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Assessment of risks to drinking water provision in Glitrevann from forest fertilization and harvesting

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REPORT

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Summary

Forest fertilization is planned in the Glitre catchment, an important drinking water source for the Drammen region. In this report, we explore whether fertilization is likely to put drinking water provision in the catchment at risk over the short term, as well as longer-term risk associated with fertilization and forest harvesting. Overall, we find there is little risk of forest fertilization reducing the water quality in Glitrevann, provided the forest management plans provided by Statskog are followed, together with fertilization and harvesting best management practices (as outlined in the Norwegian PEFC Forest Standard). We recommend routine stream monitoring be carried out during and for several years after harvesting to screen for potential effects.

Four keywords	Fire emneord
1. Forest fertilization	1. Skoggjødsling
2. Nitrogen	2. Nitrogen
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Assessment of risks to drinking water provision in Glitrevann from forest fertilization and harvesting

Preface

This report constitutes the main output from Task 3 of the SURFER project, a project funded by the Research Council of Norway under the KLIMAFORSK program. This report is also a deliverable to the Nordic Centre of Excellence Biowater (Integrating land and water management for a sustainable Nordic bioeconomy, project no. 82263).

The two key stakeholders involved in Task 3 of the SURFER project were Glitrevann water works and Statskog. Glitrevann provided the monitoring data, which forms the basis of the analyses carried out in the report. Jarle Eirik Skaret at Glitrevann was particularly helpful in providing data, background information on the catchment, and guided tours of the site, whilst Mildred Solem provided valuable comments on an earlier draft of the report. Statskog, in particular Rune Holmøy Aamold provided detailed information on forest fertilization during summer 2017, forest management scenarios for the next 70 years, and comments on an earlier draft of the report.

Leah Jackson-Blake led Task 3 and carried out the analyses, together with Francois Clayer. Dick Wright provided MAGIC modelling assistance and general advice. Salar Valinia was involved in the design of Task 3 and stakeholder interactions, particularly at the start of the project. Both authors contributed to writing the report.

Grimstad, January 2020

Leah Jackson-Blake

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Summary

Regular forest fertilization is planned in the Glitre catchment over the next 100 years to increase forest productivity. The catchment (45 km^2) is an important drinking water source, and in this report we explore whether fertilization is likely to impact drinking water provision. A small area of the catchment (0.675 km^2, or around 4% of an 18.6 km^2 subcatchment) was fertilized in June 2017, and surface water quality monitoring data from before and after fertilization allowed us to look for short-term nitrogen (N) leaching effects. Potential longer-term fertilization and harvesting effects were explored through a consideration of the nitrogen budget for the catchment and how this might change in the future, making use of process-based modelling results from a similar Norwegian catchment.

The main findings and recommendations include:

- Some evidence was found for leaching of nitrate immediately post-fertilization in June 2017, but this was small and short-lived. Short-term leaching is not expected to be a problem in the future as long as fertilization plans are adhered to and repeat fertilization of the same parcel of forest is avoided. The planned fertilization rate is around 25 ha (around 0.5% of the catchment area) once every five years at 150 kg N/ha.
- Forest harvesting results in an increase in nitrogen delivery to Glitrevann. This can be seen at present: Guritjernsbekken, where clear-felling occurred in recent years, has higher total N and nitrate concentrations than the other monitored tributaries.
- Future forest harvesting plans provided by Statskog include 1 km^2 around 2050 and 5 km^2 around 2070. Modelling studies suggest this could result in up to a 20-23% increase in N export to the lake compared to background (i.e. no harvesting) levels over 2017-2090. Forest fertilization is expected to increase the harvesting-related N flux by an additional 5% of natural levels (i.e. total N export to the lake could be 25-28% higher than background levels). Harvesting is likely to impact water quality for 10-15 years, with the most pronounced effects within the first 5 years following harvest. These estimates are worst-case, as they are based on modelling results in a more sensitive catchment and do not take into account in-stream N removal.
- If intensive harvesting at a rate of 1 km^2/year is maintained for 5 years or more, future increases in lake total N concentration associated with harvesting could cause a shift in the lake ecological status from ‘Good’ to ‘Moderate’ (according to the Water Framework Directive). Associated with this, algal biomass could increase by a factor of 2 to 5. The catchment is not particularly acid sensitive (acid neutralising capacity of 120 µeq l^{-1} and pH of 6.5), and harvesting is likely to have a limited effect on lake acidification.
- The duration of harvesting is very important in terms of water quality effects, with more pronounced effects expected when larger areas are cut over shorter time periods. To protect the lake from harvesting-associated nitrogen fluxes (and associated in-lake effects such as an increase in nitrate concentration and algal biomass), harvesting intensity should be less than 1 km^2/year (2.2% of the catchment area).
- To screen for harvesting-associated increases in N inputs to the lake, we recommend routine monitoring of tributaries downstream of areas affected by harvesting during and for several years post-harvest, accompanied by monitoring of a reference tributary that is unaffected by harvest (e.g. upstream of the harvested area, or in a nearby tributary) to be able to differentiate between harvesting and climatic effects.

- Harvesting practices play a key role in determining lake response to fertilization and harvesting, e.g. site preparation, soil protection and presence/absence of buffer strips along streams and lake shores. Taking appropriate soil protection measures and using appropriate buffer strips during harvesting are among the most important ways of preventing excessive N and carbon inputs to surface waters and could potentially be improved in the catchment, for example by extending the use of buffer strips to non-permanent water courses (i.e. beyond the requirements of the Norwegian PEFC Forest Standard). Careful timing of harvesting-related activities is also important, in relation to ground conditions (and associated damage from heavy machinery) and forecasted rainfall or snow melt.

Sammendrag

Tittel: Vurdering av risiko for drikkevannsforsyningen fra Glitrevann knyttet til skoggjødsling og hogst
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Statskog har laget en langtidsplan for gjødsling i nedbørfeltet til Glitrevann for å øke skogproduksjonen. Innsjøen er en viktig drikkevannskilde, og hensikten med denne rapporten er å undersøke om skoggjødslingen kan påvirke vannkvaliteten. Et lite område innenfor nedbørfeltet (0.675 km^2, ca. 4% av et 18.6 km^2 delnedbørfelt) ble gjødslet med nitrogen i juni 2017, og overvåking av innløpsbekkene og i Glitrevann før og etter gjødslingen gjorde det mulig å studere om tiltaket hadde noen umiddelbare effekter på vannkvaliteten. Potensielle langtidseffekter ble vurdert ved å sette opp et nitrogenbudsjett for nedbørfeltet samt å bruke resultater fra et modelleringsarbeid som nylig er gjennomført på et lignende norsk skogfelt.

De viktigste resultatene og anbefalingene fra utredningen knyttet til Glitrevann er:

- Det ble kun registrert en liten og kortvarig lekkasje av nitrat etter gjødslingen i juni 2017. Det forventes derfor heller ikke problemer i forbindelse med gjødsling i tiden framover, så lenge gjødslingsplanene blir overholdt og en unngår spredning i buffersoner mot vassdrag eller på arealer som er gjødslet tidligere. I henhold til planen skal det gjødsles omkring 25 ha (ca. 0.5% av nedbørfeltet) hvert femte år og med en dose på 150 kg/ha.
- Hogst fører til økt nitrogenavrenning til Glitrevann. Dette er illustrert gjennom en nylig gjennomført hogst i nedbørfeltet til Guritjernsbekken, og hvor det nå måles høyere konsentrasjoner av nitrat og totalt nitrogen enn i de andre innløpsbekkene til Glitrevann.
- Statskog planlegger å hogge ca. 1 km^2 skog i tiden rundt 2050 og ca. 5 km^2 i tiden rundt 2070. Modellberegninger tyder på at dette kan resultere i en 20-23% økning i nitrogen-tilførslene til innsjøen over perioden 2017-2090. Dersom skogen er gjødslet på forhånd, vil tilførslene kunne øke med ytterligere 5%, dvs. til 25-28% i forhold til dagens bakgrunnsnivå. Hogst er antatt å kunne påvirke vannkvaliteten i 10-15 år, men med de største effektene i løpet av de fem første årene. Det bemerkes at disse estimatene representerer et «worst-case»-scenario, i og med at de er basert på modellstudier i et mer forsuringsfølsomt område (Sørlandet) og at de ikke tar hensyn til bekkenes naturlige selvrensingsevne (kapasitet til å holde tilbake nitrogen).
- Dersom det gjennomføres intensiv hogst tilsvarende en avvirkning på 1 km^2/år i løpet av en femårs-periode, vil konsentrasjonen av totalt nitrogen kunne øke til et nivå som endrer innsjøens økologiske status fra «god» til «moderat» i henhold til Vannforskriften. Biomassen av alger vil også kunne øke med en faktor fra 2 til 5. Nedbørfeltet er ikke særlig forsuringsfølsomt (acid neutralising capacity på 120 µeq l^{-1} og pH på ca. 6.5), og hogst-aktiviteten vil sannsynligvis ikke ha nevneverdig effekt på forsuringstilstanden i innsjøen.
- Omfang og varighet av hogst-aktivitetene er viktig i forhold til hvor store effektene kan bli på vannkvaliteten. De største effektene vil oppstå dersom store arealer blir hugget i løpet av kort tid. For å beskytte drikkevannskilden mot uakseptabelt høye nitrogen-tilførsler og risiko for algeoppblomstringer anbefales det at hogst-intensiteten holdes under 1 km^2 per år (2.2% av nedbørfeltet).

- For å dokumentere en eventuelt hogst-relatert økning i nitrogen-tilførslene til Glitrevann anbefales det rutinemessig overvåking av påvirkede tilløpsbekker både under selve hogsten og flere år i etterkant. Samtidig, anbefaler vi overvåking av en uberørt referansebekk i nærheten, for å kunne skille mellom hogst og klimatiske effekter.
- Hogstmetode spiller en viktig rolle i forhold til hvor store effektene på nedenforliggende vannforekomster vil være. Tiltak for å beskytte skogbunnen mot kjøreskader og etablering av buffersoner mot bekker og innsjøer vil være viktig for å unngå unødvendig høye tilførsler av nitrogen og karbon til nedenforliggende vannforekomster. Gitt viktigheten av nedbørfeltet som drikkevannskilde, anbefaler vi å utvide bruken av bufferstriper til ikke-permanente vannløp (dvs. utover kravene i Norsk PEFC Skog Standard). Valg av tidspunkt for hogst-relaterte aktiviteter er også viktig, i forhold til grunnforhold (risiko for kjøreskader) og forventet nedbør eller snøsmelting.

1 Introduction

1.1 Background

Norway aims to transition towards a low carbon emission society and forestry has been identified as one of the main sectors that can contribute to this transition, through carbon sequestration in tree biomass. To encourage forest intensification, the Norwegian government has therefore provided forest owners with financial measures to support activities which will lead to an increase in forest biomass. A key measure receiving funding is forest nitrogen fertilization, which is carried out 10-15 years before harvesting to increase tree biomass.

While the carbon benefits of more intensive forestry are widely discussed, there are potential negative consequences. As well as concerns about reacidification of sensitive soils and waters, there are worries about the effects of more intensive forest management on water quality in drinking water reservoirs. Norwegian experiments conducted in the 1970s, for example, documented negative effects of forest harvesting on water quality, with potential implications for drinking water supply, particularly when treatments were used over large portions of catchments (Haveraaen, 1981).

This study is focused on assessing the potential effects of forest fertilization on surface water quality in the Glitre catchment in southern Norway. Statskog, the Norwegian state-owned land and forest enterprise, owns much of the Glitre catchment, and they plan to fertilize forest in the catchment over the coming decades with the aim of increasing forest productivity. The main lake in the catchment, Glitrevann, is an important drinking water source for the Drammen region, and there are concerns about the potential impacts of forest fertilization on drinking water provision. There is therefore a need to assess the impacts of forest management on drinking water in the catchment, and provide recommendations that will ensure safe provision of drinking water in the future.

