LAKE RESPONSE TO ATMOSPHERIC AND WATERSHED INPUTS IN THE GOAT ROCKS WILDERNESS, WA

Submitted to

Weyerhaeuser Paper Company
Longview, WA

by

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EXECUTIVE (NON-TECHNICAL) SUMMARY

In August, 1993, Weyerhaeuser Paper Company funded a five-year lake monitoring program in the Goat Rocks Wilderness and a snow sampling program in southwestern Washington as a condition of obtaining a PSD permit associated with the expansion of its industrial facilities in Longview, WA. The study showed that Gertrude Lake and Cedar Pond are two softwater lakes that have low concentrations of acid neutralizing capacity (also referred to as ANC or alkalinity). These concentrations vary greatly throughout the year with the lowest values occurring during spring. Consequently, they would be most sensitive to damage from air pollution effects during the snowmelt when the lakes are diluted by the melting snow.

The snowpack contained low concentrations of sulfate and nitrate, two acid anions that could cause lake acidification. As a consequence, the snowmelt acts to merely dilute the lakes during spring rather than contribute to any measurable acidification. The lake, watershed, and snow chemistry data were used to simulate how the lakes might respond to current levels of atmospheric inputs and to increases in sulfur and nitrogen loading. The modeling results showed that the lakes were unlikely to acidify even under two-fold increases in sulfur and nitrogen deposition.

Factors other than air pollution that may currently be modifying lake water quality in the area include continued weathering of ashfall from the 1980 eruption of Mt. St. Helens, nutrient inputs from recreational activities, and modification of nutrient-plankton dynamics caused by introduction of fish into previously fishless lakes.

ABSTRACT

In August, 1993, Weyerhaeuser Paper Company funded a lake monitoring program in the Goat Rock Wilderness and a snow sampling program in southwestern Washington as a condition of obtaining a PSD permit associated with the expansion of its industrial facilities in Longview, WA. Two lakes, Gertrude Lake and Cedar Pond, were selected for monitoring in 1993 with plans for monitoring the lakes through 1997. This report summarizes the results of the 1993-1997 lake/watershed monitoring program and the associated snow sampling program conducted from 1994 to 1998.

Gertrude Lake and Cedar Pond are small, softwater lakes located in the extreme southeastern portion of the Goat Rock Wilderness of the Gifford Pinchot National Forest, WA. The lakes were sampled on four occasions in 1993 and five times from spring to fall in each of the years 1994 to 1997. Water samples also were collected from the outlet and inlets to Gertrude Lake and from the inlet to Cedar Pond. Vegetation and soil samples were collected in the study area and instruments for recording water and air temperature were installed in 1995. In addition, a bathymetric map of Gertrude Lake was prepared using SONAR/GPS methodology.

Acid neutralizing capacity (ANC) in the study lakes varied seasonally from low values during spring snowmelt (minimum of 10 µeq/L in Gertrude Lake) to high values in the fall (maximum of 91 µeq/L in Gertrude Lake). The greatest seasonal increase in ANC was from June to July in both lakes. The seasonal increase was curvilinear in Gertrude Lake, but more linear in Cedar Pond. Other major ions and pH followed a pattern similar to ANC. Sulfate and chloride also exhibited moderate seasonal increases consistent with the increases in base cations and ANC. Nitrate and ammonium concentrations were seldom measured above detection limits. Some of the greatest differences in chemistry between the two lakes were for total aluminum and iron. Aluminum seldom approached 20 µg/L in Gertrude Lake, but fall values in Cedar Pond exceeded 90 µg/L. Iron concentrations in Gertrude Lake peaked at about 100 µg/L in early July, whereas peak concentrations of 70-80 µg/L occurred in August and September in Cedar Pond. Neither Cedar Pond nor Gertrude Lake exhibited symptoms of having received excess inputs of inorganic nitrogen from their watersheds. Nitrogen concentrations in the watershed vegetation are typical of natural systems, suggesting that nitrogen remains a limiting nutrient and will continue to be assimilated at a high rate in the watershed.

Snow chemistry in the southern Washington Cascades is very dilute and contains low concentrations of sulfate, nitrate, and hydrogen ion. Using the measured ion concentrations and information on snow water equivalents yields winter bulk deposition values ranging from 0.9 to 5.0 kg/ha for SO_4 and 0.4 to 1.2 kg/ha for total inorganic nitrogen. Trace organic anions and trace metals were generally undetected in the snow samples. Concentrations of sulfate and hydrogen ion

were generally greatest at the two northern sites, Mount Rainier and White Pass, and least at Mount St. Helens. No temporal patterns in annual concentrations of sulfate, nitrate, and hydrogen ion were observed among any of the four sites. Variations among years appeared to exhibit a weak relationship between precipitation amounts and total ion concentration within a given site. The snowpack at Mount Rainier (Paradise) contained a sulfate deposition of 2.8 kg/ha compared to 1.0 kg/ha for the winter at Pack Forest, the low-elevation NADP/NTN site. Discrete samples (top, middle, bottom) in the snowpacks generally were not statistically different from the composite samples. pH values in the top samples were significantly lower than the composite samples and the bottom samples showed a tendency to exhibit lower concentrations of sulfate, chloride, and hydrogen ion.

A dynamic process-based watershed model (MAGIC) was applied to Gertrude Lake and its watershed to forecast lake response to increased deposition of S and N. The model was successfully calibrated to current lake chemistry, although it was necessary to invoke additional watershed weathering of sulfate and chloride that presumably was being generated by weathering of ashfall from the 1980 eruption of Mount St. Helens. Watershed contributions of ANC from the talus slope were surprisingly large and were comparable to inputs from portions of the watershed with soil present. The lake was forecasted to lose approximately 5 μeq/L of ANC over the next 50 years, both in terms of annual average ANC and post-snowmelt ANC, for each 100% increase in S and N over current deposition levels. The loss in ANC would be in addition to the natural base cation dilution that presently dominates the seasonal variation in lake chemistry. At these levels, ANC would remain above zero during the open water periods. Under extreme climatic conditions, negative ANC values during spring/snowmelt might be achieved at deposition loading of 200% (or greater) over current levels. Losses in ANC during snowmelt would be expected to cause the greatest harm to aquatic biota because watershed weathering during the summer provides substantial ANC inputs to neutralize acidic deposition. These model forecasts were developed using average lake chemistry measured over the five-year study. If the minimum lake ANC values were used instead, the modeled ANC forecasts would be decreased further. In summary, the threat of chronic acidification of these lakes is low; episodic acidification is a greater concern although the increased loading for these study lakes to cause acidification would require substantial increases in S and N deposition.

I. INTRODUCTION

As a condition of obtaining a PSD permit associated with expansion of its industrial facilities in Longview, WA, Weyerhaeuser Paper Company funded a study to monitor and assess the impacts of its emissions on sensitive receptors in the southern Washington Cascades. The study area, as defined by the USDA-Forest Service, was the closest Class I wilderness area in the region. This was the southern section of the Goat Rocks Wilderness in the Gifford Pinchot National Forest (Figure 1). Class I areas are designated as areas which shall not be degraded by increased emissions of air pollutants such as sulfur, nitrogen, and particulates. The industrial expansion at Longview was projected to cause an increase in annual SO_2 and NO_x emissions, but reported emissions declined by about 40 percent for SO_2 and 10 percent for NO_x (Appendix A).

The objectives of this study were to characterize the quality of deposition in the study area (as represented by snow chemistry), measure variation in the chemistry of potentially sensitive softwater lakes in the wilderness, and assess the responses of the lakes to atmospheric and watershed inputs through application of a numerical watershed model. Although the snowpack is an incomplete representation of annual deposition, this media was selected for sampling because of the perceived importance of the snowpack chemistry in influencing water quality in Cascade Mountain lakes. This report summarizes the lake selection process, the snow chemistry for 1994 to 1998, the lake monitoring from 1993 to 1997, and the integration of these data through the watershed modeling activity.

II. METHODS

A. Lake Selection

The study area for the project was restricted to USFS Class I wilderness areas in proximity to Longview, WA. The closest Class I area was the Goat Rocks Wilderness in the Gifford Pinchot National Forest (Plate 1). The study area was further refined to exclude the northern portion of the wilderness because of the judgement that lakes in the southern portion of the wilderness would be more likely to receive potential emissions from Longview. One potential study lake, Lake LeConte (previously sampled by Eilers et al. [1987]), was located on the Yakima Indian Reservation and was not available for routine sampling. Water quality

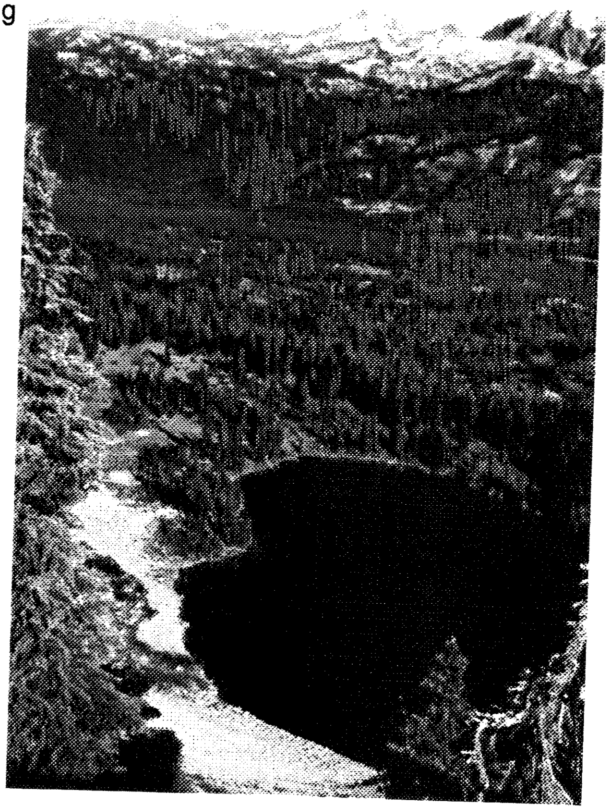
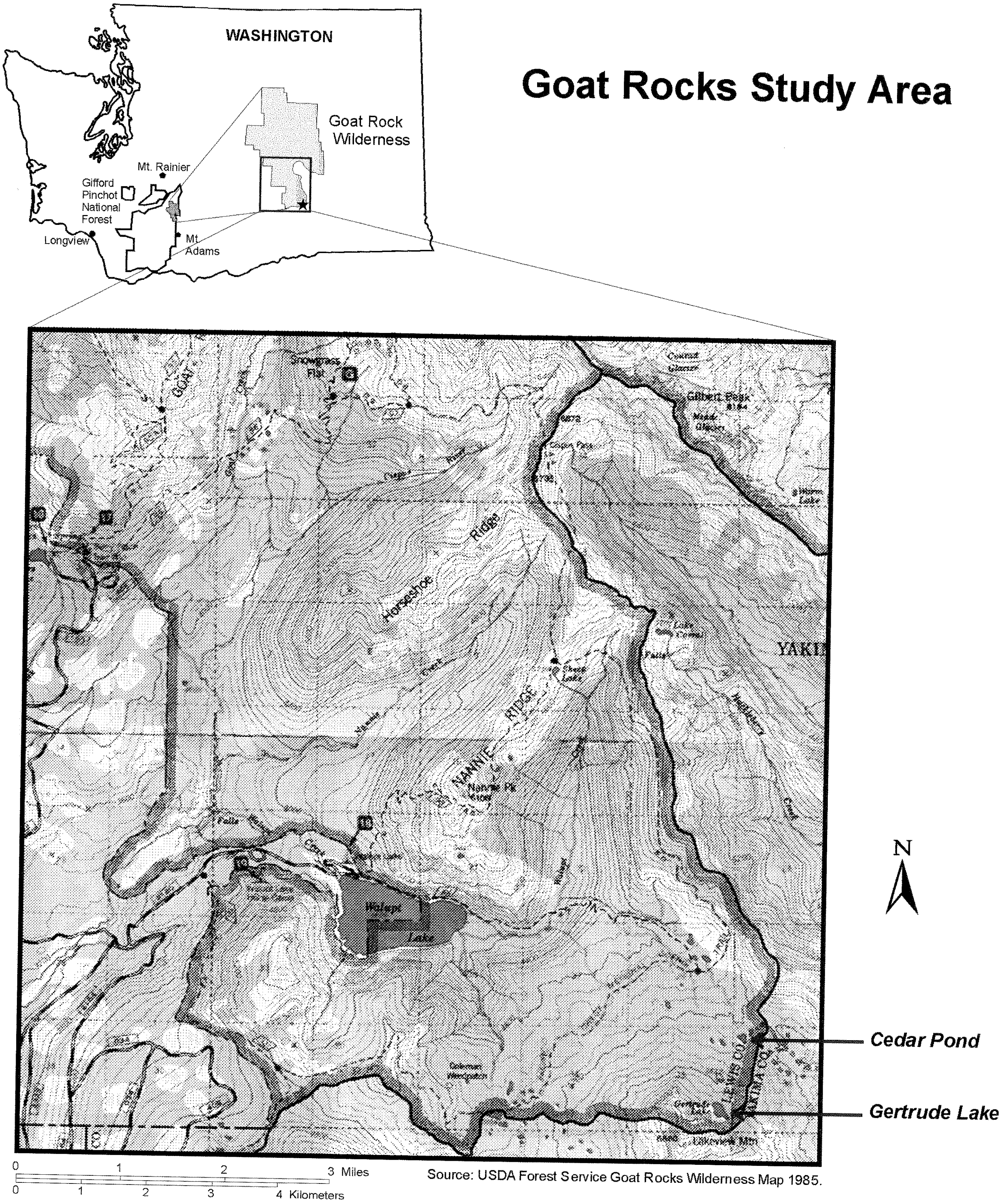


Plate 1. Gertrude Lake (foreground) and Goat Rocks Wilderness viewed from Lakeview Mountain looking NNW (September 28, 1993).

Goat Rocks Study Area



Source: USDA Forest Service Goat Rocks Wilderness Map 1985.

Figure 1. Location of lakes sampled in the Walupt Lake watershed and their proximity to the trailhead.

data collected by fisheries biologists were available for eight lakes in the Goat Rocks Wilderness (Table 1). The alkalinity and hardness measurements probably were collected using crude methods as indicated by the reported values. This earlier high alkalinity value for Gertrude Lake was suspect based on notes in the reported data and the location of the lake in a mountain cirque, which suggested less weathering than indicated by the data.

Table 1. Water chemistry data for lakes in the Goat Rocks Wilderness. These data were collected by the Washington Department of Wildlife in the 1980's.

Lake	pH	Alkalinity (μeq/L)	Hardness (ppm)
Beaver*	7.5	342	22.8
Walupt	7.5	342	17.1
Glacier	6.9	142	11.4
Coyote	6.8	228	11.4
Lost	7.5	342	17.1
Lost Hat	7.3	-	-
Lily	7.0	228	11.4
Bluff	7.5	242	11.4
Gertrude	6.9	1026**	-

* Not to be confused with a beaver pond sampled in this study
** The biologists reported problems with the reagents.

The candidate lakes were defined as those in the southern portion of the wilderness which had reasonable access. Reasonable access was judged to include those lakes < 13 km (~ 8 mi) from a trailhead or road. Several lakes which met these criteria were eliminated from further consideration based on water chemistry data that indicated the lakes would not be suitable receptors for monitoring atmospheric deposition. An additional six lakes and ponds were examined in the wilderness, but they were rejected because of their shallow depth (< 1 m). Based on these criteria, the candidate lakes listed in Table 1 were selected for sampling (Figure 1). The candidate lakes were sampled August 4-6, 1993 by filling new Nalgene sample bottles that had been pre-soaked in ultra-pure deionized water. Sheep and Gertrude Lakes were sampled near the lake centers, whereas the remaining lakes were sampled from the shore. Field conductivity measurements were made on all samples as quality control checks using a YSI Model 3000 S-C-T meter and a PURE low range meter. The samples were transferred to the cooler as soon as possible. Upon return to

Corvallis, the samples were shipped to the analytical laboratory via overnight courier. Samples were analyzed by the USDA-Forest Service (Rocky Mountain Range and Field Experiment Station, Fort Collins, CO) using methods similar to those used for the remainder of the project.

The analytical results (Appendix B) were checked for internal consistency by comparing the sums of the anions and cations, calculated versus measured ANC, and calculated versus measured conductivity. The internal checks demonstrated that the laboratory analyses for the sample lakes were accurate (Appendix C).

The analytical results show that the eight study lakes span a wide range in chemistry from the dilute lakes such as unnamed (Cedar) and Gertrude to the highly alkaline systems such as Wright Lake (Table 2). Among the five lakes sampled in the wilderness, four had ANC values < 200 μeq/L and two had ANC values < 100 μeq/L.

The acid anion concentrations (SO_4^{2-}, NO_3^-, and Cl^-) in the lakes ranged from nearly 100 μeq/L in Wright Lake to < 20 μeq/L in Gertrude and the unnamed lake (later named Cedar Pond). Both nitrate and ammonium were below the detection limits in all lakes. Sulfate, the dominant acid anion, ranged from about 10 to 80 μeq/L, which suggests that there are some significant watershed sources of sulfate to these lakes. The lower elevation lakes (~900 m to 1200 m) had significantly greater chloride concentrations ($\bar{x}$ = 14 μeq/L vs 7 μeq/L) compared to the high elevation lakes (~1500 m to 1800 m) which probably reflects a greater washout of marine aerosols at the lower elevations.

Base cation ($Ca^{2+} + Mg^{2+} + Na^+ + K^+$) ratios varied considerably among the sample lakes. Ignoring the potassium concentrations which were low in all lakes except Glacier Lake (20 μeq/L), the cation ratios of Ca:Mg:Na ranged from 5.6:0.8:1 in Wright Lake to 0.65:0.5:1 in Unnamed Lake. The higher calcium concentrations in the high alkalinity lakes are consistent with differential weathering of the more soluble calcium. Sodium concentrations exceeded magnesium (on an equivalent basis) in all lakes except Chambers Lake, highlighting the importance of sodium-bearing minerals in these watersheds. If we assume that all the chloride is from marine aerosols, seasalt-corrected sodium concentrations still exceed magnesium in five of the eight lakes. The Ca:Mg ionic ratio is relatively constant among the study lakes, again with the exception of Chambers Lake. Once again, this supports the general finding that the mineralogic composition of the watersheds is quite similar.

Table 2. Analytical results for lakes sampled in the Goat Rocks Wilderness, August 1993.

FS ID#	Sample ID	Sample Date	Julian Date	Received Date	pH	Cond (μS/cm)	SiO_2 (mg/L)	Ca	Mg	Na	K	NH_4	Cl	NO_3	SO_4	ANC
								μeq/L								
OR18	Sheep Lake	08/04/93	216	08/10/93	7.029	14.546	2.779	85.68	24.60	40.45	7.08	0.00	6.37	0.00	27.53	131.10
OR19	Beaver Pond	08/05/93	217	08/10/93	6.788	14.210	3.884	87.92	26.91	53.68	6.45	0.00	6.52	0.00	13.24	136.80
OR20	Gertrude Lake	08/05/93	217	08/10/93	6.880	6.912	3.633	42.07	26.33	31.14	5.50	0.00	6.35	0.00	13.62	75.40
OR21	Cedar Pond	08/05/93	217	08/10/93	6.628	6.369	3.677	18.11	13.33	27.93	2.61	0.00	5.61	0.00	10.62	45.30
OR22	Chambers Lake	08/06/93	218	08/10/93	7.547	55.703	5.037	396.86	114.22	107.66	7.08	0.00	13.62	0.00	45.54	594.90
OR23	Glacier Lake	08/06/93	218	08/10/93	7.401	35.103	17.355	201.45	55.38	103.09	20.49	0.00	14.64	0.00	35.46	318.40
OR24	Hugo Lake	08/06/93	218	08/10/93	7.335	49.712	4.753	393.51	77.76	82.38	7.39	0.00	11.71	0.00	34.71	512.10
OR25	Wright Lake	08/06/93	218	08/10/93	7.604	95.956	6.622	880.84	126.23	157.77	7.08	0.00	14.98	0.00	82.87	1069.90

The conductivity in these sample lakes can be used to predict ANC and base cation concentrations with a high degree of accuracy. The linear regression equations with ANC and base cations as the dependent variables yield:

$$\text{ANC } (\mu eq/L) = 11.34 \text{ (Cond)} - 37.3$$

and

$$\text{Base Cations } (\mu eq/L) = 12.08 \text{ (Cond)} - 18.6$$

Using these equations, we estimate that the ANC for Walupt Lake based on a measured conductivity of 33 μeq/L is 337 μeq/L with a base cation concentration of 380 μeq/L.

Silica concentrations are generally low in most of the sampled lakes. For all lakes except Glacier Lake, silica is highly correlated ($r^2 = 0.95$) with ANC. This high correlation suggests that silicate weathering reactions are related to base cation production (alkalinity generation) in the candidate lakes. The high silica concentration in Glacier Lake may be associated with its large watershed caused by a natural dam formed by a landslide.

The issue of representativeness of the sample with respect to the population of lakes was addressed by comparing the survey lakes to the statistically-based sample of lakes in the Pacific Northwest conducted by the U.S. Environmental Protection Agency (EPA) in 1985. The EPA sample in the Pacific Northwest consisted of 159 lakes located primarily in the Cascades. The probability design of the EPA study allows one to characterize the population of lakes, estimated at over 1700 lakes, greater than 1 ha in surface area. The lakes in the Goat Rocks Wilderness generally are well dispersed along the distributions of lakes in the Pacific Northwest (Figure 2). Of the eight survey lakes, the lakes with the lowest values along these distributions are usually Gertrude and Cedar. Sulfate concentrations in these lakes are somewhat greater than expected on the basis of the lake ANC, perhaps because of the proximity of these lakes to Mount St. Helens. We conclude that the eight lakes sampled in the southern portion of the Goat Rocks Wilderness appear to be representative of many other lakes in the Cascades. The results for Gertrude Lake and Cedar Pond are generally in the range of the lower quartile of Cascade lakes for most variables.

Ideally, the two study lakes selected for long term monitoring would be those that had easy access and had the appropriate chemistry and morphometry. Desirable lake chemistry for monitoring the potential effects of deposition of acid anions (NO_3^-, SO_4^{2-}) would be low ANC, low watershed contributions of acid anions (esp. SO_4^{2-}), low concentrations of organic acids, and low base cation concentrations. The study lakes ideally should be deep enough to avoid complications caused by drought or ice formation. The lakes were evaluated according to the criteria described above (Table 3). Of the sampled lakes, only Cedar Pond and Gertrude Lake can be considered low

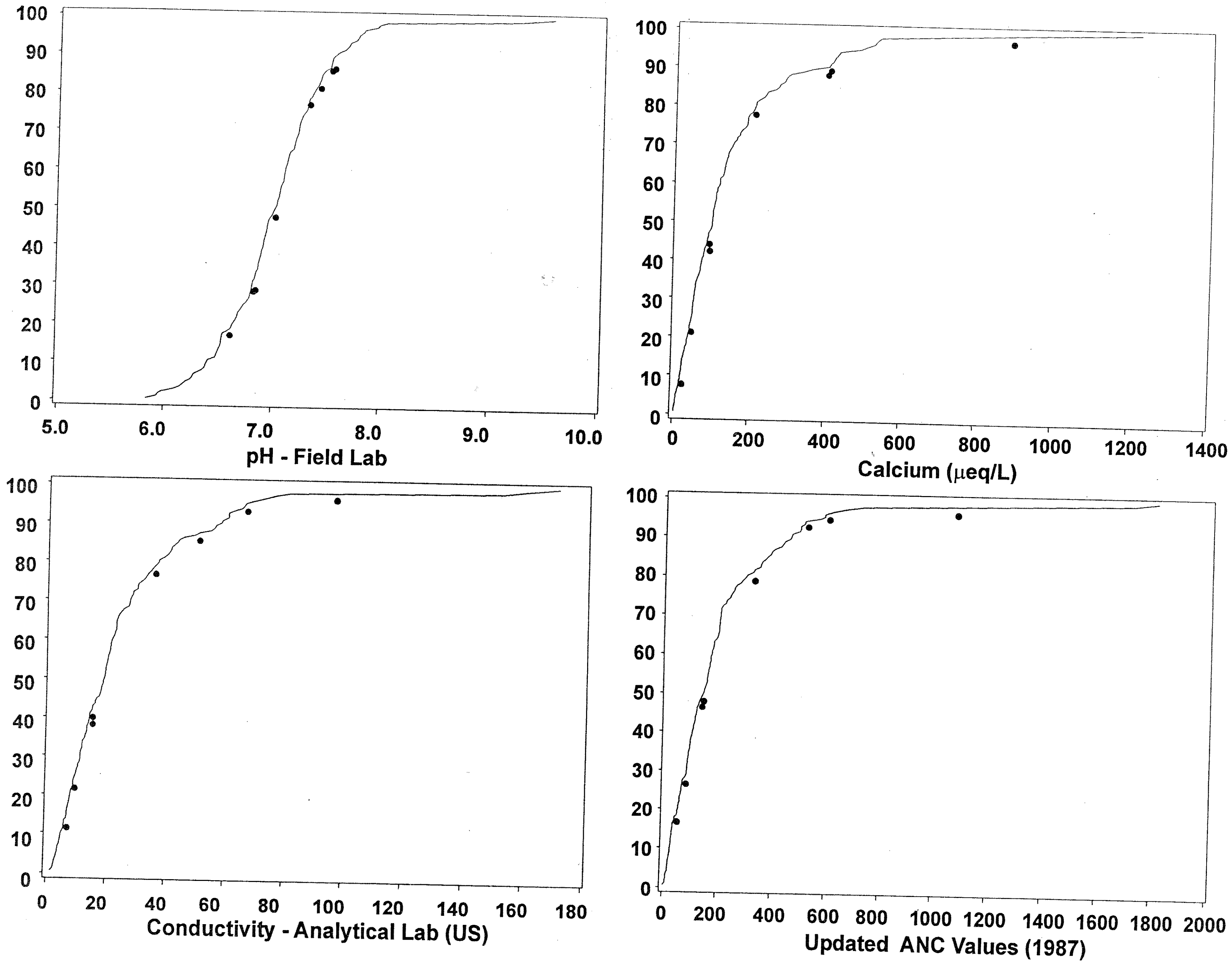


Figure 2. Cumulative frequency distributions (lines) for lakes in Washington Cascades derived from Eilers et al. (1987). Values from candidate lakes sampled in the Goat Rocks Wilderness are superimposed on these distributions.

Table 3. Candidate lakes in the Goat Rocks Wilderness sorted by ascending acid neutralizing capacity (ANC).

Lake Name	Elevation (m)	Approximate Distance from Road or Trailhead (km)	Approximate Lake Area (ha)	Lake Depth (m)	ANC (µeq/L)	Conductivity (µS)	Sulfate (µeq/L)	Organic Anion (µeq/L)
Cedar[a]	1610	10	1	2	45	6.4	11	1
Gertrude	1750	11	6	6	75	8.9	14	10
Sheep	1740	8	2	6	131	14.5	28	0
Beaver Pond	1490	8	3	3	137	14.2	13	17
Glacier	900	3	8	27	318	35.1	35	13
Hugo	1220	0	2	~3	512	49.7	35	3
Chambers	1350	0	4	12	595	55.7	46	0
Wright	900	0	2	?	1070	96.0	83	4

[a] Cedar Pond was previously an unnamed pond that was named by Forest Service personnel early in the study.

ANC systems and warrant long term sampling. Unfortunately, these two lakes are the most difficult candidate lakes to access.

B. Study Lakes

The selected study lakes, Gertrude Lake and Cedar Pond, are small lakes located in the southeastern portion of the Goat Rocks Wilderness, Gifford Pinchot National Forest (Plate 1). Gertrude Lake (elevation 1748 m) is located immediately north of Lakeview Mountain (elevation 2029 m) at the base of a major talus slope (Plate 2). The parent material in the area is andesite and granodiorite which was glaciated during the Pleistocene. The north shore of Gertrude Lake appears to be a gentle moraine divided by an intermittent outlet channel. There are no permanent stream inlets to Gertrude Lake, although there are three intermittent streams and considerable runoff from the snowpack may flow through the talus into the lake. The shoreline is comprised largely of exposed rocks and boulders with no macrophytes present.

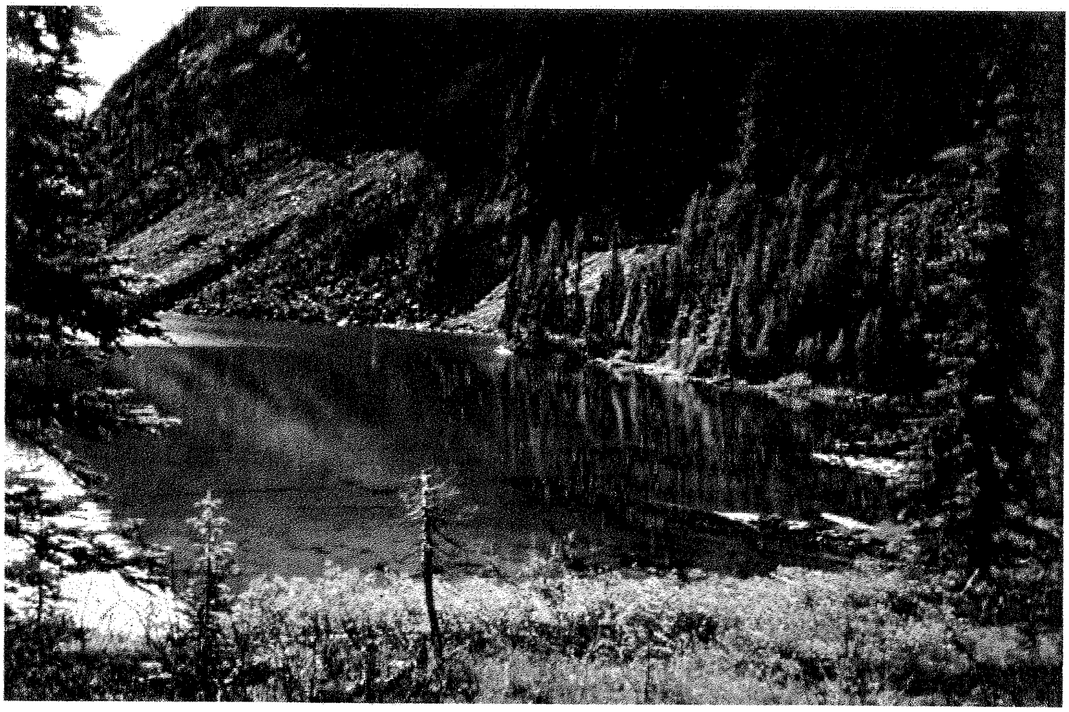


Plate 2. Gertrude Lake (Oct. 19, 1993) looking to the southeast

Cedar Pond is a shallow lake probably created as an ice melt depression during the recession of the alpine glaciation (Plate 3). It is situated about 1 km north of Gertrude Lake at an elevation of 1597 m. In contrast to Gertrude Lake, the watershed around Cedar Pond has little topographic relief and is highly vegetated. There is an intermittent surface inlet and a diffuse outlet on Cedar Pond. The lake substrate is primarily muck.

Plate 3. Cedar Pond (July 8, 1994) loooking south towards Lakeview Mountain

Much of the southern portion of the Gertrude watershed is exposed rock and talus, whereas the northern side of the watershed is comprised of modest stands of mountain hemlock (*Tsuga mertensiana*) and subalpine fir (*Abies lasiocarpa*) and understory vegetation of huckleberry *Vaccinium* sp.), heather (*Erica* sp.) and beargrass (*Xerophyllum tenax*) growing on shallow andisols. The watershed for Cedar Pond has comparatively little topographic relief (excluding the contributing area from Gertrude Lake) and is wholly vegetated in mountain hemlock and subalpine fir and understory similar to Gertrude Lake.

Both lakes are small and shallow. Gertrude Lake apparently is becoming shallower as rocks from the adjacent talus slope are dislodged and roll into the lake. The depth in Cedar Pond is maintained by accumulated vegetation at the diffuse outlet.

C. Lake Sampling

The lakes were accessed on foot via the Walupt Lake Trail. The final 3 km of the 11 km hike is unmarked and heads south at the junction of the Pacific Crest National Scenic Trail and Trail 101 (Walupt Lake Trail). The lakes were sampled at a depth of 0.5-1.0 m from an inflatable raft in the deepest portion of the lake except on June 3, 1994, June 4, 1996 (Plate 4), October 26, 1996, and July 2, 1997, when ice on the lake required that Gertrude Lake be sampled at the outlet (Table 4).

Plate 4. Gertrude Lake (June 4, 1996), sampling through the ice

Table 4. Field conditions 1993-1997, Goat Rocks Wilderness

Year	Date	Description and Notes
1993	August 4-6	Clear, warm
	August 29	Clear, warm
	September 27-28	Clear, cool; Forest Service personnel present
	October 19	Clear, cool
1994	June 3	Clear; 1-2 m of snow on ground; Gertrude ice covered; medical emergency required evacuation and hospitalization of personnel; sampled outlet
	July 7-8	Clear, warm; Forest Service EA review team present
	August 14-15	Clear, warm; installed weir, rain gage, soil sampling
	September 12-13	Cloudy, cool; temperature and precipitation gages installed
	October 10	Clear, cold; possible vandalism of equipment
1995	June 15	Rainy, cold; 1-2 m of snow on ground; sampled through ice
	July 10	Cloudy; snow on trail; lakes open
	August 23	Cloudy, high winds, cold; vegetation sampling, lake bathymetry
	September 19	Clear, warm
	October 25	Snowing, high winds, very cold; ice forming on lakeshore
1996	June 4	Cloudy, 1-2 m of snow; lakes ice-covered; sampled through ice and outlet
	June 28	Cool, windy, light rain; Forest Service personnel present
	August 13	Clear, warm; collect sediment core
	September 22	Cloudy, cold; snow on ground
	October 26	Clear; 1-1.5 m of snow; Gertrude frozen-sampled outlet; unable to locate Cedar; hiked out in dark
1997	July 2	Clear; 1-2 m of snow; Gertrude with ice; sampled outlet
	July 19-20	Clear; warm; used llamas; snow on ground
	August 4	Clear, warm; some snow still on ground
	September 8	Clear, warm; Weyerhaeuser personnel present; removed weir
	October 8	Snowing, snow accumulating; ice forming on lake perimeter

Cedar Pond was not sampled in October, 1996 because early 1m-deep snows covered the trail and attempts to locate the pond before nightfall were unsuccessful. The Nalgene bottles used for sample containers were pre-soaked in deionized water and were rinsed with the lake water three times before filling. Stream samples were collected by holding the bottles above the substrate allowing the streamflow to thoroughly rinse the sample bottles.

Samples were returned to a cooler at the trailhead generally within five hours of collection. The samples were kept on ice during transit and overnight shipping to the analytical laboratory, Environmental Science and Engineering, Inc. (now QST Environmental) in Gainesville, FL. Duplicate samples were shipped to the USDA-Forest Service research laboratory at the Rocky Mountain Range and Experiment Station in Fort Collins, CO for comparative quality assurance checks. Upon receipt from the laboratory, the data were converted into SI units, entered into sequential SAS files and checked for internal consistency, with other laboratory results in the case of split samples, and with results from the previous set of lake observations.

Selected plankton samples were collected from both lakes. The phytoplankton samples were collected in a manner identical to those for the lakewater samples with the exception that the phytoplankton was preserved with Lugol's solution. Zooplankton samples were collected from Gertrude Lake using vertical tows from the lake bottom using a 20-cm opening with an 80μ mesh size. The samples were counted and identified by Dr. Meg Falter, Aqua ID.

Lake stage was measured from staff gages installed at both lakes in 1994. However, the staff gage at Gertrude Lake was vandalized in 1995 and stage height for subsequent readings was based on photographic records of boulders on the southwest shore. The staff gage at Cedar Pond was dislodged in 1996, perhaps due to vandalism. Gage height in subsequent observations was estimated from photographic records of the lake shore. Stream discharge was measured at the outlet of Gertrude Lake at the weir installed in 1994. A Rainwise™ recording rain gage was re-installed ~100 m NE of Gertrude Lake in 1995. Installation sites for the equipment were approved by Forest Service staff based on a site visit on August 14, 1994. We deployed an OMNIDATA Stowaway® temperature logger in Gertrude Lake at a depth of 1 m below the surface on June 4, 1996 by anchoring the weighted line in the deepest portion of the lake.

Duplicate and split lake samples were collected from the lakes on several occasions and duplicate results were averaged for presentation in the plots. For statistical analyses, the results from the duplicate samples have been averaged prior to computing the statistic of interest.

A sediment core was collected from Gertrude Lake on August 13, 1996. The sediment core was 26 cm in length and was collected near the deepest part of the lake at a depth of 5.5 m. The sediment was extruded at the lake in 1 cm intervals. The top 0.5 cm of the sediment was used in a diatom calibration set developed to predict historical changes in lake chemistry for lakes in the Oregon and Washington Cascades.

A bathymetric survey (Eilers et al. 1998) of Gertrude Lake was conducted on August 23, 1995 using SONAR/GPS methodology (Gubala et al. 1994) adapted for use on an inflatable cataraft.

Vegetation samples were collected from dominant plant species in the Gertrude Lake watershed in August, 1995. Samples were collected from dominant tree species and understory species. The plant tissue samples were placed in Ziploc® bags and stored in a cooler prior to delivery to the Central Analytical Laboratory at Oregon State University. The samples were analyzed for carbon and nitrogen on a Leco CNS Analyzer.

Soil samples were collected from several vegetative cover types and locations within the Gertrude Lake watershed. Soils were collected using a standard soil probe and placed into soil bags for transport to the Central Analytical Laboratory at Oregon State University.

D. Snow Monitoring

1. Site Selection

A monitoring plan was developed to sample snow east of Longview both before and following the operation of the expanded industrial facilities. The first two years of the snow sampling program (1994 and 1995) represent snow conditions prior to the recent mill modifications. The final three years of the monitoring (1996-1998) were intended to represent snow conditions under post-mill modifications. Six site areas east of Longview, WA were targeted for snow sampling (Figure 3; Table 5). However, road access to two sites (Cold Springs Butte and Green Mountain) was prohibited following damage to bridges and roads caused by flooding in February, 1996. These locations were selected to provide broad areal coverage over the deposition zone of potential concern. Specific sampling sites within the targeted locations were selected to provide for adequate snow depth and minimal local disturbance from snowmobiles or litterfall. Most sites were sampled within 200 m of the 1994 locations. The major exception was Lone Butte where the site was relocated an additional 4 km north of the 1994 site. The 1995-1998 Lone Butte location was in the Indian Heaven Wilderness at an elevation of 1509 m compared to 1220 m for 1994. The Mount Rainier site selected for 1996-1998 was about 350 m north of the 1994 site to avoid contamination from snow campers.

Because two sites (Green Mountain and Cold Springs Butte) could not be accessed in 1996, E&S and Weyerhaeuser staff agreed to a modification to the scope of work in which additional snow samples would be collected at the remaining sites. Discrete samples were collected at the top, middle, and bottom of the snow pit in addition to the two duplicate integrated snow pit samples that were collected at all sites.

2. Field Methods

Sites were accessed on skis or snowshoes. Snow sampling sites were selected in open areas away from immediate litterfall. The sampling pits were dug through the snowpack using Lexan®-bladed shovels. A vertical wall was dug in the snow (Plate 5) and a plastic (HDPE) squared scoop, pre-rinsed in the field with ultrapure deionized water (DIW), was used to scrape 1 to 2 cm of snow from the entire face of the vertical wall. Areas of

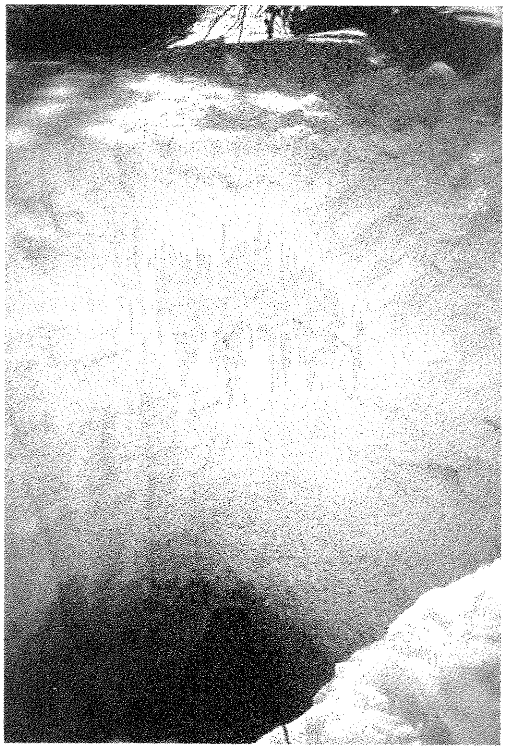


Plate 5. Snow pit at Mount Rainier (April 1, 1995). Technician standing in snow pit.

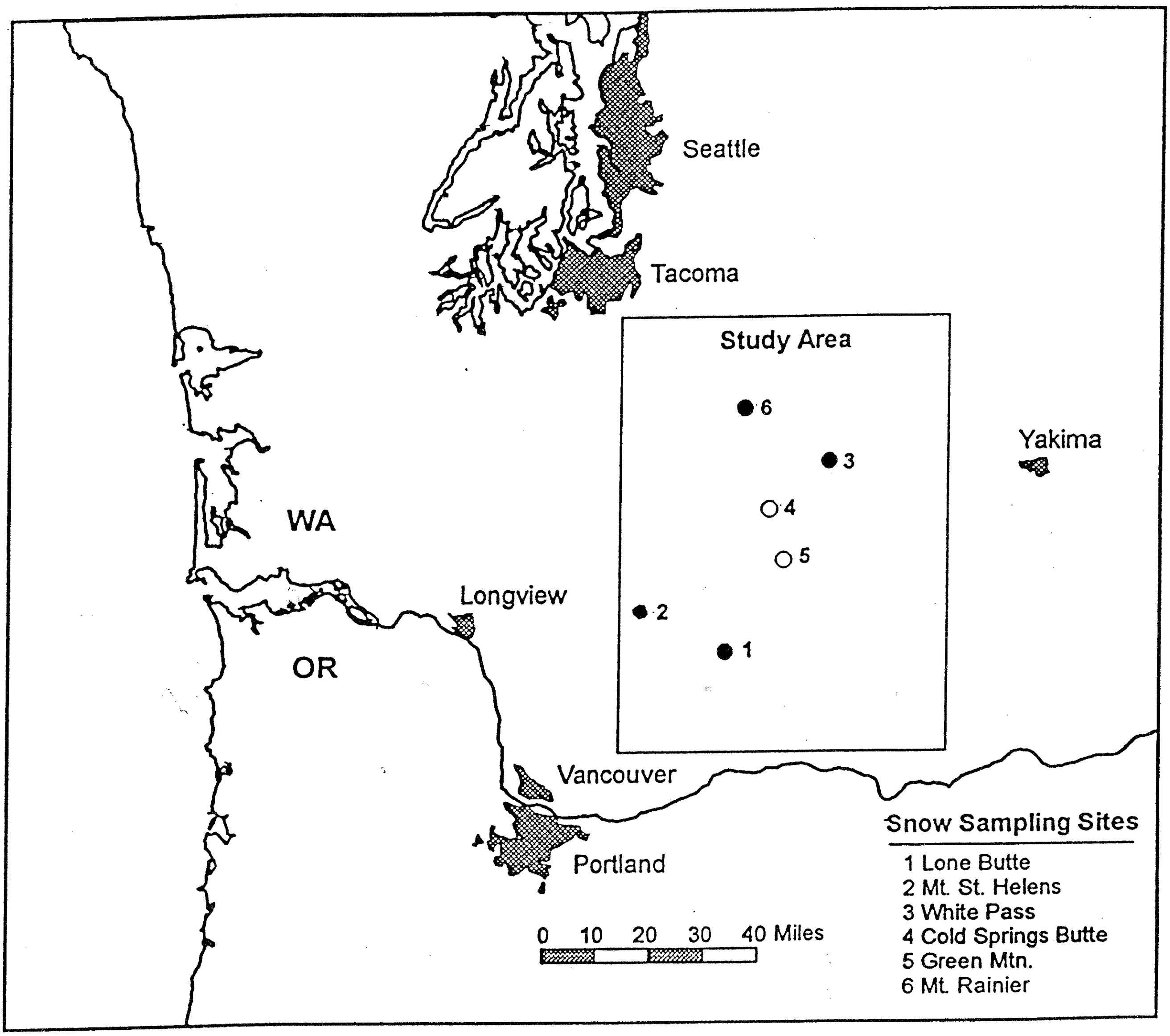


Figure 3. Location of the study area relative to major metropolitan areas in Washington and Oregon. Sites designated with closed circles were sampled in 1994-1998; sites with open circles were sampled in 1994-1995 only.

