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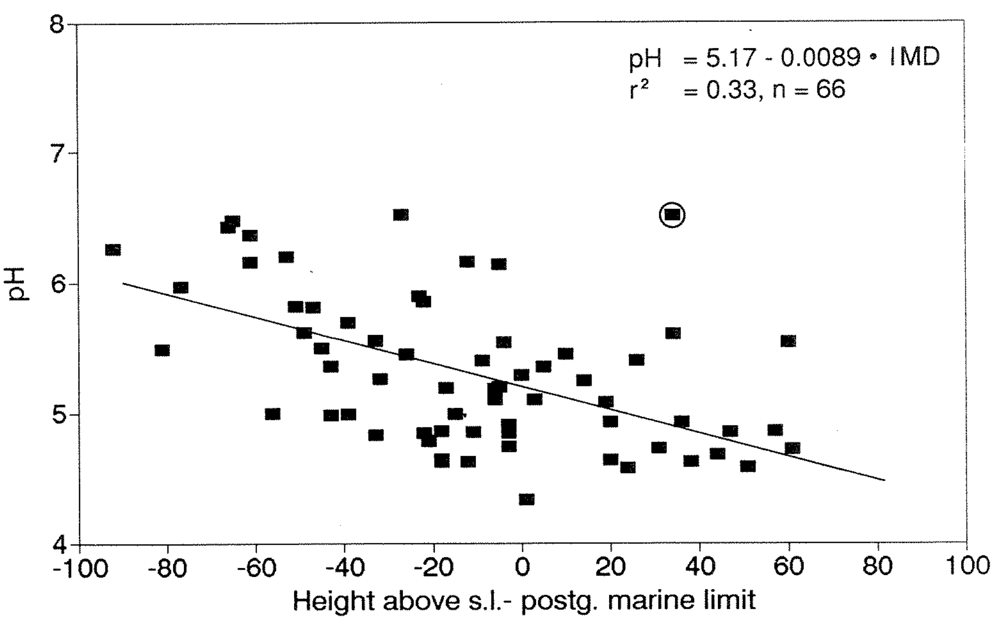
Acid Rain Research

REPORT 21/1990

Chemistry and fish status of 67 acidified lakes at the coast of Aust-Agder, Southern Norway, in relation to postglacial marine deposits.



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Abstract: 67 lakes in a 0-15 km wide coastal zone within Aust-Agder County in Southern Norway have been investigated. The area receives 1,5 g S/m^2 and 1,7 g N/m^2 as wet deposition. All lakes had about the same concentration of non-marine sulphate. Lakes in southwest were significantly less influenced by post-glacial marine deposits and markedly more acidified than lakes in the northeastern part of the region. Twentyone, probably 23, of the lakes were barren of fish. Lakes with pH higher than 5,5 in May had a broad spectrum of year classes. These fish populations represent a valuable resource in the region.

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E-88411

Chemistry and fish status of 67 acidified lakes at the coast of Aust-Agder, Southern Norway, in relation to post-glacial marine deposits.

Grimstad, May 1990
Atle Hindar

ABSTRACT

67 lakes in a 0-15 km wide coastal zone within Aust-Agder county in Southern Norway have been investigated. The lakes had no significant human activities in the catchment area. Acidity, acidification and fish status of the lakes are presented. The influence on the water quality, susceptibility of acidification and fish status by post-glacial marine deposits is evaluated.

The area receives 1.5 g S/m^2 and 1.7 g N/m^2 as wet deposition (mean for 1980-1988). Postglacial marine deposits dominate in the northeast. Few lakes with pH above 5.5 are found above the post-glacial marine limit in the region. 68 % of the investigated lakes had a pH below 5.5.

All lakes had about the same concentration of non-marine sulphate but the lakes in southwest were significantly less influenced by post-glacial marine deposits and markedly more acidified than lakes in the northeastern part of the region.

Information on fish status in the 67 lakes were gathered by interviewing of local fishermen and landowners and by test-fishing. The main fish species reported in the lakes was perch (<u>Perca fluviatilis</u>), followed by scattered populations of brown trout (<u>Salmo trutta</u>). Fish populations inhabit lakes with pH higher than 4.9 and labile aluminium lower than 100 μg Al/l measured in May. The likelihood of finding lakes with positive fish status increases when the lake is situated lower than 30 meters below the post-glacial marine limit.

Only lakes with pH higher than 5.5 in May had a broad spectrum of year classes. In these lakes the average number of year classes of perch was 10, while four lakes with pH below 5.5 still inhabiting perch, had an average number of year classes of 2.

INTRODUCTION

Acidification as an environmental problem is well documented (Likens et al. 1979, Overrein et al. 1980, Wright 1983). In spite of unchanged deposition of sulphate the last 15 yr (SFT 1989) the acidification problem is still rising in Norway (Sevaldrud et al. 1980, Sevaldrud and Skogheim 1986, Henriksen et al. 1988).

In Norway acidification damage to fish populations accelerated in the 1950's and 60's (Sevaldrud et al. 1980). Although the acidity of the precipitation decreased slightly in the 1980's (Henriksen et al. 1988) the effects of acidification continue and are worsening in the affected areas; new areas are acidifying, especially in western Norway. A 1986 resurvey showed a dramatic increase in the number of empty lakes since 1974 (Henriksen et al. 1988).

Smaller clearwater lakes at relatively high altitudes loose their fish populations before lowland lakes with slightly higher salt content (Sevaldrud et al. 1980). In Scandinavia these lakes are found in glaciated areas on granitic or other highly siliceous bedrock with overburden and soils derived from material of similar lithology (Wright 1983).

In southern Norway the most acidified lakes are found near the coast. In parts of Aust-Agder county postglacial marine deposits near the coast make this area less susceptible to acidification. The postglacial marine limit is only about 9 000 years old, but rises to about 100 meters above present sea level in the eastern parts of this county.

Many lakes in the coastal area are situated in regions partly covered by postglacial marine deposits. Those deposits of clays, silts and sands contain material more readily weathered than the thin and patchy ground moraine characteristic of higher-lying areas. Lakes below the marine limit are thus usually less sensitive to acidification. These lakes may have pH of 6.5-7.5

and intact fish populations (Wright and Snekvik 1978). Other lakes in the same region located above the marine limit exhibit a quite contrasting chemical quality with pH constantly being lower than 5.0.

Bacause of the moderate to high relief in this area, the catchments of the lakes on the marine deposits typically also include areas that are vulnerable to acidification. Therefor also the supposedly less sensitive coastal areas of Aust-Agder county might show signs of acidification and fish dieback.

The main reason for extinction of fish populations in acidic watercourses seems to be failure in recruitment (Jensen and Snekvik 1972, Rosseland et al. 1980, Harvey 1982), although kills on adult fish have also been reported (Leivestad and Muniz 1976, Skogheim et al. 1984, Hesthagen 1986 and Rosseland et al. 1980).

Inorganic aluminium species are thought to be the most significant factor causing fish mortality in dilute, acid lakes (Schofield 1977, Baker and Schofield 1980, 1982, Muniz and Leivestad 1980, Leivestad and Muniz 1980, Rosseland and Skogheim 1982, 1984). The hydroxides of aluminum are considered most toxic (Driscoll et al. 1980).

The concentration of calcium ameliorates Al toxicity. Calcium reduces the permability of the cell membranes to ions thus preventing ion loss and mortality (Muniz and Leivestad 1980, Brown 1983). The higher concentrations of sea salts present in the lakes along the coast may also reduce aluminium toxicity.

Here we report on lake acidity, acidification characteristics and fish populations in the coastal area of Aust-Agder county in relation to postglacial marine deposits.

MATERIALS AND METHODS

The investigated area

The 67 lakes of this investigation are situated in Aust-Agder county in southern Norway (Figure 1). They fall within a 0-15 km wide coastal zone from northeast to southwest. The Precambrian rocks of the area are part of the Fenno-Scandian Shield (Maijer and Padget 1987). The bedrock is mainly slowlyweathering gneiss and granitic within the Bamble Sector. Inner parts of the Grimstad region are dominated by quartzite. Amphibolites are common in the Risør region. Intrusions may also be found in the western parts. Thin and discontinous marbles are found in the Arendal area. Spots of calcitic bedrock within a watershed may have a significant impact on the total weathering rate and hence the resistence towards acidification stress (Sverdrup and Warfvinge 1988).

In upland areas the overburden is composed of the same material as the bedrock. The marine deposits are poorly developed in the southwestern parts, and alternates with barren rocks. Depressions in the bedrock have thicker deposits but not necessarily marine deposits of any significance even if they are situated below the postglacial marine limit.

Almost all areas of significant size underlain by marine deposits are utilized for agricultural activities. There are thus only a few lakes that are highly influenced by marine deposits but not by local human activities.

The postglacial marine limit falls sharply from about 100 meters above present sea level in the northeastern parts of Aust-Agder county to about 35 meters in the southwestern parts.

With respect to climatic conditions, the area can be regarded as relatively uniform, although precipitation is higher in the

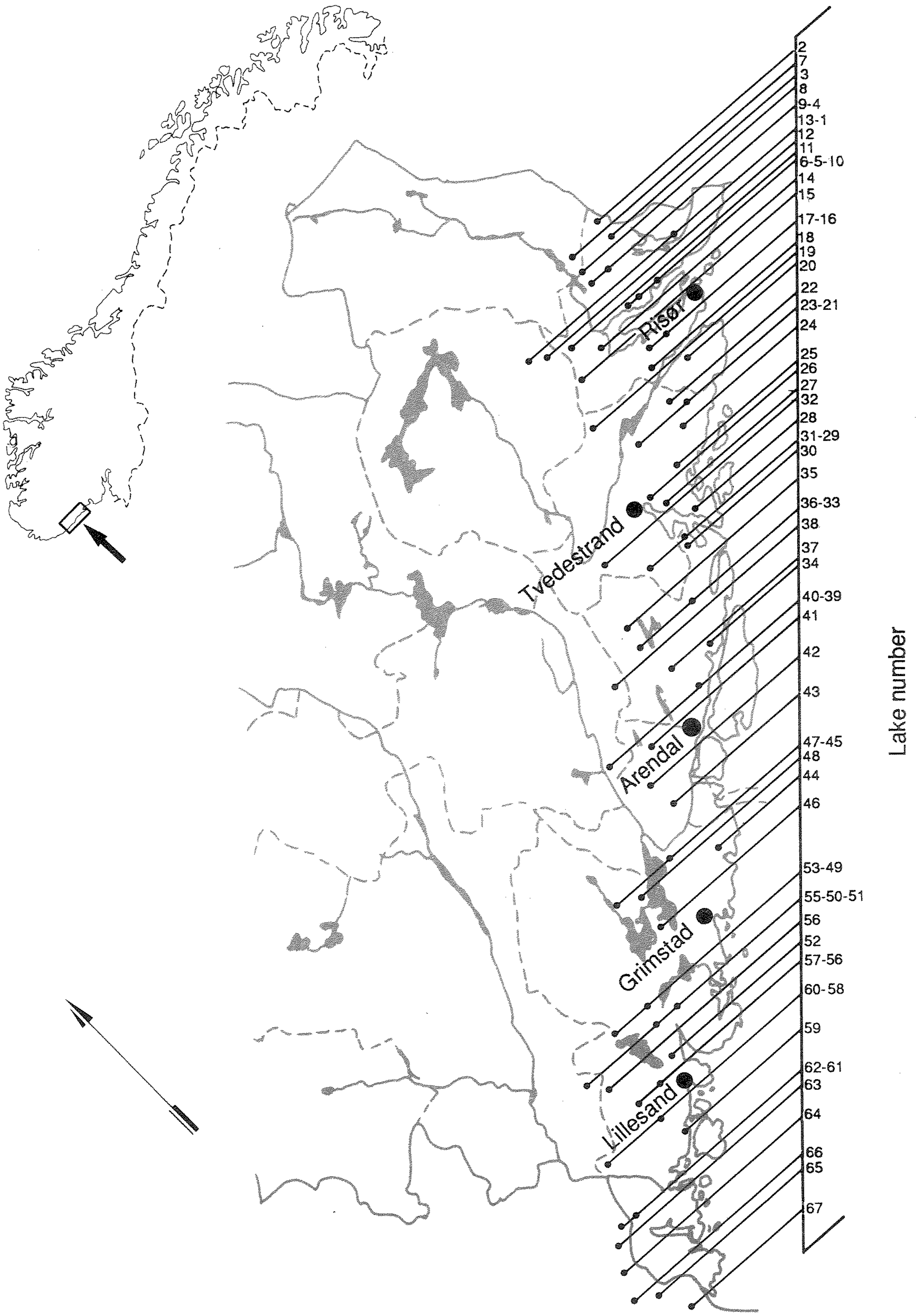


Figure 1. The situation of the investigated lakes along the coast of Aust-Agder county, Southern Norway. The lakes are referred to by lake number, going from 1 to 67 from northeast to southwest.

western regions and with increasing distance from the coast. Mean precipitation is about 1200 mm/year. The mean discharge rate is 20 l/km^2*s at the coastline in northeast, increasing to 25 l/km^2*s inland. In southwest these figures are 25 l/km^2*s and 30 l/km^2*s, respectively.