1.2 Study aims and approach

Over the short term, fertilization could lead to immediate leaching of fertilizer nitrogen (N) into surface waters. Studies elsewhere suggest this leaching is unlikely to be large (Binkley *et al.*, 1999, Nohrstedt, 2001), but given the importance of the Glitre catchment for drinking water provision, there is a need to check that impacts are also likely to be small here. A small area (67.5 ha) of the Glitre catchment was fertilized with a one-off application of mineral nitrogen fertilizer in summer 2017, and in this report we compare surface water monitoring data from before and after fertilization, between monitoring points upstream and downstream of the fertilized area, and between the fertilizer-affected tributary and tributaries elsewhere in the catchment, to screen for any immediate, short-term effects.

Over the longer term, forest harvesting brings about an increase in N mobilization and transport from soils to surface waters (de Wit *et al.*, 2014, Gundersen *et al.*, 2006, Kreutzweiser *et al.*, 2008). N fertilization is not associated with increased harvesting intensity, but it does increase the biomass that is harvested, and there is potential for increased N mobilisation and transport from soils. Here, we combine a nitrogen budget for the catchment with process-based modelling results from a similar catchment to derive future scenarios of changing nitrogen loading to the lake, and potential associated risks to drinking water quality. Results are put into context in terms of increases in nitrogen concentrations currently visible in one of the Glitre stream tributaries due to clearcutting during the last decade.

The report is structured as follows: after presenting the study site and available data (Section 2), we construct a nitrogen budget for the catchment for the present day, excluding forest management as a factor, using monitoring data and a literature review (Section 3). We then estimate short-term effects of the 2017 fertilization on nitrogen leaching from the catchment, using monitoring data from the catchment (Section 4). Potential longer-term effects of forest fertilization and subsequent harvesting are explored in Section 5, based on future forest management scenarios provided by Statskog. Here, effects of forestry practices with and without fertilization on nitrogen leaching are compared using a modelling approach. In addition, empirical data from a subcatchment in Glitre that was partially harvested between 2014 and 2019 are used to asses nitrogen export from a catchment after recent harvesting. Results are put into context in terms of how sensitive Glitrevann is likely to be to changes in nitrogen inputs in terms of acidification and algal growth (Section 6). Finally, we present recommendations for fertilization and forest harvesting practices to safeguard drinking water in the catchment (Section 7).

1.3 A note on units

Two units of area are used throughout the report:

Short name	Long name	Equivalent to
ha	hectare	1 ha = 10 da or 0.01 km^2
km^2	square kilometres	1 km^2 = 100 ha or 1000 da

2 Study catchment and available data

2.1 Overview of the catchment

Glitrevann lies in the Finnemarka hills northwest of Drammen, in Buskerud county. The lake has a shallow dam and is used to provide drinking water to around 140,000 inhabitants in the Drammen region. It has an area of 3.68 km^2, a volume of 0.111 km^3 and is on average 31 m deep (maximum depth 89 m). The lake lies at an altitude of 360 m and its surrounding catchment (around 45 km^2; Figure 1) is mostly forested, much of which is owned by Statskog. There are no permanent residents in the catchment, though there are several recreational cabins. The catchment is used for sheep and cow grazing in summer. The geology of the area is predominantly basaltic and granitic bedrock, which is generally hard-weathering and acidic. The catchment is protected due to its value as a drinking water source. Glitrevannverket is the water company responsible for drinking water provision and treatment from Glitrevann (and several other lakes in the area).

Forestry activities in the catchment are carried out in accordance with the Norwegian PEFC Forest Standard for sustainable forestry, and the property is FSC-certified. Current forestry activities include clearcutting and thinning (Figure 2), and around 4 km^2 of forest was harvested in the past ten years (R. Aamold, pers. comm. 2019). Stem-only harvest is the norm (stems are harvested and branches are left in the catchment). Most harvesting is performed with heavy motorised vehicles, aside from small amounts of thinning in steep or remote terrain (J. E. Skaret, pers. comm). Adherence to Norwegian PEFC Forest Standard guidelines involves measures to minimise soil erosion and runoff to surface water. However, the standards apply to larger streams, not streams which are likely to run dry. Some harvest-related soil disturbance was evident during a site visit in November 2019, including alongside smaller (potentially non-permanent) watercourses (Figure 2).

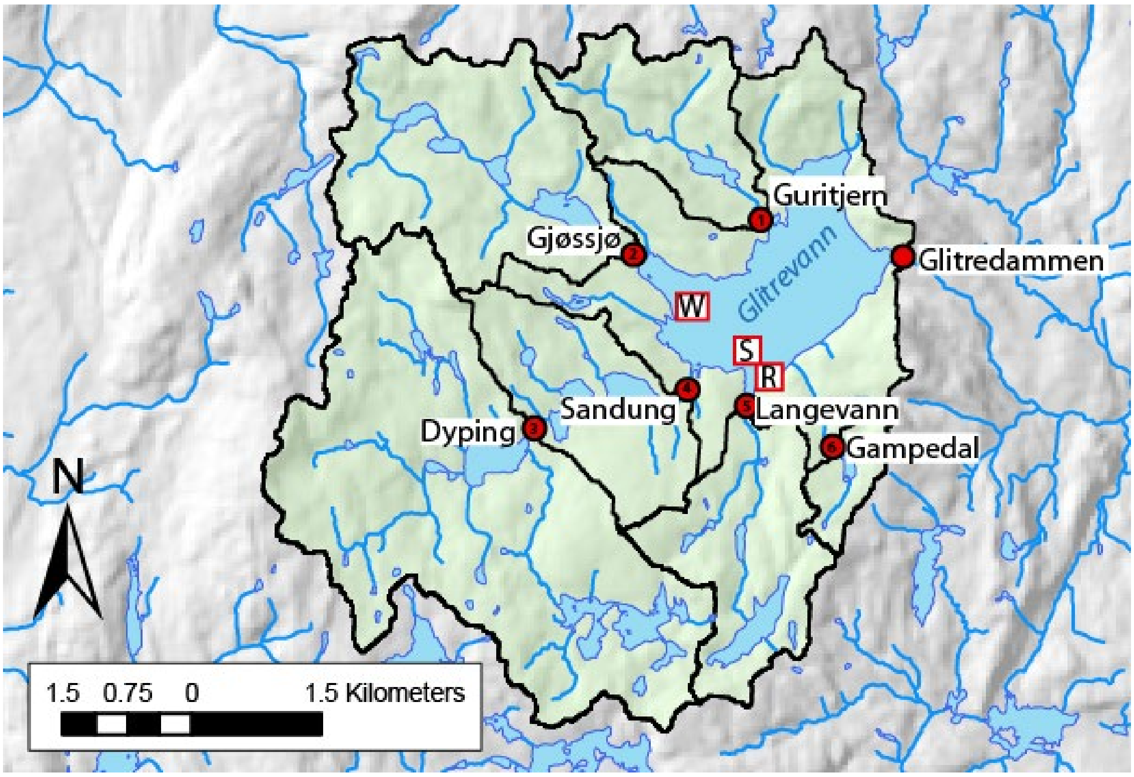

Figure 1: Glitrevann, its catchment, and the main tributaries and associated sub-catchments. Red spots mark stream sampling points, red squares mark lake monitoring points (R: raw water intake, S: south Glitre, W: west Glitre sampling points).

Monitoring point	Sub-catchment area (km^2)
1. Guritjernsbekken	3.4
2. Gjøssjøbekken	7.0
3. Dypingbekken	14.6
4. Sandungsbekken[a]	18.6 (includes Dypingbekken sub-catchment area; 4 km^2 otherwise)
5. Langevannsbekken	4.2
6. Gampedalsbekken	0.9
Glitredammen (including lake area)	45.1
Glitredammen (excluding lake area)	41.4
Elgtjernsbekken NVE[b]	7.1

Table 1. Sub-catchment areas upstream of the stream water quality monitoring points (see Figure 1 for location of monitoring points). [a]Majority of 2017 fertilization was upstream of this monitoring point, and below Dypingbekken. [b]NVE discharge monitoring point; no chemistry data available and lies outside the catchment, so not shown on Figure 1.

Figure 2: Recent forestry activity in the Glitre catchment. Top left: clear cut near the northernmost point of Glitrevann (October 2019). Top right: close to Guritjernsbekken (within the last 5 years). Bottom left: a recently thinned parcel close to Gjøssjøbekken (2019). Bottom right: a half-mature parcel. Source: NIVA

2.2 Water chemistry data

To check for any short-term flush-through effects of forest fertilization, Glitrevann water works started regular monitoring of all the main tributary streams to the lake in summer 2016, as well as in the lake itself (Figure 1). Sub-catchment areas upstream of each monitoring point are given in Table 1. Particular attention was paid to collecting samples immediately after rainfall events, to capture possible nutrient peaks. Most of the sampling took place in autumn/winter 2016 (5 samples) and 2017 (16 samples), with lower-frequency sampling in 2018 (4 samples) and 2019 (1-4 samples, depending on location and chemical variable).

An additional lake sample was collected by NIVA in October 2019, and analysed for major cations and anions to allow acid neutralising capacity (ANC) to be calculated. This provides an indication of the buffering capacity of the lake and its sensitivity to acidification.

A small amount of data was also gathered in 2002 and 2003 from a sub-set of streams in the catchment, as well as a small amount of total organic carbon (TOC) data from 1998-2001, but because of the sparsity of this data it is not used here.

2.3 Hydrology data

Discharge data are needed to calculate fluxes of nitrogen to the lake. NVE monitors discharge at Elgtjern (station ID 11.4.0, 59.88943°, 10.08316° E), just northeast of Glitrevann's catchment. According to NVE, the Elgtjern catchment is predominantly forested, with 8% lake and has similar geology to Glitre, and so discharge characteristics should be comparable. The monitoring data covers the period autumn 1975 to present (data to the end of 2018 was available for download when this report was prepared). Over this period, median annual specific discharge was 646 mm/year. Discharge was estimated for each of the stream monitoring points by area-scaling this Elgtjern NVE data.

3 Nitrogen budget for the catchment under current forest management

3.1 Overview of stream and lake chemistry

At present, Glitrevann's water quality is very good and well-suited to drinking water. The Secchi depth is around 9-10 m, concentrations of nutrients (total N and P) and major anions and cations are low, and there is little humus, sediment, algae or bacterial contamination (Berge *et al.*, 2004). pH is around 6.5, on the lower boundary of the recommended range for drinking waters in Norway (6.5-9.5), but the ANC is around 120 µeq l^{-1}, implying relatively low sensitivity to acidification. Oxygen concentrations in deep water are high (>70% saturation), even at the end of winter and summer stagnation. Water colour is around 10 mg Pt/l at depth, well below the Norwegian drinking water limit of 20 mg Pt/l (Berge *et al.*, 2004). Water colour appears to be linked to runoff and/or lake residence time, with higher colour in years when stream discharge was higher. Over the last few decades colour has increased slightly, likely due to changes in rainfall patterns as well as to recovery from acid deposition, although the increase is smaller than in many other lakes in Norway (Glitrevannverket, pers. comm; data not shown).

In the 2016-2019 monitoring data, we see that nitrogen (N) concentrations in stream samples vary somewhat between stream sites, with highest concentrations of all N species in Guritjernsbekken and lowest concentrations in Sandungsbekken and Dypingbekken (Figure 3). Guritjernsbekken experienced clearcutting in recent years, and higher N concentrations likely reflect this (explored further in 5.2.2). All streams show the typical seasonal NO_3^--N pattern observed in semi-natural systems, with an increase in concentration during winter and a peak near spring snow melt, when biological uptake of N is low, followed by relatively low concentrations during summer when biological uptake and microbial immobilisation are high (Figure 4).

Lake water chemistry was much less variable between monitoring points and over time (Figure 3, Figure 5). Though total N concentrations were similar in the stream and lake sites, NO_3^--N made up a higher proportion of the total N in the lake. This is likely due to a net conversion of organic N to inorganic N, and direct atmospheric inorganic N inputs to the lake surface.