Table 5. Sample Site Description

Site Name	Elevation[1] m (ft)	Location[2] (UTM)
1. Lone Butte	1509 (4950)	594343E 5100931N
2. Mount St. Helens	1341 (4400)	563544E 5112368N
3. White Pass	1830 (6000)	623525E 5164249N
4. Cold Spring Butte	1435 (4708)	604412E 5148339N
5. Green Mountain	1525 (5000)	608500E 5131785N
6. Mt. Rainier	1650 (5400)	596500E 5182300N
AVERAGE	1566 (5142)	

[1] From topographic maps
[2] From GPS; minor adjustments made on site maps

snow containing visible plant material (conifer needles, lichens) were avoided. The snow samples were placed in Teflon® bags that had been rinsed in Fisher ultrapure DIW. The sample bags were sealed and placed inside polyethylene bags that also had been rinsed with DIW. A sample label was attached to the outside of the polyethylene bag. Following collection of the snow samples, depth of snow in the pit was measured with a surveying tape. Air temperature was recorded and general conditions of the snow and weather were noted. The water content of the snow was measured at all sites using a standard SCS (NRCS) snow corer. At all sites except for Lone Butte, snow samples also were collected at the bottom, middle, and top of the snow pit in an attempt to examine variability within the snow column. The snow accumulation (in SWE) at or near the study sites is indicated in Figure 4.

The samples were returned to the vehicle where they were stored in coolers lined with snow or ice. Prior to shipping, the samples were placed in individual HDPE plastic buckets with lids, all of which were rinsed with DIW. The snow samples were shipped to the contract laboratory via overnight service and arrived with most of the snow still frozen.

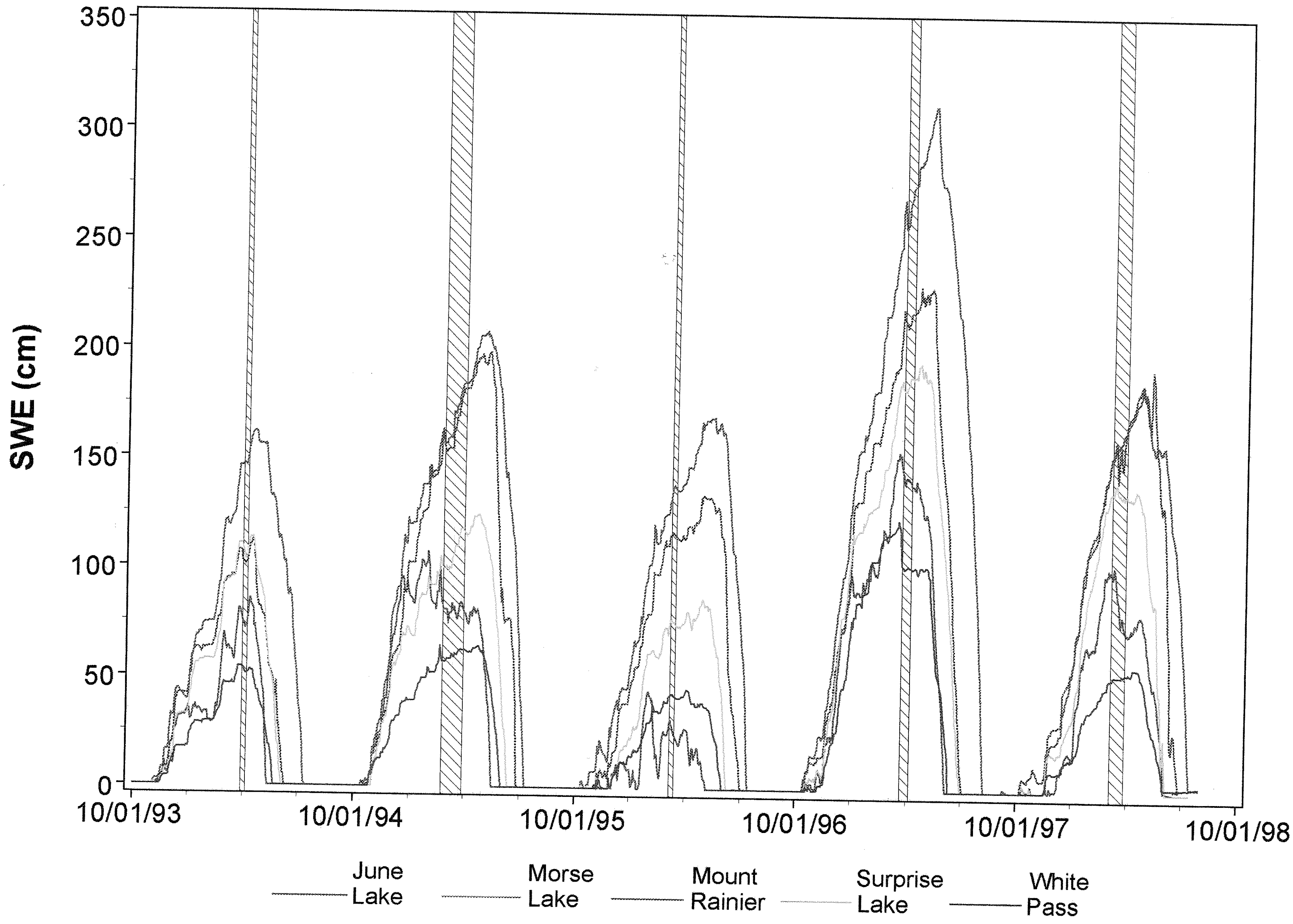


Figure 4. Snow accumulation (snow water equivalents [SWE], cm) at NRCS SNOTEL sites in the proximity of the snow pit sites. The period of snow sampling is shown as the shaded area. The snow accumulation for White Pass is substantially less than the value measured at our site because the SNOTEL site is at only 1372 m elevation.

The snow samples were received by the laboratory (ESE, Gainesville, FL) and placed in a cold room for melting. The samples were melted inside HDPE plastic buckets over a several day period. The samples were analyzed according to the methodologies outlined in Table 6, which are methods also used by ESE for analysis of samples from EPA's National Dry Deposition Network. In addition, samples were analyzed for low molecular weight organic anions (formate, acetate, and propionate) using a Dionex ion chromatograph.

Table 6. Analytical methods for analysis of snow samples

Parameter	STORET Method	Parameter	STORET Method
pH, Lab (standard units)	406 150.1-G	Phosphorus, T (mg/L as P	665 365.1-G
Specific conductivity, Lab (µmhos/cm)	95 20.1-G	Calcium, dissolved (mg/L)	915 AR
ANC, Gran Titration (µeq/L)	97640 AR	Magnesium, dissolved (mg/L)	925 AR
Sulfate, dissolved (mg/L)	946 AR	Sodium, dissolved (mg/L)	930 AR
Chloride, dissolved (mg/L)	99652 AR	Potassium, dissolved (mg/L)	935 AR
Nitrogen, NO_3, dissolved (mg/L)	618 AR	Carbon, TOC (mg/L)	680 415.1-G
Nitrogen, NH_3 + NH_4, dissolved (mg/L)	608 AR	Iron, total (µg/L)	1045 6010-G
Nitrogen, TKN (mg/L as N)	625 351.2-G	Manganese, total (µg/L)	1055 6010-G

E. Quality Assurance Review

1. Lake and Stream Chemistry

The overall caliber of the water quality data are judged to be acceptable as indicated by the checks of ion balance, acid neutralizing capacity (ANC), conductivity, and quality assurance samples (Appendix B). The ion balances for samples are accurate, except for the August 13, 1996 sample from the North Inlet to Gertrude Lake (GL96-3NI). This same sample also is an outlier on other plots of internal consistency (Appendix B) which suggests that there is an analytical error in the analysis of ANC. The actual ANC for this sample is probably closer to 200 µeq/L rather than the 261 µeq/L reported here. The plot of pH versus measured ANC shows that the Cedar Pond values are closer to the expected equilibrium with atmospheric CO_2 than those from Gertrude Lake (Appendix B). The disparity most likely reflects a real difference in CO_2 sources to the lakes as discussed later in this report.

Comparison of the primary contract laboratory (ESE) with the Forest Service (FS) research laboratory for 1994 data shows the ESE analyses underestimated base cations relative to the Forest Service in all three samples. This pattern also was observed in 1995. The sum of cations measured by ESE for the June sample in Gertrude Lake is low by 15 µeq/L relative to the measured sum of anions. The lack of agreement between the measured and calculated ANC further indicates an ion imbalance caused by a negative bias in the cations. Agreement for other parameters is generally good except for the higher pH values in the June Summit Lake sample and the August Gertrude Lake sample measured by ESE relative to those measured by the Forest Service (cf. Eilers et al. 1998). The pH value measured by the Forest Service for Gertrude Lake in August appears to be in error considering the high ANC value. The calculated pH value for the measured ANC value is 7.03 (@ P_{CO_2} $10^{-3.2}$ atm). The measured ANC value for this sample also differs by 26 µeq/L.

2. Duplicate and Blank Samples

Analysis of duplicate samples was done to compute the precision of the analytical results. The precision of the lake and stream analyses from the analytical laboratory illustrate a generally high level of precision for most of the analytes (Table 7; Appendix B).

Table 7. Precision of six duplicate lake samples.

Parameter	Unit	Mean Absolute Difference	Standard Deviation	Coefficient of Variation[a]
ANC	µeq/L	6.40	5.35	0.87
Ca	µeq/L	1.32	1.62	1.28
Cl	µeq/L	0.80	0.95	1.23
K	µeq/L	0.44	0.46	1.09
Mg	µeq/L	0.48	0.68	1.48
Na	µeq/L	0.77	0.60	0.81
NH_4	µeq/L	0.53	1.31	2.55
NO_3	µeq/L	0.00	0.00	–
pH	su	0.23	0.29	1.33
SO_4	µeq/L	0.79	1.22	1.61
Spec. Cond.	µS/cm	0.65	0.62	0.99

[a] CV corrected for small sample size using CV*=(1 + ¼ n); after Sokal & Rohlf (1981)

Blank samples composed of deionized water (DIW) were submitted to the laboratory with the routine samples to check for levels of contamination and possible bias in the analyses. The results indicate that neither of these issues was a significant factor in this data set (Table 8; Appendix B).

Table 8. Results of analysis of blank (deionized water) samples submitted as part of the quality assurance sample suite.

Parameter	USFS 8/4/97	QST 8/6/97
pH	5.69	5.73
ANC (µeq/L)	-1.8	-7.53
Conductivity (µS)	0.955	1.46
Cations		
Ca	0	0.150
Mg	0	0.247
Na	0	0.218
K	0	0.128
NH_4	0	0.713
Anions (µeq/L)		
SO_4	0	0.833
Cl	0	0.564
NO_3	0	0.572
QA Checks		
ANC_{Cal} (µeq/L)	0	0.000
$Cond_{Cal}$ (µS)	0.841	0.817
Ion Balance (µeq/L)	+4.50	-0.635

F. Watershed Model

1. Description

The Model of Acidification of Groundwater In Catchments (MAGIC) is a lumped-parameter model of intermediate complexity developed to predict the long-term effects of acidic deposition on surface water chemistry. The model simulates soil solution chemistry and surface water chemistry to predict the monthly and annual average concentrations of the major ions in these waters. MAGIC consists of: (1) a section in which the concentrations of major ions are assumed to be governed by simultaneous reactions involving sulfate adsorption, cation exchange, dissolution-precipitation-speciation of aluminum and dissolution-speciation of inorganic carbon; and (2) a mass balance section in which the flux of major ions to and from the soil is assumed to be controlled by atmospheric inputs, chemical weathering, net uptake and loss in biomass, and losses to runoff. A critical component in the MAGIC model is the size of the pool of exchangeable base cations in the soil. As the fluxes to and from this pool change over time owing to changes in atmospheric deposition, the chemical equilibria between soil and soil solution shift to yield changes in surface water chemistry. The degree and rate of change of surface water acidity thus depend both on flux factors and the inherent characteristics of the affected soils.

Cation exchange is modeled using equilibrium equations (Gaines-Thomas) with selectivity coefficients for each base cation and aluminum. Sulfate adsorption is represented by a Langmuir isotherm. Aluminum dissolution and precipitation are assumed to be controlled by equilibrium with a solid phase of aluminum trihydroxide. Aluminum speciation is calculated by considering hydrologic reactions as well as complexation with sulfate and fluoride. Effects of carbon dioxide on pH and on the speciation of inorganic carbon are computed from equilibrium equations. Organic acids are represented in the model as triprotic analogues. First-order rates are used for biological retention (uptake) of nitrate and ammonium in the soils and lake. Weathering rates are assumed to be constant. A set of mass balance equations for base cations and strong acid anions are included. Given a description of the historical deposition at a site, the model equations are solved numerically to give long-term reconstructions of surface water chemistry (for complete details of the model see Cosby et al. 1985a,b,c; 1989).

MAGIC has been used to reconstruct the history of acidification and to simulate the future trends on a regional basis and in a large number of individual catchments in North America and Europe (Lepisto et al. 1988, Whitehead et al. 1988, Cosby et al. 1989, 1990, 1996; Hornberger et al. 1989; Jenkins et al. 1990 a,b,c; Wright et al. 1990, 1994; Norton et al. 1992).

2. Model Implementation

Atmospheric deposition and net uptake/release fluxes for the base cations and strong acid anions are required as inputs to the model. These inputs are generally assumed to be uniform over the catchment. Atmospheric fluxes are calculated from concentrations of the ions in precipitation and the rainfall volume into the catchment. The atmospheric fluxes of the ions must be corrected for dry deposition of gas, particulates, and aerosols, and for inputs in cloud/fog water. The volume discharge of the catchment must also be provided to the model. The model is implemented using average hydrologic conditions and meteorological conditions in a seasonal simulation, i.e., mean monthly deposition, precipitation, and lake discharge are used to drive the model. The model is not designed to provide temporal resolution greater than monthly. Values for soil, talus, and lakewater temperature, partial pressure of carbon dioxide, and organic acid concentrations must also be provided.

As implemented in this project, the model is a three-compartment representation of a catchment. Two compartments are used to represent the terrestrial components of the catchment (talus areas and soil covered areas; see below). The third compartment is the lake. Atmospheric deposition falling on the soil compartment is subject to chemical transformations. Biological uptakes, weathering inputs, and equilibrium equations (including soil ion exchange) are used to calculate soil water chemistry. Atmospheric deposition falling on the talus compartment is subject to less change. There are no biological uptakes or ion exchange reactions used to calculate talus drainage-water chemistry. The water flowing from both soils and talus is then routed to the lake compartment where biological uptake can occur. The appropriate aqueous phase equilibrium equations are then applied to calculate lakewater chemistry.

Once initial conditions (initial values of variables in the equilibrium equations) have been established, the equilibrium equations are solved for soil water, talus drainage, and lakewater concentrations of the remaining variables. These concentrations are used to calculate the lakewater output fluxes of the model for the first time step. Atmospheric deposition and weathering inputs are added, and the mass balance equations are numerically integrated over the time step, providing new values for the total amounts of base cations and strong acid anions in the system. These in turn are used to calculate new values of the remaining variables, new lakewater output fluxes, and so forth. The output from MAGIC is thus a time trace for all major chemical constituents for the period of time chosen for the simulation. Details of the numerical integration and a computer code for implementing the model are given by Cosby et al. (1984).

3. Calibration Procedure

The aggregated nature of the model requires that it be calibrated to observed data from a system before it can be used to examine potential system response. Calibration is achieved by setting the values of certain parameters within the model that can be directly measured or observed in the system of interest (called "fixed" parameters). The model is then run (using observed and/or assumed atmospheric and hydrologic inputs) and the outputs (lakewater and soil chemical variables, called "criterions" variables) are compared to observed values of these variables. If the observed and simulated values differ, the values of another set of parameters in the model (called "optimized" parameters) are adjusted to improve the fit. After a number of iterations, the simulated-minus-observed values of the criterion variables usually converge to zero (within some specified tolerance). The model is then considered calibrated. If new assumptions (or values) for any of the fixed variables or inputs to the model are subsequently adopted, the model must be re-calibrated by re-adjusting the optimized parameters until the simulated-minus-observed values of the criterion variables again fall within the specified tolerance.

The estimates of the fixed parameters and deposition inputs are subject to uncertainties so a "fuzzy" optimization procedure was implemented for calibrating the model. The fuzzy optimization procedure consists of multiple calibrations of each catchment using random values of the fixed parameters drawn from the observed possible range of values, and random values of deposition from a range including uncertainty about the extrapolated values. Each of the multiple calibrations begins with (1) a random selection of values of fixed parameters and deposition, and (2) a random selection of the starting values of the optimized parameters. The optimized parameters are then adjusted using the Rosenbrock (1960) algorithm to achieve a minimum error fit to the target variables. This procedure is undertaken ten times. The final calibrated model is represented by the ensemble of parameter values and variable values of all of the successful calibrations.

4. Model Inputs

a. Configuration of Catchment Compartments

Based on examination of catchment maps, the percentages of the catchment occupied by the lake, the talus slopes and soil-covered areas were estimated. For the purposes of the model, any bare-rock areas that drained into an area covered by soil before entering the lake were considered part of the soil compartment; water draining this bare rock is subject to chemical modification by soils in the catchment. Bare rock areas that drain directly to the lake were considered part of the modeled talus compartment.

b. Lake Water Quality Data

The lake water quality data used (and the methods of sampling and analysis) are described elsewhere in this report. The measured lake concentrations and discharges were used to construct: 1) average annual runoff fluxes, 2) volume-weighted annual average concentrations, and 3) input/output mass balance budgets (using the atmospheric deposition data described below). These were calculated for each major ion in the lake (Table 9). For this project, alkalinity is defined as the charge balance alkalinity:

$$\text{alkalinity} = \text{SBC} - \text{SAA}$$

where SBC is the sum of base cations concentrations (calcium, magnesium, potassium, and sodium) and SAA is the sum of acid anion concentrations (sulfate, nitrate, and chloride), all concentrations in μeq/L.

c. Atmospheric Deposition

Atmospheric deposition used for this assessment was the *total* deposition flux of the major ions to the catchment. Total deposition consists of three components:

$$\text{Total deposition} = \text{wet deposition} + [\text{dry}_{\text{particulate}} + \text{dry}_{\text{gaseous}}]$$

Table 9. Volume-weighted annual average concentrations in precipitation and lake water, dry deposition factors, and mass balances for the calibration period at Gertrude Lake

Volume Weighted Annual Concentrations in Wet Deposition									
Ca	Mg	Na	K	NH_4	NO_3	Cl	SO_4	Calk	m ppt
0.76	0.99	2.33	0.31	1.72	2.97	2.67	4.93	-4.47	2.00
Dry Deposition Factors									
Ca	Mg	Na	K	NH_4	NO_3	Cl	SO_4		
1.00	1.00	1.00	1.00	1.50	1.50	1.00	1.50		
Volume Weighted Annual Concentrations in Runoff (meq/m^3)									
Ca	Mg	Na	K	NH_4	NO_3	Cl	SO_4	Calk	m runoff
22.15	12.92	14.76	3.06	0.90	0.53	4.96	10.29	38.01	1.60
Catchment Input-Output Mass Balance for all Ions									
Annual Input Fluxes (meq/m^2/yr)									
Ca	Mg	Na	K	NH_4	NO_3	Cl	SO_4	Calk	
1.52	1.98	4.66	0.61	5.17	8.91	5.34	14.80	-15.11	
Annual Output Fluxes (meq/m^2/yr)									
Ca	Mg	Na	K	NH_4	NO_3	Cl	SO_4	Calk	
35.43	20.67	23.61	4.90	1.45	0.85	7.94	16.46	60.81	
Catchment Net Flux (output-input) (meq/m^2/yr)									
Ca	Mg	Na	K	NH_4	NO_3	Cl	SO_4	Calk	
33.91	18.69	18.95	4.28	-3.72	-8.06	2.60	1.66	75.92	

Wet deposition is the flux of ions occurring in precipitation. Dry deposition results from both particulate and gaseous fluxes. There were no direct deposition measurements collected at Gertrude Lake. The deposition and precipitation data selected for use at this site were derived from the nearest available monitoring site and were modified and scaled to the site using the observed lake output fluxes to estimate the deposition inputs at the site.

For Gertrude Lake, monthly wet deposition at the Pack Forest NADP/NTN site was used as a starting point for developing estimates of annual total deposition. The monthly deposition of chloride and sodium were both reduced by 50% to correct for the effects of altitude. Gertrude Lake is higher than the Pack Forest site and sea salt aerosols are reduced at higher elevations (cf. Section II-A, p. 4, discussing the effects of elevation on chloride deposition to lakes in the area). The wet deposition of the other ions was assumed to be the same at Gertrude Lake as at Pack Forest. Dry deposition factors of 1.5 were assumed for sulfate, nitrate, and ammonium ions. The dry deposition factor for the other ions was assumed to be 1.0. The precipitation volume at Gertrude Lake was assumed to be 2.0 m/yr with a seasonal precipitation volume pattern similar to that at Pack Forest. These assumptions resulted in the estimates of annual input fluxes (and volume weighted annual concentrations in precipitation) shown in Table 10 for use in the model. Annual discharge from Gertrude Lake was calculated using the assumed evapotranspiration for the site (described in the data sources section) and the scaled precipitation at the site. The seasonal pattern of discharge was constructed based on an assumed pattern of snowmelt at the site.

It was assumed that both chloride and sulfate are conservative (i.e., no adsorption or biological removal of either ion within the catchment or lake) in the Gertrude Lake catchment. Comparing the assumed total annual deposition of these ions with the observed output of the ions indicates that an internal source of both chloride and sulfate are needed if the annual inputs and outputs are to balance. For Gertrude Lake this internal source was assumed to be the residual ash from the Mount St. Helens eruption of 1980.

The effects of ash inputs were simulated in the following manner. Data from analyses of the concentrations of anions and cations in the volcanic ash are available for ash deposited at a number of locations (cf. Hinkley 1987). We selected the analysis of ash at Tampico, WA (Taylor and Lichte 1980) for use at Gertrude Lake. The ratios of Ca^{2+}, Mg^{2+}, K^{+}, and NO_3^- to SO_4^{2-} were derived from the ash concentration data. The additional sulfate necessary to balance atmospheric inputs for Gertrude Lake was assumed to come from leaching of the ash pack and Ca^{2+}, Mg^{2+}, K^{+}, and NO_3^- were assumed to leach in the same ratio as their concentrations. Thus for the calibration year the following fluxes of ions were assumed to be weathered from the ash:

Table 10 Monthly precipitation, monthly runoff and effective monthly atmospheric deposition for Gertrude Lake

The effective monthly deposition accounts for the accumulation of atmospheric inputs in the snowpack during the snow season and the addition of snowmelt to atmospheric inputs during the melt season. The effective deposition is the flux of ions delivered to soils and talus in the model in any given month.

	Runoff (cm)	ppt (cm)
Jan	0.0	22.4
Feb	0.0	19.6
Mar	0.0	16.1
Apr	0.0	20.0
May	56.0	14.5
Jun	72.0	10.6
Jul	6.4	7.8
Aug	3.2	4.7
Sep	6.4	7.3
Oct	16.0	20.7
Nov	0.0	23.6
Dec	0.0	32.7
Annual	160.0	200.0

	snow accum (1=yes)	% of ions released from melt
Jan	1	0
Feb	1	0
Mar	1	0
Apr	1	0
May	0	70
Jun	0	30
Jul	0	0
Aug	0	0
Sep	0	0
Oct	1	0
Nov	1	0
Dec	1	0

Effective Depostion (including snowmelt and accumulation) (meq/m2)

Month	Ca	Mg	Na	K	NH4	No3	Cl	SO4	CALK
Jan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mar	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Apr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
May	0.94	1.25	2.93	0.36	2.92	4.91	2.74	9.46	-8.71
Jun	0.42	0.58	1.37	0.17	1.32	2.42	1.28	4.43	-4.26
Jul	0.06	0.05	0.10	0.03	0.37	0.74	0.59	0.29	-1.01
Aug	0.05	0.04	0.09	0.02	0.35	0.50	0.41	0.26	-0.62
Sep	0.06	0.06	0.17	0.03	0.20	0.34	0.32	0.36	-0.51
Oct	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nov	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dec	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Annual	1.52	1.98	4.66	0.61	5.17	8.91	5.34	14.80	-15.11

Calculated fluxes of ions (meq/m^2/yr) from ash into catchment in 1996 based on calibration of lakewater sulfate concentration:

Calcium	Magnesium	Potassium	Nitrate	Sulfate
1.12	0.33	0.08	0.01	1.66

Salts of chloride (NaCl and NH_4Cl) leach more readily than do salts of sulfate (Dean 1985, Dethier et al. 1981). Therefore, the leaching of sodium and ammonium from the ash were keyed to chloride leaching. The ratio of sodium and ammonium each to chloride were derived from the ash concentration data. The additional chloride necessary to balance atmospheric inputs for Gertrude Lake was assumed to derive from leaching of the ash and sodium and ammonium were assumed to leach in the same ratio as their concentrations in the ash. Thus for the calibration year, the following additional fluxes of ions were assumed to be generated from the ash:

Calculated fluxes of ions (meq/m^2/yr) from ash into catchment in 1996 based on chloride:

Sodium	Ammonium	Chloride
3.22	0.03	2.60

Weathering inputs from ash were assumed to be zero prior to the eruption of Mount St. Helens in 1980. Two possible scenarios of the persistence of the ash were considered in this study. The first scenario assumed that leaching of ions from the ash has proceeded and will proceed in the future at the same rate that is calculated for catchment input/out balance for chloride and sulfate in 1996. This is called the "constant ash" scenario. The other scenario assumes that leaching from the ash has declined since the eruption of the volcano and will eventually cease at some point in the future. To implement this second assumption, a "triangular ash" scenario was adopted. The ash leaching immediately following the eruption in 1980 was assumed to be twice that calculated to give catchment input/output balance of chloride and sulfate in 1996, and it was assumed that by the year 2012 ash leaching will have ceased. This amounts to a linear decline from maximum leaching in 1980 to zero leaching in 2012 (32 years). The model was calibrated using both historical ash scenarios, and all future deposition scenarios were run using each of the future ash scenarios.

d. Specification of Snowpack Dynamics

Two characteristics of annual snowpack dynamics must be specified for the seasonal application of MAGIC at a site where snow accumulates: (1) the months during which snow accumulates; and (2) the percentage of ions in the snowpack that are released during each month of the snowmelt.

1) *Snow accumulation*

For the months when precipitation falls as snow and is stored in a snowpack, the snow accumulation function was set to 1. The value of the snow accumulation function is zero for all months when precipitation falls as rain, except in winter when minor rain on snow events may occur. The monthly wet deposition is multiplied by the dry deposition factor to calculate total deposition for each month at the site. For every month that snow accumulates, the total deposition is added to the snowpack total. The modeled deposition inputs to the model for those months are set to zero. Catchment discharge for the snow accumulation months is set to a small value to avoid instability in the model (Table 10).

2) *Snowmelt*

The catchment discharge for each month of snowmelt is based on assumed or observed hydrographs. The preferential elution of ions that occurs during snowmelt is simulated in the model by specifying the percentage of the total snowpack accumulation of ions that is eluted in each month of snowmelt. These percentages are usually high early during snowmelt and decline as the melt proceeds. For months with no snow accumulation, the total atmospheric deposition fluxes and the ion fluxes from the snowpack, if any, are summed to yield the estimated deposition inputs for the model (Table 10).

e. Deposition History

The total historical deposition to the catchment and the temporal pattern of that deposition must be provided to complete the modeling. The pattern of the historical deposition determines the total loading of acidic deposition that the site has received, and thus affects how the model simulates responses to future changes in loading.

Such long-term, continuous historical deposition data do not exist. The approach adopted for this project was to use historical emissions to estimate historical deposition rates for sulfur and nitrogen. The emissions for each year in the historical period are normalized to emissions in the reference year, the year for which observed data are available. This produces a sequence of scale factors that have a value of 1.0 for the reference year. Values of the scale factor for other years are the fractions of reference year emissions that occurred in that year. For example, if emissions in 1950 were 86% of what they were in the reference year, then the scale for 1950 is 0.86.

Using this scaled sequence of emissions, historical deposition was estimated by multiplying the total deposition for 1996 (the reference year used in this project) by the emissions scale factor to obtain historical deposition. An implicit assumption is that the relationship between emissions and deposition is unchanged over time. Thus, if emissions in 1950 were 86% of the emissions in the reference year, then deposition in 1950 was assumed to be 86% of deposition in the reference year.

A key assumption in this procedure is that the "source" area for the emissions used to scale deposition at a site can be correctly identified. Emissions estimates for sulfur dioxide are available on a state-by-state basis from 1900 to 1989 (Gschwandtner et al. 1985a,b), which can be summed to produce a "regional" emissions history for the Pacific Northwest. That approach was adopted for this project and deposition histories for S and N for the catchment were scaled using the scaled sequence of sulfur dioxide emissions in the Pacific Northwest (EPA Region X; Figure 5).

III. RESULTS

A. Lake Chemistry

The analytical results for Gertrude Lake and Cedar Pond for the period 1993-1997 are presented in Table 11 and displayed in Figures 6-22. The values of most analytes increase from spring through fall, often by a factor of two or more. pH increases from about 6.0 in both lakes during snowmelt and reaches typical maximum values of 7.0 in Gertrude Lake and 6.7 in Cedar Pond (Figure 6). The rate of increase is greatest from June to July, usually an increase from about pH 6.0 to 6.5. The pH changes expressed as hydrogen ion are small, accounting for less than 1 µeq/L.

The seasonal change in ANC for Gertrude Lake increases from about 20 µeq/L in the spring to about 80 µeq/L in the fall (Figure 7). A minimum ANC of 10 µeq/L was measured in June 1995 following a moderately high snowpack. The typical spring ANC values measured in Cedar Pond are similar to those in Gertrude Lake, but the maximum fall value is generally less than 60 µeq/L. Most of the difference observed between the two lakes is associated with the more rapid increases in ANC in Gertrude Lake from June to July; both lakes show increases in ANC of about 20 µeq/L during the period July to November.

The seasonal patterns in base cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}; Figures 8-11), as expected, are very similar to those displayed by ANC. Calcium represents the greatest proportion of the base cations (average ion ratio in Gertrude Lake is 7.3:4.6:5.1:1 for Ca:Mg:Na:K, respectively) and therefore the pattern for calcium closely mimics the seasonal pattern for ANC in Gertrude Lake. In Cedar Pond, the ion ratios of Ca:Mg:Na are more similar to unity and increases in ion concentration are more linear than those observed in Gertrude Lake.

The acid anions (SO_4^{2-}, Cl^{-}, and NO_3^{-}; Figures 12-14) are relatively minor anions in these lakes. Sulfate concentrations in Gertrude Lake increase from a minimum of about 5 µeq/L in June to a maximum of about 11 µeq/L in July and decrease slightly in the fall. In contrast, sulfate values in Cedar Pond increase slightly during spring and show a larger increase in the fall. Chloride concentrations increase in Gertrude Lake by an average of about 2 µeq/L from spring to fall, although in 1993 and 1996 no significant increase in chloride was observed. Typical seasonal increases in chloride for Cedar Pond were generally about 2 to 3 µeq/L, although in 1995 and 1997 chloride increased by over 5 µeq/L from September to October. Nitrate in both lakes was generally

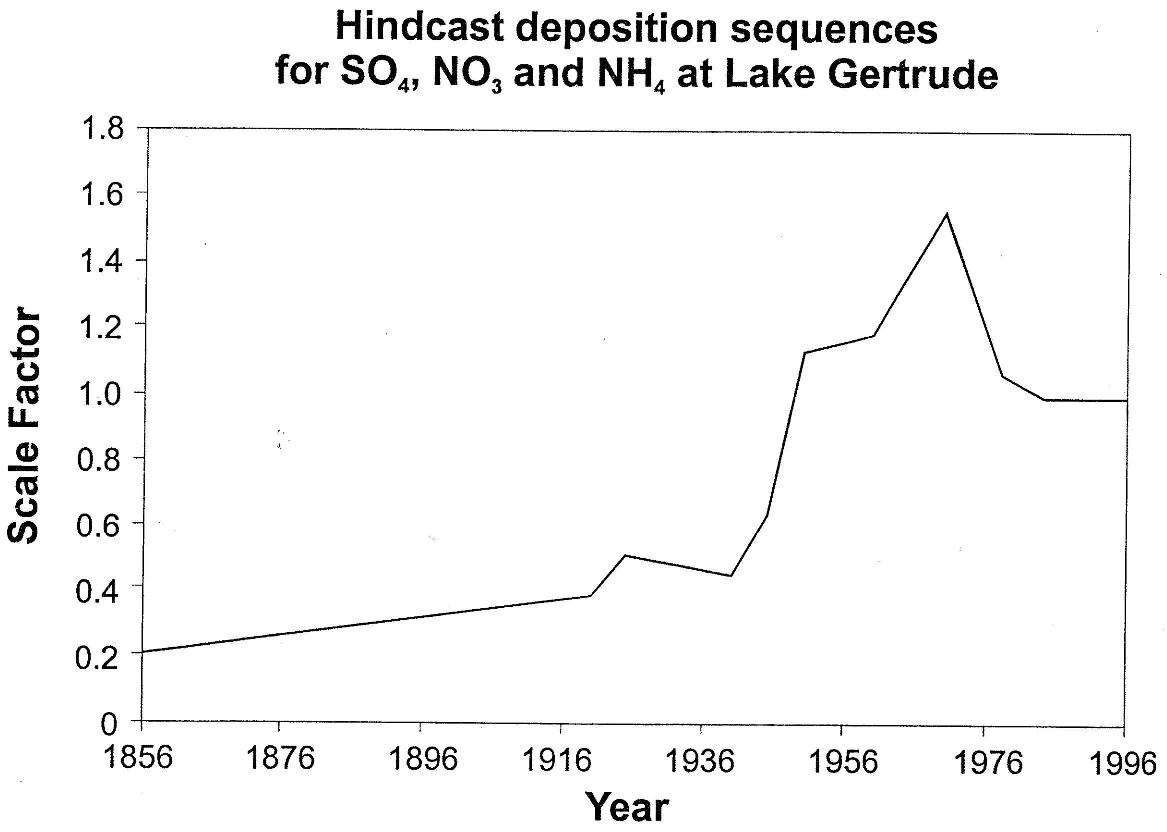


Figure 5. Hindcast deposition scenario applied in the MAGIC model calibration of Gertrude Lake. The figure presents the sequences of sulfate, nitrate, and ammonium deposition for the period 1856-1996 in which previous deposition (1856-1995) is presented as a ratio of current (1996) deposition.

Table 11. Water chemistry results for Gertrude Lake and Cedar Pond. Duplicate samples have been averaged.

LOCATION	DATE	pH	COND	Ca	Mg	Na	K	NH_4	ANC	SO_4	Cl	NO_3	TKN	Si	TP	Al	Fe
Cedar Pond	05-Aug-93	6.63	6.4	18.0	13.2	27.8	3.1	0.0	45.0	11.0	5.9	0.0					
Cedar Pond	29-Aug-93	6.60	6.9	36.0	19.1	31.0	3.0	0.1	38.1	12.3	5.1	0.2		3.7			
Cedar Pond	28-Sep-93	6.52	9.1	27.9	17.3	27.0	4.1	0.0	67.0	14.0	5.9	0.0			0.0		0.2
Cedar Pond	19-Oct-93	6.67	8.9	29.9	18.9	29.1	4.1	0.0	58.0	16.0	7.1	0.0			0.0		0.2
Cedar Pond	03-Jun-94	6.42	6.7	17.7	9.2	14.2	1.2	0.7	21.3	9.8	5.3	0.6			0.0		0.1
Cedar Pond	08-Jul-94	5.80	7.4	22.4	14.1	20.0	2.7	0.7	46.5	9.2	6.3	0.6			0.0		0.1
Cedar Pond	15-Aug-94	6.01	9.0	25.1	16.0	24.8	3.9	5.7	39.8	11.0	6.5	0.6			0.0		0.2
Cedar Pond	12-Sep-94	6.35	10.4	28.1	18.3	28.8	4.7	0.7	61.7	13.2	6.9	0.6			0.0		0.3
Cedar Pond	10-Oct-94	6.00	10.4	30.9	20.2	30.8	4.9	0.0	63.3	17.1	8.1	0.7			0.0		0.3
Cedar Pond	15-Jun-95	6.05	5.3	19.5	9.7	13.8	1.4	0.7	21.9	7.6	4.2	0.6	45.4	3.2	0.0	11.3	0.2
Cedar Pond	10-Jul-95	6.40	6.3	25.2	13.6	16.4	2.4	0.7	44.6	8.7	4.8	0.6	37.1	6.8	0.0	37.5	0.1
Cedar Pond	23-Aug-95	6.56	7.7	22.1	14.2	24.1	3.7	1.4	57.4	8.9	7.3	0.6	89.1	4.1	0.0	32.9	0.2
Cedar Pond	19-Sep-95	6.64	8.4	25.6	16.3	23.8	3.6	0.7	47.4	9.3	5.8	0.6	118.0	3.5	0.0	66.0	0.2
Cedar Pond	25-Oct-95	6.49	9.3	28.5	16.4	22.3	3.8	0.8	50.1	11.6	14.4	0.6	54.9	4.3	0.0	17.7	0.2
Cedar Pond	04-Jun-96	5.97	3.3	8.0	4.3	6.2	0.7	1.4	13.1	3.8	3.0	0.6	17.3	0.8	0.0	7.1	0.2
Cedar Pond	28-Jun-96	6.50	6.1	22.6	12.5	14.8	1.8	0.7	39.5	7.5	3.3	0.6	27.4	2.6	0.0	18.2	0.1
Cedar Pond	13-Aug-96	6.60	7.8	25.9	16.8	23.1	3.6	0.9	59.1	6.6	5.0	0.6	65.6	5.0	0.0	66.8	0.1
Cedar Pond	22-Sep-96	6.82	8.7	28.0	20.1	23.0	3.8	1.0	57.8	7.4	6.0	0.6	91.4	3.1	0.0	83.8	0.2
Cedar Pond	02-Jul-97	6.59	6.4	24.9	13.2	15.1	2.6	1.2	39.4	6.3	4.6	0.6	31.0	3.3	0.0	42.7	0.5
Cedar Pond	20-Jul-97	6.56	7.1	20.2	9.0	13.2	0.8	0.7	42.5	6.8	4.1	0.6	33.7	3.6	0.0	36.5	0.5
Cedar Pond	04-Aug-97	6.54	7.8	28.9	16.5	22.0	3.6	0.4	41.1	7.0	4.5	0.9	43.6	4.1	0.0	67.5	0.5
Cedar Pond	09-Sep-97	6.76	9.3	33.6	19.7	24.0	4.7	1.6	67.4	6.2	5.0	1.4	98.3	4.2	0.0	137.0	0.5
Cedar Pond	09-Oct-97	6.43	8.3	36.6	21.0	25.2	4.2	2.2	45.6	8.9	13.5	0.3	65.3	5.5	0.0	43.5	0.5
Cedar Inlet	15-Jun-95	6.41	6.1	21.6	10.9	15.1	1.7	0.7	25.5	8.5	6.1	0.6	33.7	3.3	0.0	9.0	0.1
Cedar Inlet	10-Jul-95	6.23	7.5	31.1	16.2	18.2	2.5	0.7	49.2	8.9	4.9	0.6	34.0	7.2	0.0	24.6	0.1
Cedar Inlet	04-Jun-96	6.20	5.2	19.9	10.2	11.7	1.4	0.7	29.9	6.0	3.4	0.6	30.2	2.5	0.0	9.5	0.1
Cedar Inlet	28-Jun-96	6.30	6.7	27.2	15.5	18.6	1.6	0.4	49.2	7.7	3.6	0.3	28.0	2.8	0.0	24.1	0.1
Cedar Inlet	20-Jul-97	6.47	6.9	28.1	15.3	18.3	2.8	0.5	44.2	6.9	4.1	0.4	46.8	4.0	0.0	36.7	0.5
Cedar Inlet	06-Aug-97	6.79	9.6	34.8	18.9	23.2	4.0	0.7	64.3	7.2	5.4	0.6	24.4	4.7	0.0	65.0	0.5
Cedar Inlet	09-Oct-97	6.28	8.2	34.3	21.2	26.4	4.3	4.0	63.9	8.5	11.1	0.0					
Gertrude Lake	05-Aug-93	6.88	8.9	42.0	26.3	31.0	5.7	0.0	75.2	13.8	6.1	0.0		3.6			
Gertrude Lake	29-Aug-93	6.49	9.9	36.6	23.4	29.6	6.2	0.0	68.2	14.0	7.6	0.0		3.3	0.0		0.2
Gertrude Lake	28-Sep-93	6.87	11.0	41.9	27.1	29.1	5.9	0.0	77.0	14.0	7.1	0.0			0.0		0.2
Gertrude Lake	19-Oct-93	6.80	12.0	41.9	26.3	33.9	7.9	0.0	91.0	14.0	9.0	0.0			0.0		0.2
Gertrude Lake	03-Jun-94	6.09	8.4	24.1	13.1	17.0	4.1	1.6	37.2	8.4	8.7	0.6			0.0		0.2
Gertrude Lake	08-Jul-94	6.02	9.3	31.9	20.0	20.6	4.4	0.7	65.6	10.9	6.0	0.6			0.0		0.2

Table 11. Continued.

