Severe acidification in coastal lakes in Suldal in southwestern Norway

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Sammendrag

Sterk forsuring i kystnære innsjøer i Suldal - Sørvest-Norge. Vikastølvatn ligger i et kystnært område i Suldal. I perioden 2018-2021 var middelverdiene for pH 4.72-4.94, labilt aluminium (LAl) 27-75 µg/l og nitrat (NO_3) 235-440 µg N/l. Tilløpene hadde maksimalverdier for LAl og NO_3-N på henholdsvis 127 og 820 µg/l. Verdiene for ikke-marint sulfat var moderate, omlag 1 mg/l. Utvidelsen av undersøkelsesområdet i mai 2021 viste høye verdier for nitrat i de lavereliggende områdene også, mens fjellområdene hadde verdier omtrent som for referanseinnsjøene, som var lokalisert i Sirdal-Lyse området. I denne delen av fylket ligger industri som slipper ut omlag 85% av de totale industriutslippene av NO_x i Rogaland. For å kunne si noe om effekten på lokal vannkvalitet kreves imidlertid mer omfattende overvåkning, og hvor også meteorologiske data trekkes inn.

Summary

Lake Vikastølvatn is located in a coastal mountain area in Suldal, Western Norway. During the study period 2018-2021, the average pH measured at 4-5 depths was 4.72-4.94, labile aluminium (LAl) 27-75 µg/l and nitrate (NO_3) 235-440 µg N/l. The tributaries had maximum values for LAl and NO_3-N of 127 and 820 µg/l, respectively. The non-marine sulfate values were moderate, about 1 mg/l. The extension of the study in 2021 revealed high nitrate values in the low-lying areas too. However, the lakes in the mountain areas had a water chemistry close to that of the reference lakes, the latter were located in the Sirdal-Lyse area. The industry in this part of Rogaland County emits large quantities of NO_X. However, assessing the influence on the local water chemistry requires more detailed monitoring, where also meteorological data are considered.

Introduction

Due to acidification, a large number of fish populations in mountain lakes all over southern Norway became extinct, primarily during the second half of the 1900s (Sevaldrud and Muniz 1980, Hesthagen et al. 1999). However, due to the presence of easily weathering bedrock and the subsequent supply of alkalinity, some local areas avoided the most serious effects of acidification.

In Suldal (Fig. 1), very few fish populations became extinct due to acidification. Surprisingly, Lake Vikastølvatn (Fig. 2) was one of the few lakes registered with a "lost" fish population, due allegedly to acidification. This lake, and the entire watershed, are located on phyllite bedrock, which is considered easily weatherable.

Acidification has declined considerably in the past decades (Garmo et al. 2014). However, sporadic pH measurements in Lake Vikastølvatn over the past two decades have revealed acidic water chemistry inconsistent with the general acidification recovery (Enge 2013). Due to these unexpected results, additional water chemistry surveys were performed between 2018 and 2021. Initially, the study area was restricted to the Vikastøl area. However, due to interesting results, the study area was extended in May 2021, to include the entire western Ropeid peninsula (Fig. 1).

Study Area

The study area is located in the western parts of the Ropeid peninsula (Fig. 1, Fig. 2). The elevation profile (Fig. 3) from Hebnes to Grytenuten (862 m a.s.l.), through Lake Vikastølvann (354 m a.s.l.), shows two plateaus, the first one at 300-400 and the second one at approximately 600-800 m a.s.l. The lower plateau is covered by mixed forest (pine and birch) and marshland while the terrain ranging from about 500 m to Grytenuten consists of barren mountain. The 300-400 m plateau also includes the largest lakes in the study area, while the lakes above this altitude are small and presumably shallow.

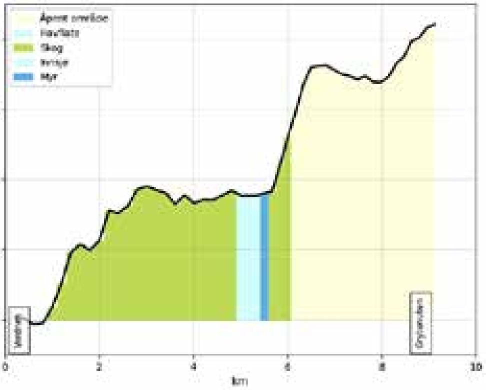

Fig. 3. Elevation profile from Hebnes to Grytenuten. (Glossary: "Åpent område" = Open range; "Havflate" = Ocean surface; "Skog" = Forest; "Innsjø" = Lake: "Myr" = Marshland). (Source: norgeskart.no)

