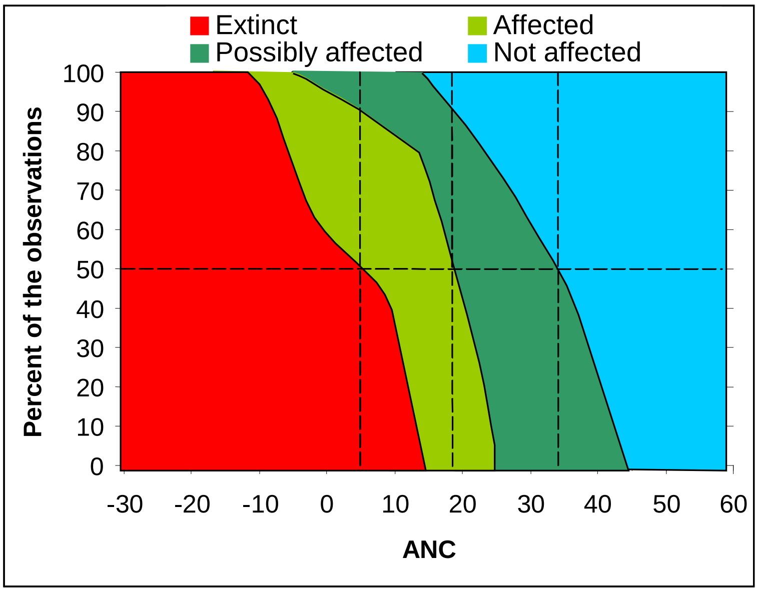


**Figure 9.** Cumulative frequency diagram of ANC (µeq $L^{-1}$) grouped by salmon population category for 73 salmon rivers in Norway in the early 1990's.

## 3.2 MAGIC calibrations

We were able to calibrate MAGIC satisfactorily to all six rivers (**Figure 10** , **Figure 11**, **Figure 12**, **Figure 13**, **Figure 14**, and **Figure 15**.)The modelled concentrations of major ions agreed well with the observed both for the calibration period as well as for the other years of the record. In particular the trend of $SO_4$ concentrations was well matched.

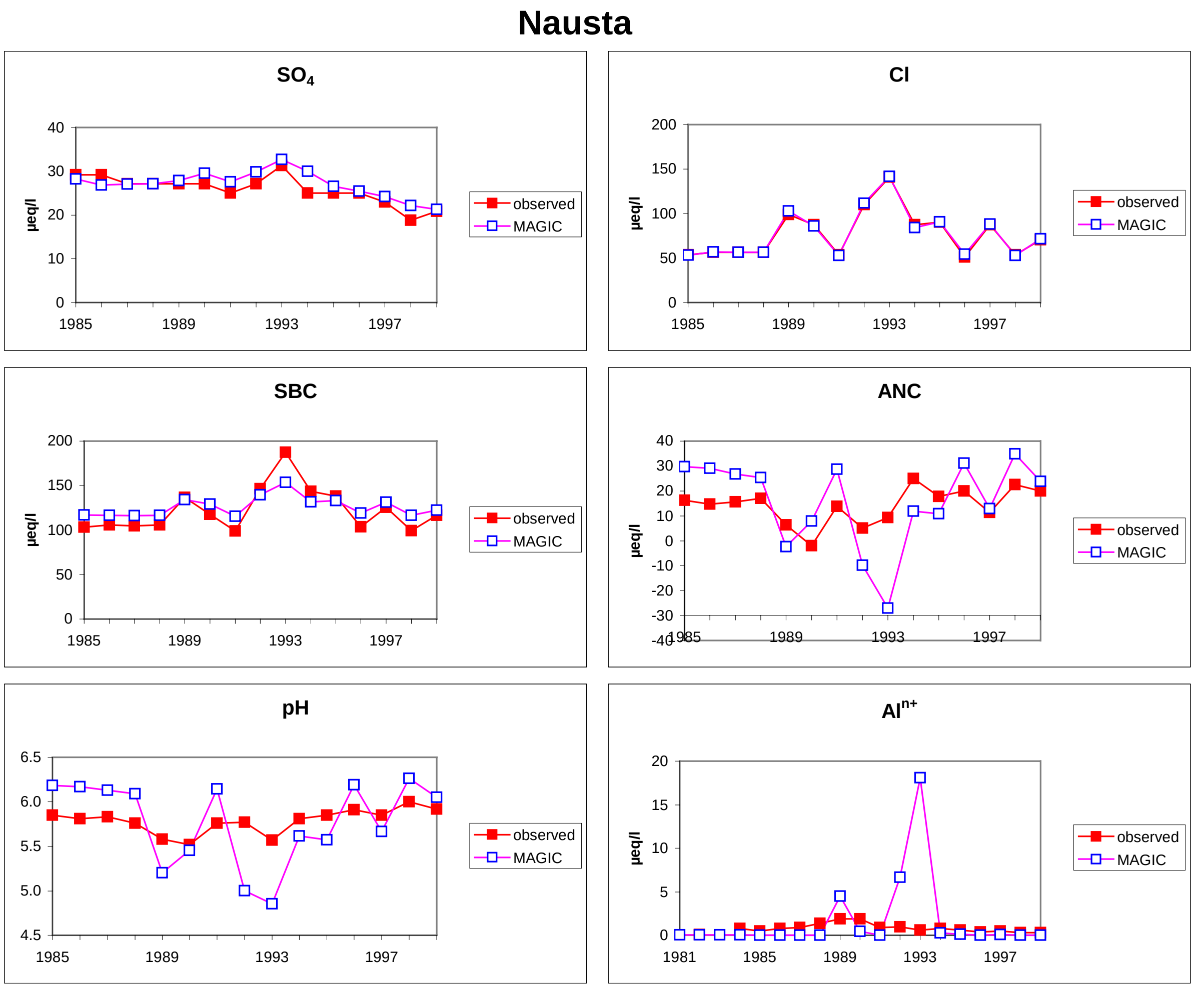


**Figure 10.** River Nausta. Observed and modelled concentrations of $SO_4$, Cl, SBC (sum base cations), ANC (acid neutralising capacity), pH and $Al_i$ (inorganic aluminium). Calibration period was 1994-96.

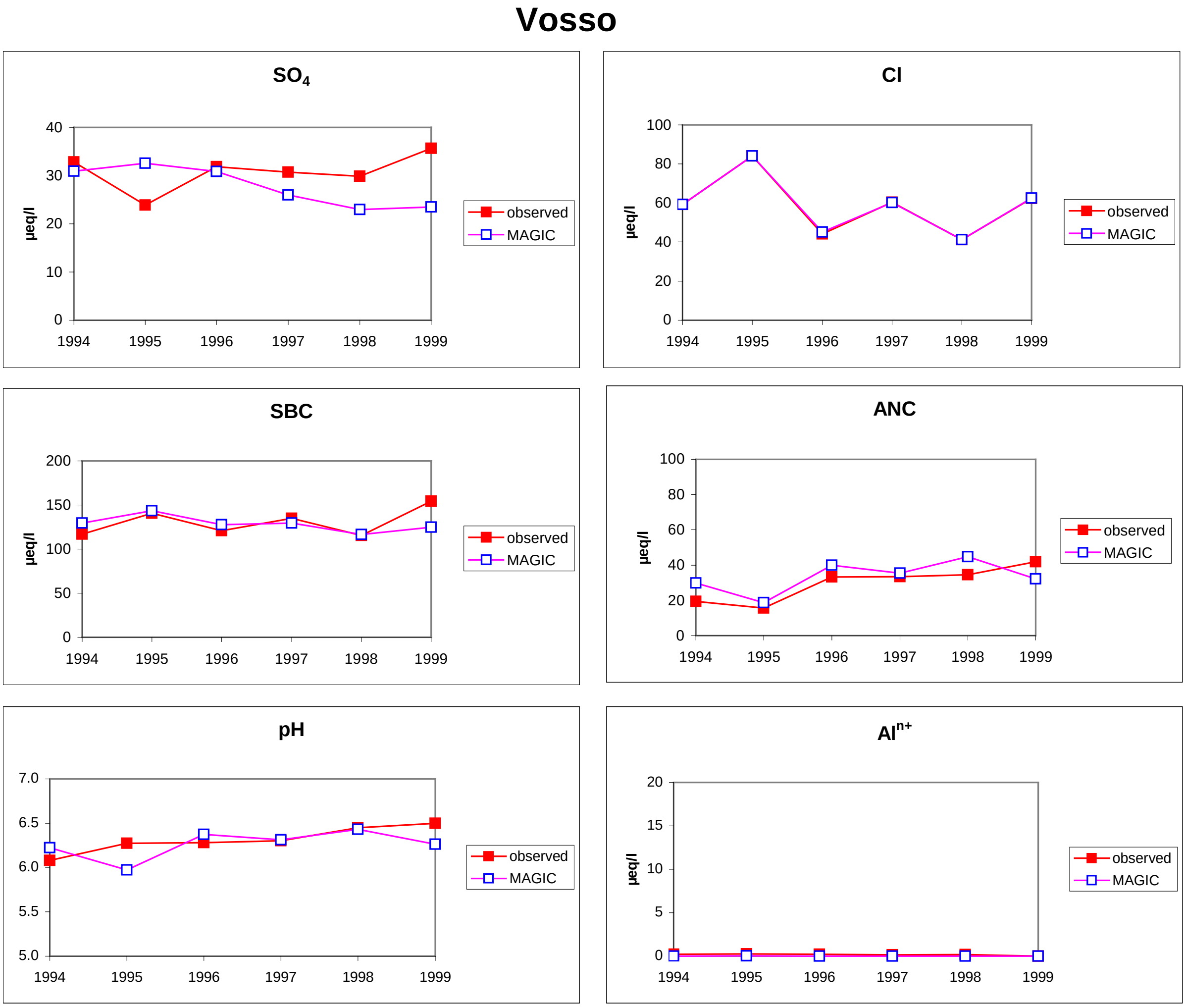


**Figure 11.** River Vosso. Observed and modelled concentrations of $SO_4$, Cl, SBC (sum base cations), ANC (acid neutralising capacity), pH and $Al_i$ (inorganic aluminium). Calibration period was 1994-97.

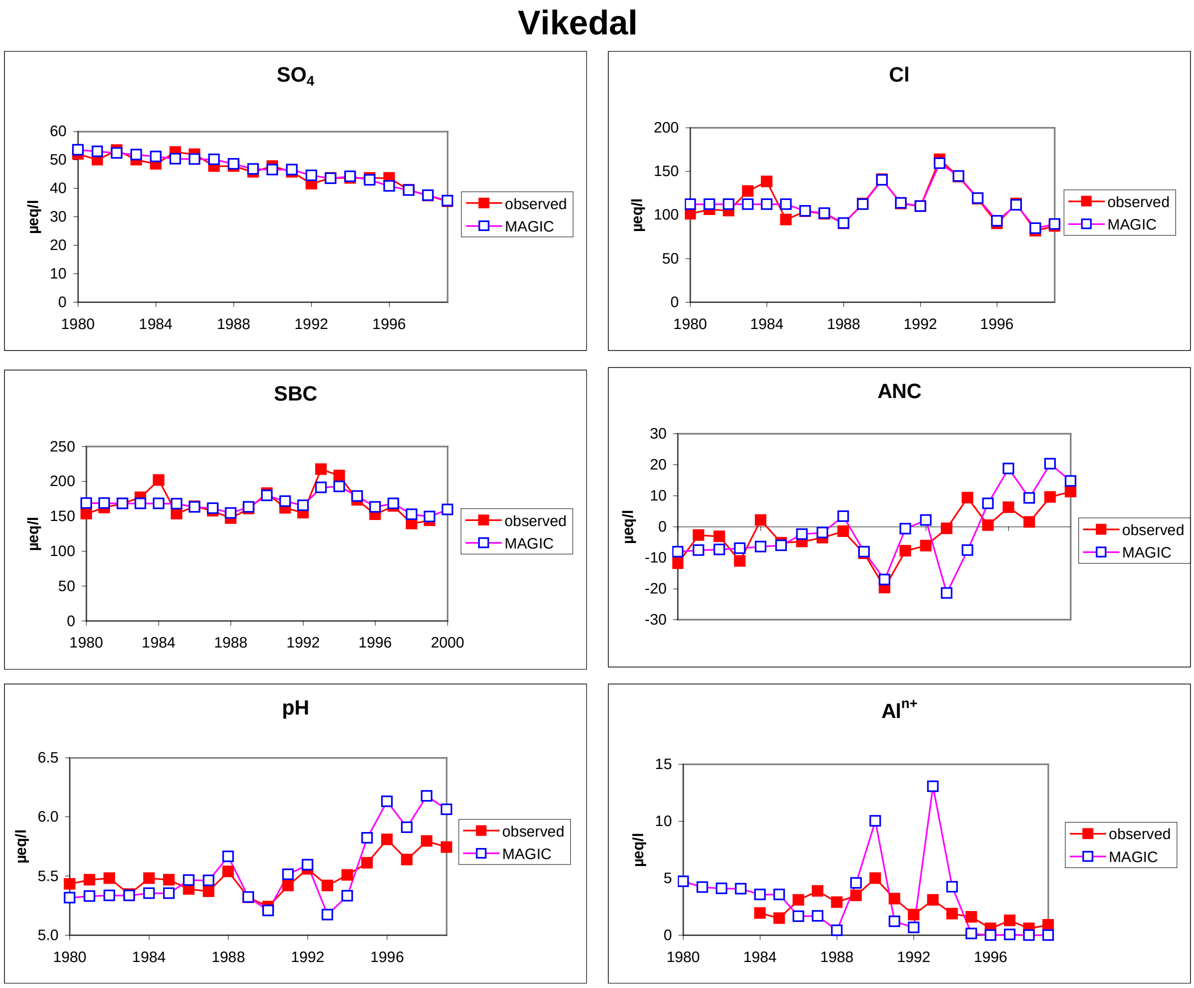


**Figure 12.** River Vikedal. Observed and modelled concentrations of $SO_4$, Cl, SBC (sum base cations), ANC (acid neutralising capacity), pH and $Al_i$ (inorganic aluminium). Calibration period was 1986-88.

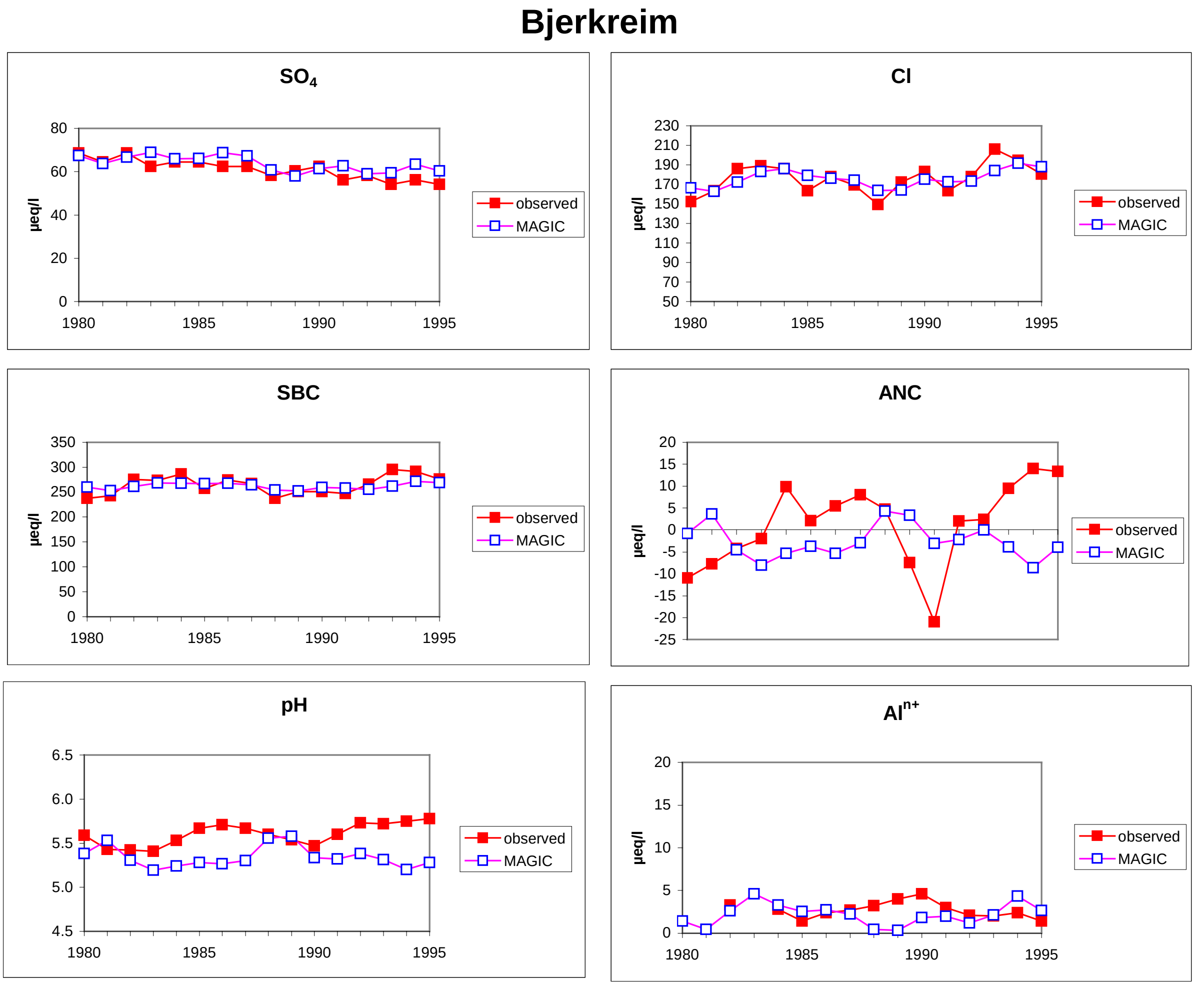


**Figure 13.** River Bjerkreim. Observed and modelled concentrations of $SO_4$, Cl, SBC (sum base cations), ANC (acid neutralising capacity), pH and $Al_i$ (inorganic aluminium). Calibration period was 1980-82.