LOCATION	DATE	pH	COND	Ca	Mg	Na	K	NH_4	ANC	SO_4	Cl	NO_3	TKN	Si	TP	Al	Fe
Gertrude Lake	15-Aug-94	6.10	10.7	32.6	21.8	23.3	5.0	6.1	63.6	11.9	7.6	0.6			0.0		0.2
Gertrude Lake	12-Sep-94	6.05	10.9	36.3	24.6	24.7	4.3	0.7	81.1	11.3	6.8	0.6			0.0		0.3
Gertrude Lake	10-Oct-94	5.74	11.7	40.9	26.3	26.6	5.3	0.7	86.4	11.9	8.3	0.6			0.0		0.3
Gertrude Lake	15-Jun-95	5.89	4.1	12.1	6.6	7.1	1.7	0.7	9.8	4.0	3.3	0.6	8.7	1.5	0.0	10.7	0.2
Gertrude Lake	10-Jul-95	6.82	8.7	36.9	20.2	19.2	3.9	0.7	63.2	10.5	5.1	0.6	5.0	7.0	0.0	106.0	0.1
Gertrude Lake	23-Aug-95	6.58	10.6	38.5	23.8	25.8	5.4	0.7	86.3	12.2	6.7	0.6	10.0	4.3	0.0	10.0	0.1
Gertrude Lake	19-Sep-95	6.94	11.8	39.3	24.9	26.7	5.6	0.7	78.6	11.1	6.3	0.6	10.0	4.3	0.0	10.0	0.3
Gertrude Lake	25-Oct-95	6.98	10.9	37.6	23.5	24.7	5.1	1.1	89.9	10.3	6.7	0.6	10.0	3.7	0.0	10.0	0.1
Gertrude Lake	04-Jun-96	6.12	5.2	16.9	9.2	12.3	2.0	0.8	26.4	5.8	5.9	1.2	5.0	1.6	0.0	8.8	0.1
Gertrude Lake	28-Jun-96	6.54	11.2	45.6	27.1	23.8	4.8	0.7	102.0	9.4	5.7	0.6	5.0	4.0	0.0	38.8	0.1
Gertrude Lake	13-Aug-96	7.08	10.3	38.0	23.8	25.4	4.8	0.7	82.1	10.6	5.4	0.6	8.2	5.5	0.0	23.2	0.1
Gertrude Lake	22-Sep-96	7.01	11.6	41.7	28.8	26.2	5.2	0.7	82.9	10.0	5.9	0.6	5.4	4.2	0.0	7.3	0.1
Gertrude Lake	26-Oct-96	6.76	11.2	39.8	26.7	26.3	5.3	2.3	88.6	10.0	6.3	0.6	5.0	2.6	0.0	5.0	0.1
Gertrude Lake	19-Jul-97	6.80	8.6	31.4	17.2	18.5	3.5	0.7	53.3	9.3	4.3	0.6	20.0	4.1	0.0	47.5	0.5
Gertrude Lake	04-Aug-97	6.46	6.8	23.0	13.9	17.6	3.1	0.2	40.5	7.5	3.3	0.7	20.0	4.6	0.0	37.9	0.5
Gertrude Lake	09-Sep-97	6.84	9.7	38.1	23.5	27.9	5.4	0.4	79.4	9.9	5.3	0.9	19.4	5.4	0.0	10.7	0.5
Gertrude Lake	09-Oct-97	6.91	9.8	35.7	21.2	25.8	4.2	2.7	77.2	9.6	7.2	0.3	10.0	5.3	0.0	10.0	0.5
Gertrude S. Inlet	10-Jul-95	5.71	2.8	7.0	4.4	4.2	1.0	0.7	5.4	2.5	2.8	0.6	20.3	1.7	0.0	24.2	0.1
Gertrude S. Inlet	28-Jun-96	5.84	2.8	5.8	3.4	3.8	0.9	0.7	6.9	1.6	1.6	0.6	12.4	0.7	0.0	15.9	0.3
Gertrude S. Inlet	19-Jul-97	6.05	3.0	6.1	4.0	4.3	1.4	1.1	5.4	1.5	2.5	0.6	29.9	0.6	0.0	31.3	0.5
Gertrude W. Inlet	07-Jul-94	5.96	4.4	12.9	5.4	10.9	0.8	0.7	20.7	8.1	4.1	0.6			0.0		0.1
Gertrude W. Inlet	10-Jul-95	6.43	3.8	13.3	5.3	8.9	0.5	0.7	11.3	8.1	2.8	0.6	5.0	4.7	0.0	5.0	0.1
Gertrude W. Inlet	13-Aug-96	6.68	21.9	91.5	66.1	53.5	10.5	0.7	261.0	11.1	9.2	0.6	12.8	13.7	0.0	62.6	0.2
Gertrude W. Inlet	22-Sep-96	6.79	24.2	100.0	77.4	50.4	13.1	0.7	215.0	9.7	14.4	0.6	15.9	5.7	0.1	61.3	0.4
Gertrude W. Inlet	06-Aug-97	6.93	11.7	48.5	17.1	25.8	5.2	0.7	74.7	13.0	5.4	2.0	20.0	7.0	0.0	5.0	0.5
Gertrude N. Inlet	15-Jun-95	6.18	14.7	69.4	47.2	34.6	7.6	0.7	131.0	11.6	7.5	0.6	20.0	9.5	0.0	51.6	0.2
Gertrude N. Inlet	10-Jul-95	6.54	13.5	55.8	36.7	33.2	6.6	0.7	112.0	12.1	6.1	0.6	19.7	15.7	0.0	47.4	0.1
Gertrude N. Inlet	28-Jun-96	6.43	11.0	50.4	32.4	29.0	5.2	0.9	101.4	10.1	5.5	0.3	12.2	6.1	0.0	28.4	0.1
Gertrude N. Inlet	02-Jul-97	6.34	11.7	48.3	32.1	27.8	6.7	0.7	91.8	8.0	5.9	0.6	22.3	8.2	0.0	41.0	0.5
Gertrude N. Inlet	19-Jul-97	6.67	16.6	62.1	42.2	36.6	7.5	0.7	136.0	10.5	5.9	0.6	30.6	11.0	0.0	49.6	0.5
Gertrude N. Inlet	06-Aug-97	6.73	25.0	97.8	73.7	51.2	9.7	0.7	205.0	13.1	10.0	0.6	20.8	15.5	0.0	77.5	0.5
Gertrude N. Inlet	09-Sep-97	6.95	30.2	117.8	95.8	62.1	14.1	0.7	262.0	10.7	10.5	0.6	15.3	17.2	0.0	33.9	0.5
Gertrude Outlet	03-Jun-94	5.94	8.6	28.8	15.4	16.1	2.9	0.7	45.1	10.6	5.9	0.6			0.0		0.1
Gertrude Outlet	04-Jun-96	6.00	6.8	26.6	15.2	15.1	2.9	0.7	44.8	7.5	5.4	1.1	16.3	2.6	0.0	14.6	0.1
Gertrude Outlet	02-Jul-97	6.74	8.2	33.6	17.9	18.7	5.1	0.7	54.0	8.1	6.0	0.6	15.9	4.1	0.0	91.7	0.5

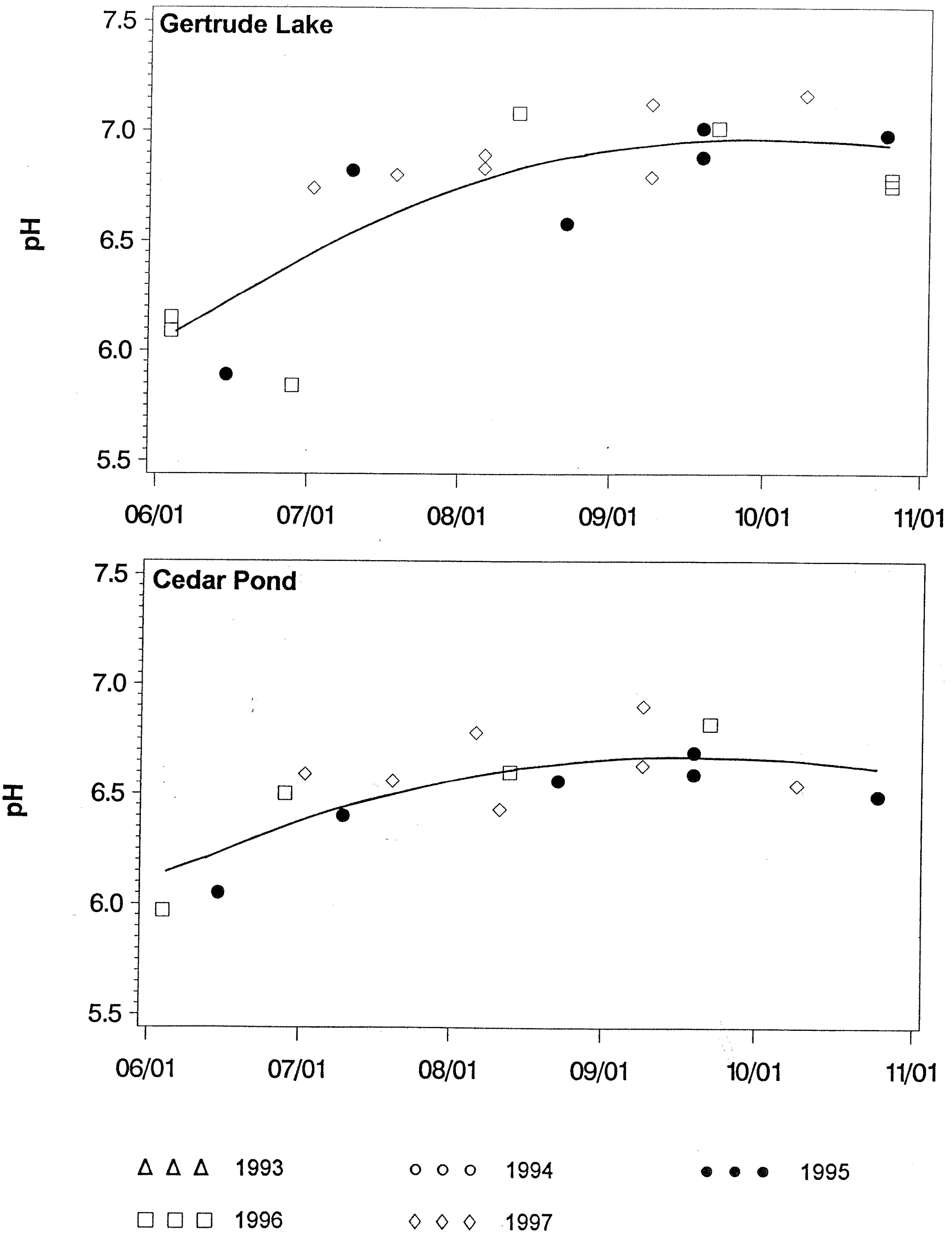


Figure 6. Lakewater pH for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline for the measured data.

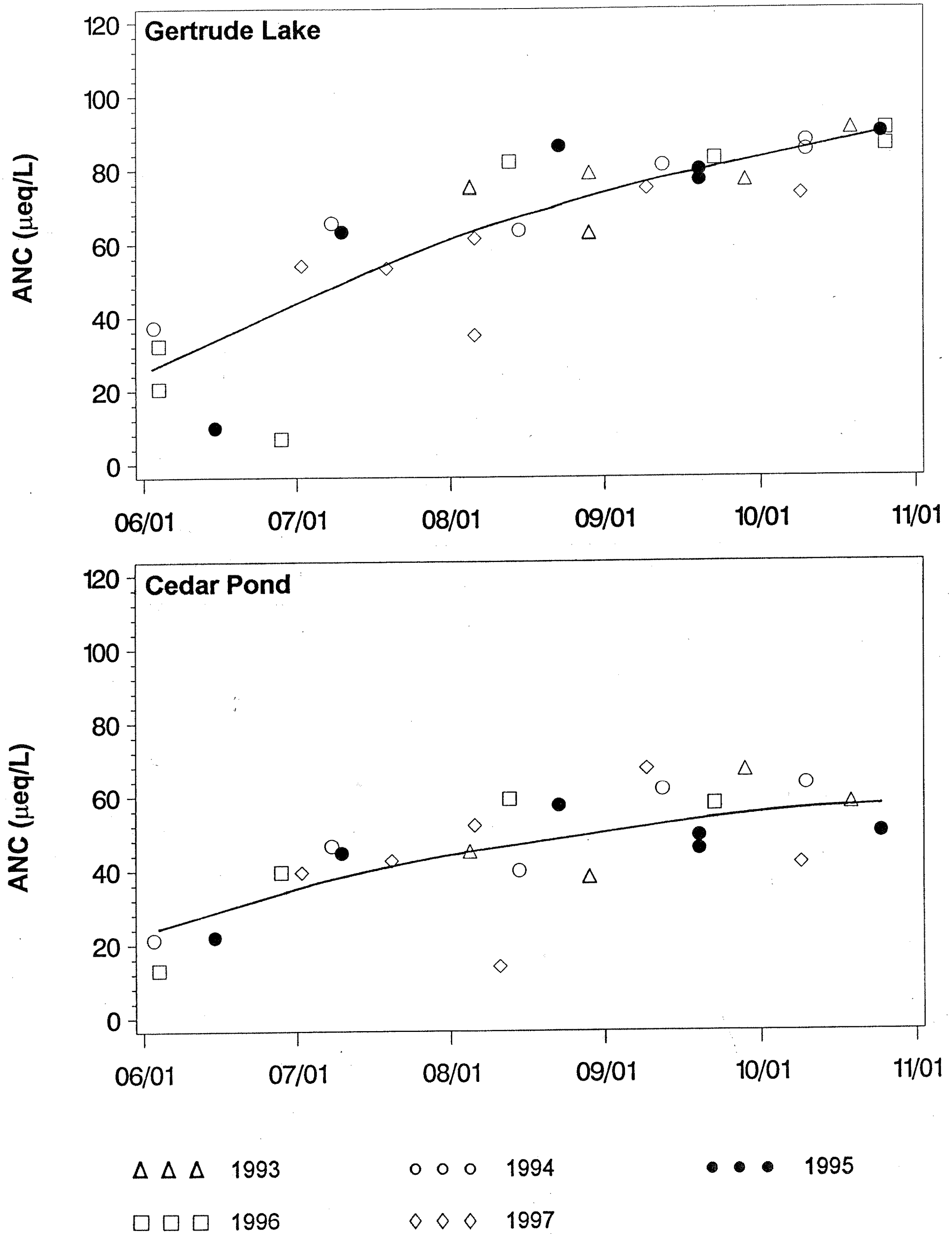


Figure 7. Lakewater acid neutralizing capacity (ANC; μeq/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline for the measured data.

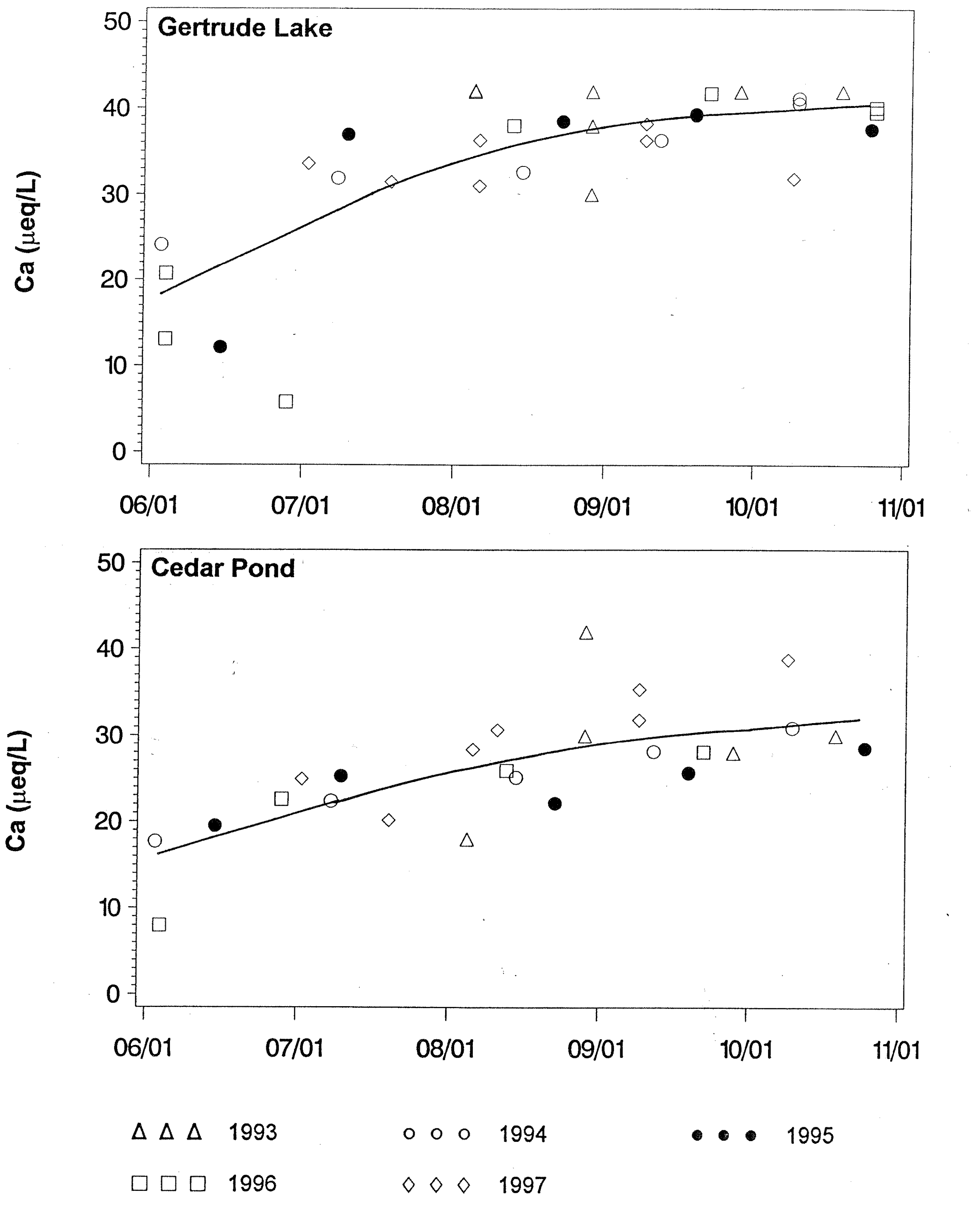


Figure 8. Lakewater calcium (Ca^{2+}, μeq/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

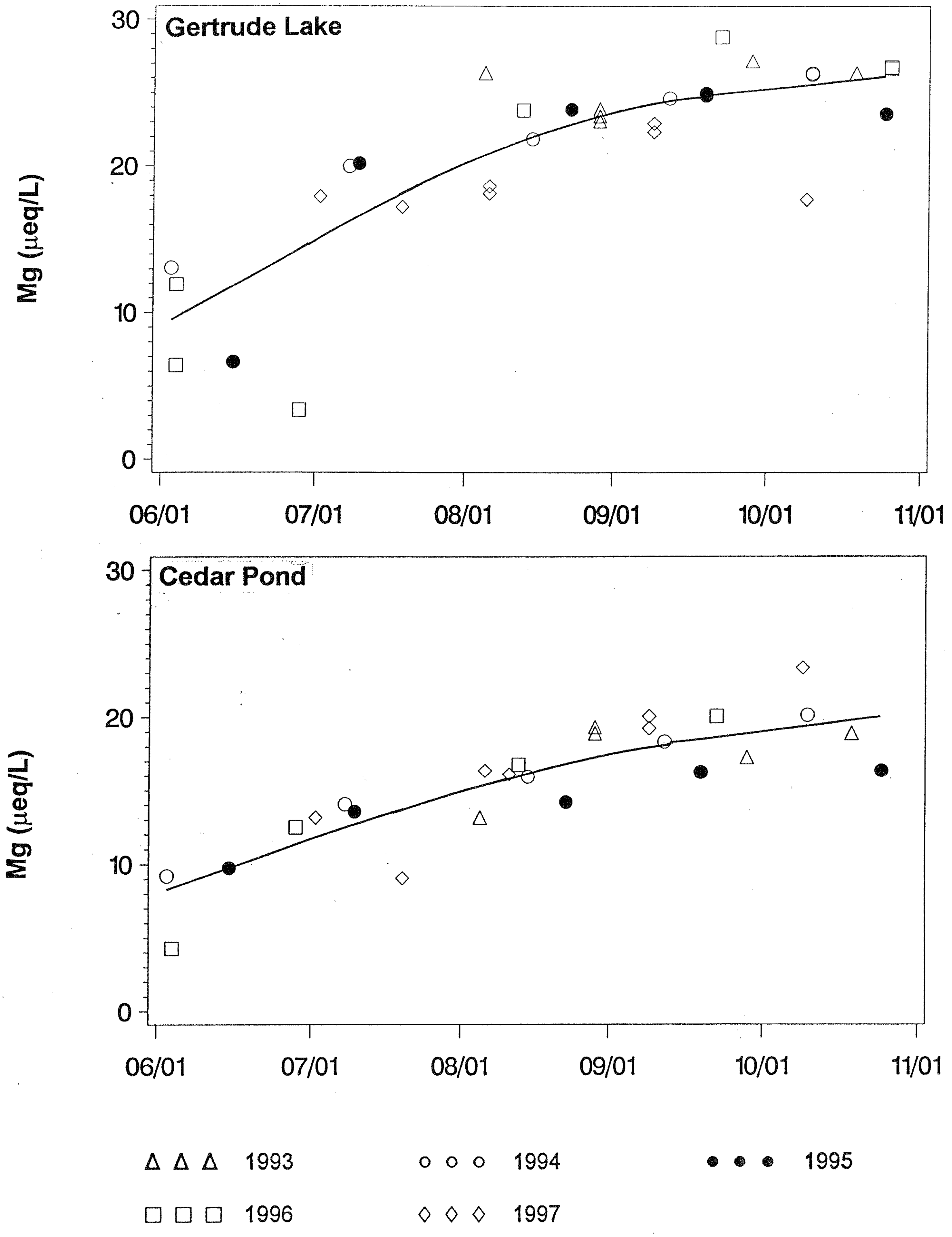


Figure 9. Lakewater magnesium (Mg^{2+}, µeq/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

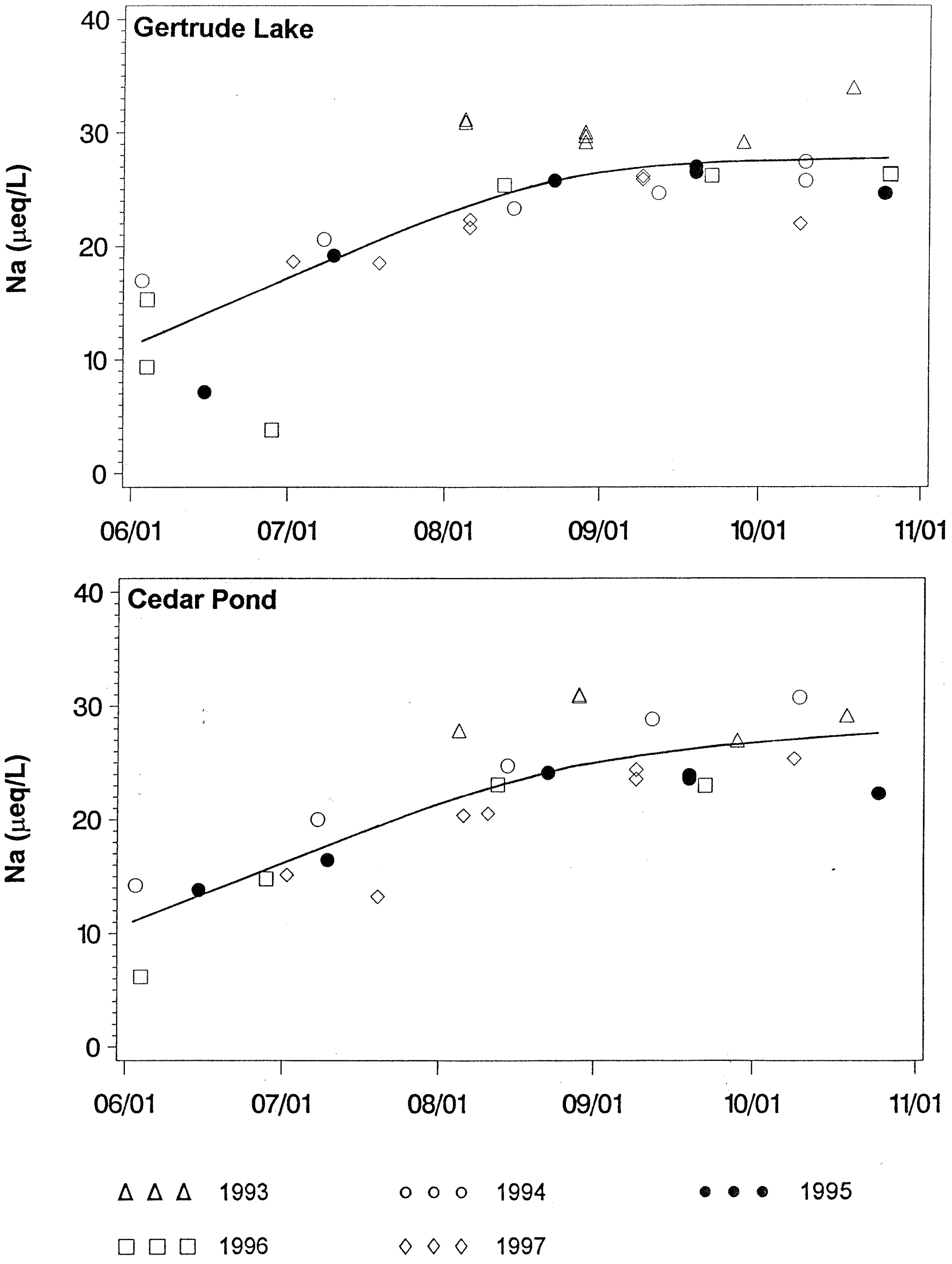


Figure 10. Lakewater sodium (Na^+, µeq/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

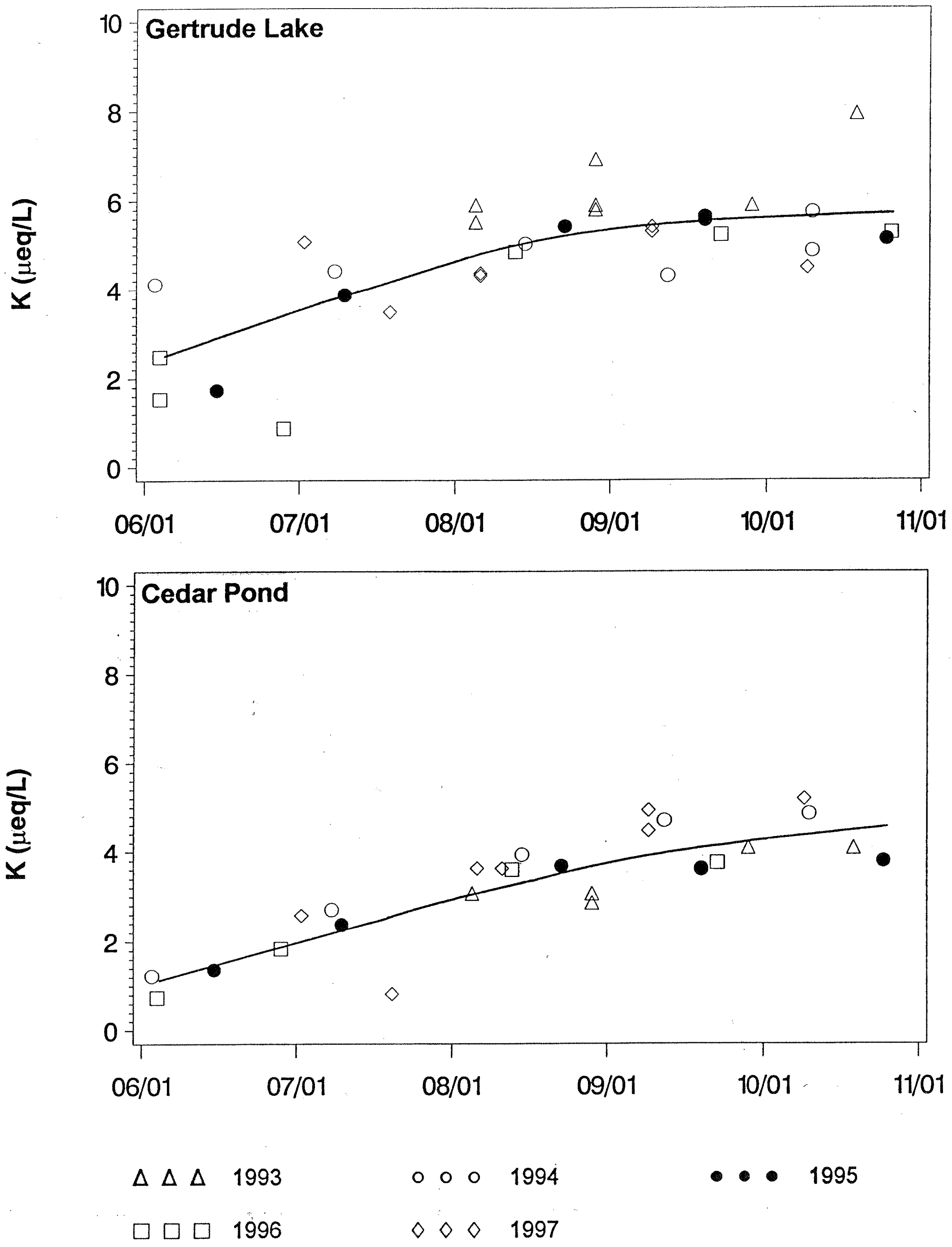


Figure 11. Lakewater potassium (K^+, µeq/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

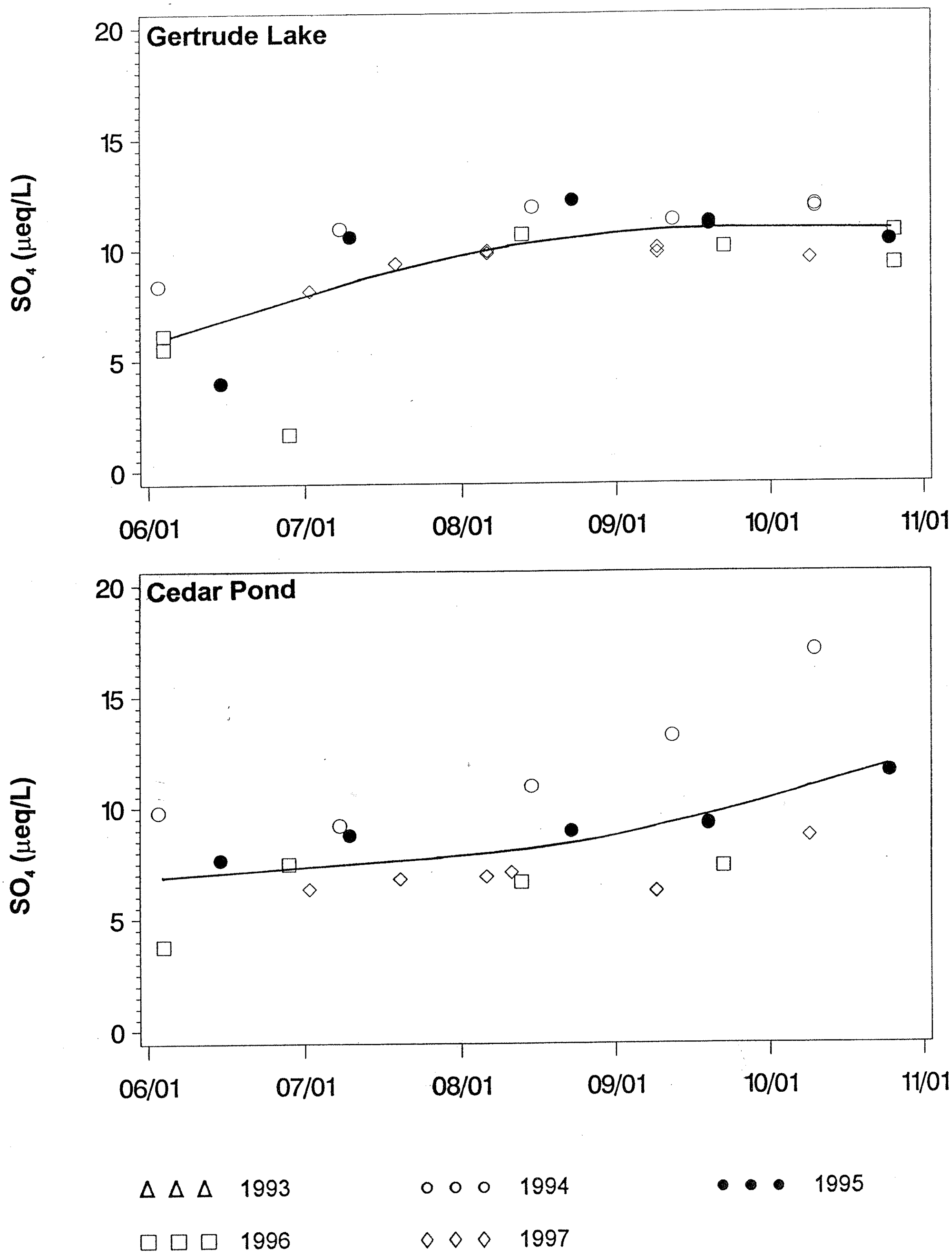


Figure 12. Lakewater sulfate (SO_4^{2-}, µeq/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

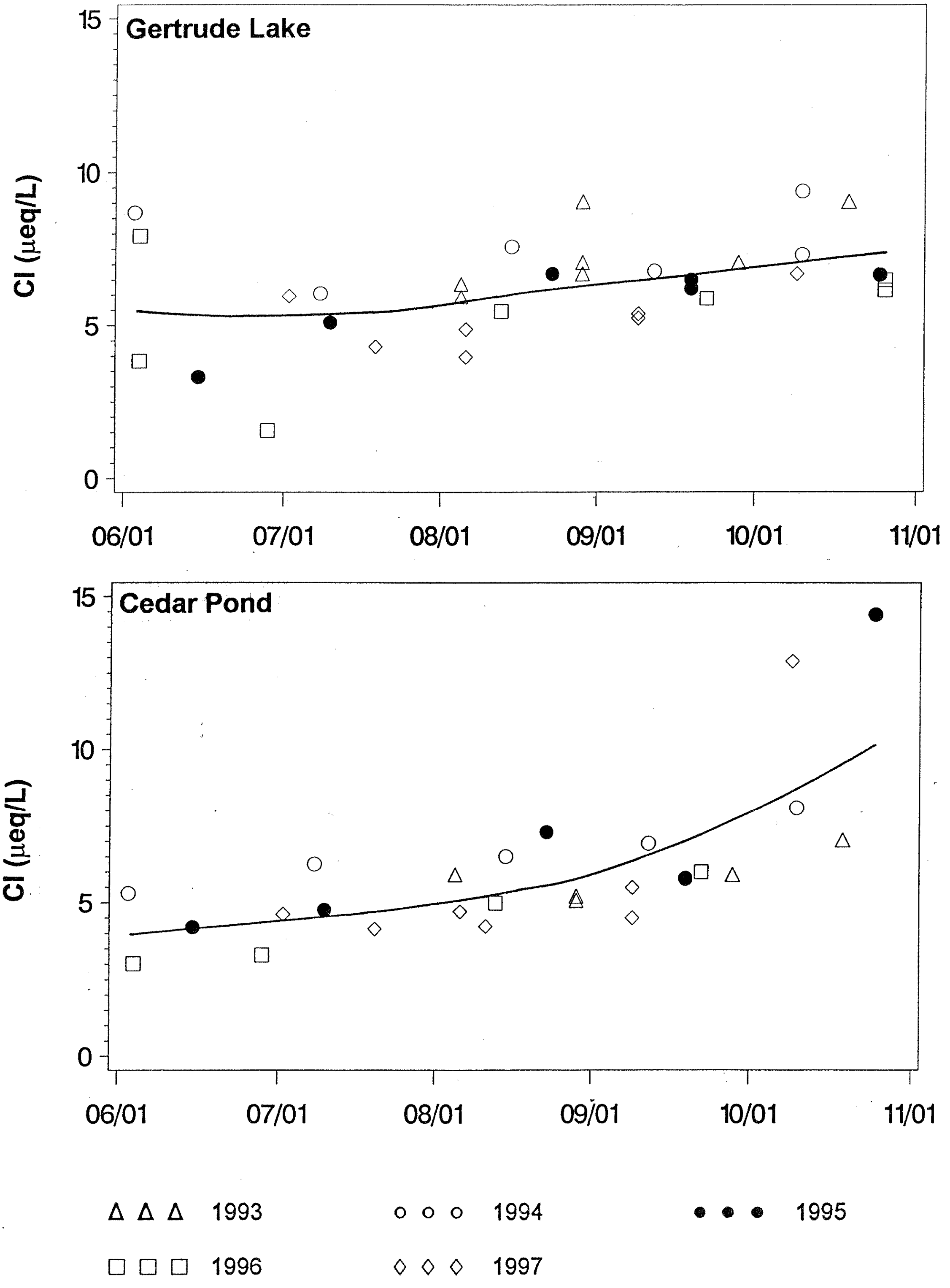


Figure 13. Lakewater chloride (Cl^-, µeq/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

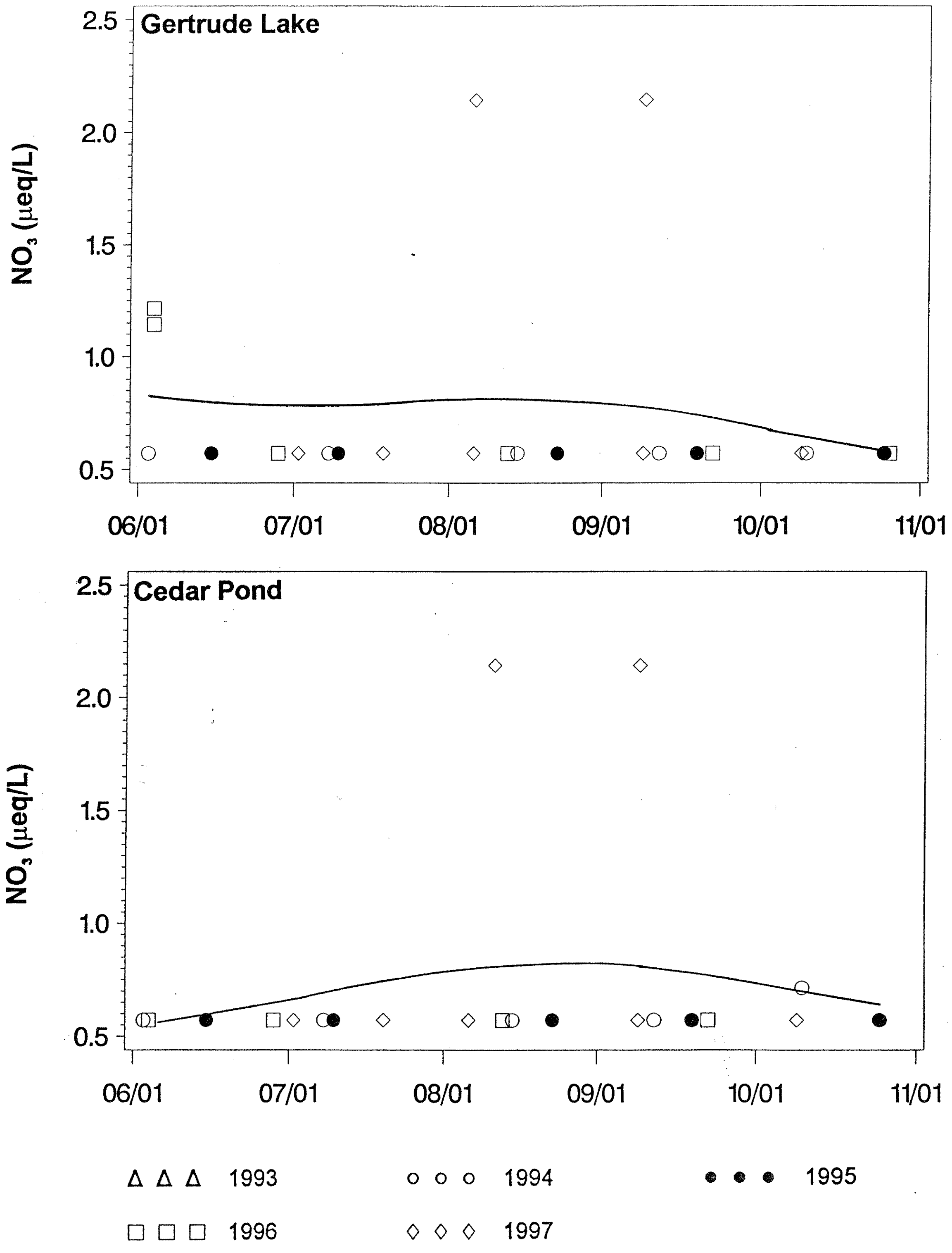


Figure 14. Lakewater nitrate (NO_3^-, μeq/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

undetectable. Specific conductance values reflect the ionic concentrations which showed a pronounced increase from spring to fall (Figure 15). As noted for the individual ions (especially ANC and Ca^{2+}), the conductivity increase from June to July is rapid in Gertrude Lake, yet is almost linear in Cedar Pond.

Total phosphorus concentrations showed no apparent seasonal pattern in Gertrude Lake, although one-half of the observations were measured above the reported detection limit of 10 µg/L (Figure 16). A larger proportion of the samples from Cedar Pond were below the detection limit. All six values measured above detection limit in Cedar Pond were recorded in the fall; five of the six were measured in September.

Nearly all of the ammonium values were measured at or near the detection limit (Figure 17). Ammonium concentrations near 6 µeq/L were measured in both lakes in August, 1994, but these extremes were never repeated and it is likely that these are errant values. Total Kjeldahl nitrogen (TKN) values were low in both lakes and varied between 0.1 and 0.3 mg/L (Figure 18). Both lakes experienced the higher concentrations in the fall and Cedar Pond displayed a distinct depression in TKN in July.

Iron concentrations increased from 10 µg/L in the spring to maximum values of near 100 µg/L in Gertrude Lake (Figure 19). These peak observations for Gertrude Lake occurred consistently in July. In Cedar Pond, the peak iron concentrations occurred in August and September and declined in October. Total aluminum concentrations increased imperceptibly in Gertrude Lake through the open water period (Figure 20). However, in Cedar Pond, aluminum concentrations increased dramatically through the summer, reaching a maximum in September and declining in October.

Silicon patterns are similar in both lakes (Figure 21). Silicon increased rapidly from June to July and either stabilized (Cedar Pond) or showed a slight decline (Gertrude).

Total organic carbon (TOC) was 1 mg/L in both lakes in spring and increased to about 2 mg/L by September in Gertrude Lake (Figure 22). In Cedar Pond, the increase in TOC began earlier and reached a maximum near 3 mg/L in September.

B. Snow Chemistry

Snow chemistry results for the four sites monitored during the entire study period (1994-1998) are summarized in Figure 23 for chloride, nitrate, hydrogen ion, base cations, and sulfate. Complete results for the composite snow samples are presented for all six sites in Table 12. Chloride is the dominant anion for all sites and all years except for 1995 at White Pass where one sulfate sample exceeded the chloride concentration. Nitrate and ammonium concentrations were low at all sites throughout the study, typically less than about 1 µeq/L.

