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

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Norwegian Institute for Water Research

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Abstract

Clear-cutting of forests have pronounced effects on chemistry of soils and runoff water. The major effects are increased water yield, changes in nutrient cycles and increased leakage of the nutrients nitrate and potassium in runoff. As part of the national monitoring programme for long-range transported air pollutants, administered by the Norwegian Pollution Control Authority (SFT), four groundwater aquifers in southern Norway were monitored for acidification trends during the period 1980-1995. For the monitoring station, Langvasslia in southeastern Norway, sampling was continued until the end of 1999. This groundwater aquifer is located about 3 km north-east of the calibrated catchment Lake Langtjern. The catchment of the groundwater aquifer, covered completely by Norway spruce, was totally clear-cut in September 1986 and was treated with glyphosate in summer 1991. The effects on 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 also inorganic aluminum decreased and ANC increased more than would have been expected without clear-cutting. NO_3 concentrations are now almost back to the levels prior to clear-cutting, whereas K still shows elevated concentrations.

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1. Grunnvann	1. Groundwater
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Effect of clear-cutting of forest on the chemistry of a shallow groundwater aquifer in southern Norway

By

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Preface

As part of the national monitoring programme for long-range transported air pollutants, administered by the Norwegian Pollution Control Authority (SFT), four groundwater aquifers in southern Norway were monitored for acidification trends during the period 1980-1995. Three of them, Birkenes, Åmli and Evje (from 1982) are located in Aust Agder county, whereas the fourth aquifer, Langvasslia, is located in Buskerud county. For economic reasons groundwater monitoring was officially terminated in 1995. The Norwegian Institute for Water Research (NIVA) and the Geological Survey of Norway (NGU) jointly sponsored the groundwater monitoring for 1996, hoping that the official monitoring could again be resumed by SFT. Unfortunately, this did not happen. Because the catchment of the groundwater aquifer in Langvasslia (LAG01) was clearcut in 1986, and that the effect on the water quality was still significant in 1996, sampling was continued by NIVA in order to follow the effects of clearcutting for some more years. The sampling was terminated at the end of 1999, thus giving a sampling period of 20 years. We present here trends and changes in water chemistry recorded for this particular groundwater aquifer with special emphasis on the effect of the clear-cutting on groundwater chemistry. This report is based on a paper submitted to *Hydrol. Earth System Sci.*

Oslo, 25.05 .2000

Arne Henriksen

Contents

Summary

Clear-cutting of forests have pronounced effects on chemistry of soils and runoff water. The major effects are increased water yield, changes in nutrient cycles and increased leakage of the nutrients nitrate and potassium in runoff. As part of the national monitoring programme for long-range transported air pollutants, administered by the Norwegian Pollution Control Authority (SFT), 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 was continued until the end of 1999. This groundwater aquifer is located about 3 km north-east of the calibrated catchment Lake Langtjern. The catchment of the groundwater aquifer, covered completely by Norway spruce, was totally clear-cut in September 1986 and was treated with glyphosate in summer 1991. The effects 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 also inorganic aluminum decreased and ANC increased more than would have been expected without clear-cutting. NO_3 concentrations are now almost back to the levels prior to clear-cutting, whereas K still show elevated concentrations.

1. Introduction

Clear-cutting of forests in lake catchments have pronounced effects on stream and lake water chemistry. Likens *et al.* (1970) reported on effects of clear-cutting and herbicide treatment in the hardwood forested Hubbard Brook watershed in New Hampshire, U.S.A. Large increases in stream-water concentrations for most major ions, especially nitrate and potassium, were recorded. Also, water yield increased substantially. Similar results were found from clear-cutting hardwood forests in the White Mountains of New Hampshire (Martin *et al.* 1985). Hornbeck *et al.* (1987) have extensively reported on effects of clear-cutting practices on runoff water in the Hubbard Brook watershed. 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 nitrate was largely balanced by increases in calcium, magnesium and potassium. Potassium was the only ion that continued to increase at year 5 after the harvest period. Neal *et al.* (1992a, 1992b) 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 program showed that nitrate and potassium, initially almost quadrupled, 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 trends reversed to give conditions similar to those pertaining prior to felling. Rosén et al (1996) studied the runoff from 3 forested catchments 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 were identified mainly on increased concentrations of potassium, ammonium, nitrate, organic- and total nitrogen. At the end of the 8-year study period the run-off and stream water successively returned 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 during the period 1980-1995. For economic reasons groundwater monitoring was officially terminated in 1996. For one of the monitored stations, Langvasslia (station code LAG01) in South Eastern Norway, sampling was continued by NIVA as a research project until the end of 1999.

The groundwater aquifer at Langvasslia is located about 3 km north-east of the calibrated catchment lake Langtjern (Henriksen and Wright 1977, Skjelkvåle and Henriksen 1995) (Figure 1) The catchment of the groundwater aquifer, covered completely by Norway spruce, 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. As a consequence of these manipulations, the water quality of the groundwater aquifer changed considerably. This offered the opportunity to study the effects of clear-cut on shallow groundwater aquifer with a small catchment. We present here trends and changes in water chemistry recorded for the groundwater aquifer at Langvasslia and with special emphasis on the effect of the clear-cutting on groundwater chemistry.

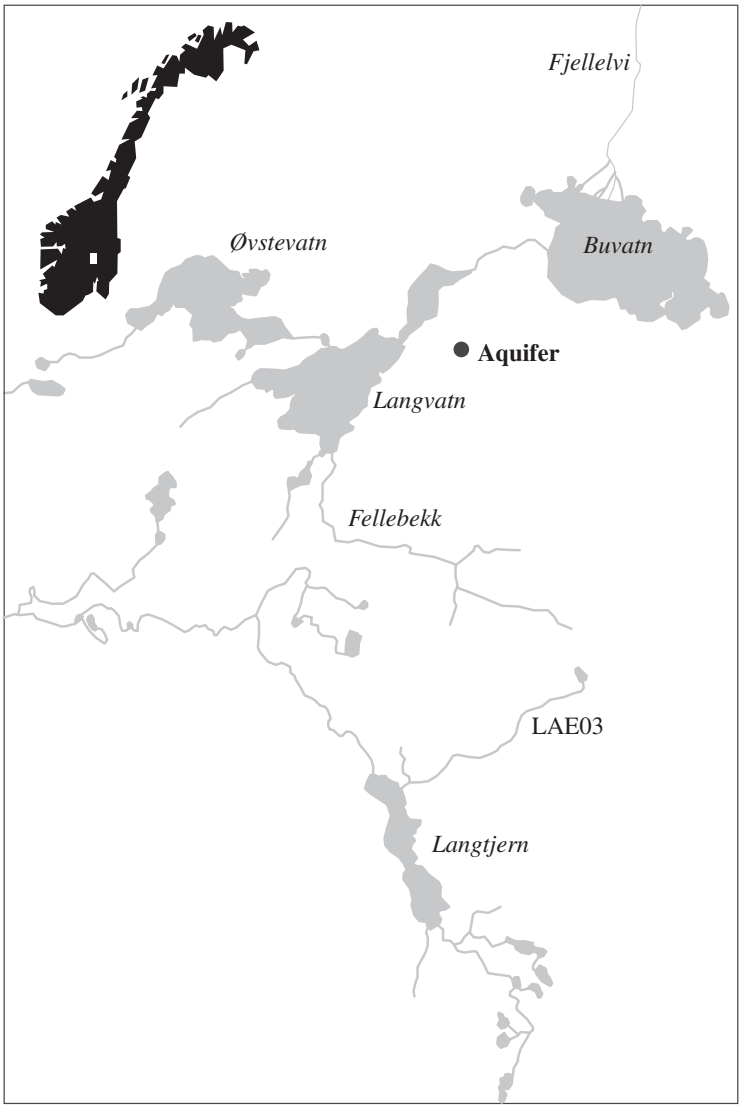

Figure 1. *Location of the Langvasslia groundwater aquifer relative to the calibrated catchment Lake Langtjern.*

Figure 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.*

2. Site description

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

3. Sampling and analysis.

The monitoring 5/4” 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 after 15 minutes pumping time. Groundwater level and groundwater temperature were measured weekly. Groundwater samples were collected monthly when possible and water yield was measured at the same time. Groundwater sampling was started in May 1980, all samples were analyzed at the Norwegian Institute for Water Research using standardized 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.

4. Results and discussion

4.1 Precipitation chemistry and amounts

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). (Figure 3). The precipitation station was located at Sønsteby farm at Gulsvik 7 km west of groundwater aquifer.

