Leakage water from rockfill dams and rock dumps – not always detrimental?

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Abstract

A number of potential negative effects on aquatic environments are associated with rockfills. In southwestern Norway, lakes and rivers downstream from large rockfills were among the very few sites where trout survived the acidification period. In this study, twelve rockfill dams, three rockfill dumps, several downstream locations and references were surveyed. High values for pH, Ca and alkalinity were detected in the leakage water from the dams, but the effects declined further downstream. Loss of alkalinity due to sulphide oxidation was established. The contribution of alkalinity from weathering always exceeded the alkalinity loss. Simulations suggest considerable positive downstream effects from the leakage at Deg dam for both periods 1986-1988 and 2017-2019. We conclude that rockfills have contributed to the survival of trout populations.

Sammendrag

Steinfyllinger er forbundet med en rekke potensielle negative effekter for akvatiske miljøer. I sørvest Norge var derimot nedstrøms steinfyllinger og i innsjøer med steintipper noen av de få stedene auren overlevde forsuringen. Tolv steinfyllingsdammer, tre steintipper, nedstrøms lokaliteter og referanser ble undersøkt. For pH, Ca og alkalitet ble det påvist høye verdier i lekkasjevannet fra dammene, men effektene avtok videre nedstrøms. Til tross for alkalitetstap som følge av oksidasjon av sulfid, var bidraget av alkalitet fra forvitring større, så nettoeffekten mhp. alkalitet ble positiv. Simuleringer viste betydelige positive nedstrømseffekter av lekkasjen fra Deg dammen for begge periodene 1986-1988 og 2017-2019. Vi konkluderer med at steinfyllingene har bidratt til å redde aurebestandene i området fra forsuringsdøden.

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Introduction

Rockfills are associated with many different kinds of pollution, such as particles, nitrogen compounds and metals. Moreover, rockfills are a potential source of sulfuric acid through the oxidation of sulphide minerals. This effect is common in the mining industry (Snoeyink and Jenkins 1980), where it is referred to as Acid Mine Drainage (AMD). Adverse effects of sulphide-oxidation have also been linked to other engineering and construction activities (Sørensen 1988, Hindar and Lydersen 1994, Hindar et al. 2015). Furthermore, acidification effects have also been reported from rockfill dams. Fell et al.

(2014) list several examples of acidic seepage caused by the oxidation of pyrite (FeS_2).

Acidification is not restricted to local sources. During the past century, atmospheric deposition of long-range transported sulphur- and nitrogen-compounds has severely affected surface waters throughout southern Norway. Waters in Sirdal and adjacent mountain areas in Rogaland are dilute and unbuffered and are therefore particularly sensitive to acidification (Enge 2013). In Sirdal, an emerging decline of the trout (*Salmo trutta*) populations was observed as early as during the late 1800s, possibly caused by effects of acidification (Enge et al. 2017). After the mid 1900s, the population decline accelerated, and in the late 1970s the vast majority of trout populations in Sirdal and adjacent mountain areas were considered lost due to acidification (Sevaldrud and Muniz 1980).

Surveys from southwestern Norway (Sevaldrud and Muniz 1980, Gunnerød et al. 1981) revealed that *all* trout populations adjacent to rock dumps and rockfill dams survived the acidification. Sporadic water chemistry measurements from dam leakages in the past decades showed higher pH, alkalinity- and conductivity-values than in the corresponding reservoirs (Enge 2009).

The primary aim of our study has been to establish the water chemistry effects of rockfill dams and rock dumps, and evaluate if these effects may explain the observed survival of trout.

Material and methods

Study area

The study comprises of rockfill dams and rock dumps within Rogaland and Agder counties that were built in the 1960s and 1970s in association with hydroelectric power development. The most comprehensive sampling was performed in Sirdal, within the Sira and Kvina watersheds. Two of the dams are among the largest in Norway, Svartevassdammen (120 m) and Deg (90 m).

Locations & sampling

Distinguishing between "leakage" and "seepage" requires more detailed data. Therefore, the general term "leakage" is consequently used in this study.

The survey included i) references, primarily sampled in the reservoirs, ii) leakage samples from 12 rockfill dams, iii) samples from downstream locations and iv) samples from three lakes affected by rock dumps.