Hydrogen on concentrations were typically near 4 µeq/L during the study except for 1994 when higher values were reported. A review of the pH values measured in 1994 suggested that the values

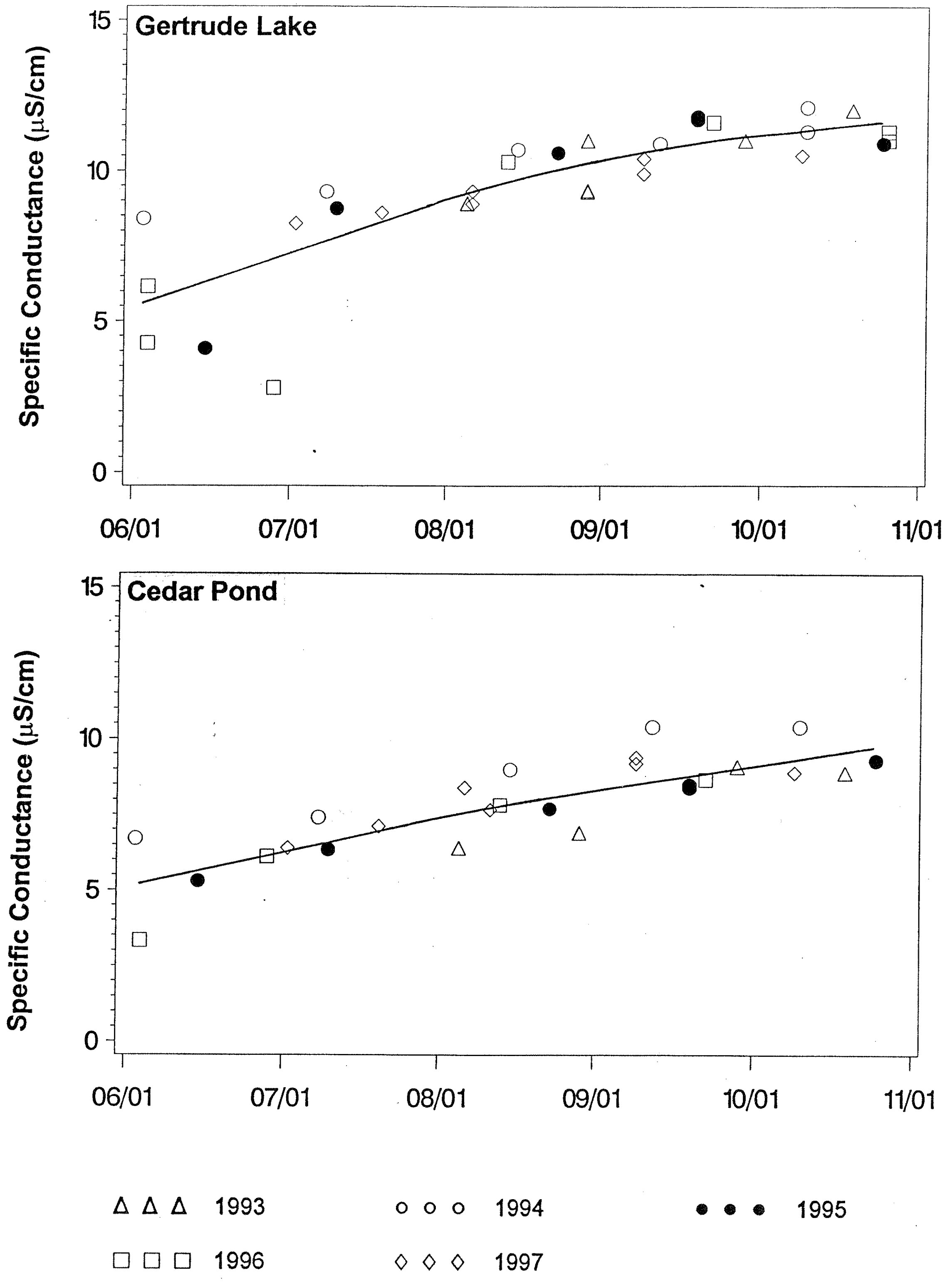


Figure 15. Lakewater specific conductance (sp. cond., μS/cm) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

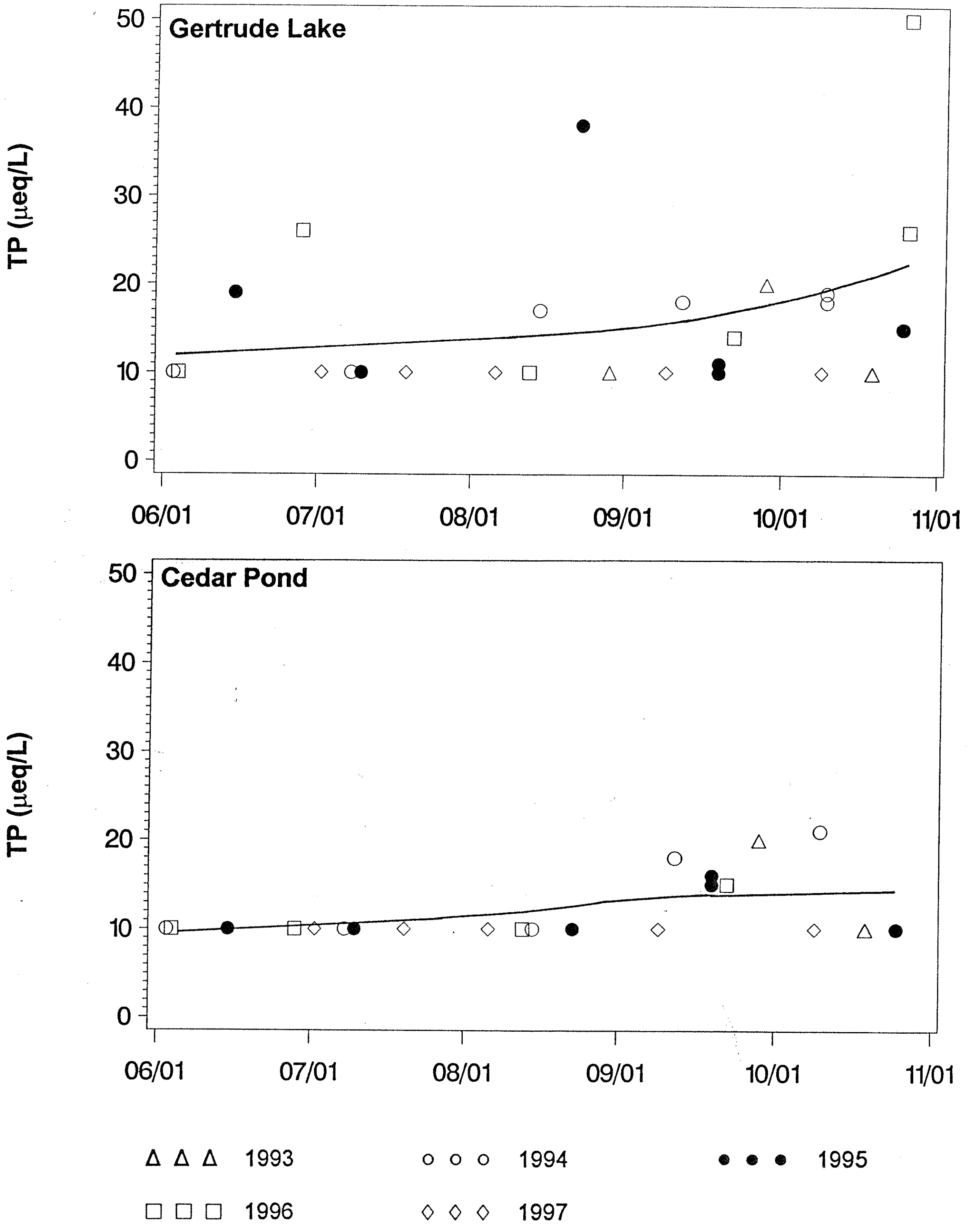


Figure 16. Lakewater total phosphorus (TP, µeq/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

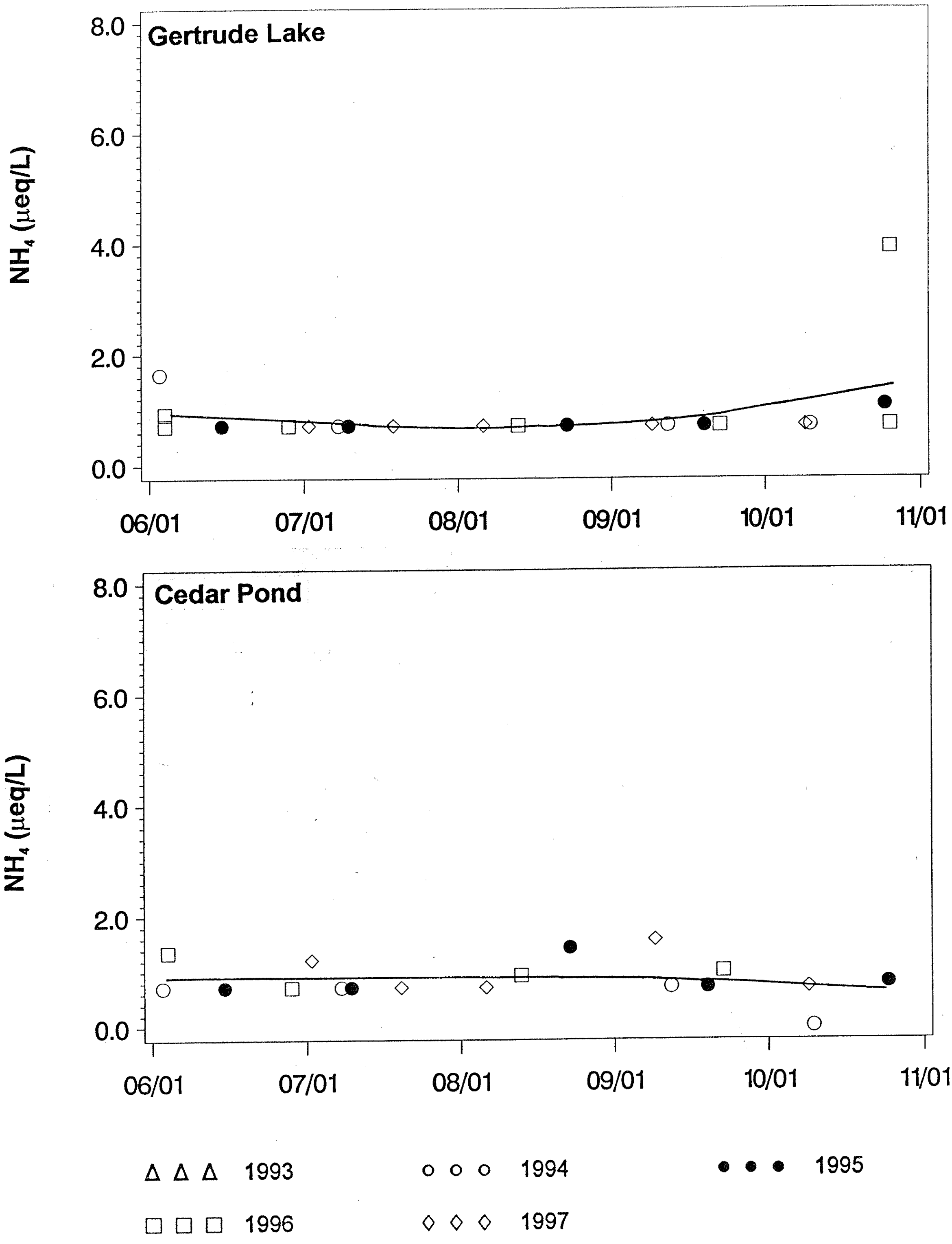


Figure 17. Lakewater ammonium (NH$_4^+$, μeq/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

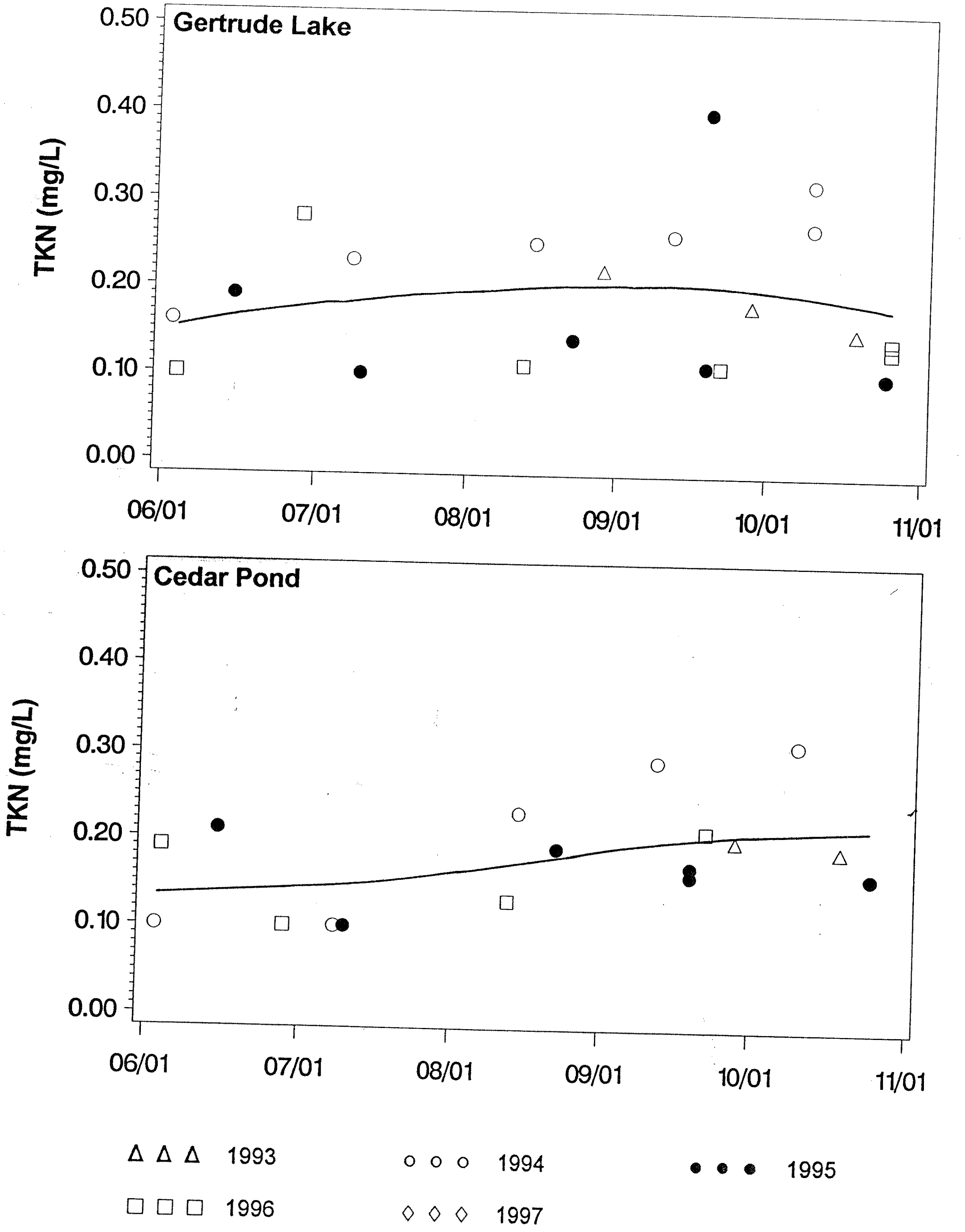


Figure 18. Lakewater total Kjeldahl nitrogen (TKN, mg/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

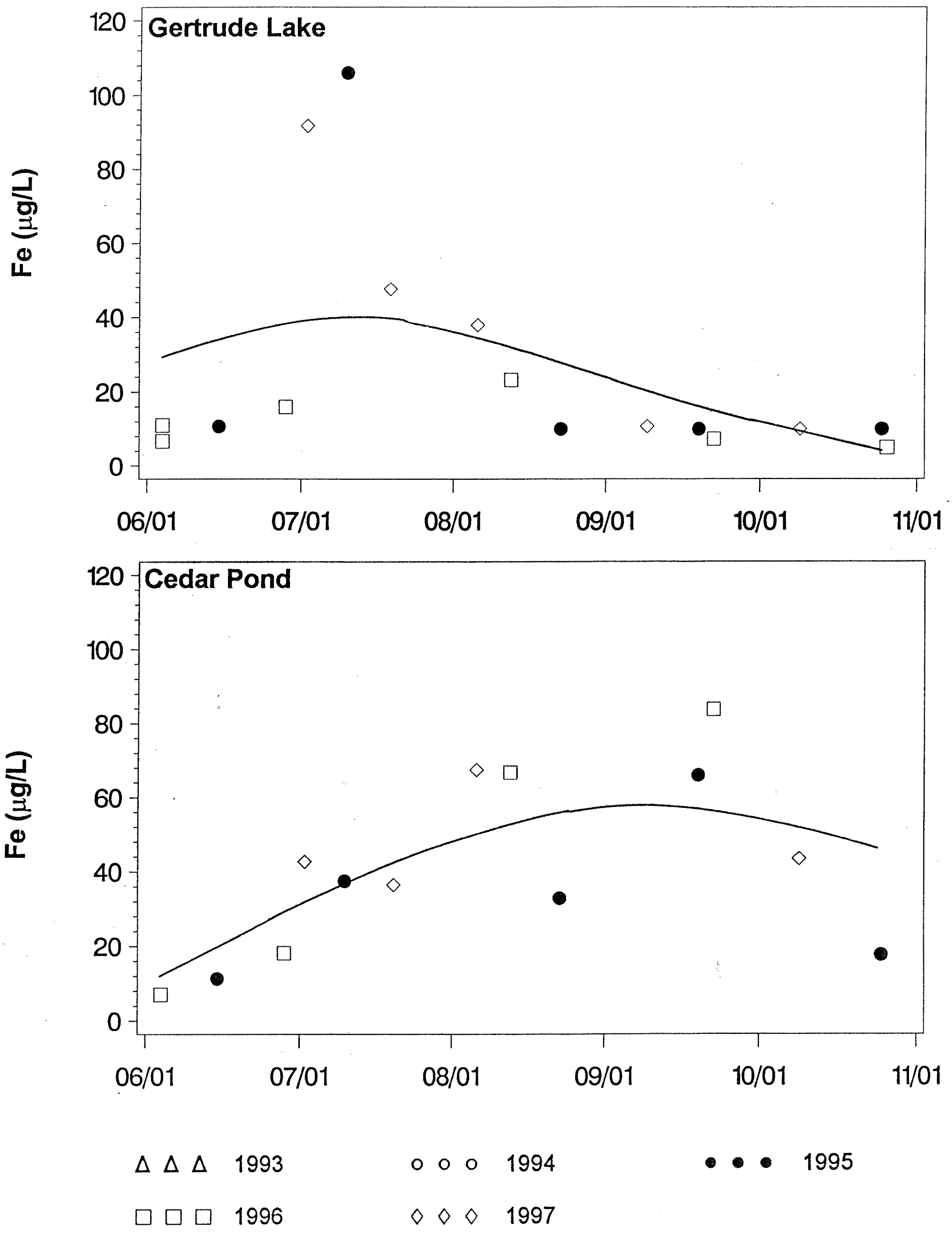


Figure 19. Lakewater total iron (Fe, µg/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

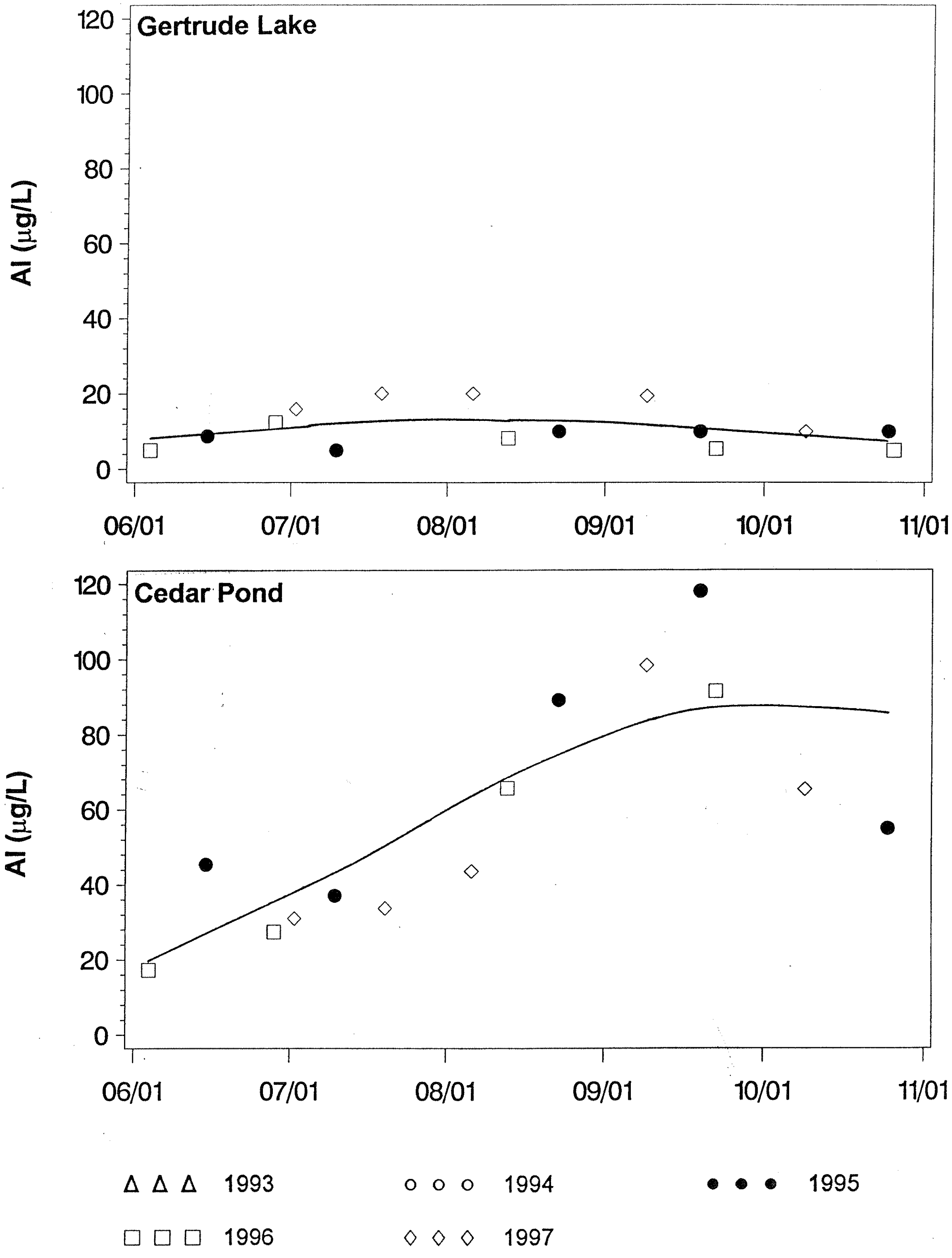


Figure 20. Lakewater total aluminum (Al, µg/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

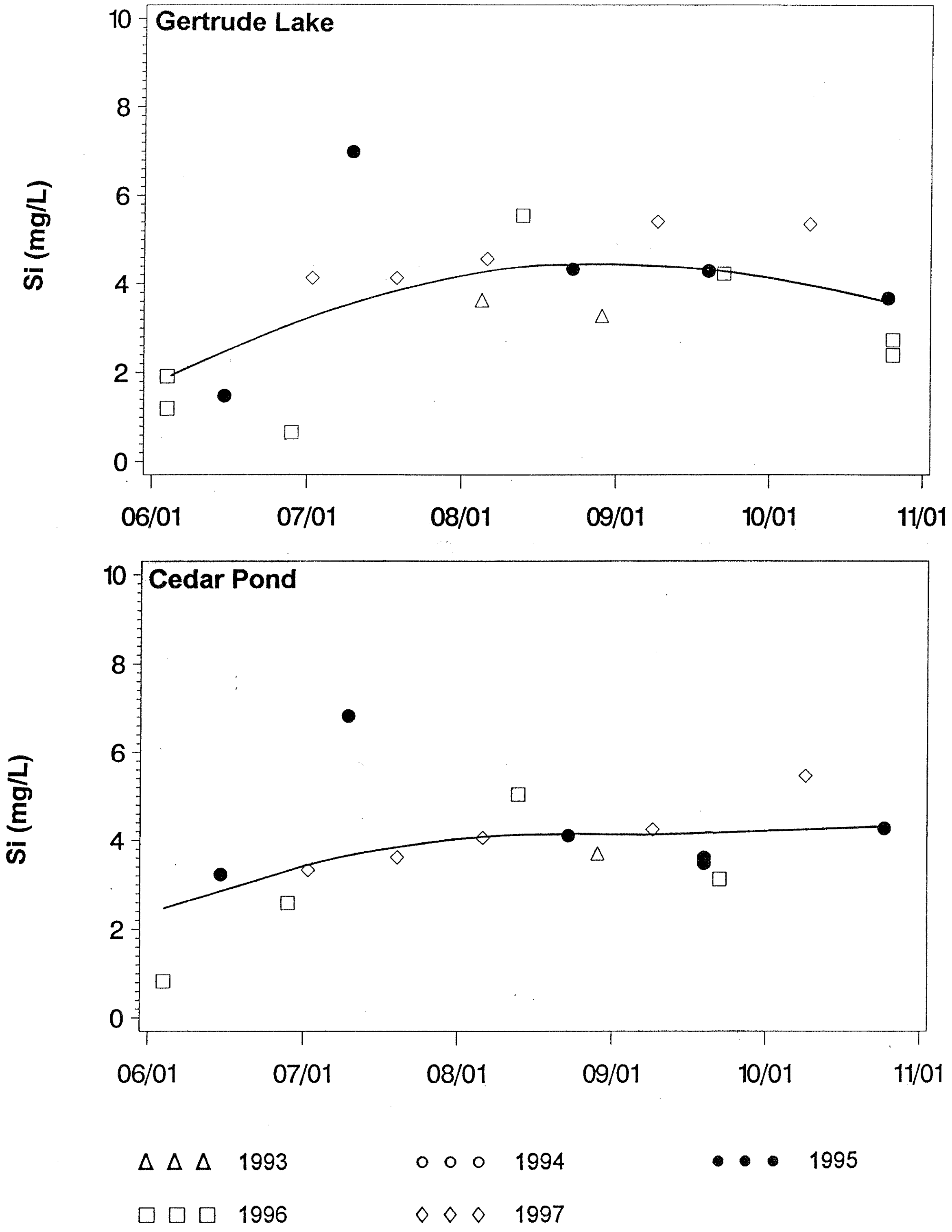


Figure 21. Lakewater silicon (Si, mg/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

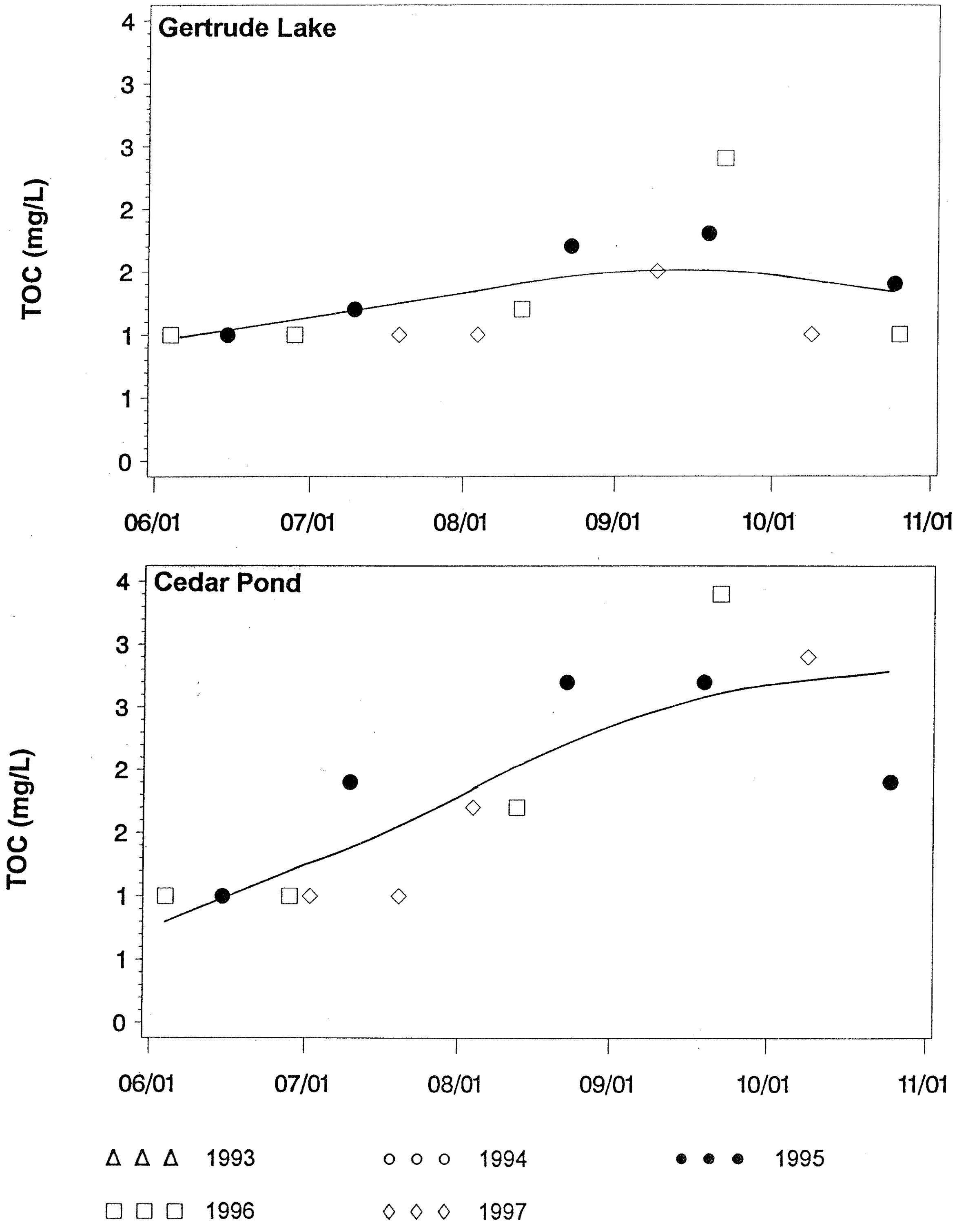


Figure 22. Lakewater total organic carbon (TOC, mg/L) for Gertrude Lake (top) and Cedar Pond (bottom) from 1993-1997 for June through October. The curve represents a cubic spline fit to the measured data.

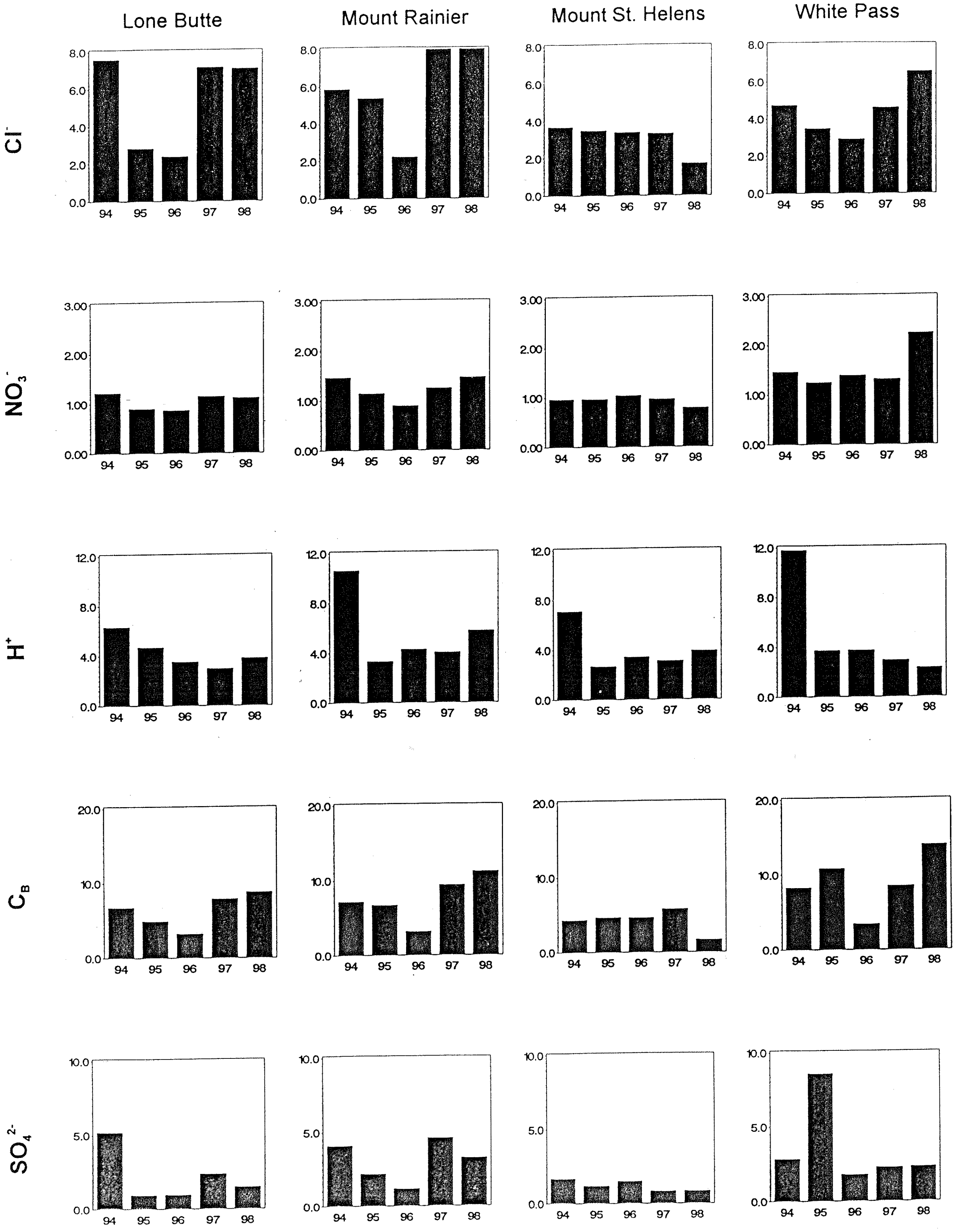


Figure 23. Concentration of chloride (Cl^-), nitrate (NO_3^-), hydrogen ion (H^+), sum of base cations (C_B), and sulfate (SO_4^{2-}) from the integrated snow samples from the four primary snow sample sites for 1994-1998. All units are in microequivalents per liter.

Table 12. Major ion chemistry for snow sample sites.

LOCATION*	TYPE**	DATE	pH	ANC	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	SO_4^{2-}	NO_3^-	Cl^-
LB	R	01-Apr-94	5.20	-0.8	1.5	1.2	3.6	0.4	0.8	5.2	1.2	7.6
SH	D	02-Apr-94	5.08	-3.4	0.5	0.7	1.6	0.2	1.2	1.6	0.9	3.2
SH	R	02-Apr-94	5.23	-3.7	1.0	0.8	3.0	0.7	1.3	1.8	1.1	4.2
WP	D	03-Apr-94	5.18	3.8	2.5	1.4	6.0	1.3	0.7	2.9	1.6	6.0
WP	R	03-Apr-94	4.77	28.1	1.3	1.0	2.5	0.5	0.6	2.9	1.3	3.5
CS	R	04-Apr-94	5.19	1.1	2.5	2.1	7.5	1.4	1.1	2.5	1.6	9.3
GB	D	05-Apr-94	5.06	2.2	0.8	0.8	2.1	0.5	0.6	1.5	1.1	2.7
GB	R	05-Apr-94	5.12	0.3	0.6	1.0	1.5	0.2	1.5	1.7	1.1	2.4
MR	D	06-Apr-94	5.00	-4.6	0.7	1.3	4.2	0.3	0.6	3.5	1.4	5.8
MR	R	06-Apr-94	4.95	-2.6	1.4	1.3	4.5	0.6	0.6	4.6	1.6	6.0
GB	D	28-Feb-95	5.00	0.9	1.4	3.1	12.7	0.6	1.8	3.7	1.6	17.0
GB	R	28-Feb-95	5.06	-2.8	1.3	3.0	12.1	0.5	1.7	3.4	1.7	15.7
LB	D	28-Feb-95	5.32	-4.5	0.9	0.7	2.9	0.4	1.2	1.0	0.9	2.9
LB	R	28-Feb-95	5.34	-4.6	1.1	0.7	2.7	0.2	1.4	0.9	0.9	2.7
CS	D	25-Mar-95	5.43	-9.7	0.6	0.7	6.0	0.3	0.6	6.2	1.1	3.0
CS	R	25-Mar-95	5.46	-13.6	0.7	0.7	6.7	0.4	0.6	6.5	1.1	4.0
WP	D	25-Mar-95	5.42	-12.3	1.1	0.9	8.7	0.4	0.6	8.0	1.2	3.7
WP	R	25-Mar-95	5.44	-11.1	1.0	0.9	8.2	0.5	0.6	9.2	1.3	3.3
MR	D	03-Apr-95	5.48	-10.3	0.9	1.2	4.4	0.3	0.6	2.2	1.2	5.2
MR	R	03-Apr-95	5.48	-11.1	0.8	1.2	4.3	0.2	0.6	2.2	1.1	5.5
SH	D	03-Apr-95	5.62	-6.9	0.6	0.7	3.0	0.2	0.6	1.3	0.9	3.3
SH	R	03-Apr-95	5.54	-9.7	0.7	0.7	3.1	0.2	0.6	1.1	1.0	3.6
LB	D	11-Mar-96	5.45	-11.4	0.5	0.7	2.0	0.2	0.6	1.1	0.9	2.5
LB	R	11-Mar-96	5.46	-10.3	0.4	0.7	1.8	0.2	0.6	0.8	0.8	2.2
WP	B	11-Mar-96	5.41	-10.4	0.4	0.7	1.8	0.3	0.6	1.2	1.1	2.2
WP	D	11-Mar-96	5.41	-11.9	0.4	0.8	2.4	0.3	0.6	2.1	1.4	3.2
WP	M	11-Mar-96	5.31	-8.3	0.4	0.7	1.7	0.1	0.6	2.1	1.4	2.2
WP	R	11-Mar-96	5.44	-4.5	0.2	0.6	2.0	0.3	0.6	1.5	1.4	2.6
WP	T	11-Mar-96	5.29	-9.5	1.3	1.4	3.8	0.4	0.6	3.9	1.9	4.1
MR	B	15-Mar-96	5.42	-5.5	0.3	0.5	1.1	0.1	0.6	0.8	0.6	1.3
MR	D	15-Mar-96	5.41	-4.5	0.7	0.5	1.6	0.2	0.6	1.2	0.9	2.0
MR	M	15-Mar-96	5.47	8.3	1.2	0.9	4.4	1.8	3.0	0.8	0.6	4.4
MR	R	15-Mar-96	5.33	-5.5	0.4	0.6	1.9	0.4	0.6	1.1	0.9	2.4
MR	T	15-Mar-96	5.29	-8.9	0.8	0.9	3.3	0.7	0.6	2.7	1.5	3.4
SH	B	15-Mar-96	5.50	-1.1	0.3	0.4	1.5	0.2	0.6	0.8	0.6	1.8
SH	D	15-Mar-96	5.42	-4.6	0.9	0.9	3.7	0.9	0.6	1.6	1.0	4.2
SH	M	15-Mar-96	5.46	-0.7	0.3	0.6	3.7	0.6	0.6	0.8	0.6	4.2
SH	R	15-Mar-96	5.52	-2.6	0.2	0.4	2.2	0.2	0.6	1.4	1.1	2.6
SH	T	15-Mar-96	5.44	-3.6	0.7	0.7	4.4	0.2	1.1	2.1	2.0	2.6
SH	B	24-Mar-97	5.57	-5.7	0.3	0.3	1.8	0.3	0.6	0.8	0.6	1.6
SH	D	24-Mar-97	5.52	-3.7	1.1	0.8	5.6	0.8	0.6	0.8	1.1	3.6
SH	M	24-Mar-97	5.58	-3.4	0.3	0.2	1.4	0.1	0.6	0.8	0.6	1.6
SH	R	24-Mar-97	5.50	-4.3	0.3	0.6	2.3	0.1	0.6	0.8	0.9	3.0

* LB=Lone Butte, SH=Mount St. Helens, WP=White Pass, CS=Cold Springs Butte, GM=Green Mountain, MR=Mount Rainier

** R=routine, integrated; D=duplicate, integrated; T=top, discrete; M=middle, discrete; B=bottom, discrete

Table 12. Continued.

LOCATION*	TYPE**	DATE	pH	ANC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	NH_4^{+}	SO_4^{2-}	NO_3^{-}	Cl^{-}
SH	T	24-Mar-97	5.51	-5.8	0.2	0.2	0.8	0.1	0.8	0.8	0.9	1.2
WP	B	24-Mar-97	5.85	3.1	5.7	1.7	7.5	1.7	1.0	2.1	0.9	7.1
WP	D	24-Mar-97	5.54	-7.6	2.0	1.1	6.1	0.9	0.6	2.5	1.3	4.4
WP	M	24-Mar-97	5.61	-3.7	1.3	0.7	1.7	0.3	0.6	0.8	1.4	2.1
WP	R	24-Mar-97	5.52	-4.9	1.5	1.0	4.0	0.5	0.6	2.2	1.4	4.9
WP	T	24-Mar-97	5.50	-3.6	0.3	0.3	0.8	0.1	1.1	1.5	1.4	1.1
LB	B	03-Apr-97	5.62	-11.0	0.5	1.2	4.2	0.4	0.6	1.5	0.7	5.5
LB	D	03-Apr-97	5.57	-9.2	0.7	1.2	5.3	0.4	0.6	2.2	1.1	6.7
LB	M	03-Apr-97	5.58	-9.1	0.6	0.8	3.9	0.5	0.6	1.4	1.5	4.7
LB	R	03-Apr-97	5.49	-9.9	0.6	1.5	5.7	0.3	0.6	2.6	1.2	7.6
LB	T	03-Apr-97	5.24	-20.1	1.2	3.6	14.7	0.5	0.6	8.5	2.1	18.9
MR	B	08-Apr-97	5.73	-4.9	1.5	0.7	2.0	0.2	0.6	1.2	0.6	2.7
MR	D	08-Apr-97	5.39	-10.9	0.5	1.3	5.7	0.3	0.6	4.7	1.4	7.4
MR	M	08-Apr-97	6.46	-3.8	8.3	1.6	6.4	0.6	0.6	5.0	1.6	8.2
MR	R	08-Apr-97	5.40	-12.8	0.8	1.6	7.8	0.7	0.8	4.5	1.1	8.7
MR	T	08-Apr-97	5.03	-25.0	1.7	5.7	23.7	0.7	0.6	16.5	1.9	31.3
LB	B	03-Apr-98	5.35	-4.7	0.6	2.1	10.4	0.4	0.6	2.3	1.4	12.9
LB	D	03-Apr-98	5.41	-3.4	0.9	1.1	5.4	0.4	0.6	1.4	1.0	6.0
LB	M	03-Apr-98	5.41	-5.8	2.5	1.6	7.1	0.5	0.6	2.0	1.6	8.5
LB	R	03-Apr-98	5.43	-4.6	0.5	1.4	7.7	0.2	0.6	1.6	1.2	8.2
LB	T	03-Apr-98	5.11	-16.7	1.3	2.1	7.4	0.4	0.6	3.7	2.7	8.7
MR	B	03-Apr-98	5.28	-5.0	0.4	1.0	4.0	0.2	0.6	1.8	1.0	4.9
MR	D	03-Apr-98	5.24	-10.3	0.6	2.1	8.6	0.2	0.6	3.2	1.4	10.8
MR	M	03-Apr-98	5.16	-8.5	0.2	0.5	1.7	0.1	0.6	3.2	1.8	2.1
MR	R	03-Apr-98	5.24	-6.6	0.8	1.8	7.8	0.5	0.6	3.4	1.5	9.4
MR	T	03-Apr-98	5.29	-6.4	0.2	0.5	2.3	0.1	0.6	1.7	0.9	3.0
SH	B	03-Apr-98	5.35	-11.1	0.3	0.7	4.1	0.2	0.8	1.3	1.4	5.2
SH	D	03-Apr-98	5.44	-10.5	0.0	0.2	1.0	0.1	0.6	0.8	0.6	1.5
SH	M	03-Apr-98	5.68	-6.3	3.7	1.4	5.2	0.9	1.4	3.4	1.2	3.9
SH	R	03-Apr-98	5.38	-9.4	0.1	0.3	1.5	0.0	0.8	0.8	0.9	1.9
SH	T	03-Apr-98	5.42	-4.8	0.3	0.4	1.3	0.1	0.6	0.8	0.9	1.7
WP	B	03-Apr-98	6.08	7.0	13.9	1.9	4.3	0.6	0.6	1.6	1.3	5.2
WP	D	03-Apr-98	5.45	-11.7	2.0	1.2	4.4	0.2	0.6	1.4	1.5	5.5
WP	M	03-Apr-98	5.25	-10.1	3.4	2.4	9.8	0.8	1.3	3.5	3.8	11.6
WP	R	03-Apr-98	5.95	7.0	10.5	1.7	6.9	1.2	1.3	3.3	3.0	7.6
WP	T	03-Apr-98	5.37	-9.8	1.6	0.8	1.0	0.1	0.7	2.2	1.3	1.1

* LB=Lone Butte, SH=Mount St. Helens, WP=White Pass, CS=Cold Springs Butte, GM=Green Mountain, MR=Mount Rainier

** R=routine, integrated; D=duplicate, integrated; T=top, discrete; M=middle, discrete; B=bottom, discrete could be biased low. Base cation concentrations were generally less than 10 µeq/L, although three composite samples exceeded this value. The dominant base cation was sodium which closely matched the expected seasalt ratio with chloride. Measurements of organic anions (acetate, formate, and proprionate), total organic carbon, metals (Pb, Al, Mn, Fe), and fluoride were typically below method detection limits.

Temporal patterns in snow chemistry of the four sites were generally absent for the study period. Variability within sites was moderate with Mount St. Helens exhibiting the least annual variability. Mount St. Helens is also noteworthy for its consistently low concentrations of sulfate relative to the other three sites. Results for the two sites that were discontinued in 1996, Green Mountain and Cold Springs Butte, show snow chemistry that is generally higher in all ions, but especially sodium and chloride.

Based on the snow chemistry, wintertime deposition in the southwestern Washington Cascades is characterized by low concentrations of sulfur and nitrogen. Using the measured ion concentrations and information on snow water equivalents yields winter bulk deposition values ranging from 0.9 to 5.0 kg/ha for SO_4 and 0.4 to 1.2 kg/ha for total inorganic nitrogen.

Analysis of snow samples from discrete locations (top, middle, bottom) in the snowpacks were compared with results from the integrated composite snow samples discussed above (Figures 24-26). The results show that the discrete samples generally were not statistically different from the composite samples (Table 13). pH values in the top samples were significantly lower than the composite samples and the bottom samples showed a tendency to exhibit lower concentrations of sulfate, chloride, and hydrogen ion, but not at the chosen level of significance ($p \leq 0.05$).

Table 13. Comparison of discrete snow samples from the top, middle, and bottom of the snowpack versus the integrated snowpack samples. The top value represents the difference between the samples in microequivalents for sulfate and chloride and in standard units for pH. The values in parentheses show the significance level for paired differences using a "t" test, n=11. Observations shown in bold are significant at $P \leq 0.05$.

	SO_4^{2-}	Cl^-	pH
Top	1.9 (0.136)	1.7 (0.529)	**-0.16** **(0.029)**
Middle	0.06 (0.191)	-0.48 (0.618)	0.07 (0.588)
Bottom	-0.71 (0.069)	-0.77 (0.439)	0.08 (0.063)

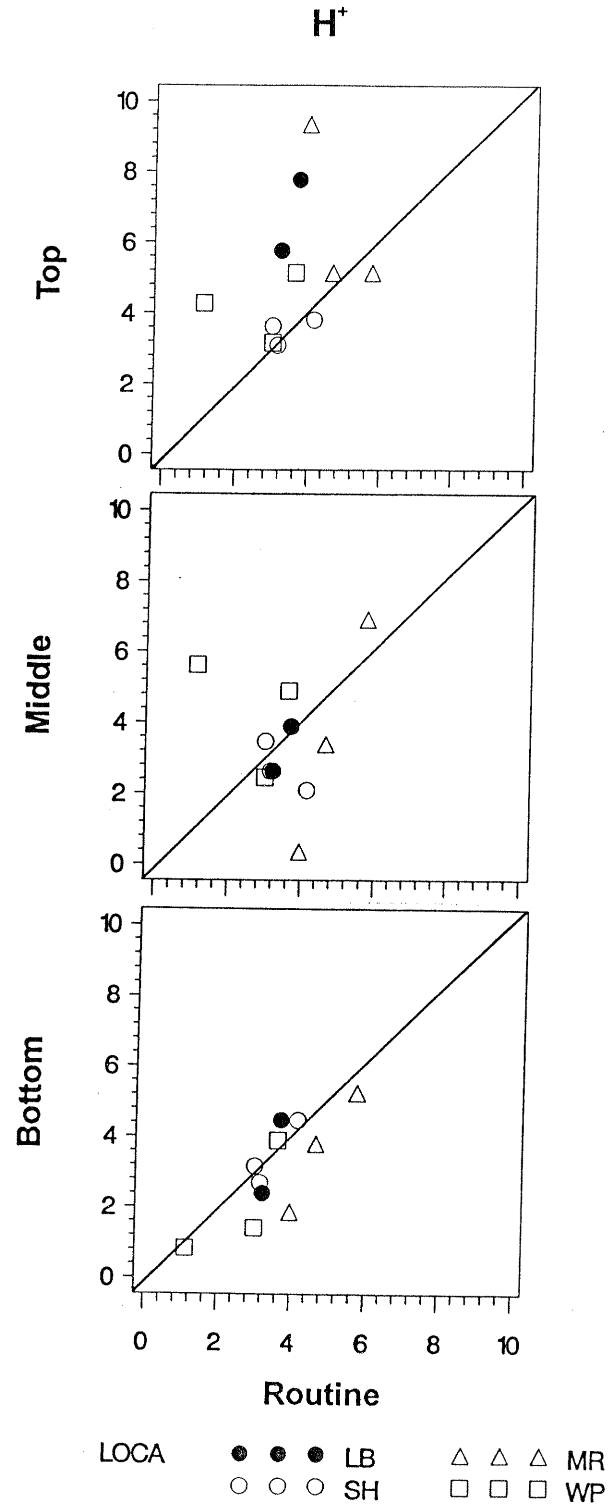


Figure 24. Comparison of hydrogen ion (H^+, µeq/L) measured in discrete samples collected from the top, middle, and bottom of the snow pits with routine integrated snow samples for the four primary snow sites.