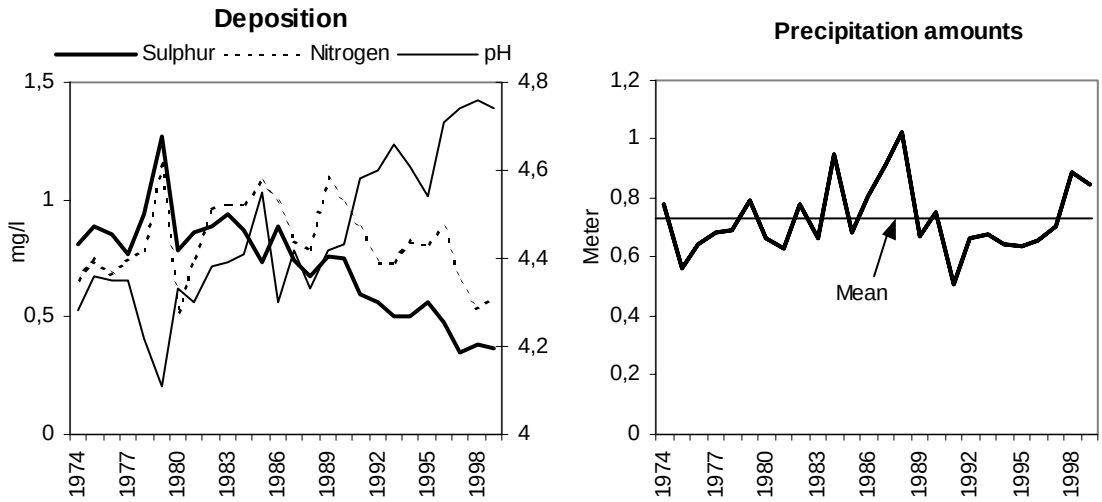

Figure 3. *Yearly weighted average concentrations in wet deposition and yearly precipitation amounts at monitoring station Gulsvik in Buskerud county, Norway, located 7 km west of groundwater aquifer (Tørseth et al. 1999).*

The trends in deposition at Gulsvik follow the general patterns for southern Norway: a significant downward trend in sulphur deposition from the early 1980's and, as a consequence, a marked increase in pH, but 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 were significantly above the average for the measurement period during the later 1980's, thereafter precipitation amounts returned to near the average for the measurement period. During the last three years, however, the amount of precipitation has again increased.

4.2 Groundwater level, temperature and yield

The groundwater level generally varies with season (figure 4): lower levels in late winter and late summer and higher water levels in spring after snowmelt and in late fall due to increased precipitation amounts. The groundwater aquifer is shallow and therefore sensitive to variations in precipitation amounts. The records include several dry periods (Figure 4). These occur all 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 further a tendency to higher water levels for two years after clear-cutting (Figures 4

and 6a), but this can partly be caused by higher precipitation amounts for those two years (Figure 3). The clear-cut also resulted in higher summer temperatures in the groundwater (Figure 5).

The water yield of the groundwater aquifer was measured only when a water sample was taken, normally once a month. 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 there is a clear relationship between water level and water yield (Figure 6b).

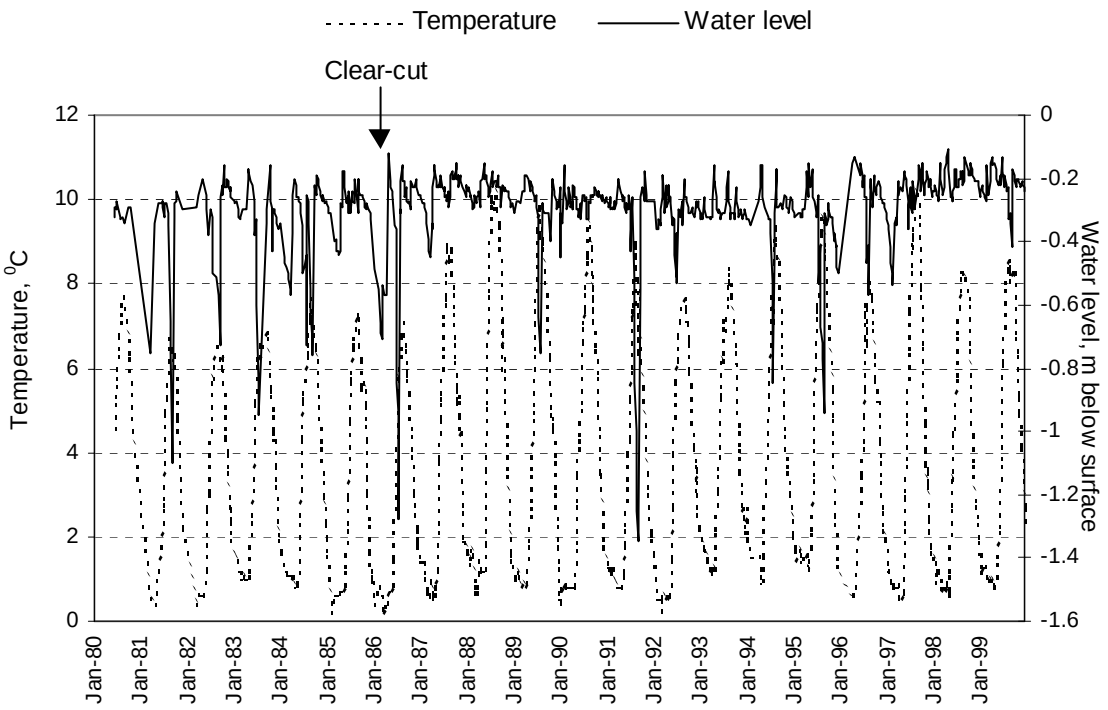

***Figure 4**. Water level below surface and water temperature in the groundwater aquifer measured weekly.*

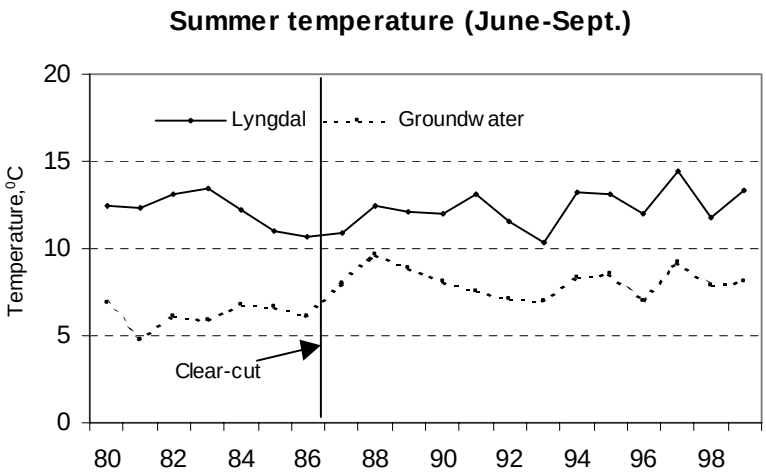

***Figure 5.** Summer temperature (July-Sept) in groundwater with air temperature at Lyngdal (Data from the Norwegian Meteorological Institute (DNMI).*

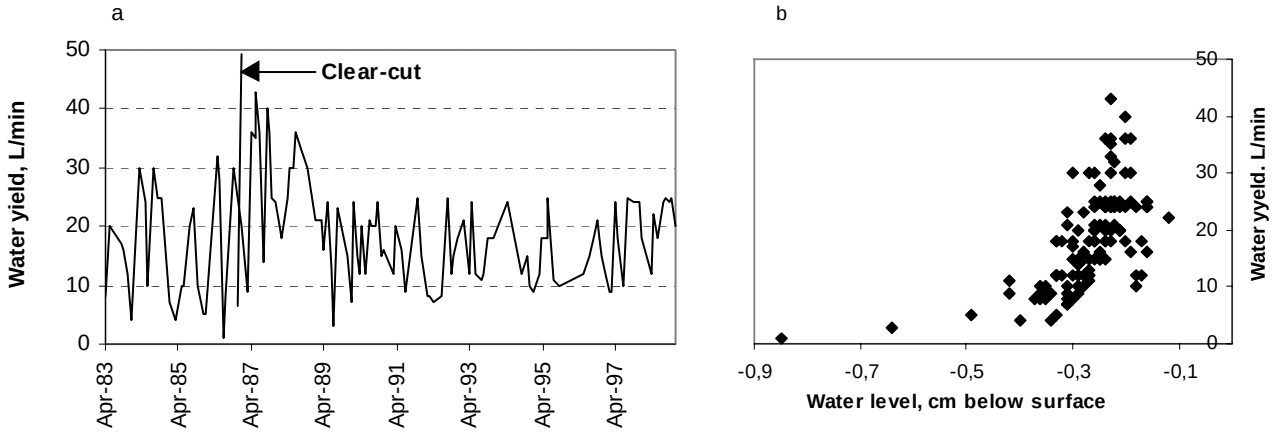

Figure 6*. Variations in water yield during the measurement period (a), and relationship between water level and water yield (b).*