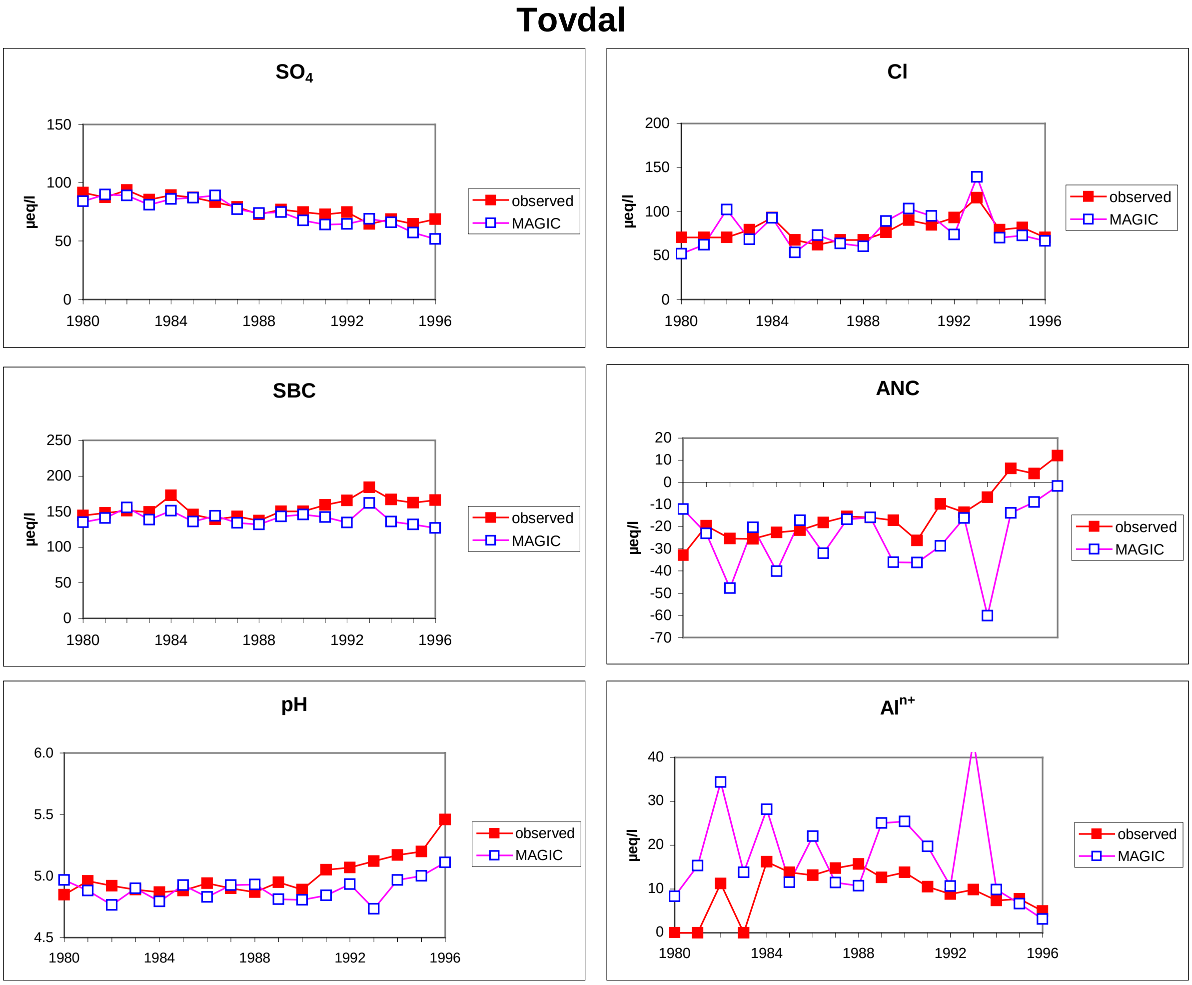


**Figure 14.** River Tovdal. Observed and modelled concentrations of $SO_4$, Cl, SBC (sum base cations), ANC (acid neutralising capacity), pH and $Al_i$ (inorganic aluminium). Calibration period was 1993-95.

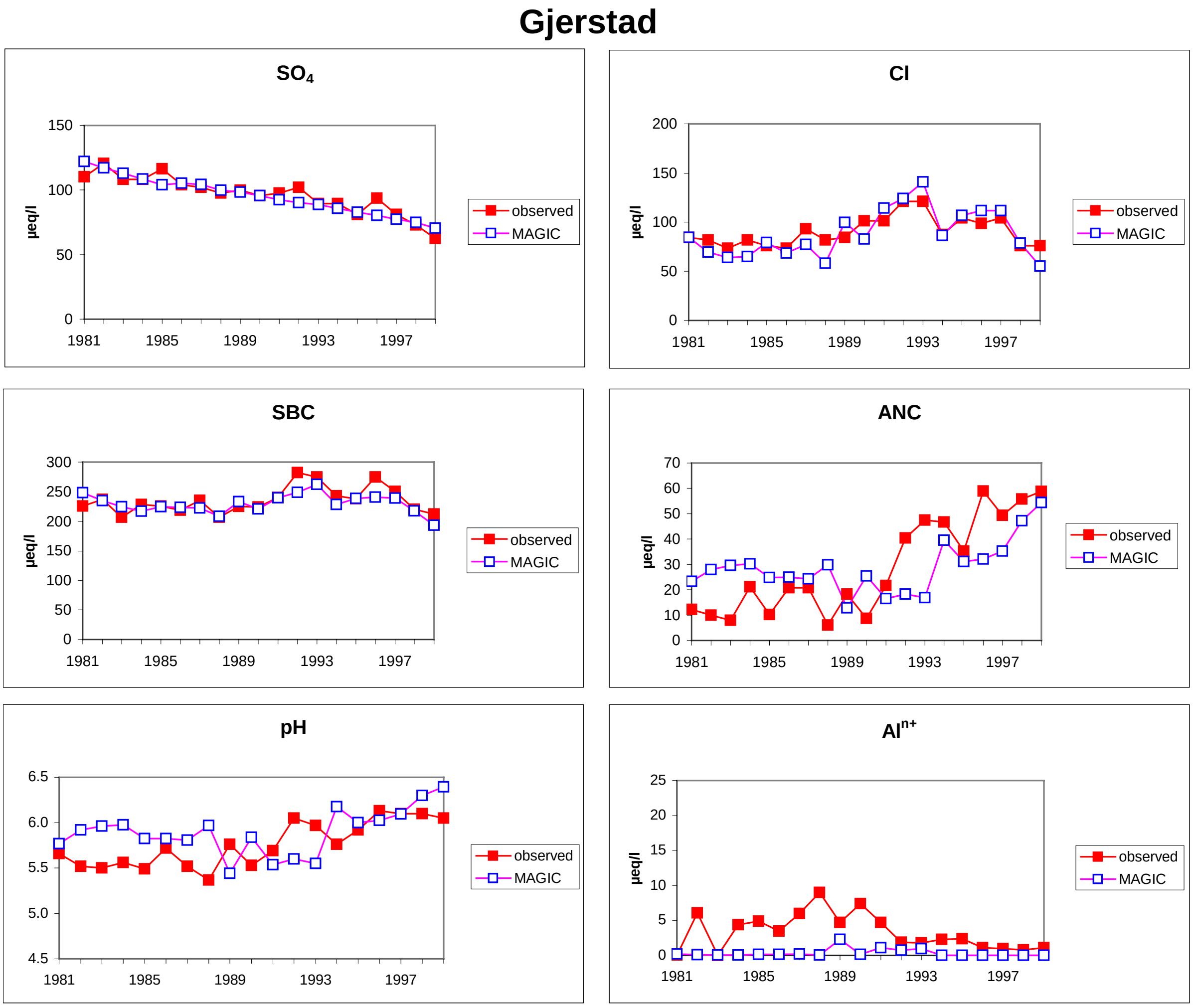


**Figure 15.** River Gjerstad. Observed and modelled concentrations of $SO_4$, Cl, SBC (sum base cations), ANC (acid neutralising capacity), pH and $Al_i$ (inorganic aluminium). Calibration period was 1981-83.

## 3.3 MAGIC reconstructed water chemistry and salmon statistics, 6 rivers, from late 1880's to 1990's

For each of the six rivers the calibrated MAGIC file was used to reconstruct yearly average water chemistry for the 140-year period from 1860 to 2000. ANC provides the best estimate of acidification in these rivers over time. The changes in ANC in each river can be compared to the changes in salmon catch as given by the official salmon statistics. The rivers are ordered here from north-to-south and thus fall along the gradient of increasing acid deposition.

The river Nausta receives small to moderate deposition of acid, but because it is highly sensitive to acid deposition, the river has low ANC. The MAGIC reconstruction indicates a decline in ANC from pre-acidification levels about 35 µeq $L^{-1}$ to about 15 µeq $L^{-1}$ in the 1990's (**Figure 16**). The catch statistics for Nausta prior to 1975 are poor and thus difficult to interpret. The construction of a fish ladder in 1975 led to greatly increased habitat for salmon, and a much large catch subsequent years. From 1975 to 2000, the number of adults caught has increased. In Skurdal et al. (2001) this increase is interpreted as due to reduced acidification. It cannot be explained by seafarm-reared escapees. For

Nausta there is thus no indication from the catch statistics that acidification has affected the salmon population.

The river Vosso lies somewhat further south and thus receives more acid deposition than Nausta. Reconstructed ANC indicates a decline from about 60 µeq L-1 to 30 µeq L$^{-1}$ (**Figure 16**). The salmon catch statistics for Vosso suggest lower levels in the 1980's and 1990's as compared to the previous 100 years. It is thus possible that acidification may in part explain the decreased salmon catches during the past 20 years.

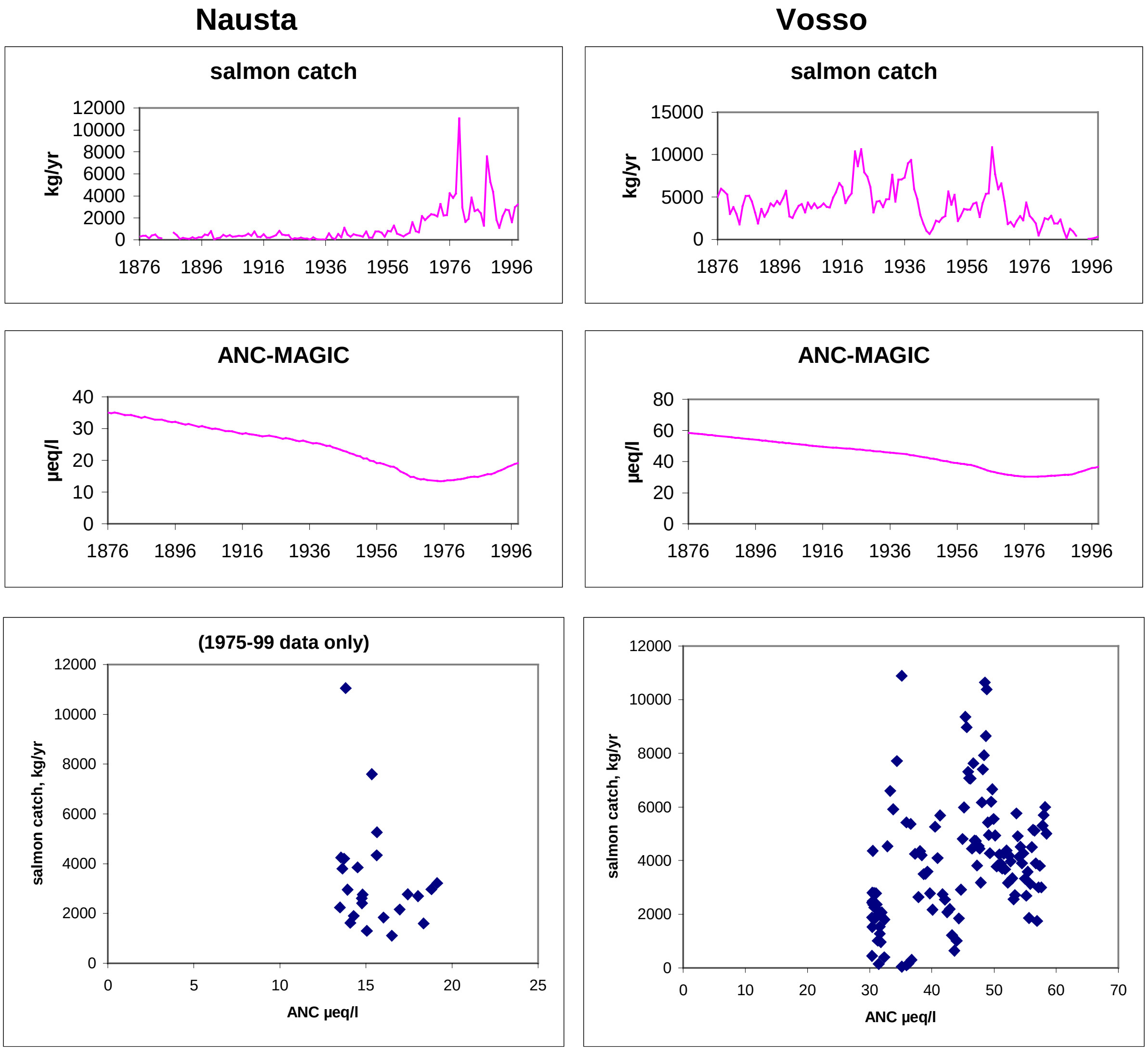


**Figure 16.** Salmon catch from the official statistics and ANC as reconstructed by MAGIC for the rivers Nausta and Vosso for the period 1876-1997.

The river Vikedal lies yet further south and is characterised by both high amounts of precipitation and acid deposition. The reconstructed ANC has declined from +40 µeq L-1 to –10 µeq L$^{-1}$ prior to liming in the mid-1980's (**Figure 17**). Salmon catch statistics for Vikedal are incomplete but do not indicate a major decline in the last few decades. There is thus no clear relationship between salmon catch and ANC for the river Vikedal.

The river Bjerkreim lies at the southwestern corner of Norway. This region receives high amounts of precipitation and acid deposition. In addition leaching of nitrogen is highest in this region. The MAGIC reconstructed ANC at Bjerkreim declined from pre-acidification levels of about +60 µeq $L^{-1}$ to about -5 µeq $L^{-1}$ (**Figure 17**). Salmon catch statistics show very large variations with no clear pattern in the past few decades. There is thus no clear relationship between the decline in ANC and salmon record at Bjerkreim.

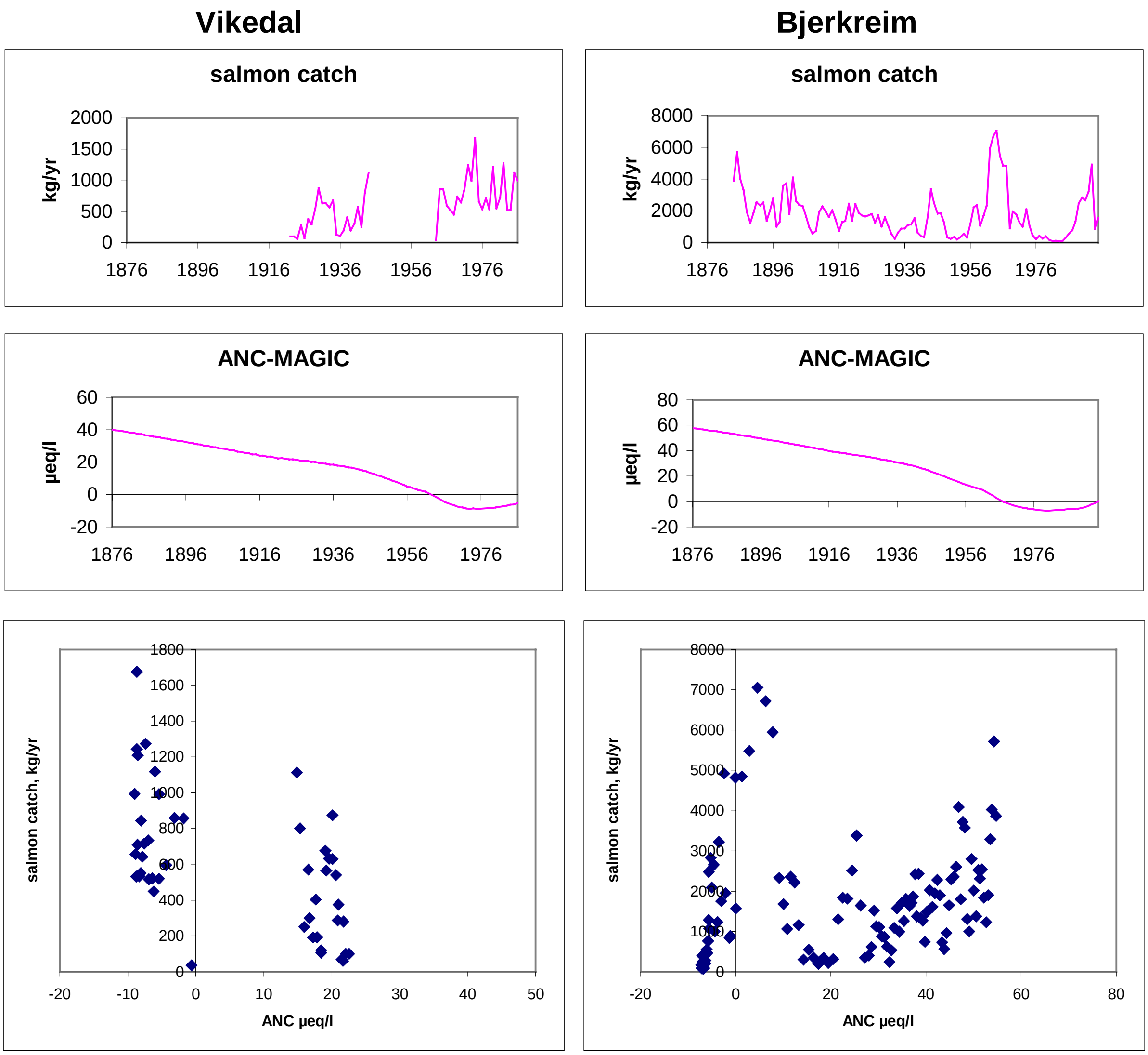


**Figure 17.** Salmon catch from the official statistics and ANC as reconstructed by MAGIC for the rivers Vikedal and Bjerkreim for the period 1876-1997.

The Tovdal river lies in southernmost Norway, the region with most widespread and serious acidification problems. The reconstructed ANC for Tovdal indicates a decline from about +40 µeq $L^{-1}$ pre-acidification to about –20 µeq $L^{-1}$ in the 1980's (**Figure 18**). The salmon catch statistics are quite dramatic and indicate a decline in catch beginning in the 1920's ending with extinction of the population in the 1970's. There is a very good correlation between ANC and salmon catch for Tovdal.