Human settlements are mainly restricted to five small cities (5000 - 15 000 inhabitants each) in the investigated area. The inland parts are sparsely populated. About 70 000 people live in the region.

Acid deposition in the area was 83 meq/m^2 strong acid (as H^+), 1.5 g S/m^2 and 1.7 g N/m^2 as a mean for wet deposition in the period 1980-1988 (SFT 1989). Mean volume weighted pH in precipitation was 4.26. The load of strong acids to the area has been nearly unchanged the last 15 yr (SFT 1989).

The lakes

The 67 lakes are all located within a 0-15 km wide zone along the coast of Aust-Agder county in Southern Norway (Figure 1). The lakes were selected from the 1:50 000 topographic maps according to the following criteria:

1. Size: Lake > 5 ha. Smaller lakes accepted if part of a lake system with short water retention time.

2. No significant human activity in the catchment area to ensure representative samples not influenced by local pollution sources.

3. Acceptable distance from road to avoid time consuming transport and risk of water-quality changes.

4. Reasonable distribution within the 0-15 km zone.

Samples from 69 lakes were collected. Two of the 69 lakes were dropped. One of them had an extreme water quality of the area with pH 7.5 and 22 mg Ca/l. The other had an unexplainable high salt content.

Lake distribution according to altitude is shown in Figure 2. Only 8 lakes are situated higher than 90 meters above present sea level.

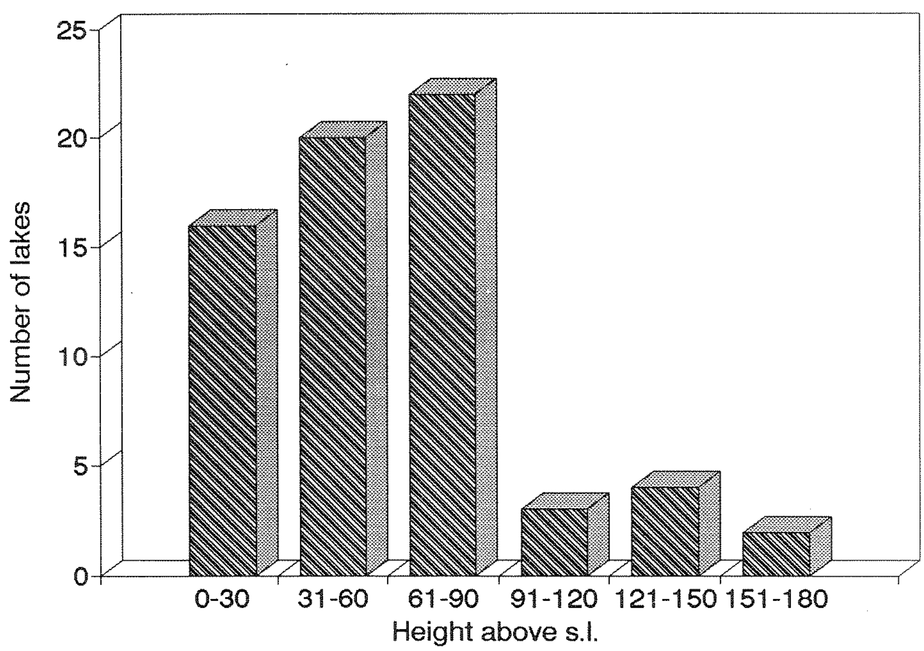


Figure 2. Number of lakes in groups according to height above present sea level.

The difference between lake altitude and the postglacial marine limit is used as a parameter to indicate the influence of marine deposits, abbreviated here to IMD-hight. The distribution of the lakes in relation to this parameter is shown in Figure 3. A normal distribution of the lakes was attained with 25 lakes (40

%) in the IMD-hight range -1 to -30 meters. This means that 25 lakes are situated 1 - 30 meters below the postglacial marine limit. Most of the lakes are situated below the postglacial marine limit.

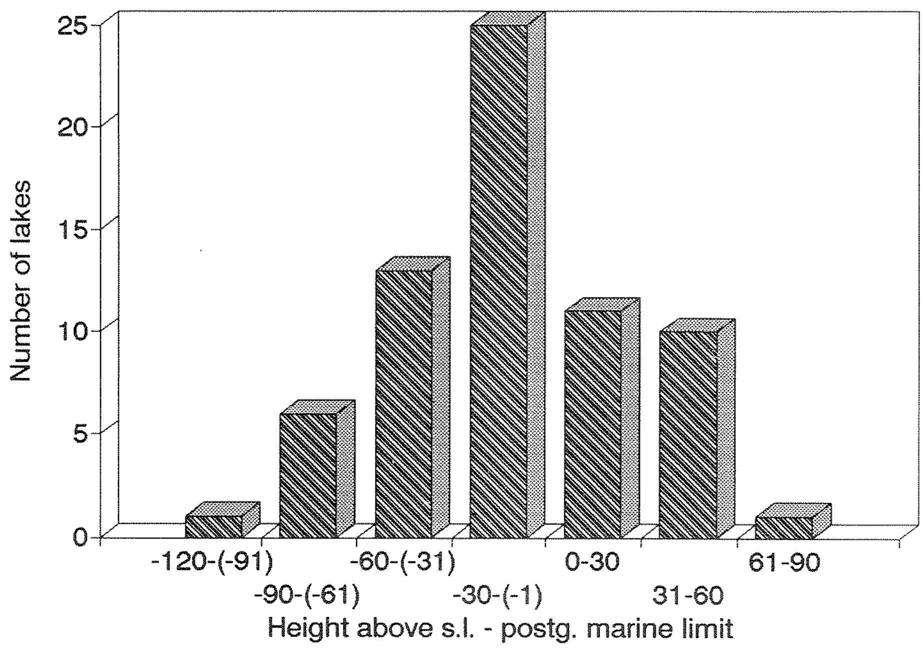


Figure 3. Number of lakes in groups according to IMD-height. IMD-height is the difference between lake height above present sea level and the post-glacial marine limit.

<u>Water sampling</u>

The lakes were sampled once at the outlet on 12-13 May 1984, about two weeks after ice-out. At this time both snowmelt and spring overturn were completed in the whole area. The water quality should be similar throughout the water body and reflect the ability of the catchment and the lake itself to withstand acidification stress. At this time of the year internal biological processes in these lakes have no important influence of pH, alkalinity, aluminium species distribution or other acidification-related parameters.

Chemical analyses

pH was measured with Radiometer PHM 82 Standard pH Meter. Stirring was avoided when pH was read (Hindar 1984). Alkalinity was measured by potentiomethric titration with HCl to pH 4.5. Alkalinity is corrected to ALK-E (equivalence alkalinity) according to Henriksen (1982) and given to the nearest 0.005 meq/l. Conductance was measured with a Phillips PW 9501 Conductivity meter. Lake colour was measured on unfiltered samples to the nearest 5 mg Pt/l with a Hellige comparator. These analyses were carried out at room temperature the same day the water was sampled.

Dissolved organic matter was measured as UV-absorbance at 254 nm with a LKB 8300 UVICORD detector. Samples were stored at 4°C until analyses. Reactive aluminium, RAl, was measured according to Dougan and Wilson (1974). Water samples were frozen in 10 ml polypropylene tubes. Reagents were mixed with water samples directly in the tubes, see Wright and Skogheim (1983). Non-labile aluminium, NLAl, was measured as RAl after passage through a cation-exhange column (DOWEX-50, X8, 50/100 mesh saturated with Na^+). Separation and preparation of samples were carried out the same day as sampling and then frozen. Labile aluminium, LAl, is the difference between RAl and NLAl. Ca, Mg, Na and K were measured by atomic absorption spectrophotometry (Perkin Elmer Mod. 603). $LaNO_3$ - solution was added the same day as sampling. Samples were stored at 4°C until analysis. Sulphate and chloride were analysed by flow-injection-analysis after ion-exhange and conductometry (modified after Stainton 1974).

Fish sampling

Information on fish status was gathered by interviewing of local fishermen and landowners.

Test-fishing was conducted in 12 of the 67 lakes in the period 24 September to 17 October 1985 with multi mesh nets consisting of 8 mesh sizes (10-45 mm) in sections. The multi mesh nets are 1.5x32 m. In addition to the 12 lakes lake 8 was test-fished on 10 August 1980 (Kleiven et al. 1990) and 29 September 1989 (Vikse and Kleiven unpubl.). In lake 46 an another test-fishing was conducted on 14 October 1989 (Kleiven unpubl.). The species caught are listed in Table 3.

Lakes with different combinations of pH and dissolved organic matter inhabiting fish stocks were choosen for test-fishing. The pH range of the lakes was 4.98-6.54. The lakes had UV-absorbance in the range 0.047-0.197 which corresponds to a colour of 20-60 mg Pt/l.

Fish analysis

Natural tip length was recorded to the nearest mm and fish weight to the nearest 2 g. Sex was recorded and fish age was determined from opercular bones (LeCren 1947) and otoliths on perch (otolith samples of fish >15 cm) and scales and otoliths on brown trout. Left opercular bone of perch was removed, boiled and cleaned. Scales of brown trout were laid between object glasses and investigated on a microfiche reader. Otoliths of both species were burned and broken before reading. Both opercular bones and otoliths were examined in etanol as refraction medium under a WILD M5A stereomicroscope with selecting magnification.

RESULTS AND DISCUSSION

Chemical characteristics

Fully 32 of the investigated lakes (48 %) fall in the pH-range of 4.2-5.1 (Figure 4). 45 lakes (67 %) had pH lower than 5.5 at the time of sampling. Wright and Snekvik (1978) reported that 85 % of about 700 lakes in southernmost Norway had a pH below 5.5. Although the acid loading in the investigated area is high compared with areas of more extensive regional surveys, the pH of the lakes was somewhat higher. This reflects the higher ability of the coastal zone to withstand acidification. The pH-values indicate, however, that also lakes in the coastal zone are under considerable acid stress.

Thirty lakes had negative alkalinity, and only one lake had alkalinity above 0.100 meq/l (Table 1). The alkalinity values are very low and the lakes have little acid-neutralizing capacity to resist further input of strong acid.

According to a traditional classification of lake acidification (Henriksen 1980) most of the lakes were transition lakes, being susceptible to further acidification.

A pattern of declining pH going from northeast to southwest was found with the most acid lakes situated in the Grimstad-Lillesand area. This indicates that the influence of post-glacial marine deposits is reduced in this area. Even lakes situated close to the sea and at relatively low altitudes were very acid. Effects of local areas with better buffering geology give rise to higher pH values in some lakes.

The effect of altitude versus post-glacial marine limit, represented by IMD-height, on pH is clearly seen in Figure 5. The regression line is:

$$pH = 5.17 - 0.0089 * \text{IMD-height},\ r^2 = 0.33,\ n = 66$$

Table 1. Chemical characteristics of the investigated lakes.

