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Hydrology & Earth System Sciences

Effects of clear-cutting of forest on the chemistry of a shallow groundwater aquifer in southern Norway

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Abstract

As part of the national monitoring programme for long-range transported air pollutants, four groundwater aquifers in southern Norway were monitored for acidification trends during the period 1980–1995. For the monitoring station, Langvasslia in south eastern Norway, sampling continued until the end of 1999. This groundwater aquifer is about 3 km north east of the calibrated catchment Lake Langtjern. The catchment of the groundwater aquifer, covered completely by Norway spruce, was clear-cut in September 1986 and was treated with glyphosate in the summer, 1991. The chemical effects on the chemistry of the groundwater are generally similar to those observed in stream-water from clear-cut areas: increases in water runoff, water temperature, concentrations of K, NO_3, and organic carbon (TOC), and decrease in SO_4 concentration. In the groundwater aquifer, inorganic Al and ANC increased more than would have been expected without clear-cutting. By 1999 NO_3 concentrations were nearly the same as prior to clear-cutting, whereas K still was elevated.

Keywords: Groundwater; clear-cutting; water chemistry; monitoring.

Introduction

Clear-cutting of forests in lake catchments has pronounced effects on stream and lake water chemistry. Likens *et al.* (1970) reported that clear-cutting and herbicide treatment in the hardwood forested Hubbard Brook catchment in New Hampshire, U.S.A. caused large increases in stream-water concentrations for most major ions, especially NO_3 and K, and water yield increased substantially. Hornbeck *et al.* (1987) also reporting on clear-cutting practices on runoff water in the Hubbard Brook catchment found the effect was at maximum one year after block cut harvest, giving about 100% higher sum of measured ions than before harvest. By year 5 after harvest, the sum of ions had returned to levels found before harvest. The large increase in NO_3 was balanced largely by increases in Ca, Mg and K. K was the only ion that continued to increase 5 years after the harvest period. Similar results were found from clear-cutting hardwood forests in the White Mountains of New Hampshire (Martin *et al.*, 1985). Neal *et al.* (1992a,b) studied the effects of harvesting on stream water chemistry at an acidic and acid sensitive spruce forested area in mid-Wales. The effects of a 3-year conifer harvesting programme showed that concentrations of NO_3 and K initially almost quadrupled and remained high for 4 years. Concentrations of aluminum in soils and stream increased and stream pH and alkalinity declined for the first two years, after which the concentrations returned to conditions similar to those prior to felling. Rosén *et al.* (1996) studied the runoff from 3 forested catchments in central Sweden during a 12-year period. Fifty percent and 95% of the surface of two of the areas were clear-cut, the third area was kept as a control. Average runoff increased by 85% and 110%, respectively, in the clear-cut areas. Stream chemistry changes included increased concentrations of K, NH_4, NO_3, organic- and total N. At the end of the 8-year study period, the run-off and stream water chemistry returned successively to pre-cut conditions.

As part of the national monitoring programme for long-range transported air pollutants, administered by the Norwegian Pollution Control Authority (SFT) (Johannessen, 1995), four groundwater aquifers in southern Norway were monitored for acidification trends from 1980 to 1995. For economic reasons, groundwater monitoring was officially terminated in 1996. For one of the monitored stations, Langvasslia (station code LAG01) in southeastern Norway, sampling was continued by the Norwegian Institute for Water Research (NIVA) as a research project until the end of 1999. This groundwater aquifer is located about 3 km northeast of the calibrated catchment Lake Langtjern (Henriksen and Wright, 1977; Skjelkvåle and Henriksen, 1995) (Fig. 1). The catchment of the ground-