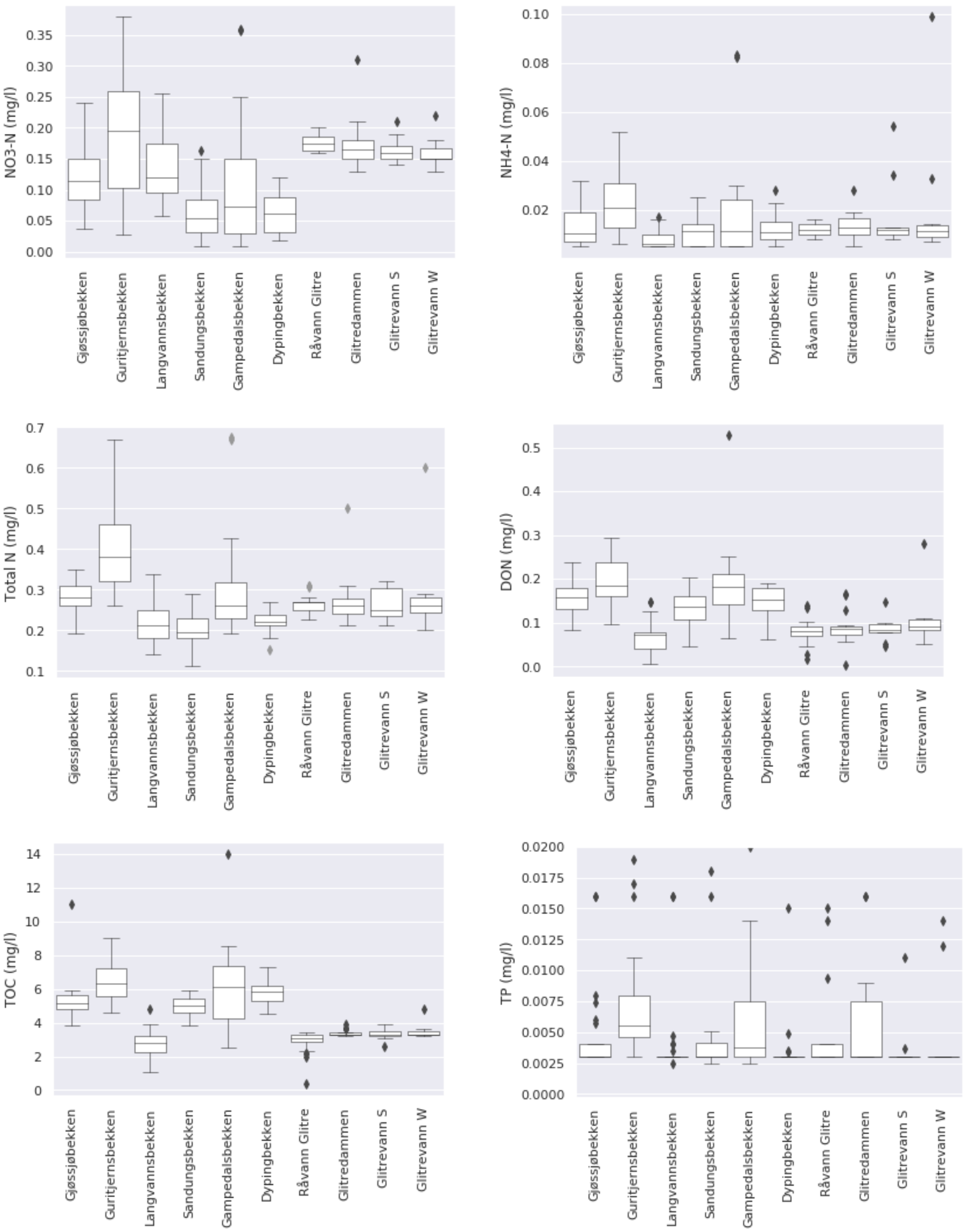

Figure 3. Summary of inter-site differences in stream and lake water chemistry over the period August 2016 – November 2019. White boxes show the inter-quartile range in the data, the horizontal line within the boxes is the median. Whiskers extend to the 95th percentiles or range of the data. Diamonds mark outliers. Sampling points are located and described in Figure 1 and Table 1.

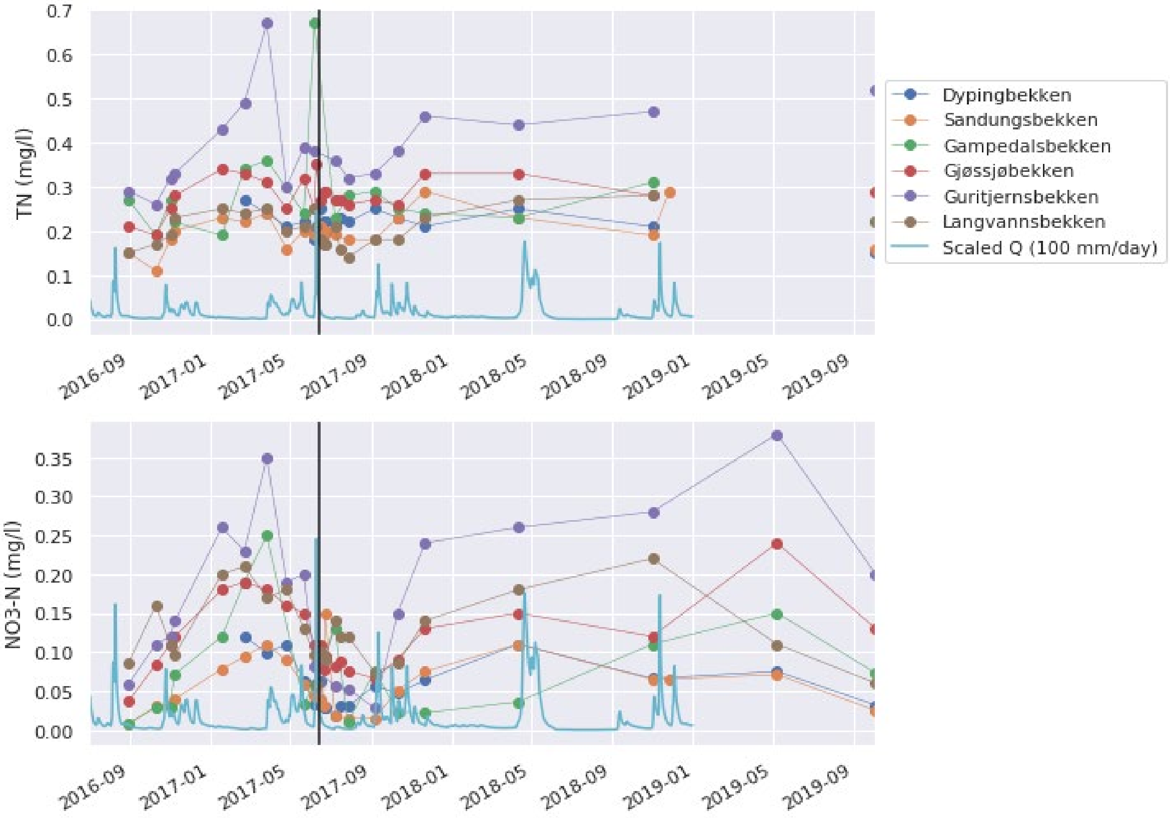

Figure 4. Total N (TN) and nitrate-N (NO_3^--N) concentrations in the monitored tributaries to Glitrevann. Q is discharge. The vertical line marks the one-off fertilization in one of the lake tributaries (see Section 4).

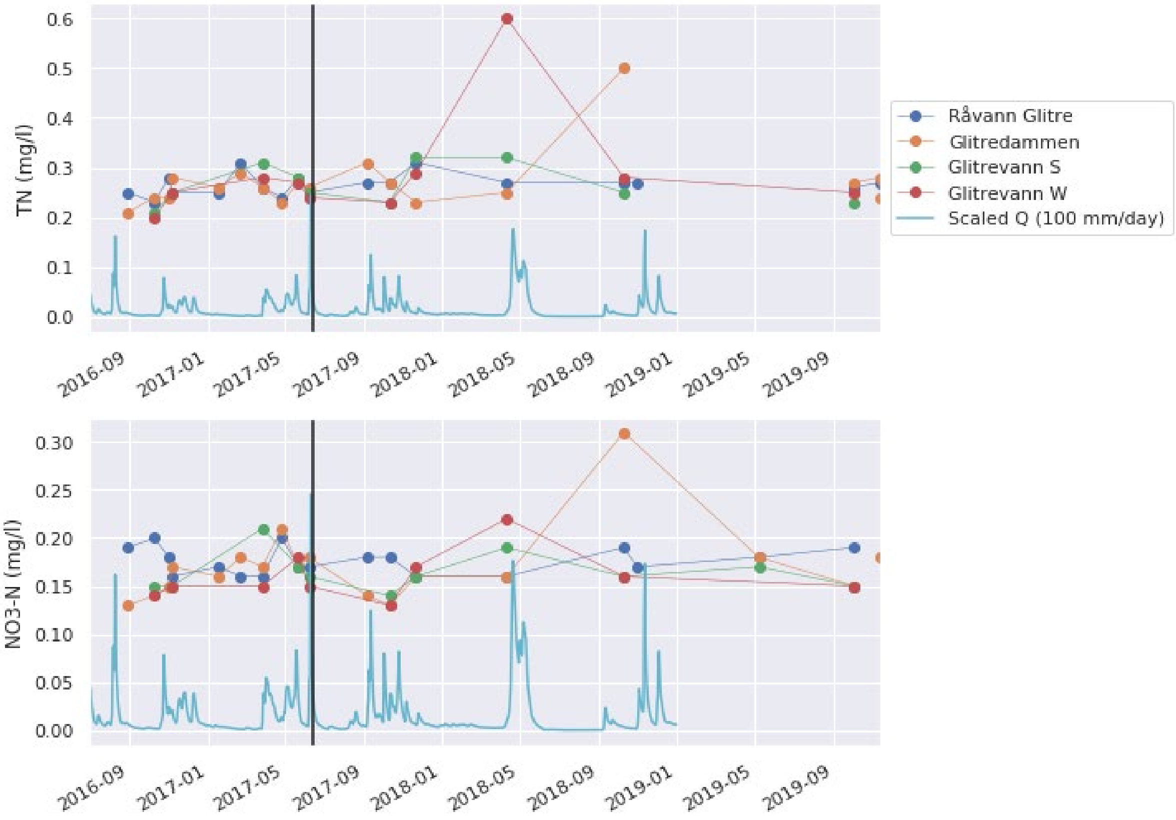

Figure 5. Total N (TN) and nitrate-N (NO_3^--N) concentrations in the Glitrevann lake water samples. The vertical line marks the one-off fertilization in one of the lake tributaries (see Section 4).

3.2 Method for calculating N fluxes to the lake

To estimate current fluxes of total N and NO_3^--N to the lake, fluxes were estimated for each of the monitored tributaries by linearly interpolating the observed chemistry data during the period September 2016 – November 2017, when there was relatively high frequency monitoring. This derived daily time series of water chemistry was then multiplied by the daily discharge for that tributary. To derive daily fluxes from the whole catchment to Glitrevann, tributary fluxes were summed and multiplied by the ratio of the total catchment area (41.4 km^2) to the monitored area (34.1 km^2), to take into account unmonitored inputs. Daily fluxes were then summed to derive monthly fluxes. Finally, monthly fluxes for the period October 2016 – September 2017 (inclusive) were summed to provide an estimate of the annual flux.

As this annual flux is only for a single year, and as the variability in annual fluxes between years is likely to be strongly linked to variations in discharge, the longer-term average flux was estimated by comparing the discharge in the period October 2016 – September 2017 with the discharge over the period 1976-2018, and assuming a simple linear relationship between discharge and flux (e.g. in years where discharge was 50% higher than in 2017, flux would also be 50% higher).