With a frequency of 2-4 weeks, the sampling was conducted throughout June 2018 to March 2019. LDPE bottles (500 ml) were used for sampling, but were occasionally supplemented with HDPE bottles (250 ml). Samples were collected at the surface of the locations (lakes) or in flowing water (rivers&brooks). In December and January, some of the locations were ice-covered. Here, the water was sampled at 0.5m depth from a drill hole in the ice, using a "Ruttner" sampler.

Water chemistry analyses

pH was determined potentiometrically according to "Standard Methods", 4500-H^+ pH Value (Eaton et al. 1995). A Cole Parmer pH-meter equipped with a Radiometer pHC4001 electrode was used. The instrument was calibrated with standard buffers (pH 4.01 & 6.86). *Conductivity* was measured according to "Standard Methods" 2510, using a VWR CO310 conductometer for field measurements, and an Amber Science instrument was used for lab measurements. The two instruments were calibrated with solutions of KCl 718 µS/cm and NaCl 210 µS/cm, respectively. *Alkalinity* was determined by titrating the sample with 0.01 N H_2SO_4 (diluted from Merck "Titrisol" 0.1 N, verified by titration of certified Na_2CO_3). Samples with expected low alkalinity were titrated using 0.0025 N acid. A full titration curve was recorded for each of the samples, and interpolation of the curves yielded the titration volumes corresponding to the applied endpoint pH=4.50. For low alkalinity values, direct use of this endpoint causes an overestimation of the true equivalence alkalinity (Snoeyink and Jenkins 1980). To adjust for this overtitration, the formula derived by Henriksen (1982) was applied:

$$ALK_E = ALK_{4.5} - 32 + 0.646 \times SQRT(ALK_{4.5} - 32)$$

(ALK_E is the equivalence alkalinity, $ALK_{4.5}$ is the alkalinity corresponding to an endpoint of pH=4.5, units: µeq/L)

Calcium, sodium and chloride were measured potentiometrically using Radiometer ionselective electrodes (ISE) according to the manuals. The determination of *Σcations* was based on the ion exchange method described by Vogel (1961), which recommends H^+ ion exchange followed by strong base titration, and subsequently adjusting the result for the loss of alkalinity. In this study, sodium ion exchange was used (Amberlite IR120 Na^+), removing the need for alkalinity adjustment. *Sulphate* was determined by conductometric titration with barium acetate, modified from Vogel (1961). The samples were pretreated by sodium cation exchange to eliminate interferences from divalent cations. Isopropanol (p.a.) was added to reduce the solubility of the precipitate (v/v=2:1). The conductivity titration curve was recorded using a Greisinger GLF 100 RW conductometer. *Fluoride* was measured photometrically using the SPANDS-method ("Standard Methods" 4500-F^- D). Absorbance was measured at 570 nm in 10 mm polystyrene cuvettes with a Shimadzu spectrophotometer (UV-120-01). *Quality:* Quality controls were performed using i) internal standards (pH, Ca, Na, Cl & SO_4), ii) certified reference material (ALK & Na), and iii) measuring duplicates (conductivity, F & SO_4). Based on the 130 samples with sufficient data, cation-anion balance for