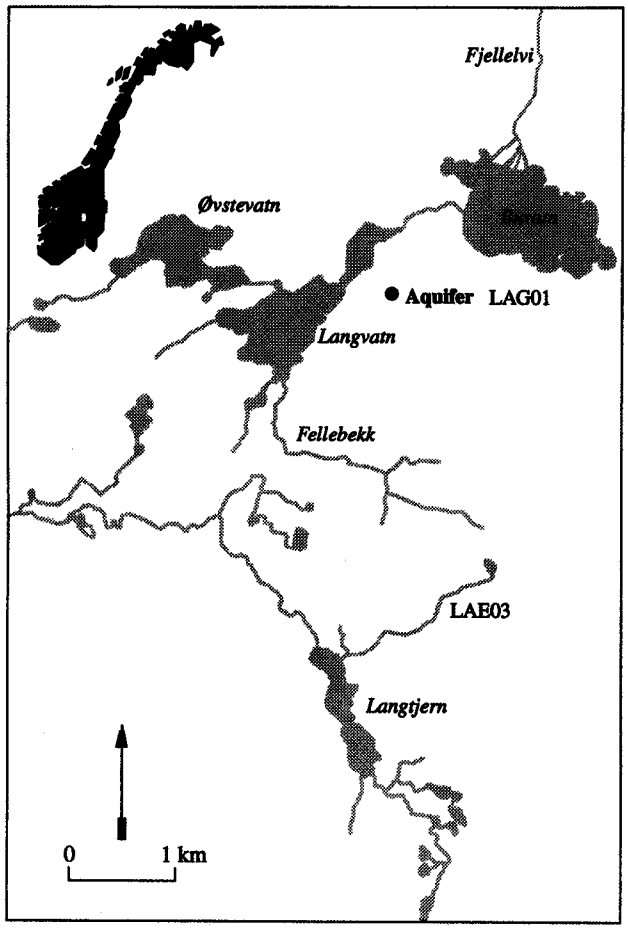

Fig. 1. *Location of the Langvasslia groundwater aquifer (LAG01) relative to the calibrated catchment Lake Langtjern.*

water aquifer was forested completely by Norway spruce, but was totally clear-cut without warning by the landowner in September 1986. The slash was not burned or removed. The catchment was treated further with glyphosate in summer 1991 to stop growth of deciduous trees. This offered the opportunity to study the effects of clear-cut on a shallow groundwater aquifer with a small catchment (Fig. 2). Trends and changes in water chemistry recorded for the groundwater aquifer at Langvasslia are presented here, with special emphasis on the effect of the clear-cutting on groundwater chemistry.

Site description

The bedrock in the area consists of banded granodioritic gneiss with layers of amphibolite of Precambrian age (Smithson, 1963), overlain by till. The groundwater aquifer is unconfined and located in till on a hill slope. The monitoring screen well is placed in till in the discharge area of the aquifer, near the bottom of the hill slope at an altitude of 425 m.a.s. The thickness of the till is about 1–3 m, with many large clods. The till is probably affected by frost and, thus, has become more permeable than a typical basal till.

Sampling and analysis

The monitoring 1.25 inches (31.8 mm) screen well was placed just above a spring outlet, with the groundwater intake for chemical analysis from 0.75–1.75 m (1 m filter) below the surface. Groundwater samples were collected

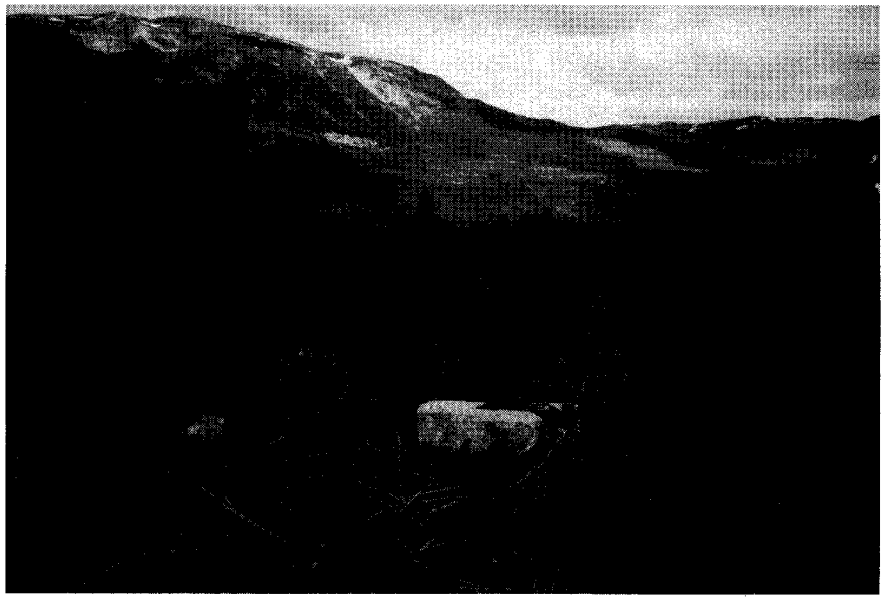

Fig. 2. *A picture of the catchment of the groundwater aquifer in 1999. The new 13-year-old forest is seen in the foreground. The dense old forest in the background is similar to the forest before clear-cutting.*

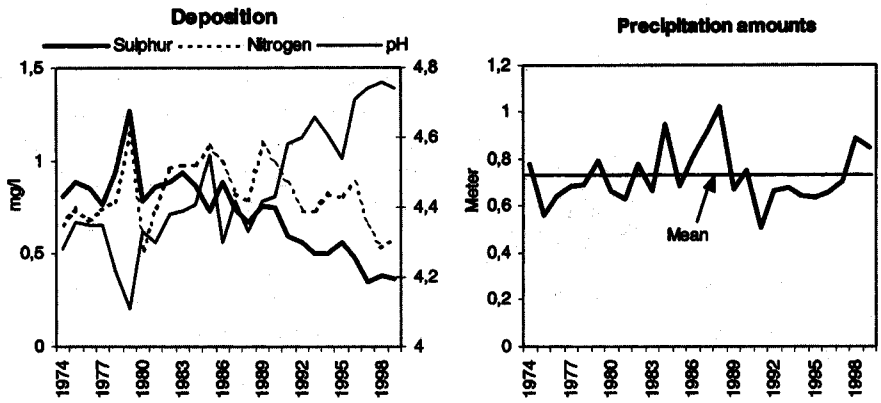

Fig. 3. *Yearly weighted average concentrations in wet deposition and yearly precipitation amounts at monitoring station Gulsvik in Buskerud county, Norway, located 7 km west of groundwater aquifer (Tørseth et al., 1999).*

