Record Number:
Author, Monographic: Jones, H. G.//Roberge, J.//Laberge, C.//Sochanski, W.//Stein, J.
Author Role:
Title, Monographic: Développement d'un modèle géochimique, numérique et transposable pour la prédiction de l'acidification des eaux de surface - Partie 1: chap. I-III
Development of a transportable numerical geochemical model to predict the acidification of surface waters - First part: chap. I-III
Translated Title:
Reprint Status:
Edition:
Author, Subsidiary:
Author Role:
Place of Publication: Québec
Publisher Name: INRS-Eau
Date of Publication: 1990
Original Publication Date: Février 1990
Volume Identification:
Extent of Work: 131
Packaging Method: pages
Series Editor:
Series Editor Role:
Series Title: INRS-Eau, Rapport de recherche
Series Volume ID: 284
Location/URL:
ISBN: 2-89146-281-5
Notes: Rapport annuel 1989-1990
Abstract: 20.00$
Call Number: R000284
Keywords: rapport/ ok/ dl

Développement d'un modèle géochimique, numérique et transposable pour la prédiction de l'acidification des eaux de surface

Development of a transportable numerical geochemical model to predict the acidification of surface waters

Première partie: Chapitres I-III

First part: Chapter I-III

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Février 1990

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Résumé

Ce rapport comprend 4 parties. Les trois premiers chapitres concernent les activités de recherche et développement du modèle de fonte du couvert de neige "SNOQUAL" telles que définis dans le contrat de recherche "Development of a transportable numerical geochemical model to predict the acidification of surface waters". Chaque chapitre est précédé par un résumé en français. La quatrième partie, l'annexe, comprend les données de fonte 1988 utilisées dans ces travaux.

Le premier chapitre "A statistical approach to field measurements of the chemical evolution of cold (< 0°C) snowcover" est identique à l'article du même nom accepté pour publication dans la revue "Environmental Monitoring and Assessment". Cette publication encadre les travaux de recherche orientés vers <u>la prédiction des conditions initiales du couvert de neige avant la fonte</u>. L'article, en effet, décrit la méthodologie statistique que nous avons employé sur le terrain pour évaluer l'évolution quantitative de la concentration de SO_4 dans le couvert en période froide. Les résultats nous permettront d'évaluer d'une façon plus précise les pertes ou les gains des anions d'acidité forte pendant la période d'accumulation du couvert qui précède la fonte printanière.

Le deuxième chapitre représente une publication qui a été présentée au "Chapman Conference: Hydrogeochemical Responses of Forested Catchments", 18-24 septembre, Bar Harbor, Maine. Cette publication sera, de plus, soumise au "Water Resources Research" en 1990. Les travaux décrits dans cette publication s'inspirent du mandat de l'INRS-Eau d'améliorer la performance du modèle de fonte SNOQUAL1 en y introduisant des paramètres de compensation pour les écarts entre la composition des eaux de fonte produite par le modèle et celle observée

"in situ". Par la suite, le modèle tel qu'amélioré aurait dû permettre de mieux simuler la composition des eaux de fonte, et ceci, pour que nous puissions établir des valeurs probablistiques pour k, le coefficient de lessivage des anions d'acidité forte du couvert de neige. La publication met en évidence les travaux de développement du modèle de fonte en décrivant deux modèles (SNOQUALR et SNOQUALD) dont les structures reflètent des processus physico-chimiques et microbiologiques dans le couvert. Ces processus sont: i) la présence d'une certaine quantité des ions qui résident à l'intérieur des grains de neige et qui ne subissent que très peu de lessivage, et 2) du matériel autre que celui compris sur, et dans, les grains de neige au commencement de la fonte. Ce matériel additionnel contribue pendant la fonte à la composition finale des eaux par les processus de dépôts secs, le lessivage lent des matières organiques et l'activité microbiologique. De ces travaux, il s'avère que le modèle SNOQUALR qui intègre un paramètre relié à la quantité des ions résiduels dans la neige est présentement le modèle le plus performant. Suite au développement du modèle SNOQUALR nous avons déterminé une valeur moyenne pour le coefficient de lessivage des ions d'acidité forte. Le modèle a ensuite permis la simulation de la composition physico-chimique (et le pH) des eaux de fonte selon des conditions hypothétiques d'une réduction de 30% et 50%, et une augmentation de 30% dans les émissions de SO$_2$ dans l'est de l'Amérique du Nord. Ces travaux de simulation ont démontré que le processus de lessivage est tellement dominant dans le contrôle de la composition des eaux de fonte que la réduction d'émissions (et, par surcroît, la réduction de concentration d'anions d'acidité forte dans la neige) ne résultera pas en une diminuation appréciable du pH des eaux de fonte.

Enfin, le troisième chapitre "The discrimination of the origin of sub-ice acidic waters in a small lake during the spring runoff" est l'article dont l'essentiel a été accepté pour présentation au Symposium sur "Episodic chemistry of streams and lakes" de l'American Geophysical Union, du 4 au 9 décembre 1990, San Francisco et "The Eighth International Northern Research Basin Symposium and Workshop, Abisko, Sweden, 26-30 Mars 1990. L'article sera soumis incessamment à "Water Resources Research" pour fins de publication. Cet article démontre la chronologie de l'acheminement des eaux de fonte de diverses sources sous le couvert de glace du Lac Laflamme pendant la fonte printanière. Ces travaux nous renseignent, d'une façon plus explicite, sur l'importance relative des eaux de diverses origines et nous permettront de mieux prédire la composition chimique de l'écoulement printanier dans le bassin. Il faudrait noter que les écoulements acides au Lac Laflamme se reproduisent sous la glace. La disparition du couvert, en effet, résulte en une réduction considérable de l'acidité des eaux de l'épilimnion par la remonté des eaux d'hypolimnion due à l'influence du vent.

Ce rapport comprend, de plus, une annexe dont le contenu est constitué de données physico-chimiques de la neige, des eaux de fonte, des eaux de ruissellement et des eaux lacustres du Lac Laflamme, printemps 1988.

CHAPITRE I

CHAPTER I

A statistical approach to field measurements of the chemical evolution of cold (< 0°C) snow cover

(Une approche statistique pour la mesure de l'évolution chimique du couvert de neige en période froide (< 0°C)

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Résumé

L'application de deux méthodes statistiques connues à des expériences sur l'évolution de la composition physico chimique du couvert de neige en période froide ($< 0^oC$), a permis de relier leurs qualités statistiques aux coûts qu'elles engendrent sur le terrain. Les méthodes utilisées étaient la régression (expérience avec une observation par jour d'échantillonnage pendant une longue période froide) et l'ANOVA (expérience avec plusieurs réplicats par jour d'échantillonnage pendant une période froide restreinte). Les puissances relatives théoriques des deux méthodes permettent de déterminer l'amplitude des changements chimiques que l'on peut détecter. L'utilisation d'estimateurs de la variance permet finalement d'estimer l'amplitude absolue (en $\mu eq\, l^{-1}$) que l'on peut détecter.

Les résultats des applications, sur l'évolution des sulfates au Lac Laflamme (Québec), montraient clairement des pertes de sulfates pour six des huit strates étudiées durant des périodes froides. Les amplitudes relatives des pertes significatives variaient entre 1% par jour et 4% par jour, cette variation dépend des concentrations initiales et des conditions météorologiques.

La comparaison des deux méthodes statistiques a démontré que pour un même nombre d'observations, la régression détecte des amplitudes absolues beaucoup plus petites que l'ANOVA, elle est donc plus puissante pour détecter des changements de concentrations dans la neige. Ces informations permettent de planifier les expériences futures en incluant le coût déxpériences sur le terrain ou en laboratoire.

Abstract

Two statistical methods for the analysis of data on the evolution of the chemical composition of cold snow (<0°C) in the field (Lac Laflamme, Quebec) were compared. The tests used on the data were regression analysis (1 sample per sampling date over a long cold period) and ANOVA (replicate samples on a restricted number of sampling dates over shorter periods). The relative power of the tests to determine the detectable amplitude of chemical changes was derived from the theoretical power of the tests under comparable conditions of sampling (number of observations) and from the estimated error variances of the measured data.

The results of the study on the evolution of SO_4 concentrations in discretely identified snow strata clearly showed that for 6 strata out of 8, significant losses of SO_4 did occur in snow during cold periods. The relative amplitude of the significant losses varied between 1% day^{-1} and 4% day^{-1} depending on the initial concentrations in the snow and the prevailing meteorological conditions.

The analysis of the data also demonstrated that for the same number of samples, the regression analysis is more efficient in detecting the chemical changes in snow than the alternative ANOVA method. The use of this information to plan sampling programs of cold snow under both field and laboratory conditions is discussed.

Introduction.

Snowcover is a major reservoir of atmospheric pollutants in the hydrologic cycle of boreal ecosystems. In the past decade the acidification of surface waters in northern regions has thus resulted in an increase in the study of snow chemistry. The main emphasis has been placed on the temporal changes in the concentrations of strong–acid anions in snow during the cold ($< 0^{\circ}C$) accumulation period when the water equivalent of the pack increases and in the melt season when the phenomenon of "acid shock" due to high hydrologic flux occurs.

One of the main difficulties in monitoring the chemical evolution of snow cover is the heterogeneous distribution of the chemical species in the pack (Tranter et al. 1986). Although the chemical composition of individual snowfalls may be relatively homogeneous over a catchment area ($10–100km^2$), subsequent wind redistribution (Delmas, and Jones 1987), small melt and freeze cycles (Colbeck 1981), and local dust and forest canopy fallout (Jones, and Sochanska 1985) will provoke small–scale disparities ($1–100m^2$) in the chemical characteristics of the snow strata laid down by the original precipitation events.

To follow chemical changes in cold snow, samples of the snow cover are taken over a period of time during which the temperature of the snow and the air are below 0^oC. The sampling method is destructive for the snow cover and successive samples have to be taken as close to the original point as possible. This, however, can be a cause for concern as the removal of snow from the original sampling point can influence the remaining snow in the immediate environment by modifying temperature gradients and air–snow interchange. As the sampling period evolves the spatial requirements for the collection of the samples increases. This in turn enhances the probability that the sampling "point" will cover areas of snow with different chemical characteristics. Thus any attempt to study the evolution in the chemical composition of cold snow covers due to real processes of transformation or translocation "in situ" has to take into consideration the apparent chemical changes that result from the spatial inequalities in snow quality.

To distinguish real chemical changes in snow from any apparent changes, the sampling strategy should be based on a statistical analysis of the spatial chemical characteristics of the snow cover at the beginning of the sampling period. In the absence of well defined spatial characteristics valid information on real in–pack changes can, however, still be obtained even if the spatial variability is less known. This would be true in the case where the in–pack chemical processes are consistent and result in concentration changes of species in the same direction (i.e. losses or gains) over time. The detection of a trend in time is then related to real changes large enough to overcome any masking effect by the chemical heterogeneity of the snow. In previous studies on the chemical evolution of cold snowpacks (Jeffries, and Snyder 1981; Jones, and Bisson 1984; Cadle et al. 1984) the sampling methods did not give rise to sufficient data from which definite conclusions on real changes in in–pack chemistry of snow could be drawn. The optimisation in the quality and quantity of field data from which unambiguous results may be obtained should thus be the major priority of the sampling methodology. Field operations are expensive: by reducing the cost in the sampling program much needed funds may be diverted elsewhere.

The following article describes two experiments which were carried out to study real changes in the chemistry of cold snow in the packs at Lac Laflamme, Quebec. To avoid any mass movement of snow (wind erosion and redeposition) during the study periods discrete in–pack strata of snow were sampled. Each study had a different sampling strategy. In the first experiment one snow sample per stratum was taken on each sampling date over a relatively long cold period. In the second study many replicate samples of each stratum were taken per sampling date over short cold periods. The two data sets were treated by two simple but different statistical analyses. The set from the long period was subjected to a trend detection analysis in which spatial variability is not a factor. The second set was analysed by analysis of variance (ANOVA) where the variance of replicates on successsive sampling dates estimates the spatial variability of snow quality. The powers of the tests involved in each method are compared and the results from the two field studies are used to estimate the chemical changes that would be detectable by each method for a reasonable sample size.

Site characteristics and sampling methodology.

Two snow courses were laid out in the watershed of Lac Laflamme a small headwater lake ($47^{o}19'$ N, $71^{o}07'$ W) in the Parc des laurentides, Quebec (Fig. 1). The mean annual temperature is 0.2^{o}C (-15^{o}C January; 15^{o}C, July). The total snowfall at Lac Laflamme is approximately 400 mm (Snow Water Equivalent, SWE) and the pack reaches a depth of 120–150 cm. The courses, approximately 25–30 m long and 1.5–2 m wide, were prepared before the winter season by removing low brush and debris from open areas of the boreal forest. The length of each snow course was staked out with two parallel lines of fence posts 2m apart (Fig. 2).

The first course was sampled in 1985; four adjacent discrete strata (1,2,3,and 4), identified by means of threads, were sampled (one sample per stratum) once a week during a cold period that ran from the January 10 to

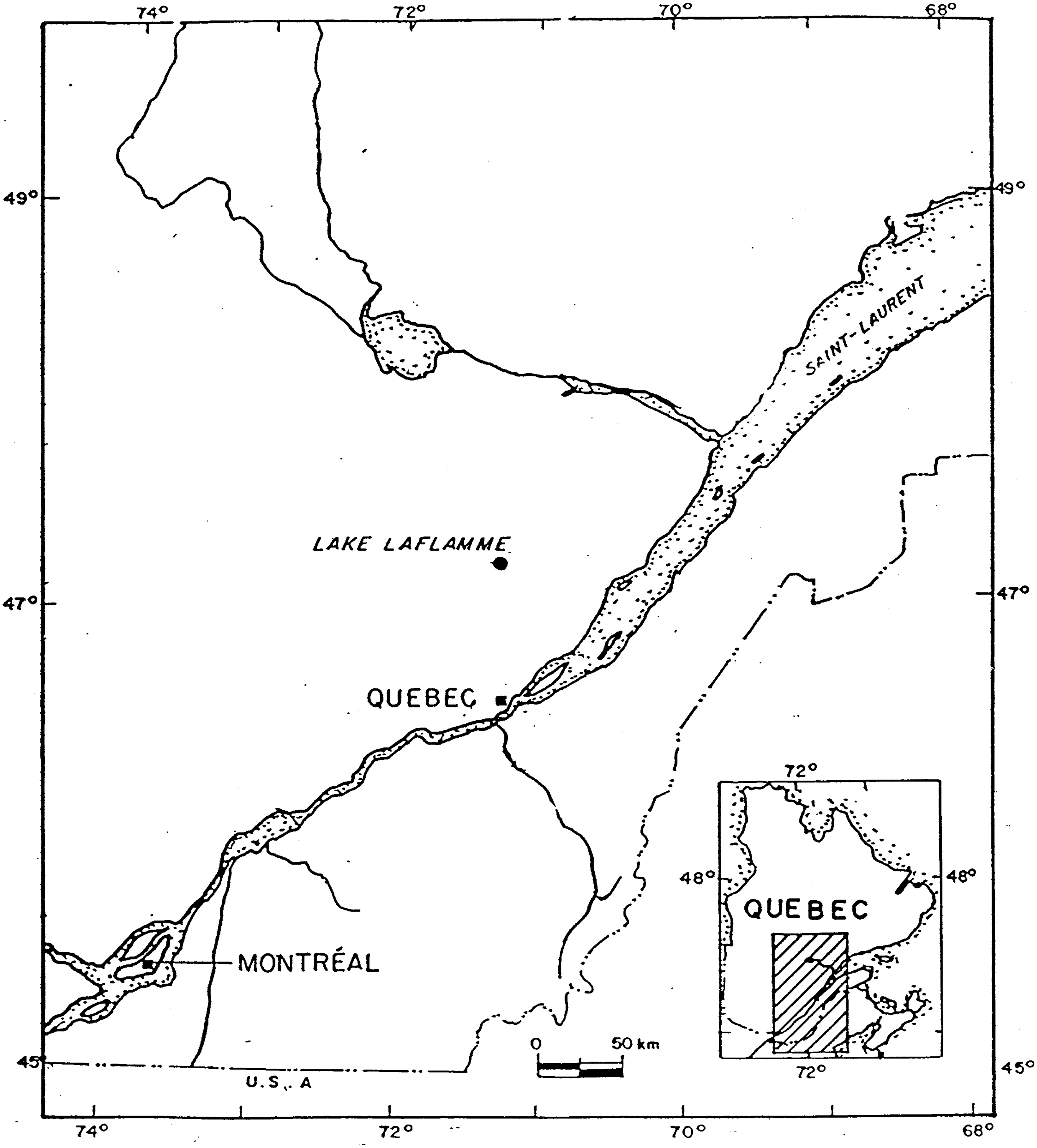
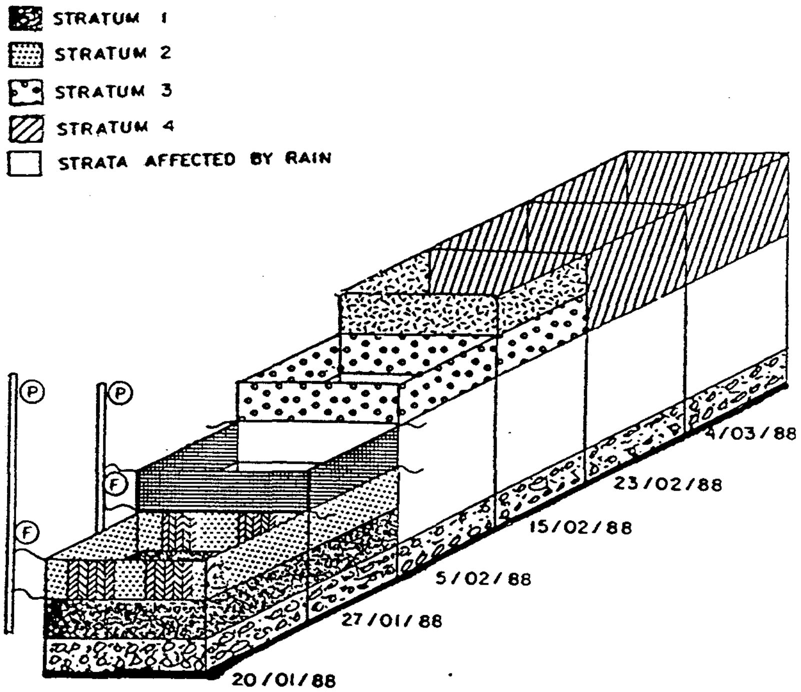


Figure 1. Location of the Lac Laflamme watershed.



F) Strata identification (tread)

P) Snow course marker

Figure 2. Snow course lay out for the experiment of 1988, Lac Laflamme, Quebec.

March 27. The sampling dates were January 10, 16, 23 and 30, February 6, 13, 20 and 27, March 7, 13, 20 and 27. During the last two sampling dates, however, some meltwater had began to penetrate the pack as the daytime air temperature increased in early spring.

The second snow course was sampled (5 samples per stratum) during intermittent short cold periods in 1988 when the January to March period experienced rain episodes. Rain–on–snow episodes displace chemical species in the pack (Jones et al. 1989) and the experiment has to be started up again with new snow strata laid down subsequent to the rain events. Four strata (1,2,3, and 4) were sampled on two different sampling dates (Fig. 2); Strata 1 and 2 were sampled on January 20 and 27, stratum 3 on February 5 and 15, and stratum 4 on February 23 and March 4.

The sampling technique for 1985 and 1988 was identical; it consisted in removing a core of constant cross–sectional area over the depth of each stratum by means of a small square corer of plastic. The samples were conserved at -20°C until melted for analyses. A complete analysis for major ions was carried out on each sample (Jones 1987); for purposes of discussion only the analyses for SO_4 are reported in this paper.

Statistical Approach: Background and Intercomparison between the Methods.

Trend analysis

The data from the 1985 study had to be treated by a time series analysis that would detect a trend in SO_4 concentrations. Of the many methods available for time series analysis those of Box and Jenkins (1976) are the most widely used. In general, the treatment of data by the methods of these authors is restricted to modelling and prediction using ARMA models; very little attention is given to the practical determination of changes in the value of the location parameter in a definite series. Furthermore an efficient use of the Box and Jenkins methods requires a relatively large amount of data i.e. at least 50 observations equidistant in time. These characteristics of the Box and Jenkins techniques make them unsuitable for the treatment of the data obtained in 1985 (10 observations over the period) and inappropriate for the majority of field experiments on snowcover. A more fitting method for such a small data set is the detection of trends over time. Two main type of trends are generally studied. First there are monotonic trends; these are gradual changes in time often associated with natural phenomena (e.g. precipitation, watershed runoff). On the other hand there are step trends due to stepwise changes in system conditions; these are often the result of forces external to the system (e.g. wastewater discharges). In the case of the 1985 experiment, the nature of the changes that were to be expected for in–pack chemistry lead us to believe that tests designed to detect monotonic trends should be used.

Tests for detecting monotonic trends may be of two types. These are parametric tests and nonparametric tests. Both types of test presuppose that successive observations are completely independent except for the possible trend. If some short–term dependence exists e.g. autocorrelation or seasonality, then the tests have to be modified to compensate for these types of dependence (Lettenmaier 1976; Hirch, and Slack 1984). Parametric tests which are best adapted to the detection of monotonic trends are those of simple linear regression over time. In the case of the analysis of the change in the concentration of any chemical species over time the regression model is:

$$C_i = C_o + \Delta t_i + e_i \tag{1}$$

where C_i is the concentration of the chemical at time t_i, C_o is the original concentration, Δ is the slope of the regression, e_i is a random error component. The values of e_i are assumed to be independent and identically distributed $N(0,\sigma^2)$. Under these conditions the estimates for the slope of the regression and for its standard deviation indicate the significance and the amplitude of the trend. The null hypothesis, H_0: $\Delta=0$, is accepted if Δ is not significantly different to 0 and the presence of a trend is then rejected. The alternative hypothesis, H_1: $\Delta\neq0$, is then associated with the presence of a trend. In some cases the linear regression model will not fit adequately the data and a nonlinear regression may be necessary. Nonlinear trends can be transformed into linear form or can be fitted to nonlinear models (Ratkowsky, 1983).

The disadvantage of parametric tests is that they are sensitive to aberrant values; one outlier in the data set may considerably influence the overall result of these tests. To overcome this deficiency one can resort to nonparametric tests for the detection of monotonic trends. Nonparametric tests like the Spearman test and the Kendall test (Conover 1971) are adequate for the detection of such trends, they are not sensitive to aberrant values as they do not presuppose normal distribution of the data and use ranks of values rather than absolute numbers. On the other hand, these tests do not yield values for regression coefficients which indicate the amplitude of the trend. Neither can the level of the series be established. Instead they will test correlation coefficients (ρ) between ranks of concentrations and time. In an analogous manner to the parametric tests the null hypothesis, H_0 is accepted if ρ is not significantly different from 0. If ρ is significantly different from 0 then the null hypothesis, H_0, is rejected and the presence of a trend , is accepted.

Power of the tests and number of samples required

The power of a test is the probability of correctly rejecting H_0 when H_1 is true i.e. that Δ or ρ are different from 0. It's expressed by $1-\beta$; where β is the type II error which qualifies the case where H_0 is incorrectly accepted. The power of a test allows the calculation of the minimum number of samples that are required to detect trends of predetermined values with a known probability. The power of the parametric test used in the linear regression model has been described by Bickel and Doksom (1977). Under H_1 we can obtain the power of this test from charts or tables of the noncentral Student distribution with noncentrality parameter δ defined by:

$$\delta^2 = \frac{\Delta^2}{\sigma^2} \sum_{i=1}^{n} (t_i - \overline{t})^2 \qquad (2)$$

Assuming equidistant observation (i.e. $t_i=i$) equation 2 can be reduced to:

$$\delta^2 = \Delta^2 \frac{N(N+1)(N-1)}{12\,\sigma^2} \qquad (3)$$

Neter and Wasserman (1974, Table A–5) published the power function curves for the linear regression test. Table 1 presents the relationship between the power $(1-\beta)$, the number of observations (N), the parameter of noncentrality (δ), and the relative amplitude of the slope with respect to the standard deviation of the error component (Δ/σ) for some values of these parameters. As an example, the table shows that with 8 observations one can correctly detect a trend of amplitude, $\Delta=.31\sigma$, 4 times out of ten. As the number of observations increases the value of Δ/σ decreases and if the criteria for an experimental program required the correct detection of a trend with an amplitude of less than 0.018σ at a success rate of 70% then more than 62 observations would be required. It should be noted that in the above examples the supposition that σ remains constant with the changes in δ is taken.

When observations are normally distributed, the power of nonparametric tests (Spearman, Kendall) is approximately of the same value of parametric tests (regression) when $N > 20$; for $N < 20$ the power of nonparametric tests is inferior to parametric tests. The former tests, however, should be used if outliers occur in the data sets or if the observations are not normally distributed.

Analysis of Variance (ANOVA).

Trend analysis is less suited to replicate sampling over short time periods. The 1988 data set was thus treated by ANOVA (Montgomery, 1984). ANOVA is a statistical tool that permits the testing of the equality of several means $(\mu_1,\mu_2,...,\mu_a)$ and is thus a generalisation of the Student t–test which can be used to test the equality of two means. The test presupposes a random sampling of the designated snowstrata within the snow course on each sampling date. Although this was not done over the whole snow course on each date the spatial heterogeneity in the chemical composition of the whole snow course was established on the first sampling date, and then a systematic and progressive sampling of the strata in the course was carried out (Fig. 2). In an ANOVA the acceptance of the null hypothesis, H_0: $\mu_1=\mu_2= ...=\mu_a$, rejects any changes in the chemical composition of snow between successive sampling dates. This null hypothesis, is rejected if at least two means are significantly different. This differences in the level of the concentrations, however, is not necessarily a systematic trend. Multiple

Table 1. Power of the regression test for the detection of trend.

N [a]	δ [b]	Δ/σ [c]	$1-\beta$ [d]
8	1.5	0.23	0.25
8	2.0	0.31	0.40
8	2.5	0.39	0.55
22	1.5	0.050	0.28
22	2.0	0.067	0.45
22	2.5	0.084	0.64
62	1.5	0.011	0.30
62	2.0	0.014	0.50
62	2.5	0.018	0.70

a. N, number of samples.

b. δ, noncentrality parameter.

c. Δ/σ, ratio of slope (Δ) to the standard deviation of error component (σ).

d. $1-\beta$, power of the test.

comparison tests (Montgomery 1984) should be used to determine the possibility of a systematic trend.

Power of the ANOVA tests and number of samples required

The power of Fischer tests (F) used by the ANOVA are based on the noncentral Fischer distribution with noncentrality parameter (δ') defined by:

$$\delta'^2 = \frac{n \sum_{1}^{a} \tau_i^2}{a\,\sigma^2} \qquad (4)$$

where n is the number af replicates, a is the number of sampling dates, σ^2 is the variance of the error component and τ_i is the difference between the mean of the ith sampling date (μ_i) and the general mean ($\mu = 1/a\,\Sigma\,\mu_i$). Montgomery (1984) gives the power curves for these tests. Table 2 presents values of the power ($1-\beta$) derived from some values of n, a, δ' and $(\Sigma\tau_i^2/\sigma^2)^{0\cdot5}$. The table shows that the power increases (for any specified value of δ') as the number of replicates increases for the same number of sampling dates; if the number of sampling dates is not the same it is difficult to compare the powers of the respective sampling strategies as the expression $([\Sigma\tau_i^2/\sigma^2]^{0\cdot5})$ does not contain the same number of terms. The direct comparison of power of trend analysis tests and ANOVA tests by comparing Tables 1 and 2 cannot be made. However, under the following circumstances a comparison of power between the statistical tests can be obtained.

Comparison of power, Trend analysis versus ANOVA.

To compare the power of trend analysis tests and ANOVA tests it is necessary to relate the amplitude of the trend Δ and the term $\Sigma\tau_i^2$ associated with temporal changes of the mean. This is straightforward if time intervals for successive samplings is the same and if there is a change of Δ between the sampling intervals for both trend analysis and ANOVA. Even if the actual time intervals are different, Δ and $\Sigma\tau_i^2$ can be related. In the case of Lac Laflamme the time interval between successive samplings of the snowcover was approximately one week (6–10 days) in both 1985 (regression analysis)

Table 2. Power of the F–tests utilized in the analysis of variance.

N[a]	n[b]	a[c]	δ[d]	$(\Sigma\tau_i^2/\sigma^2)^{0.5}$[e]	$1-\beta$[f]
8	4	2	1.5	1.06	0.42
8	4	2	2.0	1.41	0.65
8	4	2	2.5	1.77	0.84
9	3	3	1.5	1.50	0.42
9	3	3	2.0	2.00	0.65
9	3	3	2.5	2.50	0.84
12	4	3	1.5	1.30	0.49
12	4	3	2.0	1.73	0.73
12	4	3	2.5	2.17	0.92

a. N, total number of samples.

b. n, number of replicates per sampling dates.

c. a, number of factor levels (i.e. number of sampling dates).

d. δ, noncentrality parameter.

e. τ_i, mean value at time i (μ_i) minus general mean ($\mu=\Sigma\mu_i/a$);
σ^2, variance of error component.

f. $1-\beta$, power of the test.

and 1988 (ANOVA).

Between two successive sampling dates, ANOVA is reduced to the standard Student t–test which leads to the following relationship between Δ and $\Sigma\tau_i^2$,

$$\sum_{i=1}^{2}\tau_i^2 = \sum_{i=1}^{2}\left[\mu_i - \frac{\mu_1+\mu_2}{2}\right]^2$$

$$= \sum_{i=1}^{2}\left[\frac{\Delta}{2}\right]^2 = \frac{\Delta^2}{2} \qquad (5)$$

with $\mu = (\mu_1 + \mu_2)/2$ and $\Delta = \mu_2 - \mu_1$ since there is a change of Δ units between two sampling dates. In a similar way it can be shown that for more than two successive sampling dates (a>2) the general relationship between Δ and $\Sigma\tau_i^2$ is given by equation 6.

$$\sum_{i=1}^{a}\tau_i^2 = \frac{\Sigma_{i=1}^{a}(a-i)\ i^2\ \Delta^2}{a} \qquad (6)$$

By using tables 1 and 2, and equations 5 and 6 one can now compare the relative efficiency of the two statistical methods to detect changes in a dynamic system (e.g. the cold snowcover) for the same number of observations. For example it can been seen from Table 1 that for a power value of .40 (8 observations, $\delta = 2.0$) the regression analysis will detect a slope of $\Delta = .31\sigma$. For the same number of observations (N = 8) and approximately the same value for the power of the ANOVA test of .42 (Table 2, n=4, a=2, $\delta' = 1.5$), the term $(\Sigma\tau_i^2/\sigma^2)^{0.5}$ is 1.06. Substituting $(1.06)^2\sigma^2$ for $\Sigma\tau_i^2$ in equation 5 leads to a value of $\Delta=1.5\sigma$, the ANOVA test in this case can thus only detect a slope of 1.5σ from the same sample size. The comparison is, however, only valid if the variance of the error component (σ^2) is the same for both methods.

In the above example the data for the ANOVA tests were obtained on two successive samplings of 4 replicates per sampling date (n = 4, a = 2,

Table 2). Equation 6 permits the comparison between the ANOVA test, for which the successive sampling dates are more than 2, and the trend analysis. Table 2 shows that the value of the power term for the condition of $N = 9$, $n = 3$, $a = 3$ and $\delta' = 1.5$ is very similar (0.42) to the regression test (0.40) and the ANOVA test (0.42, $N=8$, $n=4$, $a=2$, and $\delta'=1.5$) cited above . If we consider that the number of observations are approximately the same ($N = 9$ v $N = 8$) then from the value of $(\Sigma\tau_i^2/\sigma^2)^{0.5}$ of 1.5 and equation 6 it can be shown that the efficiency of the ANOVA can be bettered to detecting trends of amplitude, $\Delta = 1.1\sigma$, 4 times out of 10 with the ANOVA ($n=3$, $a=3$) but the trend analysis is still the most efficient method for the detection of a change in the concentrations.

Results and discussion.

1985: Trend detection

Table 3 shows the SWE, concentrations of SO_4 at each sampling date, and the mean concentration for the study period of four adjacent strata in the snowcover at the Lac Laflamme site between January 10 and March 27, 1985. The table also reproduces the weighted concentrations of SO_4 for the strata combined as one stratum. The study of the composite stratum smooths out the irregularities that occur between individual strata and represents a better picture of the overall evolution of that part of the snowcover where the strata are found. Although there may be a consistent monotonic trend over the whole time period the different strata may be exposed to different phenomena at different times. Thus one stratum may indicate a decrease in the concentration of SO_4 due to emigration of aerosols during snow metamorphism which is reflected by an increase in the SO_4 concentration of the adjacent stratum. In addition dry deposition will increase the SO_4 particulary in those strata which comprise the surface of the pack early on in their existance even though the net dominant overall phenomenom may result in SO_4 losses for the whole pack.

The graphical representation of the results of each individual stratum are presented in Figure 3; Figure 4 records the overall evolution of the strata combined as one stratum. Strata 1,3, and 4 (Figure 3)seem to show a decrease between January 23 and March 13 while the behaviour of stratum 2

Table 3. SO_4^{2-} concentrations (μeq l^{-1}) of four adjacent strata and of the composite stratum (strata 1–4) in the snowcover at Lac Laflamme, January to March, 1985.