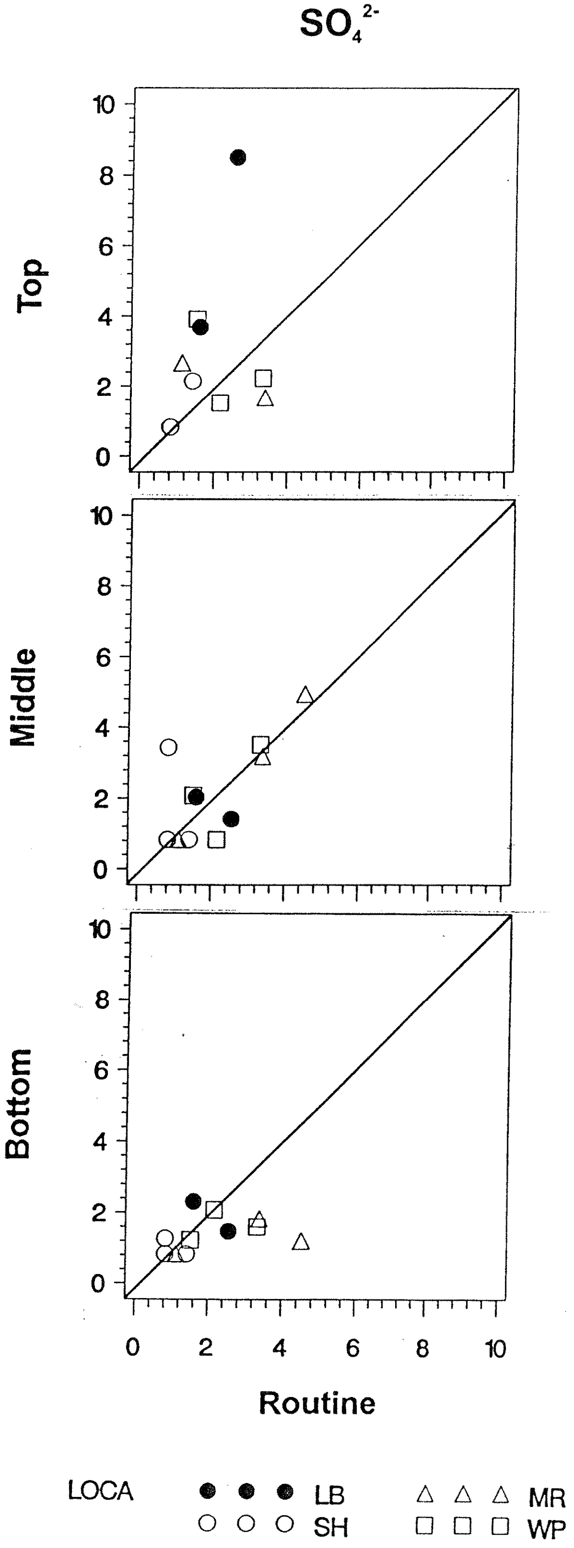


Figure 25. Comparison of sulfate (SO_4^{2-}, µeq/L) measured in discrete samples collected from the top, middle, and bottom of the snow pits with routine integrated snow samples for the four primary snow sites.

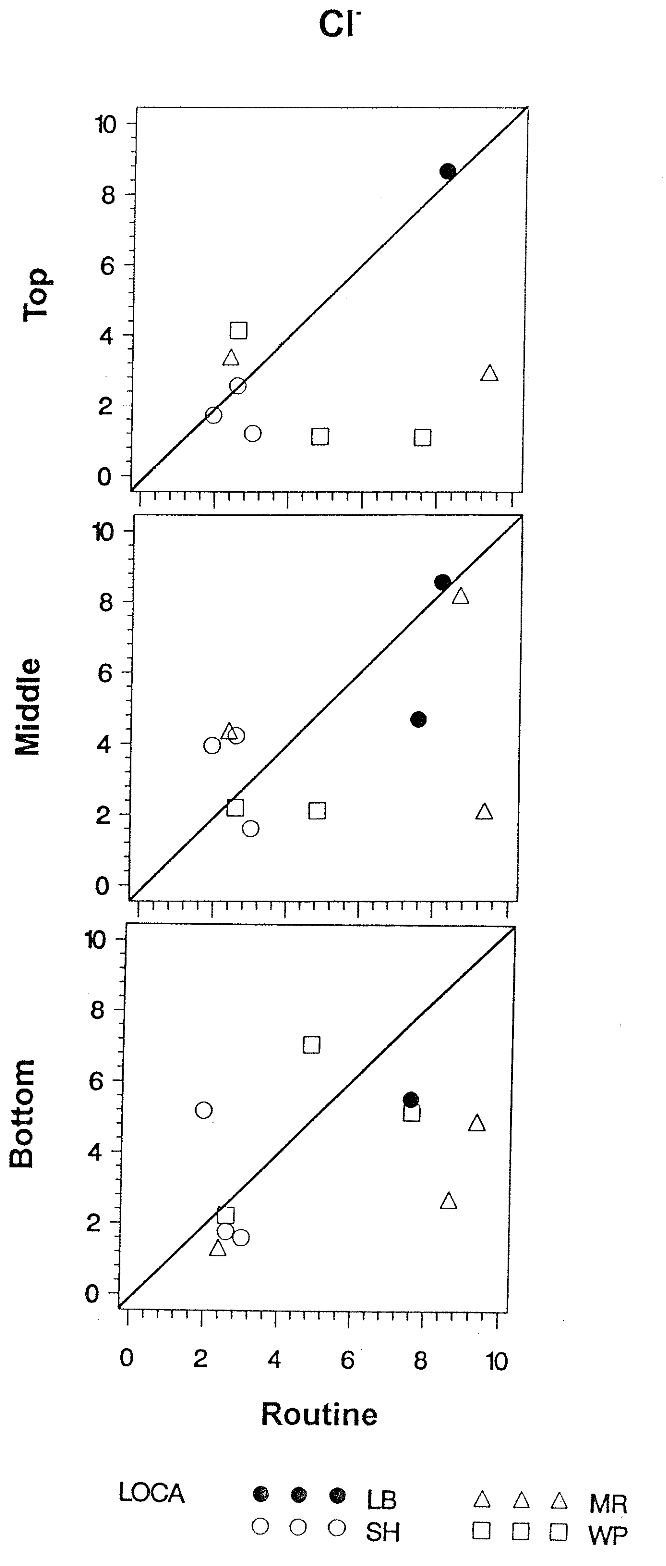


Figure 26. Comparison of chloride (Cl⁻, μeq/L) measured in discrete samples collected from the top, middle, and bottom of the snow pits with routine integrated snow samples for the four primary snow sites.

C. Watershed and Ancillary Data

In addition to the primary data collection activities related to lake and snow chemistry, several other types of data were collected in support of this project. These other data collection activities were generally conducted to support the data integration and watershed modeling activities on Gertrude Lake. Gertrude Lake was selected for modeling because of its greater size and the presence of a reproducing fish population that provided some biological relevance for the process. Some ancillary data were collected on Cedar Pond to allow for comparisons with Gertrude Lake. The additional data required for the modeling includes information on lake bathymetry, watershed hydrology, soils chemistry, vegetation chemistry, and watershed attributes. Data collected but not required for the modeling included information on lake phytoplankton and zooplankton. In addition, a sediment sample was collected from Gertrude Lake for inclusion in another study, the Cascade Diatom Calibration Set (Eilers et al. 1998).

1. Lake Bathymetry

The bathymetry of Gertrude Lake was required to compute the volume of the lake. Lake volume is essential for computing the hydraulic residence time in the lake. The results presented in Figure 27 show the lake is quite shallow with a maximum depth of less than 7 m.

2. Lake Stage

Lake stage was initially measured at both lakes with a staff gage. Both sites were apparently vandalized in 1995 and 1996 and subsequent measurements of lake stage were based on photographic reference points. The results show that maximum lake stage occurred in spring and usually decreased until the return of significant precipitation in the fall (Figure 28).

3. Stream Discharge

The surface discharge from Gertrude Lake was measured using a weir installed at the lake outlet. Stream discharge was considerable during the snowmelt period, but declined to zero discharge by late summer (Figure 29). Surface discharge from Gertrude Lake extended approximately a month after cessation of snowmelt but attenuated rather quickly as tributary flows declined. Surface flows into and exiting Gertrude Lake were generally non-existent from late August until the return of fall weather patterns.

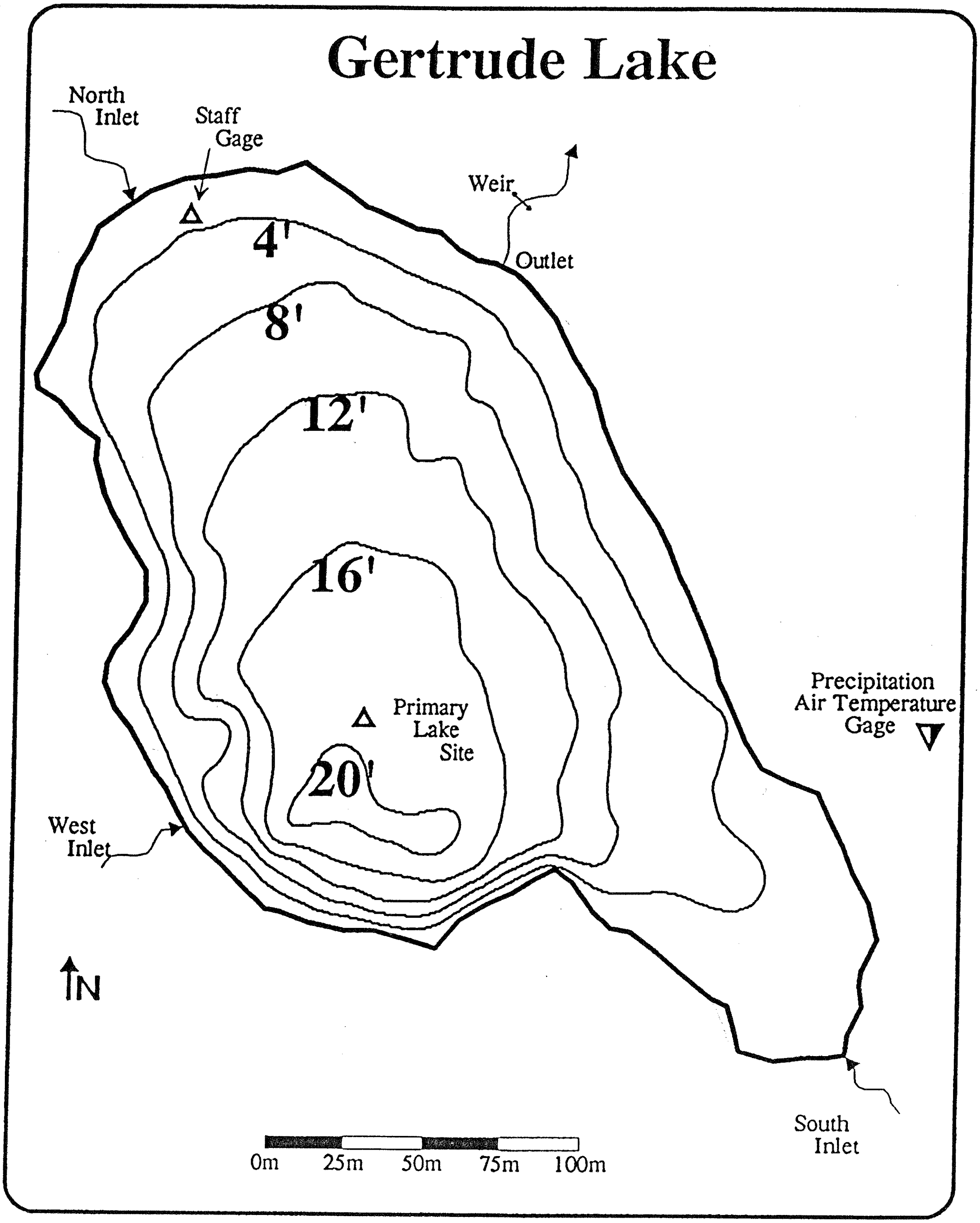


Figure 27. Lake bathymetry (contours are in feet) and locations of field instrumentation at Gertrude Lake.

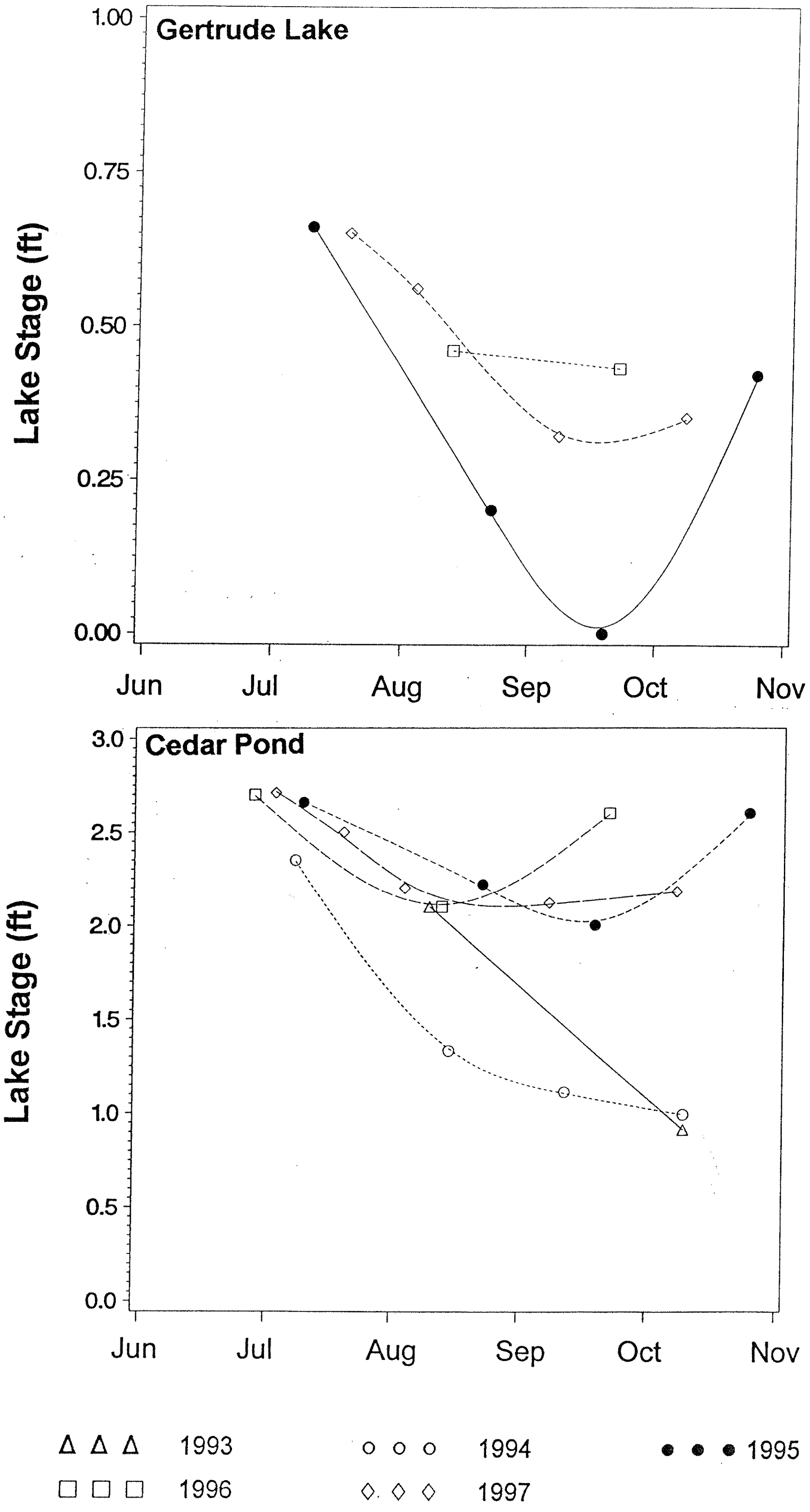


Figure 28. Lake stage (ft above arbitrary datum) for Gertrude Lake (top) and Cedar Pond (bottom).

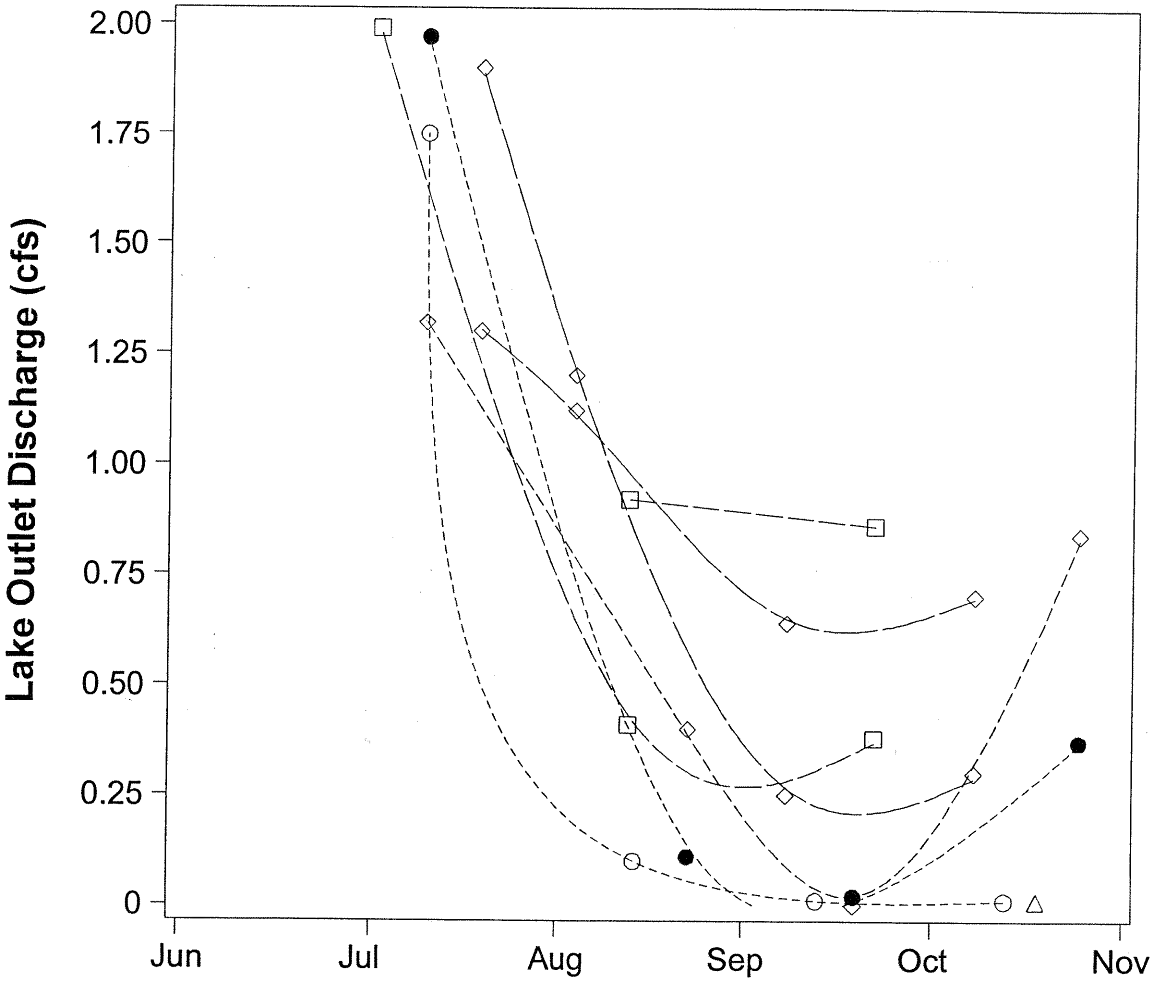


Figure 29. Lake outlet discharge (cubic feet per second) for Gertrude Lake. Values for July 1994 and July 1996 were estimated based on observed discharge.

4. Plankton

The phytoplankton community in the lakes differed both qualitatively and quantitatively among years (Tables 14 and 15). The phytoplankton community was always more abundant (based on biovolume) in Gertrude Lake compared to Cedar Pond (Table 16). This difference occurred despite the shallower depth and warmer water in Cedar Pond, factors which would act to increase primary productivity. The dominant taxa, based on biovolume, differed between the study lakes in the early years, but samples collected in 1996 and 1997 showed similar populations of the dominant taxon, *Glenodinium*. The greatest phytoplankton populations occurred in August and September 1994 when *Tetraedron minimum*, a green alga, was present in "bloom" conditions (Plate 6). The blue-

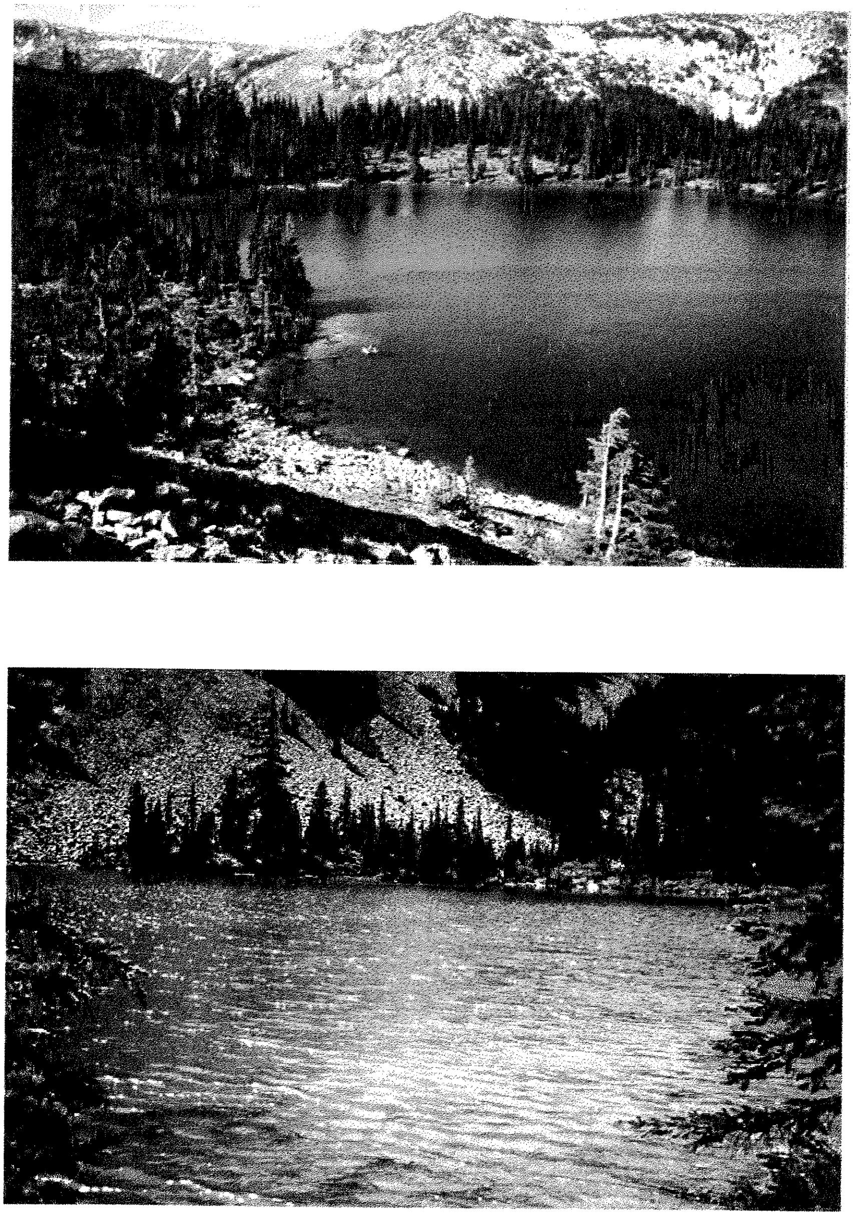


Plate 6. Gertrude Lake on July 8, 1994 and August 14, 1994, showing the contrasting lake appearance during an algal bloom of *Tetraedron minimum.*

Table 14. Phytoplankton Analysis

Date	Site	Division	Species	Density		Biovolume	
				(#/Lt)	%	(m^3/L)	%
28 Sep 93	Gertrude	Chlorophyta	Cosmarium sp.	4.98e+03	0.02	1.50e+07	2.45
28 Sep 93	Gertrude	Chlorophyta	Kirchneriella subsalsa	7.47e+04	0.32	5.27e+05	0.09
28 Sep 93	Gertrude	Chlorophyta	Cosmarium regnesi	1.51e+06	6.54	1.14e+08	18.61
28 Sep 93	Gertrude	Chrysophyta	Cyclotella sp.	1.20e+05	0.52	1.35e+07	2.20
28 Sep 93	Gertrude	Chrysophyta	Dinobryon sertularia	3.54e+05	1.53	3.74e+07	6.11
28 Sep 93	Gertrude	Chrysophyta	Tabellaria fenestrata	1.99e+04	0.09	2.00e+07	3.27
28 Sep 93	Gertrude	Chrysophyta	Synedra ulna	4.98e+03	0.02	4.22e+06	0.69
28 Sep 93	Gertrude	Cryptophyta	Cryptomonas ovata	4.98e+03	0.02	1.50e+06	0.24
28 Sep 93	Gertrude	Pyrrophyta	Glenodinium sp.	2.49e+04	0.11	1.02e+07	1.67
28 Sep 93	Gertrude	Uncertain	small green cell	2.10e+07	90.84	3.96e+08	64.65
15 Aug 94	Gertrude	Cyanophyta	Anabaena flos-aquae	1.05e+05	1.20	6.68e+06	1.05
15 Aug 94	Gertrude	Cyanophyta	Anabaena flos-aquae akinete	3.76e+03	0.04	1.13e+06	0.18
15 Aug 94	Gertrude	Cyanophyta	Anabaena flos-aquae heterocyst	7.52e+03	0.09	4.77e+05	0.07
15 Aug 94	Gertrude	Pyrrophyta	Glenodinium sp.	3.98e+04	0.45	4.13e+07	6.48
15 Aug 94	Gertrude	Chlorophyta	Quadrigula closteroides	4.58e+05	5.23	2.16e+06	0.34
15 Aug 94	Gertrude	Chlorophyta	Tetraedron minimum	8.15e+06	92.99	5.86e+08	91.88
12 Sep 94	Gertrude	Pyrrophyta	Glenodinium sp.	3.98e+04	0.20	4.13e+07	2.80
12 Sep 94	Gertrude	Chlorophyta	Tetraedron minimum	1.99e+07	99.01	1.43e+09	96.79
12 Sep 94	Gertrude	Uncertain	small flagellate	1.59e+05	0.79	6.00e+06	0.41
25 Oct 95	Gertrude	Chlorophyta	Chlorella sp. fa.	1.96e+07	89.40	1.56e+08	32.27
25 Oct 95	Gertrude	Chlorophyta	Oocystis sp.	1.60e+06	7.29	6.03e+07	12.48
25 Oct 95	Gertrude	Chlorophyta	Chlamydomonas sp.	1.91e+05	0.87	3.60e+06	0.75
25 Oct 95	Gertrude	Chrysophyta	Cyclotella sp.	7.97e+03	0.04	9.00e+05	0.19
25 Oct 95	Gertrude	Chrysophyta	Dinobryon sertularia	3.98e+05	1.81	1.52e+08	31.44
25 Oct 95	Gertrude	Chrysophyta	Tabellaria fenestrata	1.59e+04	0.07	7.16e+07	14.82
25 Oct 95	Gertrude	Euglenophyta	Trachelomonas sp.	7.97e+04	0.36	1.82e+07	3.78
25 Oct 95	Gertrude	Pyrrophyta	Glenodinium sp.	1.59e+04	0.07	2.00e+07	4.15
25 Oct 95	Gertrude	Uncertain Classif.	small flagellate	1.59e+04	0.07	6.00e+05	0.12
28 Jun 96	Gertrude	Chlorophyta	Dictyosphaerium pulchellum	1.99e+04	22.22	4.69e+04	0.04
28 Jun 96	Gertrude	Chrysophyta	Dinobryon sertularia	2.49e+03	2.78	9.49e+05	0.89
28 Jun 96	Gertrude	Chrysophyta	Stephanodiscus hantzschii	9.96e+03	11.11	1.12e+06	1.05

Table 14. Contunued

Date	Site	Division	Species	Density		Biovolume	
				(#/Lt)	%	(m^3/L)	%
28 Jun 96	Gertrude	Euglenophyta	Trachelomonas sp.	4.48e+04	50.00	1.32e+07	12.30
28 Jun 96	Gertrude	Pyrrophyta	Glenodinium sp.	1.25e+04	13.89	9.18e+07	85.72
19 Jul 97	Gertrude	Chlorophyta	Cosmarium sp.	2.49e+04	5.81	9.37e+06	6.22
19 Jul 97	Gertrude	Chlorophyta	Chlamydomonas sp.	2.49e+03	0.58	1.58e+05	0.10
19 Jul 97	Gertrude	Chlorophyta	Crucigenia tetrapedia	1.99e+04	4.65	4.83e+03	0.00
19 Jul 97	Gertrude	Chlorophyta	Scenedesmus sp.	4.98e+03	1.16	2.34e+04	0.02
19 Jul 97	Gertrude	Chrysophyta	Pennate diatom	4.98e+03	1.16	1.27e+06	0.84
19 Jul 97	Gertrude	Chrysophyta	Dinobryon sertularia	3.41e+05	79.65	1.30e+08	86.23
19 Jul 97	Gertrude	Cryptophyta	Cryptomonas ovata	2.49e+03	0.58	1.46e+06	0.97
19 Jul 97	Gertrude	Cyanophyta	Oscillatoria geminata	1.74e+04	4.07	6.15e+04	0.04
19 Jul 97	Gertrude	Pyrrophyta	Peridinium sp.	2.49e+03	0.58	8.20e+06	5.44
19 Jul 97	Gertrude	Uncertain Classif.	small flagellate	7.47e+03	1.74	2.11e+05	0.14
28 Sep 93	Cedar	Chlorophyta	Ankistrodesmus falcatus	9.96e+03	1.01	3.51e+04	0.04
28 Sep 93	Cedar	Chlorophyta	Chlamydomonas sp.	6.18e+05	62.63	4.90e+06	5.14
28 Sep 93	Cedar	Chlorophyta	Oocystis sp.	5.98e+04	6.06	1.01e+07	10.62
28 Sep 93	Cedar	Chrysophyta	Cyclotella sp.	1.99e+04	2.02	2.25e+06	2.36
28 Sep 93	Cedar	Cryptophyta	Cryptomonas ovata	2.99e+04	3.03	7.20e+07	75.51
28 Sep 93	Cedar	Cryptophyta	Rhodomonas minuta var. nann.	1.99e+04	2.02	3.00e+06	3.15
28 Sep 93	Cedar	Uncertain	small flagellate	2.29e+05	23.23	3.03e+06	3.18
15 Aug 94	Cedar	Chlorophyta	Chlamydomonas sp.	1.63e+05	11.14	3.07e+06	4.39
15 Aug 94	Cedar	Chlorophyta	Quadrigula closteroides	1.59e+05	10.87	7.50e+06	10.71
15 Aug 94	Cedar	Pyrrophyta	Glenodinium sp.	7.97e+03	0.54	1.67e+07	23.86
15 Aug 94	Cedar	Uncertain	small flagellate	1.14e+06	77.45	4.27e+07	61.04
12 Sep 94	Cedar	Chlorophyta	Chlamydomonas sp.	1.44e+06	42.49	2.71e+07	7.65
12 Sep 94	Cedar	Chlorophyta	Crucigenia rectangularis	3.51e+05	10.33	2.97e+07	8.37
12 Sep 94	Cedar	Chlorophyta	Oocystis sp.	5.42e+05	15.96	9.18e+07	25.86
12 Sep 94	Cedar	Chlorophyta	Quadrigula closteroides	1.83e+05	5.40	9.05e+06	2.55
12 Sep 94	Cedar	Chlorophyta	Scenedesmus quadricauda	3.19e+04	0.94	1.20e+06	0.34
12 Sep 94	Cedar	Chlorophyta	Sphaerocystis Schroeteri	1.27e+05	3.76	8.10e+06	2.28
12 Sep 94	Cedar	Cryptophyta	Cryptomonas ovata	6.37e+04	1.88	1.63e+08	46.02
12 Sep 94	Cedar	Uncertain	small flagellate	6.53e+05	19.25	2.46e+07	6.93

Table 14. Contunued

Date	Site	Division	Species	Density		Biovolume	
				(#/Lt)	%	(m^3/L)	%
10 Jul 95	Cedar	Chlorophyta	Chlamydomonas sp.	1.59e+05	72.73	3.00e+06	9.33
10 Jul 95	Cedar	Chlorophyta	Oocystis sp.	1.99e+03	0.91	7.50e+04	0.23
10 Jul 95	Cedar	Chrysophyta	Cyclotella sp.	7.97e+03	3.64	9.00e+05	2.80
10 Jul 95	Cedar	Chrysophyta	Pennate diatom	3.98e+03	1.82	5.62e+05	1.75
10 Jul 95	Cedar	Chrysophyta	Synedra sp.	1.99e+03	0.91	1.01e+06	3.15
10 Jul 95	Cedar	Cryptophyta	Cryptomonas ovata	1.99e+03	0.91	1.41e+06	4.38
10 Jul 95	Cedar	Cyanophyta	Oscillatoria geminata	2.79e+04	12.73	9.84e+04	0.31
10 Jul 95	Cedar	Pyrrophyta	Glenodinium sp.	7.97e+03	3.64	5.40e+06	16.80
10 Jul 95	Cedar	Pyrrophyta	Peridinium sp.	5.98e+03	2.73	1.97e+07	61.25
23 Aug 95	Cedar	Chlorophyta	Chlamydomonas sp.	2.27e+05	23.75	4.27e+06	4.48
23 Aug 95	Cedar	Chlorophyta	Crucigenia tetrapedia	1.20e+04	1.25	1.07e+05	0.11
23 Aug 95	Cedar	Chrysophyta	Dinobryon sertularia	3.98e+03	0.42	1.20e+06	1.26
23 Aug 95	Cedar	Cryptophyta	Rhodomonas minuta v nan.	6.81e+05	71.25	5.41e+07	56.68
23 Aug 95	Cedar	Pyrrophyta	Glenodinium sp.	3.19e+04	3.33	3.58e+07	37.47
19 Sep 95	Cedar	Chlorophyta	Chlamydomonas sp.	7.97e+03	3.70	1.50e+05	0.37
19 Sep 95	Cedar	Chlorophyta	Scenedesmus quadricauda	1.59e+04	7.41	9.00e+05	2.24
19 Sep 95	Cedar	Chlorophyta	Schroederia setigera	3.98e+03	1.85	2.53e+05	0.63
19 Sep 95	Cedar	Chlorophyta	Sphaerocystis Schroeteri	1.67e+05	77.78	2.52e+07	62.64
19 Sep 95	Cedar	Chrysophyta	Melosira granulata	7.97e+03	3.70	5.62e+06	13.98
19 Sep 95	Cedar	Pyrrophyta	Glenodinium sp.	1.20e+04	5.56	8.10e+06	20.14
28 Jun 96	Cedar	Chlorophyta	Closterium sp.	4.98e+02	3.23	2.36e+06	8.37
28 Jun 96	Cedar	Chrysophyta	Stephanodiscus hantzschii	1.99e+03	12.90	1.17e+06	4.15
28 Jun 96	Cedar	Euglenophyta	Trachelomonas sp.	5.98e+03	38.71	1.76e+06	6.23
28 Jun 96	Cedar	Pyrrophyta	Glenodinium sp.	1.99e+03	12.90	2.28e+07	80.76
28 Jun 96	Cedar	Uncertain	small flagellate	4.98e+03	32.26	1.41e+05	0.50
20 Jul 97	Cedar	Chlorophyta	Chlamydomonas sp.	3.71e+05	87.13	2.36e+07	46.43
20 Jul 97	Cedar	Chlorophyta	Cosmarium sp.	2.49e+03	0.58	9.37e+05	1.85
20 Jul 97	Cedar	Chrysophyta	Dinobryon sertularia	3.49e+04	8.19	4.43e+06	8.73
20 Jul 97	Cedar	Chrysophyta	Mallomonas sp.	2.49e+03	0.58	2.11e+06	4.15
20 Jul 97	Cedar	Chrysophyta	Pennate diatom	4.98e+03	1.17	1.58e+06	3.12
20 Jul 97	Cedar	Cryptophyta	Cryptomonas ovata	2.49e+03	0.58	7.50e+05	1.48
20 Jul 97	Cedar	Pyrrophyta	Glenodinium sp.	7.47e+03	1.75	1.74e+07	34.25

Table 15. Zooplankton Analysis

Date	Site	Division	Species	Density	
				(#/Lt)	%
28-Sep-93	Gertrude	Cladocera	Daphnia rosea	0.93	1.23
28-Sep-93	Gertrude	Cladocera	Holopedium gibberum	14.91	19.75
28-Sep-93	Gertrude	Copepoda	Cyclops sp.	3.73	4.94
28-Sep-93	Gertrude	Copepoda	Diaptomus sp. (small juvenile)	0.93	1.23
28-Sep-93	Gertrude	Copepoda	Diaptomus sp. (adult)	9.32	12.35
28-Sep-93	Gertrude	Rotifera	Keratella sp.	40.08	53.09
11-Jul-95	Gertrude	Cladocera	Holopedium gibberum	1.06e+01	1.28
11-Jul-95	Gertrude	Copepoda	nauplius larvae	7.96e+02	96.15
11-Jul-95	Gertrude	Rotifera	rotifer	2.12e+01	2.56
23-Aug-95	Gertrude	Cladocera	Chydorus sphaericus	4.42e+01	1.75
23-Aug-95	Gertrude	Cladocera	Holopedium gibberum	5.75e+02	22.81
23-Aug-95	Gertrude	Copepoda	Diaptomus sp.	1.86e+03	73.68
23-Aug-95	Gertrude	Copepoda	nauplius larvae	4.42e+01	1.75
19-Sep-95	Gertrude	Cladocera	Holopedium gibberum	4.00e-01	19.57
19-Sep-95	Gertrude	Copepoda	Cyclops bicuspidatus thomasi (large)	2.00e-02	0.72
19-Sep-95	Gertrude	Copepoda	Diaptomus sp.	3.00e-01	12.32
19-Sep-95	Gertrude	Rotifera	Keratella cochlearis	1.00e+00	66.67
19-Sep-95	Gertrude	Rotifera	rotifer	2.00e-02	0.72
19-Jul-97	Gertrude	Cladocera	Chydorus sphaericus	5.31e-03	0.73
19-Jul-97	Gertrude	Cladocera	Holopedium gibberum	2.71e-01	37.23
19-Jul-97	Gertrude	Copepoda	harpacticoid	5.31e-03	0.73
19-Jul-97	Gertrude	Copepoda	nauplius larvae	4.30e-01	59.12
19-Jul-97	Gertrude	Rotifera	Keratella cochlearis	1.59e-02	2.19
19-Sep-95	Cedar	Cladocera	Holopedium gibberum	3.00e-01	2.38
19-Sep-95	Cedar	Cladocera	Polyphemus pediculus	1.00e+00	11.9
19-Sep-95	Cedar	Copepoda	Cyclops bicuspidatus thomasi (large)	9.00e-02	0.79
19-Sep-95	Cedar	Copepoda	Diaptomus sp.	3.00e+00	26.19
19-Sep-95	Cedar	Copepoda	nauplius larvae	1.00e+00	8.73
19-Sep-95	Cedar	Rotifera	Polyarthra sp.	6.00e-01	5.56

Table 16. Dominant taxa based on biovolume. Biovolume is presented in cubic microns per liter.

Date	Gertrude		Cedar	
	Taxa	Biovolume	Taxa	Biovolume
September 1993	Unidentified taxa *Cosmarium*	4E8 1E8	*Cryptomonas* *Oocystis*	7E7 1E7
August 1994	*Tetraedron* *Anabaena*	6E8 7E6	Unidentified flagellates *Glenodinium*	4E7 2E7
September 1994	*Tetraedron* *Glenodinium*	1E9 4E7	*Cryptomonas* *Oocystis*	2E8 9E7
July 1995	*Peridinium* *Dinobryon*	7E7 2E7	*Peridinium* *Glenodinium*	2E7 5E6
August 1995	*Oocystis* *Dinobryon*	5E7 2E7	*Rhodomonas* *Glenodinium*	5E7 4E7
September 1995	*Cosmanium* *Cyclotella*	3E5 2E5	*Sphaerocystis* *Glenodinium*	3E7 8E6
October 1995	*Chlorella* *Dinobryon*	2E8 2E8	No Sample	-
June 1996	*Glenodinium* *Trachelomonas*	9E7 1E7	*Glenodinium* *Closterium*	2E7 2E6
July 1997	*Dinobryon* *Glenodinium*	1E8 4E7	*Chlamydomonas* *Glenodinium*	2E7 2E7

green alga, *Anabaena flos-aquae*, was also present in Gertrude Lake in August 1994, but was not observed in subsequent samples. *Oscillatoria geminata*, another blue-green species, was observed in Cedar Pond in July 1995, but again it was not seen during the remainder of the study.

Species that were abundant numerically were not necessarily dominant when expressed as biovolume because of the varying size of the algal cells. The same phytoplankton data when expressed as dominant taxa numerically reveal a different pattern (Table 17). *Chlamydomonas*, a small green alga, was generally the most abundant taxon in Cedar Pond and was only absent from one sample (June 1996). The numerically dominant taxa in Gertrude Lake were highly variable with only two samples (August and September 1994) showing the same species as dominant (*Tetraedron*). Numerical dominance between lakes was equally variable; only one sample date (June 1996) showed the same dominant taxon (*Trachelomonas*) present in both Gertrude Lake and

Table 17. Common phytoplankton taxa based on numerical abundance.

Date	Gertrude		Cedar	
	Taxa	%	Taxa	%
September 1993	*Small unidentified green* *Cosmaricum*	90.8 6.5	*Chlamydomonas* Small flagellate	62.6 23.2
August 1994	*Tetraedron* *Quadrigula*	93.0 5.2	Small flagellate *Chlamydomonas*	77.4 11.1
September 1994	*Tetraedron* Small flagellate	99.0 0.8	*Chlamydomonas* Small flagellate	42.5 19.2
July 1995	*Dinobryon* *Peridinium*	47.9 23.9	*Chlamydomonas* *Oscillatoria*	72.7 12.7
August 1995	*Oocystis* *Dinobryon*	93.0 5.2	*Rhodomonas* *Chlamydomonas*	71.2 23.8
September 1995	*Crucigenia* *Cosmarium*	57.1 28.6	*Sphaerocystis* *Scenedesmus*	77.8 7.4
October 1995	*Chlorella* *Oocystis*	89.4 7.3	No Sample	--
June 1996	*Trachelomonas* *Dictyosphaerium*	50.0 22.2	*Trachelomonas* Small flagellate	38.8 32.3
July 1997	*Dinobryon* *Cosmarium*	79.6 5.8	*Chlamydomonas* *Dinobryon*	87.1 8.2

Cedar Pond. Chlorophyll *a* concentrations from the June 18, 1996 samples were 3.4 µg/L in Gertrude Lake and 1.0 µg/L in Cedar Pond. Chlorophyll *a* values near 1 µg/L are typical of unproductive oligotrophic conditions, whereas intermediate concentrations from 5 to 10 µg/L are typical of mesotrophic systems. These and other changes highlight the difficulty in characterizing these subalpine lakes based on only one or two years of monitoring.

The zooplankton species composition in Gertrude Lake is not diverse (Table 15). The dominant taxa are *Diaptomus* sp. and *Holopedium gibberum* with minor roles played by *Chydorus sphaericus* and rotifers.

5. Secchi Disk Transparency

Secchi disk transparency exhibited a general pattern of decreasing values from July to October (Figure 30). Except for 1994 where the decrease in transparency was over 3.5 m between July and August, the decrease in transparency was generally about 1m to 1.5 m per month. The reduction in transparency is apparently entirely related to increases in phytoplankton because the reduction in streamflow is directly correlated with decreases in transparency. Therefore watershed sources of turbidity do not materially contribute to the reduction in lake transparency.