after 15 minutes pumping. Groundwater samples were collected monthly when possible. At the same time the water yield was measured by counting the time to fill a 10 litre bucket. Groundwater level and groundwater temperature were measured weekly. Groundwater sampling was started in May 1980. All samples were analysed at the Norwegian Institute for Water Research using standardised methods for the following variables: pH, conductivity, Ca, Mg, Na, K, Cl, SO_4, NO_3 alkalinity, reactive Al, non-labile Al, SiO_2, turbidity and permanganate value. As part of the national monitoring programme for long-range transported air pollutants precipitation chemistry and precipitation amounts were determined by bulk sampling on a daily basis for the period 1974 to 1992 and on a weekly basis thereafter (Tørseth *et al.*, 1999) (Fig. 3). The precipitation station was located at Sønsteby farm at Gulsvik 7 km west of the groundwater aquifer.

Results and discussion

PRECIPITATION CHEMISTRY AND AMOUNTS

The trends in deposition at Gulsvik follow the general patterns for southern Norway: a significant downward trend in sulphur deposition occurs from the early 1980s with, in consequence, a marked increase in pH, but there were no significant changes in N-deposition until the last three years (Tørseth *et al.*, 1999). In 1979, the concentrations of S, N and H^+ were the highest ever measured at Gulsvik. The precipitation amounts during the later 1980s were significantly above the average for the measurement period, thereafter precipitation amounts returned to near the average for the measurement period. During 1996–1999, however, the amount of precipitation has increased.

Groundwater level, temperature and yield

The groundwater level generally varies with season (Fig. 4): lower levels in late winter and late summer and higher levels in spring after snowmelt and in late fall due to increased rain. The groundwater aquifer is shallow and therefore sensitive to variations in precipitation. The records include several dry periods (Fig. 4). These all occur during dry summers, such as in September 1981, July 1983, July 1986, and in August-September 1991 and 1995. Water temperature varies between nearly 0°C during winter and up to 10°C during the summers of 1988 and 1997. 89% of the temperature observations above 7°C were measured in summer months *after* clear-cutting. There is a tendency to higher water levels for two years after clear-cutting (Figs. 4 and 6a), but this may be caused by higher precipitation amounts for those two years (Fig. 3). The clear-cut also resulted in higher summer temperatures in the groundwater (Fig. 5).

The water yield measurements were stopped in December 1998. During the sampling period 126 water yield measurements were taken compared with 895 water level measurements. As is expected water level and water yield are related (Fig. 6b), and yield increased abruptly after clear-cutting, returning to pre-cut values after 2 years.

Water chemistry

Water samples for chemical analyses were collected once a month whenever possible. Due to the well being frozen occasionally or very low groundwater level, the measurement frequency was less than once a month for most years. These irregularities are reflected in the number of samples collected per year (Table 1). The yearly average values for the measured chemical variables of the groundwater aquifer for the measurement period 1980–1999 (Table 1) show that the groundwater is acidic, has high concentrations of labile inorganic aluminum (L-Al) and has low concentrations of base cations. The groundwater is highly influenced by soil water, as indicated by the high concentrations of organic matter (TOC). Because of its location inland in Norway, the groundwater is little influenced by sea-salt spray, as

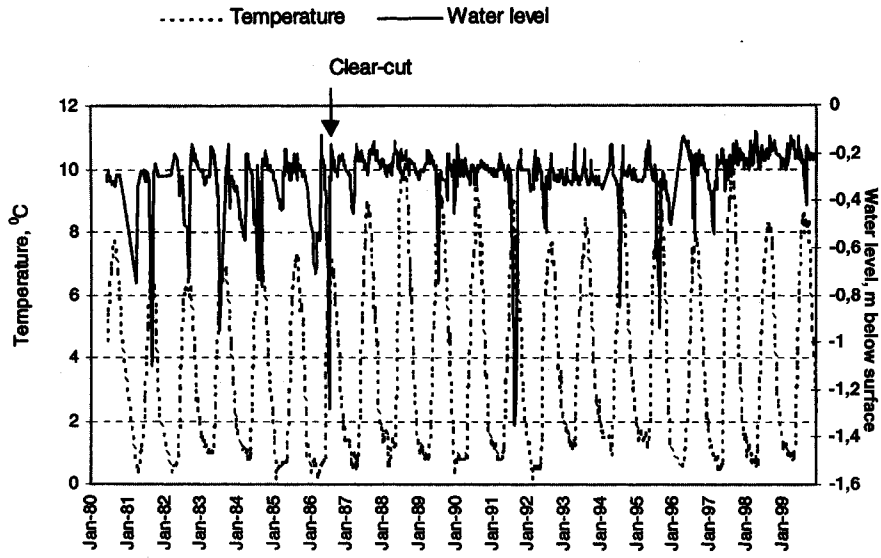

Fig. 4. *Water level below surface and water temperature in the groundwater aquifer measured weekly.*