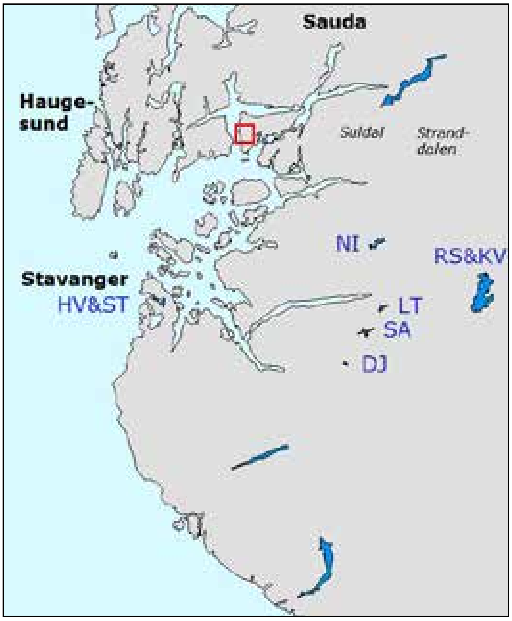

Fig. 1. Southwestern Norway. The study area is marked with a red square. The eight references are marked with blue text (NI: Nilsebuvatn, RS&KV: Roskreppfjord & Kværevatn, LT: Litle Tjodan, SA; Sandvatn, DJ: Djupavatn, HV&ST: Hålandsvatnet & Store Stokkavatnet). Other place names mentioned in the text are also included.

Fig. 2. Western part of Ropeid peninsula. Red marks: Sample locations, black triangles: Monuntain peak & altitude (m a.s.l.).

Picture 1. Aerial photo showing the 300-400 m plateau. From left the Lakes Vikastølvatn, Selvatn, Vasstølvatn (in the background), Djupadalsvatn and Aksvikstemmen (in the background). The lakes at this plateau are the largest lakes at the western Ropeid peninsula. Note the barren rock at higher altitudes (left part of the photo). Sandsfjorden is visible in the background in the right corner (Photo: County Governor of Rogaland).

Picture 2. Overview of parts of the mountain plateau >600 m (late May 2021).

The bedrock is comprised mainly of phyllite and schist with dikes of quartz (ngu.no). A simple qualitative test confirmed that the phyllite in the study area contains iron. Iron is also visible as precipitates of Fe(III)-oxides/hydroxides in several brooks in the area. One of the most common iron minerals in metamorph bedrocks is pyrite (FeS_2) (Alterman 1989). Pyrite in contact with oxygen and water may oxidize to form sulfuric acid and Fe(III)-oxides/hydroxide-precipitations.

There is a scarcity of glacial deposits in the mountain areas, except for a limited occurrence along the western shoreline of Lake Vikastølvatn

Picture 3. Fe(III)-precipitations in a small brook along the road up to Lake Vikastølvatn (Photo: Henrik van der Hoeven).

(ngu.no). This deposit is shallow (depth <0.5 m) and covers an area of 0.12 km², equal to 2.9% of the entire catchment of Lake Vikastølvatn. However, in lower-lying areas (<200 m a.s.l.), there are large glacial deposits in the slopes down to the coastline.

Lake Vikastølvatn (354 m a.s.l.) and tributaries were initially the primary targets of this survey. Moreover, this is the largest lake in the area. Therefore, Lake Vikastølvatn has been subject to more comprehensive studies than the other lakes.

The maximum altitude in the Vikastøl-catchment is 750 m a.s.l. and the most remote parts of the watershed are located 3 km from the coastline. The Vikastøl watershed comprises lakes (9%), forest (42%), marshland (5%), and barren mountain (26%) (NEVINA, nve.no). There are no human activities in the watershed.

The catchment is 4.15 km² and the runoff is 77.5 l/s per km² (NEVINA, nve.no), equal to an annual runoff of $10.1´10^6$ m³/year. The average depth is 5.5 m (Fig. 4). With an area of 0.163 km², this represents a volume of $0.90´10^6$ m³ and a retention time of 0.1 year.

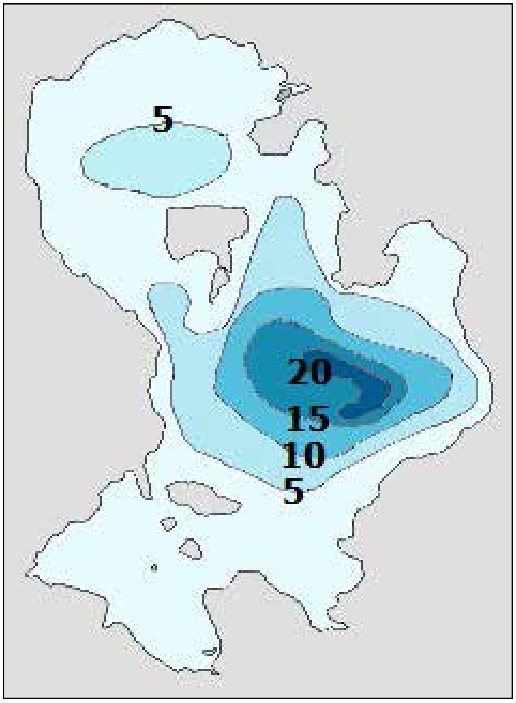

Fig. 4. Lake Vikastølvatn. The individual depths (m) were measured by a manual sonar and located on the map with GPS.