Date	Stratum 1	Stratum 2	Stratum 3	Stratum 4	Stratum 1–4
10 Jan	25.6	10.4	8.1	21.0	13.9
16 Jan	29.6	9.8	15.4	29.4	17.1
23 Jan	39.8	9.0	12.3	20.8	17.8
30 Jan	17.9	11.5	13.8	26.3	14.5
6 Fév	17.9	9.4	12.7	24.6	13.2
13 Fév	15.2	9.8	9.8	22.3	11.8
20 Fév	17.3	9.0	8.3	21.0	11.5
27 Fév	11.5	9.6	10.6	19.8	10.9
7 Mar	11.9	10.4	9.0	17.3	10.8
13 Mar	11.3	10.8	8.5	15.8	10.6
20 Mar	12.3	10.2	10.6	24.2	11.6
27 Mar	20.4	12.3	12.3	23.8	14.9
Mean	19.2	10.2	11.0	22.2	13.2
SWE[a]	30.5	56.1	36.7	7.8	

[a] Snow water equivalent measured un millimeters

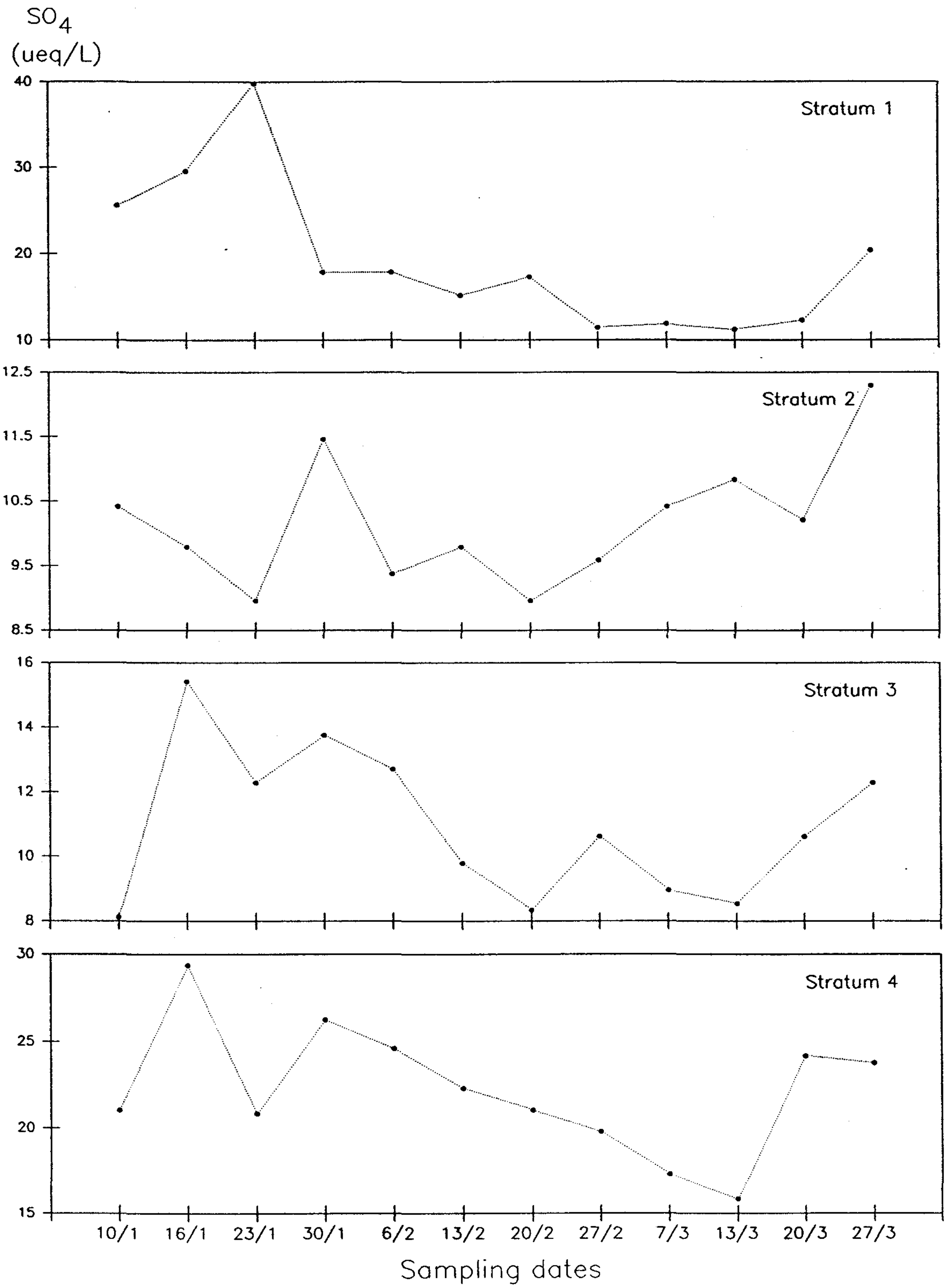


Figure 3. Evolution of SO_4 concentrations (μeq l^{-1}) in four adjacent strata in the snowcover, Lac Laflamme, Quebec, January to March, 1985 (sampling dates are schematic only).

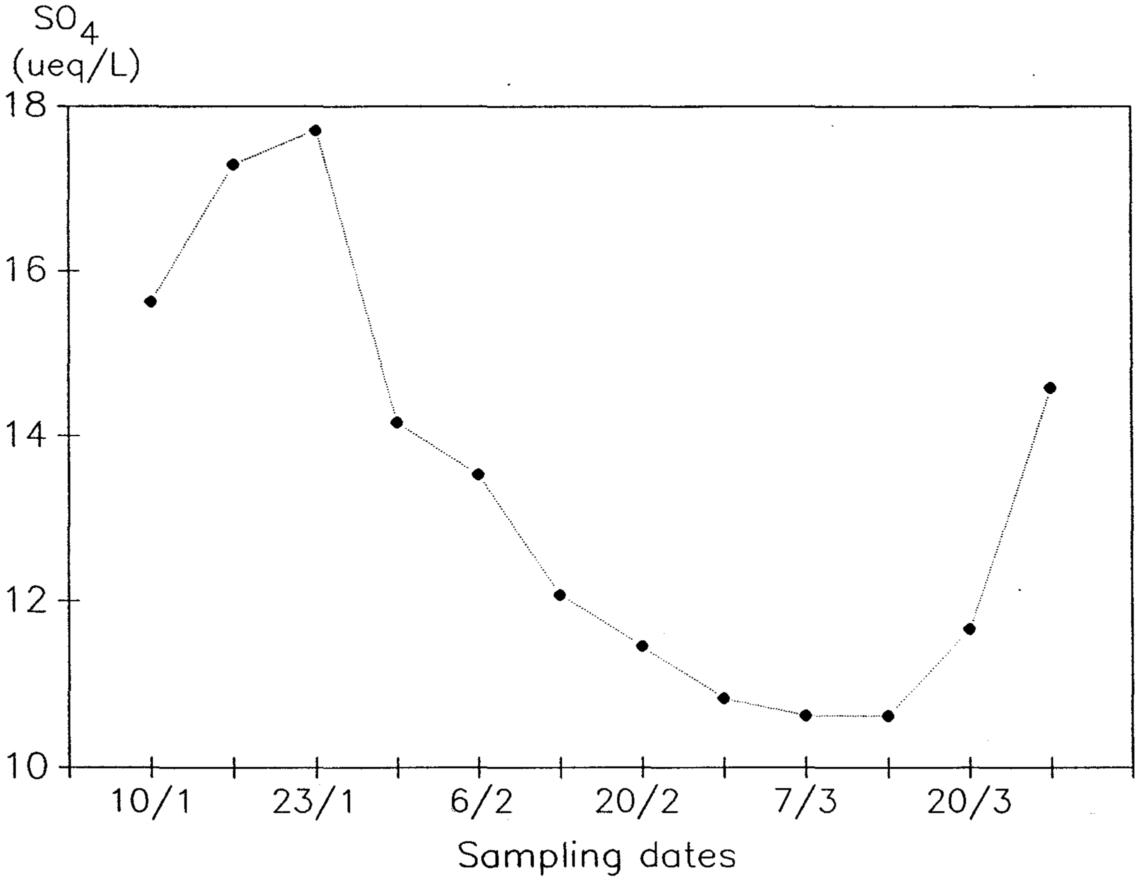


Figure 4. Evolution of weighted SO_4 concentrations (μeq l^{-1}) in the composite stratum (strata 1 to 4, Fig. 3), Lac Laflamme, Quebec, January to March, 1985 (sampling dates are schematic only).

is more erratic. Figure 4 also indicates that the overall trend between January 23 and March 13 is a decrease in SO_4 of approximately 7 μeq l^{-1}; as there was no loss or gain in SWE for this specific cold period the loss represents 39% of the original SO_4 load in the pack.

Regression analyses, however, on all the data for the strata show that the trends are significant only in the case of the first stratum and the composite stratum (Table 4). The overall trend of SO_4 losses is confirmed for the composite stratum. Spearman tests give exactly the same conclusions thus showing that no aberrant data affected the regressions. If only the data between January 23 and March 13 are subjected to the same analysis then strata 3 and 4 also show a significant downward trend in SO_4 concentrations. The results of the test lead us to the conclusion that there is a significant and progressive loss of SO_4 from the snow strata during the cold period. The increase in SO_4 concentrations at the beginning of the period may have been due to dry deposition at the pack surface (Cadle et al. 1985); the pack became deeper as the winter progressed, the lower strata (1–4) became isolated from the atmosphere, and dry deposition ceased to have a direct influence on the chemical evolution of these strata. On the other hand, the general increase of SO_4 at the end of the period is due to the percolation of meltwater from the upper part of the pack during the start of the springmelt season.

1988: ANOVA analysis.

Table 5 shows the replicate values, the mean value, and the standard deviation of SO_4 concentrations for the four strata at the Lake Laflamme site in 1988. The weather in that year consisted of melt and rain–on–snow episodes and a prolonged period for the study of changes in cold snow did not occur. The longest period of persistent cold weather was experienced between February 5 and February 15. These unfavorable weather conditions did not allow the sampling of a stratum for more than two sampling dates. The Student t–test showed that there was a significant change over time of SO_4 concentrations for strata 2,3, and 4 during their respective cold periods. In each case, losses (18%, 2; 39%, 3; 27%, 4) of SO_4 were registered; the amplitude of the losses thus averages out at between 2.5% and 4% day^{-1}.

Table 4. Regression tests and trend detection results of SO_4^{2-} concentrations in four adjacent strata and the composite stratum(1–4) in the snowcover at Lac Laflamme for the period January 10 to March 27, 1985.

Stratum	Significant Trend (Yes/No)	$\hat{\Delta}$ [a]	$\hat{\sigma}$ [b]
1	Yes, negative	–0.86	3.57
2	No	+0.06	0.51
3	No	–0.11	1.25
4	No	–0.21	1.94
Composite 1_4	Yes, negative	–0.26	1.03

a. $\hat{\Delta}$, estimated slope, measured in μeq l^{-1}week^{-1}

b. $\hat{\sigma}$, estimated standard deviation of error component, measured in μeq l^{-1}

Table 5. SO_4^{2-} concentrations (μeq l^{-1})of four distinct strata in the snowcover of Lac Laflamme for different time periods , January 20 to March 4, 1988.

		Stratum 1	Stratum 2	Stratum 3	Stratum 4
		20–1–88	20–1–88	5–2–88	23–2–88
Replicate #1		11.98	46.92	7.25	10.00
Replicate #2		11.40	50.65	7.29	10.42
Replicate #3		11.42	51.33	7.31	11.67
Replicate #4		11.52	50.98	7.33	10.83
Replicate #5		11.81	50.46	7.46	10.72
	Mean	11.63	50.06	7.33	10.73
	$\hat{\sigma}$ [a]	0.26	1.80	0.08	0.62
		27–1–88	27–1–88	15–2–88	4–3–88
Replicate #1		11.77	43.73	4.92	8.33
Replicate #2		11.90	41.13	4.52	7.92
Replicate #3		11.79	40.31	4.13	7.92
Replicate #4		11.42	40.38	4.33	7.92
Replicate #5		12.13	39.33	4.33	8.13
	Mean	11.79	40.99	4.44	8.04
	$\hat{\sigma}$ [a]	0.26	1.67	0.30	0.19

a. $\hat{\sigma}$, standard deviation of replicates, measured in μeq l^{-1}.

The tests also permitted the estimation of standard deviations of the error component: the values are 0.26 μeq l^{-1}, stratum 1; 1.74 μeq l^{-1}, stratum 2; 0.22 μeq l^{-1}, stratum 3; and 0.46 μeq l^{-1}, stratum 4.

Comparison of the two methods, 1985, 1988.

From the above estimations of σ for t–tests and regression analysis we can now compare the power of the tests to detect absolute changes in the concentrations of SO_4 over time. Table 4 shows that the values of $\hat{\sigma}$ for SO_4 concentrations varied between 0.51 μeq l^{-1} and 3.57 μeq l^{-1} for the regression analysis of snow strata sampled in 1985. In general the values of $\hat{\sigma}$ are proportional to the absolute values for the mean concentrations showing that the coefficient of variation is relatively stable. This is also true in the case of the ANOVA for the snow strata in 1988 (Table 5). We can thus compare, on one hand, the power of the two methods for strata which have low concentrations of SO_4, and, on the other hand, for strata which are more polluted in SO_4.

In the first case, stratum 2 in the 1985 series ($SO_4 \simeq 10$ μeq l^{-1}, Table 3)) can be considered as being equivalent in mean to stratum 4 ($SO_4 \simeq 10$ μeq l^{-1}) in the 1988 ANOVA study. To estimate the powers of the different tests used the estimated values of the standard deviations of error component are $\hat{\sigma} = 0.51$ μeq l^{-1}, 1985, (Table 4) and $\hat{\sigma} = 0.46$ μeq l^{-1}, 1988.

In the second case, stratum 4, 1985 ($SO_4 \simeq 20$ μeq l^{-1}), the most consistently concentrated stratum of the regression analysis, can be compared with some limitations to stratum 2, 1988 ($SO_4 \simeq 40$ μeq l^{-1}), the most polluted stratum in SO_4 used for the ANOVA. Estimated values for $\hat{\sigma}$ in this case are 1.9 μeq l^{-1} in 1985 and 1.7 μeq l^{-1} in 1988.

For the sake of comparison, the number of total samples taken (N) is set at 8. This represents 1 sample per date for 8 successive samplings in the regression analysis and 4 replicate samples per date for two samplings in ANOVA within the same time period. Substituting the respective values for $\hat{\sigma}$ of strata 2 and 4, 1985, into Table 1 (regression analysis), and strata 4 and 2, 1988, into Table 2 (ANOVA) permits the calculation of the amplitude of detectable changes over time of SO_4 concentrations at comparable powers. Thus Table 6 shows that at a power of 0.40 the regression analysis can detect Δ values of more than 0.16 μeq l^{-1} per sampling interval in the case of the

Table 6. Comparison of the power (1–β) of regression analysis tests and of ANOVA tests to detect trends of absolute amplitude (μeq l^{-1}) in SO_4 concentrations.

a) Low concentrations of SO_4 ($\simeq$ 10 μeq l^{-1})

		Regression Analysis		ANOVA	
N	δ	Δ^a	1–β	Δ^a	1–β
8	1.5	0.12	0.25	0.69	0.42
8	2.0	0.16	0.40	0.92	0.65
8	2.5	0.20	0.55	1.15	0.84

b) High concentrations of SO_4 (> 20 μeq l^{-1})

		Regression Analysis		ANOVA	
N	δ	Δ^a	1–β	Δ^a	1–β
8	1.5	0.44	0.25	2.61	0.42
8	2.0	0.59	0.40	3.47	0.65
8	2.5	0.74	0.55	4.36	0.84

a. Δ, amplitude detected in μeq l^{-1} per sampling interval.

relatively dilute snow. The ANOVA test, however, detects values of Δ of only more than 0.69 μeq l^{-1} per sampling interval for similarly dilute snow at the same power. For polluted snow strata the regression analysis at a power of 0.40 can detect a trend amplitude of 0.59 μeq l^{-1} per sampling interval compared to 2.61 μeq l^{-1} per sampling interval by the ANOVA test at the same power.

Conclusion

The results of the 1985 and the 1988 studies clearly show that losses of SO_4 can occur in snow during cold periods. Analysis of the data also demonstrates that for the same number of samples, the maximal distribution of the total number of samples over time (i.e. 1 sample per sampling date), and regression analysis, is more efficient in detecting the chemical changes in snow than the alternative method of regrouping the number of samples for a lesser number of successive sampling dates and using ANOVA.

This information can be used to plan future sampling programs of cold snow. Two senarios for sampling can be envisaged. The first senario is that in which the cost of the field sampling is the major financial burden of the study. If one has a prior knowledge of the variability of concentrations of SO_4 in the snow, a minimum value for the amplitude of the changes that are detectable for the particular study in question may be set. By constructing tables similar to Table 6, the relationship between the number of samples, the maximum number of sampling trips that the budget will permit, the amplitude of the trend that is desired, and the probable success rate of detecting the trend (power of the test) for ANOVA may be found. Conversely, if the number of samples is restricted by the budget but the field sampling is not, then a table of the power to detect the required amplitude of chemical change by regression analysis may be drawn up. This methodology, however, is only of value in simple systems e.g. in regions where the probability of prolonged cold periods is high (Arctic, Antarctic). In the Lac Laflamme area the probability of accurately forecasting cold periods of more than one week or so is very low; in addition, the budget costs for analysis of samples and field sampling are comparable. In general, the program of snow sampling at this site relies more extensively on the ANOVA approach the lost of power is then offset by fewer field samplings and lower probability of unfavorable weather conditions. On the other hand the study of chemical changes in cold snow in the laboratory where experimental conditions may be easily controlled (Jones, and Deblois 1987) is more amenable to regression analysis.

Acknowledgements

This research was made possible with the financial aid of Environment Canada and the Natural Sciences and Engineering Research Council of Canada.

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CHAPITRE II

CHAPTER II

SNOQUAL, a model for the simulation of meltwater quantity and quality in boreal forest catchments: a study of the model variants for the chemistry of snow meltwaters.

(SNOQUAL, un modèle pour simuler la quantité et la qualité des eaux de fonte dans des bassins de la forêt boréale; une étude de trois versions du modèle pour la chimie des eaux de fonte)

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November 1989

Résumé

Le modèle conceptuel SNOQUAL, établit le rapport entre la quantité et la composition chimique des eaux déchargées du couvert de neige en période de fonte. Le modèle est structuré à partir de deux modules. Le premier, SNOW-17, est quantitatif; il simule le taux de décharge des eaux de fonte selon l'échange d'énergie à l'interface neige-atmosphère. Le deuxième est qualitatif; il utilise les extraits de SNOW-17 pour calculer la concentration des ions dans chaque volume de fonte par temps de pas utilisé. Ce deuxième module est dérivé des expressions de lessivage de divers espèces ioniques du couvert de neige par les eaux de fonte. Le module qualitatif est caractérisé par un ou des coefficient(s) de lessivage (k) dont la valeur peut être différente selon l'espèce ionique lessivée.

Cet article décrit trois versions du module qualitatif qu'on a comparé pendant la calibration du SNOQUAL. Il s'agit de SNOQUAL1, SNOQUALR et SNOQUALD. Ces versions tiennent compte respectivement du processus de lessivage surficiel des crystaux de neige, du lessivage surficiel et de la charge ionique résiduelle qui se trouve à l'intérieur des grains, du lessivage surficiel de neige et du lessivage relativement plus lent du débris forestier sur le couvert de neige.

La calibration de chacun de ces modules qualitatifs par l'utilisation des données des fontes prises "in situ" au Lac Laflamme, Québec, et des fontes contrôllées en laboratoire démontre que les valeurs pour les coefficients de lessivage sont influencées par la quantité de débris organique dans le couvert. De plus, les résultats démontrent que le module qui simule le mieux les concentrations réelles observées sur le terrain au Lac Laflamme est SNOQUALR.

Enfin, on décrit les résultats d'une application du SNOQUALR pour la simulation de l'acidité (pH) des premières eaux de fonte des couverts hivernaux accumulés à partir de neige précipitée sous des conditions théoriques. Ces conditions sont soit d'une réduction soit d'une augmentation des émissions de SO_2 par rapport aux émissions présentement enregistrées en Amérique du Nord.

ABSTRACT

SNOQUAL is a conceptual model that relates the quantity of meltwater released from the snowpack to the chemical composition of the discharge. The structure of the model consists of two modules. The first, SNOW-17 (Anderson, 1973), simulates the rate of meltwater discharge from the estimation of energy exchange across the snow-air interface. The second module takes the output from SNOW-17 and calculates the concentration of ions in each discrete discharge by a routine which is derived from a, or two, first order leaching expression(s) for the soluble species from the snowpack. The qualitative module is characterized by a leaching coefficient(s) (k) the value of which can differ for each ionic species present in the pack leachate.

This paper discusses three versions of the qualitative module that have been used in the calibration of SNOQUAL. These three variants (SNOQUAL1, SNOQUALR, and SNOQUALD) attempt to reflect the physical reality of the interaction of meltwater and the snow in situ. They take into account, respectively, the leaching process of ice crystals, the suficial leaching plus the non-surficial ionic load which resides within the ice structure, and the presence of both rapid and slow leaching components (snow and canopy debris) in forested snowpacks.

The calibration of each of these qualitative modules with snow meltwater concentrations in laboratory and field experiments at Lac Laflamme, Quebec, shows that the leaching coefficients of the model variants are influenced by the quantity of organic debris in the pack. The results also show that the model which best generates meltwater concentrations close to those measured in the field is SNOQUALR.

The application of SNOQUALR to the simulation of the acidity (pH) of the first meltwaters that can be expected from snowpacks deposited under condition of either a reduction or an increase in SO_2 emissions is also given.

INTRODUCTION

In the southeastern region of the Canadian Shield the pH of the precipitation is often in the range of 3.8-4.5. These levels of acidity are judged to be detrimental to the aquatic and terrestrial ecosystems of the area. In the "Réserve faunique des Laurentides" north of Quebec City, Environment Canada has established an experimental program on the measurement and impact of acid precipitation on the aquatic ressources of the Lake Laflamme watershed (Jones and Deblois, 1987). One of the major research projects of the program is the modelling of the fluxes of acid waters through the watershed during the spring melt. The mean pH of the waters of Lake Laflamme is 6.4 during the greater part of the year; it is only during the spring melt period that the lake waters undergo episodic acidification. pH values of 4.2 for sub-ice waters in inshore spawning areas have been recorded (Charette et al., 1984).

The model development has centered mainly on the construction of a comprehensive model for the acidity of lake waters. The model is modular and consists of a snow meltwater model (SNOQUAL) which serves as the input to a model of soil solution chemistry (SOILEQ). The output from SOILEQ is then used to model the movement of meltwaters through the lake (the model SHOREMIX). A hydrological model VSAS2 based on the variable source area concept is used to simulate the meltwater pathways in the watershed from the time penetrates to the time it leaves the bassin. SNOQUAL itself consists of two modules. The first is SNOW-17 which simulates quantitatively meltwater discharge from the snowpack. The second module simulates the release of chemical components from the snow by the meltwaters.

This paper describes the meltwater leaching of snow and other in-pack material, the basic process variable of the chemical model. The various versions of the model which have been used to simulate the chemical composition of meltwaters discharged from the snowpack at Lake Laflamme are discussed. The difficulties in the calibration of the models using field data are outlined and the accuracy of the different versions of the model to generate the concentrations of the strong-acid anions SO_4^{2-} and NO_3^- in meltwaters are compared. Laboratory studies to determine the probable range of values for the leaching parameter of ionic species from the melting snowpack are also described.

STUDY SITE AND METHODOLOGY

The site: Lac Laflamme is a small headwater lake (0.06 km^{-2}; location, 47°19' N, 71°07'W) in the Parc des laurentides, Quebec (Fig. 1). The watershed (0.6 km^{-2}) is covered with close-knit mature stands of Balsam Fir interspersed with small areas of birch and spruce. The trees are heavily covered with epiphytic lichens. The mean annual temperature is 0.2°C (-15°C January; 15°C, July). The total snowfall (October-May) at Lac Laflamme is approximately 400 mm (Snow Water Equivalent, SWE) and the pack usually attains a depth of 120-150 cm at the end of the accumulation period. During the winter the pack receives considerable amounts of canopy fallout consisting mostly of lichens, bark, needles, leaves and small twigs (Jones and Deblois, 1987). The melt season

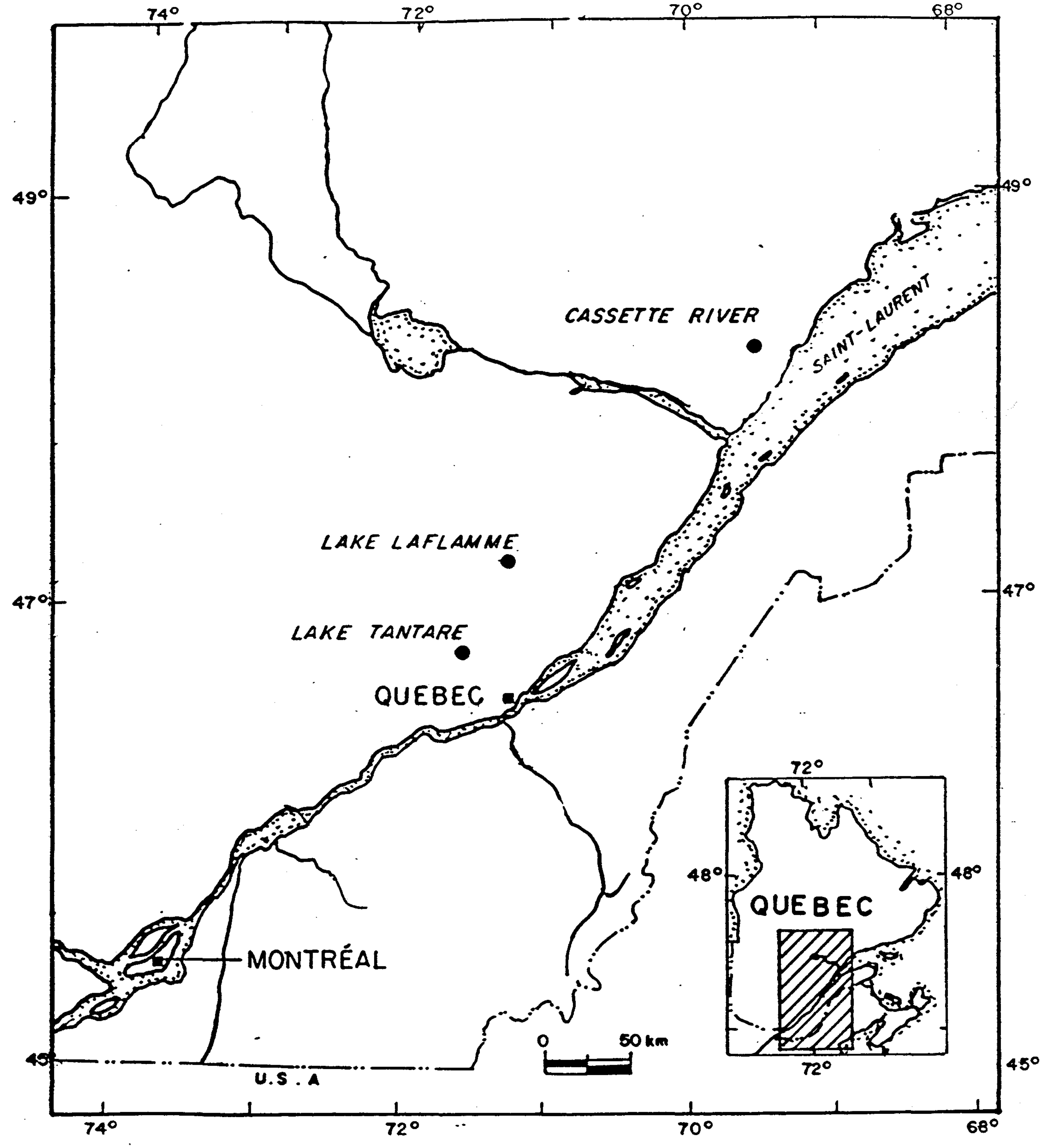

FIGURE 1: Study Site, Lac Laflamme, Québec.

generally begins towards the end of April and maximum meltwater discharge occurs during the first two weeks of May.

Field snowcover and meltwater study: four square shaped lysimeters (1 m by 1 m; sidewall height, 0.5 m) were installed for the 1988 melt season. The lysimeters were constructed of plastic covered fiberglass (Fig 2). Three were placed within a Balsam Fir stand under a closed canopy, an open canopy (50% cover), a mixed canopy of Balsam Fir and White Birch. The fourth lysimeter was placed in clear-cut area. The extent of the canopy cover was determined by photography (subtended angle of view, 23°) of the canopy cover from the forest floor. Snowcover samples were taken in the vicinity of the lysimeters using an Adirondack corer. Precipitation was sampled by means of a Sangamo wet-only collector. Meltwater samples representing the integrated sample of all meltwater discharges over 24 hours were taken at midday (noon to 14:00 hours) every day. All samples were kept at 0°C during transport to the laboratory; pH and conductivity measurements were taken on arrival and the samples filtered and conserved for further chemical analysis (Jones, 1987).

Laboratory study: a simulator for snowmelt discharge was constructed of plastic; the simulator consisted of four columns within which "clean" snow taken from open areas in the forest, and different combinations of clean snow and organic debris could be melted under carefully controlled conditions (Jones and Deblois, 1987). Between 80-100 cm of snow or snow-organic mixtures were placed in the columns and the melt conditions were adjusted to give meltwater discharges similar to those observed in the field. The amount of organic matter added to the clean snow (weight per unit area of snow surface) was approximately equal to that found on the snowcover at the Lac Laflamme site

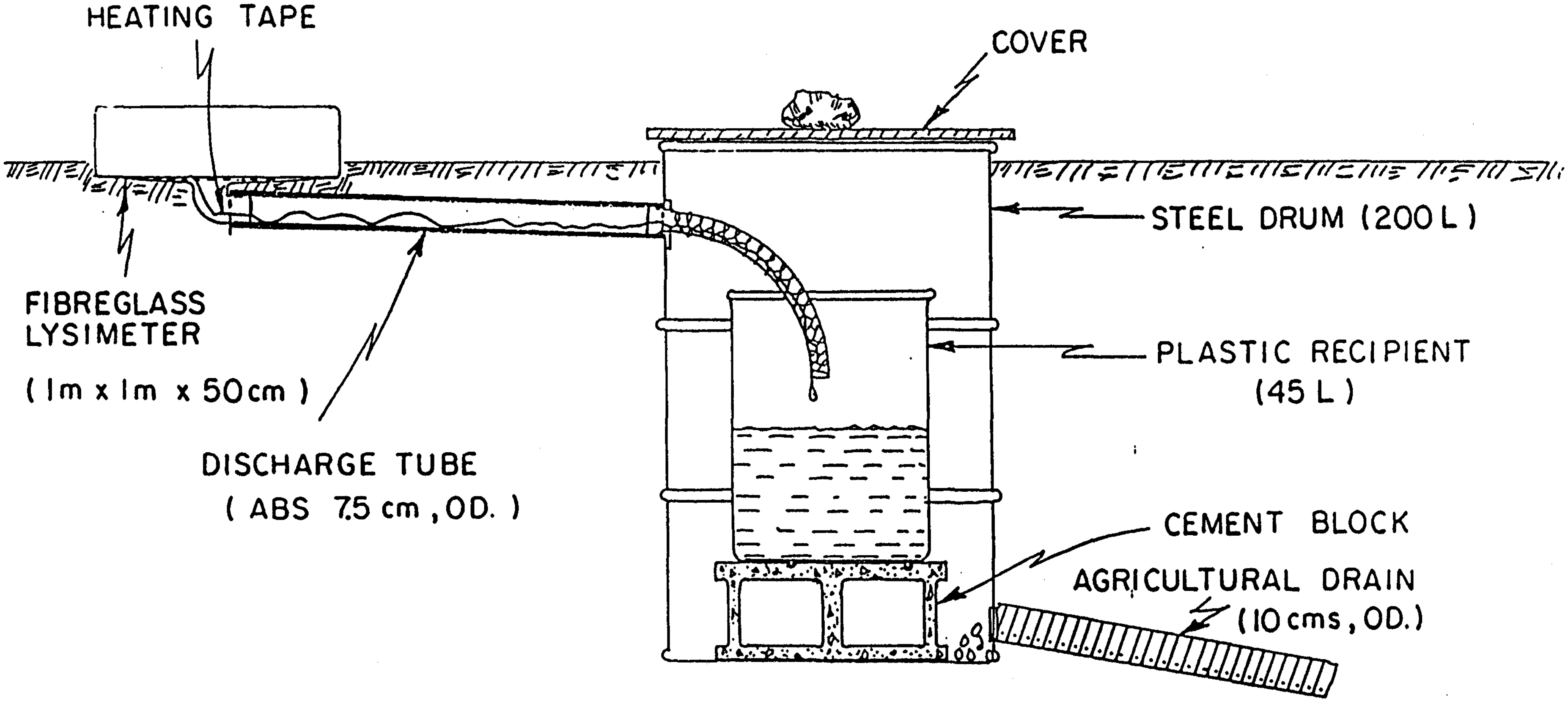

FIGURE 2: Field lysimeter, Lac Laflamme, Québec.

just prior to the springmelt. As in the case of the field lysimeters the meltwater samples were gathered every 24 hours and analysed in exactly the same manner.

Chemical analysis: the samples were analysed for the major ions (Na, K, Ca, Mg, Cl, SO_4, NO_3); details of the precise methods used may be found in Jones and Sochanska, 1985. The washing of field lysimeters with distilled water showed that contamination of meltwater by the collectors was not a feature of the experimental set-up; the laboratory lysimeters, however, did show some contamination (Cl) probably due to some microbiological degradation of the PVC used to construct the columns.

MODEL PROCESSES

The models are chemical subroutines of the global model for the simulation of snow meltwater quantity and quality (SNOQUAL, Stein et al, 1986). They are based both on the physical phenomena that are known to occur when snow meltwaters move down through the pack and on observations of meltwater composition from meltwater studies in the field (Jones, 1987) and the laboratory (Jones and Deblois, 1987). The models are of three types all of which, however, are based on the physical concept of the leaching of solubles from the pack matrix by a diminishing reserve of ice meltwaters. In all of the models the parameter for the rate of leaching is a leaching coefficient 'k' (Foster,1978).

In the first model (SNOQUAL1) the value of the leaching coefficient represents the net leaching effect of the removal of solubles from both the surface of snow crystals and other material (mostly fallout of organic matter from the canopy) in the pack. In the case of field studies the contribution of solubles from organic matter to the total amount of matter leached from the pack may be appreciable e.g. K^+. Conversely, organic matter may also show an apparent effect of adsorption of some ions e.g. NO_3 due to microbiological assimilation of nutrients in situ during the melt period (Hoham et al, 1989).

In the second model (SNOQUALR) the value of the leaching coefficient again represents the net leaching effect of solubles from the pack; the snow and organic matter being lumped together. However, in this particular model the material to be removed from the snowpack is segregated into two components. The first component consists of concentrated solutions of ionic species on the surfaces of snow grains. The segregation and concentration of ionic solutions on the surfaces of the grains is known to occur during the metamorphism of snow crystals to grains prior to the melt season (Tranter et al, 1986). This process, however, leaves some of the ions as a residual component of the original composition of the snow crystals within the ice lattice structure of the snow grains. This residual component may be easily shown from laboratory leaching experiments.

For the purposes of the modelling of snow meltwater chemistry, the residual component is not classed as a leacheable material as such, but rather is the basic contribution of the melting ice to the overall chemical composition of meltwaters. As the melting snow removes more and more of the concentrated surface solutions from the snow grains (plus surface leaching of organic matter), the composition of the meltwaters discharged from the pack approaches that of the residual concentrations in the ice lattices of the snow grains.

This residual component is expressed by means of a constant, R, the fractionation coefficient. Although it is convenient to adopt this concept of segregation of solubles in the pack based on the results of the laboratory experiments on "clean" snow, field studies on meltwaters cannot distinguish between residual solubles within ice grains and those which may be removed by the meltwaters from organic matter in the later stages of the melt.