Dam at Roskreppfjord

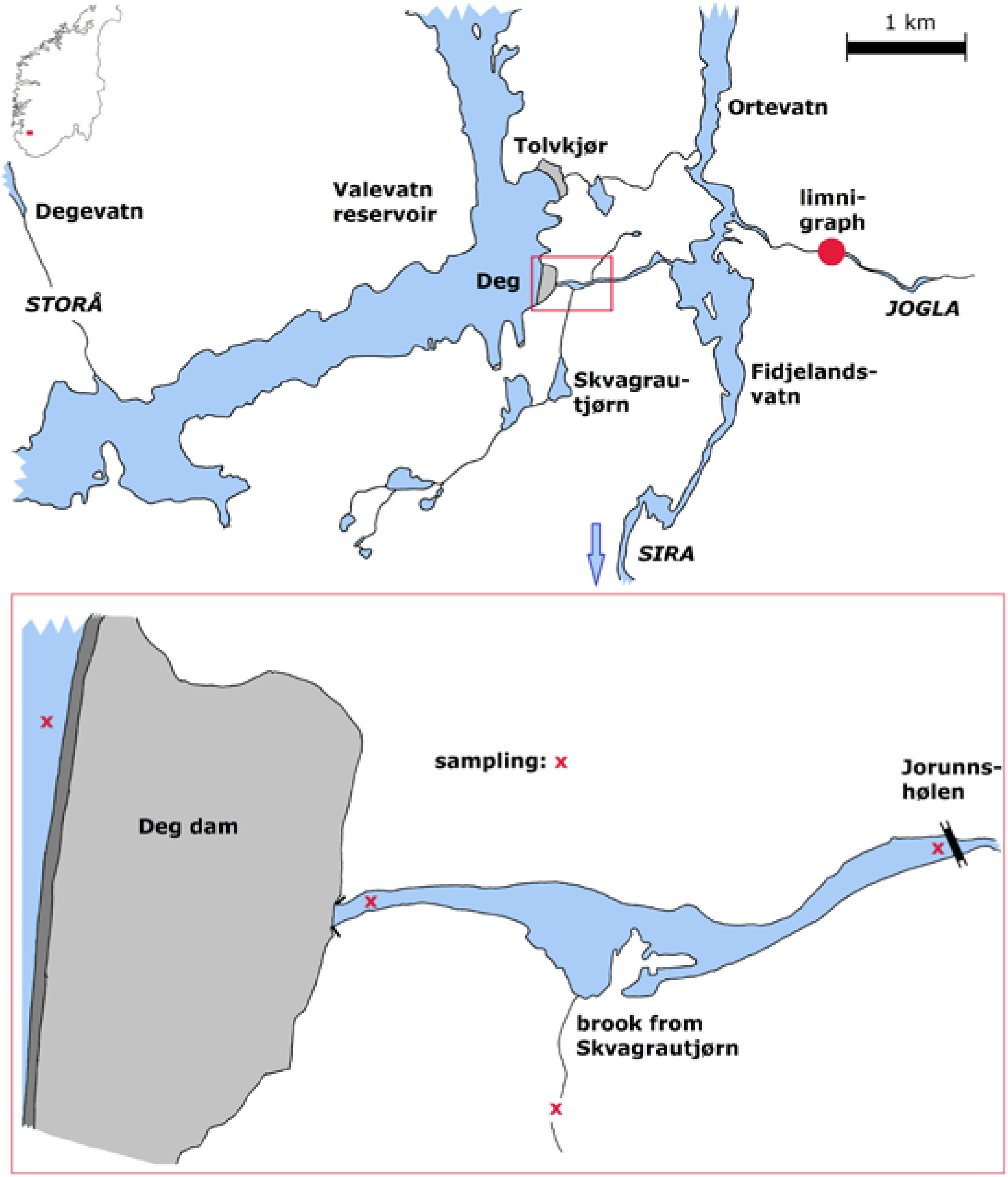

Figure 1. Deg dam and adjacent areas

all of them was well within the acceptance limits given by Eaton et al. (1995).

Alkalinity calculations

The original alkalinity "ALK_0" was calculated as the sum of non-marine base cations. The data from the direct determination of *Σcations* were applied. Here, the marine ion contribution was estimated using the relative ratio to chloride (Skartveit 1981). ALK_0 may also be estimated by the approximation $ALK_0 \approx 1.21$ x non-marine calcium (Henriksen 1980). These two methods were compared. The loss of alkalinity was calculated as the difference between original and measured alkalinity.

Simulations of water chemistry

Models were used to evaluate the suitability of the water chemistry for brown trout downstream from dams. Here, the leakage from the Deg dam was used as a case (fig. 1). Calculations were made for Jorunnshølen, located 350 m downstream of the dam. Jorunnshølen has a local catchment of 2.91 km^2 with an annual average runoff of 125 L/sec (nve.no), while the leakage contributes with 3.6±0.9 L/sec, n=305 (Per-Magne Sinnes, Sira-Kvina Power Company, pers.com.).

The simulations were performed according to Enge and Hemmingsen (2010), using flowrate data and mass flux of calcium. To calculate the flowrate at Jorunnshølen, the daily measurements from the adjacent limnigraph "Jogla" (nve.no) were downscaled with respect to average runoffs from the two catchments. Empirical relations were used to estimate pH from calcium values. The simulations were compared to observations. Here, data from the 1980s, retrieved from Enge (2009), was also included. To achieve comparable periods which include all observations, the periods March 1986-1988 and March 2017-2019 were chosen. The first period represents a period highly affected by acidification, while the latter period represents the most recent data.