Methods

Sampling

Water was sampled in Lake Vikastølvatn and tributaries throughout 2018-2021. The lake was sampled at depths of 0, 2.5, 5, 10, and 15 m with a Ruttner sampler. The sampling depths were changed to 0, 5, 10, and 20 m in 2021. In 2018 the upstream Lake Selvatn was included and was sampled at depths 0, 2.5, 5, and 7.5 m (maximum depth <10 m).

Due to the findings in Lake Vikastølvatn, the surveys were extended in May 2021, to include lakes and brooks all over the western Ropeid peninsula. These additional sites were only sampled once.

For nitrate references, water was sampled from the ultraoligotrophic mountain Lakes Nilsebuvatn, Litle Tjodan, Sandvatn, Djupavatn, Kværevatn, and Roskreppfjorden located 717, 896, 910, 713, 929, and 929 m a.s.l. (Fig. 1). These are relatively large lakes (area 0.4-30 km^2). With exception of Lake Kværevatn, they are deep lakes with presumably high retention times. These samples are further referred to as "mountain references".

Moreover, as references regarding the effects of the bedrock on the water chemistry, samples from the mesotrophic Lake Store Stokkavatn and the hyper-eutrophic Lake Hålandsvatn in Stavanger were also included. They are both low-land lakes, laying on the same type of bedrock as the study area (phyllite).

Water analyses - primary parameters

pH was determined according to "Standard Methods" 4500-H$^+$ (Eaton et al. 1995) with a Fisher Scientific pH-meter equipped with a Radiometer pHC4001 electrode. Calibration was performed with standard buffers (pH=4.004 &6.863). The calibrations were always double-checked with an independent buffer within the calibration range (pH=5.00, Merck "Certipur", NIST-traceable). Conductivity was measured with an Amber Science instrument (mod. 1056) according to "Standard Methods" 2510. Calibration was performed with a NaCl-solution (210 µS/cm), which has been verified vs. a solution prepared from certified reference material. Ca, Na, and Cl were determined with Radiometer ion-selective electrodes, while K was measured using a Sentek electrode, according to the manuals. Mg was determined photometrically with calmagite/EGTA according to Ingman and Ringbom (1966). SO_4 was titrated conductometrically with barium acetate, according to Stølen (2019). Nitrate was determined photometrically as nitrite, after reduction by Zn, modified from "Standard Methods" 4500-NO_3 (E). Strictly, this method determines the sum of nitrate and nitrite. However, in oxygenated water the concentrations of nitrite are normally negligible; typically <10 µg/l (Wetzel 2001). The internal standard for checking the cation/anions determinations was prepared using diluted seawater, where Na and Ca have been verified vs. solutions made of certified reference material/certified standards. Aluminium was determined photometrically with ECR according to "Standard Methods" 3500-Al, D. The ilabile fraction ("ILAl") was determined on an ion-exchanged sample (Amberlite IR120-Na$^+$). Labile aluminium ("LAl"), i.e. the inorganic cationic fraction, was determined as the difference between the directly determined aluminium and ILAl. The control solution was a certified Al-standard, independent of the calibration solutions. The color was measured with a spectrophotometer (Shimadzu UV120) at 410 nm in 40 mm glass cuvettes. Due to low turbidity, the samples were measured without filtration.

With one exception, the same procedures were applied for samples from the reference locations. Ca in Lake Hålandsvatn was determined with EDTA-titration according to "Standard Methods" 3500-Ca (D).

Additional to the quality assurance for the individual parameters (e.g. Enge et al. 2021), determinations of anion-cation balance and calculated conductivity vs. measured conductivity were performed on all samples with "full" analysis (n=86). For cation-anion balance, the fraction of the determinations within ±10% and ±5% were 100% and 93%, respectively. For calculated vs. measured conductivity the corresponding values were 100% and 97%.

Water analyses - additional parameters

On samples from Lake Vikastølvatn, additional parameters were sporadically analyzed. In April 2020 iron was measured on samples from five depths, using the ferrozine method (HACH 1998). Moreover, ammonium (strictly NH_3 + NH_4^+) was determined for four samples from Lake Vikastølvatn sampled in May 2021. This determination was performed with ion-selective electrode (Metrohm) according to “Standard Methods” 4500-NH_3 (D).