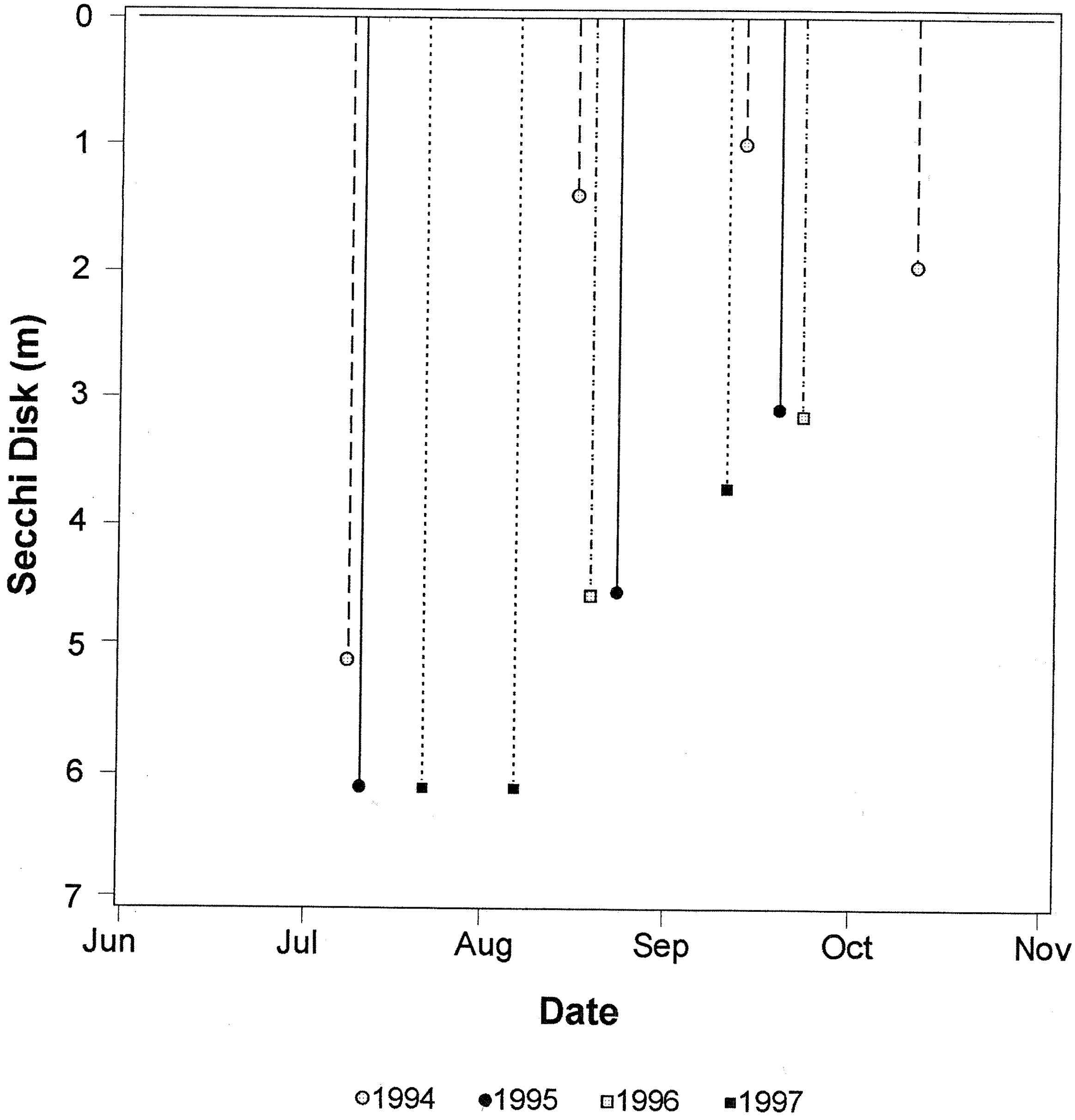


Figure 30. Secchi disk transparency (m) for Gertrude Lake. No measurements were taken in 1993.

6. Lake Temperature

Both lakes were homothermic during the open water period and single measures of water temperature reliably reflect water column temperatures. Lake temperature measurements during sampling conditions indicate (within the resolution of the data) that maximum lake temperature occurred in late July or early August (Figure 31). Continuous temperature data for July-October, 1995 shows the daily variation in temperature for Gertrude Lake (Figure 32). Despite a general trend of warming rapidly in July and rapid cooling from mid-September to October, Gertrude Lake exhibited a considerable cooling period in mid-August, with a secondary warming period through mid-September. These patterns are expected to be highly variable among years and no doubt contribute to variability in phytoplankton variability.

7. Sediment Diatoms

A 26-cm core was collected from the deepest portion of Gertrude Lake. The core was sectioned in 1 cm intervals and the upper 0.5 cm of sediment was analyzed for diatom remains. The 52 taxa that were identified show an approximate log-normal distribution with the dominant taxon being *Fragilaria brevistriata* (Table 18). Only four other taxa have relative abundances greater than 5%, two species of *Acnanthes*, *Aulacoserra ambiga* and *F. pseudoconstruens*. The surface diatom assemblage is indicative of a moderately productive Cascade lake. Although no analyses were made of subsequent sediment intervals, visual examination shows that Gertrude Lake has experienced several episodes of volcanic ash and tephra deposits (Plate 7), the most recent of which occurred in 1980 with the eruption of Mount St. Helens.

Plate 7. Sediment core from Gertrude Lake. Increments of 1 cm are inscribed on the core tube.

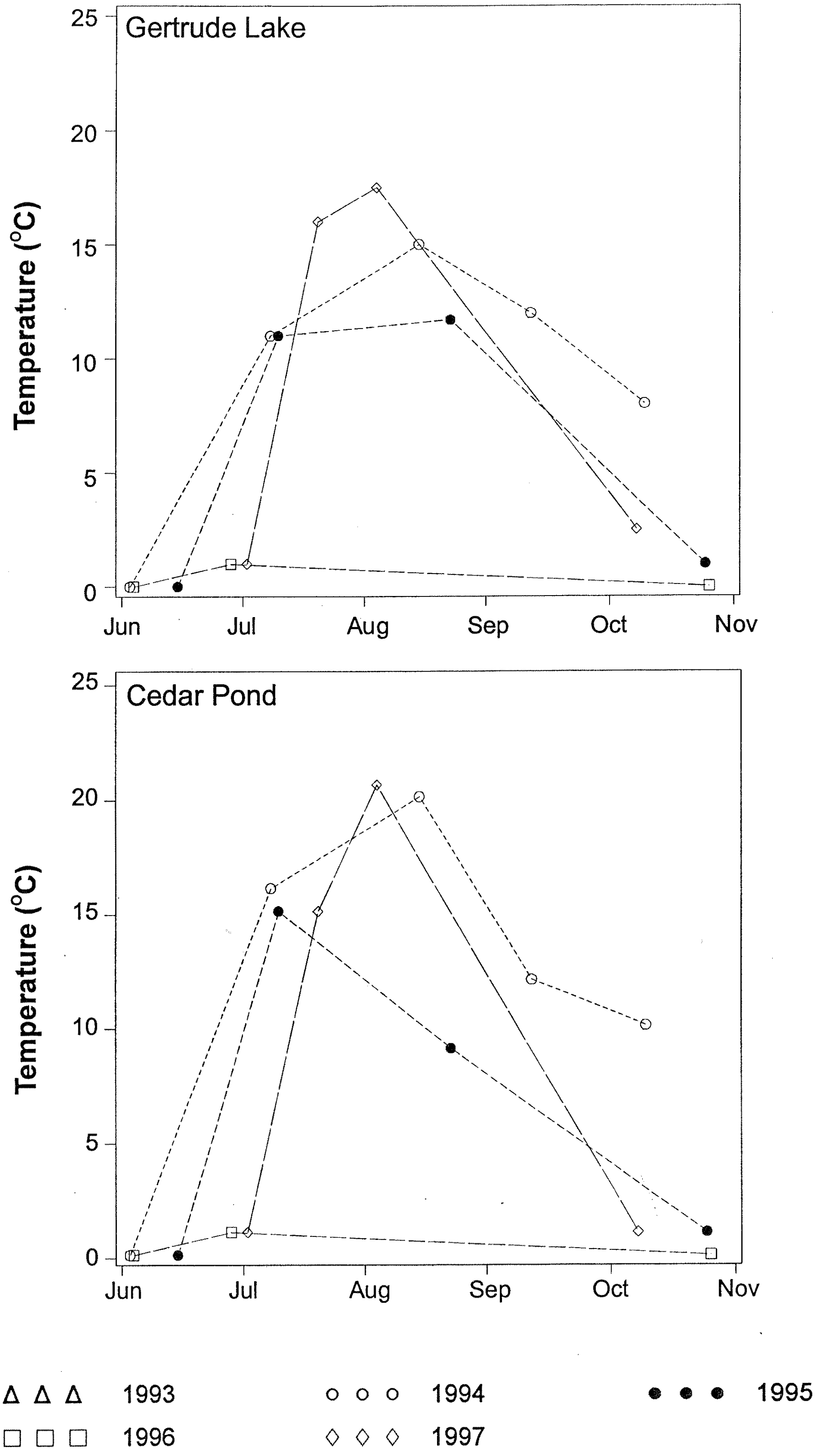


Figure 31. Lake temperature (°C) of Gertrude Lake (top) and Cedar Pond (bottom) recorded during lake sampling.

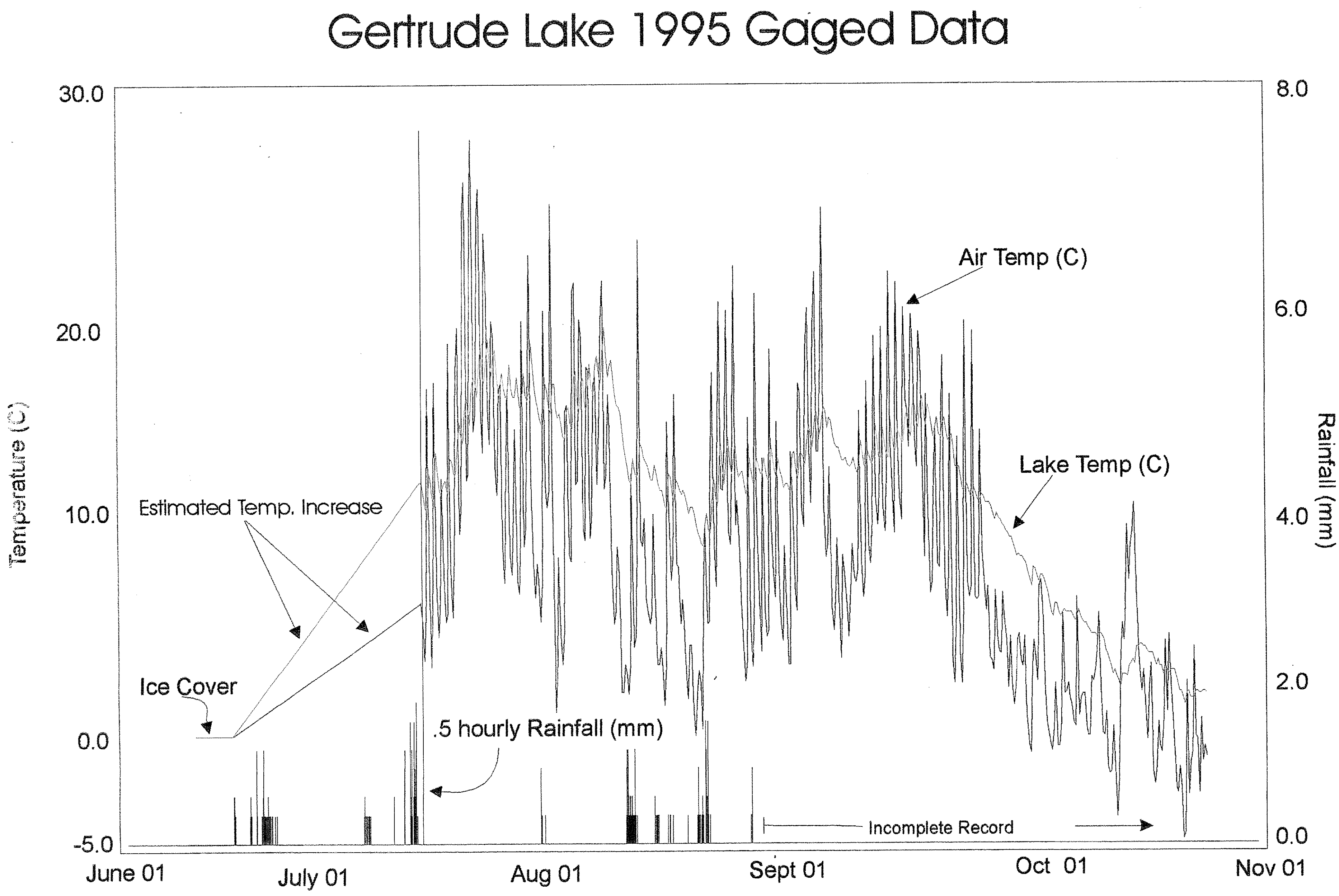


Figure 32. Continuous recording measurements of surface water temperature (red, °C), air temperatures (black, °C), and precipitation (blue, mm) for 1995.

Table 18. Sedimentary diatoms collected from surface sediments of Gertrude Lake, 1996. A total of 300 diatom frustules were counted in the sample. (Source: Eilers et al. 1998)

Division	Genus	Species	Percent Abundance
Chrysophyta	Achnanthes	curtissima	5.0
Chrysophyta	Achnanthes	levanderi	1.2
Chrysophyta	Achnanthes	linearis	2.4
Chrysophyta	Achnanthes	linearis	0.2
Chrysophyta	Achnanthes	marginulata	2.6
Chrysophyta	Achnanthes	subatomoides	6.2
Chrysophyta	Anomoeoneis	brachysira	0.8
Chrysophyta	Aulacoseira	ambigua	9.0
Chrysophyta	Aulacoseira	distans	4.4
Chrysophyta	Aulacosiera	italica	2.6
Chrysophyta	Aulacoseira	italica	0.8
Chrysophyta	Aulacosiera	valida	2.0
Chrysophyta	Cymbella	gaeumannii	0.4
Chrysophyta	Cymbella	lunata	1.8
Chrysophyta	Cymbella	minuta	1.0
Chrysophyta	Eunotia	exigua	0.2
Chrysophyta	Fragilaria	brevistriata	33.4
Chrysophyta	Fragilaria	exigua	0.2
Chrysophyta	Fragilaria	fasciculata	0.4
Chrysophyta	Fragilaria	pinnata	1.0
Chrysophyta	Fragilaria	pseudoconstruens	6.8
Chrysophyta	Frustulia	rhomboides	0.2
Chrysophyta	Gomhonema	sp. PRS 0A	0.2
Chrysophyta	Gomphonema	gracile	0.2
Chrysophyta	Navicula	cryptotenella	0.4
Chrysophyta	Navicula	laevissima	0.2
Chrysophyta	Navicula	leptostriata	0.4
Chrysophyta	Navicula	mediocris	0.4
Chrysophyta	Navicula	pseudoscutiformis	0.2
Chrysophyta	Navicula	radiosa	0.2
Chrysophyta	Navicula	radiosa	0.2
Chrysophyta	Navicula	seminulum	1.6
Chrysophyta	Navicula	subatomoides	2.2
Chrysophyta	Navicula	submuralis	2.4
Chrysophyta	Navicula	tridentula	0.4
Chrysophyta	Navicula	vitabunda	1.0
Chrysophyta	Neidium	iridis	0.2
Chrysophyta	Neidium	spp.	0.2
Chrysophyta	Nitzschia	fonticola	0.4
Chrysophyta	Nitzschia	lacuum	0.2
Chrysophyta	Nitzschia	palea	1.0

Table 18. Continued.			
Division	Genus	Species	Percent Abundance
Chrysophyta	Nitzschia	recta	0.2
Chrysophyta	Nitzschia	spp.	0.4
Chrysophyta	Pinnularia	biceps	1.0
Chrysophyta	Pinnularia	subcapitata	0.4
Chrysophyta	Stenopterobia	intermedia	0.4
Chrysophyta	Stauroneis	anceps	0.2
Chrysophyta	Stauroneis	anceps	1.0
Chrysophyta	Surirella	delicatissima	0.4
Chrysophyta	Surirella	linearis	0.2

8. Soils

Soil samples were collected from areas in the Gertrude Lake watershed where there was appreciable soil coverage. The results of the soil sample analysis illustrated considerable diversity (Table 19). The dominant soil, based on percentage coverage of the watershed, was represented by samples No. 1 and 2. These soils are shallow (generally < 0.5 m) subalpine soils with a shallow (< 3 cm) organic horizon with an abrupt transition to an undifferentiated mineral horizon. At the bases of the light tan mineral was an iron oxide zone (Plate 8). Soil sample No. 3 was unusual in that it represented mineral "soil" present on the talus slope on the south side of the watershed. This "soil"

Plate 8. Soil sample No. 1 collected near the north shore of Gertrude Lake.

Table 19. Results of soil analyses for the study area (see Figure 2).

Field No.	Lab No.	pH	P	K	NH_4+NO_3	SO_4-S	NO_3	Ca	Mg	Na	CEC	OM	Total N
			ppm					meq/100g				%	
1	12955	5.50	5.00	98.00	6.40	25.40	5.50	0.70	0.18	0.05	15.00	9.53	0.14
2	12956	5.30	20.00	23.00	2.00	2.60	0.40	0.70	0.26	0.06	7.00	3.25	0.06
3	12957	5.30	12.00	16.00	5.80	9.00	0.40	0.30	0.12	0.05	3.00	0.32	0.01
4	12958	5.50	12.00	51.00	4.50	4.00	0.40	1.50	0.49	0.08	13.30	39.52	0.31
5	12958	5.40	4.00	59.00	3.60	21.10	0.40	1.50	0.29	0.04	14.90	10.60	0.13

appeared to be ash remaining from the 1980 Mount St. Helens eruption, much of which had been washed under the rocks on the talus slope. The analytical results for this ash are noteworthy for the low concentrations of organic matter, organic nitrogen, and base cations. The ash apparently had been heavily leached leaving a high proportion of resistant silica. Soil sample No. 5 was distinctive because it was collected in a wetland environment. As expected, this sample had the highest content of organic matter and total nitrogen.

9. Vegetation Chemistry

The vegetation was sampled to assess the nutritional status of the plants relative to the nitrogen leaching. Vegetation with high concentrations of nitrogen relative to carbon are indicative of excess nitrogen sometimes encountered in regions with high N deposition. The carbon and nitrogen results for vegetation in Gertrude Lake watershed show a deficiency of N typical of undisturbed subalpine vegetation (Table 20).

Table 20. Carbon and nitrogen concentration (%) in vegetation from Gertrude Lake watershed (collected August 23, 1995).

Species	Sample ID	TKN (%)	TN (%)	C (%)	C/N
Subalpine Fir	GT-01	1.10	1.18	51.0	43
	GT-07	1.28	1.45	51.9	36
	GT-08	1.34	1.43	52.7	37
Mountain Hemlock	GT-02	0.94	0.99	49.2	50
	GT-09	1.13	1.20	50.7	42
Whitebark Pine	GT-06	1.25	1.31	53.2	41
Heather	GT-03	1.16	1.29	54.2	42
Blueberry	GT-05	2.11	2.30	49.6	22
Unidentified Groundcover	GT-04	1.33	1.66	51.8	31

D. Watershed Modeling

The results of lake chemistry, deposition chemistry, and watershed attributes were used to model major ion chemistry in Gertrude Lake. The model used for this analysis, MAGIC, forecasts major ion chemistry in the receiving water (Gertrude Lake) as a function of changes in atmospheric deposition. The model was calibrated to current conditions and hindcast to 1860 using assumptions described in the Methods Section.

The catchment-lake system was successfully calibrated (Table 21). Good fits were obtained for the model during the calibration period as measured by comparisons of simulated and observed

Table 21 **Calibration results: values of fixed and optimized parameters for calibration of Gertrude Lake. Fixed parameter values are set before calibration using observed stream and soil data. Optimized parameter values are adjusted during calibration so that simulated and observed stream and soil chemistry match.**

Soil Fixed Parameters

Units	Parameter	Constant & Triangular ash
m	Depth	0.24
fraction	Porosity	0.5
kg/m3	Bulk Density	1012
meq/kg	CEC	91
ueq/L	SO4 half sat.	100
meq/kg	SO4 Max. Adsorp.	0.2
log10	KAl	9
log10	Organic Acid pK1	2.64
log10	Organic Acid pK2	5.66
log10	Organic Acid pK3	5.94
mmol/m3	Organic acid	75
atm	Soil pCO2	0.0046
deg C	Soil Temperature	3.9
% of input	Soil Uptake NO3	100
% of input	Soil Uptake NH4	100

Talus Fixed Parameters

% Catchment	Talus Area	45
atm	Talus pCO2	0.0036
deg C	TalusTemperature	1.2
% of input	Talus Uptake NO3	0
% of input	Talus Uptake NH4	0

Lake Fixed Parameters

m/yr	Discharge	1.6
yr	Turnover Time	0.1
%	Relative area	5
log10	KAl	9
log10	Organic Acid pK1	2.64
log10	Organic Acid pK2	5.66
log10	Organic Acid pK3	5.94
mmol/m3	Organic acid	0
atm	pCO2	0.0041
deg C	Temperature	2.6

Soil Calibrated Parameters

Units	Parameter	Constant ash	Triangular ash
meq/m2/yr	Weathering Ca	54	54
meq/m2/yr	Weathering Mg	31	31
meq/m2/yr	Weathering Na	28	28
meq/m2/yr	Weathering K	7	7
%	Initial Exchangeable Ca	10.7	10.7
%	Initial Exchangeable Mg	3.8	3.8
%	Initial Exchangeable Na	0.7	0.7
%	Initial Exchangeable K	1	1
%	Initial Base Saturation	16.2	16.2
log10	Ca-Al Selectivity Coeff.	-0.21	-0.24
log10	Mg-Al Selectivity Coeff.	0.46	0.43
log10	Na-Al Selectivity Coeff.	-2	-2
log10	K-Al Selectivity Coeff.	-4.35	-4.47

Talus Calibrated Parameters

meq/m2/yr	Weathering Ca	8	8
meq/m2/yr	Weathering Mg	4	4
meq/m2/yr	Weathering Na	4	4
meq/m2/yr	Weathering K	1	1
meq/m2/yr	Weathering Cl	0	0

Lake Calibrated Parameters

% of input	Lake Uptake NH4	90	90
% of input	Lake Upake NO3	75	75

values (Table 22). The hindcast water quality of the catchment suggests that the catchment has responded to the historical increases in acidic deposition in the Pacific Northwest (Figures 33 and 34). The results described here and below were obtained using the average parameter set (see next section) derived from the "fuzzy calibration" procedure.

The model results show that future forecasts (Figures 35 and 36) for water chemistry in Gertrude Lake are relatively insensitive to assumptions regarding the weathering of the remaining volcanic ash in the watershed. Both assumptions yield similar responses for decreases in lake ANC regardless of the assumptions for weathering rates of the ash. Loss of ANC under a scenario involving a 100% increase in S and N deposition would be expected to cause a loss in ANC of about 5 μeq/L over a 20 year period following the increased deposition. A 200% increase in S and N deposition would be expected to cause a 10 μeq/L loss in average annual ANC. This would cause a reduction in pH of about 0.1 pH unit.

Table 22. Calibration results: goodness of fit for the calibrated model for Gertrude Lake. Comparison of simulated and observed annual average concentration for the calibration year 1996.

	Constant Ash Simulated	Triangular Ash Simulated	Observed
<u>Lake Variables (concentrations in μeq/L)</u>			
Ca	22	22	22
Mg	13	13	13
Na	15	15	15
K	3	3	3
NH_4	0	0	1
SO_4	10	10	10
Cl	5	5	5
NO_3	1	1	1
SBC	52	52	54
SAA	16	16	16
Calk	36	36	38
pH	5.7	5.7	6.1
<u>Soil Variables (exchangeable cations in %)</u>			
Ca	9.4	9.4	9.5
Mg	3.3	3.3	3.3
Na	0.7	0.7	0.7
K	0.9	0.9	0.9
Base saturation	14.2	14.2	14.4
pH	4.9	4.9	5.4

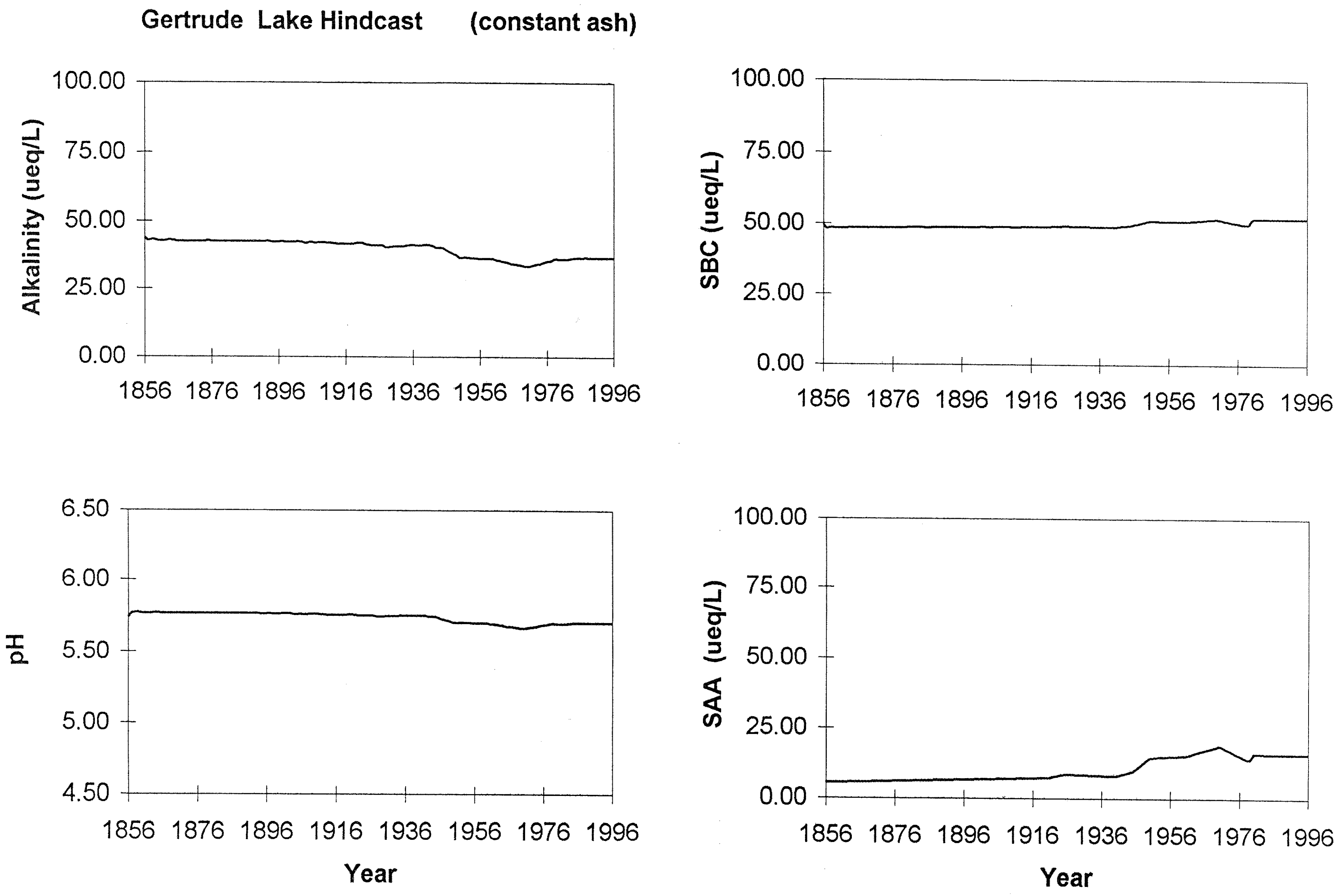


Figure 33. MAGIC model hindcasts of alkalinity (µeq/L), base cations (SBC, µeq/L), pH, and anions (SAA, µeq/L) for Gertrude Lake under an assumption of constant weathering rates for ash from Mount St. Helens.

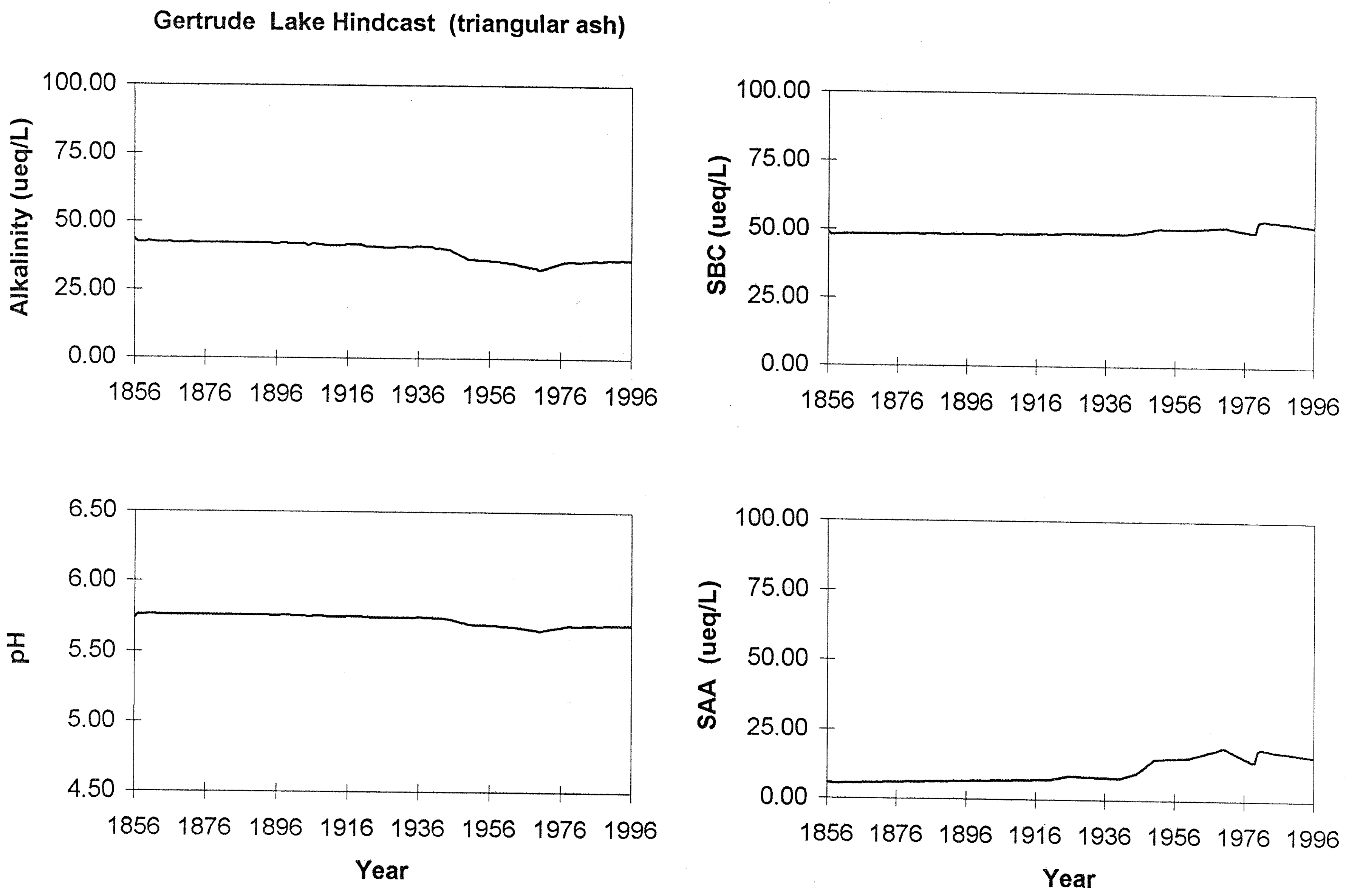


Figure 34. MAGIC model hindcasts of alkalinity (µeq/L), base cations (SBC, µeq/L), pH, and anions (SAA, µeq/L) for Gertrude Lake under an assumption of "triangular" (see text) weathering rates for ash from Mount St. Helens.

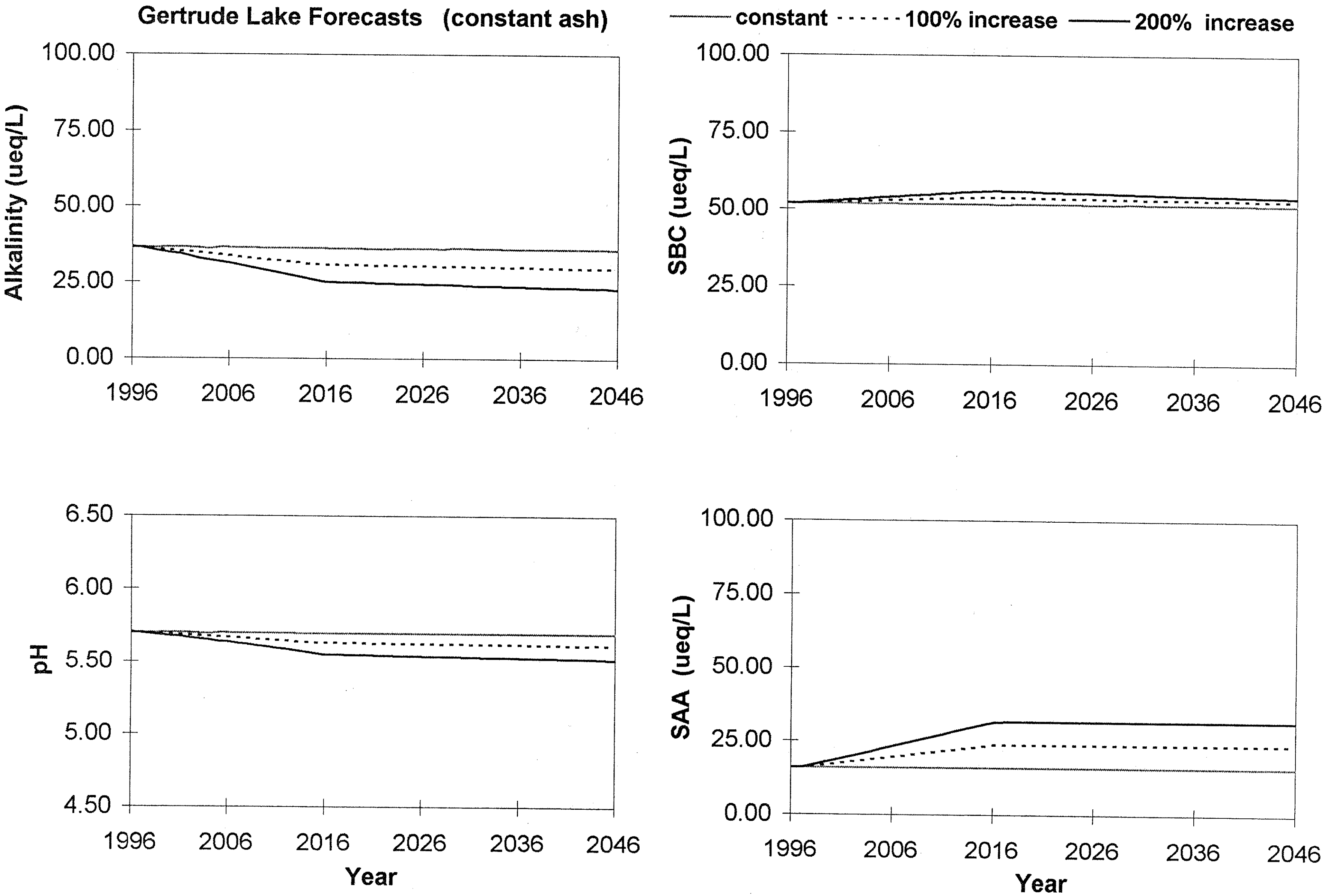


Figure 35. MAGIC model forecasts of alkalinity (μeq/L), base cations (SBC, μeq/L), pH, and anions (SAA, μeq/L) for Gertrude Lake under an assumption of constant weathering rates for ash from Mount St. Helens.

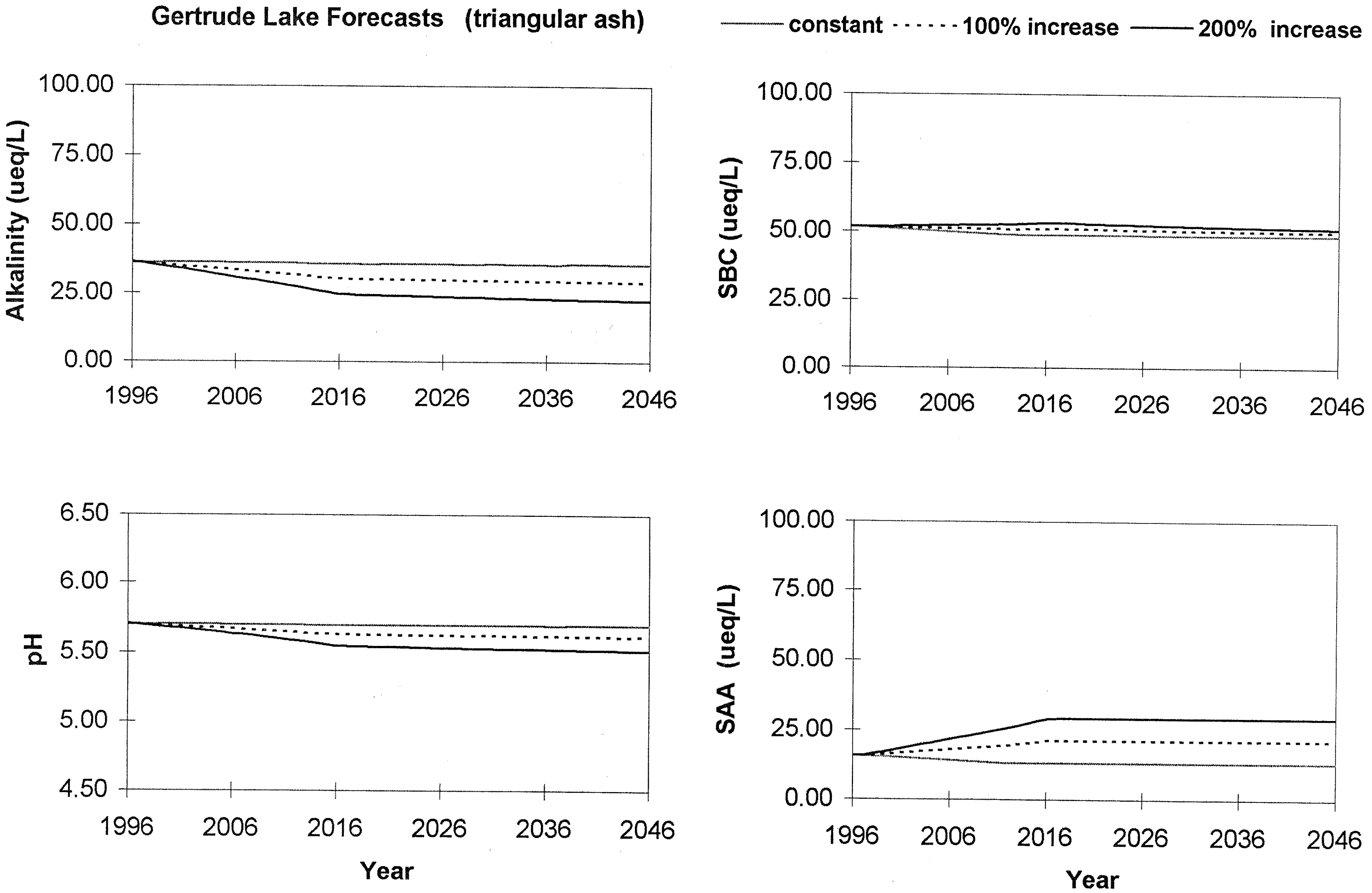


Figure 36. MAGIC model forecasts of alkalinity (µeq/L), base cations (SBC, µeq/L), pH, and anions (SAA, µeq/L) for Gertrude Lake under an assumption of "triangular" (see text) weathering rates for ash from Mount St. Helens.

The major effect on Gertrude Lake would be a forecasted reduction in lake ANC during snowmelt (Figure 37). In this case, mean spring (snowmelt) ANC was forecasted to decrease from an average of 35 μeq/L to a minimum average ANC of 18 to 29 μeq/L under a 200% increase in S and N deposition, depending on the assumptions associated with the weathering of ash. These model scenarios are based on average values observed in Gertrude Lake and do not deal with extreme values measured in the study or conditions in the lake that may have occurred prior to June.

IV. DISCUSSION

A. Snow Chemistry and Atmospheric Deposition

The snow chemistry collected in this study consistently showed that the snowpack in the study area during the period near maximum accumulation contained low concentrations of SO_4^{2-}, NO_3^-, NH_4^+, and H^+. The low concentrations of S and N in the snow deposition provides high quality runoff during snowmelt. Almost all of the ANC depression in the lake during snowmelt is presently caused by base cation dilution rather than neutralization of acid anions. Sodium and chloride were dominant ions in the snow and their presence indicates substantial input of marine aerosols into the Cascades. In general, concentrations of S and N were greatest at the Mount Rainier (Paradise) site and least at the Mount St. Helens site. Presumably the differences between these sites reflects the proximity to the major emission sources in the state. Both sites are on the south slopes of the respective peaks, but the Mount Rainier site is closer to some of the larger stationary emissions in western Washington (e.g., Centralia Power Plant) and mobile sources from the Seattle-Puget Sound region. The differences in snow concentration between these sites cannot be attributed to differences in precipitation volume because the Mount Rainier site receives nearly two-fold greater snowfall than the Mount St. Helens site which would further increase the disparity in acidic deposition between the sites.

The snow monitoring sites varied in elevation from 1340 m at Mount St. Helens to 1830 m at White Pass. Despite these differences, there was little indication that there were substantial differences in snow chemistry in the region as a function of elevation. Thus, concerns that high elevation lakes in the region would be experiencing concentrations of snowmelt runoff vastly different from runoff at lower elevation sites are probably unwarranted. In fact, there is a strong likelihood that there is a significant "wash-out" effect resulting in much of the S and N being deposited at lower elevation because of the greater scavenging efficiency of rain, fog, and clouds at lower elevations. This mechanism is suggested based on a comparison of snow chemistry at Mount Rainier with precipitation (rain) chemistry at the Pack Forest NADP/NTN site and based on higher concentrations of chloride at lower elevation lakes in the Goat Rocks wilderness (see Section IIA). Table 23 shows the differences in deposition concentration between the two sites for winter and non-winter periods, illustrating that snow appears to be a relatively inefficient collector for atmospheric

Pre-melt and snowmelt alkalinity (ueq/L) for selected years

Gertrude Lake

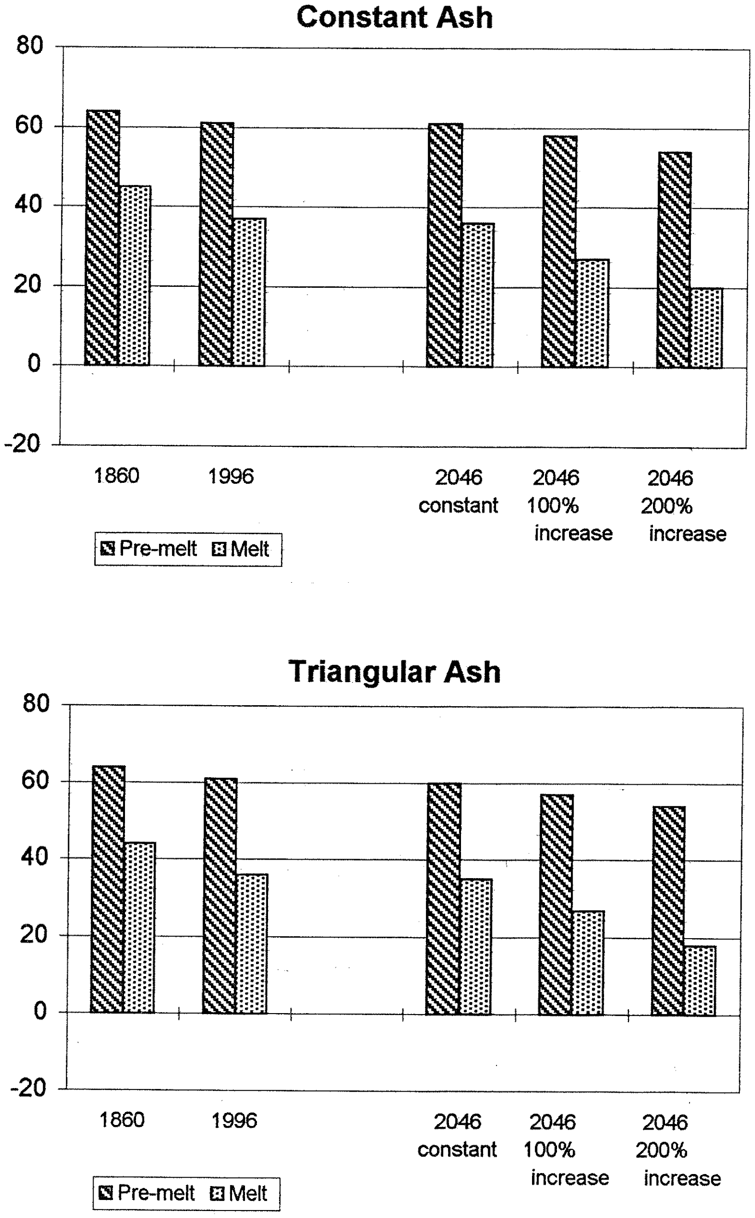


Figure 37. Changes in lake alkalinity (ANC, µeq/L) from pre-snowmelt to post-snowmelt generated by MAGIC in Gertrude Lake as a function of year and deposition rate. The 1860 date represents a hindcast estimate, the 1996 results correspond to values calibrated to data measured in this project, and the three forecasted runs are for current deposition rates, and increases in current deposition by 100% and 200%. The top set of model runs are based on assuming a constant rate of ash weathering and the bottom results assume a "triangular" rate of ash weathering.

Table 23. Comparison of wet deposition (kg/ha) of sulfate and nitrogen for this study (snow chemistry at Mount Rainier • vol. of SWE at time of sample), NRCS (E&S snow chemistry at Mount Rainier • maximum SWE at SNOTEL sites), and National Atmospheric Deposition Program (NADP) site at Pack Forest, both for winter only (Dec-Feb) and annual.