5. Water chemistry

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

Table I. *Yearly average values for analyzed variables in the groundwater aquifer Langvasslia in Buskerud county, Norway. Total organic carbon (TOC) have 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	Na	K	Cl	SO_4	NO_3	Alk	ANC	R-Al	Org-Al	L Al	SiO_2	Turb	TOC
			mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	µgN l^{-1}	µeq l^{-1}	µeq l^{-1}	µg $^{l-1}$	µg $^{l-1}$	µg $^{l-1}$	mg l^{-1}	FTU	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**

6. Comparison with surface water

The monitoring of the groundwater aquifer was designed for studying the long-term effects of acid rain on groundwater chemistry. Since the clear-cutting of its catchment came as a surprise, no reference groundwater aquifer was established. However, one of the inlets to lake Langtjern (station code LAE03, see Figure 1) is located in similar geologic settings as the groundwater aquifer and located only 3.5 km away. Here, weekly samples have been collected since 1973 (Skjelkvåle and Henriksen 1995). We have compared the yearly average values for the period 1980-1985 (prior to clear-cut) for both sites (Table II). The concentrations of major constituents are very similar. Marked differences in concentrations are found in H^+(pH), TOC and aluminum species. Groundwater has normally 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 being toxic to fish. The concentration in groundwater is 7 times higher than in surface water (Table II). 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) suggest that aluminum may be transported by dissociation of H_2CO_3. Since 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, and the HCO_3^- formed may serve as a mobile anion and facilitate the transport of the Al.

Table II. *Yearly average chemistry for an inlet creek to lake Langtjern (LAE03) and Langvasslia groundwater aquifer (LAG01) prior to clear-cut (1980-1985).*

	pH	Ca	Mg	Na	K	Cl	SO_4	NO_3	ANC	TOC	R-Al	Org-Al	L-Al
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	µg l^{-1}	µeq l^{-1}	mg C l^{-1}	µg $^{l-1}$	µg $^{l-1}$	µg $^{l-1}$
Groundwater	5.16	1.14	0.23	1.17	0.07	0.7	4.7	7	8	7.8	222	122	186
Surface water	4.68	1.11	0.24	0.61	0.09	0.8	3.6	16	5	13.7	92	76	26

Figure 7 shows variations in several chemical variables during the period 1980-1999 based on the individual observations for Langvasslia groundwater aquifer. In order to assess the effect of the clear-cut on water chemistry, we have also plotted the yearly average values for both the aquifer and the inlet stream to Langtjern (see Table II) for most of the variables (Figure 8). Below we discuss the effect of clear-cutting as superimposed on the general trends in the surface water.

6.1 Nitrate and potassium

The most marked effect of the clear-cutting is the sharp increase in the concentrations of nitrate (NO_3) and potassium (K) (Figure 7, upper panel) due to less nutrient uptake in the catchment and increased mineralization of organic matter such as dead roots. Before the clear-cutting nitrate and potassium concentrations were low, potassium about 0.08 mg/l and nitrate less than 10 µgN/l. After clear-cutting potassium increased almost immediately while nitrate started to increase a year later. Nitrate decreased during growing season every year and increased during the dormant season. The addition of glyphosate in 1991 led to increased leaching of both nitrate and potassium, especially high nitrate peaks were observed during the dormant season until 1995.

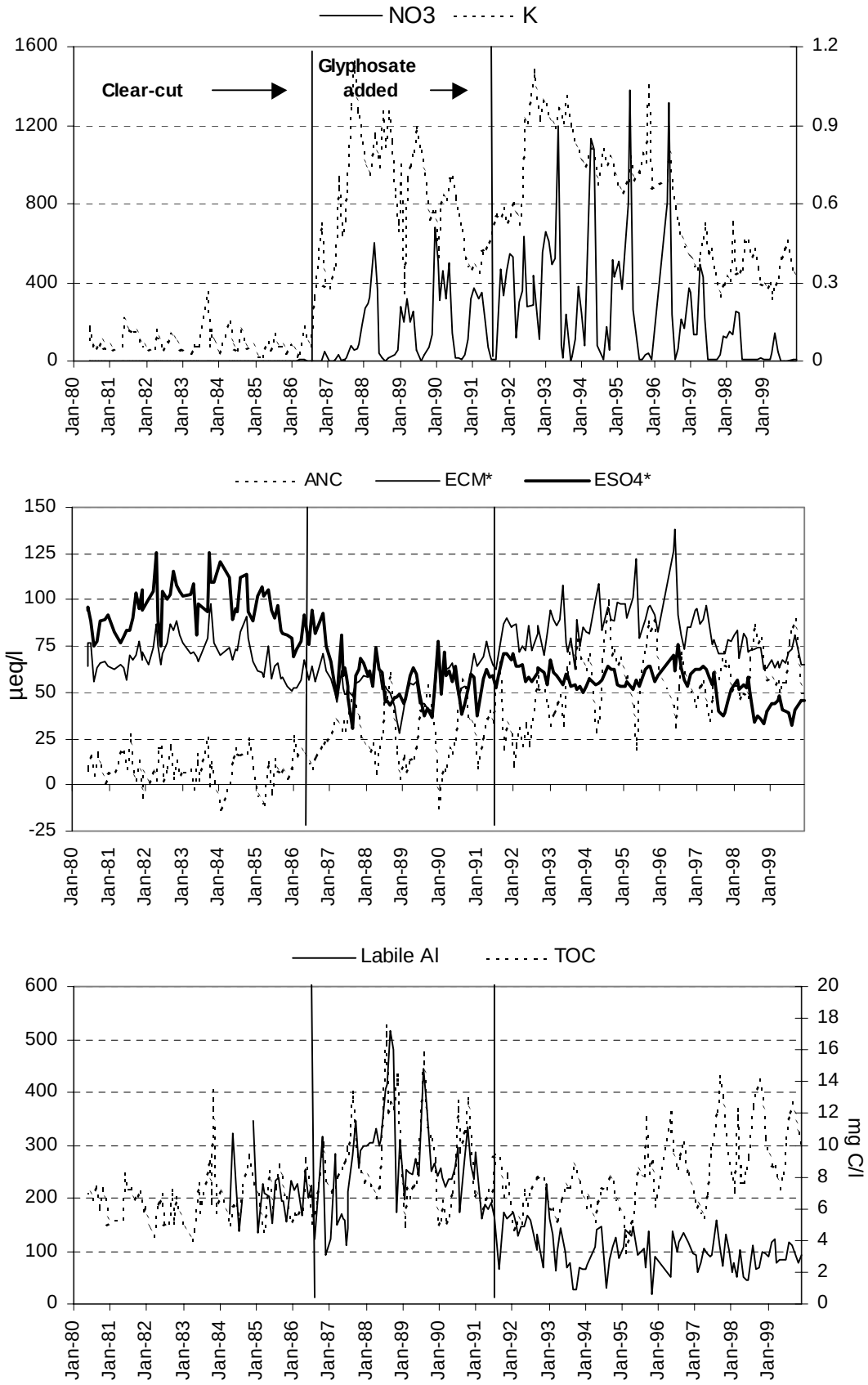

Figure 7. *Langvasslia groundwater aquifer: Variations in several chemical variables during the period 1980-1999 based on individual observations.*