The river Gjerstad also lies on the south coast, further east of Tovdal. It also receives high loading of acid deposition. The MAGIC reconstructed ANC indicates a decline from pre-acidification levels about +120 µeq L$^{-1}$ to levels about +20 µeq L$^{-1}$ in the 1980's. The salmon statistics are not complete, but suggest a decline in the early 1900's.

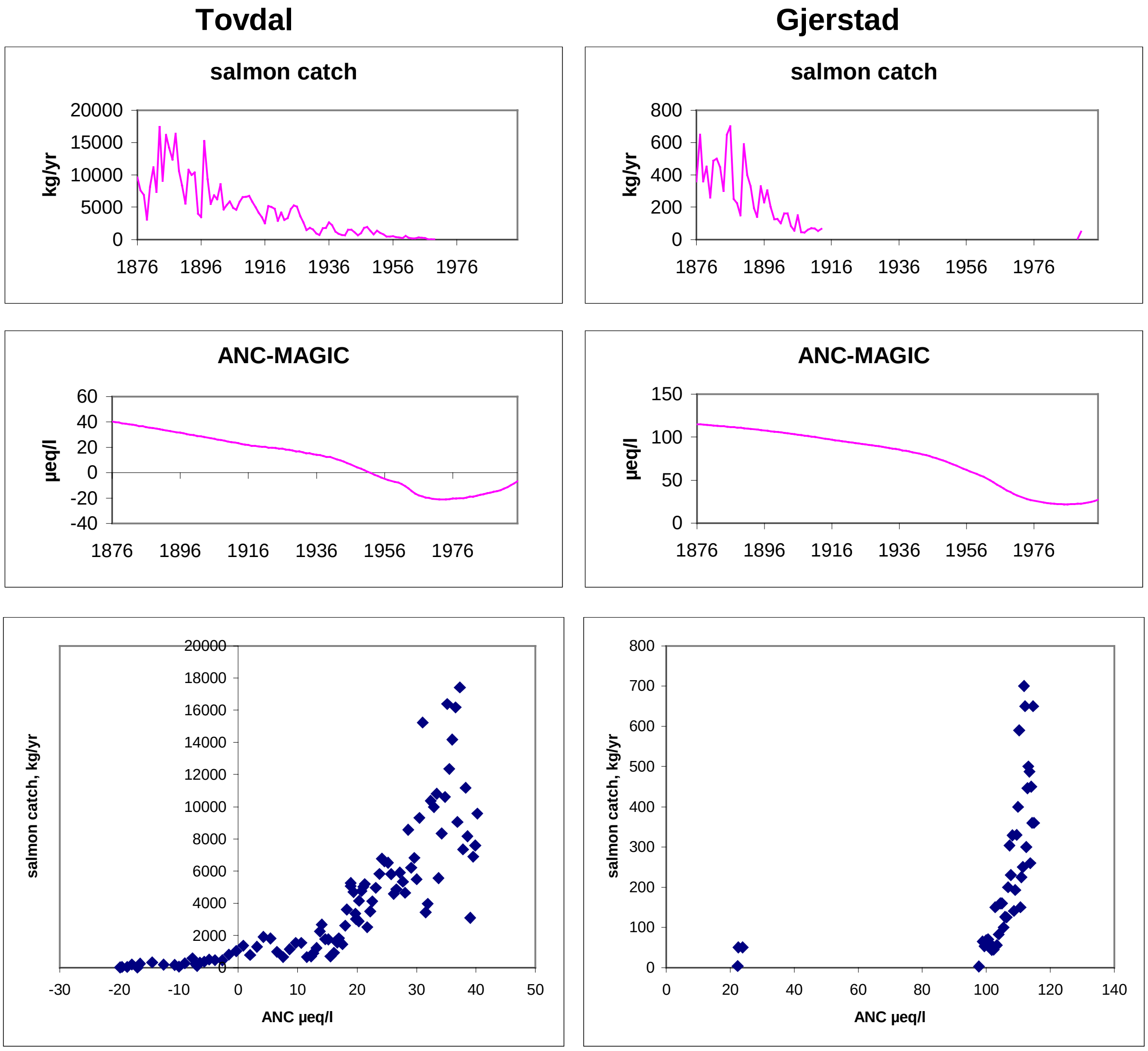


**Figure 18.** Salmon catch from the official statistics and ANC as reconstructed by MAGIC for the rivers Tovdal and Gjerstad for the period 1876-1997.

# 4. Discussion

## 4.1 Critical limits for salmon

Lien et al. (1992) set limits for Atlantic salmon at ANC +20 to + 50 µeq $L^{-1}$ for unchanged populations, 0 to –10 µeq $L^{-1}$ for reduced populations and 0 to – 25 µeq $L^{-1}$ for extinct populations (**Table 11**). This set of data was based on fish status from 30 rivers. In Kroglund et al. (1994) water quality limits were determined on a data from 37 rivers (**Figure 19**). These results did not seriously differ from those of by Lien et al. (1992). The results of our analysis here of 73 Norwegian salmon rivers (including the rivers of Lien et al. 1992 and Kroglund et al. 1994) indicate largely these same chemical thresholds for affected and extinct salmon populations.

**Table 11.** Critical limits for salmon as suggested by Lien et al. 1992) (Lien), Kroglund et al. (1994) (Krog) and this study (here).

| | pH | | | $Al_l$ µg Al $L^{-1}$ | | | ANC µeq $L^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| Source | Lien | Krog | here | Lien | Krog | here | Lien | Krog | here |
| no. rivers | 30 | 37 | 73 | 30 | 37 | 73 | 30 | 37 | 73 |
| Extinct | < 6 | < 5.9 | < 5.9 | > 25 | > 25 | > 20 | < 25 | < 20 | < 10 |
| Affected | 5.8 - 6.2 | 5.6 - 6.2 | 5.2 – 6.1 | 10 - 20 | 10 - 25 | 5 - 50 | 0 - 25 | 10 - 25 | -6 –15 |
| Possibly affected | | | 5.4 – 6.4 | | | 3 - 32 | | | 25 – 40 |
| Not affected | > 6 | > 6.1 | | < 20 | < 15 | < 10 | > 25 | > 20 | > 20 |

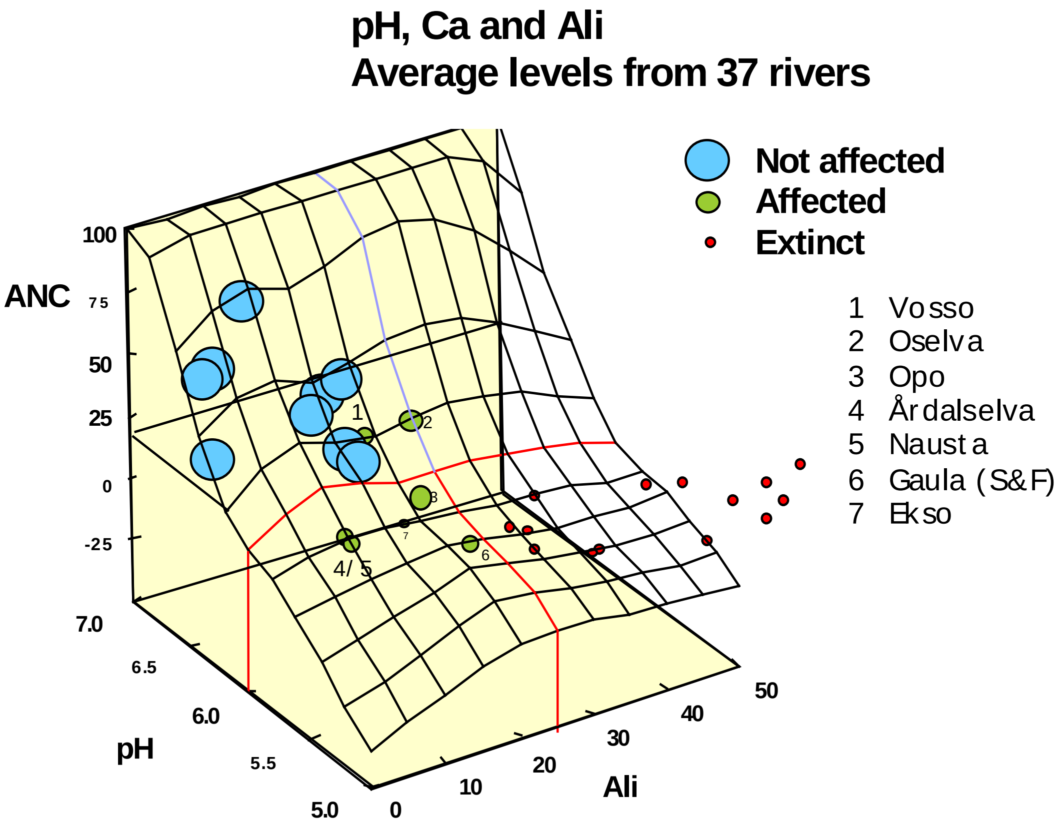


**Figure 19.** Relationship between pH, inorganic Al (LAL), and Ca concentration and salmon population status in 37 Norwegian rivers (after Kroglund et al. 1994).

In our analysis of population status and river water chemistry data for 1993-94 were mainly used. Using a different year could have yielded a somewhat different result, although the overall picture would probably be unchanged. Salmon can go extinct during the years with the poorest water quality, but on the other hand, the water quality can deteriorate beyond the qualities that caused extinction.

Episodes occurring at critical times constitute bottleneck periods in the life history of Atlantic salmon. Such episodes can be devastating to a population, and may not be reflected in the mean annual water chemistry.

The presence of acid tributaries in a river otherwise with good water quality introduces a further complication. Recruitment will be impaired by acidification in the tributaries, while the water chemistry of the main river will appear to be adequate for the fish. Acid tributaries are believed to be the cause for population decline in several rivers in western Norway (such as Suldal, Vosso, Jølstra, and Gaular).

## 4.2 Causes of declining salmon populations

There are many possible causes for the observed declines in salmon populations in Norwegian rivers during the past 20-30 years (Rieber Mohn Utvalget, NOU 1999:9). Threats such as over-fishing, parasites (*Gyrodactylus salaris),* disease (BKD, furunculosis), effects of escaped ranched salmon and human constructions such as hydro-electrical power plants are some of the many factors are acknowledged as important factors influencing salmon populations in a negative manner. Acidification is regarded as the most likely cause for the population decline in 7 rivers in southernmost Norway as well as for several other rivers located in southwestern and western Norway (Sivertsen 1989;

Hesthagen and Hansen 1991; Kroglund et al. 1994). This does not exclude contribution from other factors. Apart from factors affecting salmon within the river system, marine factors such as sealice (Finstad et al., 2000; 2001), over-harvesting, and sea temperature changes are believed to cause reduced returns of adults (Friedland et al. 1993; Rieber Mohn Utvalget, NOU 1999:9). Factors can act in concert amplifying each other. Stocking programmes and adults escaped from fish farms increases population densities and might obscure the possible population declines.

We do not have any proof that rivers here categorised as unaffected by acidification actually are unaffected, but on the other hand we do not have any data that suggest otherwise. While the two categories extinct and not likely affected can be reasonably precisely defined, the two categories “most likely” and “possibly” affected are more uncertain. In these, the salmon population structure can be affected both by reducing smolt production (lower survival from eggs to smolt) and reducing salmon marine survival (due to impaired osmoregulation caused by Al exposure in freshwater).

Apart from acidification, several of the Norwegian rivers categorised as affected and not affected are located in regions where sealice is recognised a threat to post-smolt survival. A sealice density of 10 or more is sufficient to reduce the smolt’s ability to ionoregulate in seawater. As impaired ionoregulation can be caused both by Al exposure and sealice, differentiating between these two factors can be difficult without carefully conducted measurements.

## 4.3 Salmon catch statistics

The salmon catch statistics are difficult to interpret. There are several reasons for why the catch statistics are not regarded as a reliable source of data.

1. Catches are not recorded to avoid the salmon tax.
2. Catches include both Atlantic salmon and sea trout prior to 1983.
3. Catches are positively biased by escaped farmed salmon (20 – 70% of the recorded catch can be farmed salmon). The production of farmed fish has increased exponentially from around 1980. Catches after 1980 can be artificially high due to escaped farmed salmon
4. Contributions from non-resident salmon. Small rivers with low production can be strongly influenced by adults originating from neighbouring rivers.
5. Differences in angling effort.
6. The catch may be biased during several years prior to regulation of discharge in rivers subject to hydroelectric power schemes, such that compensation for lost fisheries can be increased.
7. Changes in near-shore marine fishing methods and regulations.
8. Disruptions in catch-effort and reporting practice during World War II (1940-45).

Despite the uncertainties using the catch statistics, the catches in the rivers regarded as not affected by acidification appear to be more stable relative to the catches in affected rivers. In case the catches have declined in the not affected category, these changes can normally be ascribed to factors such as disease, parasites etc.

## 4.4 Timing of population declines and decrease in ANC

The salmon catch statistics give only indications of the time when the populations first began to decline. Historically reported fish kills already around 1910 in several rivers on the southwestern part of Norway suggest that rivers were affected by acidification at that time. Low catches already prior to 1900 can therefore be caused by acidification. Complete extinction of salmon populations in the 7 rivers in southernmost Norway took many decades.

Of the 6 rivers addressed here, only for Tovdal do the historical salmon catches and MAGIC reconstructed ANC fit the expected pattern of extinction caused by acidification. In all the other rivers the salmon statistics are either incomplete or do not show clear-cut declines in recent decades. This is despite the fact that acidification is believed to have affected salmon populations in the rivers Gjerstad, Bjerkreim, Vikedal and possibly also Vosso and Nausta. The historical salmon catch statistics therefore do not appear to be of great help in setting the critical limit for salmon.

For Tovdal, the major decline in salmon catch began in about 1900 with complete extinction in the 1970's. The plot of salmon catch against reconstructed ANC suggests that the decline began at ANC levels of about 30-40 $\mu$eq L$^{-1}$ and the population became extinct at ANC about 0 $\mu$eq L$^{-1}$ (**Figure 18**).

This is compatible with the thresholds obtained from the "snap-shot" water chemistry and fish status data from 1993-94 for the 73 Norwegian rivers (**Figure 20**). The salmon catch statistics and reconstructed ANC at Tovdal reveal 4 phases:

Phase 1875 – 1900; Based on ANC, the probability of "damage" is small. There is a large year-to-year variation in catches that could be due to water quality, but other factors can be of equal importance

Phase 1900 – 1925; Based on the reconstructed ANC reduction, the probability of damage to the salmon population has increased. The actual catches declined from one year to the next.

Phase 1925 – 1960; ANC has decreased to levels threatening extinction. Low catches were recorded throughout this period. These might be due to "strays" from neighbouring rivers.

Phase 1960 – present; ANC is below 0. The population became extinct.

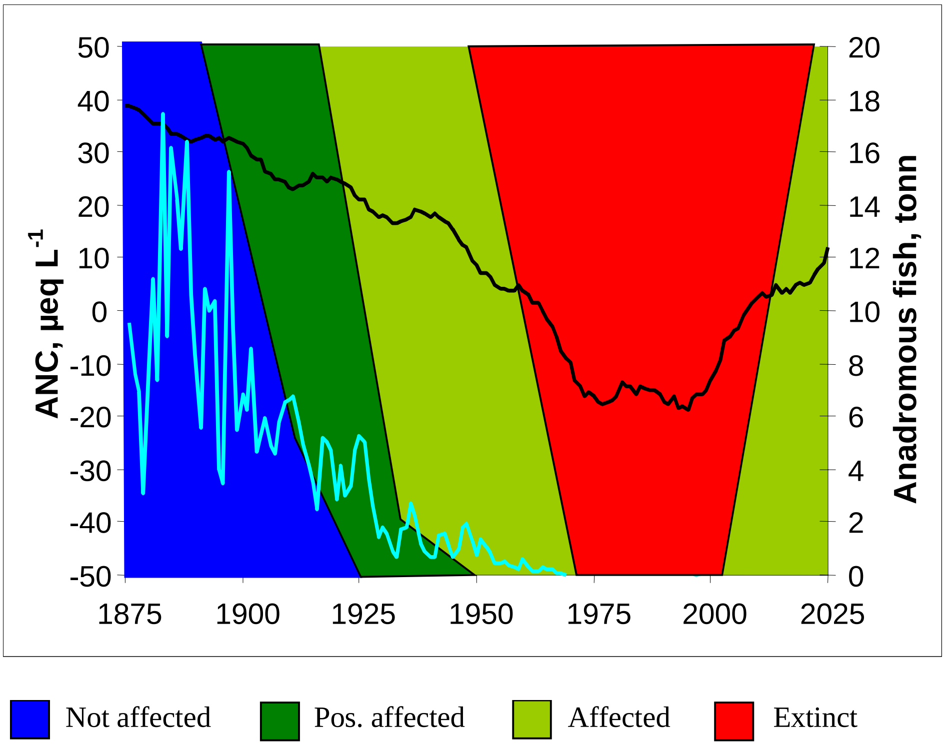


**Figure 20.** ANC reconstructed by MAGIC (left-hand scale) and salmon catch statistics (right-hand scale) over the period 1860-1995 in river Tovdal. The ANC fish categories from the 1993-94 "snapshot" are superimposed.

## 4.5 Experiments with salmon

In experiments Atlantic salmon have proven to be sensitive at $Al_i$ concentrations lower than 30 $\mu$g Al L$^{-1}$ (Skogheim and Rosseland 1986) or lower than 15 $\mu$g $Al_i$ L$^{-1}$ when seawater challenges have been included into the evaluation (Staurnes et al. 1993; Staurnes et al. 1995; Kroglund and Staurnes 1999;

Kroglund et al. 2001b; Rosseland et al. 2001). Reduced marine survival was observed when Caline-tagged smolts were exposed to 6 µg $Al_i$ and pH 5.8 for 3 months prior to ocean release (Kroglund and Finstad 2001). A similar reduction in marine survival was observed when smolts were exposed to 15 to 25 µg $Al_i$ $L^{-1}$ for 10 hours prior to release (Finstad et al. 1999). In more sub-optimal waters having lower pH and higher $Al_i$ concentrations, marine survival was reduced to zero (Hansen 1982; Staurnes et al. 1996). Based on experiments, physiological responses have been observed at concentrations of $Al_i$ close to or below the detection limit (Rosseland and Staurnes 1994). If physiological responses predict a possible population response, the high sensitivity to low concentrations of $Al_i$ prohibits the practical use of $Al_i$ to determine a water quality limit.