Nr	pH	Alk-E ueq/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	RAl ug/l	NlAl ug/l	SO4 mg/l	Cl mg/l	Cond mS/m	UV-abs units	Colour mg Pt/l
1	5.49	10	2.08	1.03	4.08	0.64	146	103	9.3	6.8	3.7	0.075	25
2	5.45	15	1.80	0.95	2.77	0.68	181	150	7.7	4.8	3.1	0.145	45
3	4.86	0	1.35	0.80	2.63	0.52	197	142	7.1	4.6	3.0	0.145	40
4	5.97	30	1.87	1.10	4.63	0.58	60	58	7.9	7.9	3.8	0.047	20
5	5.81	25	2.42	1.09	3.22	0.46	140	148	8.8	5.6	3.4	0.193	45
6	6.26	40	2.76	1.64	9.68	0.84	93	93	10.0	16.1	6.7	0.112	30
7	5.20	5	2.08	0.76	2.50	0.27	131	108	8.2	4.2	2.9	0.124	35
8	5.40	10	2.00	0.70	2.26	0.42	91	62	8.2	3.7	2.8	0.067	25
9	4.58	0	1.11	0.52	2.33	0.25	216	184	6.0	4.4	2.9	0.264	75
10	5.25	10	2.02	0.93	4.10	0.62	170	142	8.2	7.0	3.7	0.145	40
11	5.40	10	1.71	0.61	1.97	0.37	165	135	6.7	3.8	2.5	0.133	35
12	4.86	0	1.21	0.67	1.84	0.31	164	90	6.5	3.5	2.5	0.095	30
13	5.54	15	1.99	0.65	2.08	0.42	186	167	6.7	3.7	2.5	0.188	45
14	4.98	0	1.30	0.69	2.64	0.40	126	28	7.2	4.5	2.9	0.019	20
15	4.85	0	1.16	0.56	2.19	0.38	253	140	6.0	4.0	2.6	0.100	30
16	4.84	0	1.14	0.80	4.62	0.32	288	123	6.8	7.9	2.6	0.063	35
17	5.89	25	1.81	0.95	4.43	0.46	164	121	6.4	7.4	3.6	0.051	30
18	6.16	45	2.49	1.44	4.66	0.40	49	58	9.7	7.2	4.1	0.100	30
19	4.71	0	1.02	0.51	2.30	0.34	272	137	6.1	4.1	2.7	0.100	35
20	4.78	0	1.82	1.12	5.20	0.49	409	278	8.6	9.5	4.4	0.251	65
21	5.69	20	2.52	1.04	5.02	0.72	159	162	8.2	8.3	4.3	0.104	30
22	4.83	0	1.34	0.94	4.35	0.44	225	78	8.1	7.4	3.9	0.055	20
23	5.19	5	1.72	0.90	3.44	0.57	205	140	7.8	5.7	3.3	0.104	35
24	5.62	20	2.77	1.21	5.57	0.64	219	186	9.0	9.8	4.3	0.141	40
25	5.00	0	1.48	0.97	4.03	0.67	261	159	7.9	6.9	3.6	0.121	30
26	4.99	0	1.68	1.09	4.08	0.72	208	101	10.1	6.0	3.9	0.067	25
27	6.20	40	1.91	1.44	4.27	0.67	78	69	8.2	7.0	3.9	0.075	25
28	6.37	105	3.37	1.45	6.41	2.17	13	21	8.2	10.4	5.1	0.071	25
29	5.26	5	1.98	0.96	4.60	0.56	234	167	8.4	7.6	4.0	0.124	35
30	5.82	25	2.97	1.17	5.12	0.94	129	104	8.4	7.9	4.1	0.100	30
31	5.50	15	2.27	0.91	3.93	0.88	259	209	8.0	6.6	3.6	0.083	40
32	6.13	45	2.66	0.87	2.86	0.41	90	90	8.2	4.5	3.1	0.095	30
33	6.43	80	3.38	1.30	5.60	0.84	93	86	9.5	9.6	4.7	0.100	30
34	6.48	80	3.18	1.23	6.70	0.91	101	112	10.7	11.2	5.1	0.154	35
35	5.54	15	2.06	0.77	2.74	0.45	143	131	6.4	4.1	3.0	0.100	35
36	5.29	5	1.96	0.75	3.03	0.42	142	118	7.0	5.2	3.1	0.150	50
37	6.16	25	2.59	0.94	4.14	1.91	178	176	7.8	6.6	3.6	0.184	60
38	5.45	20	2.32	0.88	2.90	0.57	187	168	7.8	5.0	3.2	0.237	60
39	5.55	25	2.86	1.35	4.80	0.55	170	153	8.6	9.0	4.6	0.197	40
40	5.18	5	1.63	0.86	3.28	0.55	78	30	7.8	5.2	3.3	0.027	20
41	4.62	0	1.93	0.97	3.96	0.54	200	142	5.7	7.4	4.3	0.124	45
42	5.35	10	2.41	0.97	4.20	0.58	187	140	0.0	0.0	3.9	0.167	40
43	4.99	0	2.32	0.99	4.28	0.61	184	145	8.7	7.2	4.1	0.197	50
44	4.62	0	1.67	1.15	7.16	0.47	457	148	8.4	12.6	5.2	0.167	45
45	4.85	0	1.52	0.84	4.65	0.45	209	110	7.6	7.7	3.8	0.108	25
46	5.13	20	2.43	1.12	5.78	1.41	256	168	9.1	10.1	4.6	0.158	45
47	4.57	0	1.06	0.53	3.03	0.40	447	62	7.4	5.3	3.3	0.043	20
48	4.64	0	1.26	0.53	3.15	0.43	466	97	7.3	5.5	3.3	0.075	30
49	4.62	0	1.18	0.73	3.90	0.48	438	112	7.8	6.8	3.8	0.087	30
50	5.08	0	1.60	1.01	5.53	1.47	269	137	8.6	10.1	4.9	0.079	25
51	5.36	15	2.14	1.08	6.24	0.68	291	192	8.3	10.4	4.4	0.112	35
52	4.74	0	1.37	0.63	4.07	0.67	381	69	6.1	7.1	3.9	0.039	20
53	4.63	0	1.21	0.49	3.50	0.46	447	104	6.0	5.8	3.5	0.059	30
54	4.33	0	0.70	0.66	4.35	0.59	466	95	8.2	7.4	4.7	0.059	25
55	5.60	20	1.65	0.70	3.98	0.80	114	41	6.3	6.7	3.4	0.035	20
56	5.10	5	1.31	0.63	4.00	0.59	391	97	6.6	7.5	3.6	0.039	20
57	4.67	0	1.06	0.77	4.70	0.55	400	43	7.3	8.3	4.0	0.039	20
58	4.79	0	2.39	1.39	7.08	1.35	560	95	14.3	11.2	5.9	0.043	30
59	4.84	0	1.61	1.46	8.09	0.70	263	73	9.1	14.0	5.9	0.047	20
60	4.92	0	1.51	0.86	5.20	0.91	281	69	7.3	8.5	4.1	0.047	20
61	4.72	0	0.83	0.84	4.70	0.85	270	65	6.9	9.1	4.3	0.051	20
62	4.91	0	1.40	0.80	4.45	0.46	297	41	7.5	7.7	3.7	0.027	20
63	4.92	0	1.74	1.07	6.25	0.64	259	39	8.1	11.6	4.7	0.031	20
64	6.51	70	4.40	1.55	10.20	2.68	132	140	12.0	17.6	7.4	0.154	50
65	5.10	0	1.87	1.52	8.57	0.66	195	39	9.5	15.2	5.9	0.035	20
66	6.52	95	5.12	1.86	7.94	1.43	112	104	15.9	12.7	6.9	0.067	20
67	5.85	20	3.68	1.95	10.70	0.85	179	119	10.8	21.6	7.8	0.051	20

The probability of finding lakes with pH below 5.0 is greatly reduced in lakes situated more than 30 meters lower than the post-glacial marine limit. Correspondingly, the only few lakes with pH above 5.5 are found above the post-glacial marine limit.

Postglacial marine deposits reduce lake acidity, but only for lakes well below the limit. This finding corresponds well with the characteristic high relief in the area and the fact that many of the lakes below the postglacial marine limit receive acid input from watersheds partly above the limit.

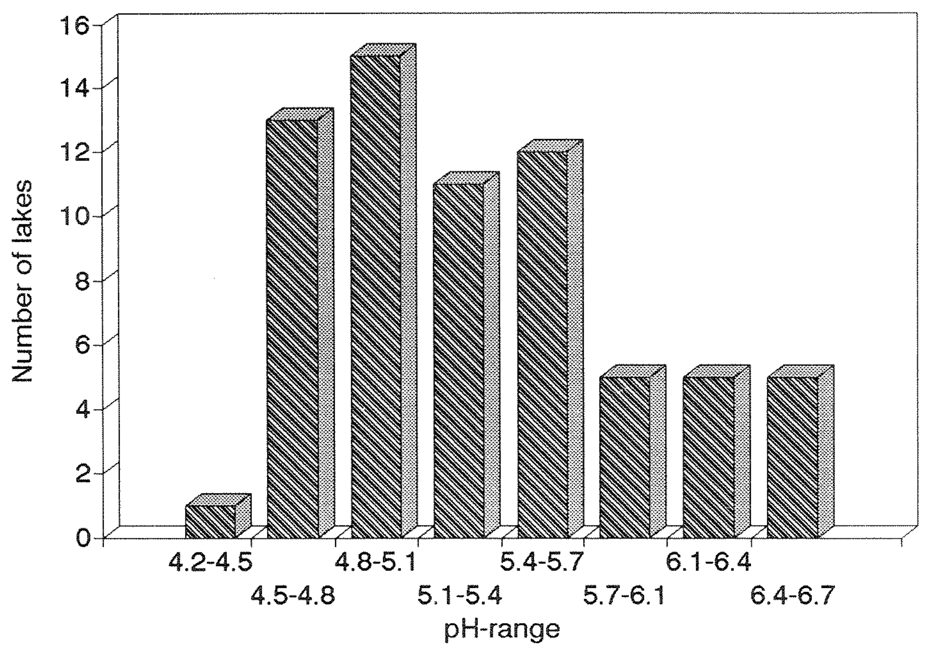


Figure 4. Number of lakes in groups according to pH-range.

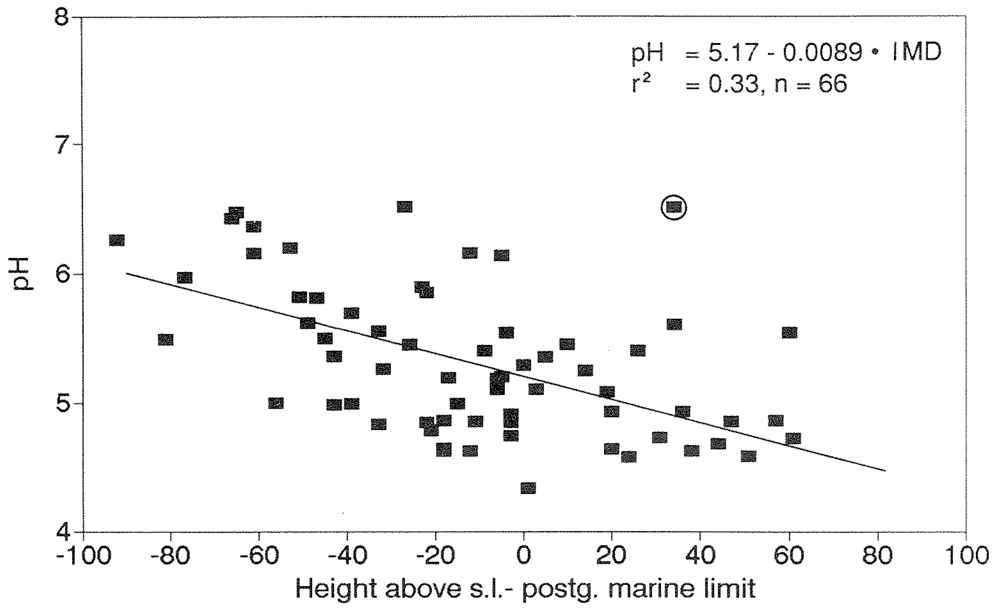


Figure 5. pH versus IMD-height of the investigated lakes. IMD-height is the difference between lake-height above present sea level and the post-glacial marine limit. (■) not included in regression.

The concentration of chloride in the lakes was higher in the southwestern parts of the region (Figure 6 a). Higher precipitation and probably different topography may explain such a gradient. The total sulphate concentration, however, was relatively constant throughout the coastal zone (Figure 6 b).

Most of the lakes in this survey are clearwater lakes, with UV-absorbance less than 0.12 (67 %) and colour less than 40 mg Pt/l (69 %). Only 7 lakes had colour of > 50 mg Pt/l. UV-values were 0.15-0.26 in these lakes. No significant correlation was found between pH and Pt-colour or UV-absorbance.