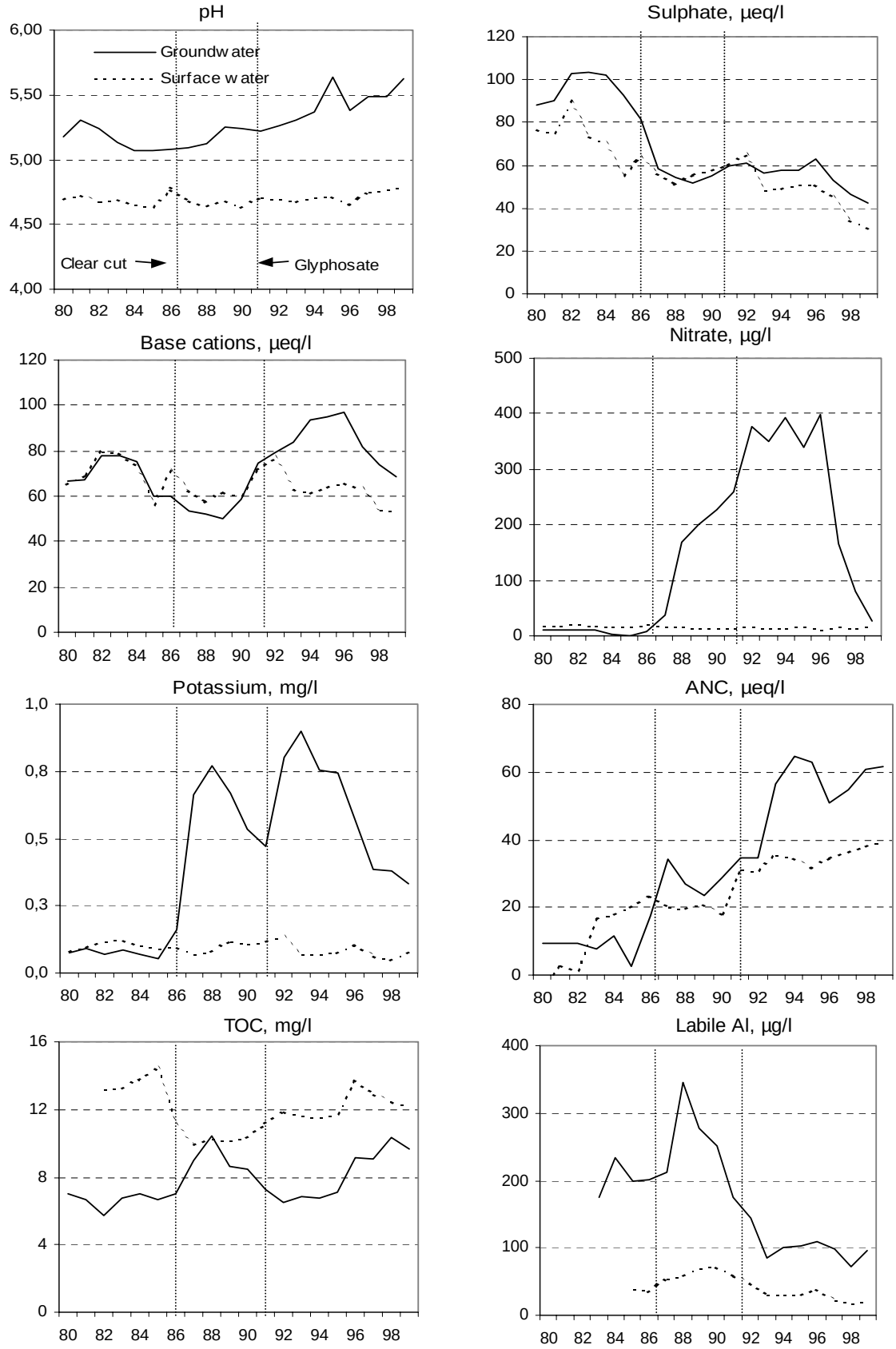

Figure 8. *Yearly average values for several components in Langvasslia groundwater aquifer (groundwater) with corresponding values for the inlet stream to Langtjern (surface water) for the period 1980-1999. ANC = acid neutralizing capacity, ECM* = non-marine Ca+Mg. ESO4* = non-marine* SO_4.

In 1997 the concentration levels of nitrate and potassium 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 nitrate concentrations were also low during the dormant season and should reach the levels before clear-cut in the near future. Potassium concentrations are still high and appear to have stabilized at a higher level than before clear-cut.

These general trends in leaching of nitrate and potassium are in general agreement with the observations made in other clear-cut in the U.S, UK and Sweden (Likens *et al.* 1970, Neal *et al.* 1992a, 1992b, and Rosén et al 1996). At Langvasslia by 1999, 13 years after clear-cut, nitrate is almost back to the concentrations before the clear-cut. This time span is substantially longer than those reported from other clear-cut experiments. Both Hornbeck *et al.* (1987) and Neal *et al.* (1992b) reported about 5 years before nitrate 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-cut, because the deciduous vegetation growth was stopped to allow the coniferous trees the possibility to dominate, as they do today.

6.2 Sulphate

Fuller *et al.* (1987) showed that whole-tree harvesting in Hubbard Brook Experimental Forest lead to increased mineralization and nitrification and consequently to 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 sulphate concentrations were substantially higher than in the surface water before clear-cut (Figure 8), but started as for the surface water to decline before the clear-cut. After the clear-cut, however, the groundwater concentrations of SO_4 declined at a faster rate than surface water. This reduction in concentration can largely be explained by reduced scavenging of gaseous and particulate sulphur species due to the removal of the trees. One year after clear-cut 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.

6.3 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 (Figure 8), due to the reduced sulphur deposition in Norway (Skjelkvåle *et al.* 1998). ANC in the groundwater has also increased, and follows largely the same pattern as for the surface water (see Figure 7 lower panel and Figure 8), but ANC has increased substantially more than in the surface water since the early 1990's.

The ANC of the groundwater aquifer increased significantly after clear-cutting in spite of rather stable sulphate concentrations. This is because the concentrations of non-marine base cations increased during the same period in contrast to the surface water (Figures 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-cut.

6.4 Total organic carbon and labile aluminum

Total organic carbon increased significantly after clear-cutting (Figure 7 center panel, Figure 8), but declined again after a few years. The high peaks of TOC all occur in the summer (Figure 8), and the peaks are highest the first years after clear-cut. The TOC peaks decreased in the first part of 1990’s, 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 (Figure 8).

The concentrations of labile Al also increased sharply during the summer months after clear-cut (Figure 7 center panel), especially 2-3 years after clear-cut. 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 (Figure 8).

7. Concluding remarks

Likens *et al.* (1970) suggest, based on the experience from Hubbard Brook, that clear-cutting reduces shading and evaporation, thus increasing temperature and water content of the forest floor. Decomposition of organic matter proceeds more rapidly, and nitrification increases greatly, leading to higher NO_3-leaching. Also potassium 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, 1992b). Martin *et al.* (1985), however, found from studies in clear-cut areas in New England, US.A that NO_3-leaching into streams was insignificant in most cases. He explained these differences as to be due to the 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, retention time of the water in the soil is important for 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, and NO_3 is now almost back to the levels before the clear-cut. Other studies indicate shorter recovery time for nitrate. The extended recovery time for the Langvasslia aquifer could be caused by the glyphosate treatment 5 years after the clear-cut, because the deciduous vegetation growth was stopped to give the coniferous trees the possibility to dominate. The leaching of K, however, is still higher than before clear-cut. 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 year of re-growth.

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Appendix A.

Chemistry data for the groundwater aquifer at Langvasslia (LAG01).