		SO_4				N			
Year	Site	This Study	NRCS	NADP Winter	NADP Annual	This Study	NRCS	NADP Winter	NADP Annual
1995	MR	5.0	NA	1.0	3.8	1.17	NA	0.26	1.36
1996	MR	0.9	1.5	0.9	5.1	0.39	0.64	0.4	1.2
1997	MR	3.0	4.1	1.3	NA	0.43	0.58	0.35	NA
1998	MR	2.5	NA	NA	NA	0.48	NA	NA	NA
Median		2.75	2.8	1.0	4.45	0.46	0.61	0.35	1.28

pollutants *or* that a greater proportion of the pollutants have been washed out at lower elevation prior to the frontal system moving into the mountains. Another feature illustrated by the comparison is the importance of non-winter precipitation in contributing to the annual deposition load of S and N. Winter deposition of S and N at Pack Forest represents about one-fourth of the annual deposition (Figure 38). Despite the absence of non-winter deposition monitoring from this study, it is the chemistry of the snowpack that has the greatest influence on ANC depression in the study lakes. Therefore, even though non-snow S and N deposition may be important on an annual basis, the wet and dry deposition inputs arrive when watershed and in-lake process also are providing the highest rates of weathering and neutralization.

B. Lake Chemistry

The lake chemistry data from Gertrude Lake and Cedar Pond indicate that both lakes start the spring with low ANC, which then increases about three-fold through the summer and fall. Assessments of lake sensitivity to acidic deposition in the western United States (e.g., Landers et al. 1987) based on fall ANC data would appear to substantially underestimate the number of sensitive systems and presumably their responsiveness to acidic inputs. However, despite the magnitude of snowmelt flux into these lakes, ANC was always positive (minimum of 10 µeq/L in Gertrude in June, 1995). Assuming the minimum ANC was represented by the spring samples from this study, then it suggests that weathering was occurring under the snowpack to generate ANC. The results from this study demonstrate that the assessment of lake water quality in these high elevation Cascade lakes varies greatly, regardless of parameter, depending on the season. Water quality variability during ice-cover further adds to the difficulty in characterizing these systems.

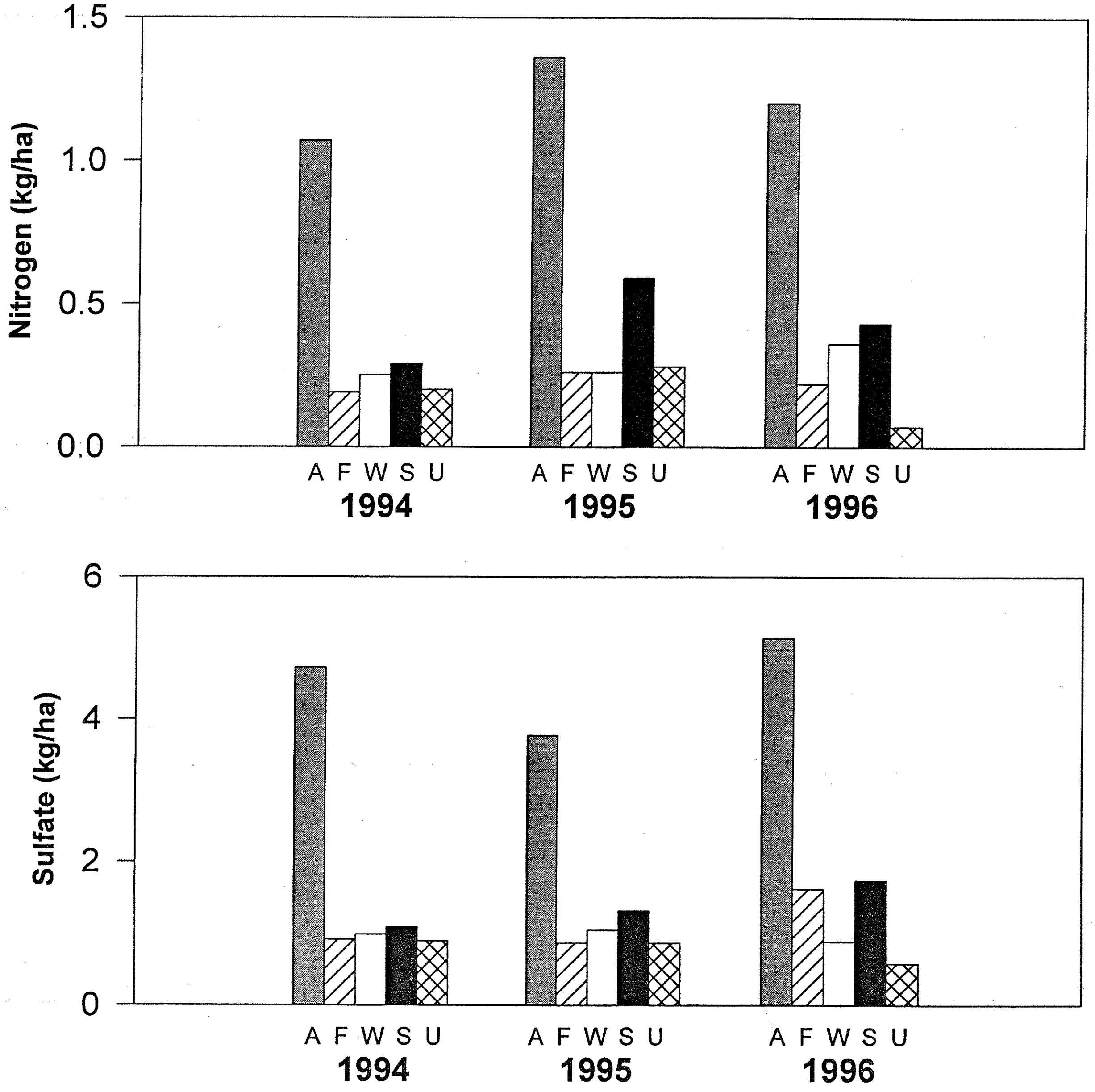


Figure 38. Deposition of nitrogen ($NO_3^-N + NH_4^+$-N) and sulfate measured at the Pack Forest NADP/NTN site in western Washington for 1994-1996. The tallest shaded var represents annual deposition (A); the adjacent results present seasonal values for fall (F), winter (W), spring (S), and summer (U).

The ANC depression that occurred in the spring in both lakes was almost entirely attributed to base cation dilution. Base cations decreased in direct proportion to the decrease in ANC and the relative contributions of acid anions (SO_4^{2-}, NO_3^-, Cl^-) was not substantially altered. Nitrate was never an important anion in these lakes, even during snowmelt. Assuming chloride was derived from marine aerosols, the only anthropogenic acid anion present in significant concentrations was sulfate, which was typically about 6 to 7 µeq/L in the spring, increasing to 10 to 15 µeq/L in the fall. Judging from the deposition chemistry for the region, additional sulfate is being delivered to the lakes from weathering processes. It is likely that some of this sulfate is derived from continued weathering of volcanic ash deposited from Mount St. Helens.

In addition to the natural disturbance to Gertrude Lake and Cedar Pond from volcanic inputs, there are anthropogenic influences on Gertrude Lake, in particular that are noteworthy. When the study was initiated, Gertrude Lake was a popular destination for horse packers originating from the Walupt Lake trailhead. Vegetation on the northeastern portion of the shoreline has been heavily grazed and trampled from tethering livestock within close proximity to the lake. The Gifford Pinchot National Forest Service staff operating out of Randle worked with the various horse packing organizations to discourage use of Gertrude Lake during the study. Recreational usership at Gertrude Lake appeared to have declined substantially during the study, but was never entirely eliminated. The opportunity for nutrient input from livestock use continued to a lesser degree. Phosphorus (TP) concentrations in Gertrude Lake typically ranged from ≤ 10 µg/L to about 20 µg/L, although four observations were reported between 20 and 50 µg/L. No seasonal phosphorus pattern in Gertrude Lake was evident and no trend was observed among years. In contrast, Cedar Pond showed increases in TP from ≤ 10 µg/L during spring and summer up to 20 µg/L in September. Other indicators of productivity such as TKN and TOC also showed maximum values in September.

Iron, aluminum, and silicon can to varying degrees indicate weathering and erosional inputs into lakes. Silicon in both lakes was lowest in spring, generally increased through summer and declined slightly in late summer or fall. This pattern closely parallels the increases in base cation concentrations. These concomitant increases in concentrations of silicon and base cations are consistent with plagioclase weathering.

The differences between chemical responses in Gertrude Lake and Cedar Pond are no more apparent than in the seasonal patterns for iron and aluminum. In Gertrude Lake, iron peaks at about 100 µg/L in early July when runoff from the tributaries is high and presumably the opportunity for physical erosion is also relatively high. However, in Cedar Pond, iron peaks at about 70 µg/L in August and September when surface runoff is absent. The pattern for aluminum in Cedar Pond is similar to that observed for iron in which the peak of aluminum (from 90-120 µg/L) occurs in September. In Gertrude Lake, the aluminum remains consistently low, seldom reaching 20 µg/L and showing no seasonal pattern. Thus, iron and aluminum appear to be tightly linked in Cedar Pond, but show no similar linkage in Gertrude Lake. Furthermore, the mechanism for the timing of high iron and aluminum in Cedar Pond is difficult to explain on the basis of erosional inputs from the watershed. Although Cedar Pond is shallow, it is small and reasonably sheltered from the wind which should minimize erosional input from wave action on the shoreline. pH remained near 6.5 during the summer and fall in Cedar Pond which would result in relatively low solubility for these metals. It is conceivable that the increases in iron and aluminum in Cedar Pond were biologically mediated through strong interaction of sediment with the water column and the benthic and pelagic biota. Another possibility is that dissolved iron and aluminum were entering the lakes through groundwater. This could help to explain the patterns observed in Gertrude Lake, although it would be unlikely that groundwater inputs would be sufficient to cause the patterns observed in September for Cedar Pond. As noted by Wetzel (1983), most iron in neutral lakes, typically found in the range of 50-200 µg/L, is dominated by $Fe(OH)_3$, organically complexed iron, and adsorbed sestonic iron.

Measures of productivity in both lakes generally showed increased values in the fall. TP, TOC, pH, TKN, and algae biovolume were all greatest in the fall in Cedar Pond. This coincides with a cessation of inputs from the watershed and a sharp increase in the hydraulic residence time of the pond. The lake level dropped, evapoconcentration increased and with elimination of surface outflow, the plankton had an opportunity to multiply rapidly. In Gertrude Lake, the chemical evidence for increased productivity in summer and fall was more ambiguous, but other measures such as Secchi disk transparency and algal biovolume clearly showed a strong tendency for greater productivity later in the year. The algal community composition supports the assessment that the lakes are moderately productive, although taxonomic diversity was relatively low. Gertrude Lake was more productive than Cedar Pond and consistently exhibited algal biovolume numbers an order of magnitude greater on all occasions for which samples were collected.

The question of whether the study lakes had been chemically altered by natural or anthropogenic factors was not directly addressed in this study. Paleolimnologic approaches are available to more definitively assess these questions. Nevertheless, the issue of how the lakes may have responded to various perturbations is relevant to this study because the responsiveness of these lakes to atmospheric deposition of S and N is not independent of their responsiveness to other factors. Other 20th century perturbations include the eruption of Mount St. Helens in 1980 and subsequent emission of gases and ash later in the 1980's, nutrient inputs from livestock, and effects of fish stocking.

The eruption of Mount St. Helens deposited several centimeters of ash in the Gertrude Lake area (Dion and Embry 1981, Sarna-Wojcizki et al. 1987). The composition of the ash was relatively high in leachable base cations, sulfur, phosphorus, and silica (Hinkley 1987). A survey of lakes receiving comparable amounts of ashfall showed no gross alterations, although no long-term analysis of changes in lake productivity or major ion chemistry was conducted on lakes beyond the blast zone of Mount St. Helens. Based on the composition of the ash, the magnitude of the ashfall[1], and results of chemical leaching studies, it is likely that Gertrude Lake and Cedar Pond showed increases in base cations, ANC, pH, sulfate, phosphorus, and perhaps nitrogen and organic matter. Most of this material has probably been incorporated into the soil or blown out of the watershed although some ash was still present under the rocks in the talus field to the south of Gertrude Lake. The current sulfate concentrations in the lake are slightly elevated above values expected based on measurements of wet deposition, even including some component for dry deposition and evapoconcentration. It appears that some watershed source, perhaps from the remnant ash, may continue to leach S into both lakes.

As noted previously, Gertrude Lake, prior to this study, was a popular horse packing destination. The overgrazing of vegetation and livestock waste was apparent on the northeastern portion of the shoreline. Because of action taken by the Forest Service staff, livestock use of Gertrude Lake decreased substantially during the study. The effect of this activity on the lake is uncertain although there was an apparent increase in Secchi disk transparency in Gertrude Lake during the course of the study. The average transparency increased by about 1 m (adjusted seasonally) over the course of the study. Clearly, other factors may have caused the change in transparency including climate. The last three years of the study were wetter than the drought at the beginning of the study and it is possible that increased runoff and cooler temperatures had an impact on the observed decline in lake productivity.

Gertrude Lake and Cedar Pond probably were fishless historically. Obstructions and waterfalls upstream of Walupt Lake would have prevented any natural migration of fish into either study site. Gertrude Lake was stocked sometime in the 20th century and currently supports a self-sustaining rainbow trout population. Introduction of fish into previously fishless lakes often results in an increase in phytoplankton because the fish consume the large zooplankton taxa. Without the large zooplankton to efficiently graze the phytoplankton, the algal growth increases, typically resulting in an increase in phosphorus and a decrease in transparency (Proulx et al. 1996, Sarnelle 1992). Whether this mechanism operated in Gertrude Lake is unknown, although a paleolimnological analysis of Diamond Lake in the Oregon Cascades supports this mechanism as one hypothesis to explain current conditions in Gertrude Lake (Eilers et al. 1997).

C. Watershed Modeling

The watershed modeling illustrated that under the conditions measured during this study, the current rates of atmospheric deposition of S and N have little impact on either Gertrude Lake or Cedar Pond. Nearly all of the current ANC-depression in the spring is associated with base cation

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[1] Examination of aerial photographs of the Gertrude Lake watershed showed considerable ash still present in 1981.

dilution caused by dilution of the lakes with high quality, low-ionic strength snowmelt. Even lake water samples collected during snowmelt while the lake was ice-covered failed to detect any significant pulses of acid anions that might be associated with the ANC depression. However, it is conceivable that elutriation of the snowpack could have caused acid pulses in May when the lake was inaccessible.

The model forecasts showed that under 100% increases in atmospheric deposition of both S and N, lake ANC concentrations would decrease by about 5 μeq/L on a long-term basis. This forecasted decrease in ANC is comparable to the hindcast change in ANC that was modeled to have occurred based on estimated changes in deposition over the last 130 years. A 200% increase in S and N deposition would cause an additional loss of about 5 μeq/L in annual average ANC. The assumptions about the exact nature of the remaining weathering from the ash deposited in the watershed from the 1980 volcanic eruption had little impact on the response of Gertrude Lake beyond the period past 2016 (20 years from the base of 1996 used in the modeling). The major impact on Gertrude Lake associated with a further increase in deposition was the forecasted decrease in lake ANC during snowmelt. The current estimated ANC decrease from pre-melt to snowmelt (spring) lake chemistry is about 25 μeq/L. Snowmelt ANC is forecasted to decrease because of a forecasted chronic decrease in pre-melt ANC and an increasing disparity between pre-melt and snowmelt lake ANC. Under a 100% increase in S and N deposition, the disparity between pre-melt and snowmelt lake ANC is expected to increase from 25 μeq/L (current) to about 30 μeq/L; under a 200% increase in deposition, the forecasted difference between pre-melt and snowmelt ANC in the lake will increase to about 35 μeq/L. These model forecasts were developed using average lake chemistry measured over the five-year study. If the minimum lake ANC values are used instead, the modeled ANC forecasts would be decreased further. In summary, the concern for chronic acidification of these lakes is low; the concern for episodic acidification is a greater concern although the increased loading for these study lakes would require substantial increases in S and N deposition.

To achieve satisfactory calibration of the model required that we increase the output fluxes of sulfate and chloride beyond what we could account for on the basis of estimated input fluxes. This was simulated as a "treatment" to the watershed using two approaches: (a) constant weathering from the ash and (b) a large increase followed by a constant rate of decline to zero weathering in 2016. The model forecasts were relatively insensitive to choice of weathering assumptions.

Although it was necessary to incorporate the weathering of volcanic ash to calibrate MAGIC in Gertrude Lake, we did not attempt to simulate other perturbations such as recreational effects associated with livestock grazing and fish introduction. Nutrient-mediated effects on ANC are currently not represented in the model nor was there a strong quantitative basis for determining how to simulate these effects - assuming that they even occurred.

One of the surprising aspects of the watershed monitoring results, and therefore its effect on the modeling, was the degree of weathering derived from the talus. The ANC generated from this relatively bare-rock portion of the watershed equaled the ANC concentrations from portions of the watershed with soil present. Thus, attempts to determine the sensitivity of other lakes in the region based on the degree of soil (or vegetation) present in the watershed may not be successful.

The model forecasts showed little change in lake chemistry over the next 50 years at current levels of S and N deposition. Rates of watershed weathering appear to be adequate to neutralize most of the current inputs. We presume that weathering rates would be maintained beyond the forecast period, although this hypothesis was not tested with the model.

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APPENDIX A

Reported Annual Air Emission Inventories for the Weyerhaeuser Paper Company Longview Pulp and Paper Mill Plant from 1993 to 1997

LONGVIEW PULP and PAPER MILL ANNUAL AIR EMISSIONS

Data from Annual Air Emission Inventory submitted to DOE - Excludes NORPAC Emissions

TONS/CALENDAR YEAR

	PM	PM-10	SO2	Nox	VOC	CO	TRS	HCl	ton ubadp +
1993	703	601	1512	3390	485	9804	* 7.3	NA	353656 **
1994	625	569	1366	3434	815	4445	112.8	57.8	330204 **
1995	518	353	1082	3529	722	3339	61.2	57.6	365433 ***
1996	372	306	994	2960	633	3204	9.3	53.6	406778
1997	272	281	763	3119	415	2803	8.6	52	399743

* = DOES NOT INCLUDE TRS from old washers

** = Includes TSV production

*** = Does not include TSV production

\+ - ubadp = unbleached air dry pulp

APPENDIX B

Complete Chemistry Data Including both Snow and Lake Water

Appendix B - Complete Chemistry Data including both Snow and Lake Water

DATE	LOCAT	SAMPLEID	TYPE	LAB	PH	ANC	SPCOND	CA	MG	NA	K	SO4	CL	NH4	TP	TKN	TOC	FORMATE	PROPIONA	FLUORIDE	ACETATE	LEAD	IRON	MN	PO4	NO3	ALT	SI	CONDCAL	CATSUM	ANSUM	cbca
08/04/93	SL	Sheep Lake	R	FS	7.03	131	14.5	85.7	24.6	40.5	7.1	27.5	6.4	0.0												0.0		2.78	17.2	157.9	165.0	124
08/05/93	BC	Beaver Pond	R	FS	6.79	137	14.2	87.9	26.9	53.7	6.4	13.2	8.5													0.0		3.88	17.3	175.1	158.6	153
08/05/93	CC	Cedar Center	R	QST	6.63	45	6.4	18.0	13.2	27.8	3.1	11.0	5.9	0.0												0.0			6.5	62.3	62.0	45
08/05/93	GC	Gertrude	R	FS	6.88	75	8.9	42.1	26.3	31.1	5.5	13.6	6.3													0.0		3.63	10.5	105.2	95.4	85
08/05/93	GC	Gertrude Center		QST	6.88	75	8.9	41.9	26.3	30.9	5.9	14.0	5.9	0.0												0.0			10.5	105.1	94.9	85
08/05/93	UL	unamed lake north of Gertrude	R	FS	6.63	45	6.4	18.1	13.3	27.9	2.6	10.6	5.6													0.0		3.68	6.5	62.2	61.5	46
08/06/93	GL	Glacier Lake	R	FS	7.40	17	35.1	201.4	55.4	103.1	20.5	35.5	14.6													0.0		17.36	25.6	380.4	67.5	330
08/06/93	CL	Chambers Lake	R	FS	7.55	595	55.7	396.9	114.2	107.7	7.1	45.6	13.6													0.0		5.04	66.1	625.8	654.1	567
08/06/93	GL	Glacier Lake	R	FS	7.40	17	35.1	201.4	55.4	103.1	20.5	35.5	14.6													0.0		17.36	25.6	380.4	67.5	330
08/29/93	CC	Cedar Center	D	FS	6.60	38	6.9	42.0	19.3	31.0	2.9	12.5	5.2	0.3												0.4		3.71	8.2	95.4	56.2	77
08/29/93	CC	Cedar Center	R	QST	6.60	38	6.9	29.9	18.9	30.9	3.1	12.1	5.1	0.0												0.0			7.4	83.1	55.2	66
08/29/93	GC	Gertrude Center	D	FS	6.76	63	9.3	30.0	23.4	29.7	5.8	14.0	6.7	0.0												0.0		3.28	9.1	89.0	83.4	68
08/29/93	GC	Gertrude Center	D	QST	5.95	79	11.0	37.9	23.9	29.1	6.9	14.0	9.0	0.0	0.01	0.22										0.0			10.8	99.0	102.0	75
08/29/93	GC	Gertrude Center	R	QST	6.76	63	9.3	41.9	23.0	30.0	5.9	14.0	7.1	0.0												0.0			9.8	101.0	84.0	80
09/28/93	CC	Cedar Center	R	QST	6.52	67	9.1	27.9	17.3	27.0	4.1	14.0	5.9	0.0	0.02	0.20										0.0			8.6	76.6	86.9	56
09/28/93	GC	Gertrude Center	R	QST	6.87	77	11.0	41.9	27.1	29.1	5.9	14.0	7.1	0.0	0.02	0.18										0.0			10.6	104.2	98.0	83
10/19/93	CC	Cedar Center	R	QST	6.67	58	8.9	29.9	18.9	29.1	4.1	16.0	7.1	0.0	0.01	0.19										0.0			8.7	82.3	81.1	59
10/19/93	GC	Gertrude Center	R	QST	6.80	91	12.0	41.9	26.3	33.9	7.9	14.0	9.0	0.0	0.01	0.15										0.0			11.6	110.3	114.0	87
04/01/94	LB	Lone Butte	R	QST	5.20	-1		1.5	1.2	3.6	0.4	5.2	7.6	1.0	0.01	0.23	1.0	0.01		0.01	0.01	50	45	5		1.2	50		3.3	13.1	14.0	-7
04/02/94	SH	Mt. St. Helens	R	QST	5.23	-4		1.0	0.8	3.0	0.7	1.8	4.2	1.6	0.01	0.10	1.0	0.01		0.03	0.01	50	45	5		1.1	55		2.7	11.4	7.1	-2
04/02/94	SH	Mt. St. Helens	D	QST	5.08	-3		0.5	0.7	1.6	0.2	1.6	3.2	1.6	0.01	0.10	1.0	0.01		0.01	0.01	50	48	5		0.9	83		3.4	11.4	5.6	-3
04/03/94	WP	White Pass	R	QST	4.77	28		1.3	1.0	2.5	0.5	2.9	3.5	0.7	0.01		1.0	0.01		0.01	0.02	50	45	5		1.3	50		7.9	22.3	35.8	-2
04/03/94	WP	White Pass	D	QST	5.18	4		2.5	1.4	6.0	1.3	2.9	6.0	0.9	0.01	0.48	1.0	0.01		0.01	0.01	50	45	5		1.6	50		3.6	17.9	14.2	1
04/04/94	CS	Cold Springs Butte	R	QST	5.19	1		2.5	2.1	7.5	1.4	2.5	9.3	1.4	0.01	0.23	1.0	0.01		0.01	0.01	50	76	5		1.6	102		3.6	20.0	14.5	0
04/05/94	GB	Green Butte	R	QST	5.12	0		0.6	1.0	1.5	0.2	1.7	2.4	1.9	0.01	0.25	1.0	0.01		0.01	0.01	50	45	5		1.1	50		3.1	10.9	5.5	-2
04/05/94	GB	Green Butte	D	QST	5.06	2		0.8	0.8	2.1	0.5	1.5	2.7	0.8	0.01	0.10	1.0	0.01		0.01	0.01	50	60	5		1.1	58		3.7	13.0	7.5	-1
04/06/94	MR	Mount Rainier	R	QST	4.95	-3		1.4	1.3	4.5	0.6	4.6	6.0	0.8	0.01	0.29	1.0	0.01		0.01	0.01	50	46	5		1.6	175		5.0	19.1	12.2	-4
04/06/94	MR	Mount Rainier	D	QST	5.00	-5		0.7	1.3	4.2	0.3	3.5	5.8	0.7	0.01	0.27	1.0	0.01		0.01	0.01	50	45	5		1.4	50		4.4	16.5	10.7	-4
06/03/94	CC	Cedar Center	R	QST	6.42	21	6.7	17.7	9.2	14.2	1.2	9.8	5.3	0.7	0.01	0.10										0.6			4.4	42.8	37.0	27
06/03/94	GC	Gertrude Lake	R	QST	6.09	37	8.4	24.1	13.1	17.0	4.1	8.4	8.7	1.6	0.01	0.16										0.6			6.2	59.1	54.8	41
06/03/94	GO	Gertrude Outlet	O	QST	5.94	45	8.6	28.8	15.4	16.1	2.9	10.6	5.9	0.7	0.01	0.12										0.6			7.0	64.4	62.2	46
07/07/94	GIS	Gertrude Inlet	R	QST	5.96	21	4.4	12.9	5.4	10.9	0.8	8.1	4.1	0.7	0.02	0.10										0.6			3.8	31.2	33.5	17
07/08/94	CC	Cedar Center	R	QST	5.80	47	7.4	22.4	14.1	20.0	2.7	9.2	6.3	0.7	0.01	0.10										0.6			6.9	60.7	62.5	43
07/08/94	GC	Gertrude Lake	R	QST	6.02	66	9.3	31.9	20.0	20.6	4.4	10.9	6.0	0.7	0.01	0.23										0.6			8.6	77.8	83.1	59
08/06/94	HL	Hugo Lake	R	FS	7.34	512	49.7	393.5	77.7	82.4	7.4	34.7	11.7													0.0		4.75	58.1	561.1	558.5	515
08/06/94	WL	Wright Lake	R	FS	7.60	1070	96.0	880.8	126.2	157.8	7.1	82.9	15.0													0.0			122.2	1171.9	1167.8	1074
08/15/94	CC	Cedar Center	R	QST	6.01	40	9.0	25.1	16.0	24.8	3.9	11.0	6.5	5.7	0.01	0.23										0.6			7.1	70.7	57.8	52
08/15/94	GC	Gertrude Lake	R	QST	6.10	64	10.7	32.6	21.8	23.3	5.0	11.9	7.6	6.1	0.02	0.25										0.6			8.9	83.5	83.6	63
09/12/94	CC	Cedar Center	R	QST	6.35	62	10.4	28.1	18.3	28.8	4.7	13.2	6.9	0.7	0.02	0.29										0.6			8.6	80.4	82.4	59
09/12/94	GC	Gertrude Lake	R	QST	6.05	81	10.9	36.3	24.6	24.7	4.3	11.3	6.8	0.7	0.02	0.26										0.6			10.1	90.7	99.7	71
10/10/94	CC	Cedar Center	R	QST	6.00	63	10.4	30.9	20.2	30.8	4.9	17.1	8.1	0.0	0.02	0.31										0.7			9.6	87.7	89.2	61
10/10/94	GC	Gertrude Lake	D	QST	5.65	88	11.3	40.6	26.2	27.4	5.7	11.9	9.4	0.7	0.02	0.32										0.6			11.5	102.2	109.5	78
10/10/94	GC	Gertrude Lake	R	QST	5.83	85	12.1	41.2	26.3	25.8	4.9	11.8	7.3	0.7	0.02	0.27										0.6			11.0	99.6	104.8	78
02/28/95	GB	Green Butte	D	QST	5.00	1	4.9	1.4	3.1	12.7	0.6	3.7	17.0	2.4	0.01	0.10	1.0	0.02	0.05	0.02	0.02	50	45	5		1.6	50		5.4	27.9	23.2	-4
02/28/95	GB	Green Butte	R	QST	5.06	-3	4.6	1.3	3.0	12.1	0.5	3.4	15.7	2.1	0.01	0.10	1.0	0.02	0.05	0.02	0.02	50	45	5		1.7	50		4.8	25.7	20.8	-4
02/28/95	LB	Lone Butte	R	QST	5.34	-5	2.6	1.1	0.7	2.7	0.2	0.9	2.7	1.8	0.01	0.10	1.0	0.02	0.05	0.02	0.02	50	45	5		0.9	50		2.1	9.4	4.5	0
02/28/95	LB	Lone Butte	D	QST	5.32	-4	2.4	0.9	0.7	2.9	0.4	1.0	2.9	1.5	0.01	0.10	1.0	0.02	0.05	0.02	0.02	50	45	5		0.9	50		2.2	9.8	4.8	0
03/25/95	CS	Cold Springs Butte	R	QST	5.46	-14	3.2	0.7	0.7	6.7	0.4	6.5	4.0	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.1	50		2.4	12.0	11.6	-3
03/25/95	CS	Cold Springs Butte	D	QST	5.43	-10	3.3	0.6	0.7	6.0	0.3	6.2	3.0	0.7	0.02	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.1	50		2.4	11.4	10.3	-3
03/25/95	WP	White Pass	R	QST	5.44	-11	3.6	1.0	0.9	8.2	0.5	9.2	3.3	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.3	50		2.7	14.2	13.8	-3
03/25/95	WP	White Pass	D	QST	5.42	-12	3.6	1.1	0.9	8.7	0.4	8.0	3.7	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.2	50		2.7	14.9	12.8	-2
04/03/95	MR	Mount Rainier	R	QST	5.48	-11	3.2	0.8	1.2	4.3	0.2	2.2	5.5	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.1	50		1.9	9.8	8.8	-2

Appendix B - Complete Chemistry Data including both Snow and Lake Water

DATE	LOCAT	SAMPLEID	TYPE	LAB	PH	ANC	SPCOND	CA	MG	NA	K	SO4	CL	NH4	TP	TKN	TOC	FORMATE	PROPIONA	FLUORIDE	ACETATE	LEAD	IRON	MN	PO4	NO3	ALT	SI	CONDCAL	CATSUM	ANSUM	cbca
04/03/95	MR	Mount Rainier	D	QST	5.48	-10	2.9	0.9	1.2	4.4	0.3	2.2	5.2	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.2	50		1.9	10.1	8.6	-2
04/03/95	SH	Mt. St. Helens	R	QST	5.54	-10	3.5	0.7	0.7	3.1	0.2	1.1	3.6	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.0	50		1.5	7.6	5.7	-1
04/03/95	SH	Mt. St. Helens	D	QST	5.62	-7	2.5	0.6	0.7	3.0	0.2	1.2	3.3	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		0.9	50		1.3	7.0	5.5	-1
06/15/95	CC	Cedar Center	R	QST	6.05	22	5.3	19.5	9.7	13.8	1.4	7.6	4.2	0.7	0.01	0.21	1.0						11			0.6	45	3.23	4.5	45.3	34.3	32
06/15/95	CI	Cedar Inlet	R	QST	6.41	26	6.1	21.6	10.9	15.1	1.7	8.5	6.1	0.7	0.01	0.10	1.0						9			0.6	34	3.29	4.9	49.8	40.7	34
06/15/95	GC	Gertrude Lake	R	QST	5.89	10	4.1	12.1	6.6	7.1	1.7	4.0	3.3	0.7	0.02	0.19	1.0						11			0.6	9	1.48	2.9	28.9	17.7	20
06/15/95	GIW	Gertrude West Inlet	R	QST	6.18	131	14.7	69.4	47.2	34.6	7.6	11.6	7.5	0.7	0.02	0.19	1.0						52			0.6	20	9.45	16.2	159.4	150.7	139
07/10/95	CC	Cedar Center	R	QST	6.40	45	6.3	25.2	13.6	16.4	2.4	8.7	4.8	0.7	0.01	0.10	1.9						38			0.6	37	6.82	6.2	58.0	58.7	44
07/10/95	CI	Cedar Inlet	R	QST	6.23	49	7.5	31.1	16.2	18.2	2.5	8.9	4.9	0.7	0.01	0.10	1.8						25			0.6	34	7.19	7.1	68.5	63.6	54
07/10/95	GC	Gertrude Lake	R	QST	6.82	63	8.7	36.9	20.2	19.2	3.9	10.5	5.1	0.7	0.01	0.10	1.2						106			0.6	5	6.98	8.4	80.3	79.4	64
07/10/95	GIE	Gertrude East Inlet	R	QST	5.71	5	2.9	7.0	4.4	4.2	1.0	2.5	2.8	0.7	0.01	0.10	1.7						24			0.6	20	1.72	2.2	18.5	11.3	11
07/10/95	GIS	Gertrude South Inlet	R	QST	6.43	11	3.8	13.3	5.3	8.9	0.5	8.1	2.8	0.7	0.01	0.10	1.0						5			0.6	5	4.68	3.0	28.4	22.8	17
07/10/95	GIW	Gertrude West Inlet	R	QST	6.54	112	13.5	55.8	36.7	33.2	6.6	12.1	6.1	0.7	0.01	0.10	2.1						47			0.6	20	15.72	13.7	132.7	130.8	114
08/23/95	CC	Cedar Center	R	QST	6.56	57	7.7	22.1	14.2	24.1	3.7	8.9	7.3	1.4	0.01	0.19	2.7						33			0.6	89	4.11	7.2	64.4	74.2	47
08/23/95	GC	Gertrude Lake	R	QST	6.58	86	10.6	38.5	23.8	25.8	5.4	12.2	6.7	0.7	0.04	0.14	1.7						10			0.6	10	4.33	10.4	93.7	105.7	74
09/19/95	CC	Cedar Center	R	QST	6.69	49	8.4	25.6	16.3	23.9	3.6	9.2	5.8	0.7	0.02	0.16	2.7						66			0.6	118	3.48	7.1	69.6	64.8	54
09/19/95	CC	Cedar Center	D	QST	6.59	46	8.5	25.6	16.3	23.6	3.6	9.3	5.8	0.7	0.02	0.17	2.7						66			0.6	118	3.61	6.9	69.4	61.4	53
09/19/95	GC	Gertrude Lake	R	QST	6.88	77	11.8	39.3	24.9	26.5	5.5	11.1	6.2	0.7	0.01	0.40	1.8						10			0.6	10	4.30	10.0	96.4	95.0	78
09/19/95	GC	Gertrude Lake	D	QST	7.01	80	11.7	39.2	24.8	27.0	5.6	11.2	6.5	0.7	0.01	0.11	1.8						10			0.6	10	4.29	10.1	96.7	98.1	78
10/25/95	CC	Cedar Center	R	QST	6.49	50	9.3	28.5	16.4	22.3	3.8	11.6	14.4	0.8	0.01	0.16	1.9						18			0.6	55	4.27	7.7	71.3	76.7	44
10/25/95	GC	Gertrude Lake	R	QST	6.98	90	10.9	37.6	23.5	24.7	5.1	10.3	6.7	1.1	0.02	0.10	1.4						10			0.6	10	3.67	10.2	91.0	107.5	73
03/11/96	LB	Lone Butte	R	QST	5.46	-10	2.3	0.4	0.7	1.8	0.2	0.8	2.2	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		0.8	50		1.6	6.5	3.8	-1
03/11/96	LB	Lone Butte	D	QST	5.45	-11	2.2	0.5	0.7	2.0	0.2	1.1	2.5	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		0.9	50		1.6	6.9	4.6	-1
03/11/96	WP	White Pass	R	QST	5.44	-4	3.7	0.1	0.6	2.0	0.3	1.5	2.6	0.7	0.01	0.22	1.0	0.01	0.01	0.01	0.01	50	45	5		1.4	50		1.7	6.6	5.5	-3
03/11/96	WP	White Pass	D	QST	5.41	-12	2.5	0.4	0.8	2.4	0.3	2.1	3.2	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.4	50		1.9	7.8	6.7	-3
03/11/96	WP	White Pass	B	QST	5.41	-10	2.4	0.4	0.7	1.8	0.3	1.2	2.2	0.8	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.1	50		1.8	7.0	4.5	-1
03/11/96	WP	White Pass	M	QST	5.31	-8	2.5	0.4	0.7	1.7	0.1	2.1	2.2	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.4	50		2.2	7.8	5.7	-3
03/11/96	WP	White Pass	T	QST	5.29	-10	3.1	1.3	1.4	3.8	0.4	3.9	4.1	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.9	50		2.7	12.1	10.0	-3
03/15/96	MR	Mount Rainier	T	QST	5.29	-9	2.7	0.8	0.9	3.3	0.7	2.7	3.4	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.5	50		2.5	10.8	7.6	-2
03/15/96	MR	Mount Rainier	M	QST	5.47	8	3.0	1.2	0.9	4.4	1.8	0.8	4.4	3.9	0.01	0.10	1.0	0.01	0.01	0.04	0.01	50	45	5		0.6	50		2.3	11.8	14.1	3
03/15/96	MR	Mount Rainier	D	QST	5.41	-5	2.8	0.7	0.5	1.6	0.2	1.2	2.0	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		0.9	50		1.7	6.9	4.1	-1
03/15/96	MR	Mount Rainier	B	QST	5.42	-6	2.2	0.3	0.5	1.1	0.1	0.8	1.3	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		0.6	50		1.6	5.9	2.7	-1
03/15/96	MR	Mount Rainier	R	QST	5.33	-6	2.5	0.4	0.6	1.9	0.4	1.1	2.4	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		0.9	50		2.0	8.0	4.5	-1
03/15/96	SH	Mt. St. Helens	R	QST	5.52	-3	2.9	0.1	0.4	2.2	0.2	1.4	2.6	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.1	50		1.5	5.9	5.1	-2
03/15/96	SH	Mt. St. Helens	M	QST	5.46	-1	2.3	0.3	0.6	3.7	0.6	0.8	4.2	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		0.6	50		1.7	8.6	5.6	-1
03/15/96	SH	Mt. St. Helens	B	QST	5.50	-1	2.2	0.2	0.4	1.5	0.2	0.8	1.8	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		0.6	50		1.4	5.5	3.2	-1
03/15/96	SH	Mt. St. Helens	T	QST	5.44	-4	3.1	0.7	0.7	4.4	0.2	2.1	2.6	1.4	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		2.0	50		2.0	9.6	6.7	-1
03/15/96	SH	Mt. St. Helens	D	QST	5.42	-5	2.7	0.9	0.9	3.7	0.9	1.6	4.2	0.8	0.01	0.10	1.0	0.01	0.01	0.01	0.01	50	45	5		1.0	50		2.0	10.1	6.8	0
06/04/96	CC	Cedar Center	R	QST	5.97	13	3.3	8.0	4.3	6.2	0.7	3.8	3.0	1.4	0.01	0.19	1.0						7			0.6	17	0.83	2.5	20.3	20.5	12
06/04/96	CI	Cedar Inlet	R	QST	6.20	30	5.2	19.9	10.2	11.7	1.4	6.0	3.4	0.7	0.01	0.10	1.0						10			0.6	30	2.55	4.6	43.8	39.9	33
06/04/96	GC	Gertrude Lake	R	QST	6.09	21	4.3	13.1	6.4	9.4	1.5	5.5	3.8	0.7	0.01	0.10	1.0						7			1.2	5	1.19	3.5	31.2	31.1	20
06/04/96	GC	Gertrude Lake	R	QST	6.15	32	6.2	20.7	11.9	15.3	2.5	6.1	7.9	0.9	0.01	0.10	1.0						11			1.1	5	1.91	5.3	51.1	47.4	35
06/04/96	GO	Gertrude Outlet	O	QST	6.00	45	6.8	26.6	15.2	15.1	2.9	7.5	5.4	0.7	0.01	0.10	1.0						15			1.1	16	2.64	6.5	60.8	58.9	46
06/28/96	CC	Cedar Center	R	QST	6.50	40	6.1	22.6	12.5	14.8	1.8	7.5	3.3	0.7	0.01	0.10	1.0						18			0.6	27	2.59	5.5	52.0	50.8	40
06/28/96	CI	Cedar Pond	R	FS	6.22	45	6.3	26.5	15.9	20.6	1.0	7.6	3.6	0.0						0.00					0	0.0			6.5	64.6	56.4	53
06/28/96	CI	Cedar Inlet	R	QST	6.37	53	7.2	27.8	15.1	16.6	2.1	7.7	3.6	0.7	0.01	0.10	1.1						24			0.6	28	2.76	6.7	62.1	65.2	50
06/28/96	GC	Gertrude Lake	R	QST	6.54	102	11.2	45.6	27.1	23.8	4.8	9.4	5.7	0.7	0.01	0.10	1.0						39			0.6	5	4.03	11.3	101.6	117.7	86
06/28/96	GIE	Gertrude East Inlet	R	QST	5.84	7	2.8	5.8	3.4	3.8	0.9	1.6	1.6	0.7	0.03	0.28	1.0						16			0.6	12	0.66	1.8	15.3	10.6	10
06/28/96	GIW	Gertrude West Inlet	R	FS	6.51	98	10.3	53.5	34.7	30.8	5.2	9.4	5.3	1.1						0.00					0	0.0			12.3	124.5	112.4	109
06/28/96	GIW	Gertrude West Inlet	R	QST	6.35	105	11.7	47.3	30.1	27.3	5.1	10.9	5.7	0.7	0.01	0.11	1.0						28			0.6	12	6.14	12.1	110.3	122.2	93
08/13/96	CC	Cedar Center	R	QST	6.60	59	7.8	25.9	16.8	23.1	3.6	6.6	5.0	0.9	0.01	0.13	1.7						67			0.6	66	5.05	7.3	69.6	71.3	57
08/13/96	GC	Gertrude Lake	R	QST	7.08	82	10.3	38.0	23.8	25.4	4.8	10.6	5.4	0.7	0.01	0.11	1.2						23			0.6	8	5.54	9.9	92.0	98.8	75