Note that due to the relatively low sampling frequency, the load estimates are highly uncertain. Assuming longer-term load is only related to longer-term variations in discharge is also a simplification, and ignores the fact that other factors which affect N loads may also have changed (e.g. N deposition; N retention, which is controlled by climatic factors).

3.3 Simple nitrogen budget for the catchment and lake

Estimated monthly stream fluxes are shown in Figure 6, where we see that highest fluxes occur during spring snow melt when both discharge and concentrations are high, and lowest fluxes in summer when the reverse is true.

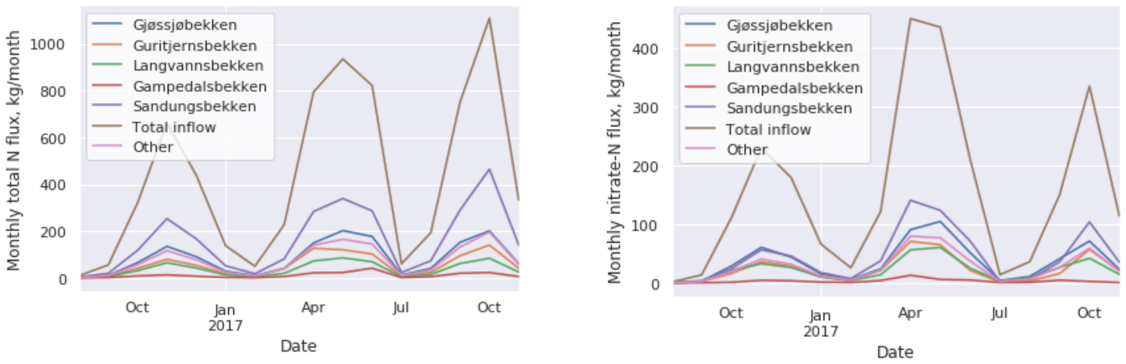

Figure 6. Estimated monthly total nitrogen (N) and NO_3^--N flux in the main tributaries of Glitrevann, as well as the total input to the lake from the catchment ('Total inflow'). 'Other' is the estimated input from unmonitored areas.

Estimated annual fluxes to the lake from catchment streams are given in Table 2, as both total delivery (kg), and area-specific delivery (kg/ha). Atmospheric N deposition to the catchment is around 5.9 kg N/ha/year (Aas *et al.*, 2017), and livestock and sewage N fluxes are thought to be low (Appendix A). The estimated total N flux to the lake of 1.5 kg/ha/year therefore suggests that around 75% of N inputs in deposition are either retained in catchment vegetation, soils and stream banks and/or denitrified and degassed from wetland soils, streams and small lakes in the catchment.

Table 2. Estimated annual fluxes of total N and nitrate-N into and out of Glitrevann. Values for 1976-2018 are calculated by assuming a linear relationship between discharge and flux.

Variable	Species	2017 flux	1976-2018	
			Median	25th-75th percentiles
Deposition input (kg/yr)	Total N		2171	
Inflow areal flux (kg/ha/yr)	Total N NO_3^--N	1.3 0.5	1.5 0.6	1.2 – 1.7 0.5 – 0.7
Inflow total flux (kg/yr)	Total N NO_3^--N	5391 2024	6254 2347	5068 – 7224 1902 – 2712
Outflow flux (kg/yr)	Total N NO_3^--N	6053 3808	7021 4417	5690 – 8111 3580 – 5103
In-lake removal (kg/yr)	Total N		1400	

We can also put together a simple input-output budget for the lake. As well as N inputs from tributaries, direct inputs from atmospheric deposition may be important, whilst the main outputs are via the lake outflow as well as in-lake chemical and biological retention and degassing. Direct N inputs via atmospheric deposition can be calculated as ~2171 kg N/year (368 ha lake area x 5.9 kg/ha/year), or around 40% of catchment inputs. In-lake removal and retention can be estimated by looking at the difference in total N inputs (from tributaries and direct deposition) and outflow total N fluxes. The result, ca. 1400 kg N/year (Table 2), suggests that in-lake retention is slightly lower than direct deposition inputs, as outflow TN fluxes are slightly higher (ca. 12%) than inflow fluxes.

4 Short-term effects of fertilization on water quality

4.1 Study design

On 13th June 2017, 67.5 ha (0.675 km^2) of forest were fertilized. Most of the fertilized area (91%, 61.5 ha) was upstream of the Sandungsbekken monitoring point (Figure 7), amounting to 3.3% of the Sandungsbekken subcatchment area. A small portion of this (14.5 ha) was upstream of the Dypingsbekken monitoring point (1% of the Dypingsbekken subcatchment area), but most lay between the Dypingsbekken and Sandungsbekken monitoring points (47 ha; 11.8% of the catchment area between the two points. See Figure 7). If fertilizer N were flushed through, we would therefore expect higher concentrations in Sandungsbekken than Dypingsbekken shortly after fertilization. As the Dypingsbekken catchment received a small amount of fertilization, a comparison is also made between Sandungsbekken and two other tributaries with most similar N chemistry that were completely unfertilised, Langvannsbekken and Gampedalsbekken (Figure 3). When doing this comparison, we should bear in mind that these two tributaries did however generally have higher nitrate concentrations than Sandungsbekken and Dypingsbekken, and Gampedalsbekken also had higher TN concentrations.

This assessment has low sensitivity to pick up fertilizer runoff effects, due to:

(1) The small proportion of the subcatchment that was fertilized (3.3% of the total Sandungsbekken subcatchment), which means any fertilizer runoff will be diluted by unaffected areas.
(2) Results are also only from a single fertilizer effect, giving a sample size of one. The study would need repeating over multiple fertilization events to provide more robust results.

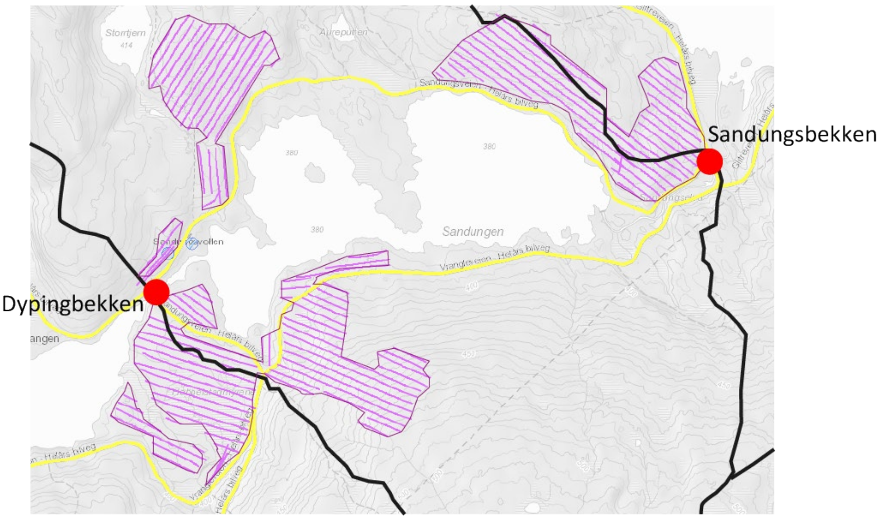

Figure 7. Area fertilized in 2017 (see Figure 1 for the location of the two monitoring points in the west of the catchment). Pink lines mark the helicopter flight path, black lines the catchment boundaries associated with the two monitoring points. Yellow lines are vehicle tracks. Source: Statskog.

4.2 Fertilization method

550 kg/ha of fertilizer were applied, amounting to 150 kg N/ha (15 000 kg N/km^2). Fertilization was carried out by helicopter (Figure 8) using Nitrogengjødsel YaraBela®OPTI-KAS™ SKOG. The elemental composition of this fertilizer is roughly 27% N (NO_3 and NH_4), 46% oxygen (as NO_3-O), 4% hydrogen (as NH_4-H), 7.4% calcium and magnesium, and 0.2% boron. The remaining 15% is not explicitly documented by the supplier, but is likely dolomite bicarbonate (HCO_3^-) (e.g. YaraBela®CAN-27). Dolomite can occasionally contain trace amounts of barium, strontium, iron, zinc or manganese, but none of these compounds present a risk for the environment at trace levels. Fertilization was carried out following Norwegian PEFC Forest Standard guidelines, including observance of 25 m buffer strips along lakes, waters and permanent water courses.

Figure 8: Forest fertilization in progress, June 2017. Source: NIVA

4.3 Do we see a short-term nitrogen flush-through after fertilization?

Before fertilization, the Dypingbekken (upstream) and Sandungsbekken (downstream) monitoring points had very similar total N and NO_3^--N concentrations (Figure 3, Figure 4, Figure 9), although Dypingbekken showed a larger peak NO_3^--N concentration in response to a flow event prior to fertilization (Figure 9). Otherwise, the only time when there was a substantial difference between the two was immediately after fertilization, when there was an unusually large summer peak in NO_3^--N in Sandungsbekken which was absent in Dypingbekken (Figure 9). It is therefore possible that this difference was due to leaching of fertilizer nitrate into the stream. This NO_3^--N peak occurred during the second rainfall event after fertilization, rather than the first. This is plausible as catchment soils would need to be wetted up before transport to the stream could occur. We can also see that the two streams (Dypingbekken and Sandungbekken) had the same NO_3^--N concentration during the next sampling, around 17 days later, and that little rain fell in the interim period (Figure 9), meaning it is unlikely that large transport of NO_3^- occurred between monitored dates.

When this suspected fertilizer nitrate peak occurred in Sandungsbekken, no nitrate peaks were seen in the other monitored tributaries (Figure 9), providing some additional support for this being fertilizer leaching. However, during the next sizeable rainfall event around the 8th of July, nitrate concentrations in both Gampedalsbekken and Langvannsbekken increased up to concentrations similar to those seen in Sandungsbekken during the suspected fertilizer runoff event. Overall, there is some evidence of fertilizer runoff, but this evidence is based on a single data point.

The evidence for fertilizer-N leaching would be clearer if a similar peak was visible in total N in Sandungsbekken, but this wasn't seen. As NO_3^--N is a part of total N, NO_3^--N can't increase without there being a corresponding change in total N unless NH_4^+-N or DON decrease. NH_4^+-N didn't change, and although DON is not measured directly, it seems unlikely that it would decrease by such a large amount. Either the total N or the NO_3^--N measurement is therefore inaccurate. Nitrate is generally easier to measure accurately than total N so, and to provide a worst-case, conservative scenario of short-term N leaching following fertilization, we will assume the NO_3^--N value is representative.