Based on exposure experiments mortality was recorded in freshwater in all exposures where $Al_i$ exceeded 15 µg Al $L^{-1}$. Zero mortality was recorded in water qualities with $Al_i$ concentrations up to 30 µg Al $L^{-1}$. Based on this dataset, 30 µg $Al_i$ can be used as a limit where extinction is a possible outcome. In the $Al_i$ range of 15 to 30, the population effects are more uncertain and will depend on exposure time. Based on seawater challenge tests, mortality was encountered when $Al_i$ exceeded 6 µg Al L-1. Zero mortality was recorded up to 30 µg Al L-1, where zero mortality prevailed at the lower concentration level (**Table 12**). In **Figure 21** mortality level is related to $Al_i$.

The effects increase with increased exposure concentration and exposure duration. These limits depend on exposure duration. Based on data derived from these experiments, population effects should be anticipated at $Al_i$ concentrations exceeding 5 µg Al $L^{-1}$, with possibility for extinction in water qualities where $Al_i$ exceeds 15 µg Al $L^{-1}$.

**Table 12.** Summary of mortality limits for inorganic Al (µg $L^{-1}$) for salmon. Data are from laboratory experiments performed to assess water quality limits (Kroglund et al. unpublished data).

| | Freshwater | Seawater | Marine survival* |
|---|---|---|---|
| No effect | <5 | <5 | <5 |
| Effect | 5-15 | 5-10 | 5-15 |
| High effect | >15 | >10 | >15 |

Transformation of $Al_i$ from toxic to non-toxic species of Al takes minutes at pH >6.4 and hours at pH levels 6.2 or lower (Kroglund et al. 2001ab). By the time traditionally sampled water bottles arrive at a water laboratory, the $Al_i$ concentration can be substantially underestimated compared to the concentrations experienced by the fish.

Smolt quality at Nausta was assessed in 1994 (Kroglund et al. 1996a). Caged hatchery reared smolts or native wild smolts exposed to water in Nausta responded in a negative manner. While the physiological status based on samples taken in freshwater did not indicate impaired water quality, the gills showed typical compensatory changes and the smolts were not seawater tolerant. The gills contained aluminium. It was concluded that the smolts were affected by acidic water. The water quality caused biological responses detected as gill tissue changes and impaired seawater tolerance (Kroglund et al. 1996a).

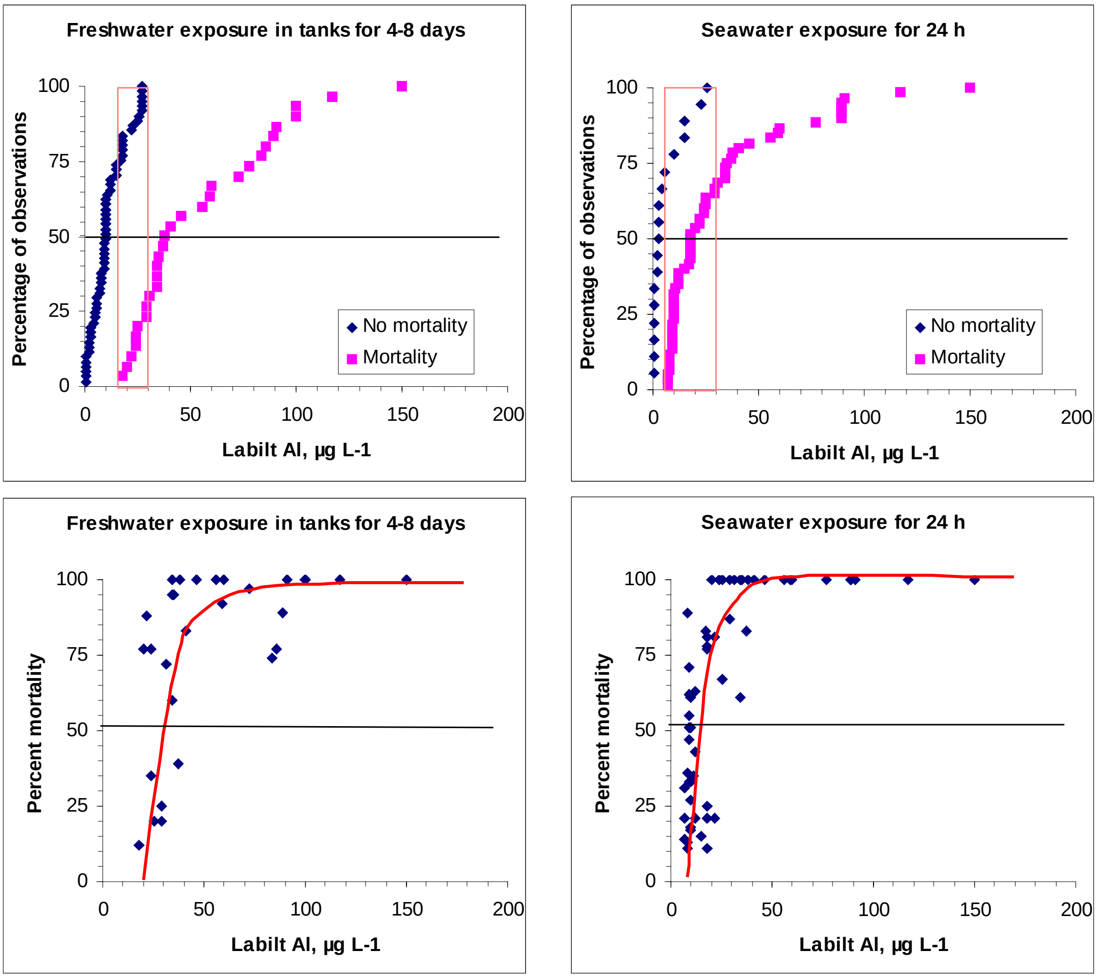


**Figure 21.** Summary of results of laboratory experiments with mortality of salmon to inorganic Al (Al$_i$). From Kroglund et al. unpublished data).

## 4.6 Strain and population differences

Strain dependent differences in water quality requirement have been described for brown trout (Dalziel et al. 1995) and perch (Vuorinen et al. 1994). If similar properties also were present in Atlantic salmon, water quality standards would need to take population specific tolerance into consideration.

Based on exposure experiments, no difference in sensitivity or tolerance was detected among 5 strains (Rosseland et al. 2001) or among two strains (Kroglund and Finstad 2001), irrespective of the water quality the strain originated from. Both works conclude that Atlantic salmon do not develop tolerance towards acidification.

## 4.7 Critical limit for salmon and implications for critical loads for surface waters in Norway

Earlier analyses, our new “snapshot” analysis, and our analysis of historical data all point to a critical limit for Atlantic salmon in Norwegian rivers of ANC about 25-30 µeq L$^{-1}$. This is somewhat higher than the critical limit for brown trout of 10-20 µeq L$^{-1}$ used to calculate critical loads for surface waters in Norway (Henriksen et al. 1999; Henriksen and Buan 2000). We do not, however, believe that the higher critical limit for salmon will necessitate revision of the critical load maps for Norway.

Whereas the habitat for salmon is the lower reaches of the river, the habitat for brown trout also includes the high elevation, headwater lakes and streams. These are typically more acid-sensitive relative to the downstream reaches. Thus if the critical limit for the headwater regions is set at ANC 10-20 µeq L$^{-1}$, this should be sufficient to maintain ANC above 30 µeq L$^{-1}$ in the salmon-carrying sections of the river.

Acidic tributaries located along the anadromous reach of the river can offset the water chemical determination. These rivers are in the evaluation plotted as possibly affected. Using the proposed ANC limits, these rivers are not necessarily protected. On the other hand, by requesting a higher ANC, a number of rivers most likely not affected will be included in the possibly affected category. These conditions with acidic tributaries can be handled otherwise.

The water quality limits presented here do not necessarily apply for watersheds outside Norway. In particular rivers with high concentrations of dissolved organic carbon may offer better protection of salmon from acidification. Based on experiments conducted in two rivers differing in organic content (< 1 mg L$^{-1}$ TOC vs. 4-6 mg L$^{-1}$ TOC), twice as much $Al_i$ was needed to produce a given accumulation of Al onto the gill surface of salmon smolts and parr. Physiological responses, however, were related to gill-Al irrespective of $Al_i$. This can be interpreted as: (1) $Al_i$ is overestimated in organic rich water, (2) the cation exchanger retains $Al_i$ species that are not retained by the fish gill, and/or (3) the cation exchanger remobilizes Al as $Al_i$ from organic-bound Al (Alo). The chemistry data from these 2 rivers indicate that for a given ANC level the concentration of $Al_i$ is higher in the high TOC river relative to the low TOC river (**Figure 22**).

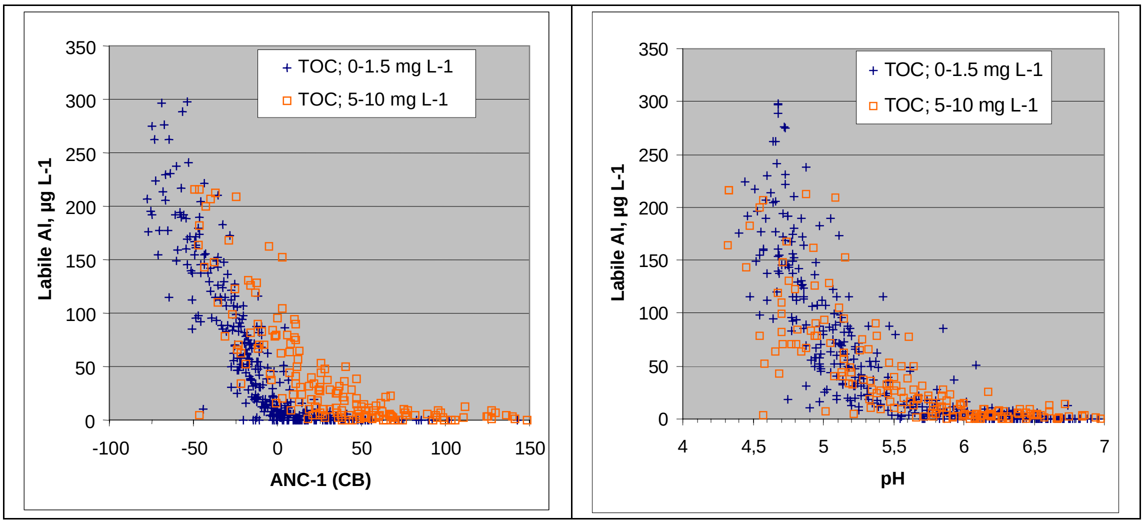


**Figure 22.** Relationships between ANC, pH and $Al_i$ in the 1500-lake survey (Skjelkvåle et al. 1996). The relationships are shown for lakes low in TOC (<1.5 mg C L$^{-1}$) and lakes with high TOC (>5 mg C L$^{-1}$) content.

The influence of TOC on $Al_i$ is also detectable in rivers outside Norway, e.g. Sweden, Scotland, England and some Canadian rivers. Little work has been performed on seawater survival in these countries. For Canadian brown water rivers, the water quality limit is set to pH around 5 (Lacroix 1989). Declining populations densities were detected when pH fell below pH 5.6. The limits used in

Canada cannot be employed for Norway, as $Al_i$ does not contribute to water toxicity in Canadian rivers, because these rivers have a high concentration of dissolved organic carbon and reactive Al is nearly completely bound to organic matter (Gunn and Belzile 1994).

# 5. Conclusion

There is a close relationship between mortality levels for Atlantic salmon determined on basis of experiments and the water quality limits detected here. Short-term exposures indicate increasing mortality in freshwater when $Al_i$ exceeds 15 µg Al $L^{-1}$. Hypoosmotic capacity as an indicator of marine survival is affected at concentrations around 8 µg $L^{-1}$ $Al_i$ or higher. These are levels fairly similar to response levels predicted based on the 73 rivers.

$Al_i$ cannot be used to discriminate safe from unsafe water qualities. $Al_i$ concentrations below the detection limit can impose a threat at the population level by affecting e.g. marine survival. On the other hand, $Al_i$ in excess of 20 µg Al $L^{-1}$ indicates toxic water.

Rivers characterised by pH higher than 6.4 are not associated with population declines that can be attributed to acidification or acidification-related factors. In the pH range 6.0-6.4, acid tributaries transporting $Al_i$ to the main river can be the cause for sub-optimal water qualities.

ANC discriminates well between affected and non-affected. No population decline due to acidification or acidification related factors were discovered at ANC levels exceeding 40 µeq $L^{-1}$. Within the ANC range 20 to 40 µeq $L^{-1}$, both affected and non-affected populations were detected. All affected populations originate in rivers having acidic tributaries along the anadromous reach of the river. These rivers represent the “difficult” cases, where uncertainties as to cause are large.

# 6. References

Aas, W., Tørseth, K., Solberg, S., Berg, T., and Manø, S. 2000. Overvåking av langtransportert forurenset luft og nedbør. Atmosfærisk tilførsel 1999. Rapport 797/00, Statens forurensningstilsyn, Oslo, Norge.

Bulger, A. J., Lien, L., Cosby, B. J., and Henriksen, A. 1993. Brown trout (*Salmo trutta*) status and chemistry from the Norwegian thousand lake survey: statistical analysis. *Can.J.Fish.Aquat.Sci.* 50: 575-585.

Bull, K. R., Achermann, B., Bashkin, V., Chrast, R., Fenech, G., Forsius, M., Gregor, H-D., Guardans, R., Haussmann, T., Hayes, F., Hettelingh, J. P., Johannessen, T., Krzyzanowski, M., Kucera, V., Kvæven, B., Lorenz, M., Lundin, L., Mills, G., Posch, M., Skjelkvåle, B. L., and Ulstein, M. J. 2001. Coordinated effects monitoring and modelling for developing and supporting international air pollution control agreements. *Water Air Soil Pollut.* in press:

Clarke, W.C. og Blackburn, J., 1977. A seawater challange test to measure smolting of juvenile salmon. Fish. Mar. Serv. Tech. Rep. 705: 1-11.

Cosby, B. J., Hornberger, G. M., Galloway, J. N., and Wright, R. F. 1985a. Modelling the effects of acid deposition: assessment of a lumped parameter model of soil water and streamwater chemistry. *Water Resourc.Res.* 21: 51-63.

Cosby, B. J., Wright, R. F., Hornberger, G. M., and Galloway, J. N. 1985b. Modelling the effects of acid deposition: estimation of long term water quality responses in a small forested catchment. *Water Resourc.Res.* 21: 1591-1601.

Dalziel, T.R.K., Kroglund, F., Lien, L., Rosseland, B.O., 1995. The ReFISH (Restoring endangered fish in stressed habitats) project, 1988-1994. 1995. Water, Air, and Soil Pollut. 85, 321-326.

DN 2001. Kalking i vann og vassdrag. Overvåking av større prosjekter i 2000. Diretorate for nature management report 2001-2. Liming of lakes and rivers. Surveillance of large skale projects.

Farmer, G.J., Saunders, R.L., Goff, T.R., Johnston, C.E., Henderson, E.B., 1989. Some physiological responses of Atlantic salmon (Salmo salar) exposed to soft, acidic water during smolting. Aquaculture 82, 229-244.

Finstad, B., Martinsen, B., Alexandersen, S., Jakobsen, P.J., Kroglund, F., Maroni, K., Sægrov, H. Raddum, G. 1999. Progress report – salmon lice and acid rain as a factor regulating Atlantic salmon and sea trout populations. Releases of salmon lice protected smolts. Progress Report to the Norwegian Directorate for Nature Management). 5 pp (In Norwegian).

Finstad, B., Grimnes, A., Bjørn, P.A. & Hvidsten, N.A. 2000. Laboratory and field investigations of salmon lice (Lepeophtheirus salmonis Krøyer) infestation on Atlantic salmon (Salmo salar L.) postsmolts. Aquacult. Res.,in press.

Finstad, B., Jonsson, N., 2001. Factors influencing the Yield of smolt releases in Norway. Nordic J. Freshw. Res. 75, 37-55.

Friedland, K., Reddin, D.G. Kocik, J.F., 1993. Marine survival of North American and European Atlantic salmon; effects of growth and environment. ICES J. Mar. Sci. 50: 481-492.

Gunn, J. M, and Belzile. 1994. Extrapolating from toxicological findings to regional estimates of acidification damage. In: Acidification of Freshwater Ecosystems: Implications for the Future, edited by C. E. W Steinberg and R. F. Wright,John Wiley & Sons Ltd. , 1994, p. 217-226.

Hansen, L.P. 1982. Gjenfangster av merket laksesmolt (*Salmo salar* L.) utsatt i to sure elver på Sørlandet. *Fauna* 35, 145-149.

Henriksen, A., Skogheim, O.K., and Rosseland, B.O. 1984. Episodic changes in pH and aluminum-speciation kill fish in a Norwegian salmon river. Vatten. Water. 40:255-260.

Henriksen, A. and Buan, A. K. 2000. Tålegrenser og overskridelse av tålegrenser for overflatevann, skogsjord og vegetasjon i Norge. Naturens Tålegrenser 4179-2000, NIVA, Oslo. 29 pp pp.

Henriksen, A., Fjeld, E., and Hesthagen, T. 1999. Critical load exceedance and damage to fish populations. *Ambio* 28: 583-586.

Henriksen, A., Kämäri, J., Posch, M., and Wilander, A. 1992. Critical loads for acidity: Nordic surface waters. *Ambio* 21: 356-363.

Henriksen, A., Lien, L., and Traaen, T. S. 1990. Critical loads for surface waters. Chemical criteria for inputs of strong acids. Acid Rain Research Report 22/1990, Norwegian Institute for Water Research, Oslo. 45 pp.

Hesthagen, T. og Hansen, L.P., 1991. Estimates of the annual loss of Atlantic salmon. *Salmo salar* L. in Norway due to acidification. Aqua. Fish. Manage. 22: 85-91.

Hindar, A., Norgaard, E., Nilsen, P., Høgberget, R., and Wright, R. F. 1999. Whole-catchment Application of Dolomite to an Acidified Forest Ecosystem in Gjerstad, Southern Norway. Acid Rain Research Report NIVA, Oslo, Norway. 89 pp.

Hindar, A. Kroglund, F. 2000 Forsuringssituasjonen for laks i Vosso og vurdering av behov for ytterligere kalkingstiltak. NIVA-report 4255: 1-40.

Kroglund, F., M. Berntssen, Å. Åtland og B.O. Rosseland. 1993. Er laksen truet ved selv svært moderate forsuring ? Eksempler fra Vosso, Hordaland, 1993. NIVA-rapport 2947, 27 s.