Results

General water chemistry

The study included a total of 217 water samples (tab. 1). The reference samples had an uniform water chemistry; slightly acidic and extremely dilute (pH=5.64±0.18, Ca=0.25±0.14 mg/L, n=44). For all parameters, higher values were found in the leakage water compared to the references (p<0.001). With average values of approximately 50 times the references, alkalinity and calcium concentrations were particularly elevated compared to the references. Three of the samples from the Deg dam were collected inside the dam, in the concentrated leakage. Average pH and calcium were 7.34±0.10 and 15±2 mg/L, respectively. This average value of calcium was used in the simulations. Downstream sites and lakes with rock dumps were sufficiently buffered to sustain pH-values of about 6 (tab. 1). However, the latter is a non-homogeneous group, including lakes with Ca-values ranging from 0.33±0.03 mg/L, n=4 (Ognhellervatn) to 5.0±0.3 mg/L, n=3 (lake at Kvinen power station).

Acidification

No difference was detected between ALK$_0$ determined as the sum of non-marine cations and determined as 1.21 x non-marine calcium (p>0.05), (fig. 2a). The loss of alkalinity was highly correlated with non-marine sulphate (r^2=0.99, p<0.001, n=130). The perfect 1:1 relationship (fig. 2b) suggests that sulfuric acid was causing the loss of alkalinity.

Considerable differences were observed between the dams regarding alkalinity and alkalinity loss (fig. 3). Despite this loss, the overall contribution of alkalinity from weathering of dam material exceeded the acidification. The remaining alkalinity was sufficient to sustain a pH>6.5 in 77 of the 88 samples from the dams. The sum of non-marine cations increased with increasing sulphate (r^2=0.57, p<0.001, n=85).

Table 1. Average values for all samples

Sample type	n	pH	Cond.	ALKe	Ca	Cl	Na	SO$_4$	F	ΣCAT
	samples		µS/cm	µeq/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L
Dams & leakages	88	7.13	87.0	412	12.9	2.2	1.8	13.5	0.33	0.82
Downstream dams	72	5.91	19.6	68	1.5	1.9	1.4	(3.4)	(0.10)	(0.28)
Lakes (rock dump)	13	6.18	20.2	76	1.7	1.9	1.3	2.9	0.12	0.23
References	44	5.64	9.9	8	0.25	1.6	1.0	(0.8)	(0.03)	(0.11)

Brackets (): Parameter analyzed for 1/3 of the samples

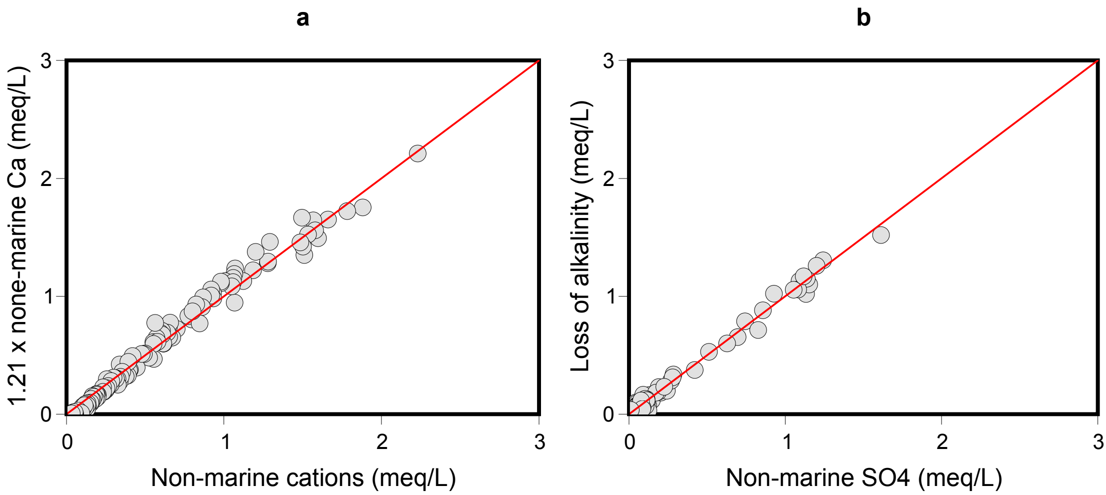

Figure 2. There was no difference between non-marine cations and 1.21 x non-marine Ca (a). A 1:1 relation between non-marine sulphate and loss of alkalinity was found (b). (Lines=1:1)