Alkalinity was determined by acidimetric titration to pH=4.5. Equivalence alkalinity, ALK_E, was calculated according to Henriksen (1982). However, it should be noted that the ALK_E approach slightly overestimates the alkalinity (Enge and Garmo 2021). The alkalinity data were not presented separately but applied in the calculation of Σanions (see next chap.).

Water chemistry calculations and compilations

ANC (Acid Neutralizing Capacity) was calculated as Σ(strong base cations) - Σ(strong acid anions). In situations where results were below the detection limit, (detection limit)/2 was used in the chemistry calculations. E.g. for potassium “K<0.05 mg/l”, a value of 0.025 was used.

Due to the very acidic water with high levels of Al, both H^+ and LAl were included in the cation sum. For LAl an average charge of 2+ was applied. For samples with alkalinity data, the approximation $[HCO_3^-]\approx$alkalinity was applied. For the remaining samples (pH<5.5) we assumed that $[HCO_3^-]\approx 0$.

Preacidification water chemistry was estimated using the spreadsheet following Hindar and Wright (2002). TOC was not measured but estimated from “color”. For the large Lake Byrkjelandsvatn, located in a mountain area in southern parts of the county, Wright et al. (2011) found that “color” (mg Pt/l) was approximately 10 × TOC (mg/l). This approximation was applied to the current samples, for estimating TOC.

Results

A total of 95 samples were included in the study. 53 of the samples were collected in the study area (Ropeid peninsula) (Tab. 1), while the

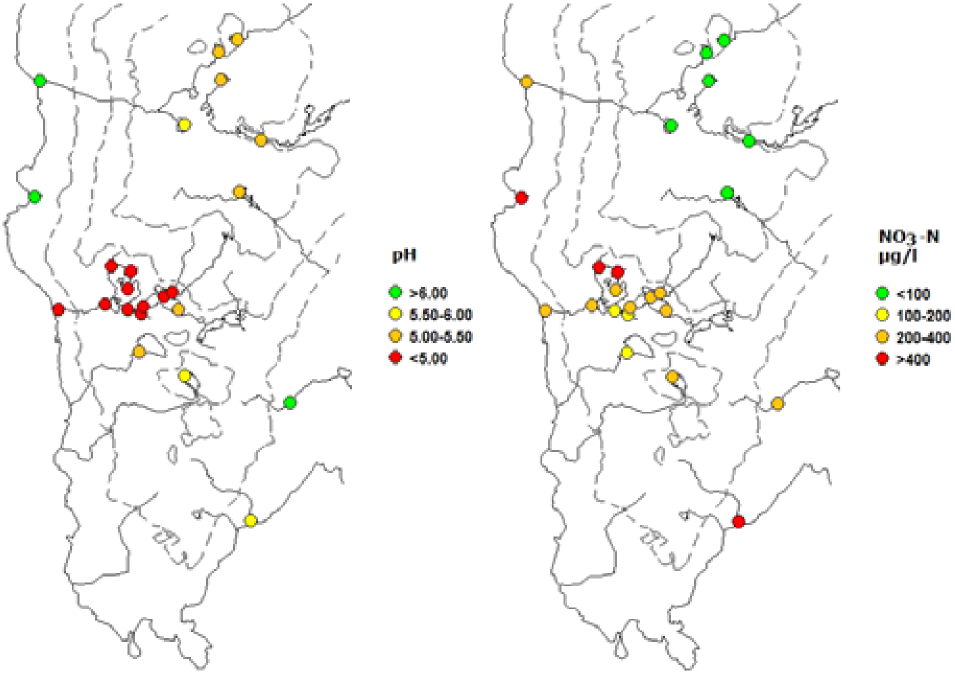

Fig. 5: Maps showing the geographic distribution for values of pH and nitrate.