Kroglund, F., B. Finstad, M. Staurnes, B.O. Rosseland, H. Hektoen, T. van Berkum og M. Iversen. 1996a. Vannkvalitetskriterier til laksesmolt. Undersøkelse av smoltkvalitet i ulike vassdrag i 1994. I: Kalking i vann og vassdrag 1996. Fou-årsrapporter 1994. DN-notat 1996.

Kroglund, F., B. Finstad, A. Kvellestad, B.M. Larsen og B.O. Rosseland. 1996b. Fastsettelse av forsuringsnivå i ulike Vestlandsvassdrag basert på økofysiologiske og økotoksikologiske metoder. DN-notat 1996.

Kroglund, F., T. Hesthagen. A. Hindar. G.G. Raddum., M Staurnes, D. Gausen. og S. Sandøy. 1994. Sur nedbør i Norge - status - utviklingstendenser og tiltak. DN-utredning 1994-10: 97 sider.

Kroglund, F. Hindar, A. Kaste, Ø. Rosseland, B.O. 1998. En vurdering av vannkvaliteten i Vossovassdraget, 1967-1997. NIVA-report 3823: 1-71.

Kroglund, F., Staurnes, M., 1999. Water quality requirements of smolting Atlantic salmon (Salmo salar) in limed acid rivers. Can. J. Fish. Aquat. Sci. 56, 2078-2086.

Kroglund, F., Teien, H.C., Rosseland, B.O., Salbu, B., Lucassen. E.C.H.E.T., 2001a. Water quality dependent recovery from aluminum stress in Atlantic salmon smolts. Water, Air, and Soil Pollution 130: 911-916.

Kroglund, F., Teien, H.C., Rosseland, B.O., Salbu, B., 2001b. Time and pH-dependant detoxification of aluminum in mixing zones between acid and non-acid rivers, Water, Air, and Soil Pollution 130: 905-910.

Kroglund and Finstad, 2001. The effects of low concentrations of inorganic monomeric aluminum on physiological status, growth, migration and marine survival in two strains of Atlantic salmon. Accepted for publication in Water, Air, and Soil Pollution.

Lacroix. G.L., 1989. Ecological and Physiological Responses of Atlantic Salmon in Acidic Organic Rivers of Nova Scotia, Canada. Water, Air, and Soil Pollut. 46, 375-386.

Leivestad, H., Hendrey, G., Muniz, I.P. og Snekvik, E., 1976. Effect of acid precipitation on freshwater organisms. In: Brække. F.H. (Red;). Impact of acid precipitation on forest and freshwater ecosystems in Norway. SNSF-project. FR 6/76: 87-111.

Lien, L., Raddum, G. G., and Fjellheim, A. 1992. Critical loads of acidity to freshwater -- fish and invertebrates. Naturens Tålegrense Fagrapport 23, Norwegian Institute for Water Research, Oslo. 36 pp.

McCormick, S. D., Hansen, L. P.,. Quinn, T. P., Saunders, R. L., 1998. Movement, migration, and smolting of Atlantic salmon (Salmo salar). - Can. J. Fish. Aquat. Sci. 55 , 77-92.

Mylona, S. 1996. Sulphur dioxide emissions in Europe 1880-1991 and their effect on sulphur concentrations and depositions. *Tellus* 48B: 662-689.

Nilsson, J. and Grennfelt, P. 1988. Critical loads for Sulphur and Nitrogen. Nordic Council of Ministers Report 1988:15, Nordic Council of Ministers, Copenhagen, Denmark. 418 pp.

NOU 1999. Til laks åt alle kan ingen gjera? Om årsaken til nedgangen i de norske villaksbestandene og forslag til strategier og tiltak for å bedre situasjonen. Norges offentlige utredninger 1999:9, 297 pp., ISBN 82-583-0476-3, (English summary).

Reuss, J. O. 1990. Critical Loads for Soils in Norway. Analysis of Soils Data from eight Norwegian Catchments. Naturens Tålegrenser Fagrapport 11b, Norwegian Institute for Water Research, Oslo. 78 pp.

Rosseland, B.O. Staurnes. M., 1994. Physiological mechanisms for toxic effects and resistance to acidic water: an ecophysiological and ecotoxicological approach. In: Steinberg, C.E.W and Wright, R.F. (eds). Acidification of Freshwater Ecosystems: Implications for the Future. John Wiley & Sons Ltd. 228-246.

Rosseland, B.O., Kroglund, F., Staurnes, M., Hindar,K., Kvellestad, A., 2001a. The super-sensitivity of the Atlantic salmon smolt stage prohibit strategic use of genetic tolerance to acid water in management programs. “Acid rain, 2000”; in press, Water, Air, and Soil Pollut.

Saunders, R.L., Henderson, E.B., Harmon, P.R., Johnston, C.E., Eales J.G., 1983. Effects of low environmental pH on smolting of Atlantic salmon (Salmo salar). Can. J. Fish. Aquat. Sci. 40, 1203-1211.

SFT. 1983. Overvåking av langtransportert forurenset luft og nedbør. Årsrapport 1982. Statlig program for forurensningsovervåking Rapport 108/83, Statens forurensningstilsyn, Oslo, Norway. 228 pp.

SFT. 1985. Overvåking av langtransportert forurenset luft og nedbør. Årsrapport 1984. Statlig program for forurensningsovervåking Rapport 201/85, Statens forurensningstilsyn, Oslo, Norway. 190 pp.

SFT. 1986. Overvåking av langtransportert forurenset luft og nedbør. Årsrapport 1985. Statlig program for forurensningsovervåking Rapport 256/86, Statens forurensningstilsyn, Oslo, Norway. 199 pp.

SFT. 1988. Overvåking av langtransportert forurenset luft og nedbør. Årsrapport 1987. Statlig program for forurensningsovervåking Rapport 333/88, Statens forurensningstilsyn, Oslo, Norway. 241 pp.

SFT. 2000. Overvåking av langtransportert forurenset luft og nedbør. Årsrapport - Effekter 1999. Statlig program for forurensningsovervåking Rapport Statens forurensningstilsyn, Oslo, Norway. 198 pp.

Simpson, D., Olendrzynski, K., Semb, A., Støren, E., and Unger, S. 1997. Photochemical oxidant modelling in Europe: multi-annual modelling and source-receptor relationships. EMEP/MSC-W Report 3/97, Norwegian Meteorological Institute, Oslo, Norway. 75 pp.

Sivertsen, A. 1989. Forsuringstruede anadrome laksefiskbestander og aktuelle mottiltak. NINA-utredning 10: 1-28.

Skogheim, O.K. og Rosseland, B.O. 1986. Mortality of smolts of Atlantic salmon. Salmo salar L., at low levels of aluminium in acidic soft- water. Bull. Environ. Contam. Toxicol. 37: 258-265.

Skjelkvåle, B. L., Henriksen, A., Faafeng, B., Fjeld, E., Traaen, T. S., Lien, L., Lydersen, E., and Buan, A. K. 1996. Regional innsjøundersøkelse 1995. En vannkjemisk undersøkelse av 1500 norske innsjøer. Statlig program for forurensningsovervåking Rapport 677/96, Statens forurensningstilsyn, Oslo, Norway. 73 pp.

Skurdal, J. Hansen, L.P., Skaala, Ø., Sægrov, H. Lura, H. 2001. Elvevis vurdering av bestandsstatus og årsaker til bestandsutvikling av laks i Hordaland og Sogn og Fjordane. DN-utredning 2001-2.

Staurnes, M., Blix, P., Reite, O. B.. 1993a. Effects of acid water and aluminium on parr-smolt transformation and sea water tolerance in Atlantic salmon, Salmo salar. Can. J. Fish. Aquat. Sci. 50, 1816-1827.

Staurnes, M., Lysfjord, G., Hansen, L.P. Heggberget, T.G., 1993b. Recapture rates of hatchery-reared Atlantic salmon (Salmo salar) related to smolt development and time of release. Aquaculture. 118, 327-337.

Staurnes, M., Kroglund, F. Rosseland, B.O., 1995. Water quality requirement of Atlantic salmon in water undergoing acidification or liming in Norway, Water, Air, and Soil, Pollut. 85, 347-352.

Staurnes, M., Hansen, L.P., Fugelli, K., Haraldstad, Ø., 1996. Short-term exposure to acid water impairs osmoregulation, seawater tolerance, and subsequent marine survival of smolts of Atlantic salmon (Salmo salar). Can. J. Fish. Aquat. Sci. 53, 1695-1704.

UN/ECE. 1999. The 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. Document ECE/EB.AIR/xx, United nations Economic Comission for Europe, New York and Geneva. xx pp.

Vuorinen, Vourinen, Rask, Suomela. 1994. The sensitivity of acidity and Al of newly hatched perch originating from strains from four lakes with different degree of acidity. In: Mueller, R. and R. Lloyd (eds), Sublethal and chronic effects of pollutants on freshwater fish FAO&Blackwell Scientific Publishers, Fishing News books. University press, Cambridge. p. 273-282.

Wedemeyer, G.A., Saunders, R.L., Clarke, W.C., 1980. Environmental factors effecting smoltification and early marine survival of anadromous salmonids. Mar. Fish. Rev. 42, 1-14.

Wright, R. F. and Henriksen, A. 1999. Gap closure; use of MAGIC model to predict time required to achieve steady-state following implementation of the Oslo protocol. Naturens Tålegrenser Fagrapport 100, Norwegian Institute for Water Research, Oslo. 44 pp.

# Appendix A. Salmon status and water chemistry

**Salmon category 0:** Water characteristics of rivers where the Atlantic salmon population is characterised as extinct, or where river catches were rare. Units: ANC, $H^+$ µeq $L^{-1}$; Ca mg $L^{-1}$; RAL, $Al_i$ µg Al $L^{-1}$.

| River | ANC | pH | $H^+$ | Ca | RAL | $Al_i$ |
|---|---|---|---|---|---|---|
| | µeq $L^{-1}$ | | µeq $L^{-1}$ | µeq $L^{-1}$ | µg $L^{-1}$ | µg $L^{-1}$ |
| Ekso | 7 | 5.7 | 1.8 | 0.8 | 52 | 19 |
| Haugdalselva | -18 | 5.0 | 10.7 | 0.5 | | 36 |
| Dirdalselva | -4 | 5.4 | 4.4 | 0.8 | 63 | 47 |
| Sogndalselva | -19 | 5.1 | 8.3 | 1.3 | | 60 |
| Nidelva | -15 | 5.4 | 3.6 | 1.2 | 104 | 61 |
| Modalselva | -6 | 5.3 | 5.3 | 0.5 | 80 | 65 |
| Lygna | -7 | 4.8 | 15.8 | 0.4 | 80 | 44 |
| Sokndalselva (Rogaland) | 5 | 5.3 | 5.6 | | 60 | 60 |
| Gjerstadelva | 8 | 5.6 | 2.6 | 1.9 | 126 | 74 |
| Frafjordelva | -8 | 5.5 | 3.4 | 0.9 | | 23 |
| Åna. Sira | -19 | 4.9 | 11.7 | 0.5 | | 70 |
| Audna | -15 | 5.1 | 8.3 | 1.2 | 132 | 92 |
| Tovdalselva | -7 | 5.2 | 6.2 | 1.0 | 145 | 98 |
| Kvina | -15 | 4.8 | 15.8 | 1.0 | | 105 |
| Storelva | -5 | 5.7 | 2.0 | 2.6 | | 60 |
| Mandalselva | -22 | 4.8 | 15.5 | 0.7 | 183 | 127 |
| Otra | -7 | 5.6 | 2.7 | 1.1 | 107 | 55 |
| Feda | | 4.5 | 31.6 | | | |
| Hellelandselva | -22 | 5.2 | 6.3 | | | |
| Storelva (Sauda) | | 5.5 | 3.2 | | | |
| Romarheimselva | | 5.0 | 10.0 | | | |
| Frøysetelva | 3 | 5.1 | 8.3 | 0.4 | 95 | 28 |
| Matreelva | | 5.3 | 5.0 | 0.5 | 70 | 28 |
| min | -22 | 4.5 | 31.6 | 0.4 | 52 | 19 |
| max | 8 | 5.7 | 31.6 | 2.6 | 183 | 127 |
| mean | -9 | 5.2 | 8.2 | 1.0 | 100 | 61 |

**Salmon category 1a:** Water characteristics of rivers where the Atlantic salmon population is characterised as affected and where acidification is regarded as a main factor. Units: ANC, $H^+$ µeq $L^{-1}$; Ca mg $L^{-1}$; RAL, $Al_i$ µg Al $L^{-1}$.

| River | ANC | pH | $H^+$ | Ca | RAL | $Al_i$ |
|---|---|---|---|---|---|---|
| | µeq $L^{-1}$ | | µeq $L^{-1}$ | µeq $L^{-1}$ | µg $L^{-1}$ | µg $L^{-1}$ |
| Gaula SogF | -2 | 5.4 | 3.6 | 0.6 | 58 | 32 |
| Rødneelv | -3 | 5.2 | 6.6 | 0.9 | | 47 |
| Vikedalselva | -2 | 5.4 | 3.7 | 0.7 | 55 | 33 |
| Myrastølselv | 5 | 5.5 | 3.2 | 0.7 | 50 | 15 |
| Austerbøelv | -5 | 5.5 | 3.2 | 0.5 | 70 | 20 |
| Bjerkreimselva | 10 | 5.8 | 1.5 | 1.1 | 40 | 20 |
| Østerbøelv | 0 | 5.6 | 2.5 | 0.4 | 30 | 15 |
| Førdeelv | -5 | 5.6 | 2.5 | 0.4 | 50 | 20 |
| Lyse | 4 | 5.7 | 1.9 | 0.7 | | 16 |
| Ortnevik | 10 | 5.8 | 1.6 | 0.5 | 45 | 15 |
| Espedalselva | 4 | 5.9 | 1.4 | 0.9 | | 10 |
| Årdalselva | 13 | 5.9 | 1.4 | 0.9 | 28 | 9 |
| Ytredalselva | 15 | 5.9 | 1.3 | 0.7 | 47 | 5 |
| Høyanger | 5 | 5.9 | 1.3 | 0.7 | 30 | 15 |
| Opo | 10 | 5.9 | 1.1 | 1.1 | | 22 |
| Ogna | -1 | 5.9 | 1.3 | 2 | | 50 |
| Vormedalselva | 4 | 6.1 | 0.8 | 2.2 | | 35 |
| Guddalsvassdraget | | 5.8 | 1.6 | 0.5 | 36 | 6 |
| min | -5 | 5.2 | 0.8 | 0.4 | 28 | 5 |
| max | 15 | 6.1 | 6.6 | 2.2 | 70 | 50 |
| mean | 4 | 5.7 | 2.2 | 0.9 | 44 | 21 |

**Salmon category 1b:** Water characteristics of rivers where the Atlantic salmon population is characterised as affected but where the cause for reduction is uncertain. Units: ANC, $H^+$ µeq $L^{-1}$; Ca mg $L^{-1}$; RAL, $Al_i$ µg Al $L^{-1}$.

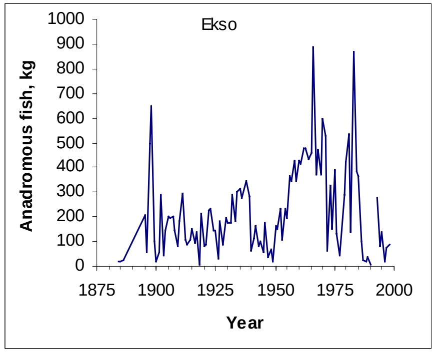
| River | ANC | pH | $H^+$ | Ca | RAL | $Al_i$ |
|---|---|---|---|---|---|---|
| | µeq $L^{-1}$ | | µeq $L^{-1}$ | µeq $L^{-1}$ | µg $L^{-1}$ | µg $L^{-1}$ |
| Nausta | 10 | 5.6 | 2.3 | 0.6 | 39 | 11 |
| Jølstra | 25 | 6.1 | 0.9 | 0.8 | 25 | 3 |
| Lona | 30 | 5.7 | 2.0 | 0.7 | 50 | 8 |
| Vosso | 36 | 6.1 | 0.9 | 0.9 | 7 | 4 |
| Suldal | 25 | 6.2 | 0.7 | 1.5 | | 15 |
| Oselva i Os | 30 | 6.2 | 0.7 | 1.9 | | 25 |
| min | 10 | 5.6 | 0.7 | 0.6 | 7 | 3 |
| max | 36 | 6.2 | 2.3 | 1.9 | 50 | 25 |
| mean | 26 | 6.0 | 1.2 | 1.1 | 30 | 11 |

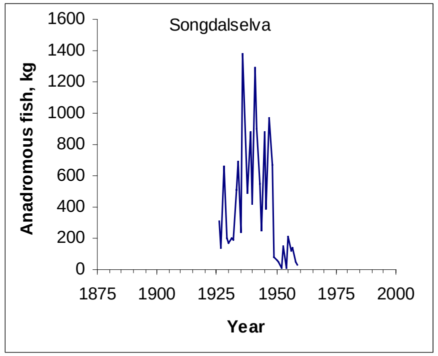
**Salmon category 2:** Water characteristics of rivers where the Atlantic salmon population is characterised as unaffected or where possible population declines can be related to other causes (diseases, parasites, hydro-power etc.). Units: ANC, $H^+$ µeq $L^{-1}$; Ca mg $L^{-1}$; RAL, $Al_i$ µg Al $L^{-1}$.