The third model (SNOQUALD) is similar to (SNOQUALR) in that the model segregates the material to be leached from the pack into components. In this model, however, a distinction is not only made between surface leachables and residual concentrations in the ice structure but also between snow and other pack components (e.g. organic matter, dry deposited material). A constant, s, the segregation coefficient, is used to distinguish between the contribution of the snow to the meltwater composition and that of the other matter. The model thus contains two leaching coefficients, k_s and k_m, representing respectively the leaching of snow and the leaching of the other components, particularly the organic matter. Laboratory studies are carried out in an attempt to distinguish the two coefficients; curve fitting will also optimise the values of k_s and k_m.

MODEL STRUCTURES

In all the models the common model parameters are the concentration of ions in the snow, C (μeq l^{-1}), the height of the pack, H (snow water equivalent, SWE, mm), and k (net leaching coefficient, mm^{-1}) or k_s and k_m in the case of SNOQUALD. Model inputs are C_o, the bulk ionic concentration of the snow prior to melt, H_o the height of the pack at the beginning of the melt, and H_i the height of the pack at the end of a specified melt period. The leaching coefficient(s), K, can either be an input or an output, the latter being the result of curve-fitting of the numbers generated by the models to the real data of snow and/or meltwater compositions in the field. C_i the concentration of an ionic species in the snow at the condition $H = H_i$ is the primary output which transposed into the meltwater concentration, C_m, is used as the basis for the curve fitting exercises to determine other model parameters (Jones et al, 1986).

The expressions 1, 2, and 3 represent SNOQUAL1, SNOQUALR, and SNOQUALD respectively.

$$C_i = C_o e^{-k\,(H_o - H_i)} \qquad (1)$$

$$C_i = C_o(1-R)\, e^{-k\,(H_o - H_i)} + RC_o \qquad (2)$$

$$C_i = C_o(1-R)s\; e^{-k_s(H_o - H_i)} - C_o(1-R)(1-s)e^{-k_m\,(H_o - H_i)} + RC_o \qquad (3)$$

In SNOQUALR the term, R, the fractionation coefficient is either an input to the model, the value being determined from laboratory studies, or an output, the value being determined by default during the calibration procedure. In SNOQUALD, R, is an input determined from observations in the field or the laboratory (the value of R is usually calculated as the mean value of measured concentration in the last 10-20% of the residual meltwaters. In this model, the second constant, segregation coefficient, s, which quantifies that part of the total bulk concentration of the pack associated with the snow grains is an input to the model (see "model calibration").

MODEL CALIBRATION

The structures of the above models are based mostly on simple physical concepts of meltwater leaching. Both meltwater leaching, particulary in the field, are however complicated by meteorological and in-pack physical and chemical conditions which make it difficult to calibrate the models using data on natural meltwaters. The calibration is thus restricted to melt periods in which there are no major perturbations of the meltwater production. The calibration is terminated in the case of appreciable rain-on-snow events (Jones et al., 1989). The calibration is also terminated when relatively long and cold periods cause meltwater production to drop to low values. The calibration is restarted after the perturbation ends. In the case of mild but continual perturbation of the system e.g. light rains or diurnal freeze and melt cycles, calibration is not interrupted.

Another factor which has to be taken into account in the calibration of the models against natural meltwaters is the combined influence of fallout of organic debris, dry deposition, wet deposition, and in-pack biological activity on pack chemistry. The result of these processes is that the total amount of chemical load removed from the pack is not equal to the load that resided in the pack just prior to the melt. The total amount of water discharged may also be different from that indicated by the reduction in the SWE of the pack during periods of light rain or condensation. At the present time we do not have enough information on these phenomena which would facilitate the calibration of the models, and any subsequent simulation, on an event or short-term basis. To partially compensate, however, for this lack in the model calibration, the calibration procedure first calculates the contribution of all these spurious inputs to the pack for any one calibration period. The calculated values are then integrated into the model, as if all the chemical load associated with these inputs had been originally present in the pack at the start of the melt sequence. Consequently, instead of using the original values of C_o and H_o, as measured directly in the field to calibrate the models, apparent values of C_o and H_o at the beginning of the melt are calculated from the field data. For any one period these apparent values of C_o and H_o are calculated from C_m and H_m, the concentration and the height of meltwater discharge respectively, and the residual concentration, C_r, and height, H_r, of the pack measured at the end of the period (expressions 4, and 5).

$$C_o \text{ (apparent)} = (\Sigma\, C_m{*}H_m + C_r{*}H_r)/(\Sigma\, H_m + H_r) \qquad (4)$$

$$H_o \text{ (apparent)} = \Sigma\, H_m + H_r \qquad (5)$$

These apparent values of C_o, H_o are used for the models SNOQUAL1 and SNOQUALR. This calibration procedure differs from the calibration procedure that was first reported for the original SNOQUAL model (Jones et al, 1986) where the original measured bulk concentration and SWE of the snowpack were used as inputs for C_o and H_o.

In the case of SNOQUALD the real measured value of the bulk concentration of any ion in the snowpack just prior to the melt and the calculated apparent value for the bulk concentration from expression 4 are used to determine the value of 's', the segregation constant (expression 3). s is assigned the value of C_o(real)/C_o(apparent). The contribution of snow grains to the overall pack composition is thus designated to be the original value of C_o as measured directly in the field prior to melt (i.e. C_o[real] = C_o[apparent] * s). The remainder (C_o[apparent] - C_o[real] = C_o[apparent](1-s)) is designated as the contribution of all the other spurious inputs (canopy fallout, dry deposition, wet deposition, and in-pack biological activity) to the final chemical composition of the pack responsible for meltwater concentration during the specified calibration period.

Once C_o(apparent) and H_o(apparent) have been calculated, a mean value of k is determined for SNOQUAL1 (expression 1) from the meltwater data of the four field lysimeters by curve fitting (method of least squares). The same procedure is used to determine k and R for SNOQUALR (expression 2). In the case of SNOQUALD the value of R from SNOQUALR is taken as an input, the value of s is also an input, and mean values for k_s and k_m are also found by curve fitting the field data.

SIMULATION OF MELTWATER QUALITY

To simulate the chemical composition of meltwaters over the whole watershed of Lake Laflamme the values of C_o, and k (SNOQUAL1); C_o, k, and R (SNOQUALR), and C_o, s, R, k_s, and k_m (SNOQUALD) are used to initialise the appropriate model. $H_o$and H_i are then generated from the physical and meteorological data by SNOW-17. Concatenation of the physical and chemical routines then simulates the quantity and quality of meltwater discharge for the whole basin.

DISCUSSION

Model calibration: laboratory, field

The calibration of the different variants of the model (SNOQUAL1, SNOQUALR, and SNOQUALD) using the real concentrations of SO_4 in meltwaters from controlled melts in the laboratory is shown in figures 3, and 4. Melt experiments for both clean snow taken from large open areas in the forest and clean snow to which organic matter (lichens, twigs, bark, needles, and leaves) taken from the forest canopy was added, were carried out. The influence of the organic matter on the leaching process may be clearly seen by comparing the elution concentrations reproduced in figures 3 and 4. The organic matter increases the SO_4 load of the meltwaters in contact with the organics over that of meltwaters from clean snow by desorption of the ion from the organic surfaces. The decrease of meltwater concentrations is thus less acute in the case of snow containing organic matter than that of snow meltwaters alone. This production of ions by the organic matter during the melt by desorption and/or microbiological processes causes an apparent decrease in the leaching coefficient.

The efficiency of each variant of the model to conform to the laboratory and the field measurements of meltwater quality by the calibration procedure may be judged by comparing the Standard Error of Estimation (SEE). The laboratory experiments showed that the calibration of SNOQUALR gave lower values of SEE than SNOQUAL1 or SNOQUALD. The same result was observed in the case of the field trials; table 1 records the SEE values for both SO_4 and NO3 for each of the four field lysimeters. SNOQUALR generates meltwater concentrations which

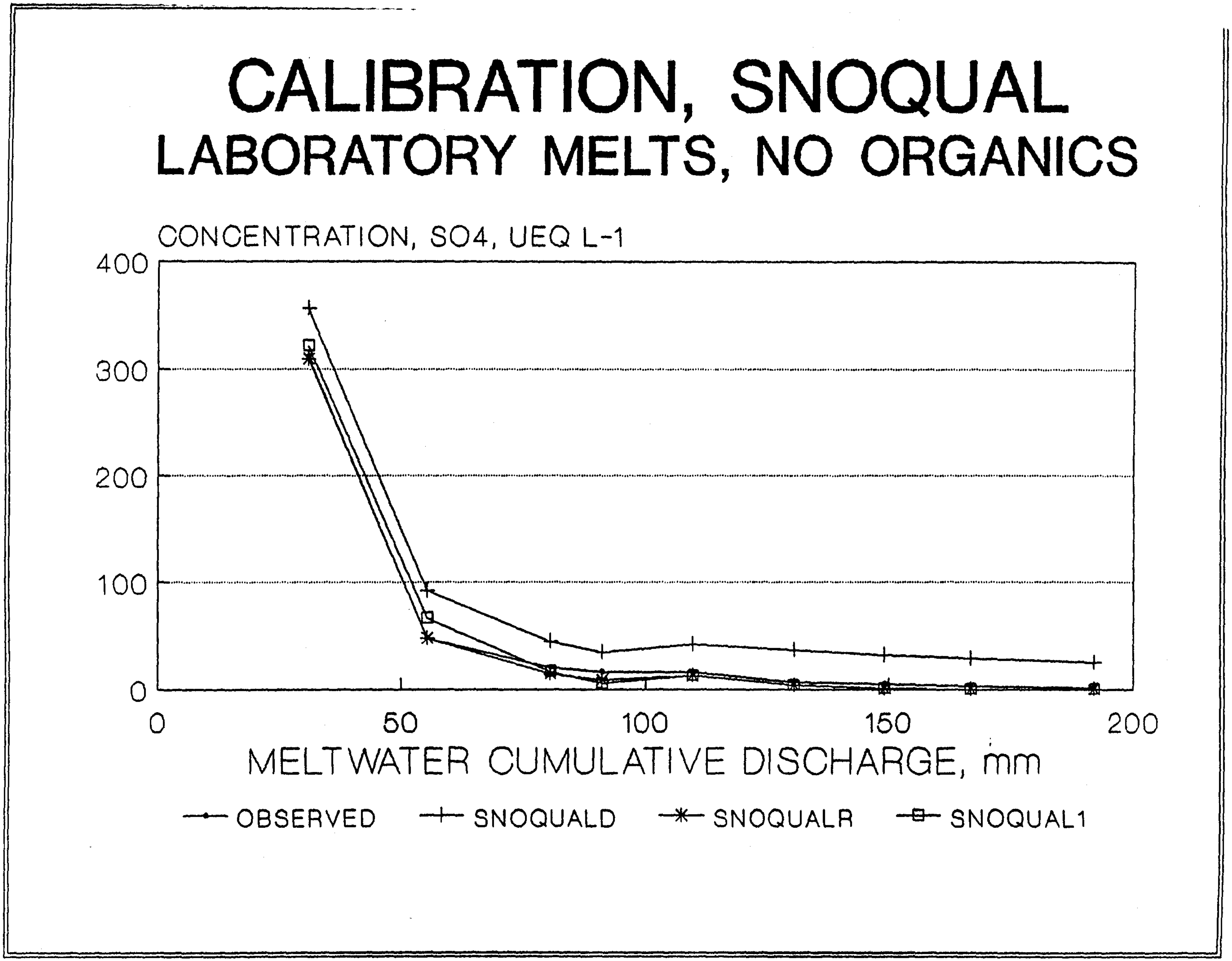

FIGURE 3: Calibration of SNOQUAL variants with data on meltwater SO_4 concentration values from laboratory melts: clean snow.

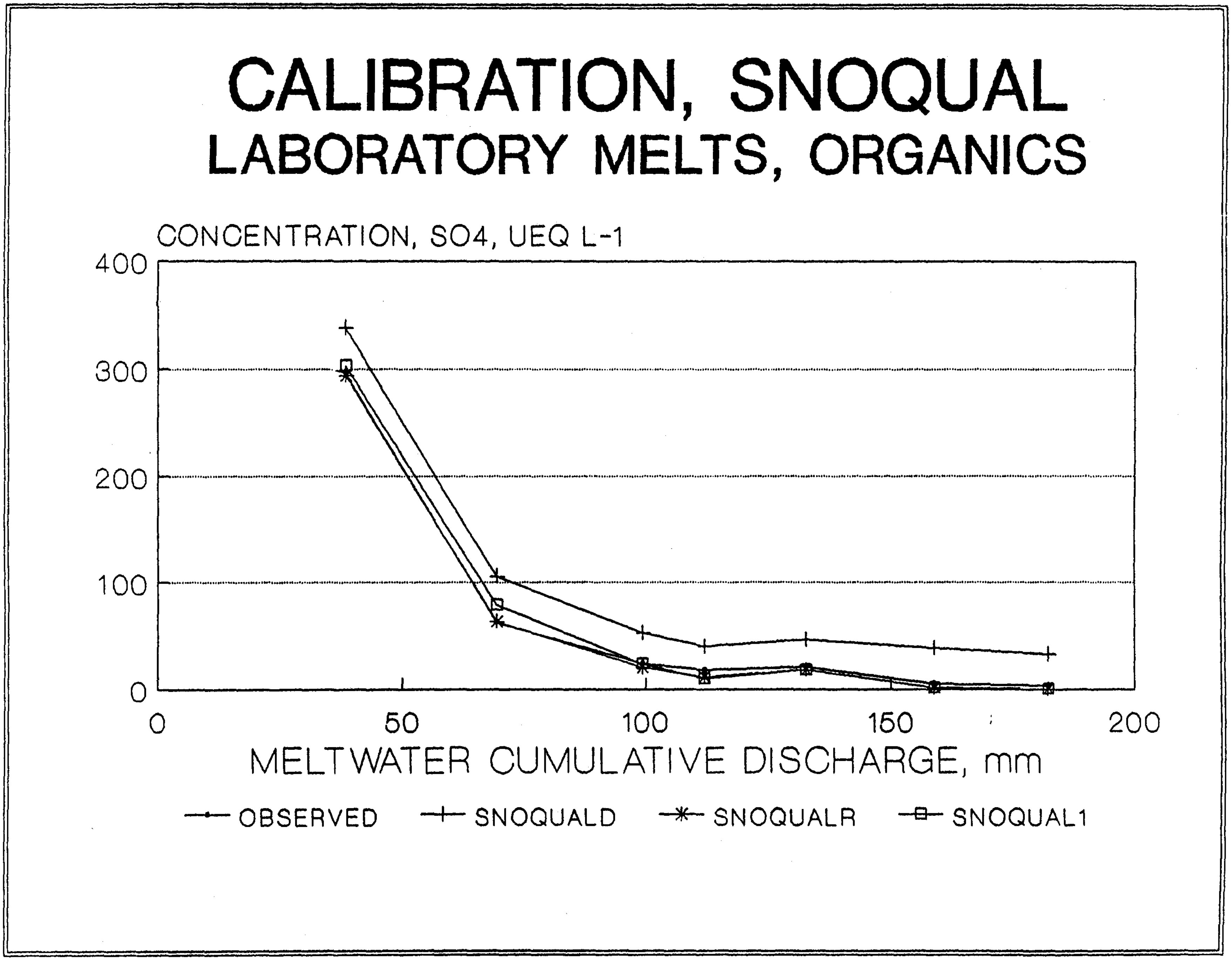

FIGURE 4: Calibration of SNOQUAL variants with data on meltwater SO_4 concentration values from laboratory melts: snow plus organic matter.

TABLE 1

Standard Error of Estimation (SEE, μeq L^{-1}) for calibration of SNOQUAL1, SNOQUALR, and SNOQUALD, Lac Laflamme, 1988.

Standard error of estimation (see)				
	FIRST MELT PERIOD		WHOLE MELT PERIOD	
	SO_4	NO_3	SO_4	NO_3
SNOQUAL1	61.10[1]	41.00	40.94	27.45
	63.50[1]	67.64	45.61	46.97
	261.57[1]	174.10	169.80	111.53
	42.56[2]	56.73	27.55	34.96
	112.62[3]	97.32	71.37	61.16
MEAN	108.27	87.36	71.05	56.41
SNOQUALR	61.10	41.00	40.80	27.40
	63.5	67.60	45.58	46.90
	261.53	174.10	168.70	111.53
	42.51	56.10	27.07	34.96
	112.59	97.30	71.33	61.12
MEAN	108.24	87.34	70.69	56.38
SNOQUALD	67.52	41.74	78.57	43.17
	64.20	66.34	49.31	46.65
	256.47	170.85	166.70	109.57
	43.69	57.63	28.87	35.39
	112.30	95.87	73.04	60.33
MEAN	108.83	86.48	79.30	59.02

[1]) lysimeters in forest; 2) lysimeter in clear cut area
3) combined lysimeter discharges.

are the closest to those measured in the field for the two melt periods shown. In the first period it can be seen that the SEE values of SNOQUAL1 and SNOQUALR are almost identical. This is due to the fact that the residue plays a negligible role in the generation of meltwater concentrations in the first stages of the melt when concentrations are very high. In the case of SNOQUALD the SEE values are also very close to SNOQUAL1 a SNOQUALR at the beginning of the melt sequence. However, for the whole melt period it can be seem that the model which perform the best is SNOQUALR followed by SNOQUAL1 and SNOQUALD in that order.

Figures 5a:b, and 6a:b, show the real concentrations of SO_4 (Fig. 5a, 6a) and NO_3 (Fig. 5b, 6b) in snow meltwaters for the two melt periods during the spring melt, 1988 at Lake Laflamme and the concentrations generated by SNOQUALR. The figures are of the concentrations in meltwaters discharged by a lysimeter under the forest canopy (Fig. 5a:b) and of a lysimeter in the clear cut area (Fig 6a:b). The lysimeter in the clear cut was in a relatively shallow snowbank; it finally discharged 360 mm of snowmelt and rain compared to the 480 mm discharged by the lysimeter in the forest. The lysimeter in the open area also discharged low amounts of meltwater during the first days of the melt compared to the lysimeter in the forest. This explains the anomaly, apparent at first right, of the similar patterns of forest and open lysimeter concentrations occuring at different points on the meltwater cumulative discharge axes of figures 5 and 6.

The melt periods (1 and 2) are separated by a five-day cold event in which the production of meltwater was very low. A rain event occurred during the first period, the meltwater discharge during this event was very concentrated. As only a small amount of melt had been discharged at that time the calibration

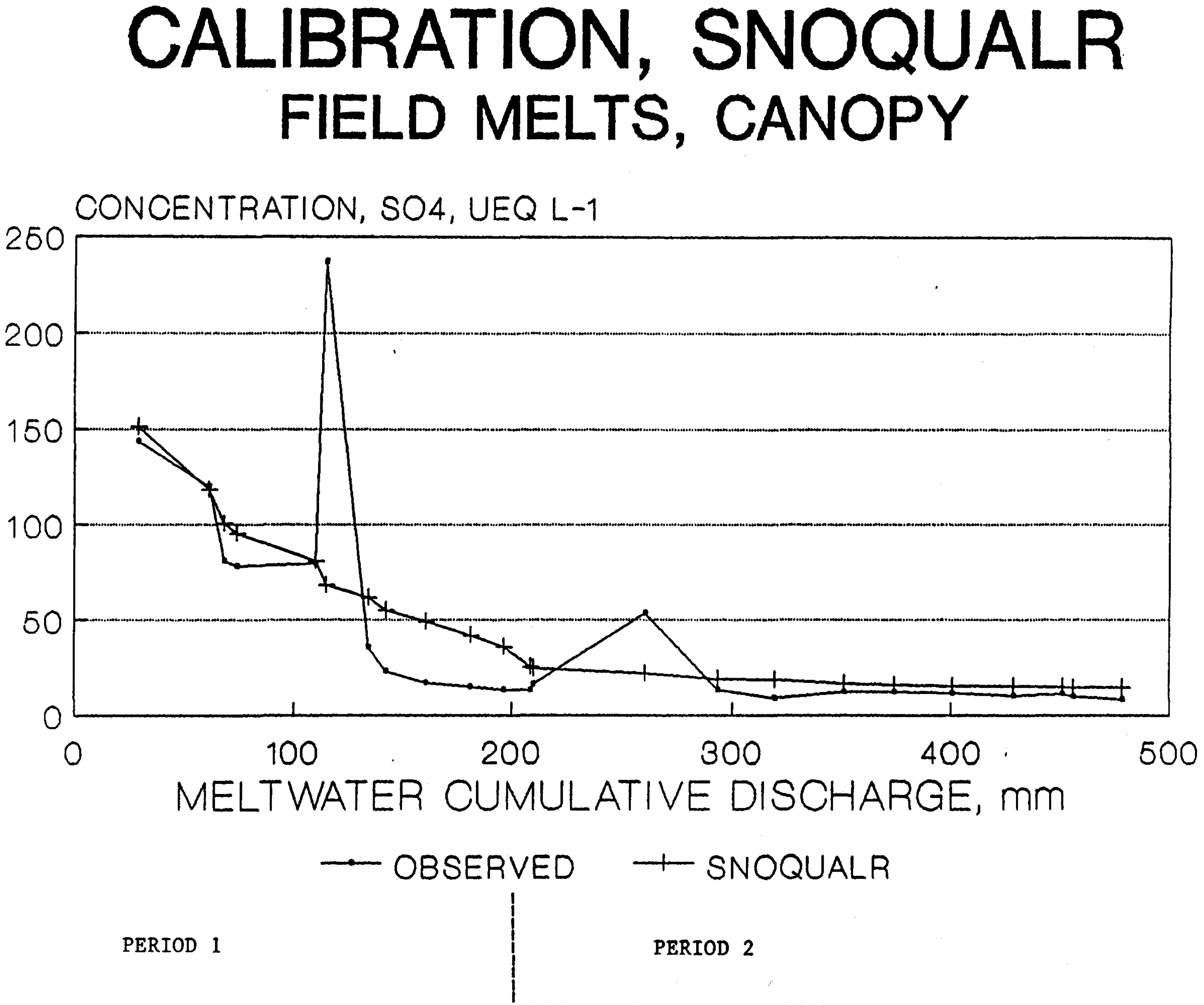

FIGURE 5a: Calibration of SNOQUALR with data on meltwater concentrations values from field lysimeter discharges: lysimeter in forest; SO_4.

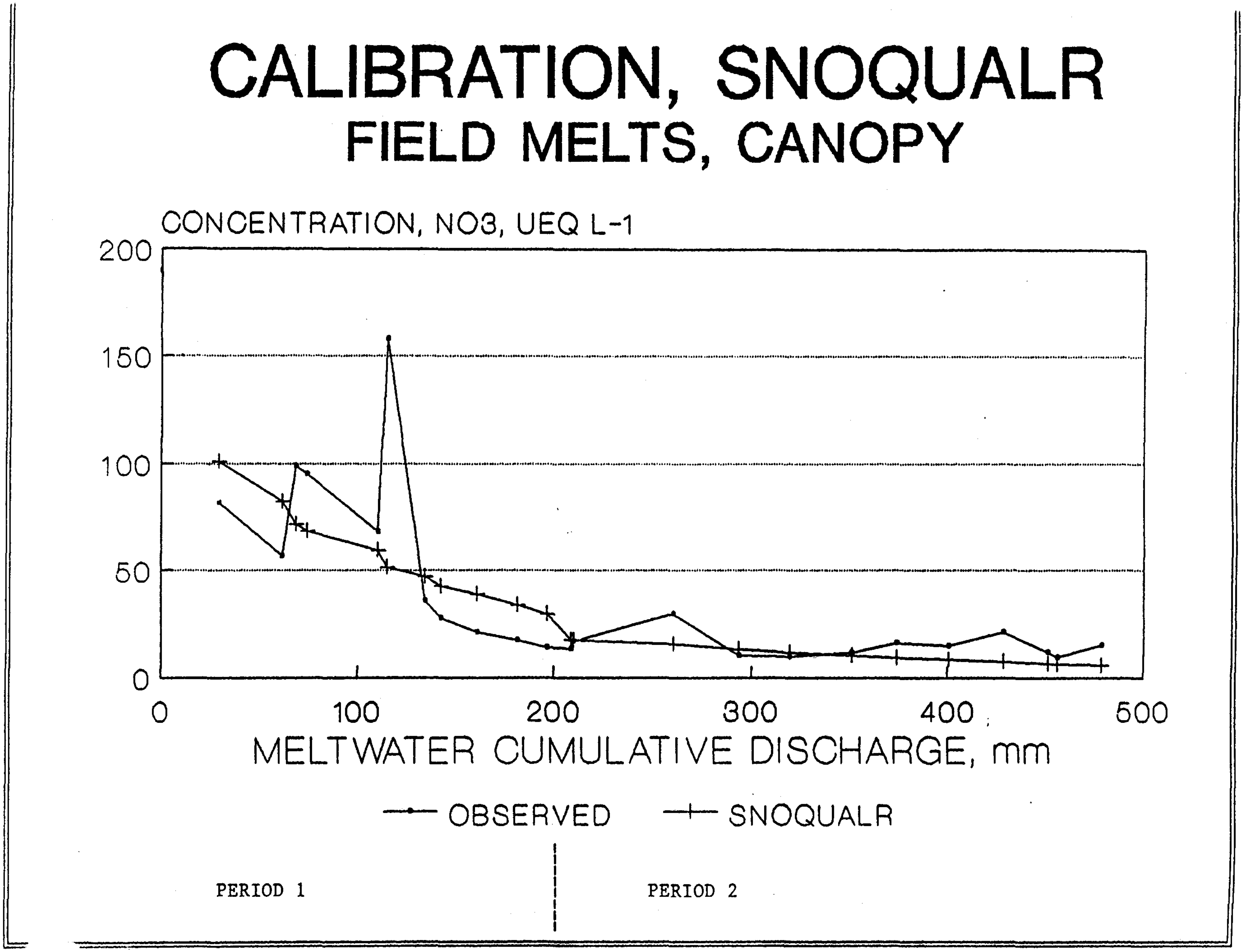

FIGURE 5b: Calibration of SNOQUALR with data on meltwater concentrations values from field lysimeter discharges: lysimeter in forest; NO_3.

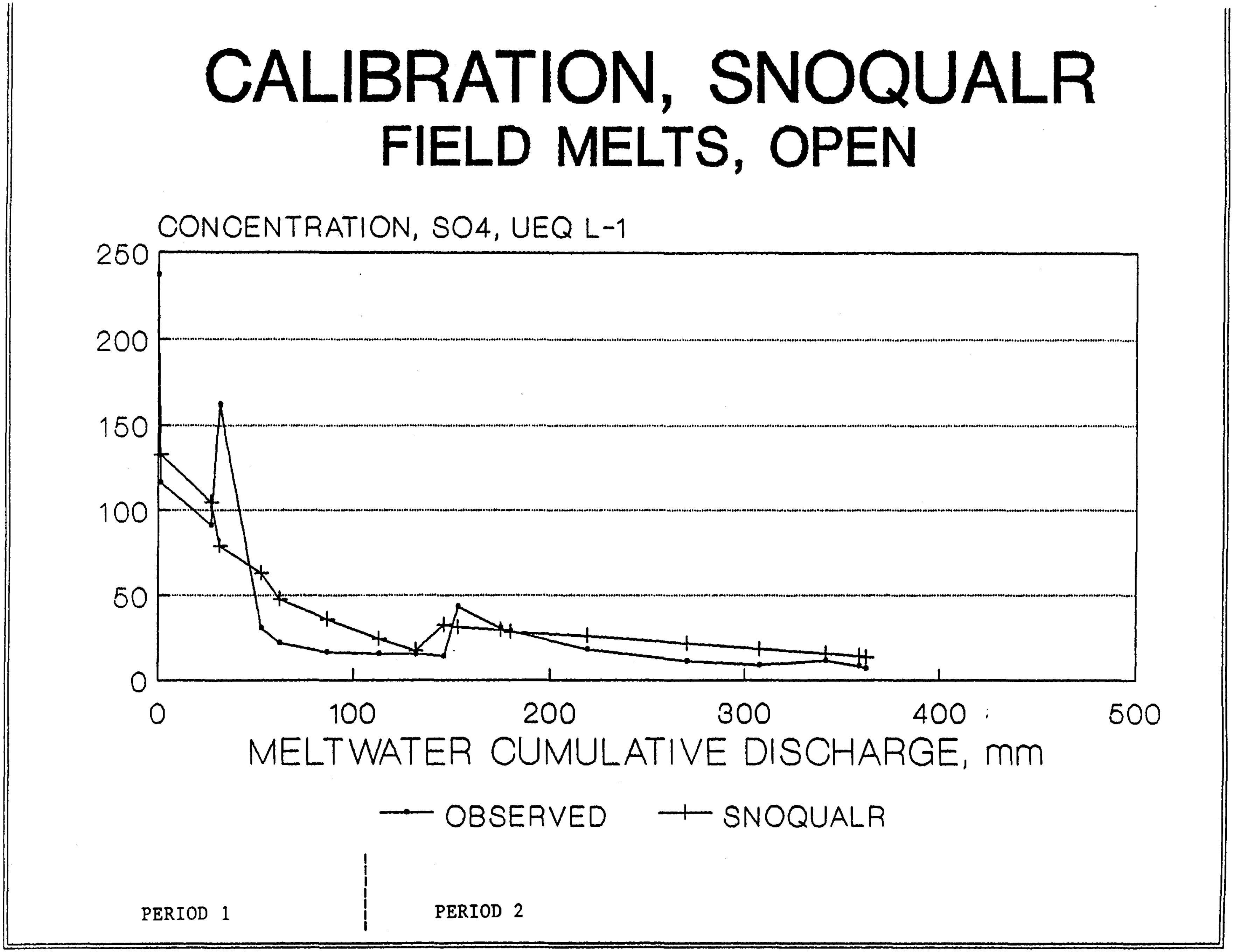

FIGURE 6a: Calibration of SNOQUALR with data on meltwater concentrations values from field lysimeter discharges: lysimeter in clear cut; SO_4.

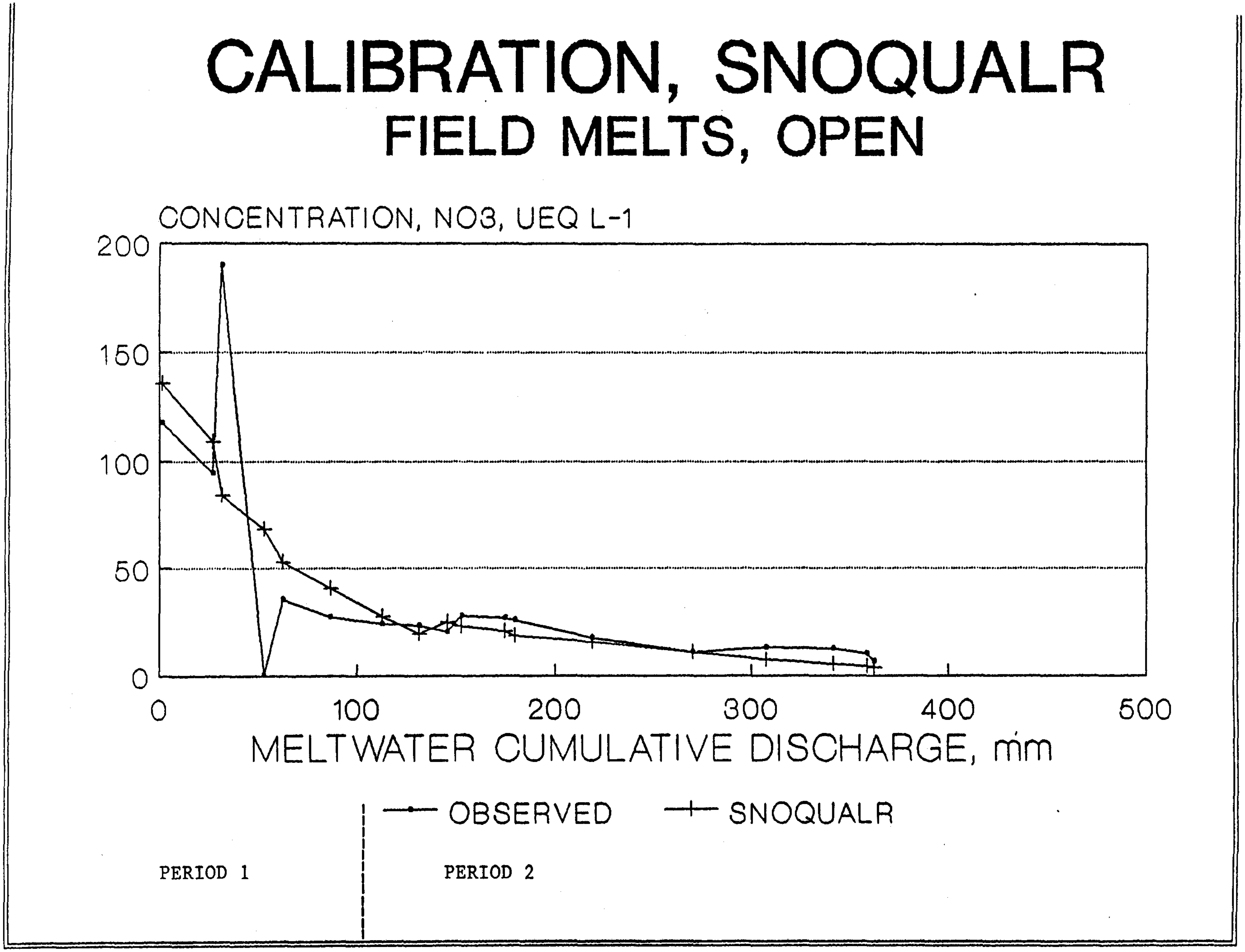

FIGURE 6b: Calibration of SNOQUALR with data on meltwater concentrations values from field lysimeter discharges: lysimeter in clear cut; NO_3.

period was not terminated at this point. The effect of the rain, however, is evident in the fact that the model does not generate a satisfactory fit to the meltwater concentrations after this event. Observed concentrations are much lower than those generated by SNOQUALR showing that an appreciable amount of the ionic load had been removed by the rain. As noted above the calibration procedure does not presently take into account any leaching of the pack by rain. The procedure will be modified in future by attempting to estimate the amount of material leached from snow by rain. Data on rain-on-snow events, such as those published by Jones et al (1989) could be used for this purpose.