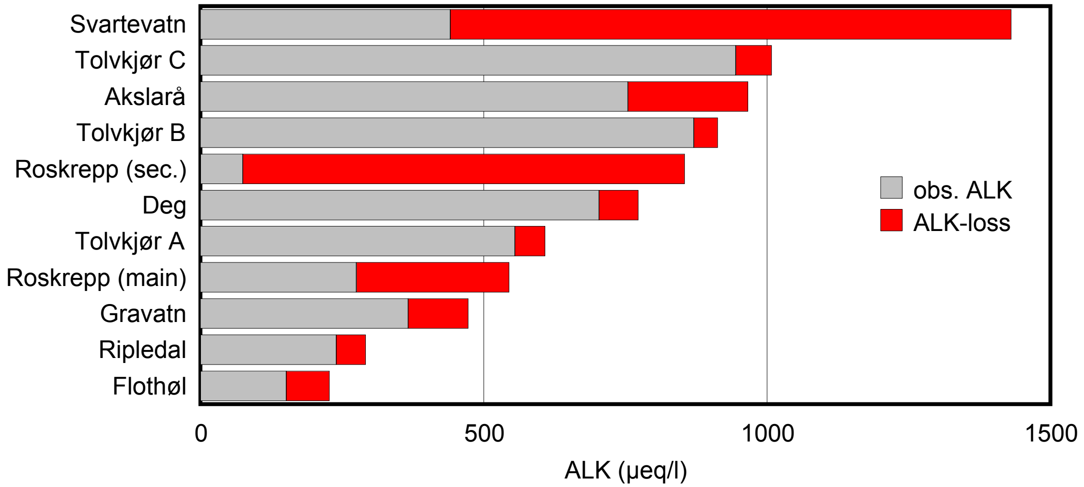

Figure 3. Considerable differences in alkalinity were detected, exemplified by dams in Sira and Kvina. The figure shows the original alkalinity (ALK$_0$) as the sum of present alkalinity and alkalinity loss.

Both pH and alkalinity-values have increased in the past 30 years. For calcium-values of 1 and 10 mg/L in Jorunnshølen, the increases in alkalinity were 11 and 162 µeq/l, respectively (fig. 4a). The corresponding values were +0.24 and +0.53 for pH (fig. 4b).

Simulations

No differences between simulated and observed pH were found (fig. 5) (p>0.05). The simulations showed a pH increase of about 0.3 units from the period of 1986-1988 to 2017-2019 (tab. 2). The fraction of pH-values <5.5 were 24% and 14%, respectively. Only negligible differences were found between the minimum values. Limited differences for calcium between the two periods were observed (tab. 2).