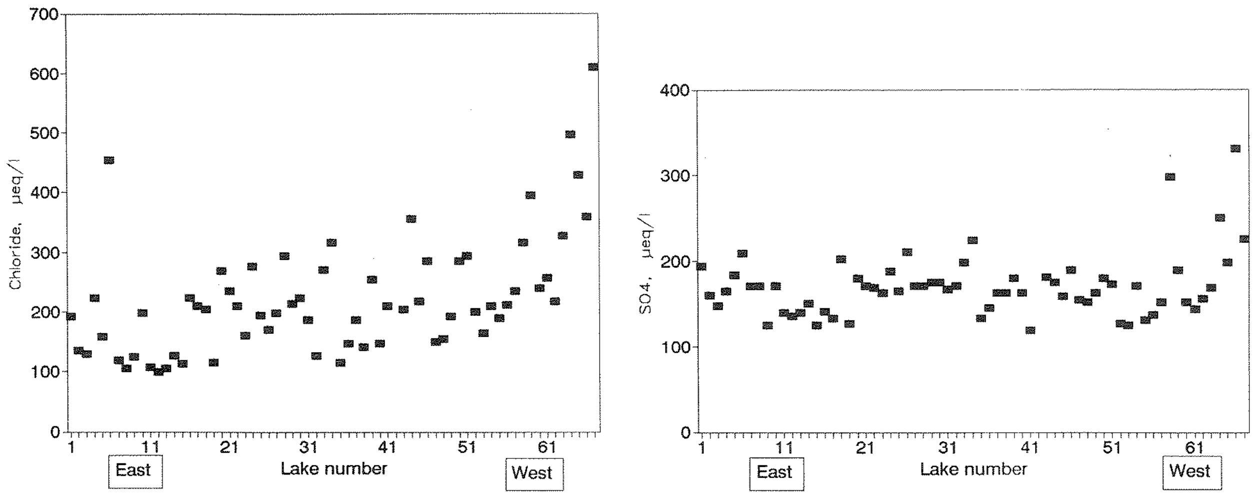


Figure 6. Concentration of chloride (a) and total SO_4 (b) versus lake number of the investigated lakes.

Aluminium concentrations were high in most of the lakes. Going from northeast to southwest reactive aluminium increased from about 100-200 μg Al/l to as high as 400-500 μg Al/l in several lakes (Figure 7).

Whereas non-labile aluminium varied independently of the east-west gradient, concentrations of labile aluminium were low in many lakes in the northeastern and central part of the coastal zone (Figure 7). In the southwestern parts, however, the level increased rapidly, reaching 300-400 μg Al/l. Al^{3+} is strongly pH dependent whereas non-labile aluminium is not, (Figure 8) as observed by Driscoll (1980).

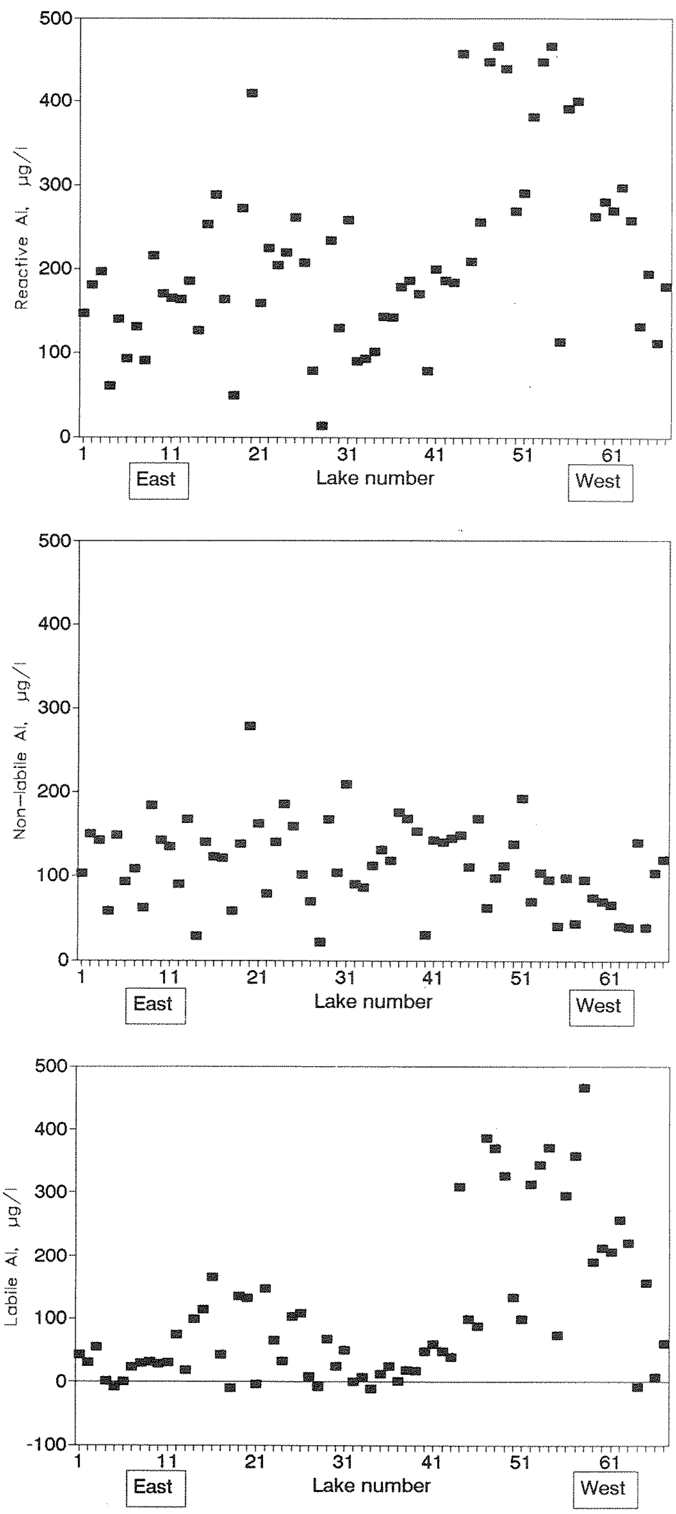


Figure 7. Concentration of reactive (RAl), non-labile (NLAl) and labile (LAl) aluminium versus lake number of the investigated lakes.

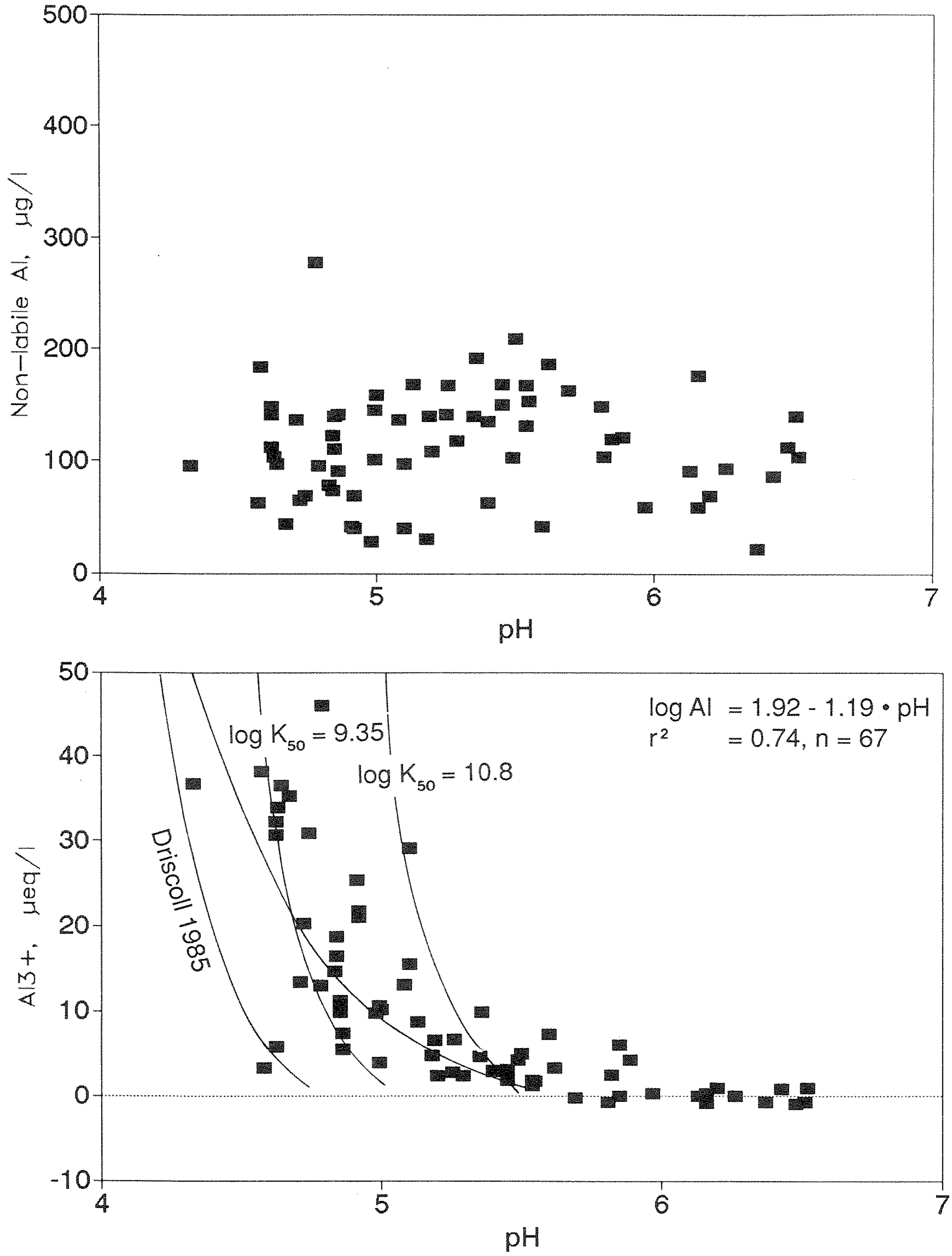


Figure 8. Concentration of non-labile aluminium (NLAl) and Al^{3+} versus pH of the investigated lakes. Also shown are equilibrium lines for log K_{so}= 9.3 (Hem and Roberson 1967) and 10.8 (Stumm and Morgan 1970), see text. An equilibrium line:
log $[Al^{3+}]$ = 6.22-2.55*pH, r^2=0.93, p<0.0001 for Adirondack surface waters (Driscoll 1985) is also shown.

The regression line of the Al^{3+} - pH relationship is:

$$\log [Al^{3+}] = 1.92 - 1.19*pH, \ r^2 = 0.74, \ n = 67$$

The low slope of the regression line inidates that more than one solid phase of aluminium is present in the area. Equilibrium lines of the form:

$$\log [Al^{3+}] = \log K_{so} - 3*pH$$

with $\log K_{so} = 9.35$ (Hem and Roberts 1967) and 10.8 (Stumm and Morgan 1970) are also shown if Figure 8. Aluminium data at low pH fit well with the equilibrium line for microcrystalline gibbsite ($\log K_{so} = 9.35$), whereas data at higher pH fit better with the equilibrium line for amorphous aluminium trihydroxide ($\log K_{so} = 10.8$). A mineral phase may be important in controlling Al chemistry at low pH, whereas organic/amorphous phases may be important at higher pH. A dynamic system with alternating dissolution and precipitation of Al-species with changing pH and CO_2 partial pressure (Norton and Henriksen 1983) in the watershed may be expected in many of these transition lakes.

Al^{3+} seems to be more readily available in lakes in this area than in Adirondack surface waters (Driscoll 1985) of similar pH (Figure 8). Regional differences of Al availability are also observed by Wright et al. (1988).

Non-labile aluminium (NLAl) is strongly dependent on the concentration of dissolved organic matter (Figure 9) as found by Driscoll (1980) and Johnson et al. (1981). The concentration of NLAl increased from about 50 μg Al/l in lakes with UV-absorbance of less than 0.05 units to 150 μg Al/l in lakes with UV-absorbance above 0.10-0.12 units.

Labile aluminium was < 100 μg Al/l in lakes with UV-absorbance > 0.10 units. An exception was lake 44, with LAl of 309 μg Al/l, UV-absorbance of 0.167 units, pH 4.62 and RAl as high as 457 μg Al/l.