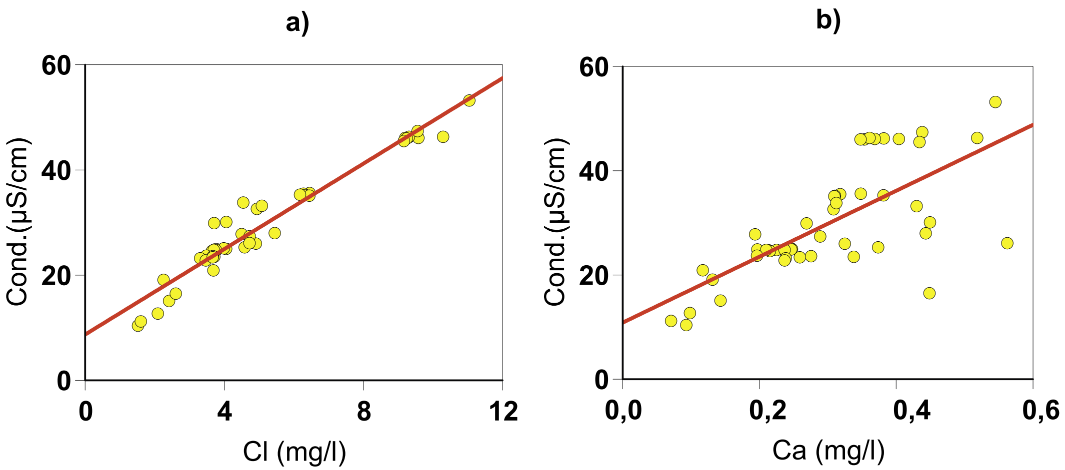

Fig. 6. Relationships between conductivity, Ca and Cl. Samples from the brooks along the coastline (n=5) were not included.

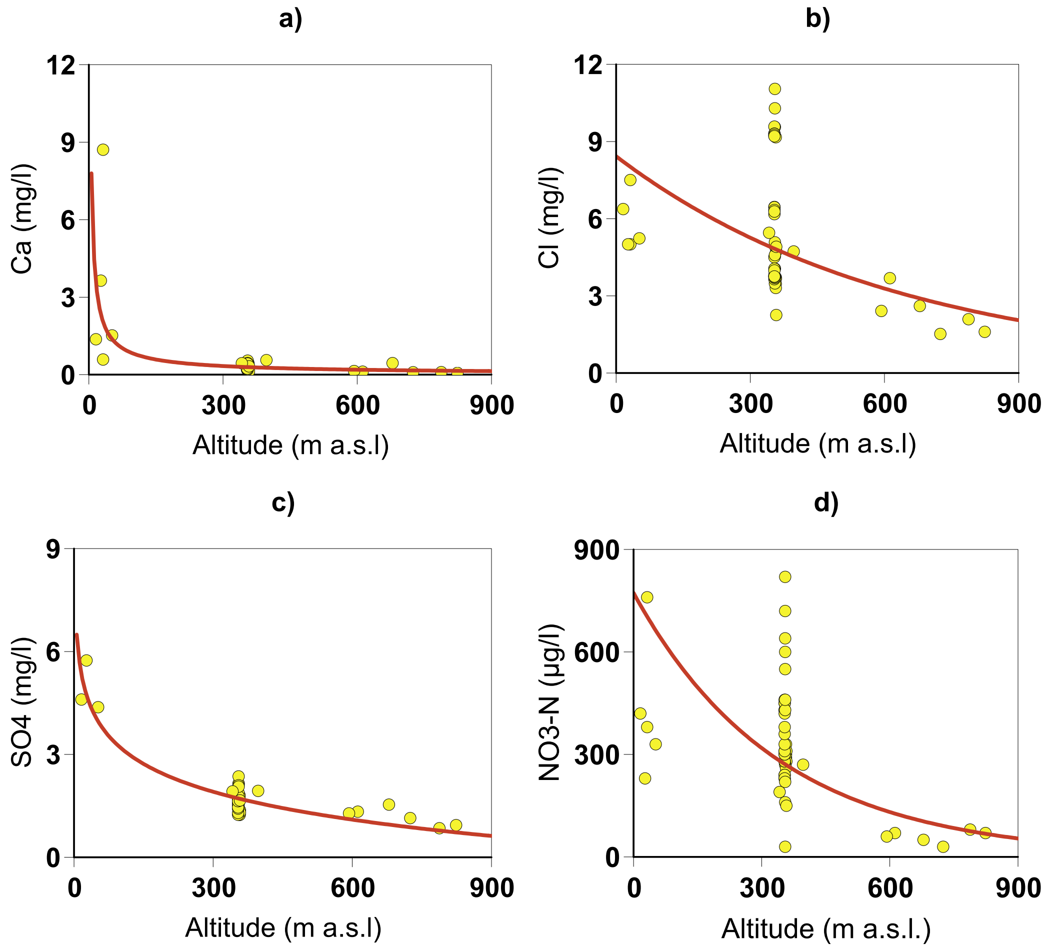

Fig. 7. Relationships between altitude and selected water chemistry parameters. a) calcium; b) chloride; c) sulfate and d) nitrate.

Tab. 1. Water chemistry results from lakes at western Ropeid peninsula. Except for the brooks, these values are average values for samples from several depths. Outlet samples were included in the lake averages. "n" is number of samples.