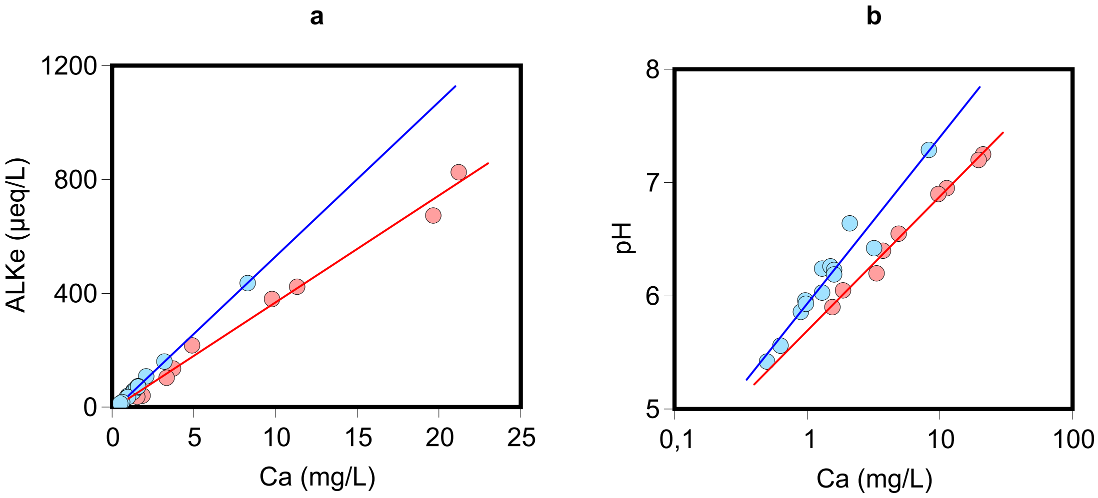

*Figure 4. pH, Ca and alkalinity data from Jorunnshølen. Red and blue colours represent data from 1986-1988 and 2017-2019, respectively. The differences (blue-red) in the empirical relations ALK vs. Ca (**a**) and pH vs. Ca (**b**) reflects reduced acidification between the two periods.*

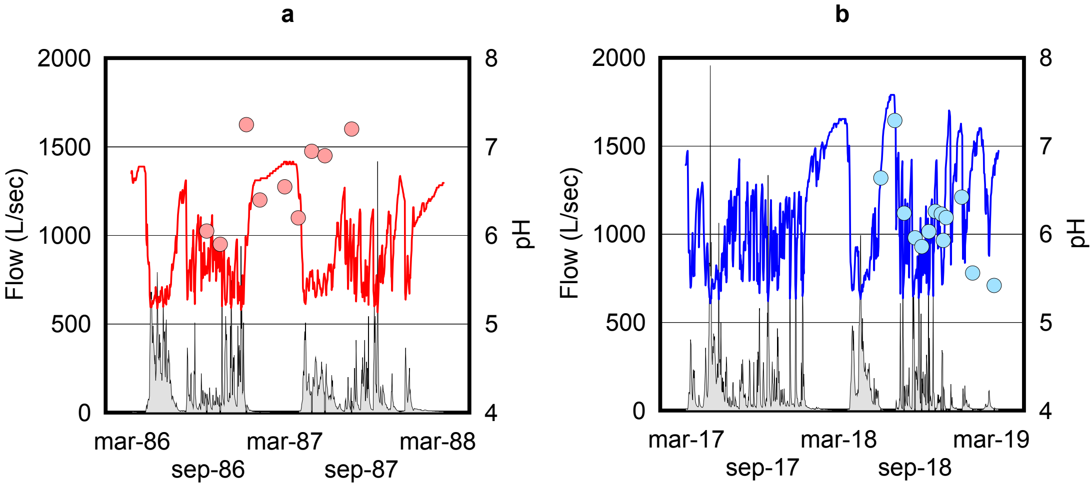

*Figure 5. Simulations of pH-values at Jorunnshølen. Figures **a** (red) and **b** (blue) blue represent data from 1986-1988 and 2017-2019, respectively. In figs. **a**&**b** lines, dots and "area" represent simulated pH, observed pH and flowrates, respectively.*

Table 2: Results from simulations of water chemistry at Jorunnshølen.

Parameter		**1986-1988**	**2017-2019**
Flow (L/sec)		103	113
pH	Average	5.98 ± 0.53	6.27 ± 0.64
	Minimum	5.13	5.22
Ca (mg/L)	Average	2.87 ± 2.69	2.77 ± 2.85
	Minimum	0.34	0.33

Discussion

This study established that the surveyed dams and rock dumps had a net buffering effect on adjacent waters.

The bedrock in the mountain areas of southernmost Norway consists mainly of slow weathering rock types such as gneiss and granite (ngu.no). Normally, this leads to highly dilute water chemistry with low levels of calcium. In Rogaland County, lakes located at an altitude of > 500 m a.s.l. showed a median calcium value of 0.23 mg/L (Enge 2013), fairly equal to the results from the current study (tab. 1). The dam leakages, exposed to the same geology, showed an average of 12.9 mg/L. This effect is probably due to the processing of the rock used in the dams. Particle breaking and fracturing enhance weathering rates by increasing the surface area and exposing fresh mineral surfaces to air and water (Price 2009).

The positive correlation found between sulphate and non-marine cations suggests that sulphuric acid has accelerated the mobilization of cations. Acid increases the rate of chemical weathering, even for slow weathering rocks such as granite (Webb 1980). However, relatively high concentrations of cations were found even at low sulphate levels, suggesting that the presence of sulfuric acid has not been critical for the observed weathering.