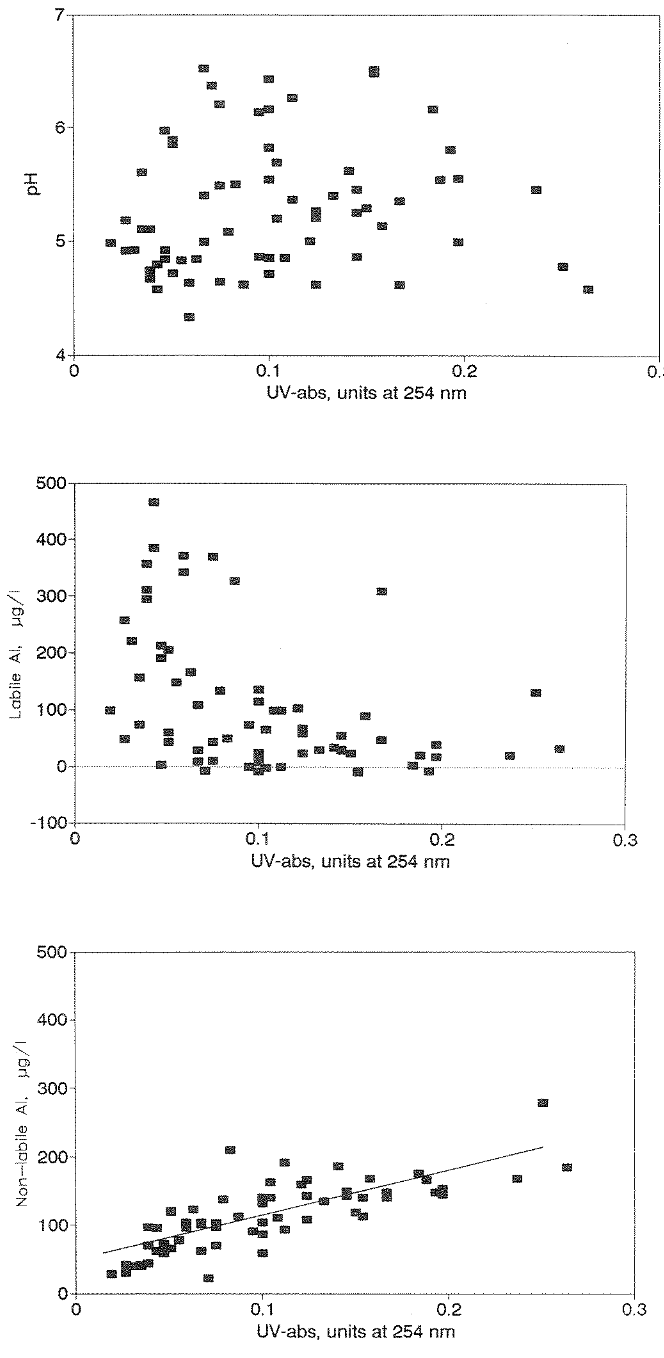


Figure 9. pH (a), labile (b) and non-labile (c) aluminium versus UV-absorbance (254 nm) of the investigated lakes. Regression line is: [NLAl] = 46 + 664*UV, $r^2 = 0.60$, n = 67

The concentration of inorganic and organic aluminium is obviously regulated both by pH and dissolved organic matter. This is in accordance with Driscoll et al. (1980).

Because dissolved organic matter complexes Al, humic acid water may be less toxic to fish. Intact fish populations are found in very acid, but humic lakes in parts of the acidified areas.

The lakes in the coastal zone of Aust-Agder had a higher salt-content than lakes in inland areas. 67 % of the lakes had conductivity of 3-5 mS/m, whereas typical values for lakes in the

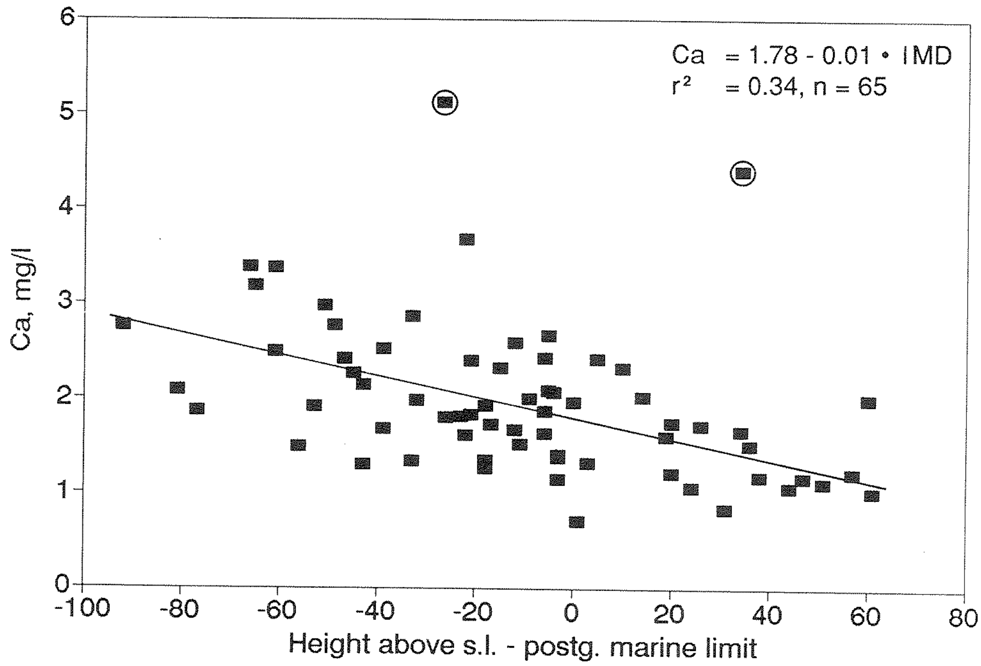


Figure 10. Concentration of total calcium versus IMD-height of the investigated lakes. IMD-height is the difference between height above present sea level and the post-glacial marine limit. ◉ not included in regression.

inland areas are about 2. The calcium level was also higher than in inland lakes. Of 684 lakes sampled in 1974-1975, both coastal and inland lakes, 24 % had Ca less than 1 mg Ca/l (Wright and Snekvik 1978). In this investigation only two lakes (3 %) had Ca less than 1 mg/l. The highest calcium-levels are found in lakes located below the post-glacial marine limit (Figure 10). The regression line is:

$$[Ca] = 1.78 - 0.0105 * \text{IMD-height}, \quad r^2 = 0.34, \quad n = 65$$

Two lakes are not included in the regression. Non-marine Ca is 5-15 % lower than total Ca.

Acidification characteristics

According to the acidification model of Henriksen (1979, 1980) lakes with high Ca concentrations have higher buffering capacities than lakes with lower concentrations. The model assumes that calsium and magnesium were originally balanced by bicarbonate.

The results of this lake survey indicate that even lakes situated lower than the postglacial marine limit are acidified (i.e. have lost some of their original bicarbonate, Figure 11). The majority of the lakes is found well below the curved line in the figure. This line separates acidified from non-acidified lakes (Henriksen 1979).

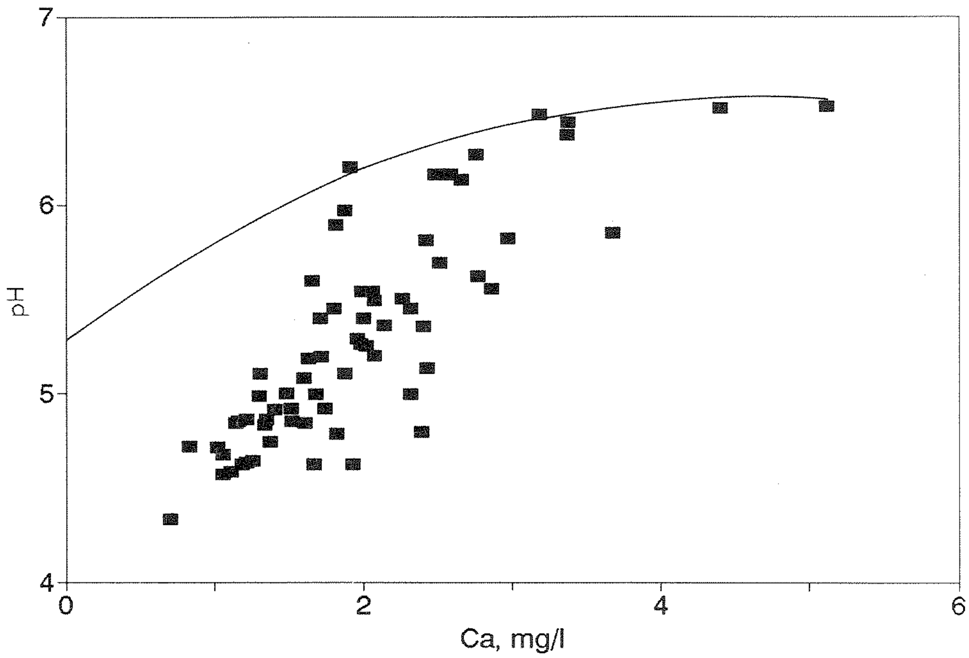


Figure 11. pH versus calcium of the investigated lakes. The empirical line of Henriksen (1979) separates acidified (below) from non-acidified lakes.

The nomograph presented by Henriksen (1980) to predict pH in lakes given non-marine Ca, non-marine Ca + Mg, non-marine SO_4 or pH in precipitation is presented for the 67 lakes in Figure 12. According to the nomograph, most of the lakes are transition lakes.

As indicated in Figure 12 the pH of precipitation should be 4.1-4.3 according to Henriksen (1980). A mean pH of 4.2-4.3 is indeed what is found in the area (SFT 1989).

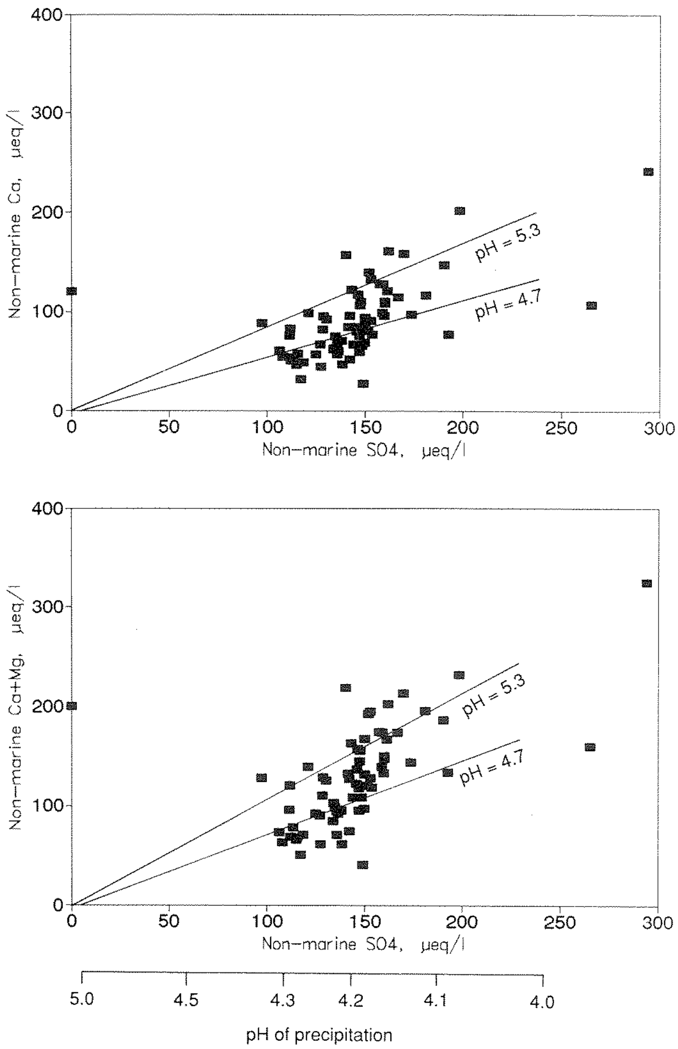
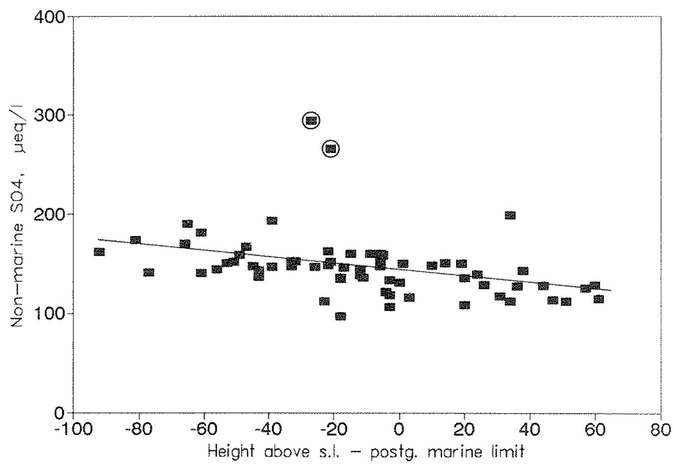


Figure 12. Nomograph of non-marine calcium (a) and the sum of non-marine calcium and magnesium (b) versus non-marine sulphate of the investigated lakes. Empirical values of precipitation from Henriksen (1980) are shown. The lines in the nomographs are the empirical lines of Henriksen (1980), separating lakes with pH above 5.3 (upper line) and below 4.7 (lower line).