The influence of organic matter on the performance of each variant of the model is reflected by the values of the leaching coefficient. Table 2 shows the values for the leaching coefficients determined by model calibration of SNOQUAL1 and SNOQUALR using data from both field and laboratory studies. In the case of the controlled laboratory melts the value of k is lower in the case of the snow containing organic matter than that of clean snow. In the field the same observation may be made i.e. the values of k for the three lysimeters placed in the forest are lower than for that of the fourth lysimeter which being situated in a clear cut area had relatively little canopy fallout. The differences between the laboratory and field results also show the influences of all the other spurious inputs to the pack that occur in the field (local dust deposition, dry deposition and deposition from light rain or condensation on the pack). Values of k in the field are approximately three times smaller than laboratory studies for clean snow and five times smaller for snow plus organic matter. In the case of SNOQUALD the preliminary results show that the values of k_s are higher than those of k of SNOQUAL1 and SNOQUALR; k_m may be

TABLE 2

k values, mm^{-1}, for laboratory and field experiments.

		k values		
		k		
		Laboratory*		Field (1988)
		Snow	Snow + organics	
SNOQUAL 1	SO_4	.04835	.03379	.00636[1]
		.05281	.03535	.00723[1]
		.05050	.03420	.00756[1]
				.01708[2]
	Mean	.051	.034	.009
	St.Dev.	±.002	±.001	±.004
	NO_3	.03831	.02000	.00525
		.04676	.03075	.00734
		.04212	.02542	.00738
				.01503
	Mean	.042	.025	.008
	St.Dev.	±.004	±.005	±.004
SNOQUALR	SO_4	.06067	.04094	.00636
		.06976	.04426	.00723
		.06491	.04173	.00756
				.01708
	Mean	.065	.042	.009
	St.Dev.	±.005	±.002	±.004
	NO_3	.06038	.02388	.00525
		.06482	.03895	.00734
		.06171	.03144	.00738
				.01503
	Mean	.062	.031	.008
	St.Dev.	±.002	±.008	±.004

* 3 experiments

[1]) Lysimeters in forest; 2) Lysimeter in clear cut area.

either positive or negative. At the present time we have not fully evaluated the results of the calibrations of SNOQUALD.

The overall results of the calibration showed that at present SNOQUALR is the model which best represents the real meltwater concentrations in both the field and the laboratory. The studies also indicate that the k values are much lower in the field than the laboratory. In addition the values for k for snow in similar physical environments are relatively constant (i.e. the three lysimeters under the forest canopy). These preliminary results lead us to suggest that we may be able to assign values to k a priori to melts; this would be an important step in the use of the model in a predictive manner. At the present time we are in the process of calibrating the three variants of the model with data on meltwater concentrations for 1984, 85, 86, and 87. The objective of this exercise is to determine the probability of success in the prediction of meltwater quality by the use of pre- determined ranges of values of both k and C_o.

Model Validation

These models have not been validated by applying them to snow meltwater studies in environments other than Lac Laflamme. Even in the case of Lac Laflamme they have not been fully validated in the sense that we have not been able to initialise all the inputs to the model prior to model use. In previous studies (Jones et al, 1986; Stein et al, 1986) we were able to validate the first original model of SNOQUAL as the C_o value used in this model was the real value for the concentrations of ions in the snowpack prior to the melt. Model validation in the case of the present models will require some method of estimating C_o according to the new definition of C_o; we hope that this can be achieved by a statistical analysis of the data that exists on the Lac Laflamme snowpack for 1984-1988.

The best performance model, SNOQUALR, however, can be used in its present form as a tool to evaluate the relative concentration of meltwaters that one would expect from snowpacks with different heights and bulk concentrations of ionic species (H_o, C_o). This is useful in attempting to evaluate the effect of the reduction of total emissions of SO_2 on the acidic pulses that are discharged from snow covers during the spring melt.

Table 3 shows the pH values generated by SNOQUALR for the first meltwaters discharged from the snowcover in spring in the Province of Québec in Eastern Canada. The simulation conditions were 1) the present conditions of SO_2 emissions and 2) three hypothetical conditions for future emissions i.e. a 30% reduction, a 50% reduction and a 30% increase in SO_2 loadings. The simulations maintain a constant loading for NO_x emissions. The procedure assumes that all SO_2 fluctuations are reflected by the SO_4 in the pack. The constant loading of NO_x is represented by a constant value for the concentration of NO_3 in the pack at any one site. Values for the bulk initial concentration of SO_4 and NO_3 were taken from data on the Lac Laflamme snowpack prior to melt in 1988. Snowpack concentrations in the snow at other sites representing southeastern Québec, northwestern Québec and eastern Québec were extrapolated from the Lac Laflamme data using the recorded winter-time concentrations of SO_4 and NO_3 at Hemmingford, Parent and Cap Seize, Québec, respectively (Jacques and Boulet, 1986). Snow water equivalent data for these sites was taken from snow survey records compiled by the Québec Government for March, 1988 (Environment Québec,

TABLE 3

Région	Height (water equivalent of pack	pH values for first meltwaters (20 mm)[5]			
		Present emissions	50% reduction	30% reduction	30% increase
Lac Laflamme [1]	350	3.95	4.07	4.03	3.90
	350	4.00	4.12	4.05	3.93
	250	4.06	4.17	4.13	4.01
South Western Québec [2]	150	4.01	4.17	4.06	3.94
	100	4.11	4.26	4.15	4.04
South Eastern Québec [3]	350	4.16	4.31	4.24	4.10
	300	4.21	4.36	4.29	4.15
	250	4.27	4.41	4.35	4.20
North western Québec [4]	200	4.13	4.24	4.19	4.07

[1] Mountainous region, [SO_4], 22.5 µeq L^{-1}; [NO_3], 28 µeq L^{-1}; March-April 1988
[2] Plain; St-Lawrence Lowland, [SO_4], 45; [NO_3], 32.7; Extrapolated
[3] Mountainous region, [SO_4], 17; [NO_3], 14; Extrapolated
[4] Low plateau, [SO_4], 22.5; [NO_3], 29.3; Extrapolated

[5] Leaching coefficients: 0.009, SO_4; 0,008, NO_3
Fractionation coefficients: 0,02, SO_4; 0.02, NO_3

Simulated pH value by SNOQUALR for pH values of the first meltwaters (20 mm) discharged from snow cover in 4 regions of Québec under present conditions of SO_2 emissions and hypothetical conditions of reduction and increase.

1988). The leaching coefficients (k) and the fractionation coefficients (r) are assumed to be constant for each ionic species over the whole study area. pH is finally calculated from the simulated SO_4 and NO_3 meltwater concentrations according to the relationship established between $[H^+]$ and $[NO_3 + SO_4]$ by Jones (1988).

From table 3 it can be seen that the pH value of 3.95 simulated for "present conditions" at Lac Laflamme is close to the mean value mesured in first meltwaters collected by field lysimeters at the site (pH = 3.91). It can also be seen that the reductions or the increase in SO_2 emissions do not have a large effect on the pH of the meltwaters at any one site (0.1 - 0.15 units of pH). This is due, in part, to the fact that NO_3 is the dominant acid anion in the pack in winter and it controls to a large extent the pH of the meltwaters. A reduction of 50% for both SO_2 and NO_X emissions would lead to a meltwater discharge of pH 4.25. It should be noted that even if the emissions of SO_2 (SO_4) and NO_X (NO_3) were reduced by 90% the first meltwaters at Lac Laflamme would still show a pH value of 4.94. This aspect of the simulation shows how dominant the leaching process is in determining the acidity of melt waters. Acidic meltwaters have in fact been reported for the melting of snow cover with relatively very low concentration of SO_4 and NO_3 (e.g. alpine meltwaters, Delmas 1989). At very low values of SO_4 and NO_3 the pH of the first meltwaters at the Lac Laflamme are in the range of 5.6 - 6.0.

Figures 7 and 8 show the typical pH patterns that one can expect for the first 20 mm of snowmelt discharge in the Province of Québec under present emission conditions and conditions representing a 50% reduction in SO_2 emissions. Due to the deeper snowpack at Lac Laflamme in the Laurentian mountains the acidic

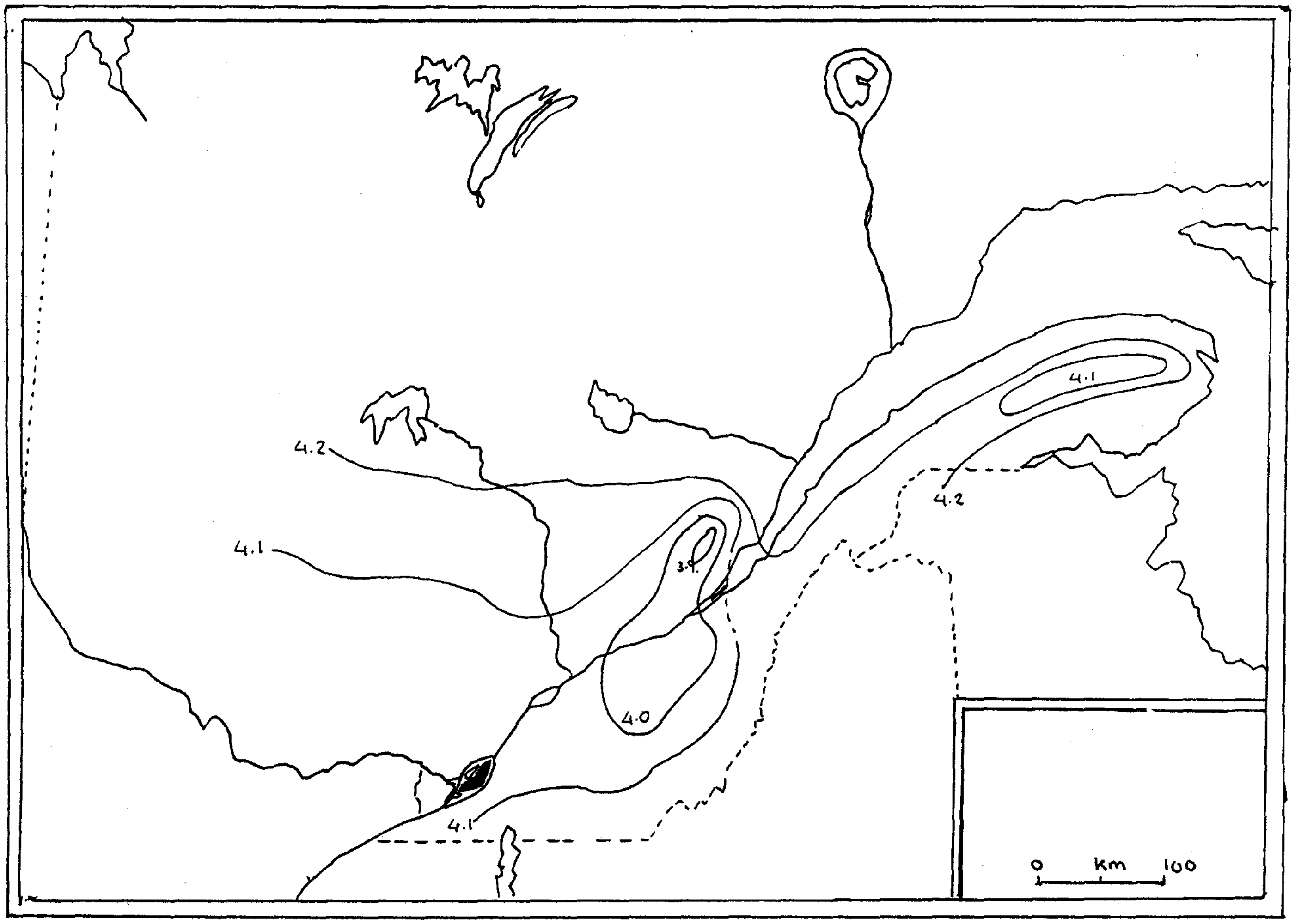

FIGURE 7: Simulated pH values by SNOQUALR for the first meltwaters (20 mm) discharged from snowcover in spring, Québec Province, 1988.

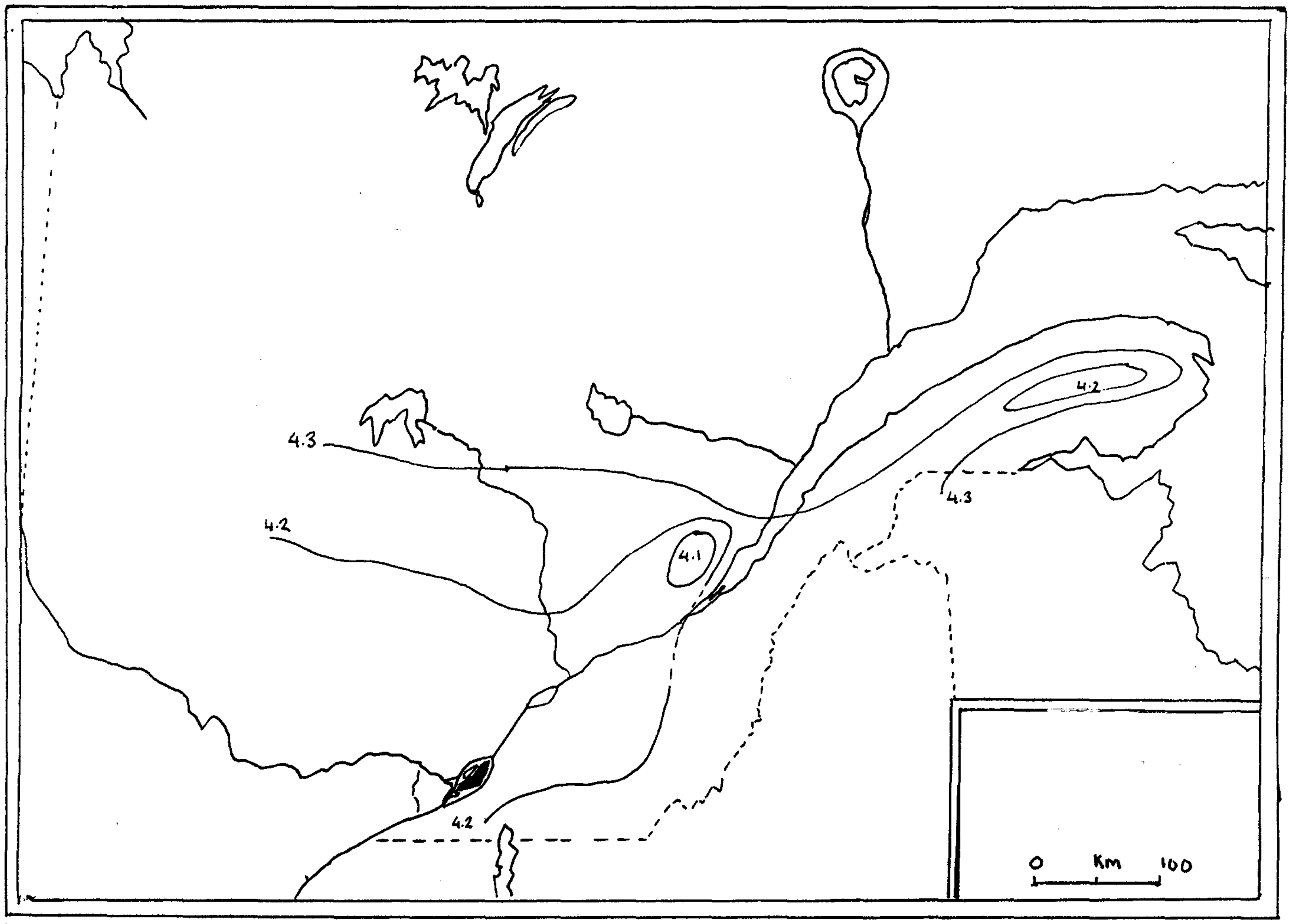

FIGURE 8: Simulated pH values by SNOQUALR for the first meltwaters (20 mm) discharged from snowcover in spring, Québec Province, assuming a 50% reduction in SO_2 emissions based on present conditions (1988).

pulse is greater than that of the more concentrated snowpacks in the southwestern part of the province. The results indicate that if one considers pH values of meltwater greater than 5 as desirable target values to reduce acidic stress on vegetation and soil microorganisms, over a 90% reduction of both SO_2 and NO_x emissions would be required.

ACKNOWLEDGMENTS

This research was made possible by the financial aid of Environment Canada, the National Science and Engineering Research Council of Canada and the Dept. of Supply and Services (Govt. of Canada).

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CHAPITRE III

CHAPTER III

THE DISCRIMINATION OF THE ORIGINS OF SUB-ICE ACIDIC WATERS IN A SMALL LAKE DURING THE SPRING RUNOFF

(L'IDENTIFICATION DES ORIGINES DES EAUX ACIDIFIÉES SOUS LE COUVERT DE GLACE D'UN PETIT LAC PENDANT LA FONTE PRINTANIÈRE)

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Résumé

La circulation sous le couvert de glace des eaux en provenance de cinq sources a été étudiée dans un petit lac de la forêt boréale pendant la fonte printanière. Ces eaux sont les eaux residant dans le lac avant la fonte printanière, les eaux de fonte du couvert de glace, les eaux de fonte de neige, les eaux souterraines et les eaux d'écoulement hypodermique. Un réseau de puits d'accès a été mis en place pour le mesure des profiles de température, conductivité et pH de la colonne d'eau. L'étude a aussi inclus le suivi de l'écoulement des eaux de fonte de neige riveraine et l'écoulement du ruisselement hypodermique sous la glace par l'utilisation d'un traceur (rhodamine).

Le pH et la conductivité sont des paramètres relativement eficaces pour distinguer les eaux de ces diverses sources. Pendant la fonte printanière, on a enregistré 3 épisodes de dépression du pH. Le premier (pH 5) s'est produit pendant la fonte hative; les eaux de fonte en provenance de la neige et du couvert de glace se sont retrouvées restreintes dans une strate d'eau (20 cm) immédiatement sous la glace. Cette strate a été déplacée lentement (1 m/h) vers l'exutoire du lac par l'entrée des eaux de fonte déchargées par les congères de neige sur la rive.

Deux épisodes (pH 5,3 et 5,1) ont été enregistrés pendant la fonte massive. Ces deux épisodes ont été les résultats d'une arrivée à l'exutoire des flux hydrologiques élevés de l'écoulement hypodermique. Ces flux ont traversé le lac sous le couvert de glace dans une strate dont l'épaisseur est située entre 20 et 40 cm. Le traceur de rhodamine a démontré que la vitesse moyenne de la

progression de l'écoulement hypodermique dans les eaux du Lac a été de > 20 m/h et que les conditions d'écoulement de la strate se sont situés entre celles d'un écoulement laminaire et celles d'un écoulement turbulent. Les eaux souterraines ayant une température plus proche de celle des eaux résidentes du lac ont remplacé ces dernières par des processus de mélange et dilution. Le couvert de glace a donc modifié la qualité des eaux littorales en assurant la stabilité de la stratification thermique et, de plus, a fortement influencé la qualité des eaux d'exutoire du lac par la ségrégation et la décharge rapide des eaux de fonte et de l'écoulement hypodermique.

Abstract

In a small boreal forest lake, the sub-ice circulation of waters from 5 distinct origins (lake premelt water, lakeshore snowpack meltwater, ice-cover meltwater, groundwater and hillslope throughflow water was studied during the springmelt period. A network of collared access holes was used to monitor the temperature, conductivity and pH profiles of the water column beneath the ice cover. The study also included the tracing of snowbank meltwaters and throughflow waters with rhodamine. Conductivity and pH appeared to be efficient parameters for discriminating most of the water types considered. During the springmelt 3 distinct low pH episodes were recorded at the lake outflow. The first episode (pH 5) occurred in the early melt period; snow and ice meltwaters layered beneath the ice forming a stratum ≈20 cm thick. It moved toward the outlet under laminar flow conditions (observed average velocity: 1 m/h), driven mainly by the influx of meltwaters from nearshore snowbanks. Two subsequent pH episodes of pH 5.3 and 5.1 were observed during the massive melt period. These episodes were due to peak flows of hillslope throughflow entering the lake at various points along the shoreline.

The throughflow input also formed a layer 20-40 cm thick in the water column. For this layer, the rhodamine tracer indicated an average velocity of >20 m/h and the presence of transitional conditions between laminar and turbulent flow. Concomitant groundwater influx did not layer but, due to its temperature, gradually mixed with and replaced the underlying premelt water. The ice cover thus not only modified the nearshore water quality by inducing thermal layering but also strongly influenced the quality of the outflow waters due to the segregation and rapid evacuation of the throughflow and surface meltwaters.

Introduction

Lake ice cover constitutes a physical barrier which limits lake-atmosphere interactions. By reducing radiative exchanges with the atmosphere, impeding wind-generated turbulence and currents, and maintaining a constant temperature interface at the upper limit of the water mass, it ensures lake thermal stratification and vertical stability. Furthermore, its presence is determinant in lake springmelt hydrology. This is of immediate importance in the aquatic environments of cold and temperate regions which experience episodic acidification during the spring melt period. At this time the biota are particularly sensitive to the presence of waters of low pH (Hultberg, 1977).

Many studies have indicated that the influx of acid waters in spring does not affect equally the whole water body of a lake due to spatial segration under the ice cover. Henriksen and Wright (1977), Hagen and Langeland (1973) and Hultberg (1977) in Scandinavia, Prentki et al. (1979) in Wisconsin, Hendrey et al. (1980) in the north-eastern United States, Charette et al. (1984) and Jones et al. (1984) in Quebec, Jeffries et al. (1979), Gunn and Keller (1985, 1986) and Booth et al. (1987) in Ontario, Bergmann and Welch (1985), and Adams and Allan (1987) in the Canadian Arctic, reported the formation directly beneath the ice, of a thin layer of cold acidic water. At the height of the spring melt the layer can extend over a depth of 1-2 m (Henriksen and Wright, 1977; Hultberg, 1977).

Depending on the springmelt chronology, the sub-ice stratum may be rich or poor in ionic content and is often associated with littoral zones. Gunn and Keller (1986) carried out an intensive study of one lake and an extensive survey of 20 lakes in northeastern Ontario. The results demonstrated that in-shore layering of meltwaters is of widespread occurrence. The duration, magnitude and timing of pH depressions were reported to differ widely between individual sites according to the distance from drainage channels, and to the slope, aspect and exposure of the drainage areas. In all cases the layering was attributed to thermal segregation rather than to differences in density due to dissolved solids.

The origins of the acidic waters in sub-ice layers are attributed to littoral runoff (Hasselrot et al., 1987; Gunn and Keller, 1985, 1986), penetration of the ice cover by surface snow meltwaters (Franzin and McFarlane, 1981), ice-cover meltwaters (Bergmann and Welch, 1985) and lake inlet flow (Jeffries et al., 1979). The relative contribution of these sources, to the laminar flow under the ice will depend on the chronology of the springmelt period and on the hydrologic and morphometric characteristics of each lake and its watershed. Previous studies place more or less emphasis on each of these sources according to the methodology used and the areas of interest in the lake basin. In particular, the spatial resolution, both horizontal and vertical, of the sampling of the sub-ice waters in most of these studies did not allow the authors to discriminate the diverse origins of these acidic waters. Bergmann and Welch (1985) used a network of drilled access holes in the ice-cover and a vertical high resolution sampling of the sub-ice waters at every few centimeters to show that the sub-ice layering of ice-cover meltwaters, inlet waters, and pre-melt lake waters is discrete over the first 40-50 cm below the lower surface of the ice. Other studies, however, only sampled sub-ice waters at one depth, e.g. ≃ 1 m, over a network of inshore access holes (Gunn and Keller, 1985), or collected samples at 1 m (or > 1 m) intervals at one (Hultberg, 1977; Hagen and Langeland, 1973; Henriksen and Wright, 1977; Franzin and McFarlane, 1981) or few (≤ 3) (Hensselrot et al., 1987) access holes in the ice cover. Temporal resolution also varied between these studies, daily to weekly or biweekly sampling periods being reported.

Thus, in many cases, low resolution sampling of sub-ice waters will not permit the discrimination of the origins of the acidic inputs during the spring melt. In addition, this type of sampling methodology will not allow any quantification of the relative contributions of the different inputs to the sub-ice acidic waters.

Lac Laflamme is a small boreal forest lake in eastern Québec (Jones, 1987). During the spring melt period, the lake outlet shows that the lake surface waters are being subjected to acidic pulses.

Jones et al. (1984) believed that the first meltwater to enter the lake and to layer beneath the ice was provided by the melt of snowbanks on the shore. Charette et al. (1984) and Jones et al. (1984) inferred that inflows from the land subsequently entered the lake both as groundwater and surface runoff, the first affecting lower waters and the second layering at the surface. In a hillslope hydrology study at the same site, Roberge and Plamondon (1987) determined that a significant part of springmelt runoff uses two pathways to reach the lake: groundwater flow and a turbulent pipe-like throughflow near the top of the soil. The throughflow consists of numerous intermittent subsurface streams and is chemically similar to surface runoff. It is a short-lived phenomenon, occurring only when the groundwater levels rise close to the soil surface, but may imply strong discharges and rather fast flow. Roberge and Plamondon stated that it was the most likely source of the acidic surface layer that spreads out from the shoreline during the height of the melt season at Lac Laflamme (Charette et al., 1984; Jones et al, 1984).

Small boreal forest lakes often have surface drainage systems which are poorly developed. Although, streams and groundwater do supply the main hydrologic input to the lake basins in spring, snowbanks on the shore and throughflow contribute a significant quantity of acid to the inshore areas at certain times. The purpose of this study was to investigate the formation and the dynamics of sub-ice layers at Lac Laflamme in relation to snowmelt and hillslope hydrology. Emphasis was placed on the origins of the sub-ice waters and their relationship to the layering process. Particular attention was paid to the inshore areas and to the inputs of meltwater from snowbanks on the shore and throughflow.

As the heterogeneity of the system necessitates a large number of measurements to map the sub-ice distribution of waters a network of access holes and the vertical sampling of the sub-ice waters at a resolution of 5-10 cms was used. The discrimination of sub-ice waters may be accomplished by the use of different chemical signatures (e.g. major ions, Hasselrot et al., 1985; metals, Franzin and McFarlane, 1981). With the high number of samples that were anticipated during the Lac Laflamme study an attempt was made to discriminate the sub-ice waters using the least number of chemical parameters as possible. In this study, we report on the use of two common and easily measured parameters, pH and conductivity, to discriminate the acidic inputs. Validation of the discrimination of snow meltwaters and hillslope throughflow in the sub-ice layers was achieved by the use of a tracer, rhodamine WT. To evaluate the overall impact of all acidic waters on the lake the outflow waters were also sampled. The field work was conducted during the spring of 1988.

Site and Methods

Lac Laflamme is a small headwater lake (6.1 ha, 42°19'N, 71°07'W, 780 masl) in a boreal forest basin (68.4 ha), 80 km north of Québec city, Canada. The volume of the lake is $\approx 125*10^3$ m^3 and its depth does not exceed 5.3 m (Fig. 1). The whole basin rests on impervious charnokitic gneiss covered by sandy till. The till thickness varies from less than 0.5 m on the summits to more than 15 m under the lake (Robitaille et Wilhelmy, 1981). The average annual mean temperature and precipitation are 0.2°C and 1 424 mm. Nearly one third of the precipitation falls as snow. At the end of the accumulation season the forest snowpack typically reaches a depth of 100 to 150 cm and a water equivalent of 350 to 400 mm. The melt season generally extends from the end of March to late May the ice-off occurs in mid-May.

We consider that during springtime any water that flows below the ice cover must be one of the following: premelt lake water, snowmelt water (from lake or lakeshore snow cover), ice cover meltwater, groundwater, throughflow water from the organic and upper mineral soil horizons or any mixture of these waters. Groundwater may consist of deep "old" groundwaters from the till aquifer and shallow "newer" waters. There is no clear cut hydrologic distinction as to where throughflow becomes shallow groundwaters or vice versa. In order to characterize the waters we considered pH and conductivity, two common variables which permit numerous low cost measurements. Data were collected in the spring of 1988. The premelt lake water data were made available by Environment Canada. They are the results of weekly sampling (18 samples in February and March) at the centre and at the outlet of the lake (M. Papineau, personal communication). To characterize snow meltwaters, we used the daily outflow samples (16) from a

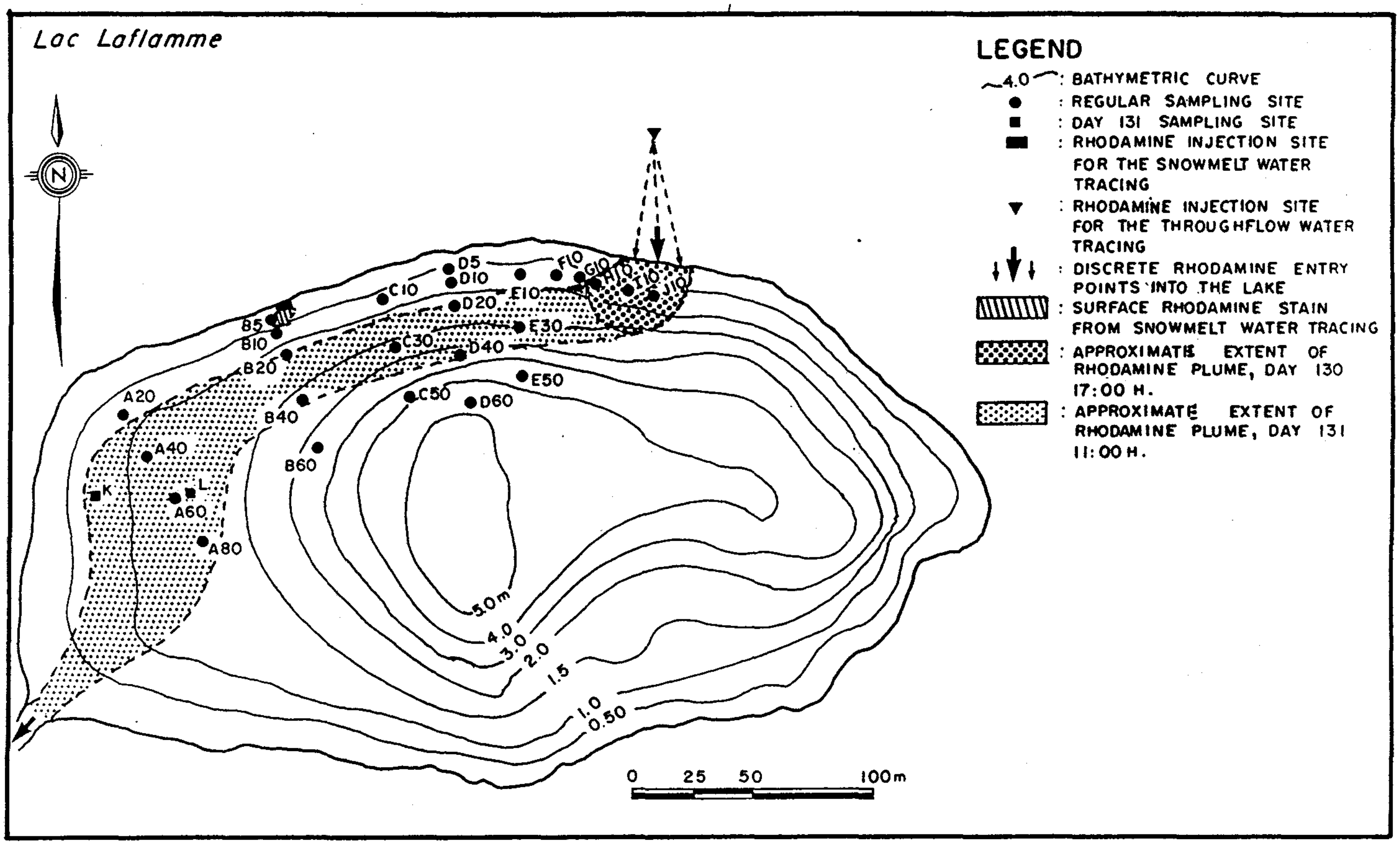

Figure 1: Lac Laflamme bathymetry, location of the sampling sites and rhodamine traces observed during the tracing of snow meltwaters and throughflow patterns under the ice cover, spring 1988.

snowmelt lysimeter (1 m^2) located at an open site (Jones, 1987). The ice cover was sampled between day 81 and day 131, at various sites (10 to 60 m offshore) in the northern part of the lake (15 samples). Groundwater was sampled in a nearshore observation well (1 m deep, 6 samples). The side wall of this well is pierced from 10 cm below the soil surface to 1 m. It remains dry all winter and only starts to collect water after the spring melt has started. The chemical signature of these well waters defines the shallow groundwaters in the mineral soil layers as opposed to the groundwaters from the deeper till. The chemical composition of deeper groundwater is much closer to that of the pre-melt lake waters than that of the shallow groundwaters. The data set from these samples was completed with data from 3 nearshore piezometers sampled during spring 1983 (17 samples) by Padilla et al. (1983). The throughflow samples (36) were taken at the gauging site of a throughflow stream on the hillslope and at 3 sites on the shore line.

Hydrologic monitoring included the snowpack outflow, throughflow discharge, lake level and lake outflow. The outflow of meltwaters from the pack was collected from 3 snowmelt lysimeters (1 m^2 each) located under the forest cover on the north slope of the basin. A surface segment of a pipe throughflow stream (Roberge and Plamondon, 1987) also on the north slope, was gauged with a 30° weir and a Stevens water level recorder. The lake level and outflow data were measured daily with a bubble-gauge recorder and a Parshall flume respectively.