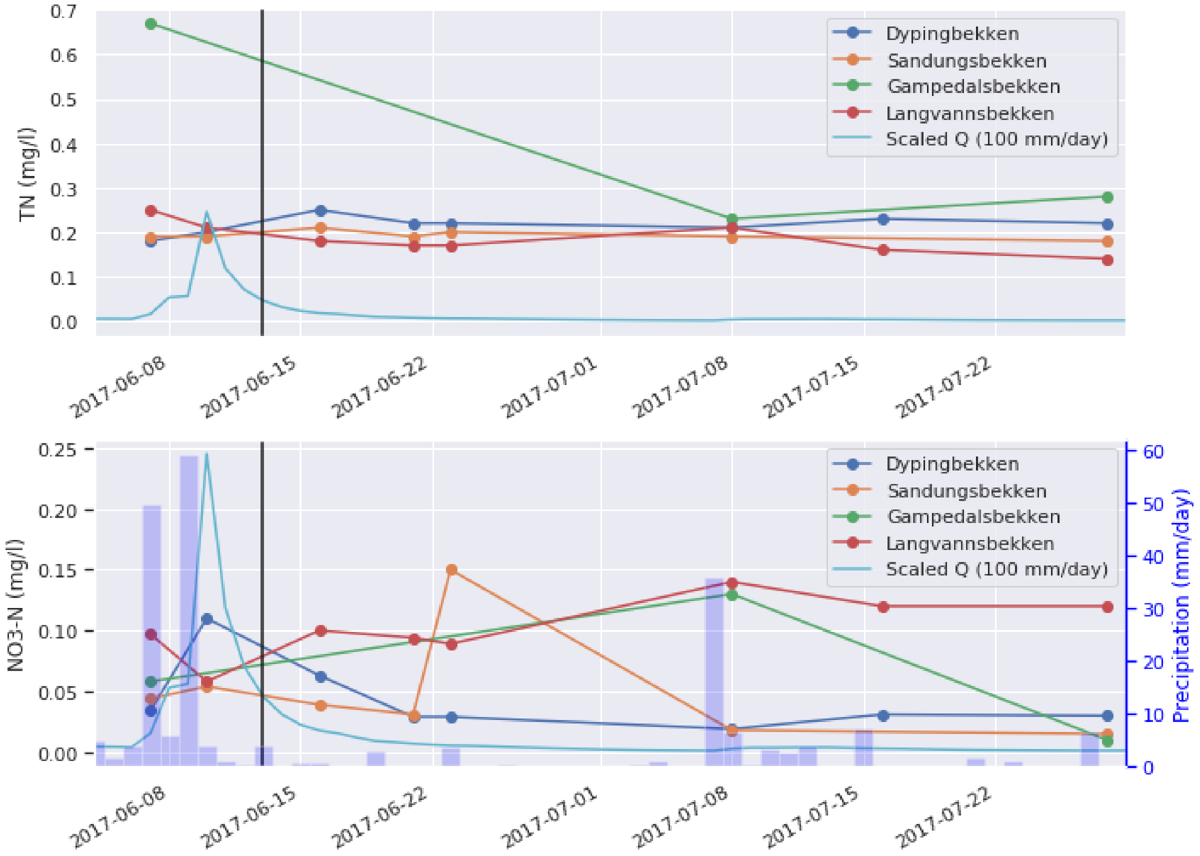

Figure 9: Concentrations of total N (TN) and nitrate-N (NO_3^--N) at monitoring points upstream (Dypingbekken) and downstream (Sandungsbekken) of the area fertilized on 13th June 2017, as well as in the two tributaries with similar chemistry to Sandungsbekken. Vertical black line marks fertilization date. Scaled discharge and precipitation are shown to indicate when flushing of fertilizer N would have been most likely to occur.

To estimate the flux of NO_3^--N associated with this potential post-fertilizer peak in NO_3^--N concentration, the data from Sandungsbekken and Dypingbekken were interpolated to daily frequency and multiplied by daily discharge to derive fluxes. It was then assumed that Dypingbekken fluxes represent the baseline, i.e. what Sandungsbekken would have looked like without fertilization (orange line in Figure 10). The difference between the two would then be due to short-term flushed inputs from fertilization (green line in Figure 10).

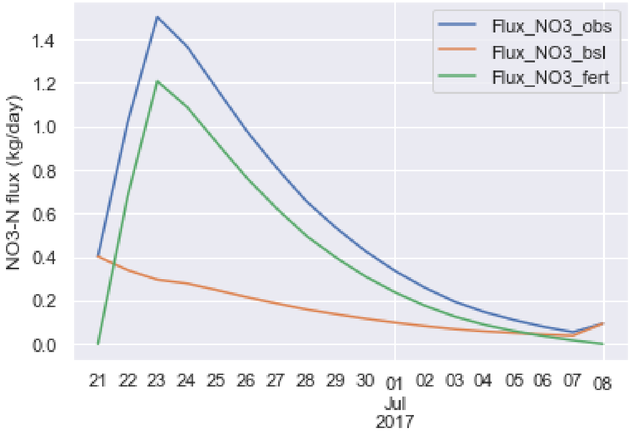

Figure 10: Estimated daily nitrate-N fluxes at Sandungsbekken, including raw observations (blue line), assumed values had fertilization not occurred (orange line, taken from Dypingbekken fluxes), and the difference of the two, assumed to be flushed fertilizer nitrate (green line).

The sum of these daily values over the peak is 7 kg of NO_3^--N, or 0.07% of the total N applied, but note that the errors involved in this calculation are large. The average daily NO_3^--N flux to Glitrevann from its catchment is around 6.5 kg (Section 3.3), so this estimated fertilizer-related peak is roughly equivalent to the whole flux to the catchment in a single day, but spread out over ~17 days.

Although these results are highly uncertain, and largely dependent on a single monitoring point, they fit with studies elsewhere which have shown that nitrogen fertilization often leads to detectable short-term increases in soil solution N concentrations and in streams draining fertilized areas (Clarke *et al.*, 2018). However, given the high demand for N in most Nordic forest soils and surface waters, water quality effects tend to be short-lived, small, and hard to detect even a few hundred metres downstream of fertilized areas (Schelker *et al.*, 2016). Future short-term N leaching following fertilization could differ from what was observed in June 2017, according to weather conditions pre- and post-fertilization, but are unlikely to be outside this order of magnitude.

4.4 Minimising short-term nitrate losses in the future

Fertilization occurred over 61.5 ha (3.3%) of the Sandungsbekken catchment, and leaching of nitrate post-fertilization appears to have been both small and short-lived. Had a much larger area been fertilized (e.g. the whole Sandungsbekken catchment), the nitrate leaching is likely to have been more substantial, e.g. of the order of 200 kg NO_3^--N (equivalent to the average mean monthly nitrate flux to the lake). However, future fertilization plans for state-owned forest in the catchment are for around 25 ha to be fertilized once every five years at the same rate used in June 2017 (150 kg N/ha; R. Aamold, pers. comm.). Accordingly, between now and 2100 around 4 km^2 (~10%) of the Glitrevann catchment would have been fertilized once. As long as forest fertilization in the future does stay within these planned limits and Norwegian PEFC Forest Standard guidelines for fertilization continue to be followed (e.g. buffer strips are observed), results from 2017, backed up by literature studies, suggest there is a low risk of high nitrate leaching immediately post-fertilization.

5 Long-term effects of fertilization on water quality

5.1 Introduction

Over the longer term, forest harvesting brings about an increase in N mobilization and transport from soils to surface waters (de Wit *et al.*, 2014, Gundersen *et al.*, 2006, Kreutzweiser *et al.*, 2008). This can result in dramatic increases in N concentrations in small boreal streams, although these effects often have limited spatial and temporal extent (Sponseller *et al.*, 2016). Harvesting impacts may persist for more than 10 years (Palviainen *et al.*, 2014), but the largest effects are typically observed during the first 3–5 years (Jerabkova *et al.*, 2011).

In this section we explore to what extent these well-documented increases in N mobilisation and transport following harvesting are likely in the Glitre catchment, and whether forest fertilization may exacerbate any increased N leaching. To do this we first use an empirical approach, based on historic monitoring data from the catchment, and in particular from the Guritjernsbekken subcatchment which has been affected by clearcutting in recent years. These figures are then used as 'ground-truthing' for a process-based modelling approach, where we transfer process-based modelling results obtained using the MAGIC model in a similar catchment to Glitre, to derive future scenarios of changing nitrogen loading to the lake under a variety of forest management scenarios.

5.2 Likely impacts of fertilization and harvesting based on historic monitoring data

5.2.1 Long-term fertilization leaching estimate

The estimated total N flux to the lake (1.5 kg/ha/year; Table 2) suggests that around 75% of N inputs in deposition are either retained in catchment vegetation, soils and stream banks and/or denitrified and degassed from wetland soils, streams and small lakes in the catchment. If this 25% leaching rate still applied under fertilization, we might expect leaching of 37.5 kg N per hectare of fertilized forest per year. Statskog plans to fertilize on average 5 ha per year, which at this rate of leaching would correspond to 187.5 kg N/yr from the fertilized 5 ha. As the total annual N export from the catchment to the lake is around 6524 kg, this represents a small increase of around 3%. Were this just an increase in nitrate-N leaching, it would represent an increase of 8%.

This rough calculation ignores potentially increased leaching rates from historically fertilized areas, but is useful as a first approximation of the maximum potential increase in N mobilisation due to fertilization. It is likely a maximum figure, as biota in catchment streams and soils may be able to remove higher amounts of N than they do at present given larger inputs.

5.2.2 Nitrogen inputs from harvesting estimated from historic monitoring

Guritjernsbekken had noticeably higher total N and NO_3^--N concentrations than the other tributaries, and estimated annual fluxes are almost twice as high here as elsewhere (Table 3). Guritjernsbekken is the only monitored subcatchment that has been affected by forest clearcutting in recent years – according to data from Statskog, around 25 ha were clearcut between 2014 and 2019 in the subcatchment (just over 7% of the 340 ha subcatchment). Assuming that the difference in N export between Guritjernsbekken and other tributaries (0.87 kg TN and 0.39 kg NO_3^--N ha^{-1} $year^{-1}$) is related to cutting, the annual N export due to cutting activities alone in this subcatchment can be estimated as 296 kg total N and 136 kg NO_3^--N (difference multiplied by the subcatchment area). Assuming this is emitted solely from the clear cut areas (25 ha) gives export coefficients of around 12 kg/ha/year total N and 5 kg/ha/year NO_3^--N from clearcut areas (Table 3). Note that these values are highly uncertain, and will change depending on the number of years since harvest (likely highest in the first year after harvesting and reducing thereafter).

N export	**Nitrate-N (kg/ha/year)**	**Total N (kg/ha/year)**
Glitrevann catchment (excluding Guritjern)	0.46	1.23
Guritjern catchment	0.85	2.10
Difference between Guritjern and remainder of catchment	0.39	0.87
Clearcut areas in Guritjern	5.3	11.9

Table 3: Nitrogen fluxes from Guritjernsbekken compared to the remainder of the catchment, and assumed implications for fluxes related to clearcutting. See Sections 3.2 and 3.3 for details of how fluxes in the first two rows were estimated.

5.3 MAGIC modelling

5.3.1 MAGIC modelling in Birkenes

MAGIC (Model of Acidification In Catchments) is a process based model of biogeochemical processes operating at the catchment scale (Cosby *et al.*, 2001, Cosby *et al.*, 1985a, Cosby *et al.*, 1985b). It has been successfully used to quantify the impacts of acid deposition, land use and climate change on freshwater quality. The latest version of MAGIC (version 8, 1 October 2010) includes new formulations of N processes in forested ecosystems (Oulehle *et al.*, 2012).

As part of the SURFER project, MAGIC was used to perform catchment biogeochemical modelling in the Birkenes catchment, a site with long-term monitoring data. Birkenes is a 0.41 km^2 coniferous-forested catchment located about 20 km from the south coast of Norway. Thanks to the long time series available from Birkenes since the early 1980s, MAGIC could be robustly set up and calibrated in the catchment, and then run to explore different forest management scenarios (Valinia et al., subm.).

5.3.2 Comparison of Birkenes and Glitre

There is limited monitoring data available from Glitrevann to set up a model like MAGIC robustly. Rather than spending a lot of resources to develop a potentially poor MAGIC calibration in Glitrevann, we therefore decided it would be more robust to transfer MAGIC modelling results from Birkenes to Glitrevann, taking into account the differences in the two catchments and forest management plans.

Birkenes and Glitrevann are both mainly forested catchments, but with somewhat contrasting attributes (Table 4). Birkenes is a much smaller catchment (0.41 km^2) with no lakes, and annual precipitation, runoff and N deposition are larger than at Glitrevann. In addition, the forest at Birkenes is, on average, at least 20 years older than at Glitrevann. Regarding the chemistry, Birkenes has lower pH, higher TOC and lower base cation levels than Glitrevann. The smaller size of the catchment, the absence of lakes and the more acid sensitive chemistry at Birkenes provide less ideal conditions for the aquatic environment to dampen N pulses following harvesting and to maintain good ecological status. Together, these differences mean that Birkenes is likely to show a more extreme response to forestry activities than Glitrevann. The N fluxes estimated for Glitrevann using MAGIC modelling results from Birkenes should thus be considered as the most pessimistic estimates.