Non-marine sulphate (SO_4*) varied very little with IMD-height (lake altitude in relation to the post-glacial marine limit) in contrast to the sum of Ca* and Mg* (Figure 13). The regression lines are:

$$[SO_4^*] = 140 - 0.29 * \text{IMD-height},\ r^2 = 0.26,\ n = 64$$
$$[Ca^*+Mg^*] = 115 - 0.75 * \text{IMD-height},\ r^2 = 0.38,\ n = 65$$



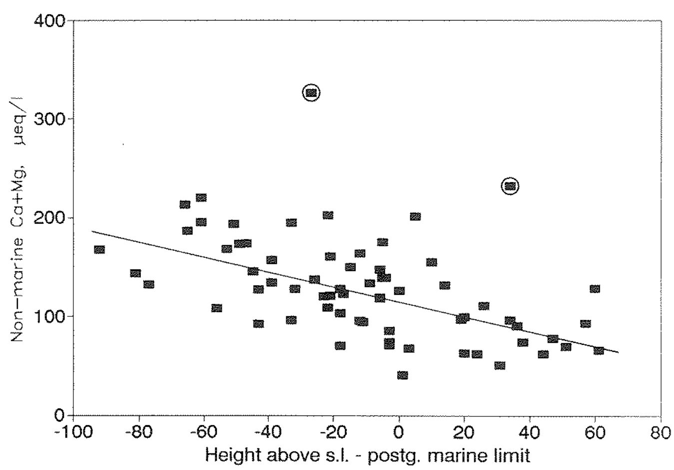


Figure 13. Concentration of non-marine sulphate (a) and the sum of non-marine calcium and magnesium (b) versus IMD-height of the investigated lakes. IMD-height is the difference between height above present sea level and the post-glacial marine limit. The concentrations are in µeq/l. (■) not included in regressions.

The concentration of Ca* and Mg* was significantly higher in lakes well below the post-glacial marine limit than in lakes above this limit. Influence of post-glacial marine sediments is obvious. This influence is not important for SO_4^* because the contribution of sulphate from acid deposition dominates.

When corrected for sea-spray SO_4 and the natural background concentration of sulphate of 0.012-0.020 meq/l for lakes in southern Norway (Henriksen 1979), acidification-SO_4* is 0.10-0.15 meq/l in lakes in the coastal zone of Aust-Agder, almost ten times the background level.

The high concentration of non-marine sulphate indicates that a considerable reduction in acid deposition must occur to give any significant improvement of the water quality in many of the investigated lakes. The higher Ca* + Mg* - concentrations in lakes below the post-glacial marine limit reflect, however, the possible advantage of this area to respond early on a reduction in acid deposition.

Fish status

The results of the interviews and test-fishing indicate that 21 of the 67 lakes in the survey are barren of fish and an addition of 2 lakes were probably barren (Tables 2 and 3). One or more species were present in the rest of the lakes.

The fish species in the lakes are brown trout (Salmo trutta), Arctic char (Salvelinus alpinus), perch (Perca fluviatilis), tench (Tinca tinca), pike (Esox lucius). One lake earlier had cisco (Coregonus albula). The most common species was perch. The brown trout population was very sparse in many lakes due to restricted recruitment areas.

Table 2. Fishing effort in the test-fished lakes and catches of perch and brown trout. Catch/effort is the number of fish/multi mesh nets/night. The lakes are ranked by pH.

Lake no.	pH in May 1984	Date of fish sampling	Number of perch/ trout		Number of nets	Catch/effort perch	Catch/effort trout
14	4.98	5.10	0	31	7	0.0	4.4
43	4.99	11.10.	25	0	4	6.3	
46	5.13	24./25.09.	74	0	4+3	10.8	
36	5.29	9./10.10.	14	3	3+3	2.3	
42	5.35	16.10.	24	17	7	3.4	2.4
38	5.45	17.10	0	11	6	0.0	1.8
13	5.54	26.09.	242	2	5	48.4	0.4
35	5.54	27.09.	94	15	4	23.5	3.8
4	5.97	19.09.	113	0	5	22.6	
37	6.16	2./3.10.	31	0	3+5	(3.9)	
27	6.20	8.10.	119	6	5	23.8	1.2
34	6.48	14.10.	157	0	4	39.3	

Perch was captured in 10 of the test-fished lakes and the catches consist of 893 perch. 85 brown trout were caught in seven lakes, 10 tench in two lakes and two char in one lake. In lake 8 (not shown in Table 2) 75 perch and 10 char were caught in August 1980.

Eel (Anguilla anguilla) occurs in many lakes, but is not included in Table 3. In addition brook trout (Salvelinus fontinalis) was reported in 5 lakes. Usually brook trout does not establish permanent populations in Norwegian lakes.

Except two lakes (lake 50 and 56) the reported barren lakes had pH < 5.0. According to the test-fishing results some of the lakes with pH < 5.5 might soon become barren. In lakes with pH > 5.5 no fish populations were lost (Table 3), which certainly reflected the true situation in these lakes.

All barren lakes had pH ≤ 5.1. With two exceptions (lake 12 and 41), all these lakes had labile aluminium higher than 100 µg Al/l.

The barren lake 58 had a calcium concentration of 2.39 mg/l, conductivity of 5.9 mS/m, pH of 4.79 and the highest recorded aluminium of the survey (465 µg Al/l as labile Al). This lake is a clearwater lake with UV-absordance of 0.043. The lake is situated 22 meters below the postglacial marine limit. The water quality is obviously toxic to fish in spite of high calcium and conductivity.

All lakes with remaining fish population had pH higher than 4.85. With one exception (lake 63), all these lakes had labile aluminium lower than 100 µg Al/l.

No or very sparse fish populations were reported in the south-western part of the coastal zone (Table 3). This is in good agreement with the water chemistry data; low pH, elevated labile aluminium concentrations and low UV-absorbance.

Aluminium is a significant factor in the understanding of fish extinction in acid lakes (Baker and Schofield 1980). The different mortality of fish in clearwaters versus humic waters with elevated aluminium concentrations, has been clearly demonstrated by Hulsman et al. (1983) on alevins of rainbow trout (Salmo gairdneri). 100% of the alevins died in a clearwater creek at pH 5.4, whereas only 1% died in a humic creek at pH 5.5. The total aluminium concentration was 137 and 167 µg Al/l, respectively.

Ca-concentration and conductivity is relatively high in lakes in the coastal zone. This may mask some of the toxicity of aluminium (Muniz og Leivestad 1980, Brown 1983) and make the water quality more favourable for fish than in inland lakes with similar pH-levels. This may be why we found fish populations in lakes with relatively low pH and labile aluminium as high as 100 µg Al/l.

Table 3. Fish status of 67 lakes in the coastal zone of Aust-Agder county in 1984-1985 based on interviews. 12 of the lakes have been test-fished. pH and lake situation in relation to the postglacial marine limit (IMD-height) are given. Species number refer to: 5 = brown trout, 6 = char, 9 = cisco, 20 = perch, 35 = tench and 37 = pike. Numbers in brackets indicate pre-acidification fish species of the lakes.

Lake	pH	IMD-height	Species by: interview	test-fishing
1	5.49	-81	5, 6, 20	
2	5.45	-26	5, 20	
3	4.86	-18	5, 20	
4	5.97	-77	5, 6, 20	6, 20
5	5.81	-47	5	
6	6.26	-92	5, 6, 20	
7	5.20	- 5	5, 6, 20	
8	5.40	- 9	5, 6, 20	6, 20 (1980) 5, 6, 20 (1989)
9	4.58	51	barren? (20)	
10	5.25	14	barren? (20)	
11	5.40	26	5, 6, 20, 35	
12	4.86	57	barren (5, 20)	
13	5.54	60	5, 20	5, 20
14	4.98	-43	5, 20	5
15	4.85	47	barren (5, 20)	
16	4.84	- 3	barren (5)	
17	5.89	-23	20	
18	6.16	-61	5?, 20	
19	4.71	61	barren (5, 20)	
20	4.78	-21	barren (5)	
21	5.69	-39	5, 20	
22	4.83	-33	barren (5, 6, 20)	
23	5.19	-17	20, 35	
24	5.62	-49	5, 20, 37	
25	5.00	-56	20, (5)	
26	4.99	-39	5, (6)	
27	6.20	-53	5, 20	5, 20
28	6.37	-61	6	
29	5.26	-32	6, 20	
30	5.82	-51	20	
31	5.50	-45	5, 20, 35	
32	6.13	- 5	5, 20, 35	

Table 3, contd.

Lake	pH	IMD-height	Species by interview	Species by test-fishing
33	6.43	-66	5, 20, 35	
34	6.48	-65	20	20, 35
35	5.54	- 4	5, 20,	5, 20, 35
36	5.29	0	5, 20	5, 20
37	6.16	-12	20, 37	20
38	5.45	10	5, 20	5
39	5.55	-33	5, 20	
40	5.18	- 6	20, 37	
41	4.62	-16	barren	
42	5.35	5	5, 20	5, 20
43	4.99	-15	5, 20	20
44	4.62	-12	barren	
45	4.85	-11	20	
46	5.13	- 6	20, 37	20 (20 1989)
47	4.57	24	barren (5, 20)	
48	4.64	-18	barren (5, 7, 20, 37)	
49	4.62	38	barren (5, 20)	
50	5.08	19	barren (5, 20)	
51	5.36	-43	5, 20	
52	4.74	- 3	barren (5, 6, 9, 20)	
53	4.63	20	barren (5, 20)	
54	4.33	1	barren (20)	
55	5.60	34	5, 6	
56	5.10	3	barren (5)	
57	4.67	44	barren (20)	
58	4.79	-21	barren (5, 6)	
59	4.84	-22	barren (5)	
60	4.92	36	barren (5, 20)	
61	4.72	31	barren (5, 20)	
62	4.91	- 3	5, (6)	
63	4.92	20	5, 6	
64	6.51	34	5, 20	
65	5.10	- 6	5, 20	
66	6.52	-27	5, 20	
67	5.85	-22	20	

Test-fishing.

Lake 37 had a mixed population of pike and perch. In spite of high pH, lake 37 become barren about 1970. The last specimens increased in size. From 1979 to 1985 a yearly average of 530 perch have been transferred from a nearby lake in the spawning time in May. According to the test-fishing results, almost only males have been transferred.

Test-fishing in lakes with pH < 5.5 (n=6) revealed sparse (n=4) or no (n=2) perch populations (Table 2). Average catch/effort in these lakes was 3.7 perch/net. Test-fishing in lakes with pH > 5.5 (n=6) confirmed good perch populations. Average catch/effort was 31.5 perch/net (lake 37 not included). Mean gillnet effort in the two groups of lakes was 5.7 and 5.2, respectively.

According to the test-fishing results, the perch population was lost in lakes 14 and 38. The water quality should be almost adequate for perch in lake 38; pH 5.45 and 2.32 mg Ca/l.