A network of 25 sub-ice access holes was set in place during February and March along the north shore of the lake (Fig. 1). Each hole was lined with a white PVC tube (13.5 cm) to prevent vertical exchange between the sub-ice waters and the meltwaters on the surface of the ice-cover (Fig. 2a). A polystyrene plate

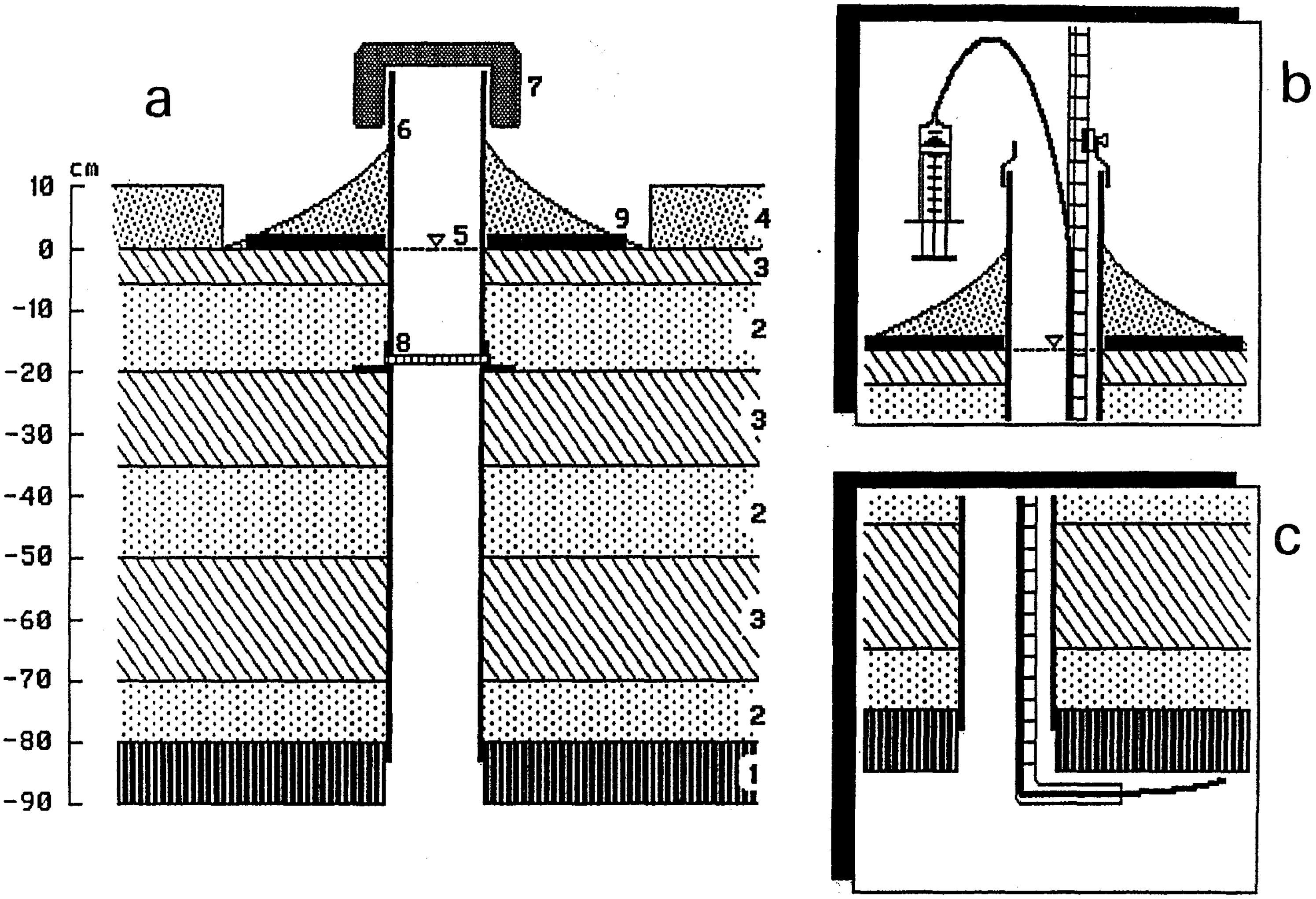

Figure 2: Typical cross-section of ice cover at Lac Laflamme in mid-March with collared access hole [a]. (1: black ice; 2: slush; 3: white ice; 4: snow; 5: hydrostatic level; 6: PVC tubing; 7: styrofoam cap; 8: tube mechanical support; 9: polystyrene plate). The inserts illustrate the water sampling installation ([b], syringe; [c], sampling probe).

(60 x 60 x 2.5 cm) was placed above the ice around the base of the tube to prevent light penetration and reduce local surface melt at the tube - ice interface. A styrofoam cap was also added to reduce cooling and ice formation inside the tube. The PVC tube was allowed to freeze into the ice cover a few days before the installation of the polystyrene plate. These access holes were used for the measurement of ice thickness, the temperature of sub-ice waters and the sampling of the waters at different depths.

Water temperatures (± 0.1°C) were measured with a digital thermocouple (Cole-Parmer). The probe was mounted on a graduated rod able to reach 1.5 m below the ice. A short horizontal bar near the end of the probe was used to locate the base of the ice. Water samples were taken with a syringe (60 cm^3) and a Tygon tube (3 mm i.d.) mounted on a similar rod (Fig. 2b). The angle at the extremity of the tube enabled one to take samples 18 cm away from the access hole (Fig. 2c). At each level the first 60 cm^3 of sample was discarded in order to flush out the water remaining in the tube and rinse the syringe. The rod structures were light and designed to minimize turbulence while being moved in the water.

The measurements of sub-ice temperature and the collection of water samples were carried out during the julian day intervals 85-131 (March 25 - May 10, 1988) and 99-131 (April 18 - May 10) respectively. Due to limitations in time, more attention was given to the access holes of the B and D series (Fig. 1). The others were sampled less frequently. At each hole, the distance between the water hydrostatic level and the base of the ice was noted. This was considered to be the best approximation of ice thickness we could obtain since it was often difficult to determine the point of contact between the surface snow and ice. In effect, our activity around each access hole significantly modified the snow and ice setting. From day 105, samples were also taken regularly (generally once or twice a day) at the lake outlet.

Rhodamine WT was used in two experiments to trace snowmelt and throughflow water. On day 99 at 12:00, one litre of rhodamine solution (20%) was poured, into a trench (0.3 m x 1 m x 0.45 m depth) at the bottom of an inshore snowpack; the snowpack was situated 2 m offshore and 5 m east of the B line of access-holes (Fig. 1). The trench was then refilled with the removed snow. On day 130 at 10:00, two litres of the same solution were poured behind the weir at the throughflow gauging site (Fig. 1), 8 m above the lake and 46 m north of the shoreline, facing access hole J10.

The aqueous samples were transported and maintained at 2°C. They were later warmed to 25°C for the laboratory determination of conductivity, pH, and rhodamine concentrations. Rhodamine concentrations were measured by means of a Perkin-Elmer fluorescence spectro-photometer using standard solutions of 0.1, 1, 10, 100, 1000, and 10000 ppb and setting the instrument to the rhodamine WT excitation and emission wavelength (555 and 580 nm; Smart and Laidlaw, 1977). The reproducibility was ±5%. Concentrations below 0.1 ppb were considered to be insignificant.

Results and Discussion

Identification of hydrologic sources

The use of pH and conductivity was a efficient tool for discriminating at least four of the five types of water considered (Fig. 3). Although the ranges for the conductivity of premelt lake water, shallow groundwater and throughflow do overlap, the waters have clearly distinctive pH ranges. In the case of meltwaters from the ice cover, the pH range is wide enough to overlap the three former waters, but it differs by lower values for conductivity.

The pH range of the meltwaters from the ice-cover is wide due to the large variability of pH values found within the ice cover. The variability is the result of the different origins of slush zones which arise either due to the infiltration and refreezing of snow meltwaters from the surface (Jones and Ouellet, 1983) or from upward resurgence of lake water through the ice-cover (Catalan, 1989).

The only category of waters difficult to identify by this simple bivariate segregation of pH and conductivity remains the snowmelt water. The potential confusion of this latter type of water with throughflow or ice cover water is partly overcome, however, by the springmelt chronology. In general, the lake snowpack vanishes before the throughflow inputs become significant. It can also be assumed that when the lake is entirely snow covered in the early melt period, the snowmelt inputs are dominant. However, when a melting ice surface coexists with residual snow patches or shoreline snowbanks, it is difficult to discriminate snowmelt and icemelt inputs solely by pH and conductivity. In such

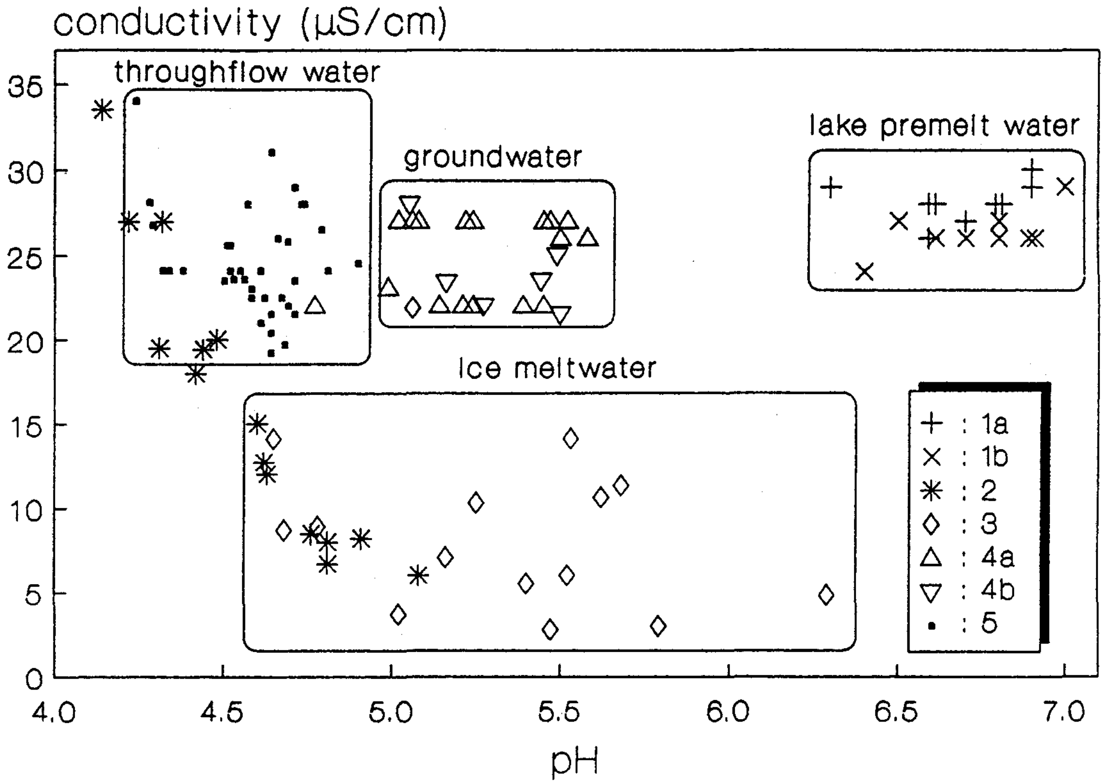

Figure 3: Discrimination of water sources using pH and conductivity, Lac Laflamme 1988. Sample identification; 1a: lake centre during winter, 1b: outlet during winter; 2: snowmelt at an open site; 3: ice cover; 4a: piezometers (1983); 4b: observation well (1988); 5: throughflow streams.

a case, however, other chemical parameters may be more appropriate for discrimination (Jones and Roberge, unpublished results) or a tracer (rhodamine WT in this study) can be used.

Hydrologic chronology of the melt period

The first outflow from the forest snowpack was recorded on day 85. Snowmelt ended on day 139 with an average cumulated outflow of 534 mm (Fig. 4c). In the first melt period (days 85-106) the cumulated outflow represented 189 mm of snowpack loss. Between days 106 and 116, the melt was interrupted by cold weather. From day 116 to 123, another 19 mm of outflow preceded the major melt period of days 124 to 139 which by itself, accounted for the last 323 mm of outflow. There was not any significant throughflow discharge until day 124, after more than 210 mm of snowmelt. From day 125 it increased rapidly to peak near 400 m^3/day but dropped below 50 m^3/day as soon as the snowpack disappeared.

The variation in lake level from the premelt reference to the peak discharge was only 18.1 cm and there was a strong linear relationship between daily lake levels and outflow discharge ($n=74$ $r^2=0.97$). On a daily basis, the recorded outflow from the lake is a good estimate of the inflow. Lake discharge responded rapidly to snowmelt and began to rise on day 86. At the end of the first melt period the cumulated outflow from the basin represented only 18.4 mm; this is hardly 10% that of the snowpack (189 mm), showing the high retention of the meltwater by the soil and sub-soil system. Of the 18.4 mm, 3.4 mm resulted from the direct loading of precipitation on the lake surface. During the cold spell, the outflow did not decrease, the total cumulated

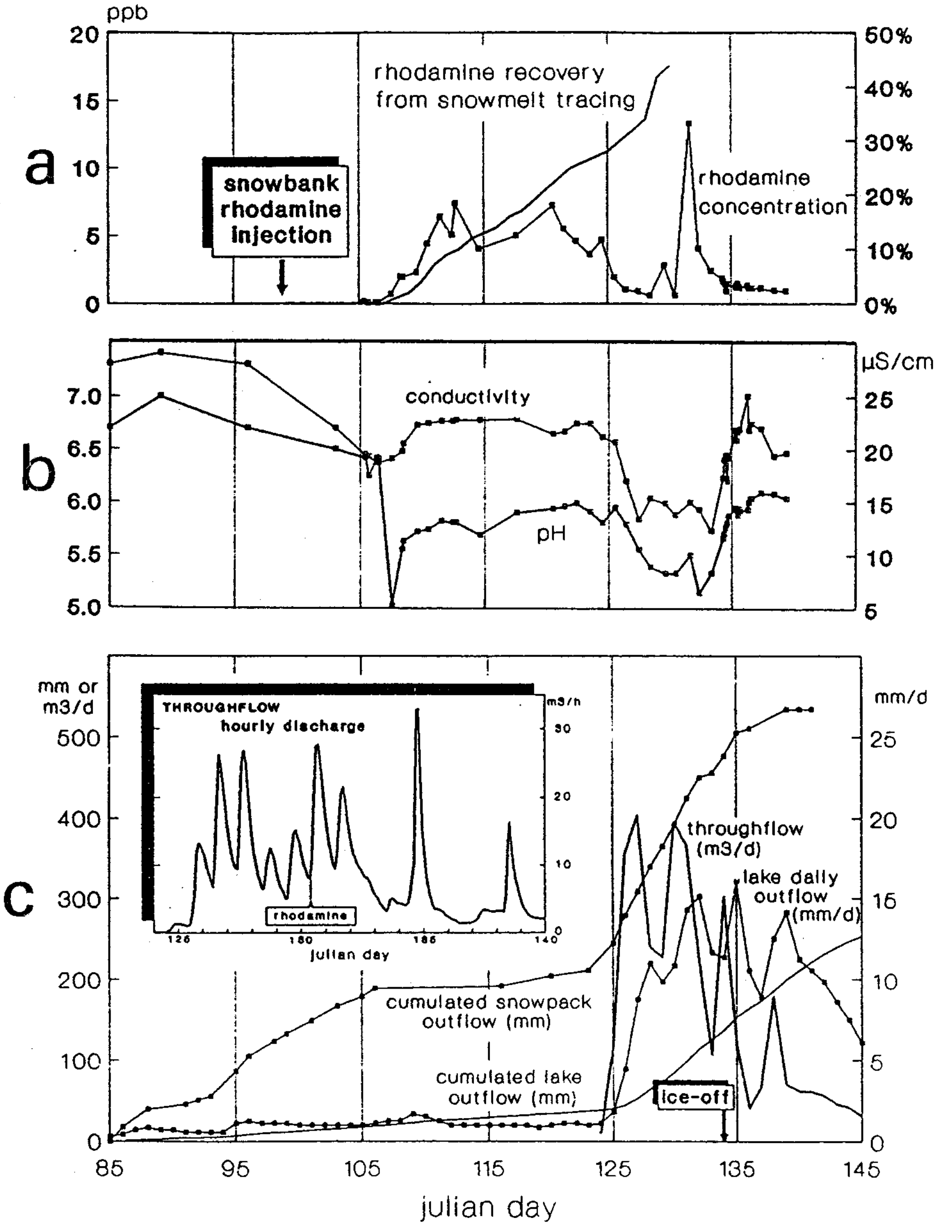

Figure 4: Hydrologic chronology of the springmelt Lac Laflamme, 1988. The lower graph [c] displays the lake daily outflow and cumulated outflow, the snowpack cumulated outflow and a throughflow stream daily discharge and hourly (insert) discharge. pH, conductivity of the outlet are displayed in [b] and rhodamine concentration as well as the rhodamine recovery curve from the snowmelt tracing are displayed in [a].

outflow for the period being 13 mm. This was accounted for by near equal proportions of snowfall on the ice cover and groundwater inflow. The lake discharge did not react to the second melt period (day 116 to 124) but displayed a dramatic rise with the onset of throughflow. A rapid decline in the lake discharge coincided with the disappearance of the forest snowpack and the throughflow recession. From the onset of throughflow to the end of snowmelt the lake discharged 161.1 mm of water, i.e. 50% of the snowpack outflow for the same period. During this interval, groundwater and throughflow are likely to be the major inputs to the lake. At that time, most of lake snowpack and shore snowbanks had gone. The total outflow volume cumulated from the onset of snowmelt was equal to 20% of lake volume up to the time that throughflow commenced, 65% at ice-off and 100% at the end of snowmelt.

The lake snowpack is an important feature along the shoreline where the wind causes large drifts to accumulate at the forest edge. The drifts extend out from the banks onto the ice cover. On most of the lake surface, however, most of the snowfall is integrated into the ice. A typical value for the water equivalent of the lake snowpack at the end of march would be < 100 mm while that of the snowcover on the shore may be > 700 mm. On day 85 the ice cover was 85 to 90 cm thick with a 10 cm basal black ice layer overlain by three alternate strata of slush and white ice (Fig. 2a). Assuming densities of 0.90 and 0.82 for black and white ice, the water equivalent of the ice cover was in the range of 620 to 750 mm. The ice cover lost 300 to 350 mm of meltwater during the first melt period and the last 450 to 500 mm after day 124. The complete ice-off occurred on day 134.

According to the springmelt hydrology, the melt chronology can be divided into 4 periods (Fig. 4c). The periods are: A first melt period (day 85 to 106) when groundwater, snowmelt and icemelt contributed significantly to the total input, a cold period (day 107 to 115) in which groundwater was the dominant input, although a slight snow or ice melt might have occurred in transient warm spells, a third period of slow melt (day 116 to 124) when groundwater was still the dominant input with, however, significant inputs of meltwater from snow and ice and, the fourth period of massive melt (day 125 to 134) during which groundwater and throughflow were dominant accompanied by a significant input of ice-cover meltwater.

Sub-ice layering, physico-chemical conditions and origin of the waters:

Meltwater from snow and ice cover

The meltwaters from shoreline and lake snowpacks seep downwards through fissures in the ice (Browman, 1970; Franzin and McFarlane, 1981) and lift the ice cover. Since most of the snow and ice on the lake is floating, these meltwaters cannot generate any outflow. Although providing a significant gain to the lake water, the melt only compensates for the loss in weight of the melted snow and ice. The nearshore conditions are somewhat different. The ice , grounded on the lake bed, supports a thick snowbank. As long as it is not floating, snowmelt represents a net inflow which contributes to the lake discharge. The initial snowpack water equivalent and the melt rate are generally higher on the shore than in the forest.

The sub-ice thermal gradient prevents vertical mixing and maintains the meltwaters (≈0°C) close to the base of the ice. During most of the melt, the measured gradients were between 2.5°C/m and 3.5°C/m. On day 103 to 109 and after day 122, meltwaters layered in the upper 10 to 20 cm of the water column, indicated in most of the profiles by a decrease in conductivity (Figs. 5b, 6a and 7b,d). This layer generally coincided with the 0°C- 0.5°C zone (Figs. 5c and 6c).

On day 99, rhodamine was added to the base of the shoreline snowpack (Fig. 4a). The tracer flowed towards the lake along the slightly sloping snow/ice interface. On day 103, it had formed a surface stain ≈10 m wide reaching 10 m offshore (Fig. 1). Beneath the ice, a concentrated rhodamine layer had accumulated at the ice/water interface with a diluted front already beyond the B20 access hole (Figs. 5d and 7a). The surface stain remained rather stable until ice-off but the sub-ice rhodamine layer continued its progression, pushed by the inflow of meltwater from the shore. By day 105, peak concentration was reached at B20 but the rhodamine layer had been pushed downward 10 cm by meltwater from the ice cover (Figs. 5d and 7c). At the B40 access hole, similar conductivity profiles indicated the presence of meltwater layering but this site was off the tracer pathway and the rhodamine trace never reached it. The tracer reached the lake outlet on day 107 (Fig. 4a), 200 m from the spiked snowpack, 8 days after the injection (average velocity ≈25 m/day or 1 m/h).

The transition between the meltwater layer and the underlying water was sharp. Little turbulent transfer was indicated by strong rhodamine concentration gradients and the sub-ice meltwater was under conditions of laminar flow.

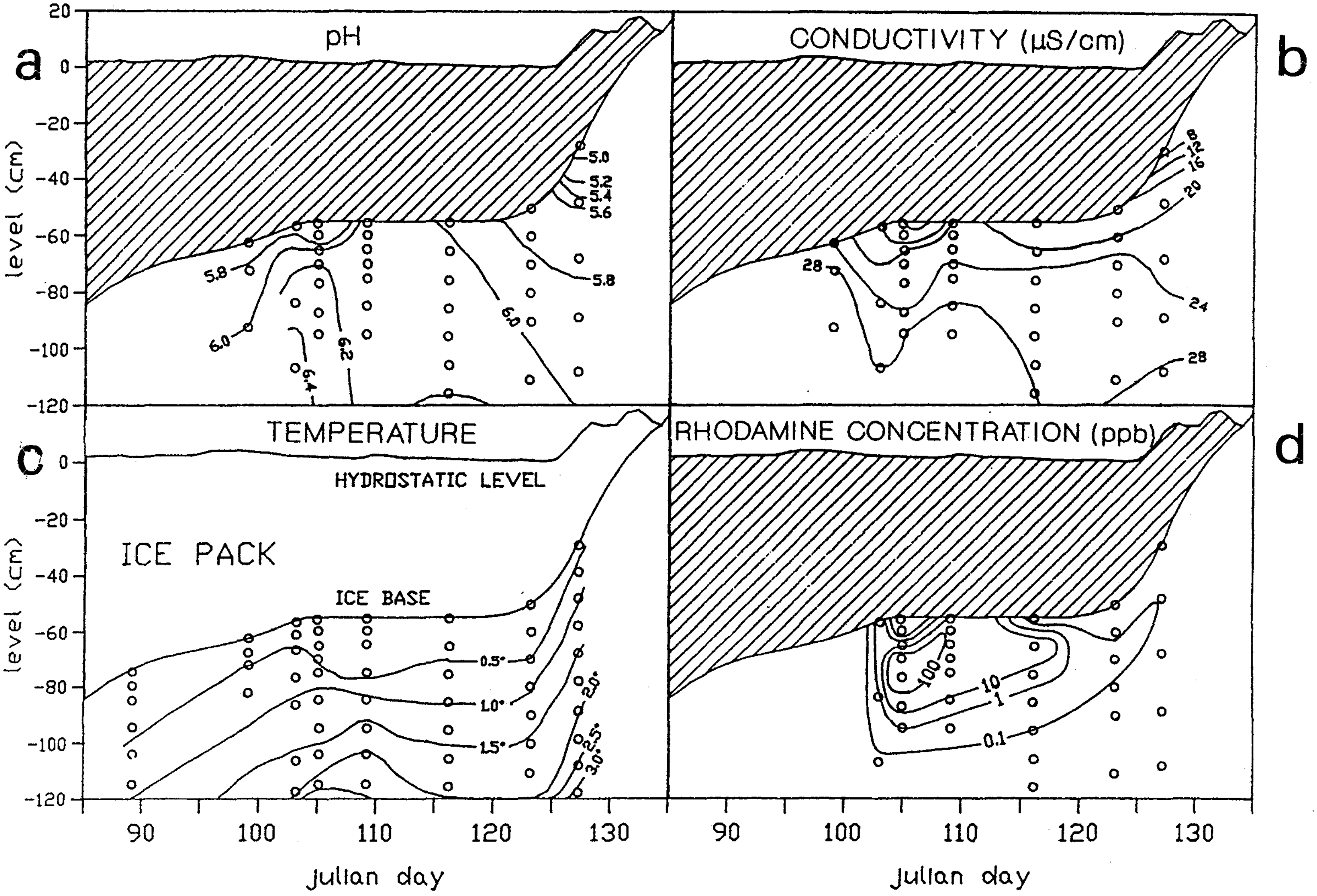

Figure 5: Sub-ice pH [a], conductivity [b], temperature [c] and rhodamine concentrations [d] at access hole B20 during the springmelt, Lac Laflamme, 1988. The measurement or sampling points are indicated by open circles.

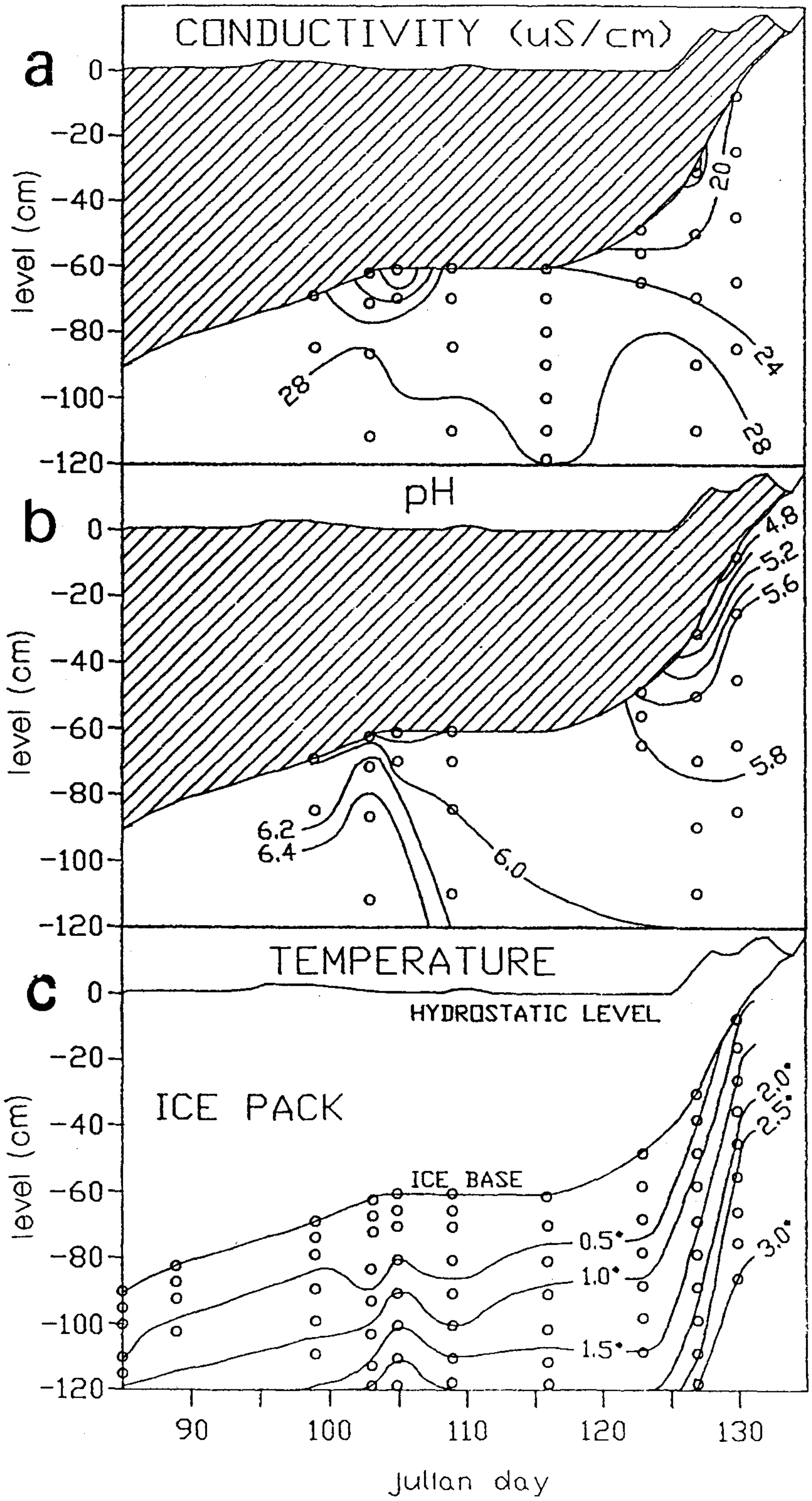

Figure 6: Sub-ice conductivity [a], pH [b] and temperature [c] at access hole D20 during the springmelt, Lac Laflamme, 1988. The measurement or sampling points are indicated by open circles.

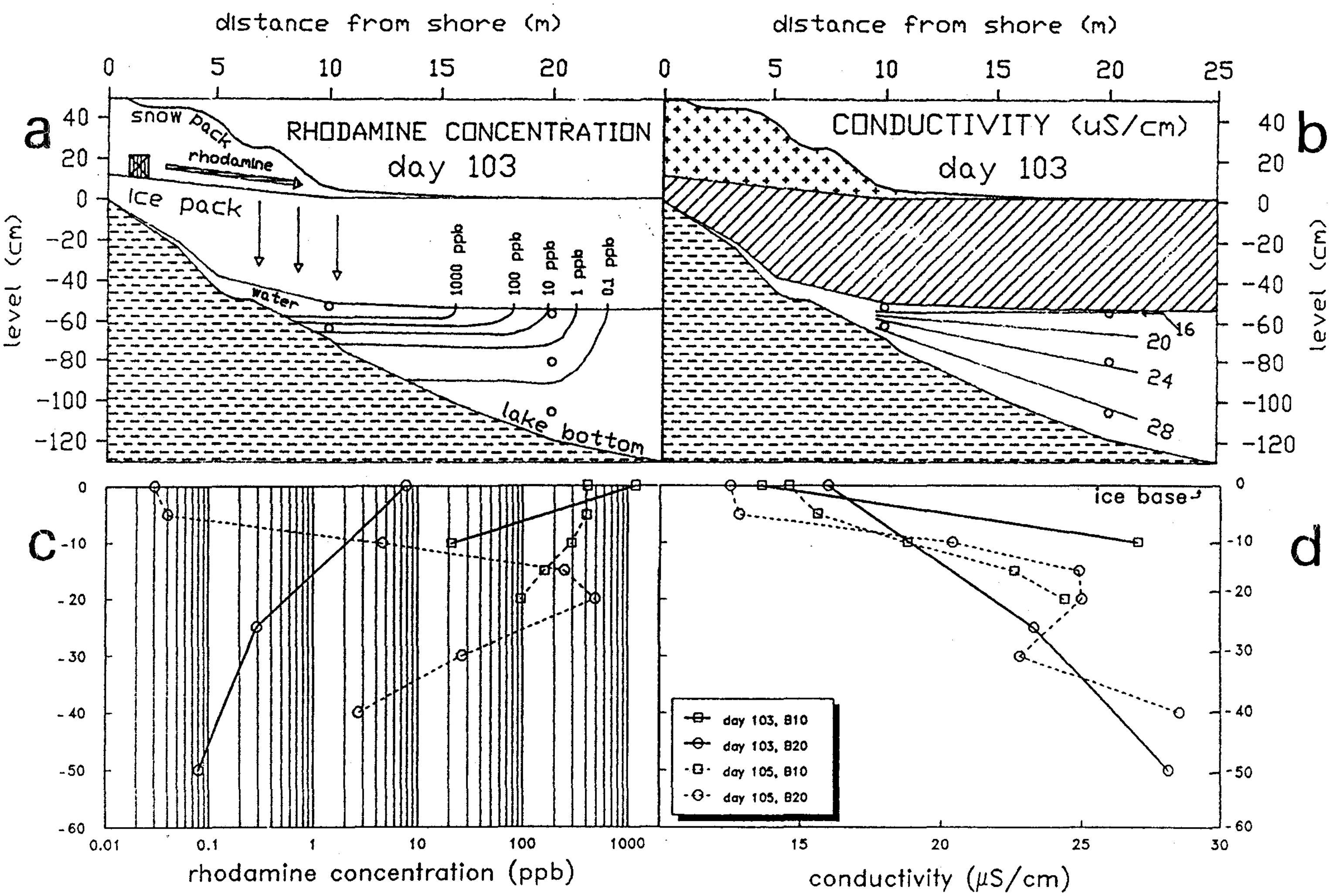

Figure 7: Sub-ice patterns of rhodamine concentrations [a] and conductivity [b] nearshore at B10 and B20 showing the presence of a meltwater layer immediately under the ice on day 103. Sub-ice profiles of Rhodamine [c] and conductivity [d] at B10 and B20, on day 103 and day 105, Lac Laflamme, 1988.

While rhodamine concentrations were declining at B20 (Fig. 5d), they continued remain high (75-350 ppb) at B10. Until ice-off, an important reservoir of rhodamine, therefore, remained in the zone of the original surface stain. For a while it fed a layered meltwater flow toward the outlet but gradually became stagnant; this occurred when most of the snowpack on the shore had melted and the underlying ice started to float. According to the estimate of the amount of rhodamine that had been discharged at the lake outlet (Fig. 4a), by day 130, nearly half of the injected rhodamine was still within the lake storage.

Groundwater inflow

Most of groundwater enters the lake in a narrow (≈10 m wide) nearshore zone (Bernier *et al.*, 1983). The groundwater temperature (1.5°C to 3°C) favours its insertion beneath the meltwater layer and its mixing with the lake premelt water. The main evidence for the inflow of groundwater in the profiles is the gradual decrease of the sub-ice pH below 40 cm depth (Figs. 5a, 6b and 8). The pH declined at this depth at access hole B20 from more than 6.5 (day 103) to less than 6.0 (day 127) whereas the conductivity remained in the 25-30 µS/cm range (Figs. 5a,b respectively). This indicated a progressive dilution and replacement of the premelt waters by incoming groundwaters.

Near the shore, a slight but significant amount of meltwater mixed with the incoming groundwaters as indicated by the B10 rhodamine profiles (Fig. 7c). At B40, 40 m from shore, the meltwater layer never contained any significant concentration of rhodamine but on and after day 109, the underlying waters (samples from 40 to 80 cm depths) did show significant concentrations of 0.2 to

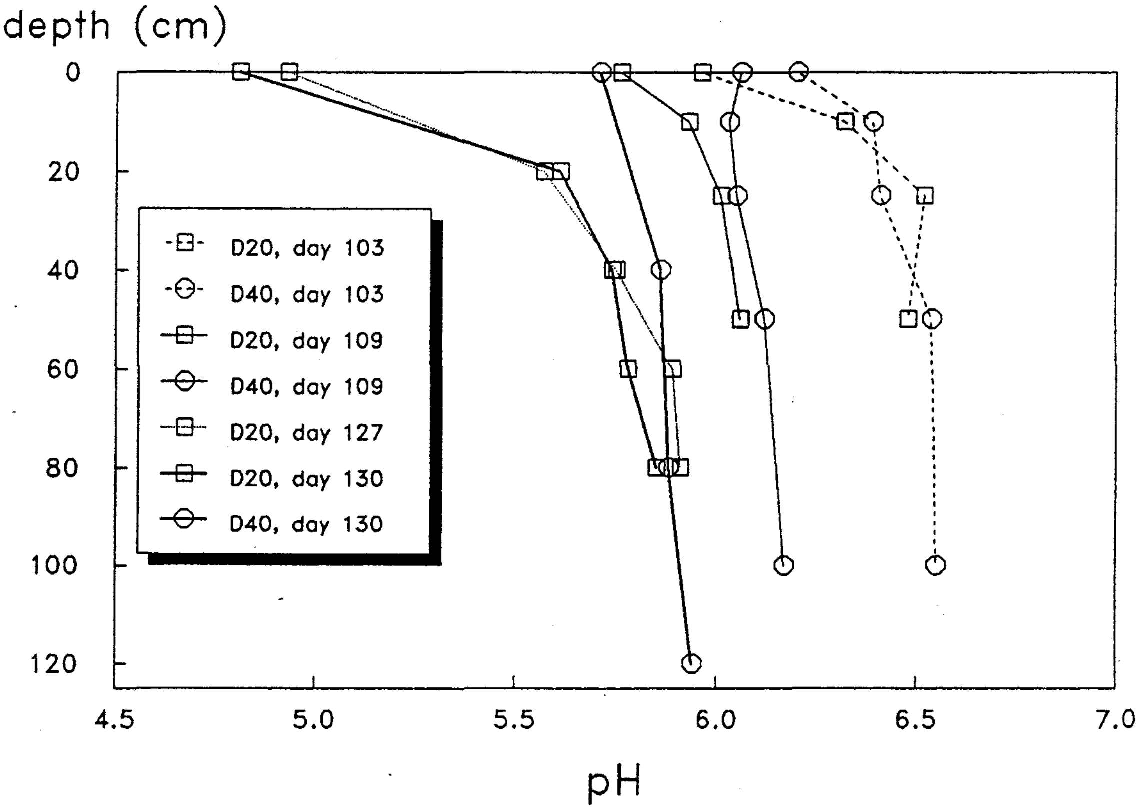

Figure 8: Profiles for various dates at D20 and D40 showing the gradual pH decrease below 40 cm depth, Lac Laflamme, 1988.