Appendix B - Complete Chemistry Data including both Snow and Lake Water

DATE	LOCAT	SAMPLEID	TYPE	LAB	PH	ANC	SPCOND	CA	MG	NA	K	SO4	CL	NH4	TP	TKN	TOC	FORMATE	PROPIONA	FLUORIDE	ACETATE	LEAD	IRON	MN	PO4	NO3	ALT	SI	CONDCAL	CATSUM	ANSUM	cbca
08/13/96	GIS	Gertrude South Inlet	R	QST	6.68	261	21.9	91.5	66.1	53.5	10.5	11.1	9.2	0.7	0.03	0.15	1.1						63			0.6	13	13.66	25.3	221.9	281.8	201
09/22/96	CC	Cedar Center	R	QST	6.82	58	8.7	28.0	20.1	23.0	3.8	7.4	6.0	1.0	0.02	0.21	3.4						84			0.6	91	3.13	7.6	75.0	71.7	61
09/22/96	GC	Gertrude Lake	R	QST	7.01	83	11.6	41.7	28.8	26.2	5.2	10.0	5.9	0.7	0.01	0.11	2.4						7			0.6	5	4.23	10.4	102.0	99.4	85
09/22/96	GIS	Gertrude South Inlet	R	QST	6.79	215	24.2	100.0	77.4	50.4	13.1	9.7	14.4	0.7	0.13	0.41	4.0						61			0.6	16	5.75	24.4	241.1	239.7	216
10/26/96	GC	Gertrude Lake	R	QST	6.78	87	11.0	39.6	26.7	26.3	5.3	9.3	6.5	0.7	0.05	0.13	1.0						5			0.6	5	2.39	10.3	98.0	102.8	82
10/26/96	GC	Gertrude Lake	D	QST	6.75	91	11.3	40.1	26.7	26.4	5.3	10.7	6.1	3.9	0.03	0.14	1.0						5			0.6	5	2.73	10.7	98.6	108.2	81
03/24/97	SH	Mt. St. Helens	R	QST	5.50	-4	2.5	0.2	0.6	2.3	0.1	0.8	3.0	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		0.9	20		1.5	6.4	4.7	-1
03/24/97	SH	Mt. St. Helens	B	QST	5.57	-6	2.1	0.3	0.3	1.8	0.3	0.8	1.6	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		0.6	20		1.2	5.5	3.0	0
03/24/97	SH	Mt. St. Helens	D	QST	5.52	-4	2.7	1.1	0.8	5.6	0.8	0.8	3.6	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		1.1	20		1.8	11.4	5.5	3
03/24/97	SH	Mt. St. Helens	M	QST	5.58	-3	2.0	0.2	0.2	1.4	0.1	0.8	1.6	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		0.6	20		1.2	4.7	3.0	-1
03/24/97	SH	Mt. St. Helens	T	QST	5.51	-6	2.3	0.2	0.2	0.8	0.1	0.8	1.2	1.0	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		0.9	20		1.3	4.5	3.0	-2
03/24/97	WP	White Pass	T	QST	5.50	-4	3.0	0.2	0.3	0.8	0.1	1.5	1.1	1.4	0.01	0.11	1.0	0.01	0.01	0.01	0.01	20	20	3		1.4	20		1.4	4.7	4.1	-3
03/24/97	WP	White Pass	D	QST	5.54	-8	3.0	2.0	1.1	6.1	0.9	2.5	4.4	0.7	0.01	0.10	1.0	0.01	0.02	0.01	0.01	20	20	3		1.3	20		2.0	13.0	8.1	2
03/24/97	WP	White Pass	M	QST	5.61	-4	2.6	1.3	0.7	1.7	0.3	0.8	2.1	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		1.4	20		1.3	6.5	4.4	0
03/24/97	WP	White Pass	R	QST	5.52	-5	2.9	1.5	1.0	4.0	0.5	2.2	4.9	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		1.4	20		1.8	10.0	8.4	-1
03/24/97	WP	White Pass	B	QST	5.85	3	3.3	5.7	1.7	7.5	1.7	2.1	7.1	1.3	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		0.9	20		2.0	18.1	13.2	7
04/03/97	LB	Lone Butte	B	QST	5.62	-11	3.1	0.5	1.2	4.2	0.4	1.5	5.5	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		0.7	20		1.5	8.8	7.7	-1
04/03/97	LB	Lone Butte	D	QST	5.57	-9	3.2	0.7	1.2	5.3	0.4	2.2	6.7	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		1.1	20		1.8	10.3	10.0	-2
04/03/97	LB	Lone Butte	M	QST	5.58	-9	3.0	0.6	0.8	3.9	0.5	1.4	4.7	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		1.5	20		1.6	8.5	7.6	-2
04/03/97	LB	Lone Butte	R	QST	5.49	-10	3.5	0.6	1.5	5.7	0.3	2.6	7.6	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		1.2	20		2.1	11.4	11.4	-3
04/03/97	LB	Lone Butte	T	QST	5.24	-20	7.0	1.2	3.6	14.7	0.5	8.5	18.9	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		2.1	20		4.4	25.7	29.5	-10
04/08/97	MR	Mount Rainier	M	QST	6.46	-4	3.8	8.3	1.6	6.4	0.6	5.0	8.2	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		1.6	20		1.8	17.2	14.7	2
04/08/97	MR	Mount Rainier	T	QST	5.03	-25	10.7	1.7	5.7	23.7	0.7	16.5	31.3	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		1.9	20		7.2	41.1	49.7	-18
04/08/97	MR	Mount Rainier	B	QST	5.73	-5	2.4	1.5	0.7	2.0	0.2	1.2	2.7	0.7	0.01	0.14	1.0	0.01	0.01	0.01	0.01	20	20	3		0.6	20		1.1	6.3	4.5	0
04/08/97	MR	Mount Rainier	D	QST	5.39	-11	4.2	0.5	1.3	5.7	0.3	4.7	7.4	0.7	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		1.4	20		2.5	11.9	13.4	-6
04/08/97	MR	Mount Rainier	R	QST	5.40	-13	4.2	0.8	1.6	7.8	0.7	4.5	8.7	1.1	0.01	0.10	1.0	0.01	0.01	0.01	0.01	20	20	3		1.1	20		2.7	14.9	14.3	-3
07/02/97	CC	Cedar Center	R	QST	6.59	39	6.4	24.9	13.2	15.1	2.6	6.3	4.6	1.2	0.01	0.50	1.0						43			0.6	31	3.33	5.6	56.0	50.9	44
07/02/97	GIW	Gertrude West Inlet	R	QST	6.34	92	11.7	48.3	32.1	27.8	6.7	8.0	5.9	0.7	0.01	0.50	3.0						41			0.6	22	8.20	11.6	115.4	106.3	100
07/02/97	GO	Gertrude Outlet	R	QST	6.74	54	8.2	33.6	17.9	18.7	5.1	8.1	6.0	0.7	0.01	0.50	1.1						92			0.6	16	4.13	7.6	75.4	68.6	61
07/19/97	GC	Gertrude Lake	R	QST	6.80	53	8.6	31.4	17.2	18.5	3.5	9.3	4.3	0.7	0.01	0.50	1.0						48			0.6	20	4.13	7.3	70.8	67.5	56
07/19/97	GIE	Gertrude East Inlet	R	QST	6.05	5	3.0	6.1	4.0	4.3	1.4	1.5	2.5	1.1	0.01	0.50	1.4						31			0.6	30	0.56	1.7	16.7	10.0	11
07/19/97	GIW	Gertrude West Inlet	R	QST	6.67	136	16.6	62.1	42.2	36.6	7.5	10.5	5.9	0.7	0.01	0.50	1.6						50			0.6	31	11.01	15.5	148.7	153.0	131
07/20/97	CC	Cedar Center	R	QST	6.56	43	7.1	20.2	9.0	13.2	0.8	6.8	4.1	0.7	0.01	0.50	1.0						37			0.6	34	3.62	5.1	43.5	54.0	32
07/20/97	CI	Cedar Inlet S	D	FS	6.43	59	7.0	29.0	16.5	22.0	2.6	7.0	4.0	0.0											0	0.0			7.3	70.5	69.9	59
07/20/97	CI	Cedar Inlet	R	QST	6.59	50	8.1	30.5	16.0	17.4	3.1	7.5	4.2	0.7	0.01	0.50	1.0						47			0.6	27	4.25	6.8	67.3	61.9	55
07/20/97	CI	Cedar East Inlet	R	QST	6.38	24	5.6	24.7	13.3	15.5	2.7	6.2	4.2	0.7	0.01	0.50	1.5						27			0.6	67	3.83	5.0	56.7	35.0	45
08/04/97	CC	Cedar Center	D	FS	6.41	57	7.3	27.7	17.1	25.1	3.5	6.9	4.5	0.0											0	0.0			7.4	73.8	68.8	62
08/04/97	CC	Cedar Center	D	IS	6.43	14	7.7	30.6	16.1	20.5	3.6	7.1	4.2													2.1			5.6	71.3	27.3	57
08/04/97	CC	Cedar Center	R	QST	6.78	52	8.4	28.3	16.4	20.4	3.6	6.9	4.7	0.7	0.01	0.50	1.7						68			0.6	44	4.06	6.9	68.9	64.2	57
08/04/97	GC	Gertrude Lake	D	FS	6.44	68	8.1	24.6	16.6	26.4	3.9	10.1	4.5	0.0											0	0.0			8.0	71.9	82.1	57
08/04/97	GC	blank	B	FS	5.69	-2	1.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0											0	0.0			0.8	4.5	0.0	2
08/04/97	GC	Gertrude Lake	D	IS	6.83	35	8.9	36.3	18.6	22.3	4.3	9.8	3.9													2.1			7.2	81.7	50.8	66
08/04/97	GC	Gertrude Lake	D	QST	6.89	61	9.3	31.0	18.1	21.6	4.3	9.9	4.9	0.7	0.01	0.50	1.0						38			0.6	20	4.57	7.9	75.1	76.7	60
08/06/97	CI	Gertrude South Inlet	R	QST	6.79	64	9.7	34.8	18.9	23.2	4.0	7.2	5.4	0.7	0.01	0.50	1.9						65			0.6	24	4.73	8.2	81.1	77.5	68
08/06/97	GD	blank	B	QST	5.73	-8	1.5	0.1	0.2	0.2	0.1	0.8	0.6	0.7	0.01	0.50	1.0						5			0.6	20	0.10	0.8	2.6	2.0	-1
08/06/97	GIS	Gertrude South Inlet	R	QST	6.93	75	11.7	48.5	17.1	25.8	5.2	13.0	5.4	0.7	0.01	0.50	1.0						5			2.0	20	6.98	10.2	96.8	95.1	76
08/06/97	GIW	Gertrude West Inlet	R	QST	6.73	205	25.0	97.8	73.7	51.2	9.7	13.1	10.0	0.7	0.02	0.50	2.3						78			0.6	21	15.50	23.6	232.6	228.7	209
09/09/97	CC	Cedar Center	D	IS	6.63	22	9.2	35.3	20.1	24.4	4.9	6.2	4.5													2.1			5.6	85.0	12.9	72
09/09/97	CC	Cedar Center	R	QST	6.90	67	9.4	31.8	19.2	23.6	4.5	6.2	5.5	1.6	0.01	0.50	8.8						137			0.6	98	4.25	8.2	79.2	79.7	67
09/09/97	GC	Gertrude Center	D	FS	6.61	84	8.7	39.8	25.4	31.5	5.5	9.8	5.3	0.0											0	0.0			10.5	102.4	99.1	87
09/09/97	GC	Gertrude Center	D	IS	6.79	32	9.9	38.2	22.9	25.9	5.4	9.8	5.4													2.1			6.3	92.5	17.3	75
09/09/97	GC	Gertrude Center	R	QST	7.12	75	10.4	36.2	22.3	26.1	5.3	10.0	5.2	0.7	0.01	0.50	1.5						11			0.6	19	5.40	9.4	90.0	90.7	74

Appendix B - Complete Chemistry Data including both Snow and Lake Water

DATE	LOCAT	SAMPLEID	TYPE	LAB	PH	ANC	SPCOND	CA	MG	NA	K	SO4	CL	NH4	TP	TKN	TOC	FORMATE	PROPIONA	FLUORIDE	ACETATE	LEAD	IRON	MN	PO4	NO3	ALT	SI	CONDCAL	CATSUM	ANSUM	cbca
09/09/97	GIW	Gertrude West Inlet	R	QST	6.95	262	30.2	117.8	95.8	62.1	14.1	10.7	10.5	0.7	0.02	0.50	1.4						34			0.6	15	17.22	29.1	290.0	283.8	268
10/09/97	CC	Cedar Center	D	FS	6.32	50	7.7	34.4	18.7	25.1	3.2	9.2	14.2	3.7											0	0.0			8.0	81.8	72.8	58
10/09/97	CC	Cedar Center	R	QST	6.54	42	8.9	38.8	23.4	25.4	5.2	8.7	12.9	0.7	0.01	0.50	2.9						44			0.6	65	5.46	8.3	93.0	64.0	71
10/09/97	CI	Cedar Inlet	D	FS	6.28	64	8.2	34.3	21.2	26.4	4.3	8.5	11.1	4.0											0	0.0			8.8	86.9	83.4	67
10/09/97	GC	Gertrude Center	D	FS	6.66	81	9.1	39.6	24.8	29.6	4.0	9.7	7.8	4.8											0	0.0			10.1	98.1	98.5	80
10/09/97	GC	Gertrude Lake	R	QST	7.16	73	10.5	31.8	17.7	22.0	4.5	9.5	6.7	0.7	0.01	0.50	1.0						10			0.6	10	5.35	8.5	76.0	90.1	59
04/03/98	LB	Lone Butte	T	QST	5.11	-17	4.1	1.3	2.1	7.4	0.4	3.7	8.7	0.7	0.01	0.16	1.0	0.01	0.01	0.01	0.01	5	10	5		2.7	11		4.0	18.9	15.1	-4
04/03/98	LB	Lone Butte	B	QST	5.35	-5	3.7	0.6	2.1	10.4	0.4	2.3	12.9	0.8	0.01	0.13	1.0	0.01	0.01	0.01	0.01	5	10	5		1.4	10		2.9	18.0	16.6	-3
04/03/98	LB	Lone Butte	D	QST	5.41	-3	2.5	0.9	1.1	5.4	0.4	1.4	6.0	0.7	0.01	0.18	1.0	0.01	0.01	0.01	0.01	5	10	5		1.0	10		2.1	11.7	8.4	-1
04/03/98	LB	Lone Butte	M	QST	5.41	-6	3.0	2.5	1.6	7.1	0.5	2.0	8.5	0.7	0.01	0.17	1.0	0.01	0.01	0.01	0.01	5	10	5		1.6	10		2.5	15.7	12.2	0
04/03/98	LB	Lone Butte	R	QST	5.43	-5	2.7	0.5	1.4	7.7	0.2	1.6	8.2	0.7	0.01	0.19	1.0	0.01	0.01	0.01	0.01	5	10	5		1.2	10		2.3	13.6	11.0	-1
04/03/98	MR	Mount Rainier	B	QST	5.28	-5	2.5	0.4	1.0	4.0	0.2	1.8	4.9	0.7	0.01	0.17	1.0	0.01	0.01	0.01	0.01	5	10	5		1.0	10		2.5	10.8	7.7	-2
04/03/98	MR	Mount Rainier	D	QST	5.24	-10	3.7	0.6	2.1	8.6	0.2	3.2	10.8	0.7	0.01	0.17	1.0	0.01	0.01	0.01	0.01	5	10	5		1.4	10		3.3	17.3	15.4	-4
04/03/98	MR	Mount Rainier	M	QST	5.16	-8	2.9	0.1	0.5	1.7	0.1	3.2	2.1	0.7	0.01	0.16	1.0	0.01	0.01	0.01	0.01	5	10	5		1.8	12		3.0	9.3	7.1	-5
04/03/98	MR	Mount Rainier	R	QST	5.24	-7	3.6	0.8	1.8	7.8	0.5	3.4	9.4	0.7	0.01	0.22	1.0	0.01	0.01	0.01	0.01	5	10	5		1.5	10		3.2	16.7	14.3	-3
04/03/98	MR	Mount Rainier	T	QST	5.29	-6	2.2	0.1	0.5	2.3	0.1	1.7	3.0	0.7	0.01	0.18	1.0	0.01	0.01	0.01	0.01	5	10	5		0.9	10		2.2	8.2	5.6	-3
04/03/98	SH	Mt. St. Helens	B	QST	5.35	-11	2.6	0.3	0.7	4.1	0.2	1.3	5.2	1.0	0.01	0.37	1.0	0.01	0.01	0.01	0.01	5	10	5		1.4	10		2.2	9.8	7.8	-2
04/03/98	SH	Mt. St. Helens	D	QST	5.44	-11	1.7	0.0	0.2	1.0	0.1	0.8	1.5	0.7	0.01	0.24	1.0	0.01	0.01	0.01	0.01	5	10	5		0.6	10		1.5	5.0	2.9	-2
04/03/98	SH	Mt. St. Helens	M	QST	5.68	-6	2.5	3.7	1.4	5.2	0.9	3.4	3.9	1.8	0.01	0.20	1.0	0.01	0.01	0.01	0.01	5	10	5		1.2	11		1.8	13.3	8.6	3
04/03/98	SH	Mt. St. Helens	R	QST	5.38	-9	1.9	0.1	0.3	1.5	0.0	0.8	1.9	1.0	0.01	0.13	1.0	0.01	0.01	0.01	0.01	5	10	5		0.9	10		1.7	6.1	3.7	-2
04/03/98	SH	Mt. St. Helens	T	QST	5.42	-5	1.9	0.3	0.4	1.3	0.1	0.8	1.7	0.8	0.03	0.13	1.0	0.01	0.01	0.01	0.01	5	10	5		0.9	10		1.6	6.0	3.4	-1
04/03/98	WP	White Pass	B	QST	6.08	7	3.4	13.9	1.9	4.3	0.6	1.6	5.2	0.8	0.01	0.10	1.0	0.01	0.01	0.01	0.01	5	10	5		1.3	10		2.2	21.6	15.0	13
04/03/98	WP	White Pass	D	QST	5.45	-12	2.5	2.0	1.2	4.4	0.2	1.4	5.5	0.7	0.01	0.23	1.0	0.01	0.01	0.01	0.01	5	10	5		1.5	10		2.0	11.3	8.4	-1
04/03/98	WP	White Pass	M	QST	5.25	-10	4.2	3.4	2.4	9.8	0.8	3.5	11.6	1.7	0.01	0.20	1.0	0.01	0.01	0.01	0.01	5	10	5		3.8	10		3.7	22.1	18.9	-2
04/03/98	WP	White Pass	R	QST	5.95	7	3.7	10.5	1.7	6.9	1.2	3.3	7.6	1.7	0.01	0.25	3.7	0.01	0.01	0.01	0.01	5	10	5		3.0	10		2.5	21.4	20.9	6
04/03/98	WP	White Pass	T	QST	5.37	-10	2.1	1.6	0.8	1.0	0.1	2.2	1.1	0.9	0.01	0.14	1.0	0.01	0.01	0.01	0.01	5	10	5		1.3	11		2.0	7.8	4.6	-1

DATE	MM/DD/YY
LOCAT	Location
TYPE	Type of Sample (R=Routine, D=Duplicate, B=Blank [for lake samples]; T=Top [snow], M=Middle, B=Bottom)
LAB	Laboratory (FS=Forest Service, QST=QST Environmental, IS=Illinois Water Survey)
PH	Lab pH, standard units
ANC	Acid neutralizing capacity, µeq/L
SPCOND	Specific conductance, µS/cm
CA	Calcium, µeq/L
MG	Magnesium, µeq/L
NA	Sodium, µeq/L
K	Potassium, µeq/L
SO4	Sulfate, µeq/L
CL	Chloride, µeq/L
NH4	Ammonium, µeq/L
TP	Total phosphorus, µg/L
TKN	Total Kjeldahl nitrogen, mg/L
TOC	Total organic carbon, mg/L
FORMATE	Formate, µeq/L
PROPIONA	Proprionate, µeq/L
FLUORIDE	Fluoride, µeq/L
ACETATE	Acetate, µeq/L
LEAD	Lead, µg/L
IRON	Iron, µg/L
MN	Manganese, µg/L
PO4	Ortho phosphate, µg/L
NO3	Nitrate, µeq/L
ALT	Total aluminum, µg/L
SI	Silicon, mg/L
CONDCAL	Calculated Conductivity, µS/cm
CATSUM	Sum of Cations, µeq/L
ANSUM	Sum of Anions, µeq/L
cbca	Calculated Alkalinity (C_B-C_A), µeq/L

APPENDIX C

QA Plots

Figure C1.	Sum of anions vs sum of cations for all chemistry samples. Labeled samples are discussed in the text.
Figure C2.	Sum of cations vs sum of anions for all chemistry samples. Note that scales have been shortened from Figure C1 to highlight the majority of data.
Figure C3.	Measured ANC vs calculated ANC for all samples.
Figure C4.	Measured ANC vs calculated ANC for all samples. Note that scales have been shortened from Figure C3 to highlight the majority of data.
Figure C5.	Measured specific conductivity vs calculated specific conductivity.
Figure C6.	pH vs ANC.
Figure C7.	Sodium vs chloride. The differences between lake and snow samples are discussed in the text.

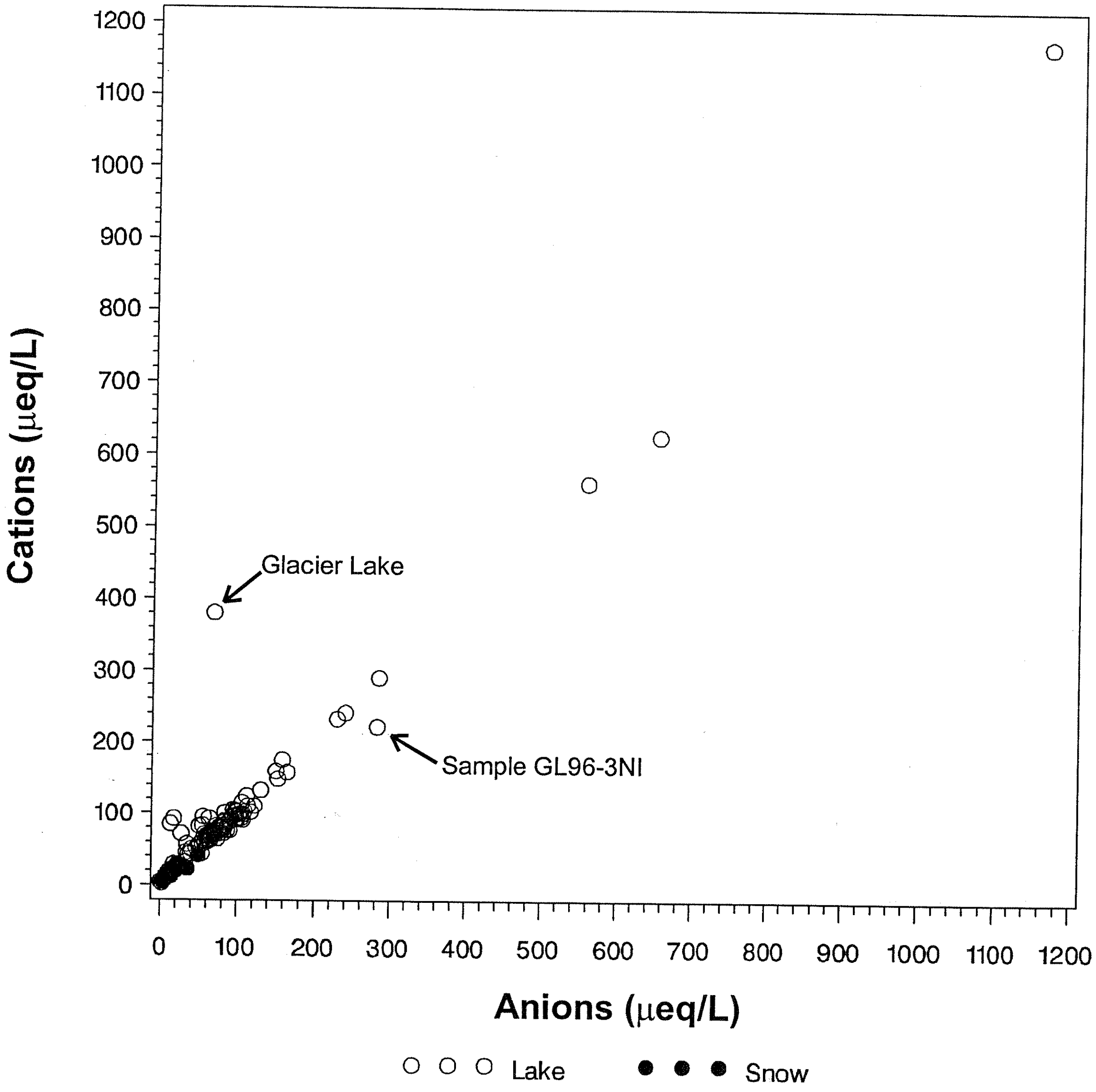

Figure C1. Sum of anions vs sum of cations for all chemistry samples. Labeled samples are discussed in the text.

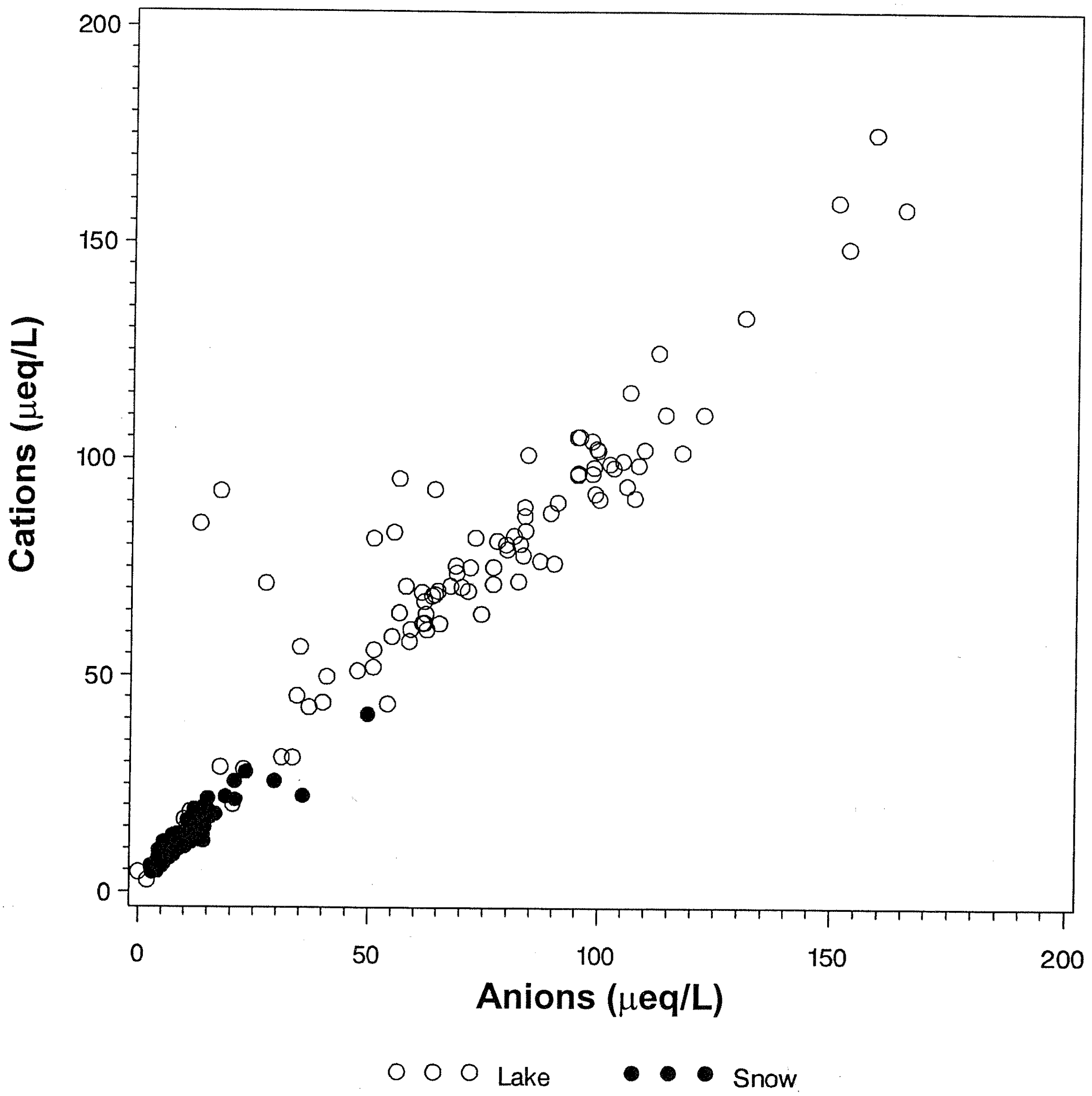

Figure C2. Sum of cations vs sum of anions for all chemistry samples. Note that scales have been shortened from Figure C1 to highlight the majority of data.

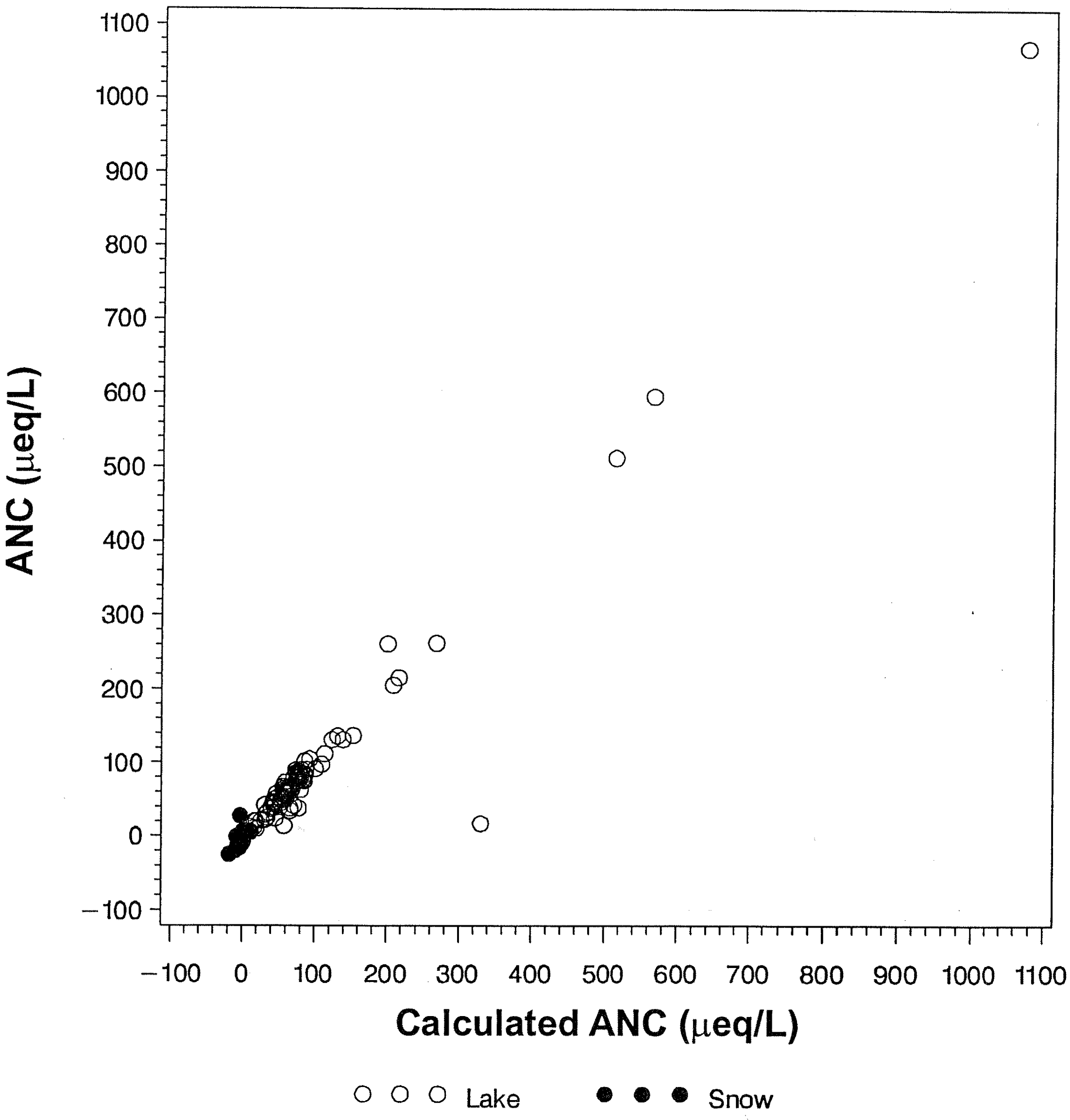

Figure C3. Measured ANC vs calculated ANC for all samples.

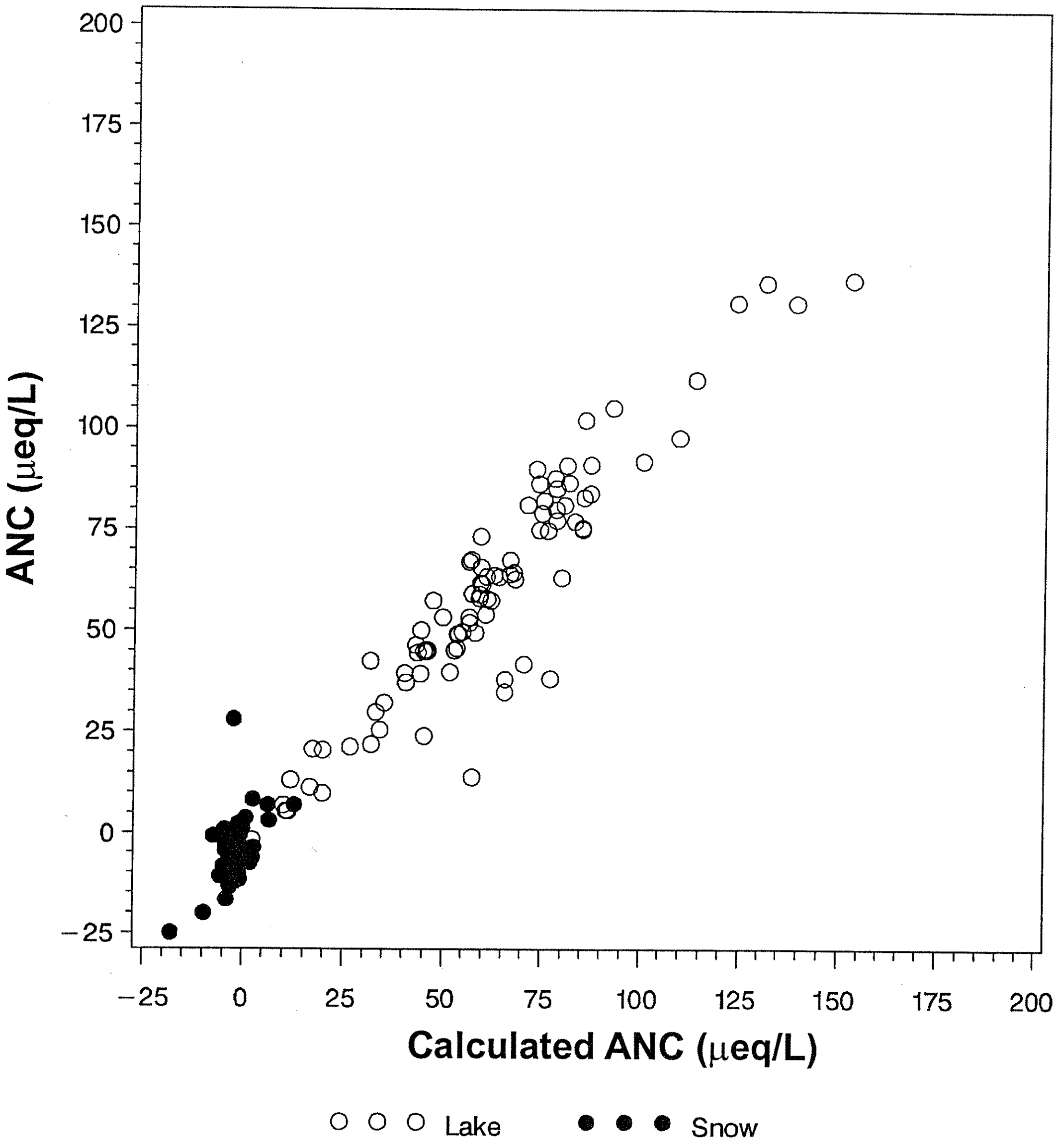

Figure C4. Measured ANC vs calculated ANC for all samples. Note that scales have been shortened from Figure C3 to highlight the majority of data.

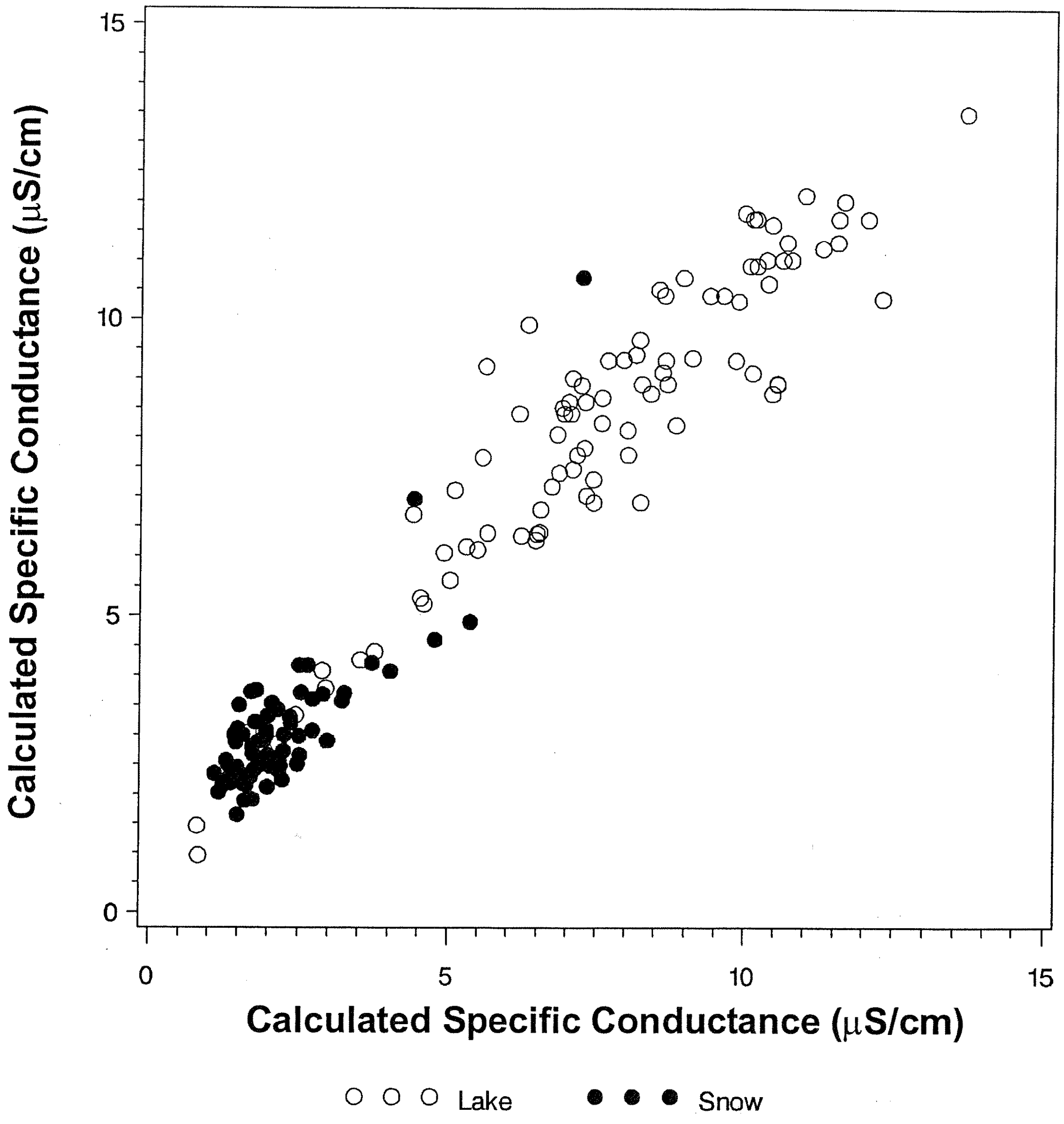

Figure C5. Measured specific conductivity vs calculated specific conductivity.

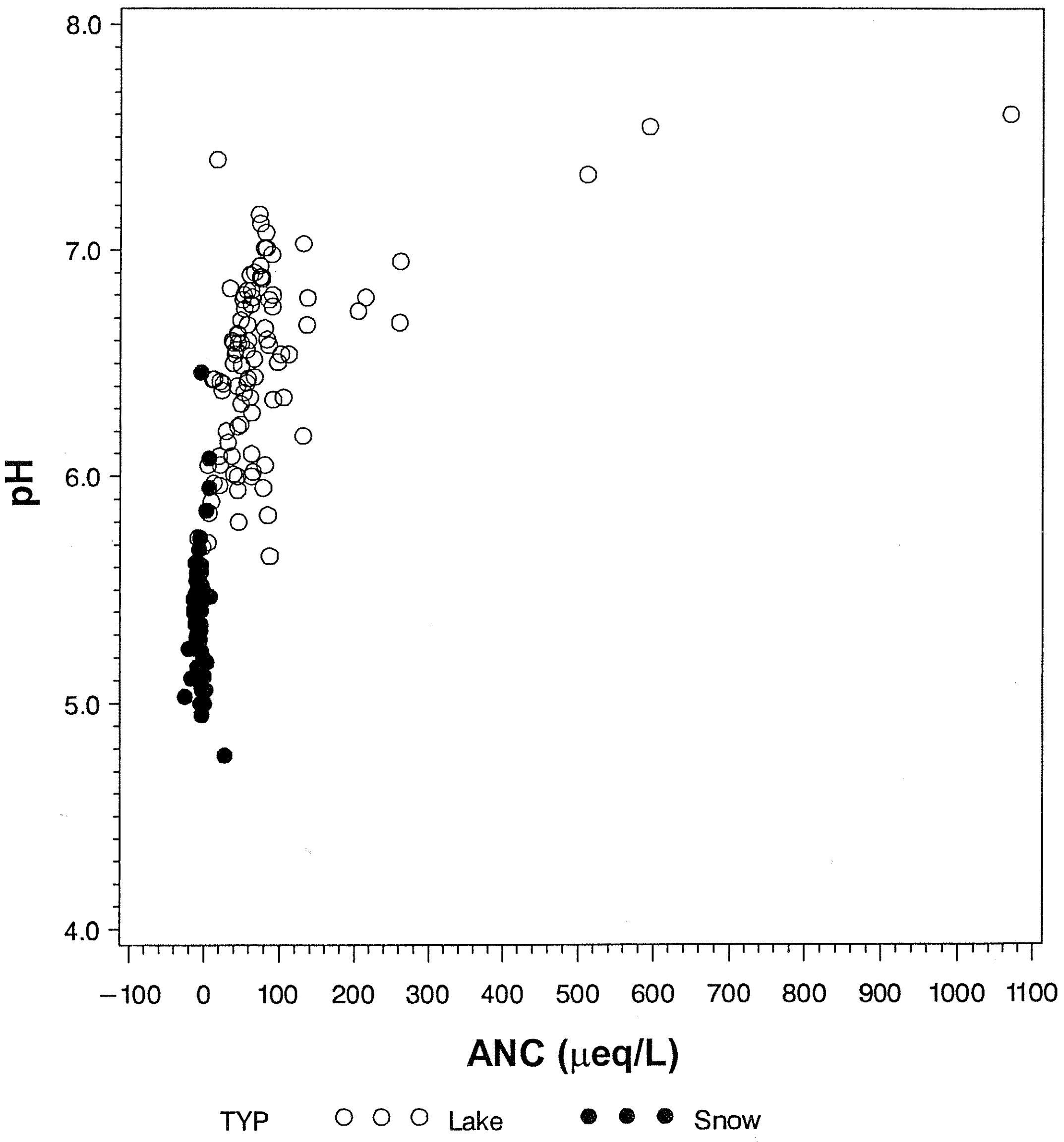

Figure C6. pH vs ANC.

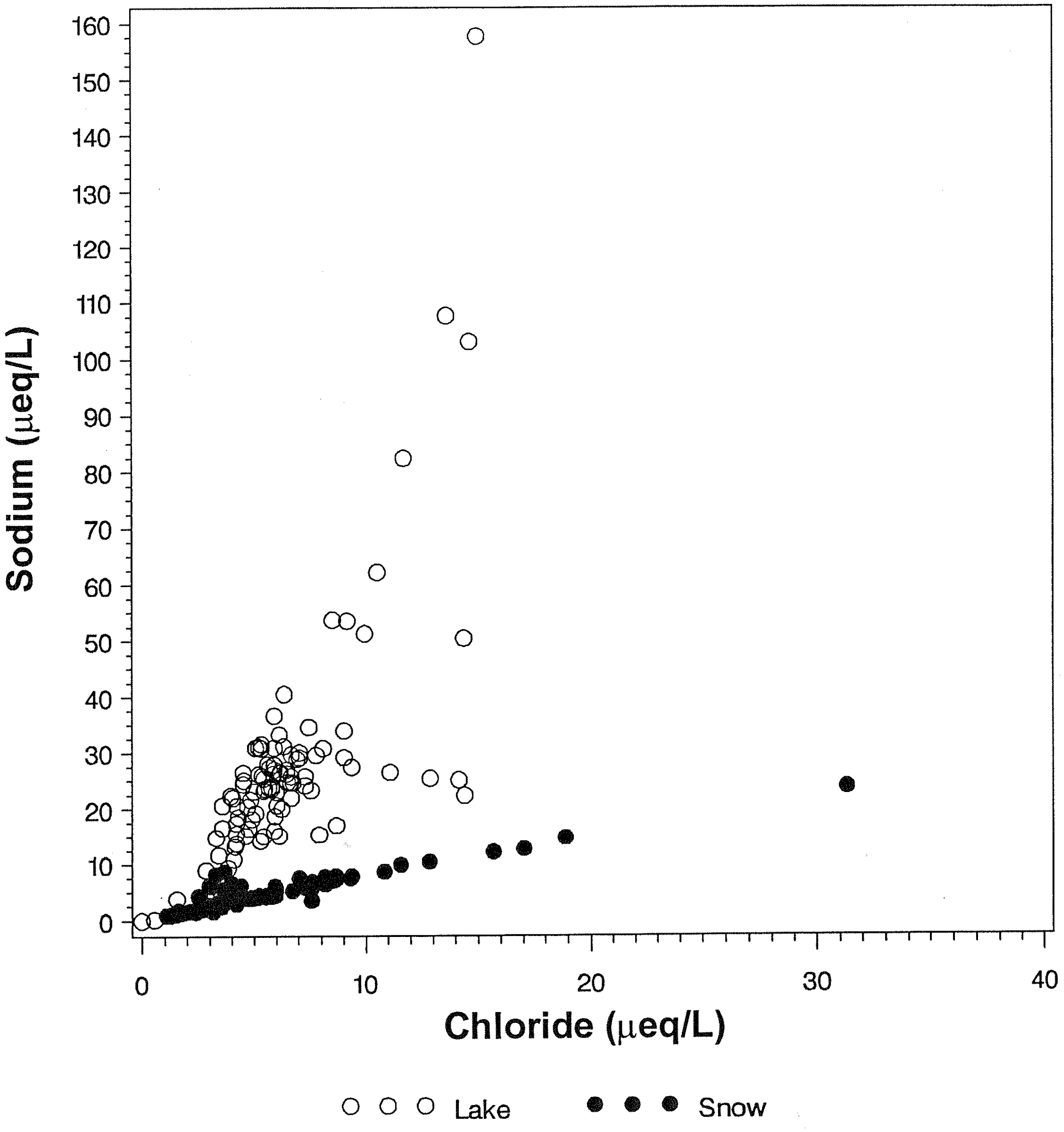

Figure C7. Sodium vs chloride. The differences between lake and snow samples are discussed in the text.