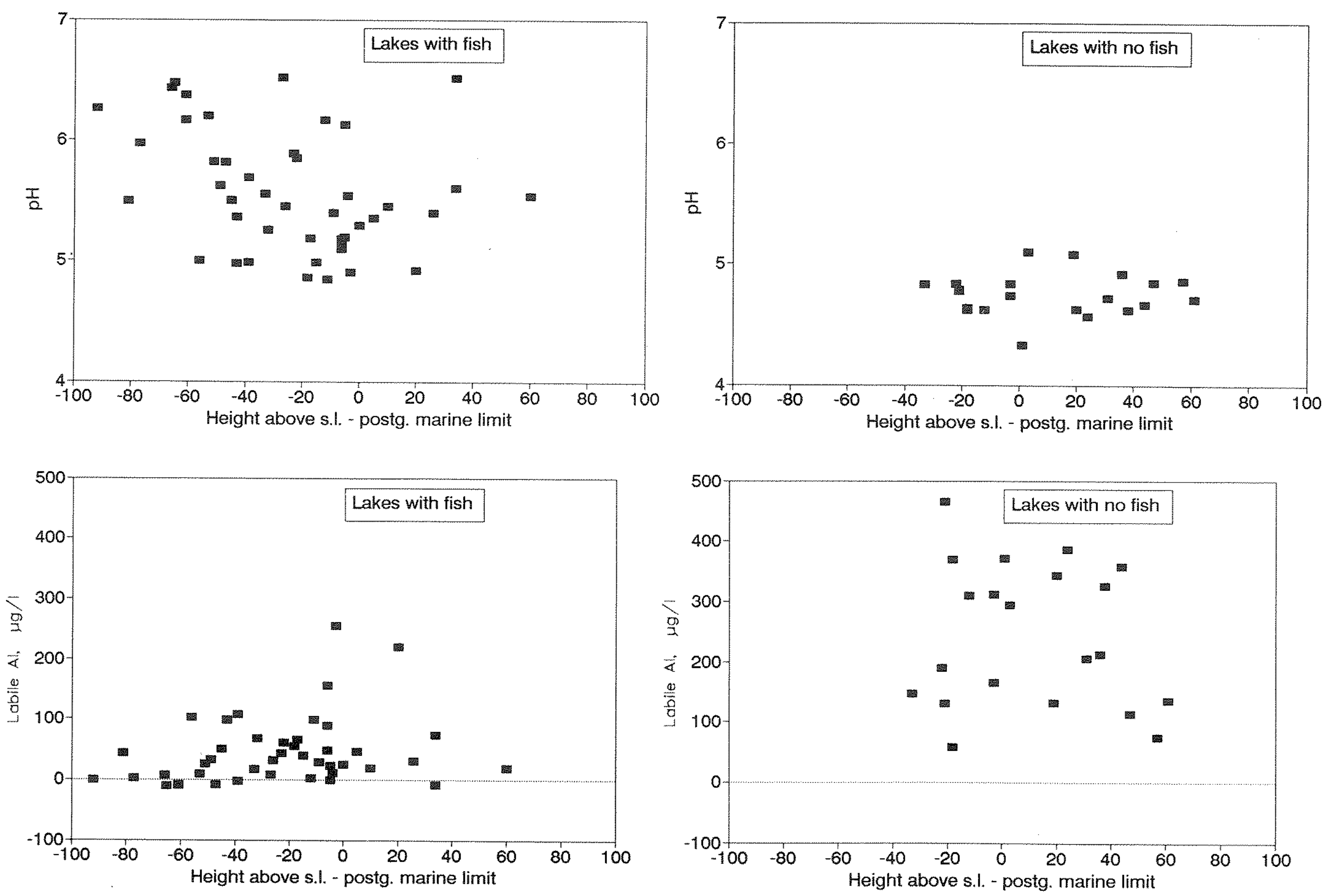


Figure 14. The relation between lake situation, water quality and fish status in lakes in the investigated area.

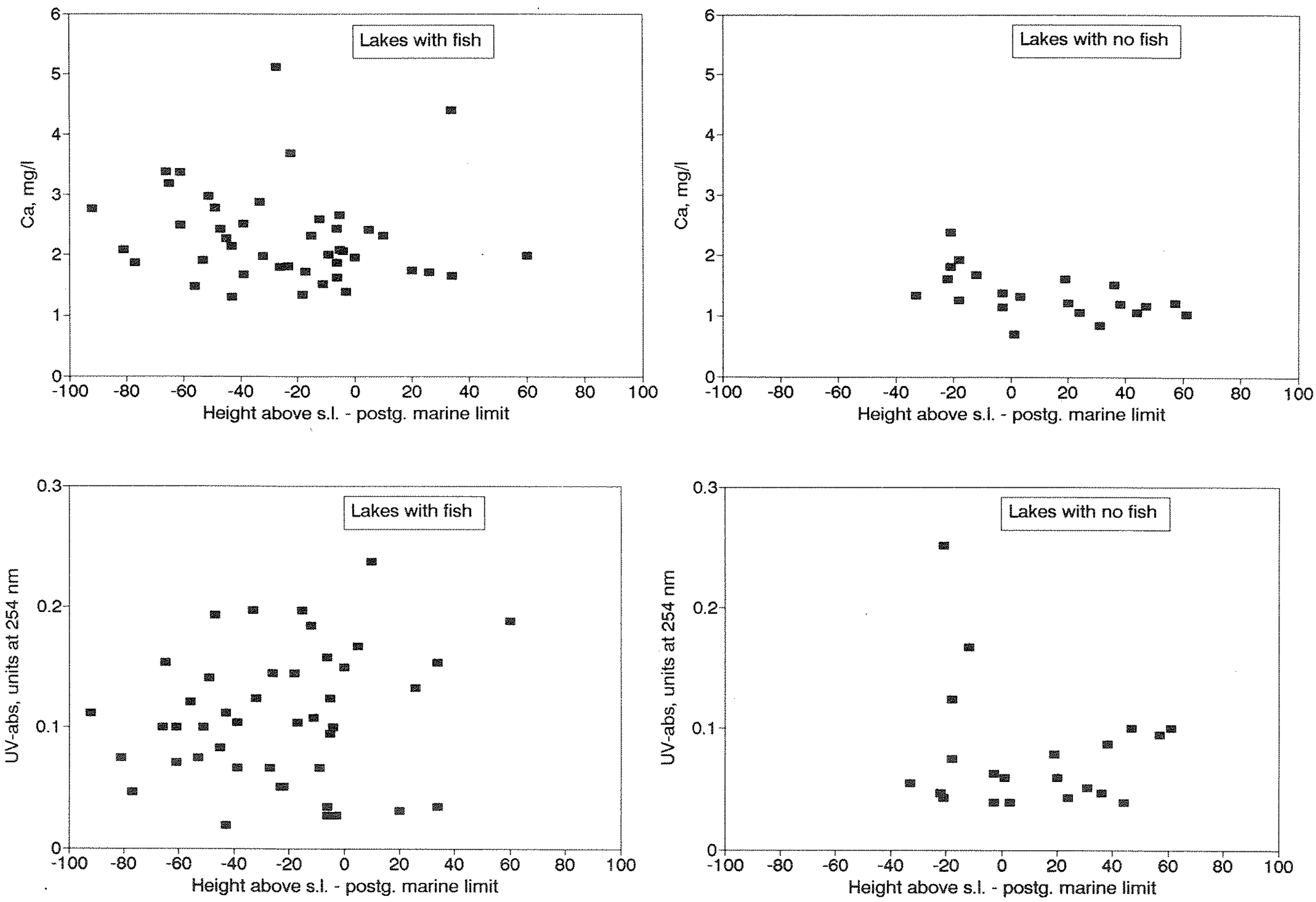


Figure 14, contd. The relation between lake situation, water quality and fish status in lakes in the investigated area.

Brown trout still existed in both these lakes. Extinction of perch before brown trout in mixed populations in this region has previously been reported by Rosseland et al. (1980) and Kleiven et al. (1990).

For the brown trout populations it is difficult to draw conclusions because its original occurence is sparse in both acidic and more neutral lakes.

The postclacial marine limit and water quality affect fish status in the region. The relations between lake situation, water quality and fish status are shown in Figure 14.

Length and age frequency

The perch in the lakes with pH higher than 5.5 had a quite broad lenght frequency distribution (Figure 15), and thus a large number of year classes. In these lakes age groups from 0^+-7^+ were quite common, and perch in age group 14^+, 16^+ and 20^+ occurred. The average number of year classes in these lakes was 10. In the four lakes with pH below 5.5 still inhabiting perch, few fish were caught and the average number of year classes in these lakes was 2.

The lakes 43, 46, 36 and 42 had one dominant year class of perch. In lakes 43 and 46 the perch populations were dominated by old specimens, a result of reproduction failure caused by acidification. Runn et al. (1977) discerned a reduction in hatchability of perch eggs in acid water at pH below 5.5. pH 5.0 seems to be the lower limit for normal reproduction (Runn et al. 1977, Rask 1983).

In lakes 36 and 42 the perch populations almost exclusively consisted of fish in age group 1^+. Lack of older fish caused by increasing mortality of adult fish is also an effect of acidification. Brook and river spawning species may be strongly affected with high postspawning mortality (Rosseland et al. 1980). These species normally enter the spawning areas at high waterflow in connection with acid, autumn rain. Also lake spawning fish, e.g. perch, may experience increased mortality on adult fish (L'Abée-Lund 1985b). Both ageing and juvenilization are reported for different species in Norway (Rosseland et al. 1980, Andersen et al. 1984, L'Abée-Lund 1985b, Kleiven et al. 1989, 1990).

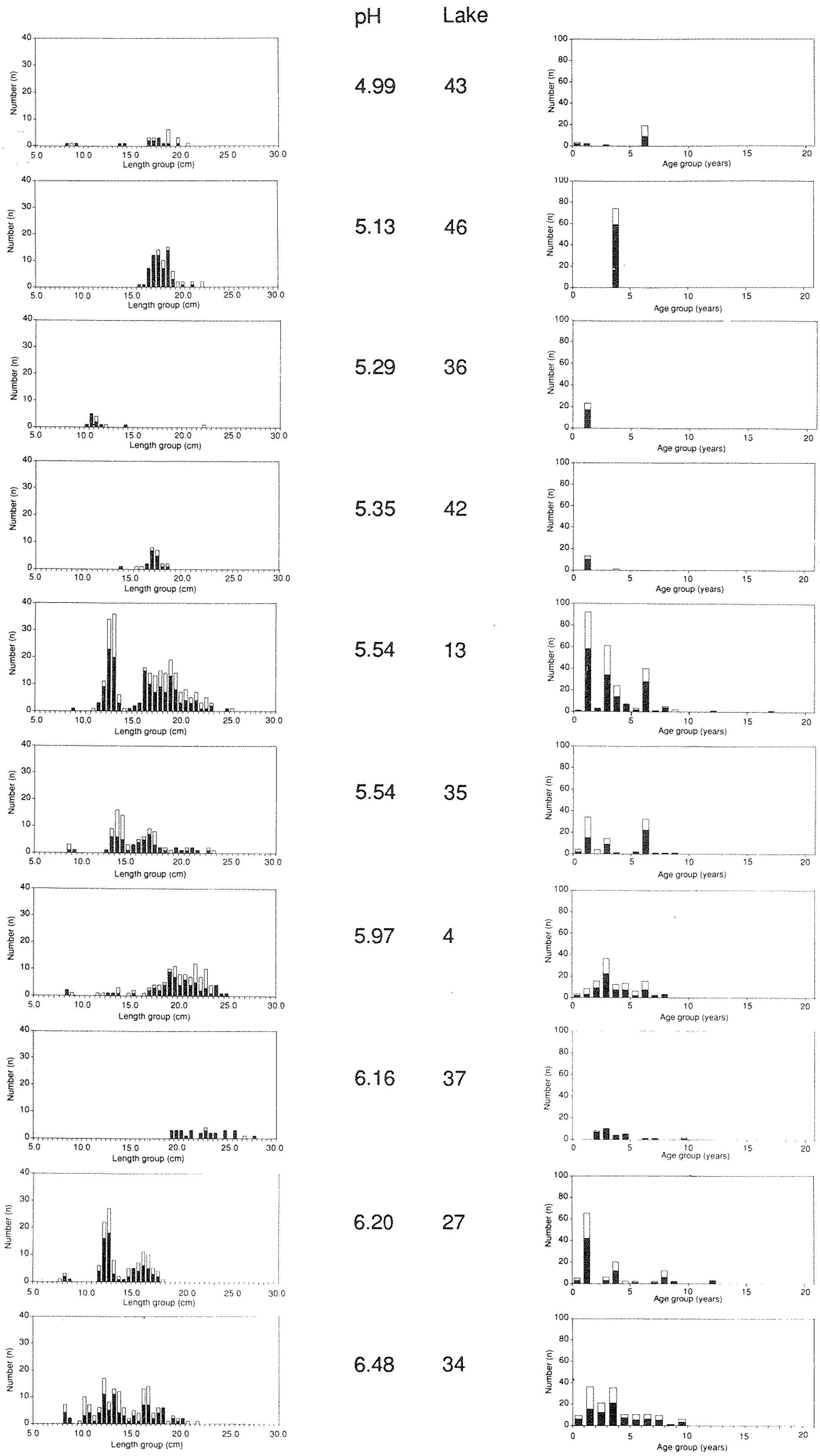


Figure 15. Length and age frequencies of perch in the coastal lakes in 1985 ranked by pH. The black part of the columns is males.