Yr	Date	pH	Cond	Ca	Mg	Na	K	Cl	SO_4	NO_3	Alk	Alk	ANC	R-Al	Org-Al	L-Al	SIO_2	Turb	Perm
			mS/m	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	mmol/l	µeq/l	µeq/l	µg/l	µg/l	µg/l	mg/l	FTU	MgO/l
1980	606	5.1	2.13	1.21	0.25	0.94	0.13	0.6	5.1	<10		13.1	9.6						8.6
1980	709	5.14	1.97	1.23	0.23	0.94	0.06	0.6	4.7	<10		18.6	15						8.1
1980	808	5.17	2.05	0.97	0.18	1.17	0.05	1.1	4.2	<10		18.6	4.9						9.1
1980	908	5.27	1.98	1.06	0.2	1.21	0.06	0.9	4.2	<10		18.6	17						7.4
1980	1003	5.33	2.08	1.12	0.19	1.24	0.08	0.9	4.8	<10		26.1	10.1				9.0	0.8	9.0
1980	1113	5.24	1.89	1.1	0.21	1.05	0.05	0.9	4.8	<10		18.6	0.8				8.7	3.5	8.1
1980	1219	5.28	1.91	1.04	0.2	1.17	0.06	0.7	4.8	<10		13.1	6.3				9.0	0.8	6.2
1981	219	5.76	2.01	0.99	0.22	1.09	0.04	0.8	4.4	<10			7.3						6.5
1981	425	5.39	2.04	1.02	0.22	1.02	0.06	0.6	4.1	<10		21.8	18.3				7.9	4.7	6.7
1981	523	5.16	1.89	1.02	0.21	1.11	0.16	0.7	4.4	10		15.3	18.1				7.5	3.8	10.1
1981	625	5.14	2	0.99	0.14	1.09	0.12	0.6	4.5	<10		10.9	8.7				8.1	2.1	9.0
1981	722	5.21	1.96	1.13	0.21	1.15	0.12	0.5	4.5	<10		21.8	26.9					2.6	9.0
1981	821	5.76	2.27	1.08	0.22	0.98	0.11	0.7	4.8	<10		49.3	4.8				9.3	3.5	8.1
1981	924	5.25	2.31	1.1	0.26	1.3	0.11	0.9	5.5	<10		25	3.1				9.5	2.9	8.4
1981	1022	5.07	2.38	1.23	0.27	1.17	0.08	0.9	5.1	<10		0	12.6				8.6	1.6	8.7
1981	1123	5.17	2.19	1.08	0.24	1.2	0.06	0.9	5.5	<10		6.4	-6.3				8.3	1.5	7.2
1981	1204	5.1	2.18	1.14	0.25	1.17	0.06	0.9	5	<10		0	6.9				8.5	1.7	7.5
1982	122	5.32	2.19	1.03	0.22	1.24	0.04	0.7	5.2	<10		19.7	1.2				9.3	0.6	5.7
1982	321	5.37	2.2	1.17	0.26	1.36	0.05	0.9	5.4	<10			6.8				9.7	3.4	5.3
1982	411	5.15	2.41	1.36	0.29	1.36	0.12	0.8	6.5	10			2.8				9.4	1.3	7.8
1982	502	5.05	2.17	1.12	0.27	1.04	0.09	0.5	4.7	<10	0.037	6.4	20.5				7.2	0.4	7.9
1982	527	5.12	1.91	0.98	0.24	1.03	0.06	0.6	4.1	<10	0.041	10.9	20.1				6.0	1.2	8.5
1982	616	5.26	2.05	1.12	0.23	1.15	0.04	0.6	5.4	<10	0.048	18.6	1.7				6.7	0.7	6.2
1982	727	5.34	2.23	1.25	0.23	1.13	0.07	0.7	5.2	<10	0.058	29.3	9.5				7.6	0.5	6.2
1982	831	5.53	2.64	1.4	0.29	1.38	0.1	1	5.5	<10			21.4				9.1	6.4	8.9
1982	926	5.25	2.53	1.43	0.24	1.4	0.09	1.1	6	<10	0.05	20.7	3.7				9.4	1.4	6.3
1982	1028	5.17	2.44	1.43	0.29	1.28	0.07	1	5.7	<10	0.046	16.4	12.9				7.2	1.3	8.2
1982	1126	5.13	2.22	1.3	0.28	1.21	0.04	1	5.5	<10	0.041	10.9	4.9				8.5	2.0	7.0
1983	107	5.17	2.16	1.25	0.24	1.19	0.05	0.8	5.3	<10	0.042	12	7.2				8.7	0.8	5.9
1983	320	5.14	2.2	1.14	0.23	1.38	0.03	0.8	5.3	<10	0.034	2.9	7.6				8.9	0.5	4.9
1983	415	5.21	2.07	1.16	0.23	1.24	0.06	0.8	5.6	<10	0.033	1.6	-2				9.3	0.7	5.8
1983	523	5.08	1.86	1.08	0.23	0.9	0.06	0.5	4.4	<10	0.036	5.3	16.1				5.1	1.4	9.4
1983	614	5.06	1.98	1.06	0.22	1.09	0.06	0.6	5.1	<10	0.034	2.9	2.9				7.1	0.8	7.1
1983	913	5.23	2.64	1.33	0.27	1.57	0.26	1.4	5.2	<10	0.053	24	25.7				9.2	6.7	11.1
1983	925	5.21	2.56	1.48	0.3	1.3	0.06	1	6.5	<10	0.045	15.3	-0.6	362	255	107	9.0	1.1	7.9
1983	1016	4.92	2.76	1.62	0.31	1.22	0.12	1.3	6.2	<10	0.033	1.6	11.9				7.4	2.2	16.6
1983	1115	5.17	2.22	1.24	0.25	1.19	0.07	0.8	5.7	<10	0.041	10.9	0.9	452	211	241	9.0	1.9	7.1
1984	103	5.09	2.15	1.15	0.22	1.29	0.03	0.8	6.3	<5	0.044	14.2	-13.3				8.3	5.6	8.8
1984	413	5.07	2.38	1.18	0.25	1.29	0.15	0.8	5.8	10	0.04	9.8	1.3	348	178	170	9.4	0.8	6.2
1984	511	5.16	1.78	1.06	0.21	1.03	0.06	0.4	4.7	<1	0.035	4.1	14.6	530	209	321	6.8	0.9	7.6
1984	609	5.13	1.99	1.16	0.22	1.16	0.05	0.4	5	<1	0.034	2.9	19.7	440	212	228	8.0	0.3	7.8
1984	705	5.33	2	1.17	0.22	1.21	0.04	0.6	4.9	<1	0.045	15.3	17.3	348	210	138	8.5	0.9	6.5