Area (altitude)	Site	n	Date/ period	pH	Cond.	Color	Al	LAl	Ca	Mg	Na	K	Cl	SO_4	NO_3	ANC
(m a.s.l.)					µS/cm	mg Pt/l	µg/l	µg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l N	µeq/l
Coastal areas (<100m)	(five brooks)	5	2018-2021	6.23	50.4	7	35	8	3.16	0.84	3.6	0.20	5.8	4.9	424	51
Plateau 300-400 m	Lake Vikastølv.	6	Apr-2018	4.78	34.1	24	89	50	0.31	0.39	3.2	0.13	6.0	1.4	440	-42
	Lake Vikastølv.	6	Apr-2020	4.72	46.1	11	100	75	0.37	0.67	5.0	0.17	9.3	1.7	292	-26
	Lake Vikastølv.	4	Jan-2021	4.85	24.8	30	62	27	0.21	0.30	2.4	0.13	3.7	1.8	235	-15
	Lake Vikastølv.	4	May-2021	4.94	25.0	16	66	46	0.24	0.38	2.3	<0.05	3.9	1.5	345	-19
	Grønnlibekken	4	2018-2021	4.82	37.6	6	143	109	0.43	0.54	3.7	0.11	6.2	2.0	653	-36
	Maramyr-bekken	3	2018-2021	4.73	36.6	21	119	66	0.34	0.42	3.6	0.07	6.1	2.0	537	-43
	(eigth lakes & brooks)	15	2018-2021	4.97	27.2	28	43	17	0.32	0.32	2.7	0.13	4.7	1.6	245	-19
Mountain areas (>600 m)	(six lakes)	6	May-2021	5.25	14.5	22	32	15	0.16	0.21	1.4	<0.05	2.3	1.2	60	-8

Tab. 2. Water chemistry results from reference lakes (see Fig. 1). The results are average values for samples from several depths. "n" is number of samples. (Parentheses: ALKE)

Area- (altitude)	Site	n	Date/ period	pH	Cond.	Color	Al	LAl	Ca	Mg	Na	K	Cl	SO_4	NO_3	ANC
(m a.s.l.)					µS/cm	mg Pt/l	µg/l	µg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l N	µeq/l
Mountain area (>600 m)	Kværevatn	3	Jul-2020	5.89	6.9	16	16	6	0.27	0.09	0.6	<0.05	0.9	0.7	36	7
	Roskreppfjorden	5	Jul-2020	5.76	8.8	6	28	14	0.27	0.11	0.8	<0.05	1.3	0.8	64	2
	Nilsebuvatn	5	Aug-2020	5.62	8.4	7	18	9	0.13	0.11	0.9	0.07	1.4	0.6	53	0
	L.Tjodan	5	Aug-2020	5.57	11.5	6	19	8	0.17	0.15	1.3	<0.05	2.1	0.7	57	0
	Sandvatn	4	Aug-2019	5.53	9.6	6	17	5	0.15	0.14	1.0	<0.05	1.6	0.6	90	-2
	Sandvatn	4	Feb-2020	5.32	13.9	3	23	12	0.19	0.20	1.5	<0.05	2.5	0.8	82	-3
	Djupavatn	4	Apr-2021	5.50	12.0	21	39	9	0.21	0.15	1.3	<0.05	2.0	0.9	70	1
Lowland, "phyllite"	St.Stokkavatn	5	Feb-2021	7.33	153	11			13.0	3.0	11.3	2.5	19.2	16.2		(498)
	Hålandsvatn	7	Jul-2020	8.07	209				19.7						458	(954)

Tab. 3: Natural state water chemistry ("nat.") were calculated using data from lake Vikastølvatn according to Hindar and Wright (2002). Averages based on samples from several depths were used.

	Apr-18 (nat.) D			Apr-20 (nat.) D			Jan-21 (nat.) D			May-21 (nat.) D		
pH	4.78	4.87	-0.09	4.72	5.08	-0.36	4.85	5.58	-0.73	4.94	5.65	-0.71
SO_4^*	0.6	0.5	0.1	0.4	0.5	-0.1	1.3	0.5	0.8	1.0	0.5	0.4
NO_3	440	0	440	292	0	292	235	0	235	343	0	343
LAl	50	31	19	75	7	68	27	0	27	46	0	46
ANC	-42	-6	-36	-26	-4	-22	-15	17	-32	-19	11	-30

remaining 42 samples (Tab. 2) were reference samples and originated from the mountain areas in Sirdal- and Lyseheiene (n=30) and from the Stavanger area (n=12).

The most striking findings were the low pH- and high nitrate values. Both parameters showed a distinct geographic variability throughout the study area (Fig. 5).