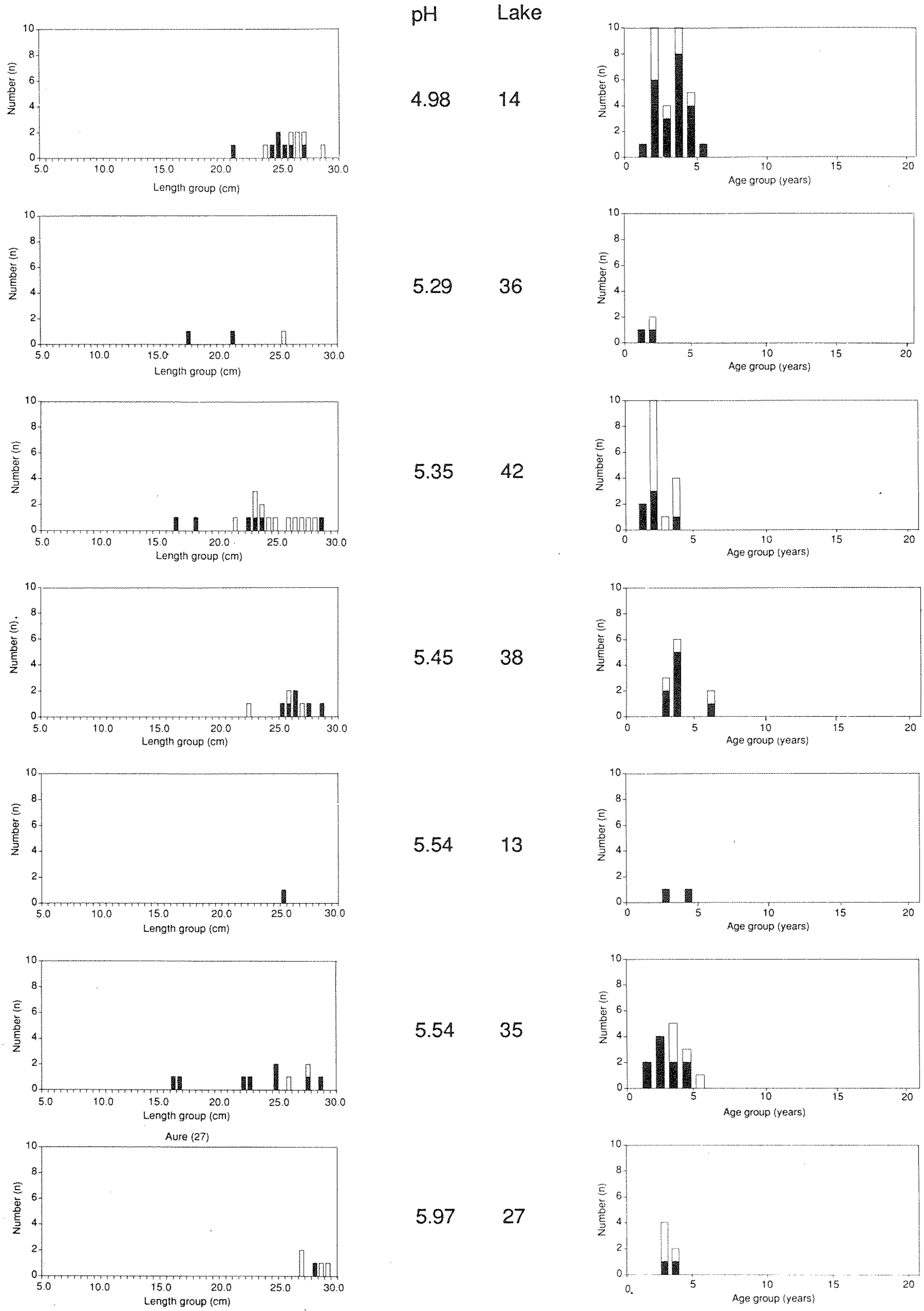


Figure 16. Length and age frequencies of brown trout in the coastal lakes in 1985 ranked by pH. The lake number (Table 2) is given.

Strong year classes occurred in many lakes in 1978, 1982, 1984 and in a few lakes in 1981. Lake 8 (test-fished in 1980) had a strong year class in 1978. In other lakes in the Sørlandet region, strong year classes occurred in the years 1978, 1981 and 1984 (L'Abée-Lund 1985 a,b, Kleiven et al. 1989, 1990).

The length frequency of the sparse catches of brown trout cover a broad specter from 15 to 38 cm (Figure 16). No special length group dominated. The age frequency shows relatively young fish, with only a few individuals older than 5 years. No tendency could be discerned between the most acid and the less acid lakes, respectively.

Sex ratio

Sex ratio for perch in the lakes are quite variable (Table 4). Males dominated in all populations (53-80 %), especially in the most acidic lakes. Lake 8 had 53 % males in 1980. Great diversity in sex ratio for perch is reported (summarized by Alm 1946 and Thorpe 1977). Sumari (1971) reported 49-63 % males in 9 Finnish ponds (age group $\geq 1^+$). In 4 acidified Norwegian lakes of 43-162 ha, the figures of males in August/September were 47-69 % during 4-6 years (Kleiven et al. 1990).

Sex ratio for brown trout were much more variable than for perch. In spite of few data, there was a tendency of dominance by males in the less acid lakes (Table 4).

Growth

Except for lake 42, the first two years growth of perch, expressed as mean empirical length, was similar in the lakes (Table 5).

From two years age the growth differed much for perch, but no tendency in different growth rate in acidic contra more neutral lakes was observed (Table 5). For some lakes, however, the number of perch is sparse, which make the comparison difficult. The greater perch growth observed in lake 37 must be ascribed to the special situation mentioned in this lake; a sparse population and good chemical conditions.

Table 4. Sex ratio for perch and brown trout in the test-fished lakes. All age groups are included. The lakes are ranked by pH.

Lake no.	pH in May 1984	Perch			Brown trout		
		Male	Female	% male	Male	Female	% male
14	4.98				23	8	74.2
43	4.99	14	11	56.0			
46	5.13	59	15	79.7			
36	5.29	10	4	71.4	2	1	67.7
42	5.35	17	7	70.8	6	11	35.3
38	5.45				8	3	72.7
13	5.54	154	87	63.9	2	0	100.0
35	5.54	54	40	57.4	10	5	66.7
4	5.97	64	49	56.6			
37	6.16	29	2	(93.5)*			
27	6.20	73	46	61.3	1	4	20.0
34	6.48	8	68	56.7			

* See text for explanation.

Except for lake 14, the growth of brown trout, expressed as mean empirical length, was relatively uniform and independent of pH (Table 6). Lake 14 had a chemistry characterized by pH 4.98, 1.30 mg Ca/l and 98 µg labile Al/l. Brown trout and perch were reported to inhabit the lake, but obviously the perch had disappeared. Lake 14 is a clear-water lake (UV-abs. 0.019, the lowest recorded value of this investigation). Brown trout in lake

42 had no accelerated growth compared with the other lakes (Table 6).

The growth-pattern of freshwater fish populations are often changed in acidified localities. Increased growth rate are reported for a variety of species, e.g. brown trout (Jensen and Snekvik 1972, Anderson and Andersson 1984) and perch (Eriksson et al. 1983).

Table 5. Mean empirical length (cm) for perch in test-fished lakes. The lakes are grouped as in Table 4. The figures in brackets are the number of fish in each age group.

Lake no.	Age group 1	2	3	4	5	6	7	8	9	10
43	8.7 (3)	14.0 (2)						18.3 (19)		
46					18.3 (74)					
36		11.3 (13)			22.4 (1)					
42		16.3 (23)								
13	8.9 (1)	12.4 (92)	15.0 (3)	16.7 (61)	18.0 (24)	17.6 (7)	18.3 (3)	19.6 (40)	20.5 (1)	21.3 (5)
35	8.4 (4)	12.7 (34)	13.9 (4)	14.3 (14)	14.4 (1)		15.6 (2)	17.1 (32)	16.8 (1)	18.4 (1)
4	8.3 (3)	12.8 (8)	16.6 (15)	18.7 (36)	20.2 (12)	20.7 (13)	20.9 (6)	21.6 (15)	22.3 (2)	22.9 (3)
27	8.2 (5)	12.5 (65)		15.1 (6)	15.7 (20)	16.3 (2)	16.3 (2)		17.1 (2)	17.0 (12)
37*			20.3 (8)	21.8 (10)	22.5 (4)	24.7 (5)				
34	8.4 (9)	11.4 (36)	13.1 (21)	14.1 (35)	15.5 (10)	16.6 (10)	17.7 (10)	17.8 (9)	18.4 (1)	18.7 (6)

*See text.

The improved growth is explained by changes in intra- and/or inter-specific competition due to reduced densities of fish when recruitment fails. In spite of more available food supplies in acidified lakes with declining fish populations, growth depression is reported, e.g. brown trout (Rosseland et al. 1980, Hultberg and Andersson 1982). Sadler and Turnpenny (1986) found decreased growth of yearlings of brown trout in tank experiment with acid water with elevated aluminium content. The growth depression observed in acid water is explained by increased energetic costs for maintanance of the surplus energy necessary for growth (Rosseland et al. 1980). For yellow perch (Perca flavescens) Ryan and Harvey (1980) reported increased growth rate up to the age of 3 and thereafter decreased growth. The growth depression was, however, linked to lack of suitable food items. Yellow perch become piscivores at about 3 years, but few or no fish prey species were present at the low pH tolerated by the yellow perch.

Table 6. Mean empirical length (cm) for brown trout in test-fished lakes. The lakes are grouped as in Table 4. The figures in brackets are the number of fish in each age group.

Lake no.	Age group 1	2	3	4	5	6	7	8	9	10
14		20.0 (1)	24.4 (10)	29.4 (4)	33.7 (10)	34.2 (5)	28.3 (1)			
36		16.8 (1)	22.3 (2)							
42		15.9 (2)	21.6 (10)	24.5 (1)	25.4 (4)					
38				25.9* (3)	24.6 (6)	27.7 (2)				
13				23.7 (1)		32.2 (1)				
35		15.6 (2)	22.7 (4)	26.7 (5)	27.5 (3)	30.5 (1)				
27				25.3 (4)	28.6 (2)					

*Included one fish with extreme growth (33.7 cm).

The fish stock characteristics for both perch and brown trout in the investigated lakes are in good agreement with other results obtained in the region (Rosseland et al. 1981, L'Abée-Lund 1985a, 1985b, Kleiven et al. 1989, 1990).

CONCLUSIONS

Acidification of lakes and rivers has greatly reduced fish populations in southern Norway. This survey shows that a considerable reduction in acid deposition must occur to give any significant improvement of the water quality in many of the investigated lakes. Marine deposits make lakes in the coastal area of Aust-Agder less sensitive to acidification than lakes inland and they may respond earlier to a reduction in acid deposition.

Almost all 67 lakes are acidified due to high deposition of strong acids, but only 21 (possibly 23) are recorded as barren of fish. Lakes well below the post-glacial marine limit with significant agricultural acitvities in the watershed are not included in this survey. They probably represent an additional set of lakes with intact fish populations.

Remaining fish populations represent a valuable resource in this part of Norway in terms of reestablishing of fish stocks in recovered or limed lakes in the future.

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