Yr	Date	pH	Cond	Ca	Mg	Na	K	Cl	SO_4	NO_3	Alk	Alk	ANC	R-Al	Org-Al	L-Al	SIO_2	Turb	Perm
			mS/m	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	mmol/l	µeq/l	µeq/l	µg/l	µg/l	µg/l	mg/l	FTU	MgO/l
1984	804	4.99	2.46	1.31	0.26	1.32	0.12	0.6	5.9	<1	0.036	5.3	16.2	436	240	196	8.6	0.7	9.2
1984	923	4.96	2.5	1.48	0.28	1.4	0.06	0.9	6.1	<1	0.034	2.9	17.1				8.7	0.5	10.7
1984	1021	4.93	2.27	1.26	0.25	1.19	0.05	0.6	5.1	1	0.027	0	24.4				7.4	0.8	11.6
1984	1130	4.95	2.05	1.06	0.22	1.07	0.06	0.7	4.8	<1	0.014	0	8.3	612	265	347	7.8	1.4	9.4
1985	118	5.08	1.96	0.97	0.21	1.13	0.02	0.6	5	<1	0.033	1.6	-5.8	378	243	135	8.4	1.1	8.5
1985	306	5.11	2	0.93	0.21	1.11	0.02	0.5	5.2	<1	0.033	1.6	-10	456	228	228	9.2	0.6	5.6
1985	324	5.1	2.02	0.93	0.21	1.17	0.05	0.8	5	<1	0.037	6.4	-10.9	398	188	210	8.9	1.0	6.1
1985	508	4.89	2.13	1.12	0.26	1.17	0.07	0.4	5.1	<1	0.022	0	12.4	508	305	203	8.7	0.8	10.3
1985	602	5.08	1.73	0.88	0.2	0.95	0.04	0.4	4.6	<1	0.038	7.6	-4.4	420	267	153	7.1	0.6	7.5
1985	711	5.06	2	1.01	0.2	1.09	0.1	0.4	4.4	<1	0.039	8.7	13.9	528	294	234	8.3	0.9	9.3
1985	808	4.96	1.97	1.03	0.21	1.07	0.06	0.4	4.7	<1	0.035	4.1	7.5	604	365	239	7.9	1.4	10.9
1985	904	5.02	1.78	0.93	0.17	1.03	0.06	0.5	4.1	<1	0.024	0	7.2	520	326	194	7.7	0.7	9.9
1985	928	5.11	1.72	0.93	0.18	0.98	0.06	0.5	4	2	0.033	1.6	7.9	502	309	193	7.8	0.5	8.5
1985	1031	5.2	1.63	0.88	0.17	1.1	0.03	0.7	4	<1	0.037	6.4	3.4	450	294	156	8.8	0.7	8.3
1985	1218	5.11	1.77	0.8	0.18	1.17	0.06	0.6	3.9	<1	0.036	5.3	9	468	235	233	11.0	1.0	6.4
1986	114	5.29	1.86	0.84	0.18	1.29	0.05	0.6	3.4	2	0.037	6.4	26.3	464	250	214			7.0
1986	214	5.16	1.79	0.82	0.19	1.16	0.02	0.6	3.6	<1	0.037	6.4	15.6	444	216	228	9.1	1.2	7.0
1986	329	5.23	1.88	0.86	0.21	1.18	0.03	0.5	3.8	4	0.041	10.9	18.8	384	217	167	9.2	1.7	7.4
1986	502	4.93	2.13	1.03	0.24	1.14	0.13	0.5	4.5	4	0.024	0	16	552	300	252	8.4	1.5	11.4
1986	608	5.01	1.77	0.89	0.18	0.91	0.07	0.4	3.7	3	0.024	0	12.1	442	242	200	7.5	2.1	9.9
1986	709	4.96	1.81	1	0.21	1.15	0.06	0.5	4.6	2	0.036	5.3	8.7	452	228	224	9.3	13.0	6.3
1986	806	5.05	2.25	0.94	0.2	1.43	0.25	1.1	4.1	3	0.035	4.1	15.3	380	257	123	9.7	1.1	7.2
1986	1021	4.89	2.41	1.14	0.26	1.33	0.52	1.1	4.6	3	0.024	0	22.4	620	305	315	9.0	1.1	12.6
1986	1202	5.24	1.9	0.94	0.23	1.11	0.29	0.6	3.7	47	0.026	0	24.2	415	323	92	7.7	1.2	9.4
1987	109	5.09	1.82	0.91	0.2	1.1	0.28	0.7	3.3	2	0.033	1.6	28.3	395	272	123	8.2	0.5	8.7
1987	225	5.16	1.78	0.8	0.18	1.16	0.35	0.9	2.6	2	0.039	8.7	34.5	510	227	283	9.1	0.6	9.1
1987	322	5.19	1.7	0.73	0.18	1.19	0.37	1	2.4	4	0.033	1.6	34	490	340	150			10.0
1987	424	5.06	2.01	0.95	0.23	1.16	0.7	0.7	4	29	0.031	0	29.6	488	317	171	8.0	0.6	10.6
1987	524	5.08	1.68	0.83	0.17	0.88	0.48	0.4	2.9	3	0.037	6.4	34.1	473	311	162	6.0	0.9	11.0
1987	602	4.98	1.7	0.77	0.17	1	0.5	0.5	3.1	5	0.033	1.6	29.7	491	334	157	7.1	0.4	11.2
1987	614	4.96	1.84	0.75	0.18	0.98	0.54	0.5	2.9	1	0.002	0	34.1	460	350	110	6.6	0.4	12.2
1987	628	5.09	1.74	0.81	0.19	0.85	0.54	0.4	2.6	4	0.038	7.6	41.1	500	358	142	6.0	0.9	11.8
1987	710	5.14	1.77	0.82	0.18	0.96	0.68	0.8	2.4	19	0.04	9.8	41	465	252	213	7.2	0.6	11.7
1987	817	5.14	2.12	0.85	0.2	1.16	0.98	1.6	1.7	80	0.041	10.9	48.1	570	290	280	8.9	0.5	16.5
1987	918	5.04	2.16	0.89	0.22	1.1	1.14	1.1	3	58	0.034	2.9	41.9	600	255	345	7.8	0.8	
1987	1020	5.12	2.01	0.89	0.2	0.98	0.95	0.8	3.1	60	0.042	12	36.4	500	244	256	6.4	1.0	11.1
1987	1106	5.11	2.14	0.91	0.21	0.95	0.93	0.9	3.4	85	0.037	6.4	25.5	530	240	290	6.8	0.5	10.2
1987	1209	5.16	2.5	0.93	0.23	0.99	0.83	0.9	3.3	185	0.042	12	22.3	498	199	299	7.8	0.8	9.5
1988	115	5.12	2.1	0.93	0.22	1.07	0.74	1	3	270	0.044	14.2	20	516	217	299	8.5	0.6	10.1
1988	205	5.1	3.3	0.95	0.22	1.09	0.72	1	3.1	290	0.041	10.9	17.9	500	196	304	8.5	1.3	9.3
1988	305	5.24	2.04	0.97	0.21	1.05	0.71	1	2.7	325	0.04	9.8	21.9	520	217	303	8.5	0.7	8.8
1988	407	5.07	2.57	1.17	0.26	1.13	0.87	0.9	3.7	600	0.033	1.6	5.9	512	182	330	7.6	1.0	8.3
1988	509	5.09	2.19	0.99	0.22	0.94	0.78	0.6	3.1	365	0.037	6.4	20.8	459	161	298	6.4	0.5	9.1
1988	605	5.15	1.97	0.81	0.18	0.79	0.74	0.5	3	38	0.041	10.9	29.2	544	235	309	5.6	0.6	12.3
1988	707	5.18	2.05	0.92	0.17	1	0.95	1	2.3	18	0.047	17.5	50.3	755	349	406	6.7	0.6	21.7
1988	731	5.17	2.15	0.84	0.19	0.97	0.82	0.9	2.3	<1	0.05	20.7	47.4	780	366	414	6.9	0.7	14.9
1988	831	5.05	2.13	0.81	0.18	1.14	0.95	0.8	2.2	13	0.039	8.7	59.8	882	366	516	7.2	0.6	15.7
1988	1002	5.06	2.14	0.73	0.15	0.93	0.83	1	2.4	22	0.033	1.6	30.7	885	403	482	7.5	1.8	15.3
1988	1030	5.11	2.14	0.63	0.14	0.89	0.63	1	2.4	31	0.04	9.8	17.4	481	309	172	7.5	1.8	17.9
1988	1129	5.17	2.12	0.52	0.11	0.99	0.5	1.1	2.5	56	0.034	2.9	3.8	614	305	309	7.9	1.2	12.3
1989	113	5.15	2.06	0.65	0.21	1.1	0.75	1.2	2.3	275	0.045	15.3	15.4	469	271	198	8.3	0.8	6.1
1989	202	5.18	2.02	0.75	0.23	0.96	0.26	1.2	2.4	200	0.048	18.6	6.7	462	208	254	7.8	1.2	9.0