General water chemistry

Airborne sea salts are the primary source of ions in the mountain area, while the bedrock is an important ion contributor in the lower areas. For the locations above 200 m a.s.l. (n=48), chloride correlated far better to conductivity (r^2=0.95) than calcium (r^2=0.49) (Fig. 6). Calculations showed that 70% of the conductivity of these samples were of marine origin, while 16% was attributed to H^+. The remaining conductivity originated from weathering and pollution.

With a maximum value of 8.7 mg/l, the Ca-values in the brooks along the coastline were relatively high. However, calcium values decreased with increasing altitude (Fig. 7a), down to extremely low values in the mountain areas (minimum: 0.07 mg/l). Also, the chloride values decreased with increasing altitude (Fig. 7b), i.e. with increasing distance from the coast.

We detected high sulfate values in the brooks along the coastline (Tab. 1). The levels of sulfate of the low-land samples, ranged from 4.4 to 5.7 mg/l. Lower values were found at higher altitudes (Fig. 7c). Non-marine sulfate (SO_4*) for all samples with sufficient data was calculated to 1.1±0.9 mg/l (n=51). The moutain *references* had SO_4*=0.5±0.1 mg/l (n=30).

Below an altitude of about 400 m extremely high nitrate values were found (Fig. 7d). In the high mountain area, the values were as low as in the mountain references.

Acidification

Lake Vikastølvatn had highly acidic water chemistry. pH, LAl, and NO_3 for the individual samples were 4.70-4.99, 21-78 µg/l, 230-460 µg/l, respectively (n=20). With pH, LAl, and NO_3 of 4.71-4.93, 50-127 µg/l, 430-820 µg/l, the tributaries Grønlibekken and Maramyrbekken were also strongly acidic (n=7). However, the mountain lakes were significantly less acidic (pH=5.02-5.77, LAl= 6-21 µg/l, and NO_3= 30-80 µg/l, n=6). This water chemistry was close to that of the mountain references. In the brooks along the coastline, high concentrations of both NO_3 and SO_4 were measured. However, there was apparently sufficient alkalinity to neutralize the acid.

For the typical acidification parameters pH, NO_3, LAl, and ANC, natural state water chemistry were calculated for the samples from Lake Vikastølvatn (n=20). Considerable differences between observed water chemistry and estimated natural state values were detected (Tab. 3). ANC was 30 µeq/l lower, indicating severe acidification. Surprisingly, only small effects were registered for sulfate (average ΔSO_4*=+0.3 mg/l).

In a multiple regression of ANC vs. Ca, NO_3, Cl and SO_4* (r^2=0.93, p<0.001, n=51), a significant positive effect was found for Ca (p<0.001), while negative contributions of NO_3 (p<0.001) and Cl (p<0.001) were detected. Apparently, there were no effects of SO_4* (non-marine sulfate) (p>0.05). When excluding the three SO_4-values from the coastal area, in this context outliers, exponential regression demonstrated a significant negative correlation between chloride and non-marine SO_4 (r^2=0.44, p<0.001, n=48).

Other parameters

Fe was measured 29±3 µg/l (AVG±SD) at the five lake samples (depths: 0-15 m) from Lake Vikastølvatn (April 2020). The four samples from May 2020 (depths: 0-20 m) showed ammonium values below the detection limit (<50 µg N/l). All these values were very low, and will not be further used.

Discussion

The most acidic water was detected in the Vikastøl-area. The mountain areas were apparently less susceptible to acid deposition, and in the lower areas, the local geology largely countered the acidification effects.

Highly acidic water with low values for Ca was found in the Vikastøl area. This was unexpected due to the easily weatherable bedrock. Normally, phyllite bedrock is associated with high pH and calcium levels in the adjacent waters. On the Stavanger peninsula, where the bedrock is phyllite, the pH values were above seven (Tab. 2) while Lake Vikastølvatn had pH values of <5 (Tab. 1). The corresponding calcium values were 10-20 mg/l and 0.19-0.40 mg/l, respectively.

In the highest areas at the Ropeid peninsula, calcium levels as low as 0.07 mg/l (Nutatjørn) have been measured, suggesting a limited supply of calcium from the bedrock. This effect is amplified by dilution due to the high annual precipitation, close to 4000 mm (compiled from nve.no). However, along the coastline calcium values as high as 8.7 mg/l have been found (Fig. 7c). In the Vormestrand brook, calcium increased from 0.10 mg/l in Lake Skurvenuttjørn (788 m a.s.l.) to 3.6 mg/l in the inlet to Vindafjord, despite the same type of bedrock. The difference between these areas is primarily that glacial deposits are scarce in the mountain areas, while large deposits are found in the slopes down to the coastline. Glacial deposits are rock material grinded by glaciers. Due to the large surface area available for weathering, glacial deposits are more effective in supplying the water with alkalinity than the solid bedrock itself (Wright and Henriksen 1978). Moreover, such deposits may also include foreign rock types, i.e. material other than the local bedrock (Andersen et al. 1987).