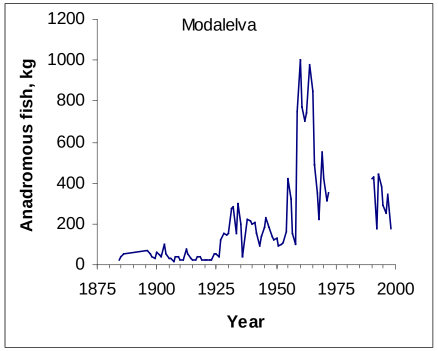
| **River** | **ANC** | **pH** | **$H^+$** | **Ca** | **RAL** | **$Al_i$** |
|---|---|---|---|---|---|---|
| | µeq $L^{-1}$ | | µeq $L^{-1}$ | µeq $L^{-1}$ | µg $L^{-1}$ | µg $L^{-1}$ |
| Etne | 31 | 6.4 | 0.4 | 1.9 | | 1 |
| Drammenselva | 150 | 6.7 | 0.2 | 3.5 | | 5 |
| Altaelva | 492 | 7.2 | 0.1 | 8.1 | | 5 |
| Beiarelva | 172 | 6.6 | 0.2 | 4.0 | | 5 |
| Gaula trønder | 300 | 7.1 | 0.1 | 6.3 | | 5 |
| Halselva | 318 | 7.2 | 0.1 | 5.9 | | 5 |
| Imsa | 97 | 6.7 | 0.2 | 3.4 | | 5 |
| Orkla | 393 | 7.2 | 0.1 | 8.7 | 154 | 5 |
| Rauma | 56 | 6.3 | 0.5 | 1.9 | | 5 |
| Reisaelva | 286 | 7.0 | 0.1 | 5.6 | | 5 |
| Lærdalselva | 93 | 6.7 | 0.2 | 2.1 | 16 | 0 |
| Øyensåa | 50 | 6.0 | 1.1 | 1.1 | 52 | 3 |
| Numedalslågen | 83 | 6.5 | 0.3 | 2.7 | | 7 |
| Stryneelva | 34 | 6.4 | 0.4 | 2.4 | | 5 |
| Figgjo | 47 | 6.3 | 0.5 | 2.5 | | 8 |
| Driva | 149 | 6.9 | 0.1 | 4.3 | | 2 |
| Nordfolda | 30 | 6.1 | 0.7 | 1.1 | | |
| Stjørdalselva | 94 | 7.2 | 0.1 | | | |
| Skalleelv | 152 | 6.7 | 0.2 | 1.8 | | |
| Stabburselva | 234 | 6.9 | 0.1 | 4.3 | | |
| Bjordalselv | 70 | 6.4 | 0.4 | 1.5 | 50 | 5 |
| Stryneelva | 25 | 7.2 | 0.1 | | | |
| Tana | | 7.2 | 0.1 | | | |
| Vefsna | 356 | 7.2 | 0.1 | 7.1 | | |
| Ørstaelva | 57 | 6.5 | 0.3 | 1.6 | | 4 |
| Eidselva | 19 | 6.2 | 0.6 | 1.1 | | 8 |
| min | 19 | 6.0 | 0.1 | 1.1 | 16 | 0 |
| max | 492 | 7.2 | 1.1 | 8.7 | 154 | 8 |
| mean | 152 | 7.0 | 0 | 4.0 | 68 | 5 |

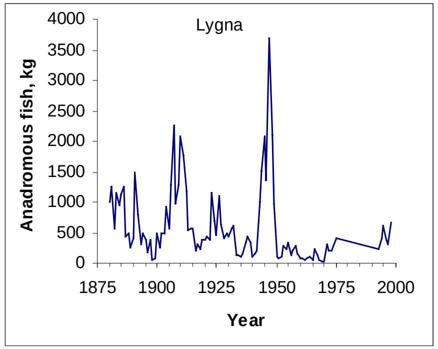
# Appendix B. Salmon catch statistics for Norwegian rivers

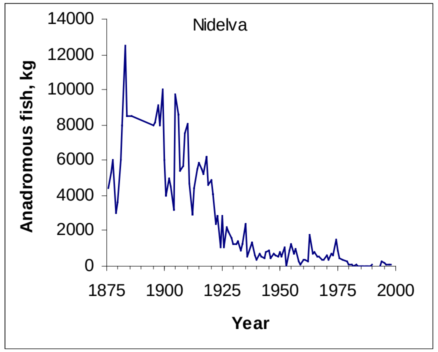
## Category 0; extinct

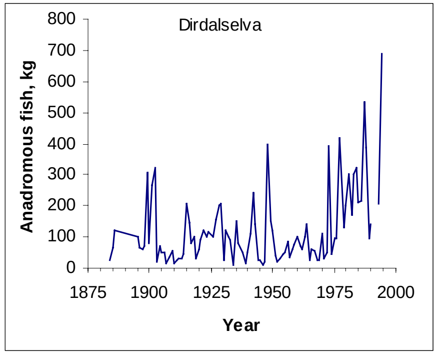


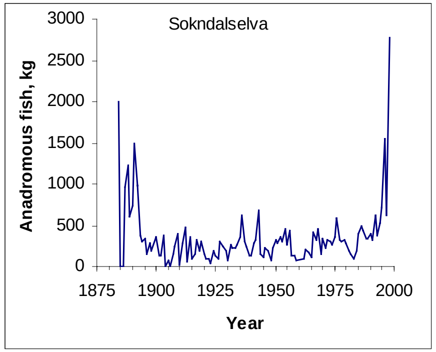


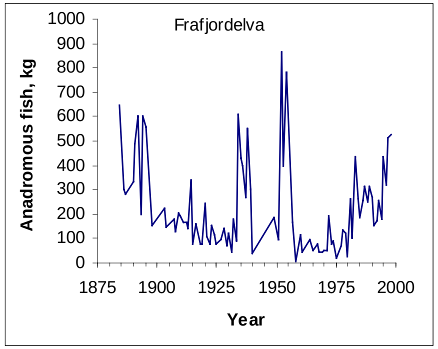


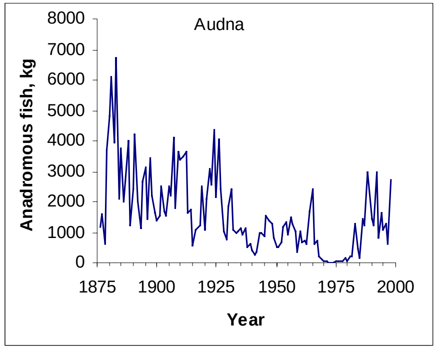











Audna
Anadromous fish, kg
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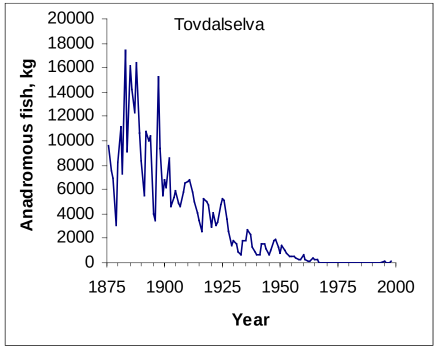
1000
2000
3000
4000
5000
6000
7000
8000
1875
1900
1925
1950
1975
2000
Year


Tovdalselva
Anadromous fish, kg
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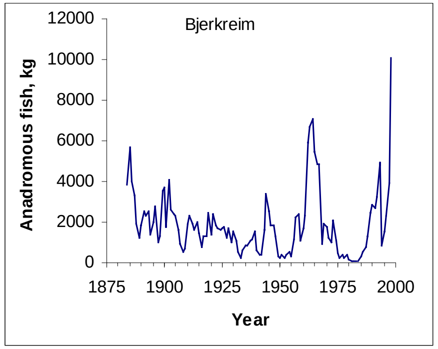
8000
10000
12000
14000
16000
18000
20000
1875
1900
1925
1950
1975
2000
Year


Bjerkreim
Anadromous fish, kg
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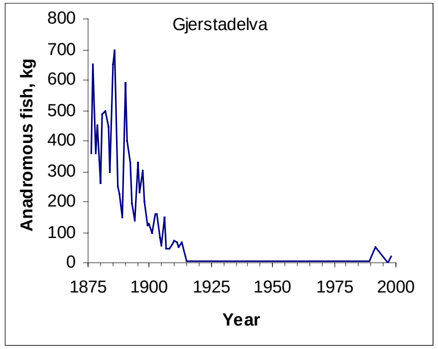
2000
4000
6000
8000
10000
12000
1875
1900
1925
1950
1975
2000
Year


Gjerstadelva
Anadromous fish, kg
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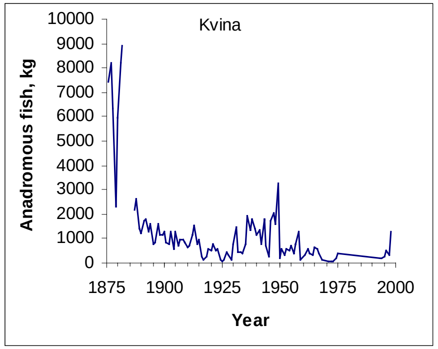
300
400
500
600
700
800
1875
1900
1925
1950
1975
2000
Year


Kvina
Anadromous fish, kg
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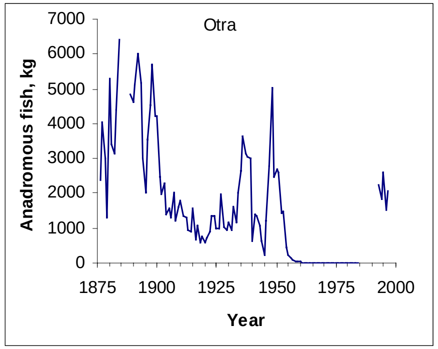
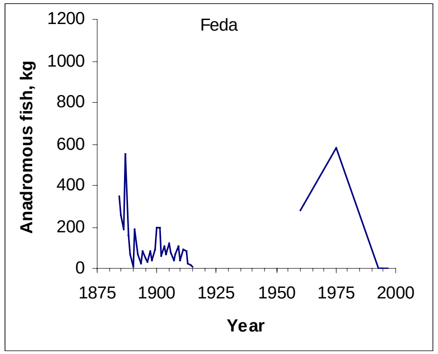
2000
3000
4000
5000
6000
7000
8000
9000
10000
1875
1900
1925
1950
1975
2000
Year


Otra
Anadromous fish, kg
0
1000
2000
3000
4000
5000
6000
7000
1875
1900
1925
1950
1975
2000
Year


Feda
Anadromous fish, kg
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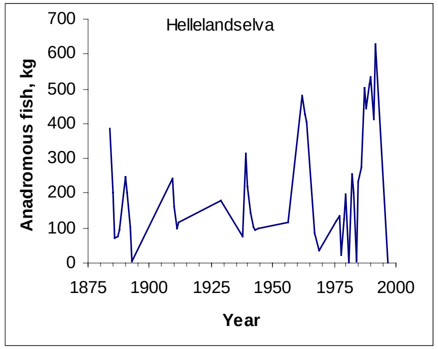
400
600
800
1000
1200
1875
1900
1925
1950
1975
2000
Year


Hellelandselva
Anadromous fish, kg
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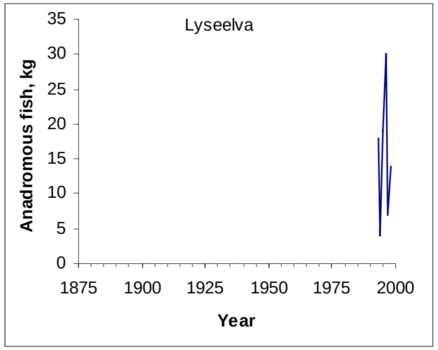
200
300
400
500
600
700
1875
1900
1925
1950
1975
2000
Year


Lyseelva
Anadromous fish, kg
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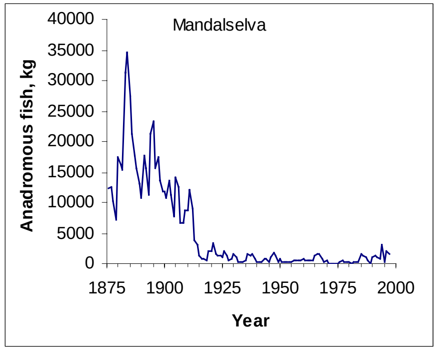
15
20
25
30
35
1875
1900
1925
1950
1975
2000
Year


Mandalselva
Anadromous fish, kg
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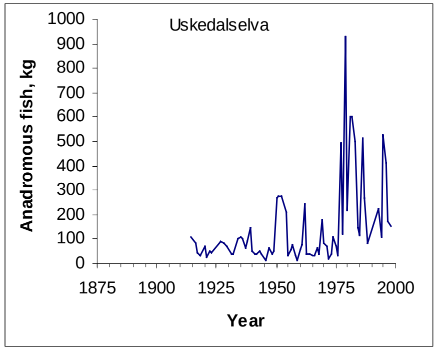
20000
25000
30000
35000
40000
1875
1900
1925
1950
1975
2000
Year


Uskedalselva
Anadromous fish, kg
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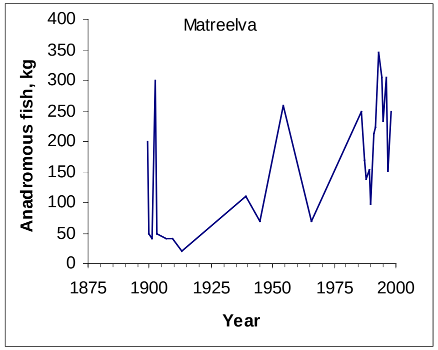
300
400
500
600
700
800
900
1000
1875
1900
1925
1950
1975
2000
Year


Matreelva
Anadromous fish, kg
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50
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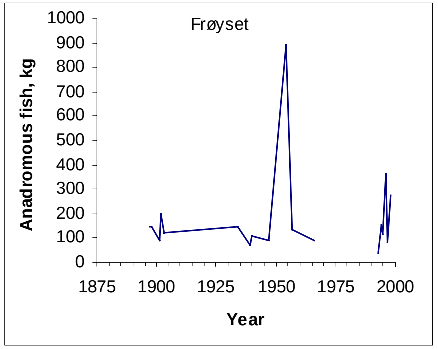
150
200
250
300
350
400
1875
1900
1925
1950
1975
2000
Year



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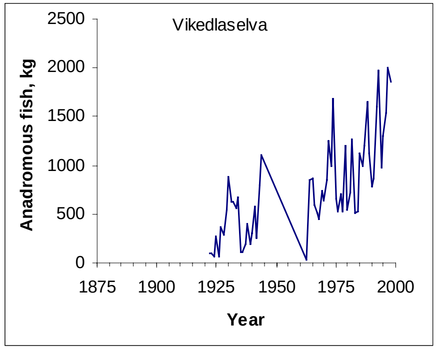

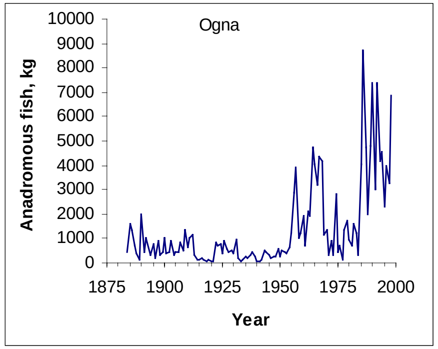

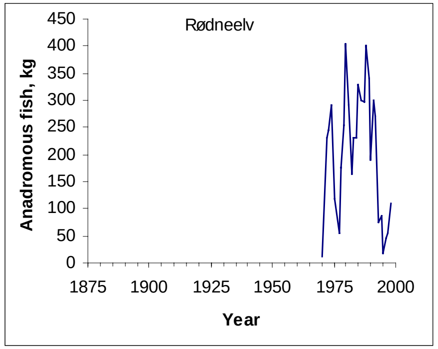

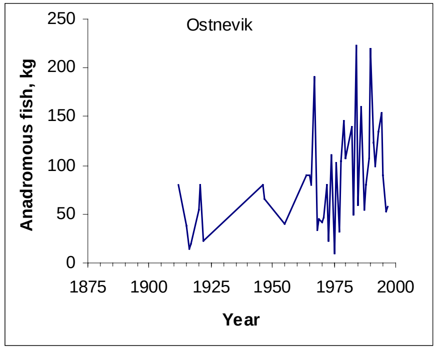

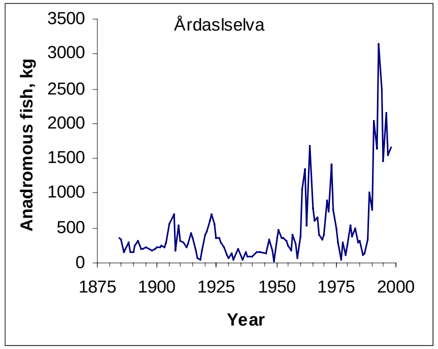

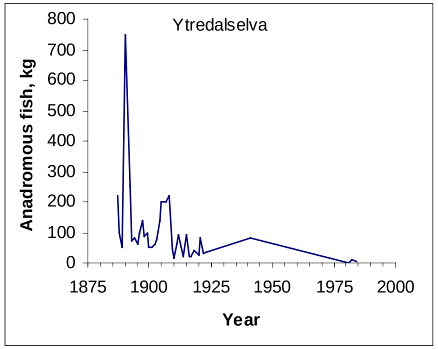

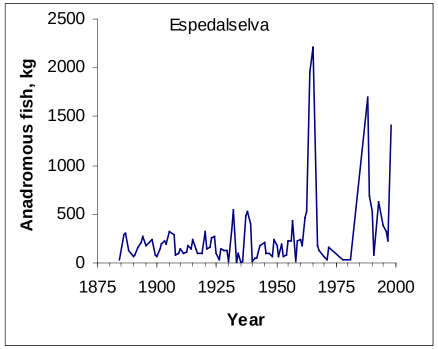

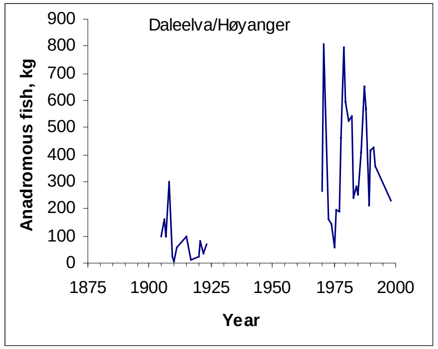

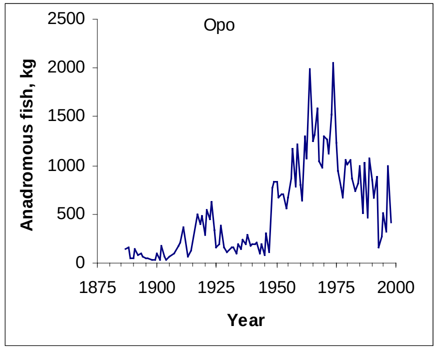

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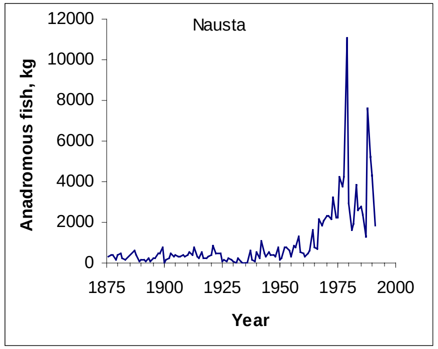