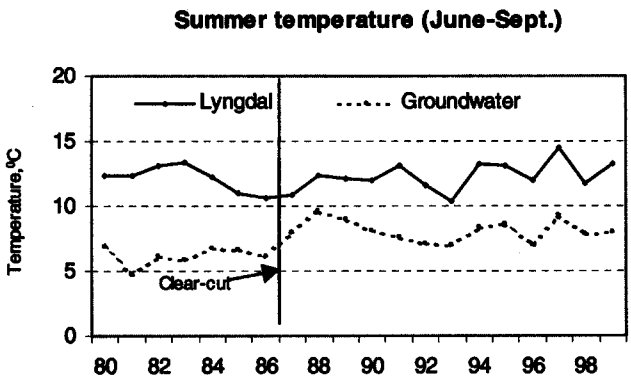

Fig. 5. *Summer temperature (July-Sept) in groundwater with air temperature at Lyngdal (Data from DNMI, the Norwegian Meteorological Institute.)*

reflected in the low concentrations of chloride and sodium. The average ratio of Na/Cl is 1.44 as compared to the seawater ratio of 0.85, indicating the presence of some geological sources of sodium in the catchment of the aquifer.

Comparison with surface water

The monitoring of the groundwater aquifer was designed to study the long-term effects of acid rain on groundwater chemistry. Since the clear-cutting of the forest in the catchment came as a surprise, no reference groundwater aquifer was established. However, one of the inlets to Lake Langtjern (station code LAE03, see Fig. 1) is located in a similar geological setting as the groundwater aquifer and is located only 3.5 km away. Here, weekly samples have been

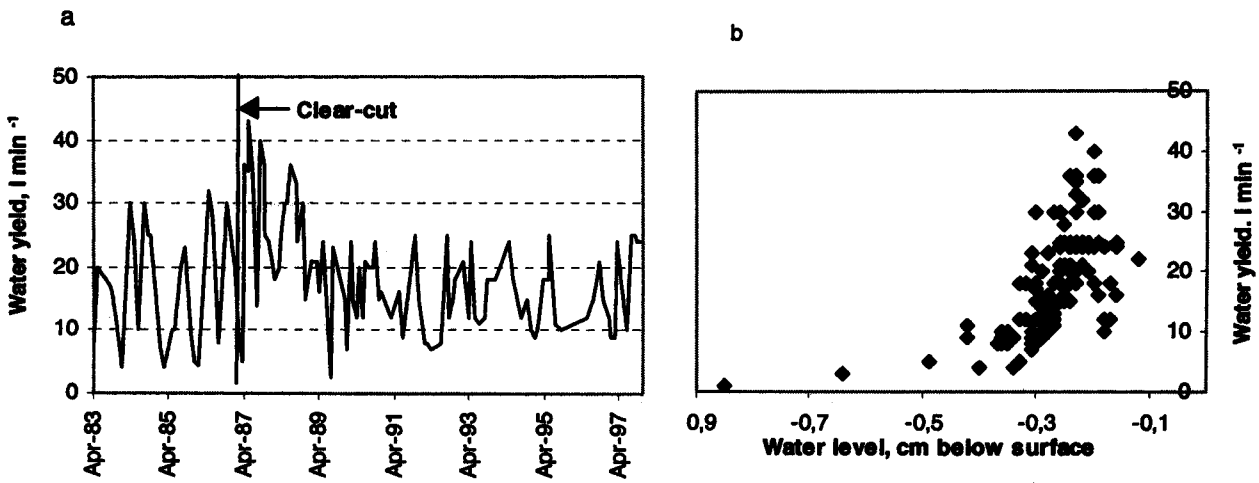

Fig. 6. *Variations in water yield during the measurement period (a), and relationship between water level and water yield (b).*

Table 1. Yearly average values for analysed variables in the groundwater aquifer Langvasslia in Buskerud county, Norway. Total organic carbon (TOC) has been estimated from measured permanganate values (PERM) by the empirical equation: TOC = PERM/1.24 based on 87 samples of surface waters in Norway (not published). R-Al = Reactive Al, Org-Al = non-labile Al, L-Al = Labile Al. N = Number of samples per year.