0.7 ppb (Fig. 9). This rhodamine represents the small amount of snow meltwater that has been mixed into the shallow groundwaters entering near the shoreline. The effect of this quantity of snow meltwater on the temperature of the groundwater is, however, so small that it does not influence the progression of the groundwaters through the lake. In addition, this presence of rhodamine away from the main trace, suggests that the flow velocity and direction of the groundwaters of this lower layer are distinct from those of meltwaters in the upper layer. As the layers move outwards from the shore they follow different flow patterns, the upper layer being probably more influenced by the lower surface topography of the ice cover.

Throughflow waters

The temperature of throughflow streams are close to 0°C. They enter the lake at various points along the shoreline and flow beneath the ice. Since throughflow occurs late in the melt season, the ice in the littoral zone is generally floating and detached from the banks. The throughflow discharge follows diurnal cycles. In 1988, the strong inflow of throughflow water began during the afternoon of day 125 (Fig. 4c). The injection of the rhodamine corresponded with the low on the discharge curve of day 130 (Fig. 4c). The throughflow discharge peak of that afternoon represents the second highest recorded for the season.

The tracer became visible on the shore 45 minutes after the injection (average velocity: 60 m/h). It entered the lake at three points facing access holes I10 and J10 (Fig. 1). The more concentrated inflow appeared at the central point. The transparency of the black ice and discontinuous white ice layers enabled a

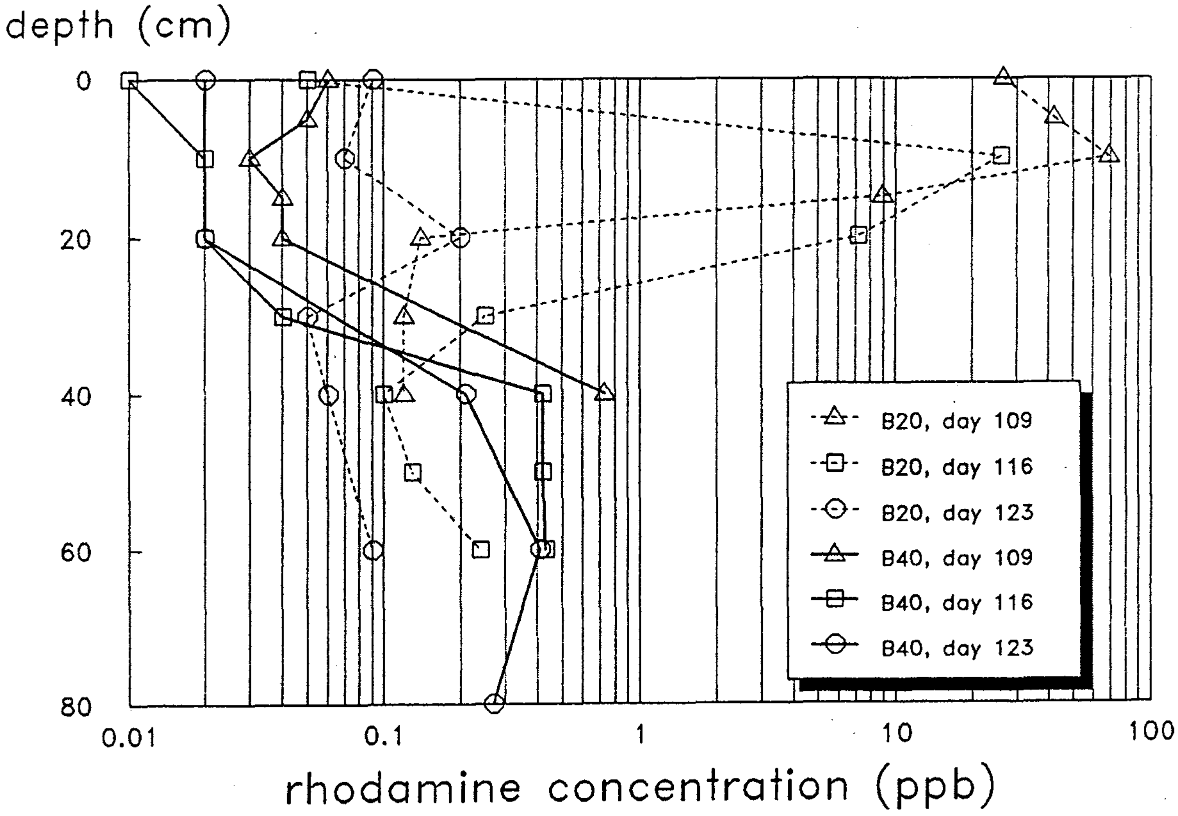

Figure 9: Comparison of rhodamine concentration profiles at B20 and B40 for days 109, 116 and 123, Lac Laflamme, 1988.

visual estimate of the progression of the sub-ice rhodamine front. The front first accumulated along the shore to form a single plume which then extended to 25-30 m offshore at 17:00 (Fig. 1). At I10, sampling of the water column was carried out at 11:00-11:30, before the arrival of the plume. Similar samples were taken around 14:00 at D20 and D40 (outside the plume) and around 16:00 at H10, I10 and J10 (inside the plume). The three shore-throughflow streams sampled repeatedly on that day displayed pH and conductivities in the ranges of 4.4-4.8 and 19-24 µS/cm.

From the profiles obtained at D20, D40, I10, H10 and J10 (Fig. 10) it can be observed that the throughflow layered beneath the ice, forming floating strata <20 cm or <10 cm thick, depending on the site (Fig. 10c, 16:00).

The diurnal cycles in throughflow discharge caused pulses of these strata to expand from the shore daily. For example, at 11:00, on day 130 the pulse of throughflow for that day had not yet reached I10. The pH and conductivity profiles indicate that the waters adjacent to the under side of the ice cover were ice-cover meltwaters and there was no evidence of the presence of throughflow water of day 129 in the profile (Fig. 10c, 11:00). At 14:00, the throughflow pulse had replaced the meltwater layer observed at 11:00 (Fig. 10d). The pH profiles at D20 and D40 (Fig. 10c) also showed that at 14:00 hr the throughflow pulse now skirting the lake perimeter 20 m off shore had reached D20 but not D40 (Fig. 1)

The velocity of the throughflow as it enters the lake is much more important than that of meltwater from the snow and ice cover. Significant turbulence and mixing therefore occur at the base of the layer, this is shown by the downward

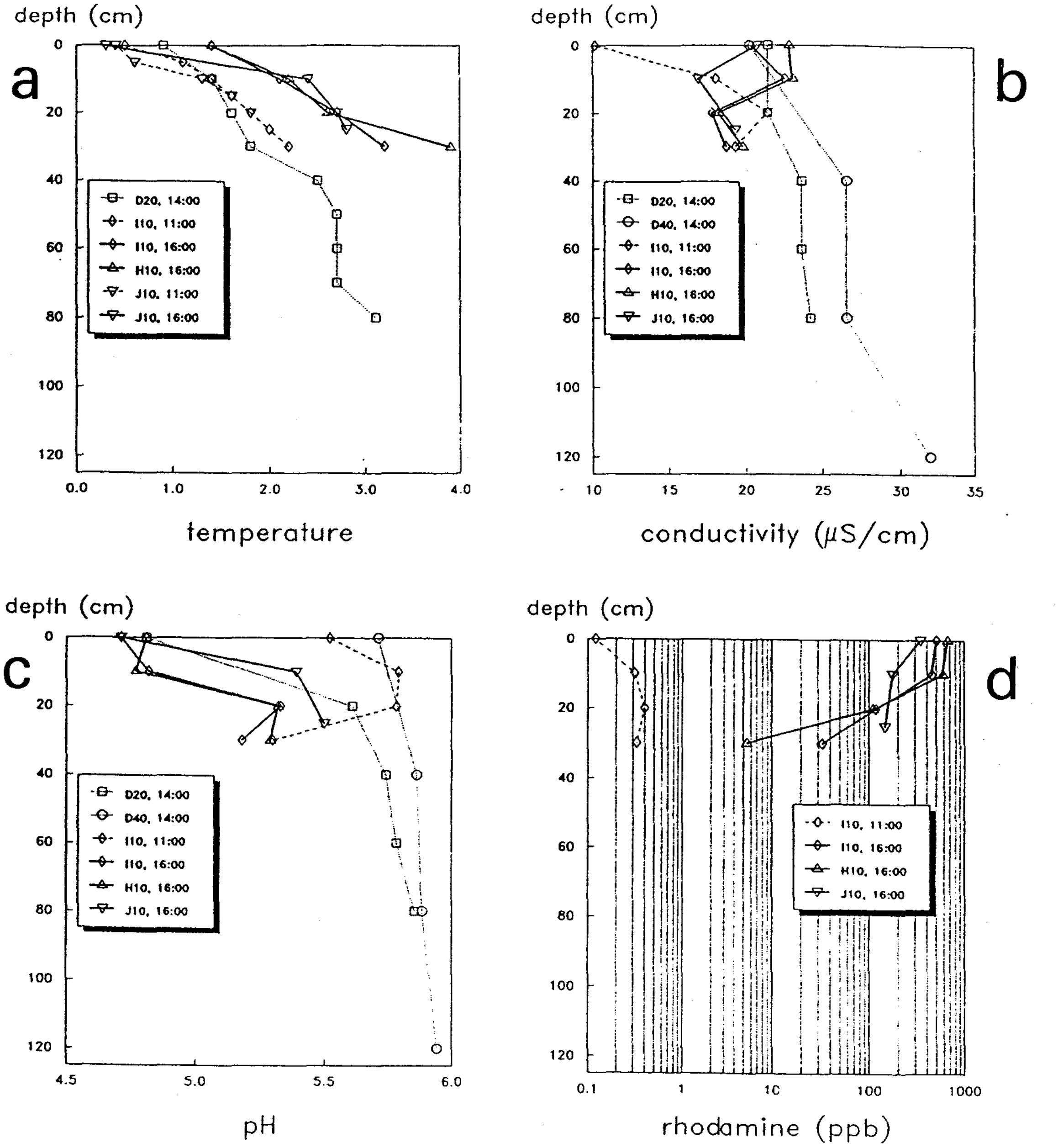

Figure 10: Temperature [a], conductivity [b], pH [c] and rhodamine [d] profiles obtained on day 130, Lac Laflamme, 1988.

tailing of rhodamine concentrations (Fig. 10d). In contrast to the melt period with no throughflow, the conductivity and pH values below the depth of 40 cms do not allow the discrimination of the origin of the lower waters. The pH values could arise from different combinations of pre-melt waters, groundwaters and throughflow. In conjonction with the rhodamine profile, however, it can be seen that the waters below 40 cms are a mixture of shallow groundwaters and premelt water. From the pH values of shallow groundwaters and premelt waters (Fig. 3), it can be seen that the water layer between 40 and 60 cms consists mostly of a shallow groundwater front moving through the inshore region.

On the morning of day 131, the black ice was exposed over most of the lake and covered by numerous meltwater ponds. The ice was thin and prohibited access to the great majority of the sampling sites but the rhodamine trace was visible. Using field notes and photos, the approximate extent of the plume was mapped (Fig. 1). At 11:00 it had already reached the outlet (average velocity >20 m/h). It was possible, however, to sample at two locations (K and L) within the rhodamine plume. The profiles (Fig. 11d) were obtained through natural openings in the ice. In both cases it was observed that two upper sub-ice layers were present, a layer of ice meltwater at the base of the ice and a lower throughflow layer (rhodamine peak and pH of 4.7) at a depth of 20 to 30 cm. In addition, the pH (depth $\geq$ 40 cm) of the bottom waters indicated a mix of shallow groundwater and lake premelt water (Fig. 11c).

The profiles thus show a partial mixing of the throughflow water with both the underlying and overlying waters during the period of massive melt. The transfer, however, is more important in the downward direction due to the lower temperature gradient.

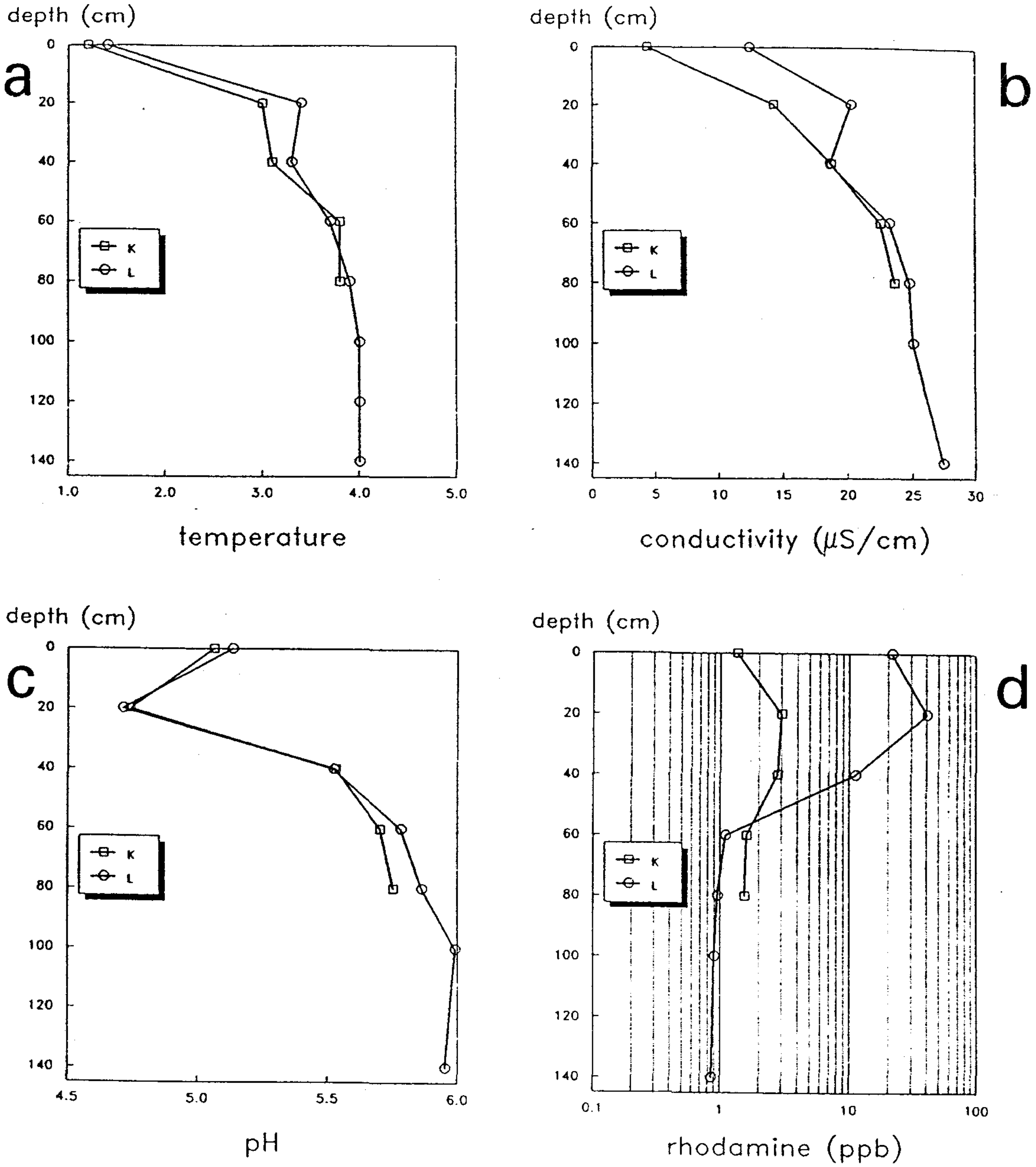

Figure 11: Temperature [a], conductivity [b], pH [c] and rhodamine [d] profiles obtained within the rhodamine plume on day 131, Lace Laflamme, 1988.

The radiative warming of the whole profile beneath the transparent ice cover occurs (e.g. I10 11:00 - 16:00 hrs, Day 130, Fig. 10a and prevents a complete mixing of the local ice-cover meltwater with the throughflow stratum. The partial mixing observed is thus attributed to the hydraulic state of the throughflow water layer. A Reynolds number can be approximated for this layer by assuming that it takes the form of a wide rectangular conduit with a depth of 20 to 40 cm. The Reynolds number for conduit flow is:

$$Re = V * 4Rh / \mu$$

where Re is the Reynolds number, V the flow velocity, Rh the hydraulic radius of the conduit and the μ the kinematic viscosity of the water. The hydraulic radius is the cross-sectional area of the conduit divided by its perimeter. For a rectangular conduit where the width is far greater than the height, $Rh \approx \frac{1}{2}$ height.

From the pH and rhodamine gradients of the profiles and the progression of the throughflow fronts, Rh can be set at 0.15 m and V at > 20 m/hr. In the 0°-4° range, $\mu = 6*10^{-3}$ m^2/h. The estimated Reynolds number is then > 2000. For conduit conditions, Re = 2000 is the upper limit of laminar flow. Therefore the throughflow layer is likely to be in a transitional state, somewhat close to maintaining an individual layer but not enough to prevent any turbulent mixing.

Lake outflow

In the stream draining the lake outflow complete mixing of the different layers of sub-ice acidic waters occurs. Although this study deals with the inshore layering and the subsequent evacuation of snow and ice-cover meltwaters, throughflow and groundwaters by the outflow, it is recognised that the waters of the one main tributary of the lake (extreme east end of the basin) also contribute to the outflow. This could lead to confusion in the interpretation of the relationship between inshore layering and the pH depressions of waters at the outlet. However, the drainage system of Lac Laflamme is poorly developed and streamflow is very low in the early melt while during conditions of high hydrologic flux. Jones et al. (1984) have shown that the chemical characteristics of the main tributary approach those of the intermittent streams. The presence of waters from the main tributary does not therefore significantly affect the chemical signatures of the outflow waters during conditions of both low and high flow.

Until day 95, the lake outlet samples (pH, conductivity) reflected only the lake premelt water (Fig. 4b). The slow decline in pH and conductivity from day 95, suggests that some meltwater from the lake surface was being progressively incorporated into the pre-melt waters of the outflow. The rapid drop in pH from 6.4 to 5.0 on day 107 (Fig. 4b coincides with the appearance of rhodamine (Fig. 4a. Therefore, the cause for this low pH episode was the arrival of meltwaters from the nearshore snowbanks. The higher concentrations of acid in the first meltwaters from snow (Jones et al., 1984) can account for such a low value of pH. Additional evidence is supplied by the fact that during this episode the conductivity was actually starting to rise. This rise in conductivity is attributed to the mixing of the initial meltwaters of high conductivity from the shoreline with the low conductivity meltwaters from the ice cover (Fig. 3). After the initial pulse of acidity in the outflow both snowbank and ice-cover meltwaters continued for a while to contribute to lake outflow as indicated by the presence of rhodamine and moderately low pH values (≃ 5.7 - 6.0; Fig. 4b). The conductivity of the outflow would seem to indicate that lake discharge was a relatively constant mixture of ice-cover meltwater, shoreline snowbank meltwater, deep groundwater, and pre-melt lake water during the stable cold period (day 107-115). This consistency may, however, only be apparent as snow and ice-cover meltwaters declined due to the cold weather and groundwater discharge decreased due to the lowering of the water table. The slight but progressive rise of the pH of the outflow (5.7 to 6.0) would suggest the increasing contribution of lake pre-melt waters. The stability of the conductivity of the outflow is then due to the mixing of premelt water with a diminishing supply of meltwaters which, however, have progressively lower and lower values of conductivity (Fig. 3).

The onset of the massive melt (day 125) induced rapid changes in outflow waters which appeared on day 126 and persisted until ice-off. Two distinct acidic episodes of pH 5.3 and 5.1 were noted (Fig. 4b). They occur at the two peak outflow periods recorded during the ice-on period (day 129 and 132). The almost simultaneous decline in conductivity and pH during these events reflected a substantial increase in the relative contribution of meltwater from the ice cover, the shallow groundwater, and the important, though irregular, presence of acidic throughflow waters. This is consistent with the sub-ice profiles on day 130 and 131 (Fig. 10c, 11c).

Ice-off occurred on day 134. The disappearance of the ice triggered the turnover of the lake, and throughflow, groundwaters, and meltwaters became mixed into the main water body. At the outlet this resulted in an immediate rise of pH and conductivity and although throughflow discharges remained high until day 139, the outflow pH was relatively stable at pH 6.

The presence of an ice cover, by favoring the layering process, allows the throughflow and meltwaters to be more concentrated in the outflow water (and thereby evacuated faster) than if they had been mixed into the main water body of the lake (Fig. 12). Consequently it also increases the relative residence time of the premelt water and the deep groundwater inflow. This ice-cover induced layering of acidic inflows into lake systems during the springmelt accentuates the acidic pulse in the downstream areas of the watersheds by reducing the potential neutralisation of the lake inflows by the resident premelt lake waters.

Conclusion

The field study shows that there were flows of acidic sub-ice strata across the Lac Laflamme during the melt period (Fig. 12). In the early stages of the melt a low velocity flow was driven by the melt of snowbanks on the shoreline. In the massive melt a higher velocity flow was driven by throughflow inputs. Both included ice-cover meltwater. The lake outflow with the highest acidity was caused by snowmelt water. This acidic episode of pH 5.0 was observed before the groundwater became an important contributor to the lake discharge. Two subsequent episodes of slightly less severity (pH 5.3, 5.1) but of longer duration were dominated by hillslope throughflow. Shallow groundwaters also entered the lake close to the shoreline. They mixed with and gradually replaced the premelt waters at a greater depth than the snow meltwater and throughflow layers. The layering process accelerated the evacuation of the acidic inputs and reduced the potential for the renewal of the deeper waters. Beneath the ice cover, groundwater was thus the only inflow able to renew the premelt water. A key terrestrial process in determining the sub-ice profiles is soil infiltration capacity. It controls the groundwater recharge and the duration and importance of throughflow water into the lake system.

The relative contribution of lake surface meltwaters, snow meltwaters, groundwaters, and hillslope surficial waters (throughflow, overland flow, streams) to the acidity of inshore areas will vary according to the springmelt chronology and such factors as the lake/basin area ratio, the soil thickness, soil permeability and frost conditions, and snowmelt rates. If the origins of the waters can be successfully discriminated then the application of measures to reduce the effect of acidity in the sensitive inshore areas (e.g. onshore or inshore liming) can be put into effect with greater efficiency.

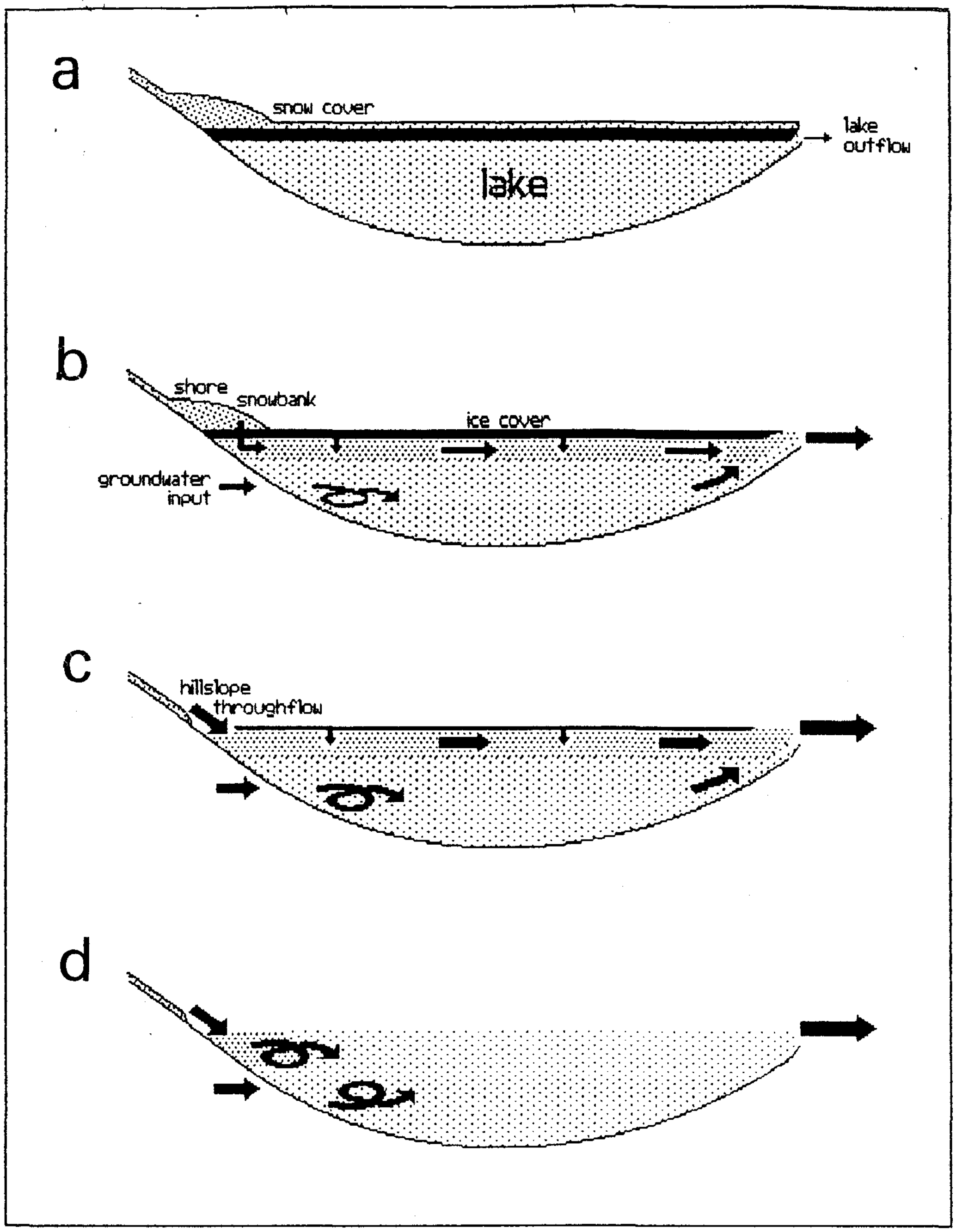

Figure 12: Hydrologic chronology of acidic inputs to Lac Laflamme, Québec, 1988: end of winter [a], snow and ice-cover meltwater layering and deep groundwater input [b], hillslope throughflow and ice-cover meltwater layering [c], and turnover of Lake after ice-off [d].

Acknowledgements

The field assistance of Richard Barry, Roger Beauchemin, Michel Cloutier, Claudia Hernandez, Denis Labonté and Steeve Pépin greatly facilitated our work. The work was financially supported by the Natural Sciences and Engineering Research Council of Canada, the Inland Waters Directorate (Québec region) of Environment Canada, and the Dept. of supply and services (Govt. of Canada). Environment Canada also provided some hydrologic data.

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APPENDIX

APPENDICE

CLEF: voir carte A1 pour identification des sites d'échantillonnage.
KEY : see map A1 for sampling site identification.

car 1: carotte de neige intégrée (site 1)
snow core (site 1)

car 2: carotte de neige intégrée (site 2)
snow core (site 2)

car 3: carotte de neige intégrée (site 3)
snow core (site 3)

lys 1: lysimètre des eaux de fonte de neige (site 1)
snow meltwater lysimeter (site 1)

lys 2: lysimètre des eaux de fonte de neige (site 2)
snow meltwater lysimeter (site 2)

lys 3: lysimètre des eaux de fonte de neige (site 3)
snow meltwater lysimeter (site 3)

lys 4: lysimètre des eaux de fonte de neige (site 4)
snow meltwater lysimeter (site 4)

Lc1 amb: Eaux ambiantes littorales du lac (0.5 - 1m, site c1)
Ambient inshore lake waters (0.5 - 1m depth, site c1)

Lc1 inter: Eaux interstitielles littorales (sédiments, site c1)
Interstitial inshore waters (sediments, site c1)

Ld1 amb: Eaux ambiantes littorales du lac (0.5 - 1m, site d1)
Ambient inshore lake waters (0.5 - 1m depth, site d1)

Ld1 inter: Eaux interstitielles littorales (sédiments, site d1)
Interstitial inshore waters (sediments, site d1)

L trib. amont: Tributaire principal du lac (avant embouchure dans le lac)
Main tributary upstream from inlet to lake

L trib. aval : Eaux ambiantes du lac en aval de l'enbouchure du tributaire principal
Ambient lake waters within diffusion plume of main tributary

L0, 1, 2, 3, 4, 5,6: Lysimètres des eaux du sol organique
Organic soil meltwater lysimeters

Piezo 1-10: Piezomètres site 1, 10 cms dans le sol
Piezometers site 1, 10 cms below soil surface

Piezo 1-20: Piezomètres site 1, 20 cms dans le sol
Piezometers site 1, 20 cms below soil surface

Piezo 1-40: Piezomètres site 1, 40 cms dans le sol
Piezometers site 1, 40 cms below soil surface

Piezo 1-80: Piezomètres site 1, 80 cms dans le sol
Piezometers site 1, 80 cms below soil surface

Piezo 2-10: Piezomètres site 2, 10 cms dans le sol
Piezometers site 2, 10 cms below soil surface

Piezo 2-40: Piezomètres site 2, 40 cms dans le sol
Piezometers site 2, 40 cms below soil surface

Piezo 2-80: Piezomètres site 2, 80 cms dans le sol
Piezometers site 2, 80 cms below soil surface

Piezo A:	Piezomètre site A, échantillon intégré, 10 cms - 1m, dans le sol Piezometer, site A, integrated sample, 10 cms - 1m below soil surface
Sangamo A:	Échantillonneur de précipitation humide A Wet-only precipitation collector A
Sangamo B:	Échantillonneur de précipitation humide B Wet-only precipitation collector B
Al. diss:	Al total dissous Total dissolved Al
Al - Cv:	Al monomérique réactif Reactive monomeric Al
Al - Cv:	Al monomérique non-labile Non-labile monomeric Al

RESULTATS D'ANALYSE - INRS-EAU - HIVER 1988 - JONES/ENV. CANADA

Rapport en date du 14 fevrier 1989

DATE	ECHANTILLON	Al diss (ug/L)	Al-CV (ug/L)	Al-CVR (ug/L)	Cond (umho)	pH	Cl (mg/L)	PO4 (mg/L)	NO3 (mg/L)	SO4 (mg/L)	NH4 (mg/L)	F- (mg/L)	Mg (mg/L)	K (mg/L)	Ca (mg/L)	Na (mg/L)
3-25	car 1	5	31	< 10	21,2	4,41	0,22	< 0.1	1,95	1,27	0,135	0,007	0,051	0,13	0,18	0,09
3-26	car 1	7	33	< 10	18,4	4,51	0,17	< 0.1	1,86	0,96	0,127	0,004	0,050	0,06	0,14	0,08
3-28	car 1	37	25	< 10	13,9	4,66	0,20	< 0.1	1,76	0,99	0,191	0,004	0,051	0,18	0,16	0,19
3-30	car 1	3	19	< 10	15,9	4,61	0,23	< 0.1	1,77	0,99	0,115	0,006	0,050	0,07	0,24	0,12
3-31	car 1	3	21	< 10	18,0	4,59	0,22	< 0.1	1,46	0,96	0,077	0,005	0,029	0,07	0,16	0,06
4-01	car 1	3	47	< 10	13,5	4,63	0,16	< 0.1	1,26	0,74	0,089	0,007	0,029	0,06	0,14	0,06
4-02	car 1	3	40	< 10	14,0	4,54	0,13	< 0.1	1,36	0,76	0,090	0,007	0,013	0,06	0,11	0,05
4-04	car 1	3	< 10	< 10	10,2	4,75	0,12	< 0.1	1,03	0,68	0,078	0,005	0,008	0,07	0,07	0,04
4-05	car 1	3	< 10	< 10	10,0	4,80	0,14	< 0.1	1,01	0,73	0,089	0,005	0,050	0,21	0,17	0,04
4-07	car 1	13	< 10	< 10	13,0	4,63	0,13	< 0.1	1,26	0,72	0,086	0,005	0,022	0,06	0,07	0,04
4-08	car 1	17	< 10	< 10	5,5	5,11	0,12	< 0.1	0,63	0,41	0,059	0,004	0,051	0,22	0,17	0,05
4-10	car 1	5	< 10	< 10	12,6	4,76	0,17	< 0.1	1,53	0,83	0,088	< 0.004	0,051	0,29	0,36	0,05
4-12	car 1	9	< 10	< 10	7,5	5,05	0,13	< 0.1	0,95	0,55	0,072	0,004	0,051	0,21	0,25	0,03
4-14	car 1	9	< 10	< 10	9,5	5,10	0,19	< 0.1	0,92	0,63	0,113		0,051	0,38	0,17	0,05
4-15	car 1	5	< 10	< 10	8,5	4,91	0,13	< 0.1	1,00	0,57	0,068	0,007	0,051	0,14	0,17	0,02
4-21	car 1												0,005	0,06	0,10	0,02
4-25	car 1	3	< 10	< 10	5,9	5,15	0,10	< 0.1	0,41	0,48	0,111		0,002	0,06	0,02	0,02
4-29	car 1	12			8,4	4,87	0,13	< 0.1	0,79	0,65	0,072		0,045	0,33	0,19	0,04
5-02	car 1	8			5,1	5,28	0,17	< 0.1	0,55	0,41	0,079		0,042	0,35	0,16	0,04
5-04	car 1	14			9,5	4,85	0,15	< 0.1	1,19	0,72	0,069		0,051	0,50	0,34	0,05
5-05	car 1	38			9,0	4,89	0,11	< 0.1	0,84	0,76	0,091		0,051	0,22	0,30	0,08
5-06	car 1	6			4,2	5,39	0,12	< 0.1	0,39	0,36	0,046		0,050	0,22	0,14	0,03
5-07	car 1	11			8,9	4,91	0,13	< 0.1	0,93	0,54	0,081		0,068	0,24	0,25	0,02
5-08	car 1	3			5,2	5,29	0,15	< 0.1	< 0.04	0,37	< 0.010		0,051	0,31	0,20	0,04
5-09	car 1	4			4,5	5,12	0,22	< 0.1	0,51	0,35	0,079		0,031	0,20	0,06	0,09
5-10	car 1	3	24	16	5,2	5,07	0,15	< 0.1	0,70	0,47	0,104		0,051	0,22	0,10	0,02
5-11	car 1	20			5,2	5,16	0,11	< 0.1	0,51	0,35	0,109		0,051	0,14	0,11	0,02
5-12	car 1	9			5,1	5,30	0,20	< 0.1	< 0.04	0,29	0,039		0,113	0,44	0,27	0,04
5-13	car 1	17			4,3	5,39	0,13	< 0.1	< 0.04	0,33	0,015		0,051	0,23	0,23	0,03
5-14	car 1	33			5,7	4,72	0,12	< 0.1	< 0.04	0,35	0,017		0,051	0,07	0,19	0,02
5-15	car 1	56			5,9	4,89	0,15	< 0.1	< 0.04	0,33			0,050	0,41	0,19	0,03
3-25	car 2	16	28	< 10	19,0	4,43	0,16	< 0.1	1,70	1,10	0,131	0,005	0,051	0,05	0,18	0,08
3-26	car 2	9	28	< 10	16,6	4,57	0,19	< 0.1	1,51	1,07	0,129	0,005	0,051	0,08	0,17	0,07
3-28	car 2	8	24	< 10	18,8	4,45	0,16	< 0.1	1,90	1,02	0,139	< 0.004	0,050	0,06	0,13	0,06
3-30	car 2	11	25	23	23,0	4,47	0,42	< 0.1	1,69	1,17	0,098	0,005	0,051	0,46	0,17	0,11
3-31	car 2	4	19	< 10	17,0	4,55	0,23	< 0.1	1,70	1,03	0,140	0,004	0,051	0,08	0,17	0,01
4-01	car 2	24	65	44	18,5	4,47	0,15	< 0.1	1,57	0,88	0,119	0,005	0,051	0,18	0,20	0,07
4-02	car 2	5	28	15	12,5	4,74	0,14	< 0.1	1,40	0,88	0,172	0,005	0,051	0,22	0,29	0,05
4-04	car 2	8	< 10	< 10	12,0	4,70	0,15	< 0.1	1,22	0,91	0,096	0,005	0,051	0,21	0,21	0,04
4-05	car 2	3	< 10	< 10	8,0	5,43	0,14	< 0.1	1,01	0,70	0,165	0,005	0,051	0,33	0,34	0,04
4-07	car 2	3	< 10	< 10	9,6	4,74	0,14	< 0.1	0,94	0,64	0,094	0,006	0,034	0,05	0,09	0,04
4-08	car 2	6	10	< 10	10,5	4,15	0,14	< 0.1	1,55	0,68	0,089	0,005	0,049	0,13	0,13	0,04
4-10	car 2	3	< 10	< 10	10,3	4,82	0,14	< 0.1	0,99	0,64	0,107	0,005	0,049	0,13	0,09	0,04
4-12	car 2	3	< 10	< 10	7,7	5,13	0,12	< 0.1	0,94	0,55	0,104	0,005	0,051	0,19	0,22	0,02
4-14	car 2	24	< 10	< 10	9,0	4,96	0,15	< 0.1	1,26	0,67	0,073	0,006	0,097	0,41	0,44	0,04
4-15	car 2	12			8,5	4,95	0,15	< 0.1	0,62	0,49	0,052	0,010	0,051	0,31	0,19	0,04
4-25	car 2	34			12,9	4,72	0,20	< 0.1	0,75	0,96	0,094		0,051	0,56	0,14	0,05