Yr	Date	pH	Cond	Ca	Mg	Na	K	Cl	SO_4	NO_3	Alk	Alk	ANC	R-Al	Org-Al	L-Al	SIO_2	Turb	Perm
			mS/m	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	mmol/l	µeq/l	µeq/l	µg/l	µg/l	µg/l	mg/l	FTU	MgO/l
1989	312	5.21	2.05	0.87	0.23	1.14	0.7	1.1	3	315	0.044	14.2	13.8	434	186	248	8.0	0.8	8.3
1989	414	5.46	2.32	0.85	0.22	1.01	0.75	1	3.2	195	0.032	0	14.9	415	169	246	7.4	1.4	9.1
1989	512	5.09	1.99	0.88	0.22	1.02	0.8	0.9	3	255	0.038	7.6	20.8	430	156	274	7.1	0.8	9.5
1989	618	5.23	1.99	0.71	0.18	1.1	0.89	0.9	2.5	55	0.05	20.7	39.5	498	256	242	6.6	0.2	12.0
1989	725	5.36	1.93	0.81	0.15	1.18	0.8	1.4	2	<1	0.07	42	43.3	850	404	446	6.9	3.6	19.6
1989	825	5.21	1.96	0.7	0.15	1.36	0.71	0.9	2.1	35	0.035	4.1	53	650	275	375	7.6	2.5	13.8
1989	1010	5.36	1.88	0.67	0.17	1.21	0.54	1.1	1.9	68	0.046	16.4	38.4	545	294	251	7.2	0.7	12.8
1989	1113	5.33	2.51	0.8	0.22	1.32	0.57	1.2	2.8	138	0.041	10.9	28	464	197	267	6.7	0.6	11.2
1989	1211	5.18	2.49	1.05	0.35	1.33	0.57	1.3	3.9	680	0.036	5.3	-12.8	384	141	243	8.7	0.6	6.2
1990	115	4.99	2.47	0.92	0.22	1.11	0.4	1	2.5	505	0.042	12	6.2	389	132	257	8.6	0.9	6.5
1990	209	5.33	2.18	0.97	0.25	1.19	0.6	1.1	3.6	310	0.042	12	8	390	152	238	7.8	1.0	8.0
1990	309	5.22	2.24	0.96	0.26	1.18	0.63	1.1	3	460	0.044	14.2	10.4	390	168	222	8.1	0.9	6.3
1990	405	5.31	2.05	0.97	0.25	1.09	0.62	0.9	3.1	315	0.041	10.9	19.8	388	153	235	7.1	0.5	7.0
1990	501	5.11	2.23	1.02	0.25	1.01	0.7	0.8	2.8	500	0.033	1.6	16.7	394	157	237	6.2	1.2	8.8
1990	608	5.21	1.99	0.91	0.21	1.06	0.7	0.9	3.2	140	0.047	17.5	24.7	466	210	256	5.7	1.1	10.8
1990	704	5.18	1.79	0.73	0.16	1.04	0.62	0.4	2.5	18	0.046	16.4	46.1	580	283	297	6.3	0.9	15.8
1990	801	5.31	1.96	0.83	0.18	1	0.56	0.6	1.9	13	0.049	19.7	56.6	500	327	173	5.5	1.2	11.8
1990	911	5.38	1.92	0.87	0.18	1.09	0.5	0.7	2.2	11	0.048	18.6	52.1	600	332	268	6.5	0.8	13.5
1990	1009	5.26	1.93	0.82	0.21	1.13	0.39	0.9	2.6	32	0.025	0	35.5	595	261	334	7.4	1.1	16.0
1990	1108	5.31	2.12	0.95	0.23	1.23	0.36	0.9	3	107	0.032	0	33.5	473	209	264	7.5	0.9	12.5
1990	1206	5.28	2.12	1.09	0.26	1.22	0.35	0.8	2.9	315	0.033	1.6	32.4	417	180	237	8.5	0.5	8.4
1991	106	5.21	2.11	1.11	0.28	1.24	0.36	2.2	2.1	370	0.041	10.9	9.4	470	184	286	9.0	1.7	8.6
1991	306	5.2	2.07	1.08	0.27	1.21	0.34	1	2.9	320	0.05	20.7	26	410	249	161	8.9	0.7	7.4
1991	407	5.23	2.22	1.21	0.27	1.24	0.42	0.8	3.1	350	0.048	18.6	35.2	405	216	189	8.3	0.4	8.1
1991	506	5.24	1.96	1.07	0.25	1.1	0.43	0.6	2.9	215	0.05	20.7	40.1	410	230	180	7.5	1.1	8.9
1991	606	5.26	2.07	1.06	0.23	1.06	0.45	1	3	71	0.053	24	33.7	449	259	190	6.8	0.9	8.0
1991	705	5.29	1.73	0.97	0.21	1.04	0.49	0.5	2.6	4	0.056	27.2	54.9	509	345	164	6.6	0.6	11.6
1991	816	5.33	2.28	1.18	0.21	1.21	0.56	0.5	3	11	0.067	38.8	65.8	400	335	65	7.2	1.8	11.3
1991	1004	5.18	2.6	1.44	0.3	1.36	0.55	1.5	3.6	465	0.043	13.1	19.3	406	233	173	8.1	0.5	8.4
1991	1103	5.08	2.65	1.48	0.32	1.37	0.58	1.5	3.6	335	0.046	16.4	33.4	455	293	162	8.3	0.9	10.1
1991	1209	5.2	2.42	1.33	0.32	1.28	0.53	1.1	3.4	460	0.04	9.8	27.3	439	272	167	8.5	1.1	7.9
1992	105	5.12	2.49	1.35	0.33	1.21	0.56	1.3	3.6	550	0.044	14.2	10.6	423	251	172	9.1	0.7	5.8
1992	205	5.22	2.53	1.38	0.33	1.31	0.6	1.4	3.3	530	0.05	20.7	22.3	428	278	150	9.5	0.7	6.2
1992	306	5.29	2.24	1.19	0.28	1.29	0.56	1.6	3.3	115	0.05	20.7	30.8	414	287	127	8.4	2.0	6.7
1992	406	5.38	2.34	1.18	0.3	1.18	0.52	1.3	3.3	300	0.05	20.7	21.4	429	284	145	8.0	0.8	6.3
1992	505	5.19	2.21	1.12	0.28	1.15	0.63	1	2.8	355	0.037	6.4	33.2	411	266	145	7.1	0.8	8.9
1992	605	5.17	2.61	1.42	0.3	1.14	0.92	1.4	3	635	0.046	16.4	21.4	429	263	166	7.3	15.0	7.8
1992	705	5.28	3	1.24	0.25	1.21	0.91	1.5	2.9	280	0.048	18.6	35.7	425	266	159	8.2	0.9	9.0
1992	902	5.35	2.4	1.34	0.29	1.42	1.1	1.3	3.1	285	0.044	14.2	59.1	489	387	102	8.4	0.6	9.9
1992	904	5.2	2.62	1.38	0.3	1.43	1.11	1.2	3.2	435	0.04	9.8	52.6	474	343	131	9.0	0.5	10.0
1992	1103	5.37	2.42	1.14	0.26	1.34	0.92	1.3	3.1	114	0.048	18.6	50.7	433	365	68	8.4	0.7	9.8
1992	1202	5.31	2.49	1.32	0.31	1.45	0.99	1.4	2.8	558	0.059	30.4	42.1	422	194	228	8.1		8.0
1993	105	5.28	2.58	1.49	0.34	1.29	0.98	1.2	3.4	655	0.046	16.4	32.1	443	283	160	9.4	1.1	7.5
1993	205	5.24	2.49	1.41	0.34	1.42	0.92	1.3	3.1	610	0.055	26.1	38.9	402	271	131	8.5	0.9	7.4
1993	304	5.25	2.51	1.34	0.33	1.35	0.91	1.2	3	495	0.052	22.9	44.4	362	300	62	8.9	1.1	6.4
1993	401	5.23	2.48	1.4	0.33	1.37	0.89	1.2	2.9	520	0.056	27.2	48	358	257	101	8.6	1.1	6.5
1993	501	5.12	2.8	1.59	0.41	1.36	0.96	0.8	2.7	1200	0.049	19.7	32.3	428	284	144	7.1	0.6	8.1
1993	609	5.47	2.12	1.23	0.26	1.15	0.93	0.9	3	80	0.053	24	63	392	293	99	7.6	0.8	9.2
1993	624	5.4	2.17	1.15	0.25	1.17	0.91	1	3	13	0.07	42	60.5	403	333	70	8.2	0.5	9.1
1993	730	5.28	2.1	1.28	0.26	1.43	1.01	0.9	2.7	235	0.065	36.7	74.9	367	288	79	9.1	1.1	9.1
1993	904	5.38	2.11	0.95	0.25	1.17	0.9	0.8	2.7	<1	0.062	33.5	63	422	395	27	9.3	0.8	10.9
1993	1001	5.4	2.1	1.52	0.24	1.06	0.88	0.9	2.6	20	0.058	29.3	83.3	386	359	27	8.5	0.7	10.4