Differences in water chemistry enrichment between the dams, such as increases in cation concentrations, depend on factors such as geology, size and geometry of the dams. The latter two factors indirectly determine contact time and path length of the leakage. Tolvkjør dam (fig. 1) has a complicated geometry. Three separate leakages from this dam were surveyed. The leakage associated with the longest base width had twice the alkalinity than the leakage with the shortest width (fig. 3).

Substantial differences in acid production were detected (fig. 3). This does not entirely depend on the presence and availability of sulphi-

Deg dam March 2019. (illustrasjonsbilde) des in the dam material, but may also be linked to the age of the dam. A gradual decrease in acidity has been observed at Corin dam in Australia, which contains about 1% pyrite (Fell et al. 2014). Except for the Flørli dam, all dams in our study were built throughout the same period, about 50 years ago, indicating that ageing does not explain the differences in acidity between the dams.

Due to a constant leakage rate from Deg, and a highly variable flowrate from the Skvagrau catchment, the mixing ratio ranged from 0.2%-88% Deg-water at Jorunnshølen (fig. 1). When the water from Deg predominates, high calcium-values are measured at Jorunnshølen. For these high calcium-values, a substantial increase in pH and alkalinity have been observed throughout the past 30 years (fig. 4), presumably due to declining acidification from the dam (c.f. Fell et al. 2014). Low calcium-values, in contrary, indicate the dominance of dilute water from the Skvagrau catchment. In case of low calcium-values, a moderate improvement in the water chemistry has been observed (fig. 4), in line with the general improvement of the water chemistry in this area during the past decades (Enge 2013).

Prior to the Sira-Kvina regulation, Storå (fig. 1) contributed 3/4 of the total runoff from Valevatn. Therefore, the water chemistry in Storå is most likely representative for Valevatn. Storå has been monitored for 35 years. During the five-year period from 1985 to 1989, pH was 4.77±0.12, n=26 (Enge et al. 2016). Without regulation and "liming-effect" from the dam, we may assume that such detrimental water chemistry would have dominated the entire river stretch from the dam and downstream to Fidjelandsvatn during the 1980s.

A fish survey in 1987 (Larsen et al. 1989), found that the trout population in Valevatn (fig. 1) was extinct while Ortevatn had a reduced population. However, the lake downstream of these two, Fidjelandsvann (fig. 1), had a dense population of trout. Recruitment in the river downstream Jorunnshølen was also established. Young trout were hardly detected elsewhere in

Leakage from Svartevassdammen. (illustrasjonsbilde) this part of Sira. The simulations showed pH=5.98±0.53 and pH_{min}=5.13 in Jorunnshølen during 1986-1988 (tab. 2). Even the minimum pH was not critical for trout. Moreover, this is a "worst-case scenario". The applied model simulates mixing of water chemistries only (Enge and Hemmingsen 2010), and does not consider the levelling effect, caused by an eventual water volume at the mixing site; in this case Jorunnshølen.

Fish actively avoid adverse water chemistry and migrate towards better water chemistry (Peterson et al. 1988). Even if detrimental water chemistry had occurred due to acidic water from the local catchment (Skvagrau), the trout could easily have migrated towards Deg (fig. 1). Therefore, we suggest that the population downstream of Deg survived due to the water chemistry effects of the dam. Between Jorunnshølen and Fidjelandsvatn there are excellent spawning sites for trout. Subsequently, the effects of the dam may also have sustained the dense population of trout in Fidjelandsvatn at a time when neighbouring lake populations were either extinct or reduced.

In lakes affected by rock dumps, the liming effects are often diluted due to large lake volumes. The survival of the trout in such lakes, e.g. Ognhellervatn, is probably due to slightly better water chemistry around the dumps.

Even though pronounced acidification was detected inside the dams, the net effects on pH and alkalinity were positive. Downstream sites and lakes affected by rock dumps had also satisfactory water chemistry. Therefore, rockfills should be subjected to careful evaluation, rather than be viewed as inherently detrimental. However, it should be noted that despite the positive effects on fish, the dams and rockfills have created an "unnatural" water chemistry with considerably higher calcium-values than the adjacent waters.

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