RESULTATS D'ANALYSE - INRS-EAU - HIVER 1988 - JONES/ENV. CANADA

Rapport en date du 14 fevrier 1989

DATE	ECHANTILLON	Al diss (ug/L)	Al-CV (ug/L)	Al-CVR (ug/L)	Cond (umho)	pH	Cl (mg/L)	PO4 (mg/L)	NO3 (mg/L)	SO4 (mg/L)	NH4 (mg/L)	F- (mg/L)	Mg (mg/L)	K (mg/L)	Ca (mg/L)	Na (mg/L)
4-29	car 2	33			9,0	4,83	< 0.03	< 0.1	< 0.04	< 0.02	0,072		0,051	0,24	0,15	0,03
5-02	car 2	11			9,1	4,87	0,14	< 0.1	0,76	0,70	0,130		0,051	0,17	0,10	0,03
5-04	car 2	24			7,7	5,20	0,21	< 0.1	0,67	0,65	0,201		0,060	0,39	0,35	0,08
5-05	car 2	14			11,0	4,86	0,14	< 0.1	0,71	0,52	0,102		0,051	0,19	0,18	0,04
5-06	car 2	10			6,5	4,94	0,19	< 0.1	0,69	0,50	0,060		0,051	0,17	0,13	0,05
5-07	car 2	6			6,2	5,21	0,16	< 0.1	0,38	0,37	0,141		0,051	0,37	0,13	0,03
5-08	car 2	8			5,8	5,03	0,14	< 0.1	< 0.04	0,36	< 0.010		0,038	0,37	0,07	0,02
5-09	car 2	59			8,5	5,00	0,64	< 0.1	1,10	0,63	0,178		0,051	0,83	0,16	0,29
3-25	car 3	28	24	< 10	18,0	4,50	0,15	< 0.1	1,53	1,12	0,131	0,005	0,051	0,10	0,13	0,08
3-26	car 3	20	34	< 10	19,2	4,45	0,16	< 0.1	1,78	1,07	0,126	0,005	0,028		0,15	
3-28	car 3	9	19	< 10	18,8	4,64	0,14	< 0.1	1,19	0,83	0,094	< 0.004	0,051	0,06	0,12	0,05
3-30	car 3	11	15	11	14,6	4,61	0,25	< 0.1	1,42	1,01	0,061	0,005	0,051	0,20	0,18	0,10
3-31	car 3	7	17	< 10	15,8	4,58	0,36	< 0.1	1,53	0,98	0,083	0,004	0,051	0,12	0,14	0,11
4-01	car 3	8	36	12	14,5	4,52	0,15	< 0.1	1,35	0,84	0,097	0,004	0,051	0,17	0,20	0,08
4-02	car 3	46	31	< 10	14,5	4,62	0,15	< 0.1	1,35	0,74	0,097	< 0.004	0,051	0,12	0,13	0,07
4-04	car 3	9	< 10	< 10	12,4	4,67	0,14	< 0.1	1,34	0,83	0,110	0,005	0,051	0,15	0,13	0,05
4-05	car 3	7	< 10	< 10	11,2	4,69	0,13	< 0.1	1,20	0,73	0,083	0,005	0,047	0,12	0,09	0,06
4-07	car 3	13	10	< 10	12,0	4,73	0,16	< 0.1	1,31	0,80	0,087	0,005	0,051	0,43	0,33	0,05
4-08	car 3	83	< 10	< 10	8,5	4,79	0,13	< 0.1	0,98	0,54	0,077	0,004	0,021	0,07	0,05	0,05
4-10	car 3	7	< 10	< 10	7,5	5,10	0,11	< 0.1	0,69	0,48	0,068	0,004	0,110	0,18	0,25	0,03
4-12	car 3	3	< 10	< 10	8,5	4,84	0,14	< 0.1	0,85	0,53	0,081	< 0.004	0,010	0,04	0,01	0,03
4-14	car 3	4			8,6	4,85	0,11	< 0.1	0,84	0,50	0,075		0,044	0,07	0,08	0,03
4-15	car 3	318	< 10	< 10	10,3	4,75	0,12	< 0.1	1,02	0,62	0,067	0,0022	0,08	0,03	0,02	
4-25	car 3	3	21	11	8,7	4,89	0,11	< 0.1	0,63	0,63	0,118		0,038	0,11	0,11	0,03
4-29	car 3	9			8,2	4,87	< 0.03	< 0.1	< 0.04	< 0.02	0,119		0,050	0,13	0,10	0,02
5-02	car 3	6			8,8	4,87	0,11	< 0.1	0,79	0,58	0,100		0,030	0,09	0,08	0,03
5-04	car 3	12			6,3	4,85	0,10	< 0.1	0,44	0,43	0,057		0,022	0,08	0,06	0,02
5-05	car 3	10			11,5	4,70	0,13	< 0.1	1,09	0,72	0,053		0,051	0,20	0,22	0,01
5-06	car 3	7	20	12	6,2	5,06	0,20	< 0.1	0,45	0,44	0,025		0,044	0,18	0,08	0,03
5-07	car 3	9			5,6	4,99	0,11	< 0.1	0,18	0,34	< 0.010		0,026	0,15	0,03	0,02
5-08	car 3	9			10,5	4,72	0,16	< 0.1	1,05	0,68	< 0.010		0,051	0,16	0,29	0,03
5-09	car 3	11	19	8	6,0	5,05	0,23	< 0.1	0,51	0,42	0,034		0,051	0,27	0,10	0,07
5-10	car 3	9	24	19	4,8	4,94	0,15	< 0.1	0,40	0,32	< 0.010		0,028	0,14	0,03	< 0.01
5-11	car 3	21	34	28	4,7	5,52	0,13	< 0.1	< 0.04	0,36	< 0.010		0,039	0,06	0,18	0,05
5-12	car 3	21	38	36	3,8	50,00	0,15	< 0.1	< 0.04	0,31	0,019		0,037	0,38	0,06	0,03
3-29	c'-20-0	22	25	17	32,0	5,88	0,39	< 0.1	2,36	4,09	0,184		0,615	0,23	3,18	1,17
3-29	c-20-0	3	25	14	31,0	5,80	0,41	< 0.1	1,26	3,98	0,153		0,550	0,31	3,08	1,09
3-31	L c1 amb	120			30,0	6,34	0,61	< 0.1	2,38	4,41	0,271	0,021	0,549	0,51	3,90	0,85
4-02	L c1 amb	104			36,0	6,28	0,50	< 0.1	1,92	3,90	0,214		0,997	0,39	4,65	1,06
4-06	L c1 amb				55,0	6,88	0,43	< 0.1	1,32	3,86	0,162		2,028	0,38	7,30	2,24
4-07	L c1 amb	128	45	25	16,0	5,73	0,39	< 0.1	1,24	2,84	0,115	0,013	0,268	0,44	1,36	0,64
4-08	L c1 amb	125	20	25	15,0	5,84	0,35	< 0.1	1,17	2,74	0,090	0,010	0,268	0,24	1,33	0,46
4-09	L c1 amb	138			19,5	6,27	0,36	< 0.1	1,12	3,06	0,099		0,372	0,26	1,84	0,63
4-10	L c1 amb	102	44	17	13,4	5,66	0,35	< 0.1	0,85	2,11	0,078	0,008	0,183	0,20	1,15	0,43
4-11	L c1 amb	92			13,0	5,59	0,40	< 0.1	0,80	2,06	0,059	0,008	0,189	0,21	1,14	0,47

RESULTATS D'ANALYSE - INRS-EAU - HIVER 1988 - JONES/ENV. CANADA

Rapport en date du 14 fevrier 1989

DATE	ECHANTILLON	Al diss (ug/L)	Al-CV (ug/L)	Al-CVR (ug/L)	Cond (umho)	pH	Cl (mg/L)	PO4 (mg/L)	NO3 (mg/L)	SO4 (mg/L)	NH4 (mg/L)	F- (mg/L)	Mg (mg/L)	K (mg/L)	Ca (mg/L)	Na (mg/L)
4-12	L c1 amb	9	< 10	< 10	4,5	5,37	0,13	< 0.1	0,45	0,42	0,037	< 0.004	0,047	0,03	0,12	< 0.01
4-13	L c1 amb	15	< 10	< 10	4,2	5,45	0,16	< 0.1	0,34	0,43	0,053		0,051	0,04	0,18	0,05
4-14	L c1 amb	37	< 10	< 10	6,5	5,76	0,21	< 0.1	0,46	0,95	0,028	0,012	0,112	0,17	0,51	0,20
4-15	L c1 amb	88			35,2	6,34	0,34	< 0.1	1,56	3,28	0,034	0,014	0,999	0,22	4,12	1,42
4-21	L c1 amb	156			40,0	6,11	0,40	< 0.1	1,69	4,22	0,054	0,031	0,999	0,29	3,90	1,57
4-26	L c1 amb	76			4,9	6,14	0,35	< 0.1	1,92	3,64	0,079		1,488	0,29	4,80	1,98
4-29	L c1 amb	127	38	20	31,0	5,91	0,48	< 0.1	1,43	3,60	0,170		0,695	0,31	4,00	1,11
5-02	L c1 amb	190			35,5	6,09	0,38	< 0.1	1,58	4,04	0,071		0,999	0,31	4,44	1,44
5-04	L c1 amb	135			30,0	6,10	0,35	< 0.1	1,44	3,28	0,050		0,695	0,29	3,39	1,14
5-05	L c1 amb	157			32,0	6,08	0,30	< 0.1	1,11	3,32	0,050		0,950	0,25	3,78	1,29
5-06	L c1 amb	143			27,0	6,12	0,34	< 0.1	1,13	3,79	0,040		0,694	0,32	3,57	1,06
5-07	L c1 amb	157			21,8	5,72	0,25	< 0.1	0,64	3,68	0,010		0,507	0,29	3,09	0,78
5-08	L c1 amb	157											0,771	0,27	3,63	1,16
5-09	L c1 amb	157	75	58	29,0	5,69	0,27	< 0.1	1,16	3,56	0,017		0,957	0,31	3,75	1,16
5-10	L c1 amb	165	78	58	20,5	5,68	0,29	< 0.1	0,55	3,57	0,028		0,507	0,37	2,91	0,96
5-11	L c1 amb	165			29,0	6,21	0,27	< 0.1	0,84	3,32	0,015		0,878	0,27	3,90	1,20
5-12	L c1 amb		114	87	20,0	5,45	0,29	< 0.1	0,51	3,43	0,020					
5-18	L c1 amb	130	49	35	19,0	5,95	0,22	< 0.1	0,50	3,20	0,026		0,495	0,20	2,85	0,68
3-31	L c1 inter	80			47,8	6,74	0,55	< 0.1	1,02	3,98	0,248	0,032	1,340	0,46	5,15	1,74
4-02	L c1 inter	140			52,0	6,63	0,55	< 0.1	0,98	3,79	0,232	0,063	1,510	0,37	5,55	1,94
4-06	L c1 inter	70			50,0	6,88	0,47	< 0.1	1,13	3,53	0,187	0,068	1,630	0,53	5,73	2,30
4-07	L c1 inter	45	< 10	< 10	55,0	6,38	0,45	< 0.1	1,32	3,65	0,206	0,032	1,600	0,33	5,65	2,09
4-08	L c1 inter	52			51,0	6,42	0,38	< 0.1	1,34	3,93	0,172	0,050	1,460	0,30	5,15	1,99
4-09	L c1 inter	61			51,0	6,42	0,33	< 0.1	1,53	3,51	0,122	0,018	1,570	0,30	5,51	2,12
4-10	L c1 inter	52			54,0	6,36	0,37	< 0.1	1,45	3,72	0,155	0,026	0,972	0,27	3,58	1,47
4-11	L c1 inter	80			35,5	6,48	0,37	< 0.1	1,34	2,95	0,113	0,019	1,030	0,26	3,77	1,53
4-12	L c1 inter	82	15	< 10	37,0	6,50	0,36	< 0.1	1,40	3,03	0,108	0,008				
4-13	L c1 inter	60			52,0	6,51	0,47	< 0.1	1,88	3,35	0,133	0,024	1,550	0,27	5,27	2,21
4-14	L c1 inter	24			25,5	6,34	0,26	< 0.1	1,22	1,72	0,060	0,018	0,737	0,15	2,51	1,11
4-15	L c1 inter	30			48,0	6,45	0,30	< 0.1	2,08	2,87	0,066	0,040	1,430	0,21	4,77	2,10
4-21	L c1 inter	62			58,0	6,35	0,38	< 0.1	2,27	3,65	0,104		1,730	0,33	5,85	2,49
4-26	L c1 inter	54			19,0	6,16	0,36	< 0.1	2,18	3,61	0,167		1,720	0,35	5,86	2,46
4-29	L c1 inter	65			55,0	6,36	0,39	< 0.1	2,03	3,64	0,147		1,630	0,32	5,60	2,30
5-02	L c1 inter	52			58,0	6,32	0,39	< 0.1	2,31	3,56	0,144		1,770	0,32	5,95	2,32
5-04	L c1 inter	77			50,5	6,41	0,36	< 0.1	2,20	3,92	0,086		1,470	0,27	5,08	1,76
5-05	L c1 inter	46	28	< 10	52,5	5,99	0,52	< 0.1	2,45	3,70	0,086		1,850	0,29	6,10	2,61
5-06	L c1 inter	22			65,0	6,58	0,39	< 0.1	2,73	3,45	0,064		2,020	0,28	6,57	2,82
5-07	L c1 inter	52			52,0	6,24	0,35	< 0.1	2,20	3,64	0,031		1,560	0,23	5,23	2,30
5-08	L c1 inter	132											1,010	0,26	3,59	1,59
5-09	L c1 inter	196	93	66	25,0	5,60	0,27	< 0.1	1,00	3,72	0,012		0,596	0,23	2,31	1,03
5-10	L c1 inter	155	88	64	23,8	5,71	0,28	< 0.1	0,75	3,63	0,016		0,568	0,26	2,32	1,04
5-11	L c1 inter	140			29,0	6,22	0,30	< 0.1	0,86	3,55	0,020		0,713	0,24	2,77	1,22
5-12	L c1 inter	119	84	66	28,5	5,86	0,25	< 0.1	0,76	3,40	0,024		0,757	0,22	2,88	1,28
3-31	L d1 amb	185	12	< 10	47,2	6,72	1,07	< 0.1	0,79	3,64	0,220	0,042	0,896	1,89	4,52	2,06
4-02	L d1 amb	18			49,0	6,41	0,64	< 0.1	0,64	3,37	0,173	0,037	0,916	1,54	4,62	1,81
4-06	L d1 amb	85			36,0	6,55	0,53	< 0.1	2,79	4,93	0,123	0,044	0,681	0,52	3,59	1,37

RESULTATS D'ANALYSE - INRS-EAU - HIVER 1988 - JONES/ENV. CANADA

Rapport en date du 14 fevrier 1989

DATE	ECHANTILLON	Al diss (ug/L)	Al-CV (ug/L)	Al-CVR (ug/L)	Cond (umho)	pH	Cl (mg/L)	PO4 (mg/L)	NO3 (mg/L)	SO4 (mg/L)	NH4 (mg/L)	F- (mg/L)	Mg (mg/L)	K (mg/L)	Ca (mg/L)	Na (mg/L)
4-07	L dl amb	57	11	< 10	37,5	6,40	0,75	< 0.1	2,47	4,63	0,145	0,017	0,645	1,14	3,48	1,50
4-08	L dl amb	61			36,0	6,15	0,62	< 0.1	1,91	4,21	0,123	0,020	0,658	1,15	3,41	1,40
4-09	L dl amb	25			13,5	6,41	0,32	< 0.1	1,60	1,67	0,133	0,006	0,163	0,37	0,88	0,44
4-10	L dl amb	21	< 10	< 10	9,0	5,26	0,25	< 0.1	1,36	0,91		0,005	0,036	0,27	0,20	0,16
4-11	L dl amb	15	12	< 10	7,5	5,11	0,25	< 0.1	1,13	0,69	0,107	0,005	0,025	0,25	0,14	0,13
4-12	L dl amb	17	< 10	< 10	9,2	6,07	0,28	< 0.1	0,77	1,02	0,096	0,006	0,123	0,28	0,60	0,33
4-13	L dl amb	70	< 10	< 10	8,5	5,79	0,44	< 0.1	0,67	0,79	0,104	0,006	0,076	0,37	0,41	0,34
4-14	L dl amb	19	< 10	< 10	14,2	5,99	0,45	< 0.1	0,66	1,51	0,083		0,199	0,52	1,04	0,59
4-15	L dl amb	25			18,0	6,52	0,30	< 0.1	0,48	2,08	0,030	0,013	0,298	0,32	1,57	0,66
4-21	L dl amb	38			31,0	6,10	0,39	< 0.1	0,41	3,23	0,041		0,575	0,58	3,11	1,07
4-26	L dl amb	110			26,0	6,00	0,40	< 0.1	0,74	2,70	0,184		0,402	0,79	2,25	0,87
4-29	L dl amb	48			26,0	6,22	0,37	< 0.1	0,77	3,01	0,057		0,463	0,39	2,54	0,90
5-02	L dl amb	26			31,5	6,11	0,42	< 0.1	0,80	3,21	0,069		0,588	0,55	3,20	1,09
5-04	L dl amb	48			21,8	6,24	0,36	< 0.1	1,03	2,72	0,029		0,330	0,39	1,89	0,71
5-05	L dl amb	172	267	120	27,5	4,70	0,24	< 0.1	1,41	4,13	0,029		0,233	0,40	1,54	0,45
5-06	L dl amb	134	130	74	24,8	4,49	0,24	< 0.1	1,71	2,90	0,047		0,135	0,28	0,85	0,33
5-07	L dl amb	159			30,5	4,45	0,26	< 0.1	2,85	3,71	0,015		0,185	0,54	1,20	0,37
5-08	L dl amb	147											0,215	0,40	1,37	0,43
5-09	L dl amb	180	329	91	27,5	5,52	0,25	< 0.1	2,85	3,73	< 0.010		0,166	0,34	1,06	0,32
5-10	L dl amb	204			20,5	4,60	0,21	< 0.1	2,03	3,03	0,017		0,175	0,32	1,09	0,33
5-11	L dl amb	186	146	101	18,5	5,93	0,29	< 0.1	1,29	3,55	0,016		0,279	0,39	1,54	0,64
5-12	L dl amb	186	285	109	21,0	5,09	0,24	< 0.1	1,97	3,82	0,022		0,256	0,42	1,54	0,51
5-18	L dl amb	110	49	38	19,5	6,05	0,22	< 0.1	0,52	3,22	0,020		0,406	0,20	1,98	0,74
3-31	L dl inter	140			48,0	6,66	0,94	< 0.1	< 0.04	3,07	0,236	0,038	0,921	2,51	4,98	1,91
4-02	L dl inter	190			858	1,27	4,48	1,79								
4-06	L dl inter	224			44,5	6,54	0,50	< 0.1	1,69	3,81	0,205		0,964	0,66	4,90	1,83
4-07	L dl inter	23	< 10	< 10	42,5	6,44	0,42	< 0.1	2,35	3,93	0,168	0,022	0,926	0,43	4,69	1,62
4-08	L dl inter	228			39,5	6,59	0,38	< 0.1	2,79	3,95	0,096	0,038	0,919	0,32	4,57	1,60
4-09	L dl inter	160			41,0	6,31	0,33	< 0.1	2,53	3,66	0,066	0,013	0,882	0,26	4,41	1,51
4-10	L dl inter	91			40,0	6,27	0,35	< 0.1	2,64	3,63	0,041	0,012	0,894	0,23	4,44	1,52
4-11	L dl inter	45			40,0	6,43	0,35	< 0.1	2,92	3,63	0,026	0,012	0,904	0,21	4,49	1,56
4-12	L dl inter	125	< 10	< 10	38,0	6,53	0,32	< 0.1	2,39	3,47	0,024	0,010	0,859	0,20	4,25	1,51
4-13	L dl inter	77			40,0	6,46	0,32	< 0.1	2,65	3,56	0,013	0,011	0,890	0,18	4,39	1,52
4-14	L dl inter	256			38,5	6,30	0,32	< 0.1	2,33	3,49	0,014	0,023	0,859	0,20	4,20	1,47
4-15	L dl inter	240			26,5	6,52	0,32	< 0.1	0,90	2,73	0,025	0,016	0,530	0,20	2,82	0,98
4-21	L dl inter	638			38,9	6,09	0,49	< 0.1	0,54	3,46	0,061	0,023	0,852	0,29	4,36	1,49
4-26	L dl inter	87			47,0	6,12	0,72	< 0.1	< 0.04	3,65	0,064		0,843	0,68	4,41	1,71
4-29	L dl inter	130			48,5	6,31	0,61	< 0.1	< 0.04	3,60	1,092		0,785	0,68	4,15	1,64
5-02	L dl inter	616			44,0	6,22	0,41	< 0.1	0,77	3,57			0,813	0,38	4,33	1,43
5-04	L dl inter	38			40,0	6,14	0,40	< 0.1	0,93	3,75	0,513		0,659	0,32	3,68	1,23
5-05	L dl inter	248	21	12	35,5	5,78	0,32	< 0.1	0,92	3,67	0,513		0,633	0,34	3,48	1,15
5-06	L dl inter	57			37,0	6,06	0,37	< 0.1	1,08	4,08	0,813		0,574	0,39	3,17	1,05
5-07	L dl inter	80			34,0	5,7573	0,34	3,01	1,02							
5-08	L dl inter	83											0,411	0,29	2,24	0,79
5-09	L dl inter	260	46	25	27,0	5,55	0,29	< 0.1	1,88	3,22	0,636		0,461	0,29	2,43	0,84
5-10	L dl inter	1210	1383	39	32,0	5,89	0,30	< 0.1	< 0.04	3,54	0,729		0,560	0,46	2,92	1,02
5-11	L dl inter	93			27,0	6,08	0,35	< 0.1	1,77	3,27	0,419		0,438	0,41	2,37	0,81

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DATE	ECHANTILLON	Al diss (ug/L)	Al-CV (ug/L)	Al-CVR (ug/L)	Cond (umho)	pH	Cl (mg/L)	PO4 (mg/L)	NO3 (mg/L)	SO4 (mg/L)	NH4 (mg/L)	F- (mg/L)	Mg (mg/L)	K (mg/L)	Ca (mg/L)	Na (mg/L)
5-12	L dl inter	109	85	64	26,0	5,70	0,29	< 0.1	0,92	3,41	0,405		0,439	0,33	2,30	0,86
4-10	L trib amont	228	142	84	18,0	5,03	0,25	< 0.1	1,01	1,99	< 0.010	0,009	0,324	0,24	2,00	0,63
4-14	L trib amont	212			20,5	6,39	0,21	< 0.1	1,48	4,53	< 0.010		0,404	0,18	2,20	0,88
4-21	L trib amont	112	35	29	23,0	5,83	0,23	< 0.1	1,24	4,51	< 0.010		0,447	0,17	2,43	1,00
4-26	L trib amont	106			24,0	6,06	0,23	< 0.1	1,38	4,50	0,073		0,400	0,21	2,22	0,78
4-29	L trib amont	238	87	59	22,1	5,95	0,21	< 0.1	1,39	4,65	< 0.010		0,413	0,19	2,29	0,82
5-02	L trib amont	128			23,0	6,06	0,23	< 0.1	1,41	4,66	< 0.010		0,280	0,24	1,86	0,60
5-04	L trib amont	212	122	84	20,0	5,82	0,19	< 0.1	1,17	4,87	< 0.010		0,210	0,32	1,38	0,46
5-05	L trib amont	260	270	137	18,5	4,74	0,11	< 0.1	0,45	4,08	< 0.010		0,179	0,28	1,18	0,40
5-06	L trib amont	334	255	116	17,4	5,01	0,15	< 0.1	0,40	3,80	< 0.010		0,160	0,26	1,08	0,37
5-07	L trib amont	257			17,2	4,86	0,14	< 0.1	0,27	3,53	< 0.010		0,135	0,19	0,91	0,32
5-09	L trib amont	260	305	125	16,0	5,00	0,15	< 0.1	0,37	3,54	< 0.010		0,142	0,24	0,95	0,35
5-10	L trib amont	298	276	127	16,4	4,70	0,16	< 0.1	0,38	3,13	0,013		0,157	0,20	1,02	0,36
5-11	L trib amont	252	337	132	15,1	5,68	0,15	< 0.1	0,00	3,18	< 0.010		0,196	0,17	1,20	0,45
5-12	L trib amont	240	301	127	15,5	5,28	0,15	< 0.1	0,00	3,52	0,011		0,188	0,18	1,17	0,43
5-13	L trib amont	249	136	68	15,5	4,81	0,15	< 0.1	0,99	3,42	0,010		0,196	0,25	1,21	0,42
5-14	L trib amont	270	150	77	17,0	4,85	0,19	< 0.1	< 0.04	3,59	0,017		0,213	0,23	1,30	0,48
5-15	L trib amont	244	129	69	16,4	4,32	0,19	< 0.1	0,48	3,72	0,011		0,201	0,20	1,25	0,44
5-16	L trib amont	242	123	66	16,1	4,65	0,18	< 0.1	0,48	3,68	< 0.010		0,169	0,25	1,10	0,34
5-17	L trib amont	220	142	75	15,2	5,11	0,17	< 0.1	< 0.04	3,25	0,015		0,196	0,20	1,25	0,45
5-18	L trib amont	203	130	64	14,6	5,47	0,19	< 0.1	< 0.04	3,65	0,012		1,230	0,67	4,83	1,76
3-31	L trib aval amb	96			37,0	6,44	0,46	< 0.1	2,66	5,47	0,097	0,034	0,711	0,38	3,56	1,57
4-02	L trib aval amb	76			38,0	6,31	0,42	< 0.1	2,44	5,31	0,100	0,044	0,697	0,27	3,53	1,45
4-06	L trib aval amb	38	13	< 10	23,0	4,75	0,34	< 0.1	3,19	3,00	0,170		0,196	0,08	1,01	0,48
4-07	L trib aval amb	64	27	9	25,5	4,90	0,37	< 0.1	4,10	3,94	0,211	0,011	0,296	0,12	1,57	0,70
4-08	L trib aval amb	62	98	21	20,0	5,72	0,31	< 0.1	2,76	3,92	0,120	0,095	0,356	0,14	1,85	0,75
4-09	L trib aval amb	80			24,0	6,36	0,27	< 0.1	1,29	4,09	0,059	0,008	0,468	0,20	2,45	0,88
4-10	L trib aval amb	86	56	46	26,0	5,77	0,27	< 0.1	0,99	4,52	0,045	0,012	0,518	0,25	2,75	0,99
4-11	L trib aval amb	74			20,0	6,05	0,23	< 0.1	1,00	3,49	0,045	0,009	0,384	0,17	2,05	0,75
4-12	L trib aval amb	100	52	40	23,5	6,08	0,26	< 0.1	0,75	4,10	0,030	0,004	0,477	0,24	2,57	0,94
4-13	L trib aval amb	80			23,5	6,20	0,25	< 0.1	0,74	3,78	0,034	0,010	0,471	0,22	2,45	0,93
4-14	L trib aval amb	42			12,5	6,16	0,19	< 0.1	0,82	1,92	0,043	0,008	0,218	0,10	1,14	0,45
4-15	L trib aval amb	88			23,0	6,34	0,24	< 0.1	0,63	3,69	0,021		0,451	0,21	2,48	0,90
4-21	L trib aval amb	100	26	33	26,9	5,93	0,28	< 0.1	0,51	4,31	0,036	0,018	0,521	0,23	2,75	1,07
4-26	L trib aval amb	82			23,0	6,05	0,24	< 0.1	0,83	3,66	< 0.010		0,430	0,18	2,29	0,91
4-29	L trib aval amb	114			23,5	6,01	0,25	< 0.1	0,64	4,05	0,040		0,454	0,18	2,49	0,89
5-02	L trib aval amb	112			23,8	6,11	0,26	< 0.1	0,79	4,20	0,055		0,443	0,22	2,42	0,92
5-04	L trib aval amb	124	103	85	23,2	5,85	0,24	< 0.1	0,74	4,70	< 0.010		0,403	0,24	2,28	0,80
5-05	L trib aval amb	170	172	117	20,0	5,04	0,16	< 0.1	0,28	4,16	< 0.010		0,261	0,24	1,64	0,56
5-06	L trib aval amb	180	234	108	20,2	5,08	0,22	< 0.1	0,50	4,07	0,019		0,211	0,32	1,36	0,49
5-07	L trib aval amb	114			24,5	5,63	0,26	< 0.1	0,91	3,65	0,030		0,467	0,28	2,34	0,85
5-08	L trib aval amb	142											0,360	0,25	1,92	0,73
5-09	L trib aval amb	142	104	70	19,0	5,53	0,23	< 0.1	0,86	3,46	0,017		0,360	0,24	1,87	0,70
5-11	L.trib aval amb	132			20,0	6,19	0,26	< 0.1	0,68	3,32	0,010		0,413	0,24	1,96	0,81
5-12	L trib aval amb	114	102	83	19,5	5,79	0,23	< 0.1	0,42	3,20	0,021		0,373	0,24	1,93	0,77
5-18	L trib aval amb	102			19,5	6,12	0,22	< 0.1	0,47	3,13	0,023		0,422	0,21	2,01	0,76