Catchment properties	Glitrevann	Birkenes
Location	59.8675, 10.0679	58.3853, 8.2416
Catchment area (km^2)	45.1	0.41
Lake area (km^2)	3.8	0
Water residence time (yr)	4.6	-
Altitude range (m a.s.l.)	358–580	210–300
Annual precipitation (mm)	850	1400
Annual runoff (mm)	650	1200
Mean age of the forest (yr)	< 80	> 100
Mean N deposition (kg/ha/yr)	6	12–14
Mean pH	6.4	4.9
Mean TOC (mg/L)	3.5	6.4
Mean NO_3^- (µeq/L)	7.9	8.5
Base cations (Mg + K + Ca ; µeq/L)	152.6	51.1
Non-marine base cations (µeq/L)	147.0	21.0*

Table 4: Comparison of Glitrevann and Birkenes catchments. *Annual mean for 2018.

5.3.3 Future forest management scenarios

The future Statskog management plan includes fertilization, thinning and clearcutting activities over the next 70 years (Figure 11; R. Aamold, pers. comm. 2019). Fertilization at the standard rate of 150 kg N/ha is planned for around 25 ha (0.25 km^2) every five years. Clearcutting activities are planned over three main periods: (i) over 2009-2019, 4 km^2 were harvested, of which 0.7 km^2 were cut over 2014-2019 and included in the scenario presented in Figure 11; (ii) 1 km^2 will be ready for harvest around 2050, and (iii) 5 km^2 by 2070. In addition, 6 km^2 of forest will be thinned by 2050.

Assuming that the clearcutting activities around 2050 and 2070 are spread over 3 and 5 years, respectively, this gives a cumulated harvested area of just under 7 km^2 by 2090. By this time, just over 4 km^2 will have been fertilized (Figure 11). Note that forest fertilization does not affect the timing of harvesting or the area harvested, only the amount of biomass that is harvested.

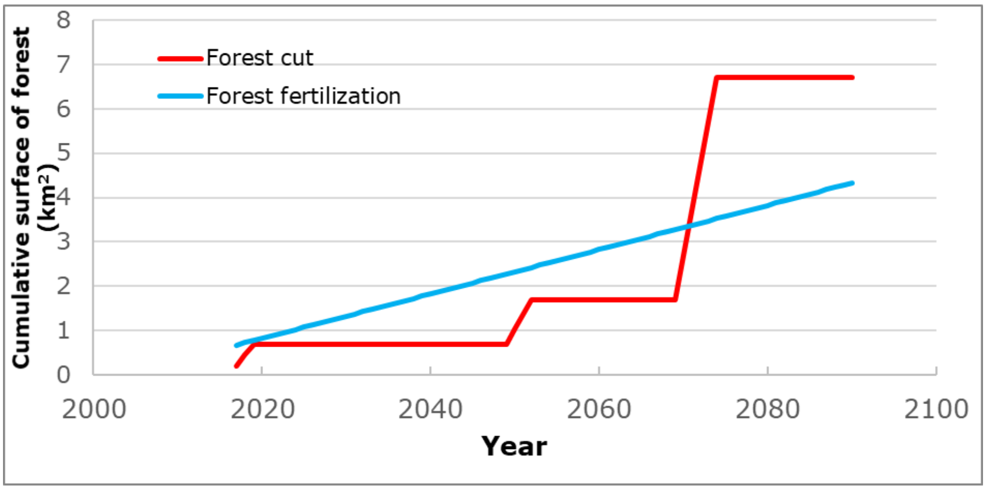

Figure 11: Cumulative surface of forest clearcut and fertilized over the period 2017-2090. Source: R. Aamold (Statskog) (pers. comm, 2019).

5.3.4 Transfer of modelling results from Birkenes to Glitre

In Norway, current practice is for most stands to be harvested in a conventional manner, in which the stems are removed and the needles, branches and tops (forest residues) are left on site (stem-only harvesting, SOH). An alternative practice, known as whole tree harvesting (WTH), involves also removing branches and tops for e.g. biofuel production. WTH removes more material than SOH, so it usually brings about more dramatic impacts on the harvested forest ecosystem and surface waters (Achat *et al.*, 2015, Thiffault *et al.*, 2011). For the MAGIC modelling at Birkenes, four harvesting scenarios were considered: SOH and WTH, both with and without fertilization at a rate of 150 kg N/ha over the whole Birkenes catchment. Fertilization was assumed to occur 11 years prior to harvesting (around the time we would expect fertilization to happen in practice), and in each clearcutting scenario it was considered that the whole 0.41 km^2 catchment was cut.

To transfer modelling results from Birkenes to Glitre, area-weighted TN fluxes obtained from MAGIC modelling at Birkenes (i.e. standardized by km^2) in the 16 years following harvesting were used to calculate the annual TN export for the whole Glitrevann catchment. In brief, for each year, the area-weighted fluxes from Birkenes were multiplied by the surface area undergoing cutting at Glitrevann as described in the forest management scenarios (Section 5.3.3, and Figure 11). Thinning was assumed to have no effect on N export from soils, as nitrate leached from thinned areas is likely to be taken up by remaining trees.

5.3.5 Results

Annual total N exports predicted by MAGIC in the 15 years following clearcutting, on top of natural release, are shown in Figure 12 in terms of fluxes per hectare of clear cut forest. Depending on the harvesting practice, total N exports reach 29 to 37 kg N ha^{-1} year^{-1} in the harvesting year and decrease back to zero within 9 to 13 years following clearcutting. The estimated total N export due to harvesting in the Guritjernsbekken subcatchment, as estimated from monitoring data (see Section 5.2.2 for details), is also plotted on Figure 12. MAGIC predictions and flux estimates from Guritjernsbekken are in general agreement. Flux estimates from Guritjernsbekken are lower than MAGIC predictions, consistent with the fact that the transfer of MAGIC results from Birkenes to Glitrevann will yield pessimistic estimates.

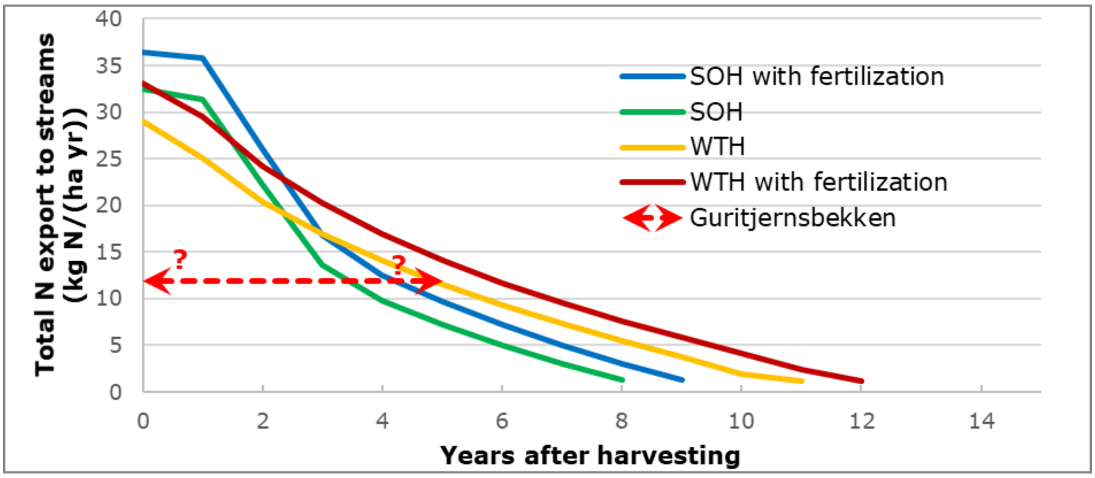

Figure 12: Predicted total N export to Glitrevann due to clearcutting in the 15 years following harvesting according to various forest management practices. The estimated total N export due to cutting activities in the Guritjernsbekken sub-catchment is also plotted for comparison (see Section 5.2.2 for details). Note that the exact temporal extent of the flux from Guritjernsbekken is unknown as stressed by the question marks, but is sometime within the last 6 years. SOH: stem only harvest. WTH: whole tree harvest.

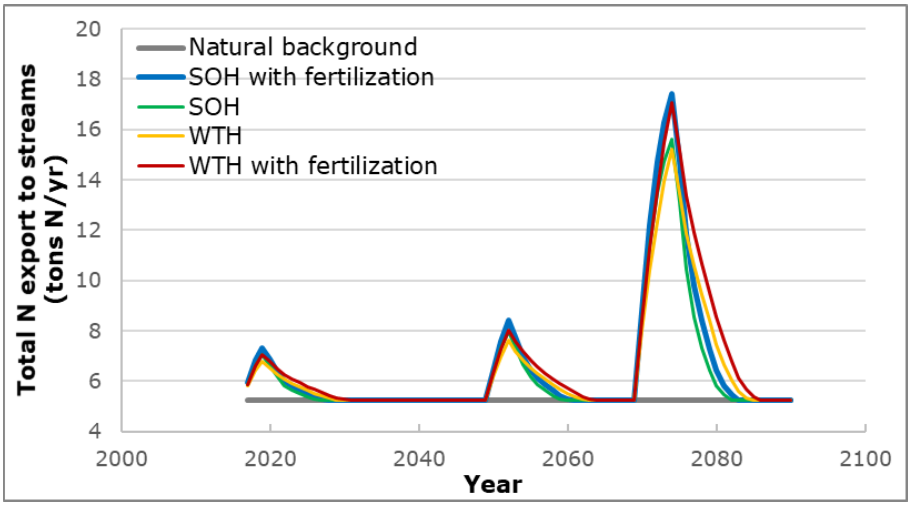

Figure 13: Predicted annual total N export to Glitrevann according to various forest harvesting practices over 2017-2090 (as described in section 5.3.3).

Annual TN export for the whole catchment is shown in Figure 13 and Figure 14 as predicted by MAGIC over 2017-2090 following the harvesting scenarios described in section 5.3.3, including three harvesting periods (i.e., present day, 2050 and 2070 when 1.6%, 2.2% and 11% of the catchment is clear-cut, respectively). Figure 13 clearly shows three distinct periods with elevated TN export following these three simulated harvesting periods. Note that the annual export in 2017 is already larger than natural levels due to ongoing harvesting activities. The increase in TN export following the 2070 harvesting period reaches its maximum about 5 years after the start of harvesting, independent of the harvesting method (Figure 14). The amplitude of the peak in TN export is larger for the harvesting of fertilized forest than for unfertilized forest (Figure 14 and Table 5).

Accumulated over the whole period 2017-2090, harvesting results in around a 20% increase in TN export relative to natural (i.e. no harvest) fluxes. Fertilization brings about an additional accumulated 5% increase in TN export compared to harvesting alone and a 1-year increase in the duration of the harvesting impact (Table 5). This increase in N mobilisation due to fertilization is of a similar size to that estimated using the empirical N budget for the catchment (Section 5.2.1).

In terms of harvesting method, in the first years SOH generates slightly higher TN exports than WTH (Figure 12), but its impact on the forest ecosystem is 3 years shorter than under WTH. As a result, the TN export is larger for WTH than for SOH by about 4% (Table 5).

Scenario	Accumulated increase in TN export over the whole simulated period (2017-2090)	Peak annual TN export (in 2074)	Duration of harvesting impact (yr)
SOH	+ 19.8 %	+ 298 %	12
WTH	+ 22.7 %	+ 290 %	15
SOH with fertilization	+ 24.4 %	+ 333 %	13
WTH with fertilization	+ 28.4 %	+ 326 %	16

Table 5: Impacts of fertilization on total N (TN) export at Glitrevann according to various forest harvesting practices (based on MAGIC modelling results from Birkenes). All percentages refer to increases compared to natural TN export.