Year	N	pH	Ca mg l^{-1}	Mg mg l^{-1}	Na mg l^{-1}	K mg l^{-1}	Cl mg l^{-1}	SO_4 mg l^{-1}	NO_3 µgN l^{-1}	Alk µeq l^{-1}	ANC µeq l^{-1}	R-Al µg l^{-1}	Org-Al µg l^{-1}	L Al µg l^{-1}	SiO_2 mg l^{-1}	Turb FTU	TOC mg l^{-1}
1980	10	5.18	1.09	0.21	1.10	0.07	0.7	4.4	10	15	9.6				8.9	1.7	8.2
1981	10	5.30	1.08	0.22	1.13	0.09	0.8	4.4	10	15	9.4				8.5	2.7	7.9
1982	11	5.25	1.24	0.26	1.24	0.07	0.8	5.1	10	12	9.6				8.2	1.7	7.0
1983	9	5.13	1.26	0.25	1.23	0.09	0.9	5.1	10	9	7.7	407	233	174	8.2	1.8	8.0
1984	9	5.07	1.20	0.24	1.22	0.07	0.6	5.0	2	6	11.7	452	219	233	8.2	1.3	8.2
1985	11	5.07	0.95	0.20	1.09	0.05	0.5	4.5	1	4	2.7	476	278	198	8.5	0.9	7.9
1986	11	5.08	0.94	0.21	1.19	0.16	0.7	4.0	8	4	17.7	461	260	202	8.7	2.9	8.2
1987	12	5.09	0.85	0.20	1.03	0.66	0.8	2.9	38	6	34.3	498	285	213	7.4	0.7	10.1
1988	12	5.13	0.86	0.19	1.00	0.77	0.9	2.7	169	10	27.1	621	276	345	7.4	1.0	11.4
1989	11	5.25	0.80	0.21	1.16	0.67	1.1	2.6	202	14	23.7	509	232	277	7.5	1.2	9.7
1990	12	5.24	0.92	0.22	1.11	0.54	0.8	2.8	227	10	28.5	465	214	252	7.1	0.9	9.5
1991	10	5.22	1.19	0.27	1.21	0.47	1.1	3.0	260	20	34.5	435	262	174	7.9	1.0	8.4
1992	11	5.26	1.28	0.29	1.29	0.80	1.3	3.1	378	17	34.5	434	289	145	8.3	2.3	7.7
1993	12	5.31	1.32	0.30	1.27	0.90	1.0	2.8	351	31	56.6	395	310	85	8.5	0.9	8.0
1994	10	5.37	1.44	0.33	1.28	0.76	0.8	2.9	394	43	64.4	386	286	100	8.4	1.0	8.0
1995	10	5.63	1.48	0.33	1.20	0.74	0.9	2.9	339	63	63.1	364	261	103	8.3	1.6	8.3
1996	9	5.39	1.51	0.32	1.13	0.57	0.8	3.1	398	42	50.7	397	288	109	7.7	1.2	10.2
1997	11	5.49	1.32	0.26	1.11	0.38	0.8	2.7	165	47	54.7	376	277	98	7.7	0.6	10.2
1998	12	5.49	1.21	0.21	1.05	0.38	0.7	2.3	80	39	60.8	401	328	73	7.5	0.9	10.3
1999	11	5.63	1.10	0.21	0.97	0.33	0.5	2.1	27	53	61.7	399	304	96	7.4	1.1	9.6
Mean	11	5.28	1.15	0.25	1.15	0.43	0.8	3.4	154	23	33.2	440	271	169	8.0	1.4	7.8

Table 2. Yearly average chemistry for an inlet creek to Lake Langtjern (LAE03) and Langvasslia groundwater aquifer (LAG01) prior to clear-cutting (1980–1985) and after clear-cutting (1987–1999).

	pH	Ca mg l^{-1}	Mg mg l^{-1}	Na mg l^{-1}	K mg l^{-1}	Cl mg l^{-1}	SO_4 mg l^{-1}	NO_3 µg l^{-1}	ANC µeq l^{-1}	TOC mg C l^{-1}	R-Al µg l^{-1}	Org-Al µg l^{-1}	L-Al µg l^{-1}
Groundwater													
Prior	5.16	1.14	0.23	1.17	0.07	0.7	4.7	7	8	7.8	445	243	202
After	5.35	1.17	0.26	1.14	0.61	0.9	2.8	233	46	8.4	437	278	159
Surface water													
Prior	4.68	1.17	0.25	0.65	0.10	0.8	4.1	19	5	13.7	236	157	79
After	4.70	0.99	0.20	0.71	0.09	0.6	2.5	14	30	11.5	202	159	43

collected since 1973 (Skjelkvåle and Henriksen 1995). The yearly average values for the period 1980–1985 (prior to clear-cut) for both sites (Table 2) have been compared. The concentrations of major constituents are very similar with marked differences found only in H^+(pH), TOC and aluminum species. Normally groundwater has significantly higher CO_2-pressure than surface water. Norton and Henriksen (1983) found for the particular aquifer studied here that the PCO_2 at the time of sampling was $10^{-2.08}$ at pH 5.14. After purging the sample with N_2 the PCO_2 rose to $10^{-3.33}$ and the pH rose to 5.49.