Yr	Date	pH	Cond	Ca	Mg	Na	K	Cl	SO_4	NO_3	Alk	Alk	ANC	R-Al	Org-Al	L-Al	SIO_2	Turb	Perm
			mS/m	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	mmol/l	µeq/l	µeq/l	µg/l	µg/l	µg/l	mg/l	FTU	MgO/l
1993	1029	5.31	2.09	1.17	0.27	1.29	0.82	0.9	2.7	109	0.059	30.4	68.3	433	363	70	8.0	0.6	9.6
1993	1127	5.29	2.19	1.31	0.31	1.27	0.8	0.8	2.5	380	0.072	44.1	64.8	365	299	66	7.9	0.7	8.2
1993	1229	5.36	2.05	1.28	0.3	1.23	0.76	0.9	2.7	245	0.075	47.2	62.4	369	304	65	8.8	1.0	7.5
1994	128	5.33	2.59	1.29	0.29	1.32	0.74	1	2.9	79	0.073	45.1	70.3	349	273	76	8.8	1.2	8.4
1994	404	5.33	2.73	1.51	0.37	1.43	0.81	0.8	2.7	1130	0.058	29.3	29.2	374	268	106	7.6	1.8	6.5
1994	430	5.15	2.65	1.6	0.39	1.2	0.77	0.5	2.7	1075	0.049	19.7	36.7	416	276	140	7.1	0.6	7.9
1994	605	5.46	5.14	1.28	0.29	1	0.68	0.6	2.8	80	0.065	36.7	67.7	399	252	147	8.1	1.1	9.1
1994	801	5.42	2.2	1.56	0.28	1.49	0.81	0.7	3.2	11	0.091	64	99.2	354	324	30	9.0	0.8	9.1
1994	901	5.25	2.2	1.38	0.31	1.28	0.75	0.8	3.1	172	0.071	43	69.8	391	307	84	8.9	0.8	9.8
1994	930	5.44	1.96	1.34	0.32	1.09	0.78	0.7	3.1	53	0.081	53.5	72.5	428	321	107	8.6	1.4	9.5
1994	1101	5.65	2.09	1.5	0.35	1.33	0.75	0.8	2.7	515	0.072	44.1	65.1	401	277	124	8.7	0.5	8.2
1994	1201	5.31	2.14	1.53	0.33	1.36	0.71	0.9	2.7	430	0.083	55.6	68.5	364	276	88	8.5	0.5	7.4
1995	113	5.51	2.37	1.5	0.35	1.26	0.66	0.9	2.7	505	0.077	49.3	57.7	362	254	108	8.4	0.4	6.8
1995	204	5.52	2.14	1.37	0.33	1.23	0.64	0.8	2.8	365	0.078	50.4	58.5	389	249	140	8.3	0.9	4.0
1995	408	5.54	2.34	1.54	0.37	1.25	0.69	0.9	2.6	800	0.075	47.2	42.7	340	213	127	7.3	0.7	6.4
1995	428	5.35	2.74	1.8	0.45	1.14	0.78	0.7	2.8	1380	0.058	29.3	19.8	372	227	145	7.8	0.5	7.2
1995	603	5.52	1.79	1.23	0.25	0.96	0.69	0.4	2.6	265	0.068	39.9	57	422	330	92	5.7	0.6	10.5
1995	803	5.67	2.2	1.43	0.28	1.07	0.72	0.7	3.1	5	0.092	65	74.7	429	326	103	8.9	1.0	10.0
1995	831	5.67	2.1	1.55	0.29	1.28	0.79	0.8	3.2	5	0.104	77.5	87.5	359	290	69	9.8	5.9	14.5
1995	929	5.58	2.4	1.51	0.33	1.22	0.76	0.8	3.2	28	0.121	95.1	83.8	388	251	137	9.5	1.8	10.2
1995	1101	6.02	2.69	1.53	0.32	1.54	1.05	1.6	2.9	37	0.127	101.3	88.4	259	240	19	8.8	2.2	11.1
1995	1202	5.96	2.25	1.31	0.29	1.06	0.66	1	3	4	0.099	72.3	61.3	317	227	90	8.7	1.6	7.6
1996	505	5.19	2.79	1.94	0.45	1.2	0.69	1.1	3.5	805	0.075	47.2	42.3	389	339	50	6.1	1.3	14.9
1996	527	5.21	3.28	2.09	0.49	1.2	0.83	1	3.1	1315	0.053	24	31.4	377	239	138	7.2	2.6	11.6
1996	701	5.52	2.06	1.43	0.29	1.14	0.66	0.5	3.7	240	0.068	39.9	53.4	417	317	100	7.8	0.7	10.6
1996	725	5.51	1.86	1.26	0.25	1.12	0.58	0.4	3.1	5	0.075	47.2	70.8	433	318	115	8.1	1.2	11.6
1996	901	5.42	1.89	1.15	0.24	1.05	0.52	0.5	2.8	60	0.081	53.5	59.4	413	278	135	8.6	1.5	12.6
1996	1002	5.41	2.12	1.37	0.28	1.18	0.47	1	2.7	215	0.076	48.3	55	410	288	122	7.8	0.4	10.4
1996	1027	5.33	1.96	1.37	0.28	1.11	0.44	0.9	3	170	0.063	34.6	50.9	419	304	115	8.0	0.5	10.1
1996	1217	5.49	2.05	1.49	0.31	1.07	0.4	0.8	3.1	375	0.068	39.9	42.7	320	223	97	7.8	1.1	8.7
1997	104	5.45	2.07	1.5	0.31	1.13	0.39	0.8	3.1	345	0.072	44.1	47.7	311	219	92	7.9	0.6	7.5
1997	203	5.48	1.95	1.39	0.28	1.12	0.36	0.8	3.1	134	0.08	52.5	53.6	320	260	60	7.9	0.4	7.8
1997	303	5.51	2.11	1.42	0.29	1.17	0.35	0.8	3.2	138	0.086	58.7	55.5	303	226	77	8.2	0.4	7.1
1997	401	5.41	2.28	1.52	0.32	1.21	0.41	0.8	3.1	495	0.072	44.1	42.8	303	199	104	8.0	1.0	6.8
1997	504	5.45	2.11	1.36	0.29	1.03	0.47	0.8	2.9	430	0.059	30.4	34.9	333	238	95	7.1	0.5	8.6
1997	529	5.52	1.95	1.22	0.24	1.04	0.52	0.7	2.7	220	0.06	31.4	47.5	418	327	91	6.7	0.4	12.1
1997	620	5.58	1.93	1.28	0.23	1.09	0.41	0.6	3	4	0.082	54.6	61	404	312	92	7.2	0.6	12.5
1997	730	5.58	1.82	1.2	0.23	1.04	0.43	1.2	2.1	5	0.081	53.5	57.1	393	236	157	7.2	0.4	15.0
1997	911	5.41	1.82	1.18	0.21	1.14	0.33	0.8	1.9	4	0.081	53.5	71.8	476	367	109	8.3	1.0	17.8
1997	1001	5.59	1.86	1.14	0.23	1.06	0.3	0.8	2	4	0.085	57.7	65.1	442	369	73	8.5	0.8	16.2
1997	1031	5.41	1.77	1.3	0.24	1.13	0.25	0.9	2.3	34	0.068	39.9	64.5	429	299	130	8.1	0.7	12.5
1997	1203	5.39	1.74	1.27	0.24	1.06	0.29	0.8	2.6	127	0.06	31.4	50.9	371	270	101	7.6	1.8	11.0
1998	102	5.45	1.76	1.32	0.25	1.07	0.32	0.8	2.7	121	0.07	42	53.7	346	286	60	7.9	0.6	9.8
1998	130	5.59	1.68	1.34	0.26	1.07	0.31	0.7	2.8	150	0.065	36.7	54	359	281	78	8.0	1.0	8.7
1998	227	5.09	1.86	1.14	0.2	1.06	0.53	0.8	2.6	138	0.038	7.6	46.4	293	243	50	8.1	0.3	15.2
1998	403	5.48	1.73	1.34	0.24	1.12	0.33	0.7	2.7	255	0.062	33.5	49.6	358	257	101	7.9	0.9	9.5
1998	501	5.53	1.53	1.3	0.22	1.05	0.34	0.6	2.6	245	0.062	33.5	48.8	328	278	50	7.0	0.4	9.5
1998	529	5.6	1.5	1.18	0.22	1.03	0.35	0.8	2.9	7	0.072	44.1	47.3	377	331	46	6.7	0.7	10.6
1998	612	5.73	1.5	1.16	0.21	1.04	0.46	0.4	2.5	8	0.076	48.3	68.3	374	329	45	6.9	0.4	11.6
1998	801	5.43	1.61	1.21	0.19	1.04	0.46	0.4	1.7	5	0.077	49.3	86	460	349	111	7.2	0.8	15.5
1998	829	5.6	1.55	1.24	0.21	1.08	0.4	0.7	1.9	4	0.068	39.9	76.8	488	422	66	7.7	0.8	16.8
1998	1001	5.37	1.63	1.25	0.2	1.09	0.43	0.7	1.8	4	0.068	39.9	79.7	505	437	68	7.9	1.3	17.5

Yr	Date	pH	Cond	Ca	Mg	Na	K	Cl	SO_4	NO_3	Alk	Alk	ANC	R-Al	Org-Al	L-Al	SIO_2	Turb	Perm
			mS/m	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	mmol/l	µeq/l	µeq/l	µg/l	µg/l	µg/l	mg/l	FTU	MgO/l
1998	1031	5.4	1.47	1.05	0.18	0.96	0.35	0.7	1.7	5	0.06	31.4	62.4	461	361	100	7.1	1.8	16.1
1998	1201	5.58	1.65	1.04	0.19	0.95	0.3	0.6	2	16	0.085	57.7	56.8	457	360	97	8.1	1.6	12.8
1999	105	5.61	1.79	1.1	0.21	1.01	0.29	0.7	2.2	6	0.09	62.9	57.5	385	295	90	7.8	0.5	11.6
1999	205	5.74	1.68	1.03	0.2	1.04	0.28	0.7	2.2	8	0.082	54.6	54.1	389	274	115	7.8	2.1	10.9
1999	309	5.63	1.79	1.1	0.2	1.03	0.3	0.7	2.3	6	0.092	65	55.8	443	322	121	7.6	3.0	10.7
1999	330	5.62	1.83	1.02	0.21	1.05	0.24	0.7	2.4	40	0.093	66	47.4	364	285	79	8.0	0.7	9.7
1999	427	5.58	1.56	1.08	0.2	0.95	0.29	0.4	2	143	0.073	45.1	56	343	258	85	6.3	0.6	9.0
1999	528	5.65	1.37	1.09	0.18	0.87	0.32	0.5	2	47	0.063	34.6	56.1	345	260	85	5.8	0.6	10.3
1999	626	5.63	1.45	1.12	0.21	0.91	0.39	0.2	1.9	3	0.072	44.1	77.3	414	331	83	6.9	1.0	13.0
1999	729	5.68	1.44	1.16	0.21	0.95	0.43	0.3	1.6	<1	0.082	54.6	85.6	436	321	115	7.5	0.3	14.9
1999	830	5.66	1.55	1.28	0.23	1.03	0.46	0.3	2	2	0.088	60.8	89.1	507	398	109	9.0	1.5	15.7
1999	1029	5.48	1.64	1.05	0.21	0.92	0.33	0.7	2.3	4	0.065	36.7	50.2	375	298	77	7.6	1.5	13.3
1999	1201	5.68	1.45	1.03	0.22	0.93	0.32	0.7	2.3	9	0.059	30.4	49.9	392	300	92	7.6	0.8	12.2
1999	1202	5.66	1.55	1.03	0.22	0.93	0.32	0.7	2.3	9	0.088	60.8	49.9	392	300	92	7.6	0.8	12.2

Appendix B.

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