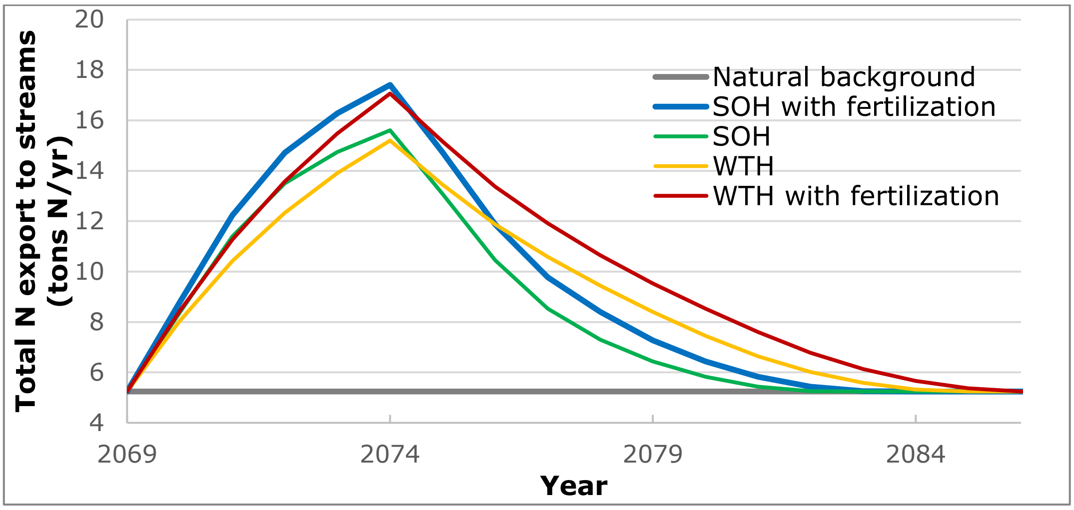

Figure 14: Predicted annual total N export to Glitrevann according to various forest harvesting practices over 2069-2086.

For the 2070 harvesting period, peak annual TN export under SOH (the current practice in the catchment), reached in 2074, is 298% higher than natural levels for unfertilized forest, rising to 333% given fertilization (Table 5). Hence, the harvesting of 5 km^2 over 5 years (Section 5.3.3) would cause a TN export that is about four times higher than the natural export. This should be considered a maximum estimate, given that historically Statskog have rarely harvested more than 1 km^2 per year in Glitrevann, and given that the MAGIC modelling results from Birkenes are a worst-case scenario.

In summary, forest harvesting is likely to result in an increase in N delivery to Glitre, consistent with literature and data from elsewhere, and historic data from within the catchment (Section 5.2.2). Forest fertilization is likely to increase the harvesting-related nitrogen flux by an additional 5% over the period 2017-2090, from an increase of 20-23% to an increase of 25-28% compared to natural levels. The duration of harvesting is important in terms of water quality effects, with more pronounced effects expected when larger areas are cut over shorter time periods.

6 Sensitivity of Glitrevann to changes in N inputs and risk to drinking water provision

As described in Section 3.1, Glitrevann's water quality is currently very good and well-suited to drinking water. We now consider the risks for a deterioration in lake water quality in the future, and potential implications of this in terms of drinking water provision and ecological status of lake waters according to the Water Framework Directive (WFD).

6.1 Potential future changes to nutrient status and algal biomass

At present, Glitrevann has a total N (TN) concentration between 250 and 300 µg l^{-1}, within "Very Good" ecological status according to the WFD. Knowing the water residence time in Glitrevann, its annual discharge, the present TN concentration, and the background catchment TN inputs, we can estimate the impact of the predicted future catchment TN exports on the lake TN concentration under different management scenarios (Figure 15). For the current and 2050 harvesting activities, TN concentrations should stay within the "Very good" WFD category. However, TN concentrations in Glitrevann could increase by up to 2.5 times in the worst-case scenario in the 2070s, leading to a shift in the WFD ecological status from “Very good” to “Moderate”. However, the projected dramatic increase in lake TN concentration in the 2070s is due to the intensive forest harvest rate of 1 km^2 per year over 5 years (Section 5.3.3), which is likely higher than is realistic for the catchment. If the same area of forest were cut over a longer time period, the peak in TN concentration would be lower and the WFD ecological status would remain “Good” or “Very Good”.

Note that these predicted lake TN concentrations assume that nitrogen is not degraded in the streams prior to reaching the lake, which likely leads to overestimation of the lake concentrations. Riparian, in-stream and smaller lakes could be responsible for removing a certain amount of the TN exported from the catchment after forest harvesting, e.g. of the order of 5-20% (Schelker *et al.*, 2016). The magnitude of this dampening effect varies seasonally as streams are usually N-limited in summer and carbon and temperature limited in winter. Hence, more in-catchment removal and retention would be expected in summer than in winter. These calculations also ignore direct N deposition to the lake and in-lake retention and removal, although these fluxes are thought to be approximately in balance in the lake (Section 3.3).

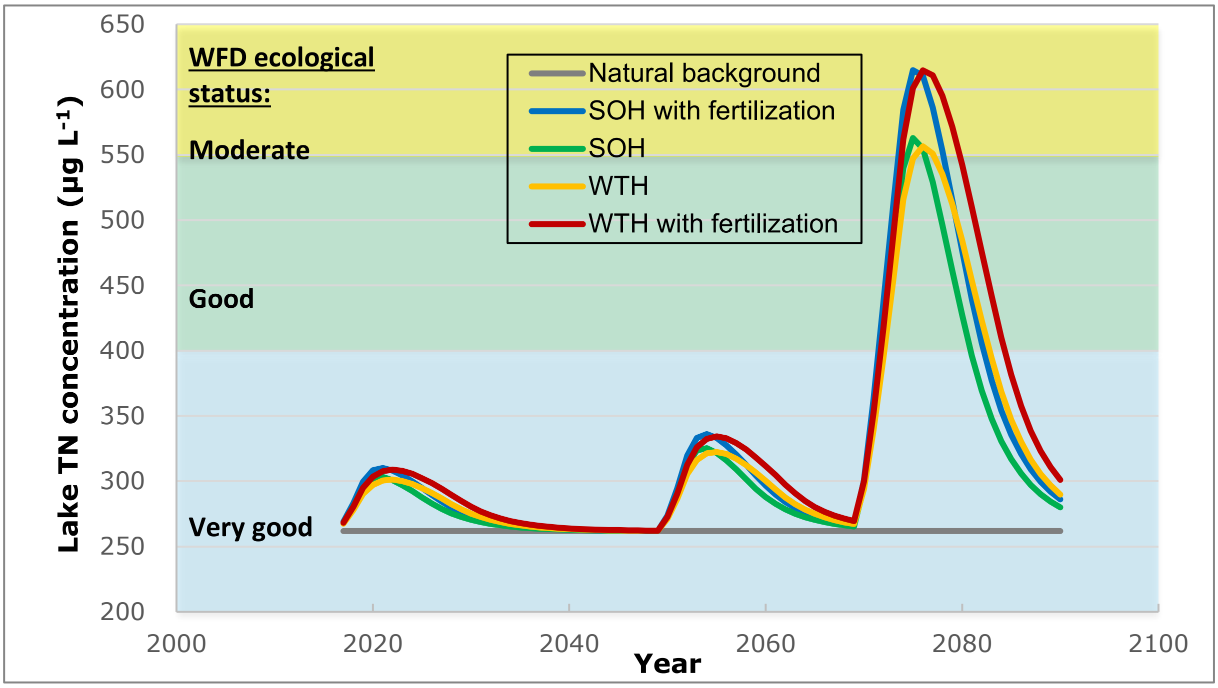

Figure 15: Predicted total N (TN) concentration in Glitrevann according to various forest harvesting scenarios over 2017-2090.

Algal abundance in Glitre is low and the species composition is typical of clear, oligotrophic lakes. However, increased inorganic N loadings may enhance phytoplankton biomass and production. For example, Deininger *et al.* (2017) monitored changes in phytoplankton production, biomass and community composition in response to whole lake inorganic N fertilization in six boreal unproductive lakes. They measured a change in TN concentration similar to that predicted in the 2070s in Glitrevann (Figure 15), i.e. from about 300 µg l^{-1} prior to fertilization to about 500 µg l^{-1} following fertilization. N fertilization resulted in increased phytoplankton biomass and production in all lakes by a factor of 2 to 5, but community composition did not change. Hence, we could expect similar increases in phytoplankton biomass in Glitrevann during the 2070s under the possible management scenarios, again with the caveat that the predicted lake TN concentrations are a maximum, and do not take stream and riparian biological removal into account.

At most times of the year, any increase in algal biomass is unlikely to affect drinking water provision in Glitrevann. The lake is thermally stratified in summer and winter most years, which acts as a barrier against mixing of surface and deeper water. Algal growth occurs mostly in the upper water layers, whilst the intake for drinking water is 30 m deep, protecting drinking water quality whenever stratification is in place. During periods of circulation, the drinking water intake is more vulnerable. Autumn circulation can be a particularly vulnerable time during long moist autumns, when the lake can be circulating for 2-6 weeks (or longer some years).

6.2 Potential future changes to lake acidification

Acid neutralizing capacity (ANC) is a useful indicator of acidification risk. It is calculated as the difference between the concentration of non-marine base cations $[BC^*]$ and strong acid anions in lake water. Here, we derived future projections of ANC as follows:

1. Estimate future lake NO_3^--N concentrations: historically, NO_3^--N made up 50–70% of total N in Glitrevann, so estimate future nitrate concentrations from predicted total N concentrations assuming this ratio still holds (Section 6.1).
2. Estimate base cation release associated with future harvesting: use the “F-factor” to estimate the proportion of current base cation leaching which is due to ion exchange processes in catchment soils. The F-factor is an empirical ratio describing the change in base cation concentrations due to changes in strong acid anion concentrations (Henriksen & Posch, 2001), and can be derived empirically as:

$$\mathrm{F} = \sin\left(\frac{\frac{\pi}{2}[\mathrm{BC}^*]}{[\mathrm{S}]}\right)$$

   where [S] is the base cation concentration at which F = 1, and for $[BC^*] > [S]$, F = 1. For Norway, [S] has been set to 400 $\mu eq\ l^{-1}$ (ca. 8 mg Ca l^{-1}) (Brakke *et al.*, 1990). For Glitrevann, we obtain an F-factor of 0.45, meaning that when NO_3^- increases by a given amount, base cation release increases by just under 50% of this amount (in $\mu eq\ l^{-1}$).

Glitrevann currently has an ANC of around 120 $\mu eq\ l^{-1}$, i.e. “Very good” ecological status according to the WFD (ANC > 70 $\mu eq\ l^{-1}$). During the most intensive projected harvesting period in the 2070s, increased nitrate inputs to the lake would only reduce the ANC by around 10 $\mu eq\ l^{-1}$ (Figure 16). Glitrevann is not therefore particularly acid sensitive, and is unlikely to experience problematic pH decreases due to forest fertilization, harvesting or associated nitrate leaching. We estimate for example that a massive harvesting event at a rate of 1 $km^2\ yr^{-1}$ for 20 years would only shift the ANC WFD ecological status from “Very Good” to “Good”.