In Jæren, on the other hand, the opposite situation exists. Here, high calcium values are found in the water (Enge 2013), despite slow weathering bedrock (gneiss). However, this area comprises massive glacial deposits, up to about 100 m thick (Andersen et al. 1987). These results suggest that the presence of glacial deposits is crucial, and subsequently, that easily weatherable bedrock alone is apparently not sufficient to counter acidification.

We observed unexpectedly high values for non-marine sulfate (1.1±0.9 mg/l, n=51). The mountain reference had 0.5±0.1 mg/l non-marine sulfate. The two major sources of non-marine sulfate are pollution and sulfide oxidation. The phyllite often contains pyrite (FeS_2) (Alterman 1989), a mineral producing sulfuric acid when oxidized. Since we have established that the phyllite in the study area contains iron, we cannot reject the possibility that this includes pyrite, and that the "extra" sulfate, compared to the references, may be attributed to pyrite oxidation. The high values along the coastline are not explainable by acidic deposition and are attributed to local sources.

Nitrate determination was based on "Standard Methods". This method applies the highly toxic metal Cd as a reducing agent. Due to safety precautions, we modified the method for using Zn-powder as reductor. Zn is also an acknowledged reducing agent for nitrate determinations (e.g. Merino 2009), but the procedure is somewhat more complicated. It should also be noted that the Zn-reduction method has previously been included in "Standard Methods". The Zn-method was used for all nitrate determinations in the current study, including the references.

The nitrate values in Lake Vikastølvatn were about five times higher than in the reference samples. While the Vikastøl samples were collected largely during the winter and spring, the majority of the reference samples were taken during spring and summer. Normally, summer samples have low levels of nitrate due to biological activity. However, for oligotrophic lakes, a retention time of >0.3 years largely eliminates the seasonal variations for nitrate (Kaste et al. 2003). This is confirmed by data from several of the reference lakes. For Lake Sandvatn no significant differences between February- and August values were detected and in Lake Djupavatn low nitrate values were registered in April 2021. The national lakes survey in 2019 (Hindar et al. 2020) showed average nitrate (+nitrite) values of 27 µg/l and 35 µg/l for the regions Vestlandet and Sørlandet, respectively, a reduction of about 60% compared to 1995.

These values are only slightly lower than the nitrate values from the mountain references in the current study (lake averages: 36-90 µg/l). Thus, we suggest that the applied reference samples are fairly representative. Based on this, the nitrate levels in Lake Vikastølvatn are much higher than normal, and comparable to the levels found in the eutrophic Lake Hålandsvatn.

The nitrate concentrations measured at sites located below 400 m a.s.l. were high, up to 820 µg/l, but the values decreased with increasing altitude (Fig. 7d), to values as low as in the reference lakes. The water from the higher area was sampled during the late snowmelt. In the "tail" of the snowmelt, the meltwater is close to distilled water (Johannessen et al. 1980). Due to the small lakes with low retention times, nitrate may have been washed out by the melting water. Therefore, we cannot entirely reject the possibility that the high altitude lakes may periodically have elevated nitrate values.

In the multiple regression of ANC vs. Ca, NO_3, Cl, and SO_4*, no apparent effect of the latter was detected ($p>0.05$). This lack of relationship is assumably caused by intercorrelation effects. An inverse relationship between Cl and SO_4* was found ($r^2=0.44$, $p<0.001$, $n=48$). Harriman et al. (1995) observed the same effect in sea-salt exposed sites in NW Scotland and explained this effect with selective retention of acidic deposition in the soil. This effect caused low or even negative values for SO_4*. Due to ion exchange effects, high values for Cl may also be associated with low pH- and ANC-values (Hindar et al. 1994, Hindar and Enge 2006). These intercorrelation effects mask the acidification due to non-marine sulfate.

Regarding the acidification parameters, SO_4* in Lake Vikastølvatn was 0.3 mg/l (6 µeq/l) higher than in the natural ("pre-acidification") state, while the corresponding value for NO_3 was 23 µeq/l. This suggests that NO_3-acidification is the primary issue in the study area. The industry in this part of Rogaland County emits large quantities of NO_X. In the vicinity (radius 40 km) of the Vikastøl area, emissions representing 85% of the industrial NOx-emission in Rogaland County are located (norskeutslipp.no). However, assessing the influence on the local water chemistry requires detailed monitoring, where also meteorological data are considered.

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