A major difference is found for labile inorganic aluminum, the species considered to be toxic to fish. The concentration in groundwater is 7 times higher than in surface water (Table 2). The groundwater has percolated through the unsaturated zone and, thus, its water chemistry reflects the net integrated effects of the processes taking place in this zone. Norton and Henriksen (1983) suggested that because the groundwater aquifer is highly over-saturated with CO_2, the dissociation of H_2CO_3 produces concentrations of H^+ capable of rendering particulate Al soluble. The HCO_3^- formed may serve as a mobile anion and facilitate the transport of the Al.

Figure 7 show variations in several chemical variables during the period 1980–1999 based on the individual observations for the Langvasslia groundwater aquifer. To assess the effect of the clear-cutting on water chemistry, the yearly average values for both the aquifer and the inlet stream to Langtjern (see Table 2) have been plotted for most of the variables (Fig. 8). The effect of clear-cutting as superimposed on the general trends in the surface water is discussed below.

NITRATE AND POTASSIUM

The most marked effect of the clear-cutting is the sharp increase in the concentrations of NO_3 and K (Fig. 7a) due to less nutrient uptake in the catchment and increased mineralization of organic matter such as dead roots. Before the clear-cutting NO_3 and K concentrations were low; K was about 0.08 mg l^{-1} and NO_3 less than 10 µg N l^{-1}. After clear-cutting, K increased almost immediately while NO_3 started to increase a year later. NO_3 decreased during the

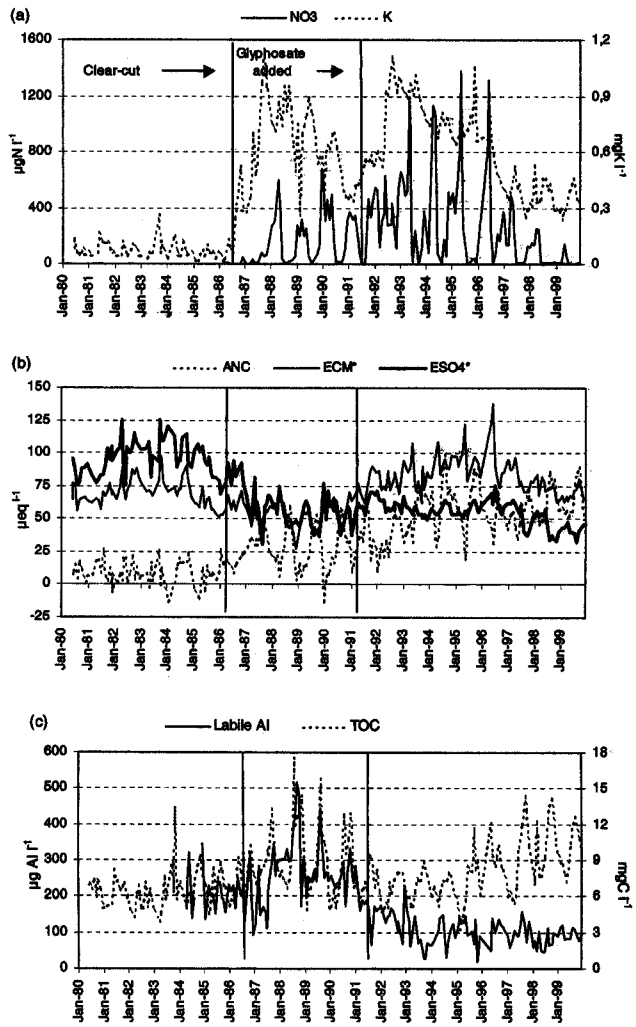

Fig. 7. *Langvasslia groundwater aquifer: Variations in several chemical variables during the period 1980–1999 based on individual observations. ANC = acid neutralizing capacity, ECM* = non-marine Ca+Mg, ESO4* = non-marine SO_4.*