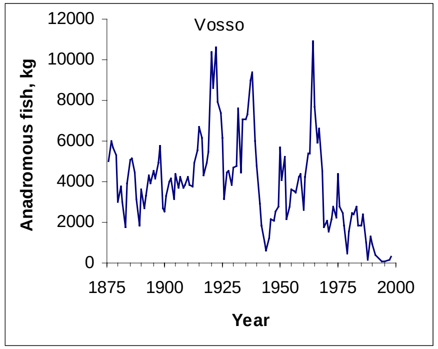

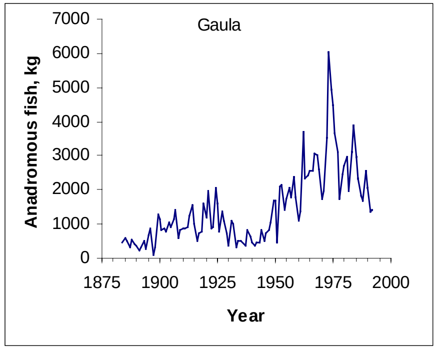

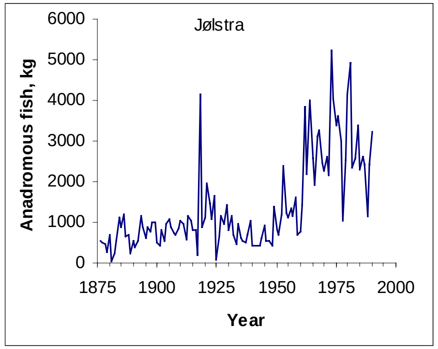

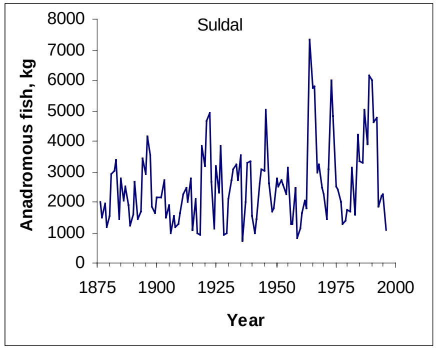

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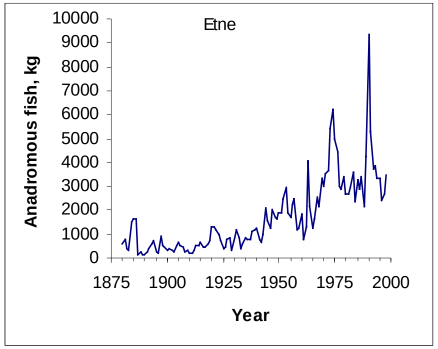
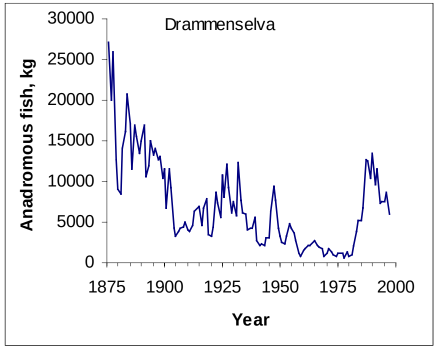
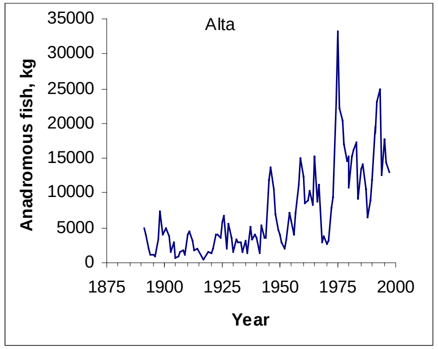
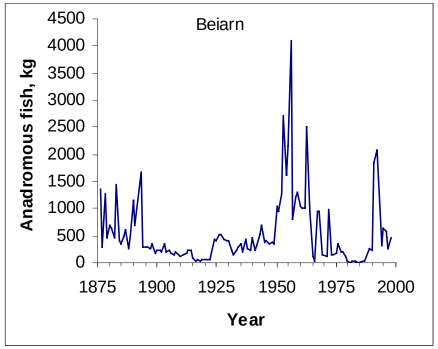
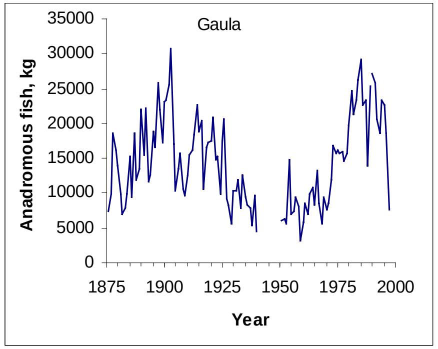
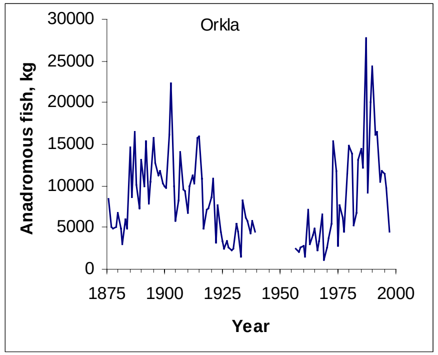


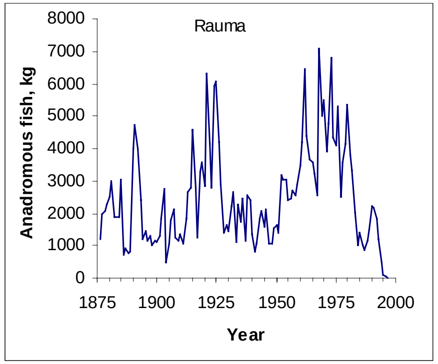


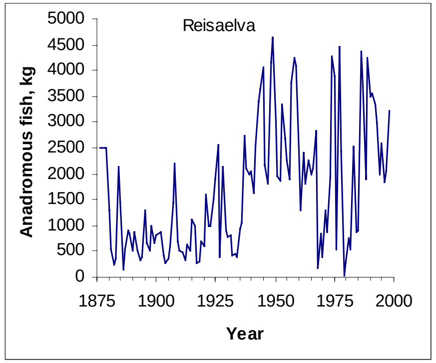


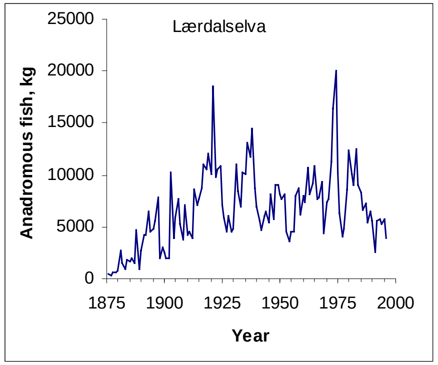


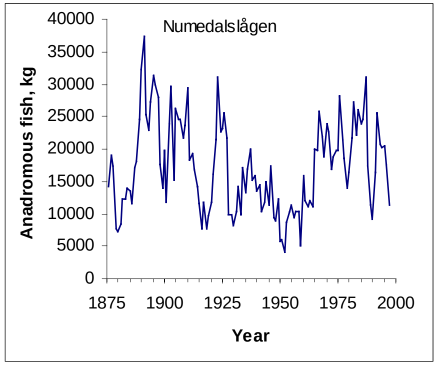


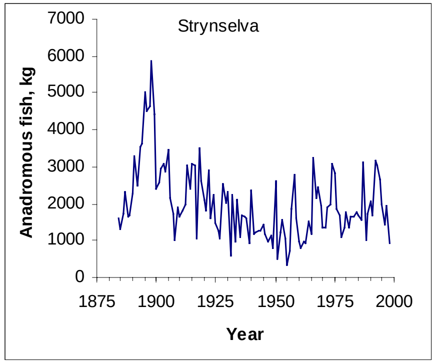


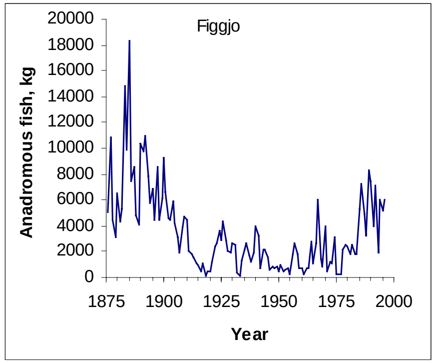


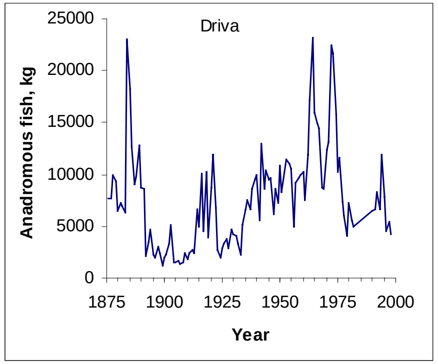


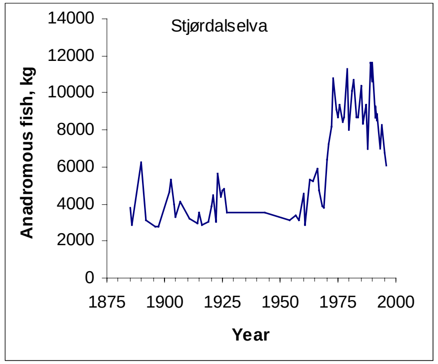

Lærdalselva
Anadromous fish, kg
25000
20000
15000
10000
5000
0
1875
1900
1925
1950
1975
2000
Year

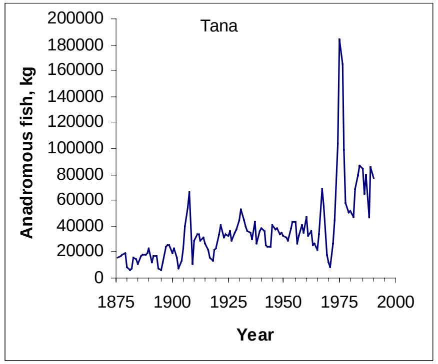

Numedalslågen
Anadromous fish, kg
40000
35000
30000
25000
20000
15000
10000
5000
0
1875
1900
1925
1950
1975
2000
Year

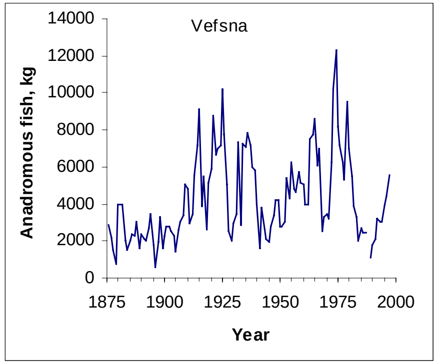

Strynselva
Anadromous fish, kg
7000
6000
5000
4000
3000
2000
1000
0
1875
1900
1925
1950
1975
2000
Year

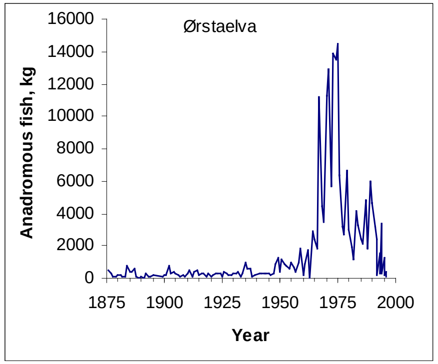

Figgjo
Anadromous fish, kg
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
1875
1900
1925
1950
1975
2000
Year


Driva
Anadromous fish, kg
25000
20000
15000
10000
5000
0
1875
1900
1925
1950
1975
2000
Year


Stjørdalselva
Anadromous fish, kg
14000
12000
10000
8000
6000
4000
2000
0
1875
1900
1925
1950
1975
2000
Year


Tana
Anadromous fish, kg
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
1875
1900
1925
1950
1975
2000
Year


Vefsna
Anadromous fish, kg
14000
12000
10000
8000
6000
4000
2000
0
1875
1900
1925
1950
1975
2000
Year


Ørstaelva
Anadromous fish, kg
16000
14000
12000
10000
8000
6000
4000
2000
0
1875
1900
1925
1950
1975
2000
Year

## Naturens Tålegrenser - Oversikt over utgitte rapporter

1 Nygaard, P. H., 1989. Forurensningers effekt på naturlig vegetasjon en litteraturstudie. Norsk institutt for skogforskning (NISK), Ås.

Uten nr. Jaworovski, Z., 1989. Pollution of the Norwegian Arctic: A review.
Norsk polarinstitutt (NP), rapportserie nr. 55. Oslo.

2 Henriksen, A., Lien, L. & Traaen, T.S. 1990. Tålegrenser for overflatevann. Kjemiske kriterier for tilførsler av sterke syrer. Norsk institutt for vannforskning (NIVA), O-89210.

3 Lien, L., Henriksen, A., Raddum ,G. & Fjellheim, A. 1989. Tålegrenser for overflatevann. Fisk og evertebrater. Foreløpige vurderinger og videre planer. Norsk institutt for vannforskning (NIVA), O-89185.

4 Bølviken, B. & medarbeidere, 1990. Jordforsuringsstatus og forsuringsfølsomhet i naturlig jord i Norge. Norges geologiske undersøkelse (NGU), NGU-rapport 90.156. 2 bind (Bind I: Tekst, Bind II:Vedlegg og bilag).

5 Pedersen, H. C. & Nybø, S. 1990. Effekter av langtransporterte forurensninger på terrestriske dyr i Norge. En statusrapport med vekt på $SO_2$, NOx og tungmetaller. Norsk institutt for naturforskning (NINA), Utredning 005.

6 Frisvoll, A. A., 1990. Moseskader i skog i Sør-Norge. Norsk institutt for naturforskning (NINA), Oppdragsmelding 018.

7 Muniz, I. P. & Aagaard, K. 1990. Effekter av langtransportert forurensning på ferskvannsdyr i Norge - virkninger av en del sporelementer og aluminium. Norsk institutt for naturforskning (NINA), Utredning 013.

8 Hesthagen, T., Berger, H. M. & Kvenild, L. 1992. Fiskestatus i relasjon til forsuring av innsjøer. Norsk institutt for naturforskning (NINA), Forskningsrapport 032.

9 Pedersen, U., Walker, S.E. & Kibsgaard, A. 1990. Kart over atmosfærisk avsetning av svovel- og nitrogenforbindelser i Norge. Norsk institutt for luftforskning (NILU), OR 28/90.

10 Pedersen, U. 1990. Ozonkonsentrasjoner i Norge. Norsk institutt for luftforskning (NILU), OR 28/90.

11 Wright, R. F., Stuanes, A. Reuss, J.O. & Flaten, M.B. 1990. Critical loads for soils in Norway. Preliminary assessment based on data from 9 calibrated catchments. Norsk institutt for vannforskning (NIVA), O-89153.

11b Reuss, J. O., 1990. Critical loads for soils in Norway. Analysis of soils data from eight Norwegian catchments. Norsk institutt for vannforskning (NIVA), O-89153.

12 Amundsen, C. E., 1990. Bufferprosent som parameter for kartlegging av forsuringsfølsomhet i naturlig jord. Universitetet i Trondheim, AVH (stensil).

13 Flatberg, K.I, Foss, B., Løken,A. & Saastad, S.M. 1990. Moseskader i barskog. Direktoratet for naturforvaltning (DN), notat.

14 Frisvoll, A.A., & Flatberg, K.I., 1990. Moseskader i Sør-Varanger. Norsk institutt for naturforskning (NINA) , Oppdragsmelding 55.

15 Flatberg, K.I., Bakken, S., Frisvoll, A.A., & Odasz, A.M. 1990. Moser og luftforurensninger. Norsk institutt for naturforskning (NINA) , Oppdragsmelding 69.

16 Mortensen, L.M. 1991. Ozonforurensning og effekter på vegetasjonen i Norge. Norsk landbruksforsk. 5:235-264.

17 Wright, R.F., Stuanes, A.O. & Frogner, T. 1991. Critical Loads for Soils in Norway Nordmoen. Norsk institutt for vannforskning (NIVA), O-89153.

18 Pedersen, H.C., Nygård, T., Myklebust, I. og Sæther, M. 1991. Metallbelastninger i lirype. Norsk institutt for naturforskning (NINA), Oppdragsmelding 71.

19 Lien, L., Raddum, G.G. & Fjellheim, A. 1991. Tålegrenser for overflatevann evertebrater og fisk. Norsk institutt for vannforskning (NIVA), Rapport 0-89185,2.

20 Amundsen, C.E. 1992. Sammenlingning av parametre for å bestemme forsuringsfølsomhet i jord. NGU-rapport 91.265.

21 Bølviken, B., R. Nilsen, J. Romundstad & O. Wolden. 1992. Surhet, forsuringsfølsomhet og lettløselige basekationer i naturlig jord fra Nord-Trøndelag og sammenligning med tilsvarende data fra Sør Norge. NGU-rapport 91.250.

22 Sivertsen, T. & medarbeidere. 1992. Opptak av tungmetaller i dyr i Sør-Varanger. Direktoratet for naturforvaltning, DN-notat 1991-15.

23 Lien, L., Raddum, G.G. & A. Fjellheim. 1992. Critical loads of acidity to freshwater. Fish and invertebrates. Norwegian Institute for Water Research (NIVA), Rapport O-89185,3.

24 Fremstad, E. 1992. Virkninger av nitrogen på heivegetasjon. En litteraturstudie. Norsk institutt for naturforskning (NINA), Oppdragsmelding 124.

25 Fremstad, E. 1992. Heivegetasjon i Norge, utbredelseskart. Norsk institutt for naturforskning (NINA), Oppdragsmelding 188.

26 Flatberg, K.I. & Frisvoll, A. 1992. Undersøkelser av skader hos to sigdmoser i Agder. Norsk institutt for naturforskning (NINA), Oppdragsmelding 134.

27 Lindstrøm, E.A.1992. Tålegrenser for overflatevann. Fastsittende alger. Norsk institutt for vannforskning (NIVA), O-90137/E-90440, rapport-2.

28 Brettum, P. 1992. Tålegrenser for overflatevann. Planteplankton. Norsk institutt for vannforskning (NIVA), O-90137/E-90440, rapport-3.

29 Brandrud, T.E., Mjelde, M. 1992. Tålegrenser for overflatevann. Makrovegetasjon. Norsk institutt for vannforskning (NIVA), O-90137/E-90440, rapport-1.

30 Mortensen, L.M. & Nilsen, J. 1992. Effects of ozone and temperature on growth of several wild plant species. Norwegian Journal of Agricultural Sciences 6: 195-204.