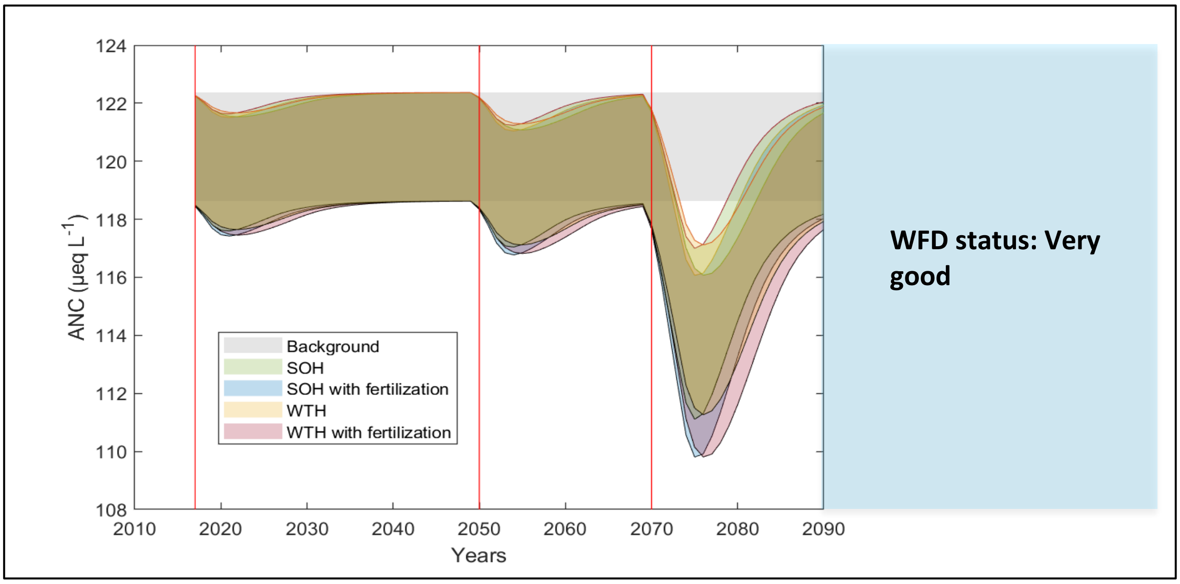

Figure 16: Predicted ANC in Glitrevann according to various forest management scenarios over 2017-2090. The band for each scenario represents the uncertainty in the proportion of total N that is nitrate-N (50-70%). WFD status according to ANC is "Very Good" throughout the range of potential ANC values.

7 Conclusions and recommendations

The main conclusions can be summarised as follows:

- There was some evidence for leaching of nitrate immediately post-fertilization in June 2017. However, leaching was small and short-lived and is not expected to be a problem in the future as long as future fertilization plans are adhered to.
- Forest harvesting is likely to result in an increase in nitrogen (N) delivery to Glitrevann, with up to a 20-23% increase in N export to the lake compared to background levels (i.e. no forest harvesting or fertilization). Elevated stream N levels can be seen at present in a sub-catchment affected by clearcutting between 2014 and 2019, which we attribute to harvesting.
- Forest fertilization is expected to increase the harvesting-related nitrogen flux by an additional 5% of background levels over 2017-2090 (i.e. total N export to the lake could be 25-28% higher than background natural levels). These estimates are worst-case, as they are based on modelling results in a more sensitive catchment, and do not take into account in-stream N removal.
- Harvesting is likely to impact water quality for 10-15 years, with the most pronounced effects within the first 5 years.
- The duration of harvesting is very important in terms of water quality effects, with more pronounced effects expected when larger areas are cut over shorter time periods.
- If intensive harvesting at a rate of 1 km^2/year (around 2.2% of the catchment area) is maintained for 5 years or more, future increases in lake total N concentration associated with harvesting could cause a shift in the lake ecological status from 'Good' to 'Moderate' (according to the Water Framework Directive). Algal biomass could also increase by a factor of 2 to 5.

- Harvesting is likely to have a very limited effect on acidification in the Glitre catchment, which is not particularly acid sensitive.

Main recommendations include:

- Future fertilization plans for state-owned forest in the catchment are for around 25 ha to be fertilized once every five years at 150 kg N/ha. As long as forest fertilization in the future does stay within these planned limits, data from 2017 (backed up by literature studies) suggest there is little risk of high nitrate leaching immediately post-fertilization.
- To protect the lake from harvesting-associated nitrogen fluxes (and associated in-lake effects such as an increase in nitrate concentration and algal biomass), harvesting intensity should be less than 1 km^2/year (around 2.2% of the catchment area). Historic rates of 0.66 km^2/year over the period 2014-2019 were not accompanied by negative effects for raw drinking water in the lake, and a conservative approach would be to remain within these levels in the future.
- To screen for harvesting-associated increases in N inputs to the lake, we recommend routine monitoring of tributaries downstream of areas affected by harvesting, accompanied by monitoring of a reference tributary that is unaffected by harvest (e.g. upstream of the harvested area, or in a nearby tributary) to be able to differentiate between harvesting and climatic effects.
- Measures implemented during harvesting (e.g. measures to ensure soil and stream bank protection from machinery and use of buffer strips along streams and lake shores) play a key role in protecting surface waters from excessive N and carbon inputs during harvesting (Broadmeadow & Nisbet, 2004). Adherence to Norwegian PEFC Forest Standard guidelines ensures many of these measures are implemented. However, during site visits to Glitre, some harvest-related soil disturbance was apparent, and buffer strips did not seem to be in use e.g. in Guritjernsbekken (Figure 2). The Norwegian PEFC Forest Standard requires buffers along permanent water courses, but in this sensitive drinking water catchment a more protectionist approach should be considered, e.g. by expanding the use of buffers to non-permanent water courses. Careful consideration of the timing of harvesting-related activities is also important, in relation to time of year, ground conditions, and forecasted rainfall and snow melt.

References

Aas W, Hjellbrekke A-G, Fagerli H, Benedictow A (2017) Deposition of major inorganic compounds in Norway 2012-2016. NILU rapport.

Achat DL, Deleuze C, Landmann G, Pousse N, Ranger J, Augusto L (2015) Quantifying consequences of removing harvesting residues on forest soils and tree growth–a meta-analysis. Forest Ecology and Management, **348**, 124-141.

Berge D, Tjomsland T, Bækken T, Brettum P, Romstad R (2004) Utredning om Glitre Tilstand og utvikling-overføring av nye felter-vanninntakets plassering-behov for nye beskyttelsestiltak.

Binkley D, Burnham H, Lee Allen H (1999) Water quality impacts of forest fertilization with nitrogen and phosphorus. Forest Ecology and Management, **121**, 191-213.

Brakke D, Henriksen A, Norton S (1990) A variable F-factor to explain changes in base cation concentrations as a function of strong acid deposition. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, **24**, 146-149.

Broadmeadow S, Nisbet T (2004) The effects of riparian forest management on the freshwater environment: a literature review of best management practice.

Clarke N, Økland T, Holt Hanssen K, Nordbakken J-F, Wasak K (2018) Short-term effects of hardened wood ash and nitrogen fertilisation in a Norway spruce forest on soil solution chemistry and humus chemistry studied with different extraction methods. Scandinavian Journal of Forest Research, **33**, 32-39.

Cosby BJ, Ferrier RC, Jenkins A, Wright RF (2001) Modelling the effects of acid deposition: refinements, adjustments and inclusion of nitrogen dynamics in the MAGIC model. Hydrology and Earth System Sciences, **5**, 499-517.

Cosby BJ, Hornberger GM, Galloway JN, Wright RE (1985a) Time scales of catchment acidification. A quantitative model for estimating freshwater acidification. Environmental science & technology, **19**, 1144-1149.

Cosby BJ, Wright RF, Hornberger GM, Galloway JN (1985b) Modeling the Effects of Acid Deposition: Estimation of Long-Term Water Quality Responses in a Small Forested Catchment. Water Resour. Res., **21**, 1591-1601.

De Wit HA, Granhus A, Lindholm M, Kainz MJ, Lin Y, Braaten HFV, Blaszczak J (2014) Forest harvest effects on mercury in streams and biota in Norwegian boreal catchments. Forest Ecology and Management, **324**, 52-63.

Deininger A, Faithfull CL, Bergström AK (2017) Phytoplankton response to whole lake inorganic N fertilization along a gradient in dissolved organic carbon. Ecology, **98**, 982-994.

Gundersen P, Schmidt IK, Raulund-Rasmussen K (2006) Leaching of nitrate from temperate forests effects of air pollution and forest management. Environmental reviews, **14**, 1-57.

Haveraaen O (1981) *Virkning av hogst på vannmengde og vannkvalitet fra en østnorsk barskog*, Norsk institutt for skogforskning.

Henriksen A, Posch M (2001) Steady-state models for calculating critical loads of acidity for surface waters. Water, Air and Soil Pollution: Focus, **1**, 375-398.

Jerabkova L, Prescott CE, Titus BD, Hope GD, Walters MB (2011) A meta-analysis of the effects of clearcut and variable-retention harvesting on soil nitrogen fluxes in boreal and temperate forests. Canadian Journal of Forest Research, **41**, 1852-1870.

Kreutzweiser DP, Hazlett PW, Gunn JM (2008) Logging impacts on the biogeochemistry of boreal forest soils and nutrient export to aquatic systems: a review. Environmental reviews, **16**, 157-179.

Nohrstedt H-Ö (2001) Response of coniferous forest ecosystems on mineral soils to nutrient additions: a review of Swedish experiences. Scandinavian Journal of Forest Research, **16**, 555-573.

Oulehle F, Cosby B, Wright R *et al.* (2012) Modelling soil nitrogen: The MAGIC model with nitrogen retention linked to carbon turnover using decomposer dynamics. Environmental Pollution, **165**, 158-166.

Palviainen M, Finér L, Laurén A, Launiainen S, Piirainen S, Mattsson T, Starr M (2014) Nitrogen, phosphorus, carbon, and suspended solids loads from forest clear-cutting and site preparation: long-term paired catchment studies from eastern Finland. Ambio*,* **43**, 218-233.

Schelker J, Sponseller R, Ring E, Högbom L, Löfgren S, Laudon H (2016) Nitrogen export from a boreal stream network following forest harvesting: seasonal nitrate removal and conservative export of organic forms. Biogeosciences*,* **13**, 1-12.

Sponseller RA, Gundale MJ, Futter M, Ring E, Nordin A, Näsholm T, Laudon H (2016) Nitrogen dynamics in managed boreal forests: Recent advances and future research directions. Ambio*,* **45**, 175-187.

Thiffault E, Hannam KD, Paré D, Titus BD, Hazlett PW, Maynard DG, Brais S (2011) Effects of forest biomass harvesting on soil productivity in boreal and temperate forests—A review. Environmental reviews*,* **19**, 278-309.

Appendix A: Potential contributions of livestock and human sewage to the catchment N budget

1. Livestock

An estimate of 500 cows and 5000 sheeps are grazing in Finnemarka (430 km^2) each summer. Considering an average weight of 800 kg and 100 kg per cow and sheep, respectively, and an N release rate of 0.3 g kg^{-1} of animal day^{-1} (average rate for cows; United States Department of Agriculture data) and 4 months of grazing per year, it can be estimated that total Finnemarka livestock N deposition is about 32 400 kg of N. Assuming that livestock are grazing homogeneously throughout the area, about 3 120 kg of N would be excreted within the Glitre catchment, equivalent to around 0.75 kg N ha^{-1} yr^{-1}. This N will primarily be sourced from catchment vegetation, and so is not a net input to the catchment, but N excreted by livestock tends to be more mobile and bioavailable compared to plant-bound N. Nonetheless, most of the excreted N would be retained in soils. If we assume that only N excreted within 20 m of streams is exported directly to the stream, and around 60 km of streams in the catchment, this corresponds to a contributing area of around 1.2 km^2 (3% of the catchment area), and therefore 3% of 3.3 tonnes, or 90 kg of livestock N to be exported annually to Glitrevann. This is around 0.20 kg/ha/year, i.e. insignificant compared to deposition inputs and other fluxes, particularly given the errors involved.

2. Sewage

A similar rough calculation for sewage N exports can be applied. Tourism in Norway in 2017 represented 33 millions overnight stays (including foreign, domestic and business stays). Assuming that a maximum of 10% of these stays occur in 10% of Norway's natural areas, including Glitre, and knowing that a human releases 12 g N day^{-1}, approximately 4000 overnight stays would occur in the Glitre catchment which would represent a maximum of 48 kg N annual human deposition, or 0.01 kg/ha/year. An alternative estimation method produces similar results. There are around 40 cabins in the catchment (data from Glitrevannverket), a number of which appear well-used. Assuming that during 100 days a year (two days a week, during weekends) half these cabins have two people in them, and assuming a human release of 12 g N day^{-1}, then this would amount to 48 kg N of sewage inputs to the catchment per year.

Much of this N is likely to be emitted to leach fields rather than directly to water courses. Assuming a retention rate of 75%, this would amount to around 7 kg N, i.e. the average daily flux of N to the lake from the catchment. Sewage inputs are therefore low enough to be neglected from the catchment N budget.

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