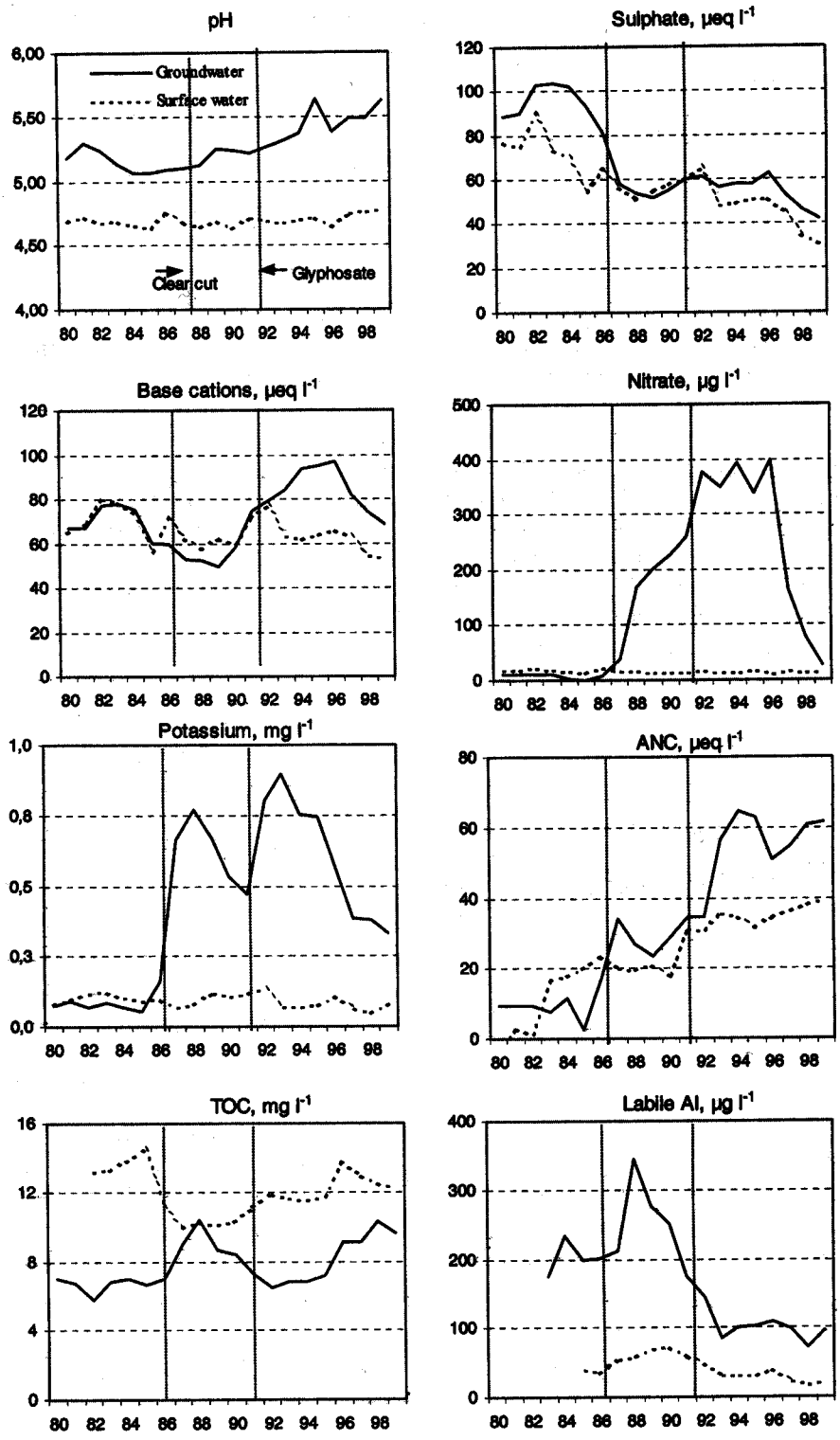

Fig. 8. *Yearly average values for several components in Langvasslia groundwater aquifer (groundwater) with corresponding values for the inlet stream to Langtjern (surface water) for the period 1980–1999. ANC = acid neutralizing capacity, ECM* = non-marine Ca+Mg, ESO4* = non-marine SO_4.*

growing season every year and increased during the dormant season. The addition of glyphosate in 1991 led to increased leaching of both NO_3 and K; especially high NO_3 peaks were observed during the dormant season until 1995. In 1997, the concentration levels of NO_3 and K were back to the levels before the glyphosate treatment, but still

significantly higher than before the clear-cutting. During the last two years, however, the NO_3 concentrations were also low during the dormant season and should reach the levels before clear-cutting in the near future. After 13 years, K concentrations are still at a higher level than before clear-cutting.

These general trends in leaching of nitrate and K are in general agreement with the observations made in other clear-cut areas in the U.S., UK and Sweden (Likens *et al.*, 1970; Neal *et al.*, 1992a,b; and Rosén *et al.*, 1996). At Langvasslia by 1999, 13 years after clear-cutting, NO_3 is almost back to the concentrations before. This period is substantially longer than those reported from other clear-cutting experiments. Both Hornbeck *et al.* (1987) and Neal *et al.* (1992b) reported about 5 years before NO_3 returned to pre-harvest conditions. Rosén *et al.* (1996) found that at the end of the 8 year study period, the run-off and stream-water successively returned to pre-cut conditions. The extended recovery time for the Langvasslia aquifer could be caused by the glyphosate treatment 5 years after the clear-cutting, because deciduous vegetation growth was stopped to allow the coniferous trees the opportunity to dominate, as they do today.