31 Pedersen, H.C., Myklebust, I., Nygård, T. & Sæther, M. 1992. Akkumulering og effekter av kadmium i lirype. Norsk institutt for naturforskning (NINA), Oppdragsmelding 152.

32 Amundsen, C.E. 1992. Sammenligning av relativ forsuringsfølsomhet med tålegrenser beregnet med modeller, i jord. Norges geologiske undersøkelse. NGU-rapport 92.294.

33 Frogner, T., Wright, R.F., Cosby, B.J., Esser, J.M., Håøya, A.-O. & Rudi, G. 1992. Map of critical loads for coniferous forest soils in Norway. Norsk institutt for vannforskning (NIVA), O-91147.

34 Henriksen, A., Lien, L., Traaen, T.S. & Taubøll, S. 1992. Tålegrenser for overflatevann - Kartlegging av tålegrenser og overskridelser av tålegrenser for tilførsler av sterke syrer. Norsk institutt for vannforskning (NIVA), O-89210.

35 Lien, L. Henriksen, A. & Traaen, T.S. 1993. Tålegrenser for sterke syrer på overflatevann -Svalbard. Norsk institutt for vannforskning (NIVA), O-90102.

36 Henriksen, A., Hesthagen, T., Berger, H.M., Kvenild, L., Taubøll, S. 1993. Tålegrenser for overflatevann - Sammenheng mellom kjemisk kriterier og fiskestatus. Norsk institutt for vannforskning (NIVA), O-92122.

37 Odasz, A.M., Øiesvold, S., & Vange, V. 1993. Nitrate nutrition in *Racomitrium lanuginosum* (Hedw.)Brd., a bioindicator of nitrogen deposition in Norway. Direktoratet for naturforvaltning. Utredning for DN 1993-2.

38 Espelien, I.S. 1993. Genetiske effekter av tungmetaller på pattedyr. En kunnskapsoversikt. Norsk institutt for naturforskning (NINA), Utredning 051.

39 Økland, J. & Økland, K.A. 1993. Database for bioindikatorer i ferskvann - et forprosjekt . Laboratorium for ferskvannsøkologi og innlandsfiske (LFI), Zoologisk Museum, Oslo, Rapport 144, 1993.

40 Aamlid, D. & Skogheim, I. 1993. Nikkel, kopper og andre metaller i multer og blåbær fra Sør-Varanger, 1992. Rapport Gkogforsk 14/93. 14/93.

41 Kålås, J.A., Ringsby, T.H. & Lierhagen, S. 1993. Metals and radiocesium in wild animals from the Sør-Varanger area, north Norway. Norsk institutt for naturforskning (NINA), Oppdragsmelding 212.

42 Fløisand, I. & Løbersli, E. (red.)1993. Tilførsler og virkninger av lufttransporterte forurensninger (TVLF) og Naturens tålegrenser. Sammendrag av foredrag og postere fra møte i Stjørdal, 15.-17.februar 1993. Norsk institutt for luftforskning (NILU), OR 17/93.

43 Henriksen, A. & Hesthagen, T. 1993. Critical load exceedance and damage to fish populations. Norsk institutt for vannforskning (NIVA), O-89210.

44 Lien, L., Henriksen, A. & Traaen, T.S. 1993. Critical loads of acidity to surface waters, Svalbard. Norsk institutt for vannforskning (NIVA), O-90102.

45 Løbersli, E., Johannessen, T. & Olsen, K.V (red.) 1993. Naturens tålegrenser. Referat fra seminar i 1991 og 1992. Direktoratet for naturforvaltning, DN-notat 1993-6.

46 Bakken, S. 1993. Nitrogenforurensning og variasjon i nitrogen, protein og klorofyllinnhold hos barskogsmosen blanksigd (*Dicranum majus*). Direktoratet for naturforvaltning (DN). Utredning for DN 1994-1.

47 Krøkje, Å. 1993. Genotoksisk belastning i jord . Effektstudier, med mål å komme fram til akseptable grenser for genotoksisk belastning fra langtransportert luftforurensning. Direktoratet for naturforvaltning (DN). Utredning for DN 1994-2.

48 Fremstad, E. 1993. Heigråmose (*Racomitrium lanuginosum*) som indikator på nitrogenbelastning. Norsk i nstitutt for naturforskning (NINA) Oppdragsmelding 239.

49 Nygaard, P.H. & Ødegaard, T.H. 1993. Effekter av nitrogengjødsling på vegetasjon og jord i skog. Rapport Skogforsk 26/93.

50 Fløisand, I. og Johannessen, T. (red.) 1994. Langtransporterte luftforurensninger. Tilførsler, virkninger og tålegrenser. Sammendrag av foredrag og postere fra møte i Grimstad, 7.-9.3.94. Norsk institutt for luftforskning NILU OR: 17/94

51 Kleivane, L. Skåre, J.U. & Wiig, Ø. 1994. Klorerte organiske miljøgifter i isbjørn. Forekomst, nivå og mulige effekter. Norsk Polarinstitutt Meddelelse nr. 132.

52 Lydersen, E., Fjeld, E. & Andersen, T. 1994. Fiskestatus og vannkjemi i norske innsjøer. Norsk institutt for vannforskning (NIVA) O-93172

53 Schartau, A.K.L. (red.) 1994. Effekter av lavdose kadmium-belastning på littorale ferskvanns-populasjoner og -samfunn. Norsk institutt for naturforskning (NINA) Forskningsrapport 055.

54 Mortensen, L. (1994). Variation in ozone sensitivity of *Betula pubescens* Erh. from different sites in South Norway. Direktoratet for naturforvaltning (DN). Utredning for DN, Nr. 1994-6.

55 Mortensen, L. (1994). Ozone sensitivity of *Phleum alpinum* L. from different locations in South Norway. Direktoratet for naturforvaltning (DN). Utredning for DN, Nr. 1994-7.

56 Frogner, T., Wright, R.F., Cosby, J.B. and Esser, J.M. (1994). Maps of critical loads and exceedance for sulfur and nitrogen to forest soils in Norway. Norsk institutt for vannforskning (NIVA) O-91147.

57 Flatberg, K.I. & Frisvoll, A.A. 1994. Moseskader i Agder 1989-92 (1994). Norsk institutt for naturforskning (NINA), Oppdragsmelding 298.

58 Hesthagen, T. & Henriksen, A. (1994). En analyse av sammenhengen mellom overskridelser av tålegrenser for overflatevann og skader på fiskebestander. Norsk institutt for naturforskning (NINA), Oppdragsmelding 288.

59 Skåre, J.U., Wiig, Ø. & Bernhoft, A. (1994). Klorerte organiske miljøgifter; nivåer og effekter på isbjørn. Norsk Polarinstitutt Rapport nr. 86 - 1994.

60 Tørseth, K. & Pedersen, U. 1994. Deposition of sulphur and nitrogen components in Norway. 1988-1992. Norsk institutt for luftforskning (NILU): OR 16/94.

61 Nygaard, P.H. 1994. Virkning av ozon på blåbær (*Vaccinium myrtillus*), etasjehusmose (*Hylocomium splendens*), furumose *(Pleurozium schreberi*) og krussigd (*Dicranum polysetum*). Rapport Skogforsk 9/94.

62 Henriksen, A. & Lien, L. 1994. Tålegrenser for overflatevann: Metode og usikkerheter. Norsk institutt for vannforskning (NIVA), O-94122.

63 Hilmo, O. & Larssen, H.C. 1994. Morfologi hos epifyttisk lav i områder med ulik luftkvalitet. ALLFORSK Rapport 2.

64 Wright, R.F. 1994. Bruk av dynamiske modeller for vurdering av vann- og jordforsuring som følge av redusert tilførsel av sur nedbør. Norsk institutt for vannforskning (NIVA), O-94112.

65 Hesthagen, T., A. Henriksen & Kvenild, L. 1994. Overskridelser av tålegrenser for overflatevann og skader på fiskebestander i norske innsjøer med spesiell vekt på Troms og Finnmark. Norsk institutt for naturforskning (NINA), Oppdragsmelding 298.

66 Sagmo Solli, I.M, Flatberg, K.I.F., Söderström, L., Bakken S. & Pedersen, B. 1996. Blanksigd og luftforurensningsstudier. NTNU. Vitenskapsmuseet. Rapport botanisk serie 1996-1.

67 Stuanes, A. & Abrahamsen, G. 1996. Tålegrenser for nitrogen i skog - en vurdering av kunnskapsgrunnlaget. Aktuelt fra Skogforsk 7-96.

68 Ogner, G. 1995. Tålegrenser for skog i Norge med hensyn til ozon. Aktuelt fra Skogforsk 3-95.

69 Thomsen, M., Nellemann, C. Frogner, T., Henriksen A., Tomter, S. & Mulder, J. 1995. Tilvekst og vitalitet for granskog sett i relasjon til tålegrenser og forurensning. Rapport fra Skogforsk 22-95.

70 Tomter, S. M. & Esser, J. 1995. Kartlegging av tålegrenser for nitrogen basert på en empirisk metode. Norsk institutt for jord- og skogkartlegging (NIJOS). Rapport nr 10/95.

71 Pedersen, H.Chr. (red.). 1995. Kadmium og bly i lirype: akkumulering og cellulære effekter. Stiftelsen for naturforskning og kulturminneforskning (NINA-NIKU) Oppdragsmelding 387

72 Bakken, S. & Flatberg, K.I.F. 1995. Effekter av økt nitrogendeposisjon på ombrotrof myrvegetasjon. En litteraturstudie. ALLFORSK Rapport 3.

73 Sogn, T.A., Stuanes, A.O. & Abrahamsen, G. 1995. Akkumulering av nitrogen - en kritisk parameter for beregning av tålegrenser for nitrogen i skog. Rapport fra Skogforsk 21/95.

74 Nygaard, P.H. & Eldhuset, T. 1996. Forholdet mellom basekationer og aluminium i jordløsning som kriterium for tålegrenser i skogsjord. Norsk institutt for skogforskning (NISK). Rapport fra Skogforsk 1/96

75 Mortensen, L. 1993. Effects of ozone on growth of several subalpine plant species. Norw. J. Agric. Sci. 7: 129-138.

76 Mortensen. L. 1994. Further studies on the effects of ozone concentration on growth of subalpine plant species. Norw. J. Agric. Sciences 8:91-97.

77 Fløisand, I. & Løbersli, E. (red.) 1996. Lufttransporterte forurensninger - tilførsler, virkninger og tålegrenser. Norsk institutt for luftforskning (NILU) OR 2/96.

78 Thomsen, M.G., Esser; J., Venn, K. & Aamlid, D. 1996. Sammenheng mellom trærs vitalitet og næringsstatus i nåler og humus på skogovervåkingsflater i Sørøst-Norge (in prep).

79 Tørseth, K., Mortensen, L. & Hjellbrekke, A.-G. 1996. Kartlegging av bakkenær ozon etter tålegrenser basert på akkumulert dose over 40 ppb. Norsk institutt for luftforskning (NILU) OR 12/96.

80 Esser, J.M. & Tomter, S.M. 1996. Reviderte kart for tålegrenser for nitrogen basert på empriske verdier for ulike vegetasjonstyper. Norsk institutt for jord- og skogkartlegging (NIJOS).

81 Henriksen, A. , Hindar; A., Styve, H., Fjeld, E. & Lien, L. 1996. Forsuring av overflatevann, beregningsmetodikk, trender og mottiltak. Norsk institutt for vannforskning (NIVA). Rapport LNR 3528-96.

82 Henriksen, A., Hesthagen, T. & Fjeld, E. 1996. Overskridelser av tålegrenser for overflatevann og skader på fiskebestander. Norsk institutt for vannforskning (NIVA). Rapport LNR 3565-96.

83 Wright, R. F., Raastad, I.A., & Kaste, Ø. 1996. Atmospheric deposition of nitrogen, runoff of organic nitrogen, and critical loads for soils and waters. Norsk institutt for vannforskning (NIVA) Report SNO 3592-97

84 Mortensen, L.M. 1995. The influence of ozone pollution on growth of young plants of Betula pubescens Ehrh. And Phleum alpinum L. Dose-response relations. Norw. J. Agr. Sci. 9:249-262

85 Mortensen, L.M. 1996. Ozone senistivity of Betula pubescens at different growth stages after budburst in spring. Norw. J. Agr. Sci. 10:187-196.

86 Tørseth, K., Rosendahl, K.E., Hansen, A.C., Høie, H. & Mortensen, L.M. 1997. Avlingstap som følge av bakkenært ozon. Vurderinger for perioden 1989-1993. SFT-rapport.

87 Rognerud, S, Hognve, D. & Fjeld, E. 1997. Naturlige bakgrunnskonsentrasjoner av metaller. Kan amosfæriske avsetninger påvirke metall-konsentrasjoner slik at det ikke reflekterer berggrunnens geokjemi? Norsk institutt for vannforskning (NIVA) Rapport LNR 3670-97

88 Skjelkvåle, B.L., Wright, R.F. & Tjomsland, T. 1997. Vannkjemi, forsuringsstatus og tålegrenser i nasjonalparker; Femundsmarka og Rondane. Norsk institutt for vannforskning (NIVA) Rapport LNR 3646-97

89 Nordbakken; J.-F. 1997. Småskalaendringer i ombrotrof myrvegetasjon i SØ-Norge 1990/91-96. Botanisk Hage og Museum, Univ. Oslo Rapp. 1

90 Sogn, T.A., Kjønnås, J., Stuanes, A.O., & Abrahamsen, G. 1997. Akkumulering av nitrogen - variasjoner avhengig av bestandsutvikling, nitrogentilførsel og simulert snødekke. Norges Landbrukshøgskole, Institutt for jord- og vannfag, Rapport nr. 10/97.

91 Nygaard, P.H., Ødegård, T. & Flatberg, K.I.F. Vegetasjonsendringer over 60 år i fattig skog- og myrvegetasjon i Karlshaugen skogreservat. Skogforsk (in prep)

92 Knutzen, J., Gabrielsen, G.W., Henriksen, O.E., Hylland, K., Källqvist, T. Nygård, T., Pacyna, J.S. Skjegstad, N. & Steinnes, E. 1997. Assessment of the applicability for pollution authorities ofthe concept “critical load” of long-range transported micrpollutants in relation to aquatic an terrestrial ecosystems. Norsk institutt for vannforskning (NIVA) Report SNO 3751-97.

93 Tørseth, K. & Semb, A. 1997. Deposition of major inorganic components in Norway 1992-1996. Norsk institutt for luftforskning (NILU), OR 67/97.

94 Henriksen, A. 1998. Application of the first order acicvity balance (FAB) model to Norwegian surface waters. Norsk institutt for vannforskning (NIVA) Report SNO 3809-98

95 Sogn, T.A. & Wright, R.F. 1998. The model MERLIN applied to Nordmoen, Norway. Norsk institutt for vannforskning (NIVA) Report SNO 3844-98

96 Skjelkvåle, B.L. & A. Henriksen, 1998. Vannkjemi, forsuringsstatus og tålegrenser i nasjonalparker; Hardangervidda. Norsk institutt for vannforskning (NIVA). Report SNO 3895-98

97 Henriksen, A. 1998. Binding grid cells – Norway. An evaluation. Norsk institutt for vannforskning (NIVA) Report SNO 3942-98

98 Lükewille, A. & A. Semb. 1998. Deposition in Norwegian Mountain areas. Norsk institutt for luftforskning (NILU) OR 66/97

99 Strand, L.T., Stuanes, A.O. & G. Abrahamsen. 1998. Akkumulering av karbon og nitrogen i unge jordsmonn. Institutt for jord og vannfag, rapport nr 9/98.

100 Wright, R.F. & Henriksen, A. 1999. Gap closure; use of MAGIC model to predict time required to achieve steady-state following implementation of the Oslo protocol. Norsk institutt for vannforskning (NIVA) Report SNO 4012-99

101 Henriksen, A. 1999. Tålegrenser i fjellområder. Hva vet vi og hva bør vi vite? Rapport fra seminar 16.-17. Februar 1999. Rondablikk Føyfjellshotell. Norsk institutt for vannforskning (NIVA) Rapport LNR 4017-99

102 Wright, R.F. 1999. Risk of N leaching from forests to surface waters in Norway. Norsk institutt for vannforskning (NIVA) Report SNO 4038-99

103 Wright, R.F., Mulder, J. & Esser, J.M., 1999. Soils in mountain uplands regions of southwestern Norway: nitrogen leaching and critical loads. Norsk institutt for vannforskning (NIVA) Report SNO 4130-99

104 Lindstrøm, E.A., Kjellberg, G. & Wright, R.F. 1999. Tålegrensen for nitrogen som næringsstoff i norske fjellvann: økt "grønske"? Norsk institutt for vannforskning (NIVA) Rapport LNR 4187-2000

105 Thomsen, M.G. & Nellemann, Chr. 2000. Mortalitet og tilvekst i relasjon til forurensningsbelastningen i Sør Norge 1920-2000 (under trykking)

106 Henriksen, A & Buan, A.K. 2000. Tålegrenser og overskridelse av tålegrenser for overflatevann, skogsjord og vegetasjon i Norge. Norsk institutt for vannforskning (NIVA). Rapport LNR 4179-2000

107 Aarrestad, P.A. & Vandvik, V. 2000. Vegetasjonsendringer i vestnorsk kystlynghei - effekter av skjøtselsformene brann og sauebeite ved rehabilitering av gammel lynghei på Lurekalven i Hordaland. - NINA fagrapport 044.

108 Oredalen, J.T. & Aas, W. 2000. Vurdering av atmosfærisk fosforavsetning i sørøst-Norge. Norsk institutt for vannforskning Rapport LNR 4310-2000.

109 Bruteig, I., Thomsen, M.G. & Altin, D. 2001. Vekstrespons hos tre aerofyttiske algar på tilførsel av nitrogen. NINA oppdragsmelding 680. (*Rapporten er feilnummerert og har fått nummer 108)*

110 Sogn; T.A., Mulder, J., Haugen, L.E., Berge, G., Rustad, K.B. & Stuanes, A. 2001. N-omsetning i hei-/fjellområder: En første tilnærming til dynamiks modellering av N-omsetningen. Institutt for jord- og vannfag, Norges landbrukshøgskole. Rapport nr 11/2001.

111 Kroglund, F., Wright, R.F. & Burchart, C. 2001. Acidification and Atlantic salmon: critical limits for Norwegian rivers. Norwegian Institute for Water Research Report No O-20191

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