SULPHATE

Fuller *et al.* (1987) showed that whole-tree harvesting in Hubbard Brook Experimental Forest led to increased mineralization and nitrification, substantial NO_3 loss, acidification of soil solutions and increased soil adsorption of SO_4. As a consequence, stream-water concentrations and effluxes of SO_4 declined and NO_3 increased after tree harvesting. At the Langvasslia aquifer, SO_4 concentrations were substantially higher than in the surface water before clear-cutting (Fig. 8), but had started to decline before the clear-cutting. After the clear-cutting, however, the groundwater concentrations of SO_4 declined at a faster rate than those in the surface water. This reduction in concentration can be explained largely by reduced dry deposition of gaseous and particulate sulphur species due to the removal of the trees. One year after clear-cutting, the concentrations both in groundwater and in surface water are similar, and the concentrations remained fairly constant until 1993 when the groundwater concentrations again were higher than the surface water concentrations. Apparently, the growing forest again scavenged significant amounts of sulphur from the atmosphere. Thus, there is no need to invoke changes in soil acidity and SO_4 adsorption to explain the observed pattern in SO_4 concentrations in groundwater at Langvasslia.

ANC AND BASE CATIONS (CA+MG)

A characteristic aspect of surface water quality recovery from acidification in Norway is the decline in sulphate concentration and a stable base cation concentration (Skjelkvåle *et al.*, 1998). Acid Neutralizing Capacity (ANC) (Reuss and Johnson, 1986) has increased in the surface water, especially since 1990 (Fig. 8), due to the reduced sulphur deposition in Norway (Skjelkvåle *et al.*, 1998). ANC in the groundwater has also increased, and follows generally the same pattern as for the surface water (see Figs. 7c and 8), but ANC has increased substantially more than in the surface water since the early 1990s.

The ANC of the groundwater aquifer has increased significantly after clear-cutting and glyphosate treatment, although the SO_4 concentrations have not decreased correspondingly. This is because the concentrations of non-marine base cations increased during the same period in contrast to the surface water (Figs. 7 and 8). After 5 years, however, base cation concentrations started to decline approaching the levels of the surface water. The "episodic" base cation increase can indicate a short-lived change in weathering or mineralization of organic matter in the soil due to the clear-cutting, or reduced biological uptake.

TOTAL ORGANIC CARBON AND LABILE ALUMINUM

Total organic carbon increased significantly after clear-cutting (Figs. 7b and 8), but declined again after a few years. The high peaks of TOC all occur in the summer (Fig. 8), and the peaks are highest during the first few years after clear-cutting. The TOC peaks decreased in the first part of 1990s, but have increased significantly during the later years. This is in accordance with the general increase in TOC of surface water observed in southern Norway (SFT, 1999) as also reflected in the TOC trend in the inlet stream to Langtjern (Fig. 8).

The concentrations of labile Al also increased sharply during the summer months after clear-cutting (Fig. 7c), especially 2–3 years after clear-cutting. Labile Al started to decline around 1990, following the general trends in surface waters in Norway (Skjelkvåle *et al.*, 1998), as also reflected in the inlet stream to Langtjern (Fig. 8).

Concluding remarks

Based on the experience from Hubbard Brook, Likens *et al.* (1970) suggest, that clear-cutting reduces shading and transpiration, thus increasing temperature and water flux through the forest floor. Decomposition of organic matter proceeds more rapidly and nitrification increases greatly, leading to higher NO_3-leaching. Also K leaching increases due to reduced nutrient uptake by vegetation. These conclusions are in accordance with findings by other researchers (Vitousek *et al.*, 1979; Rosén, 1984; Martin *et al.*, 1985; Hornbeck *et al.*, 1987; Rosen *et al.*, 1996; Neal *et al.*, 1992a,b). Martin *et al.* (1985), however, found from studies in clear-cutting areas in New England, U.S.A. that

NO_3-leaching into streams was insignificant in most cases. He explained that these differences were caused by differing characteristics of the catchments. Although the increased nitrification may cause high NO_3-concentrations in the soil solution, the NO_3 may not reach the stream body because of de-nitrification in the saturated zone in the soil and uptake by re-growing vegetation. Thus, the retention time of the water in the soil is important in assessing the effect of clear-cutting on NO_3-content of soil water and thus also on groundwater. In the catchment of Langvasslia groundwater aquifer the soil cover is thin, and thus the retention time of the water in the soil profile is short. Consequently, de-nitrification reactions and uptake by vegetation are low, leading to high leaching of NO_3 into the groundwater.

The elevated leaching of NO_3 and K persisted for 11 years, but NO_3 is now almost back to the levels before the clear-cutting. Other studies indicate shorter recovery time for NO_3. The extended recovery time for the Langvasslia aquifer could be caused by the glyphosate treatment 5 years after the clear-cutting, because the deciduous vegetation growth was stopped to give the coniferous trees the opportunity to dominate. The leaching of K, however, is still higher than before clear-cutting. A similar observation was made by Hornbeck *et al.* (1987) in a study of 10 years of recovery from clear-cutting in Hubbard Brook, where the effects of the cutting remained evident through the 10 years of re-growth.

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