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3-31	L trib aval inte	223			33,0	6,34	0,87	< 0.1	1,75	3,98	0,177		0,502	0,61	2,98	1,67
3-23	Lo 1 (Y T)	50											0,113	0,41	0,64	0,22
3-23	Lo 2 (Y T)												0,056	0,31	0,51	0,21
3-25	Lo 2 (Y T)												0,067	0,37	0,53	0,33
4-07	Lo 1 (Y T)		38		26,0	4,64	0,32	< 0.1	1,61	2,69		0,008				
4-07	Lo 2 (Y T)		123		28,5	4,28	0,33	< 0.1	1,31	2,24		0,011				
4-07	Lo 3 (Y T)		126		21,0	4,47	0,24	< 0.1	1,29	1,42		0,010				
4-07	Lo 4 (Y T)		87		22,5	4,41	0,31	< 0.1	1,65	2,20		0,011				
4-07	Lo 5 (Y T)		68		36,0	4,25	0,45	< 0.1	1,07	5,08		0,008				
4-07	Lo 6 (Y T)		87		35,0	4,28	0,40	< 0.1	0,55	4,64						
4-09	Lo 2 (Y T)	11											0,051	0,17	0,23	0,09
4-11	Lo 2 (Y T)	11											0,050	0,19	0,19	0,11
4-13	Lo 2 (Y T)												0,050	0,20	0,17	0,16
4-17	Lo 2 (Y T)	8											0,006	0,17	0,11	0,15
3-26	lys 1	70			71,0	3,92	0,80	< 0.1	5,06	6,94	0,378	0,008	0,188	0,62	1,18	0,36
3-28	lys 1	50			54,0	4,04	0,55	< 0.1	3,52	5,80	0,239	0,005	0,184	0,56	0,97	0,24
3-31	lys 1	28			60,0	3,96	0,78	< 0.1	5,59	4,56	0,221	0,006	0,115	0,52	0,79	0,35
4-01	lys 1	26	28	< 10	62,0	3,91	1,10	< 0.1	6,13	3,92	0,271	0,010	0,113	0,33	0,70	0,35
4-02	lys 1	26	27	< 10	60,0	3,98	0,80	< 0.1	5,90	3,78	0,291	0,006	0,113	0,53	0,75	0,43
4-04	lys 1	26	21	< 10	51,0	3,97	0,35	< 0.1	4,23	3,84	0,332		0,113	0,23	0,61	0,17
4-05	lys 1	8	10	< 10	32,0	4,17	0,22	< 0.1	2,19	2,57	0,161	0,004	0,108	0,21	0,39	0,11
4-07	lys 1	12	10	< 10	22,5	4,30	0,20	< 0.1	2,05	1,53	0,097		0,051	0,21	0,27	0,11
4-08	lys 1	8	< 10	< 10	16,0	4,57	0,15	< 0.1	1,61	1,03	0,066	0,005	0,048	0,10	0,20	0,05
4-10	lys 1	12	< 10	< 10	15,0	4,53	0,12	< 0.1	1,31	0,81	0,048	0,004	0,042	0,10	0,17	0,03
4-12	lys 1	10	< 10	< 10	11,7	4,71	0,13	< 0.1	1,08	0,72	0,056		0,0			
4-14	lys 1	4	< 10	< 10	10,2	4,76	0,13	< 0.1	0,86	0,63	0,059		0,031	0,11	0,14	0,03
4-15	lys 1	4			9,5	4,81	0,13	< 0.1	0,84	0,64	0,047	0,006	0,023	0,13	0,12	0,03
4-25	lys 1 (glace)				11,7	4,87	0,25	< 0.1	1,04	0,79	0,131		0,051	0,24	0,30	0,10
5-04	lys 1	16			26,5	4,45	0,21	< 0.1	1,84	2,58	0,249		0,052	0,35	0,51	0,06
5-05	lys 1	38			8,5	5,61	0,06	< 0.1	0,64	0,64	0,103		0,009	0,08	0,19	0,01
5-06	lys 1	8			6,5	5,01	0,12	< 0.1	0,60	0,42	0,061		0,002	0,04	0,06	0,01
5-07	lys 1	4			8,0	4,88	0,14	< 0.1	0,71	0,58	0,088		0,002	0,05	0,10	0,01
5-08	lys 1	6			9,8	4,84	0,13	< 0.1	1,00	0,59	0,100		0,008	0,05	0,10	0,01
5-09	lys 1	12			8,5	4,83	0,15	< 0.1	0,92	0,56	0,087		0,004	0,05	0,07	0,01
5-10	lys 1	12			6,5	5,28	0,14	< 0.1	1,31	0,49	0,107		0,031	0,04	0,13	0,09
5-11	lys 1	20			16,0	5,04	0,16	< 0.1	0,73	0,55	0,099		0,002	0,08	0,08	0,03
5-12	lys 1	12			6,5	5,06	0,11	< 0.1	0,59	0,47	0,086		0,016	0,05	0,10	0,01
5-13	lys 1	14			4,7	5,20	0,11	< 0.1	0,93	0,39	0,065		0,002	0,04	0,05	0,01
5-14	lys 1	30			24,0	4,25	0,30	< 0.1	1,04	2,78			0,092	0,04	0,61	0,05
5-15	lys 1	26			5,7	4,77	0,17	< 0.1	< 0.04	0,50	0,066		0,037	0,19	0,16	0,01
5-18	lys 1	20											0,054	0,21	0,50	0,04
3-26	lys 2 (6 cm)	32	42	< 10	44,2	4,13	0,42	< 0.1	3,40	3,98	0,350	0,007	0,113	0,35	0,68	0,24
3-28	lys 2	22	39	< 10	43,5	4,09	0,31	< 0.1	3,88	3,23	0,250	0,004	0,061	0,20	0,49	0,16
3-31	lys 2	48	67	< 10	72,0	3,83	0,52	< 0.1	6,29	4,66	0,251	0,013	0,113	0,35	0,72	0,39

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4-01	lys 2	62	36	< 10	81,0	3,82	0,71	< 0.1	7,77	5,18	0,331	0,011	0,113	0,33	0,80	0,40
4-02	lys 2	42	36	< 10	89,0	3,77	0,85	< 0.1	8,64	5,45	0,388	0,006	0,113	0,36	0,92	0,41
4-04	lys 2	32	30	< 10	72,0	3,80	0,42	< 0.1	6,35	5,22	0,456	0,005	0,109	0,19	0,68	0,20
4-05	lys 2	14	14	< 10	43,5	4,04	0,30	< 0.1	3,76	2,86	0,310	0,004	0,051	0,20	0,45	0,13
4-07	lys 2	16	15	< 10	35,5	4,13	0,27	< 0.1	3,68	2,40	0,222	0,008	0,051	0,19	0,46	0,13
4-08	lys 2	11	11	< 10	26,5	4,28	0,19	< 0.1	2,83	1,63	0,130	0,004	0,051	0,12	0,35	0,06
4-10	lys 2	14	10	< 10	23,0	4,35	0,16	< 0.1	2,24	1,28	0,081	0,004	0,051	0,10	0,32	0,04
4-12	lys 2	10	< 10	< 10	18,5	4,52	0,15	< 0.1	1,97	1,09	0,068	0,004	0,050	0,19	0,27	0,02
4-14	lys 2	10	< 10	< 10	20,0	4,46	0,18	< 0.1	2,00	1,13	0,060		0,050	0,08	0,34	0,04
4-15	lys 2	4	< 10	< 10	16,0	4,57	0,17	< 0.1	1,65	0,96	0,052	0,005	0,050	0,20	0,38	0,03
4-25	lys 2 (glace)	15			5,1	5,21	0,16	< 0.1	0,16	0,36	0,041		0,002	0,17	0,11	0,05
4-25	lys 2 (4,5 cm)	14			37,0	4,19	0,30	< 0.1	3,02	3,17	0,331		0,051	0,23	0,58	0,14
4-29	lys 2	5			34,0	4,42	0,17	< 0.1	2,64	3,00	0,367		0,051	0,17	0,39	0,04
5-02	lys 2	10			26,5	4,65	0,25	< 0.1	2,17	2,56	0,239		0,051	0,20	0,46	0,07
5-04	lys 2	15	102	11	17,0	4,54	0,17	< 0.1	1,42	1,55	0,166		0,051	0,16	0,29	0,02
5-05	lys 2	8	26	< 10	7,5	5,52	0,05	< 0.1	0,54	0,58	0,057		0,002	0,03	0,01	< 0.01
5-06	lys 2	6	< 10	< 10	5,4	5,03	0,11	< 0.1	0,41	0,34	0,032		0,001	0,04	0,02	< 0.01
5-07	lys 2	3			6,2	4,76	0,12	< 0.1	0,67	0,49	0,056		0,002	0,03	0,06	< 0.01
5-08	lys 2	8			9,0	4,76	0,11	< 0.1	0,91	0,57	0,075		0,002	0,03	0,06	< 0.01
5-09	lys 2	14	37	3	9,0	4,79	0,13	< 0.1	1,03	0,61	0,076		0,003	0,04	0,08	< 0.01
5-10	lys 2	23	25	14	10,0	4,65	0,14	< 0.1	1,06	0,62	0,085		0,016	0,05	0,20	< 0.01
5-11	lys 2	19	32	11	8,5	4,81	0,15	< 0.1	0,97	0,64	0,115		0,001	0,11	0,10	0,06
5-12	lys 2	15	26	13	7,0	4,93	0,13	< 0.1	0,76	0,52	0,093		0,028	0,07	0,12	0,03
5-13	lys 2	10			5,6	5,05	0,11	< 0.1	0,99	0,42	0,064		0,001	0,04	0,05	0,03
5-14	lys 2	25			20,0	4,28	0,19	< 0.1	1,02	2,16	0,215		0,051	0,22	0,42	0,01
5-15	lys 2	18			5,8	4,74	0,16	< 0.1	0,47	0,52	0,057		0,023	0,10	0,14	0,01
5-18	lys 2	28			14,9	4,45	0,13	< 0.1	0,85	1,72	0,052		0,051	0,16	0,38	0,01
3-26	lys 3 (14 cm)	54	75	27	75,5	3,88	1,08	< 0.1	4,50	6,25	0,355	0,009	0,270	0,83	1,39	0,23
3-28	lys 3	39	56	29	58,0	3,98	0,59	< 0.1	3,12	6,16	0,222	0,005	0,184	0,79	1,03	0,23
3-31	lys 3		55	17	64,0	3,91	0,77	< 0.1	5,59	4,99	0,208	0,007				
4-01	lys 3		26	< 10	78,5	3,85	0,73	< 0.1	7,22	5,36	0,320	0,010				
4-02	lys 3		32	< 10	73,0	3,86	0,79	< 0.1	6,87	4,83	0,316	0,009				
4-04	lys 3	37	27	16	56,0	3,90	0,41	< 0.1	4,23	4,90	0,313	0,007	0,113	0,49	0,62	0,20
4-05	lys 3	32	19	15	42,0	4,02	0,30	< 0.1	3,00	3,52	0,144	0,005	0,113	0,54	0,47	0,16
4-07	lys 3	16	15	< 10	29,5	4,19	0,24	< 0.1	2,23	2,15	0,095	0,008	0,051	0,39	0,33	0,16
4-08	lys 3	11	13	< 10	22,5	4,27	0,18	< 0.1	1,99	1,47	0,059	0,006	0,051	0,18	0,32	0,05
4-10	lys 3	7	10	< 10	20,5	4,38	0,16	< 0.1	1,61	1,15	0,053	0,004	0,051	0,19	0,23	0,05
4-12	lys 3	6	< 10	< 10	15,0	4,58	0,14	< 0.1	1,24	0,89	0,047	0,004	0,050	0,11	0,16	0,02
4-14	lys 3	7	< 10	< 10	15,0	4,55	0,17	< 0.1	1,20	0,90	0,052		0,051	0,18	0,17	0,04
4-15	lys 3	8			14,5	4,58	0,16	< 0.1	1,28	0,92	0,047	0,005	0,051	0,19	0,14	0,02
4-25	lys 3 (glace)	9			5,1	5,02	0,18	< 0.1	0,13	0,72	0,061		0,049	0,19	0,13	0,02
4-25	lys 3 (3,5 cm)	45			85,0	3,84	1,41	< 0.1	4,15	9,29	0,600		0,270	2,02	1,35	0,33
4-29	lys 3	20			38,0	4,32	0,30	< 0.1	1,93	3,82	0,298		0,113	0,65	0,47	0,10
5-02	lys 3	28			41,0	4,17	0,36	< 0.1	2,30	4,16	0,263		0,113	0,69	0,53	0,12
5-04	lys 3	12	79	16	18,6	4,49	0,18	< 0.1	1,08	1,70	0,180		0,051	0,26	0,21	0,05
5-05	lys 3	7			8,5	5,40	0,07	< 0.1	0,65	0,69	0,108		0,009	0,08	0,03	0,01

RESULTATS D'ANALYSE - INRS-EAU - HIVER 1988 - JONES/ENV. CANADA

Rapport en date du 14 fevrier 1989

DATE	ECHANTILLON	Al diss (ug/L)	Al-CV (ug/L)	Al-CVR (ug/L)	Cond (umho)	pH	Cl (mg/L)	PO4 (mg/L)	NO3 (mg/L)	SO4 (mg/L)	NH4 (mg/L)	F- (mg/L)	Mg (mg/L)	K (mg/L)	Ca (mg/L)	Na (mg/L)
5-06	lys 3	8	20	< 10	8,4	4,83	0,12	< 0.1	0,71	0,50	0,072		0,004	0,05	0,01	0,01
5-07	lys 3	3			9,9	4,70	0,15	< 0.1	0,93	0,64	0,100		0,013	0,06	0,19	0,04
5-08	lys 3	7			11,0	4,61	0,14	< 0.1	1,07	0,65	0,105		0,012	0,06	0,08	0,02
5-09	lys 3	7	31	5	8,8	4,91	0,15	< 0.1	0,92	0,56	0,095		0,005	0,06	0,04	0,02
5-10	lys 3	13	20	17	6,8	4,87	0,13	< 0.1	0,65	0,46	0,081		0,001	0,06	0,01	0,01
5-11	lys 3	14	22	18	5,5	5,05	0,18	< 0.1	0,51	0,51	0,101		0,002	0,09	0,02	0,03
5-12	lys 3	5	30	21	5,6	5,09	0,18	< 0.1	< 0.04	0,41	0,103		0,028	0,11	0,04	0,02
5-13	lys 3	8			4,2	5,23	0,15	< 0.1	0,42	0,28	0,092		< 0.002	0,05	< 0.01	< 0.01
5-14	lys 3	65			44,0	4,01	0,56	< 0.1	1,29	5,70	0,252		0,184	1,31	1,15	0,11
3-31	lys 4	68			55,0	4,06	0,64	< 0.1	5,75	4,57	0,216	0,008	0,110	0,20	1,40	0,38
4-01	lys 4	57	51	< 10	92,0	3,80	0,90	< 0.1	6,78	5,89	0,380		0,113	0,38	1,48	0,53
4-02	lys 4	46	54	< 10	98,0	3,72	0,87	< 0.1	7,32	5,63	0,417	0,008	0,113	0,37	0,94	0,51
4-04	lys 4	27	16	14	65,0	3,84	0,33	< 0.1	5,39	4,04	0,384		0,051	0,08	0,33	0,13
4-05	lys 4	12	< 10	< 10	33,5	4,14	0,24	< 0.1	2,98	1,96	0,231	0,004	0,051	0,09	0,16	0,10
4-07	lys 4	12	< 10	< 10	27,0	4,22	0,19	< 0.1	2,85	1,39	0,150	0,005	0,051	0,15	0,14	0,10
4-08	lys 4	9	11	< 10	19,5	4,31	0,15	< 0.1	2,08	1,01	0,095	0,004	0,030	0,05	0,09	0,04
4-10	lys 4	6	10	< 10	18,0	4,42	0,13	< 0.1	1,70	0,80	0,077	0,004	0,013	0,05	0,07	0,04
4-12	lys 4	7	< 10	< 10	15,0	4,60	0,14	< 0.1	1,50	0,75	0,070	0,004	0,019	0,05	0,09	0,03
4-14	lys 4	6	< 10	< 10	49,0	4,55	0,14	< 0.1	1,45	0,75	0,063	0,008	0,018	0,06	0,08	0,03
4-15	lys 4	9			12,7	4,62	0,12	< 0.1	1,28	0,68	0,058	0,008	0,004	0,05	0,01	0,02
4-25	lys 4 (glace)	5			2,4	5,31	0,10	< 0.1	< 0.04	0,26	0,046		< 0.002	0,05	< 0.01	< 0.01
4-25	lys 4 (5,5 cm)	8			27,0	4,32	0,25	< 0.1	2,09	2,48	0,392		< 0.002	0,05	< 0.01	< 0.01
4-29	lys 4	10			20,0	4,48	0,10	< 0.1	1,68	1,49	0,303		0,047	0,05	0,11	0,01
5-02	lys 4	9			19,4	4,44	0,16	< 0.1	1,60	1,40	0,157		0,050	0,06	0,27	0,02
5-04	lys 4	9			12,0	4,63	0,09	< 0.1	1,09	0,87	0,142		0,015	0,04	0,05	0,01
5-05	lys 4	6			8,0	5,81	0,05	< 0.1	0,68	0,53	0,067		< 0.002	0,05	< 0.01	< 0.01
5-06	lys 4	7			8,5	4,76	0,11	< 0.1	0,81	0,43	0,066		< 0.002	0,04	< 0.01	< 0.01
5-07	lys 4	4			8,2	4,91	0,11	< 0.1	0,78	0,56	0,079		< 0.002	0,05	< 0.01	< 0.01
5-08	lys 4	4			6,7	4,81	0,09	< 0.1	0,64	0,40	0,066		< 0.002	0,05	< 0.01	< 0.01
5-09	lys 4	20			6,0	5,08	0,09	< 0.1	0,42	0,34	0,055		< 0.002	0,05	< 0.01	< 0.01
3-30	piezo 1-10	190	97	80	85,0	5,28	3,02	< 0.1	2,12	15,96	0,120	0,025	1,100	2,44	8,52	2,09
4-04	piezo 1-10	133	102	70	60,0	4,62	1,51	< 0.1	2,21	9,66	0,023	0,007	0,610	2,03	4,18	0,93
4-05	piezo 1-10	103	92	62	50,0	4,33	1,23	< 0.1	1,79	8,56	0,032	0,010	0,427	1,63	2,56	0,85
4-07	piezo 1-10	108			35,5		0,91	1,38	1,30	6,77	0,039	0,011	0,384	1,39	2,42	0,66
4-08	piezo 1-10	150	88	63	27,0	4,90	0,77	< 0.1	< 0.04	5,15	< 0.010	0,009	0,352	1,21	2,06	0,47
4-10	piezo 1-10	175	80	59	22,5	5,60	0,78	< 0.1	0,41	3,27	0,022	0,007	0,347	1,17	2,18	0,51
4-12	piezo 1-10				20,0	4,94	0,74	< 0.1	0,00	2,68		0,006				
4-21	piezo 1-10	158	104	71	87,0	4,16	1,97	< 0.1	1,37	14,23	0,089	0,017	0,735	2,38	4,54	0,60
5-04	piezo 1-10	263	149	110	24,5	4,79	0,75	< 0.1	< 0.04	3,93	< 0.010	0,010	0,368	1,58	1,72	0,36
5-05	piezo 1-10	100	79	55	12,5	5,31	0,27	< 0.1	< 0.04	1,35	< 0.010		0,135	0,73	0,65	0,15
5-06	piezo 1-10	358	420	165	28,9	4,47	0,38	< 0.1	< 0.04	4,84	< 0.010		0,239	0,69	1,29	0,42
5-07	piezo 1-10	323			30,0	4,39	0,33	< 0.1	< 0.04	4,45	< 0.010		0,185	0,42	0,96	0,49
5-08	piezo 1-10	323	454	179	28,0	4,33	0,33	< 0.1	< 0.04	4,56	0,013		0,196	0,42	0,93	0,50
5-09	piezo 1-10	248	353	138	26,5	4,42	0,41	< 0.1	0,37	3,53	0,017		0,158	0,44	0,77	0,53
5-10	piezo 1-10	330	433	144	26,8	5,08	0,28	< 0.1	0,43	3,91	< 0.010		0,142	0,28	0,75	0,42
5-11	piezo 1-10	325	475	225	27,0	4,36	0,27	< 0.1	< 0.04	4,00	< 0.010		0,131	0,29	0,70	0,43

RESULTATS D'ANALYSE - INRS-EAU - HIVER 1988 - JONES/ENV. CANADA

Rapport en date du 14 fevrier 1989

DATE	ECHANTILLON	Al diss (ug/L)	Al-CV (ug/L)	Al-CVR (ug/L)	Cond (umho)	pH	Cl (mg/L)	PO4 (mg/L)	NO3 (mg/L)	SO4 (mg/L)	NH4 (mg/L)	F- (mg/L)	Mg (mg/L)	K (mg/L)	Ca (mg/L)	Na (mg/L)
5-12	piezo 1-10	315	531	260	29,5	4,26	0,29	< 0.1	< 0.04	4,40	0,031		0,149	0,32	0,78	0,45
5-14	piezo 1-10	255	178	113	39,5	4,15	0,70	< 0.1	0,66	5,40	0,185		0,252	1,20	1,53	0,40
4-04	piezo 1-20	545	203	82	42,0	5,11	1,37	< 0.1	3,38	8,40	0,034	0,005	0,688	1,56	2,90	1,09
5-05	piezo 1-20	343	203	82	20,0	5,21	0,41	< 0.1	< 0.04	2,83	0,117		0,265	0,88	1,29	0,37
5-06	piezo 1-20	528	268	129	21,4	5,20	0,53	< 0.1	< 0.04	4,05	0,025		0,425	0,60	1,59	0,49
5-07	piezo 1-20	488			26,0	4,97	0,46	< 0.1	< 0.04	5,77	0,047		0,327	0,55	1,22	0,47
5-08	piezo 1-20	590	318	179	25,5	4,95	0,40	< 0.1	< 0.04	6,18	0,045		0,548	0,62	1,83	1,98
5-09	piezo 1-20	595	555	184	28,0	4,48	0,34	< 0.1	< 0.04	5,71	0,032		0,222	0,55	0,94	0,61
5-10	piezo 1-20	620	494	235	25,9	4,81	0,37	< 0.1	< 0.04	6,10	0,027		0,385	0,47	1,34	0,64
5-11	piezo 1-20	600	530	241	24,5	4,73	0,35	< 0.1	< 0.04	5,77	0,032		0,336	0,55	1,08	0,61
5-12	piezo 1-20	538	555	263	26,0	4,75	0,35	< 0.1	< 0.04	5,25	0,040		0,304	0,56	0,96	0,58
5-13	piezo 1-20	563	290	114	25,5	4,66	0,33	< 0.1	< 0.04	5,43	0,038		0,264	0,59	0,88	0,56
5-14	piezo 1-20	570			24,0	4,56					0,050		0,305	0,59	0,96	0,16
5-15	piezo 1-20	614	307	128	24,5	4,65	0,36	< 0.1	< 0.04	5,45	0,066		0,355	0,59	1,06	0,55
5-16	piezo 1-20	563	356	132	27,0	4,40	0,37	< 0.1	< 0.04	5,45	0,066		0,184	0,60	0,77	0,57
5-17	piezo 1-20	538	356	142	24,8	4,60	0,42	< 0.1	< 0.04	5,33	0,105		0,257	0,65	0,94	0,59
3-25	piezo 1-40	1650	187	53	48,5	5,16	1,25	< 0.1	0,07	10,15	< 0.010	0,029	1,000	1,34	3,88	0,97
3-30	piezo 1-40	525	872	166	112,0	4,33	2,98	< 0.1	5,36	18,31	0,126	0,045	1,480	2,37	6,33	2,42
5-05	piezo 1-40	510	141	99	40,0	5,22	0,50	< 0.1	4,08	6,56	0,046		0,696	0,64	4,02	0,73
5-06	piezo 1-40	620	239	59	31,0	5,09	0,88	< 0.1	< 0.04	7,97	< 0.010		0,567	0,36	2,14	0,90
5-07	piezo 1-40	860			31,0	4,91	0,65	< 0.1	< 0.04	>7.7	< 0.010		0,464	0,33	1,87	0,83
5-08	piezo 1-40	630	338	56	27,0	4,84	0,47	< 0.1	< 0.04	6,57	< 0.010		0,373	0,29	1,46	0,83
5-09	piezo 1-40	630	336	49	28,0	4,78	0,52	< 0.1	< 0.04	6,73	0,017		0,367	0,31	1,33	0,98
5-10	piezo 1-40	600	335	59	25,8	5,09	0,38	< 0.1	< 0.04	6,53	< 0.010		0,387	0,21	1,28	0,91
5-11	piezo 1-40	575	326	60	24,0	5,07	0,34	< 0.1	< 0.04	6,33	< 0.010		0,390	0,19	1,22	0,92
5-12	piezo 1-40	600	379	75	25,5	4,80	0,33	< 0.1	< 0.04	6,09	0,011		0,381	0,20	1,17	0,93
5-13	piezo 1-40	555	194	31	24,0	4,92	0,31	< 0.1	< 0.04	5,87	< 0.010		0,359	0,17	1,14	0,91
5-14	piezo 1-40	545	175	32	22,0	4,83	0,29	< 0.1	< 0.04	6,02	< 0.010		0,346	0,16	1,11	0,89
5-15	piezo 1-40	565	172	31	22,5	4,84	0,31	< 0.1	< 0.04	6,00	< 0.010		0,329	0,15	1,08	0,87
5-16	piezo 1-40	475	158	28	19,0	4,95	0,30	< 0.1	< 0.04	5,83	< 0.010		0,312	0,16	1,05	0,85
5-17	piezo 1-40	535	152	27	19,0	5,06	0,31	< 0.1	< 0.04	5,53	< 0.010		0,299	0,16	1,04	0,83
4-07	piezo 1-80	488			20,1	5,24	0,40	< 0.1	< 0.04	5,95	0,160		0,284	0,15	1,17	0,86
4-08	piezo 1-80	510	79	21	20,0	5,16	0,37	< 0.1	< 0.04	6,35	0,122	0,057	0,286	0,12	1,17	0,85
4-10	piezo 1-80	538	84	20	20,0	5,28	0,32	< 0.1	< 0.04	5,67	0,084	0,017	0,273	0,13	1,13	0,85
4-12	piezo 1-80	520	79	< 10	20,0	5,33	0,33	< 0.1	< 0.04	5,71	0,055	0,007	0,174	0,14	1,21	0,65
4-14	piezo 1-80	595	116	18	23,0	5,22	0,40	< 0.1	< 0.04	6,15	0,047	0,028	0,164	0,18	1,21	0,68
4-15	piezo 1-80	565	131	16	21,5	5,13	0,35	< 0.1	< 0.04	6,11	0,063	0,090	0,164	0,19	1,18	0,78
4-21	piezo 1-80	535	75	17	23,5	5,03	0,48	< 0.1	< 0.04	5,71	0,051	0,031	0,157	0,26	1,23	0,80
4-25	piezo 1-80	560	347	42	22,0	4,99	0,42	< 0.1	< 0.04	6,12	0,010		0,153	0,10	1,14	0,74
4-29	piezo 1-80	588	261	40	22,5	5,14	0,56	< 0.1	< 0.04	5,65	0,013		0,172	0,13	1,19	0,71
5-02	piezo 1-80	565	315	37	21,0	5,06	0,46	< 0.1	< 0.04	5,91	< 0.010		0,163	0,14	1,22	0,76
5-04	piezo 1-80	595	235	26	23,7	4,70	0,39	< 0.1	< 0.04	5,10	0,019		0,149	0,30	1,24	0,76
5-05	piezo 1-80	358	119	39	32,0	5,25	0,63	< 0.1	1,70	5,03	< 0.010		0,343	0,67	3,12	0,60
5-06	piezo 1-80	548			22,0	5,05	0,34	< 0.1	< 0.04	5,59	0,027		0,153	0,13	1,27	0,58
5-07	piezo 1-80	560			23,0	4,90	0,32	< 0.1	< 0.04	5,65	0,024		0,142	0,13	1,23	0,61

RESULTATS D'ANALYSE - INRS-EAU - HIVER 1988 - JONES/ENV. CANADA

Rapport en date du 14 fevrier 1989

DATE	ECHANTILLON	Al diss (ug/L)	Al-CV (ug/L)	Al-CVR (ug/L)	Cond (umho)	pH	Cl (mg/L)	PO4 (mg/L)	NO3 (mg/L)	SO4 (mg/L)	NH4 (mg/L)	F- (mg/L)	Mg (mg/L)	K (mg/L)	Ca (mg/L)	Na (mg/L)
5-08	piezo 1-80	565	168	23	23,0	4,95	0,42	< 0.1	< 0.04	5,92	0,032		0,149	0,19	1,23	0,69
5-09	piezo 1-80	538	232	27	22,5	4,88	0,37	< 0.1	< 0.04	5,79	0,032		0,159	0,18	1,21	0,79
5-10	piezo 1-80	283	267	42	24,1	4,86	0,38	< 0.1	< 0.04	6,07	0,020					
5-11	piezo 1-80	520	262	44	23,5	5,04	0,35	< 0.1	< 0.04	5,96	0,014		0,178	0,14	1,14	0,97
5-12	piezo 1-80	525	313	55	25,0	4,86	0,35	< 0.1	< 0.04	5,82	0,024		0,180	0,16	1,11	1,00
5-13	piezo 1-80	500	151	18	24,0	5,00	0,35	< 0.1	0,28	6,03	0,018		0,179	0,13	1,10	1,01
5-14	piezo 1-80	470	131	18	22,0	4,91	0,32	< 0.1	< 0.04	5,99	0,013		0,174	0,13	1,06	1,06
5-15	piezo 1-80	518	160	19	23,0	4,91	0,33	< 0.1	< 0.04	6,09	< 0.010		0,163	0,13	1,05	1,12
5-16	piezo 1-80	500	124	15	20,0	5,05	0,32	< 0.1	< 0.04	6,05	0,023		0,162	0,13	0,99	1,15
5-17	piezo 1-80	438	113	14	23,0	5,16	0,35	< 0.1	< 0.04	5,65	0,021		0,166	0,16	1,00	1,08
4-04	piezo 2-10	518	477	226	83,0	4,16	11,40	< 0.1	1,19	15,25	0,172	0,014	0,684	6,70	3,98	0,68
4-07	piezo 2-10	315	234	144	67,0		1,81	< 0.1	0,41	9,89	0,058	0,017	0,467	5,00	2,60	0,51
4-08	piezo 2-10	325	213	134	39,5	4,35	0,94	< 0.1	< 0.04	6,04	0,029	0,017	0,209	5,60	1,38	0,29
4-10	piezo 2-10	228	145	90	29,0	4,47	0,60	< 0.1	< 0.04	2,82	0,020	0,009	0,114	2,48	0,82	0,18
4-12	piezo 2-10	330	169	88	25,5	4,60	0,52	< 0.1	< 0.04	2,38	0,059	0,009	0,102	2,31	0,79	0,18
4-14	piezo 2-10	388	210	129	30,0	4,55	0,61	< 0.1	< 0.04	5,04	0,028		0,139	2,80	1,02	0,22
4-15	piezo 2-10	288	230	173	37,0	4,43	0,81	< 0.1	< 0.04	3,23	0,045	0,046	0,188	3,45	1,44	0,34
4-25	piezo 2-10	345	730	408	83,0	4,14	2,86	< 0.1	1,02	11,58	0,097		0,565	6,60	3,17	0,59
4-29	piezo 2-10	238			56,0	4,44					0,250		0,658	6,50	3,21	0,50
5-02	piezo 2-10	308	567	328	71,0	4,25	2,29	< 0.1	< 0.04	>10	0,021		0,571	6,20	3,01	0,53
5-04	piezo 2-10	210	292	138	39,9	4,15	1,11	< 0.1	< 0.04	5,88	0,013		0,212	3,60	1,37	0,24
5-05	piezo 2-10	308	323	130	24,5	4,78	0,48	< 0.1	< 0.04	2,52	< 0.010		0,209	2,31	1,35	0,18
5-06	piezo 2-10				19,3	4,71	0,52	< 0.1	< 0.04	1,91	< 0.010		0,104	1,82	0,68	0,11
5-07	piezo 2-10	100			18,2	4,78	0,49	< 0.1	0,30	1,84	0,032		0,095	1,43	0,58	0,12
5-08	piezo 2-10	158	327	145	19,5	4,58	0,50	< 0.1	0,42	1,67	< 0.010					
5-10	piezo 2-10		386	219	20,2	4,51	0,41	< 0.1	0,00	1,60						
5-14	piezo 2-10	248	188	143	44,0	4,27	1,01	< 0.1	0,29	5,47	0,221		0,266	3,20	1,66	0,27
3-25	piezo 2-40		309	218	33,8	6,05						0,021				
5-05	piezo 2-40	680	365	74	33,5	5,03	0,71	< 0.1	< 0.04	8,53	< 0.010		0,481	0,37	2,18	0,84
5-06	piezo 2-40	508			31,0	5,31	0,42	< 0.1	3,03	5,02	0,038		0,527	0,28	3,15	0,58
5-07	piezo 2-40	515			34,0	5,27	0,49	< 0.1	3,27	5,34	0,026		0,625	0,38	3,45	0,68
5-08	piezo 2-40	515	300	124	27,0	5,06	0,56	< 0.1	3,64	4,95	0,028		0,398	0,35	2,92	0,72
5-10	piezo 2-40	488	288	115	34,7	5,19	0,52	< 0.1	3,70	5,00	0,012		0,589	0,26	3,27	0,68
5-11	piezo 2-40	525	367	144	29,0	5,20	0,48	< 0.1	3,80	4,85	0,017		0,431	0,21	2,91	0,60
5-12	piezo 2-40	515	405	146	30,5	5,09	0,46	< 0.1	3,54	4,69	0,018		0,446	0,21	2,93	0,65
5-13	piezo 2-40	515	241	108	26,5	5,12	0,36	< 0.1	3,44	4,54	0,040		0,283	0,14	2,47	0,56
5-14	piezo 2-40	563	199	111	27,5	5,09	0,49	< 0.1	3,10	4,56	0,036		0,384	0,31	2,74	0,67
5-15	piezo 2-40	563	225	112	27,0	5,13	0,47	< 0.1	3,09	4,88	0,035		0,321	0,25	2,52	0,44
5-16	piezo 2-40	515	214	99	35,5	5,21	0,50	< 0.1	3,12	4,64	0,035		0,305	0,31	2,54	0,54
5-17	piezo 2-40	570	212	116	26,0	5,34	0,61	< 0.1	2,56	4,99	0,163		0,365	0,30	2,75	0,60
5-04	piezo 2-80	438	78	42	35,2	5,40	0,89	< 0.1	2,15	5,55	< 0.010		0,590	0,52	3,92	0,75
5-05	piezo 2-80	588	226	30	22,5	5,01	0,22	< 0.1	< 0.04	5,75	0,012		0,142	0,10	1,24	0,71
5-06	piezo 2-80	400			30,0	5,43	0,77	< 0.1	1,69	5,13	< 0.010		0,404	0,54	3,07	0,62
5-07	piezo 2-80	338			30,0	5,25	0,54	< 0.1	2,72	4,86	0,014		0,362	0,43	2,74	0,57
5-08	piezo 2-80	310	80	24	27,5	5,24	0,40	< 0.1	3,35	4,58	0,011		0,355	0,30	2,58	0,36

RESULTATS D'ANALYSE - INRS-EAU - HIVER 1988 - JONES/ENV. CANADA

Rapport en date du 14 fevrier 1989

DATE	ECHANTILLON	Al diss (ug/L)	Al-CV (ug/L)	Al-CVR (ug/L)	Cond (umho)	pH	Cl (mg/L)	PO4 (mg/L)	NO3 (mg/L)	SO4 (mg/L)	NH4 (mg/L)	F- (mg/L)	Mg (mg/L)	K (mg/L)	Ca (mg/L)	Na (mg/L)
5-10	piezo 2-80				26,2	5,32	0,36	< 0.1	3,70	4,68	0,021		0,368	0,26	2,47	0,37
5-11	piezo 2-80	275	130	41	24,0	5,12	0,30	< 0.1	0,29	4,65	< 0.010		0,321	0,27	2,32	0,40
5-12	piezo 2-80	238	115	48	26,5	5,25	0,30	< 0.1	3,33	4,58	0,024		0,304	0,21	2,27	0,38
5-13	piezo 2-80	248	75	15	23,5	5,27	0,31	< 0.1	3,34	4,50	< 0.010		0,289	0,26	2,25	0,43
5-14	piezo 2-80	265	76	23	24,5	5,11	0,36	< 0.1	2,91	4,59	0,017		0,296	0,35	2,22	0,43
5-15	piezo 2-80	238	84	21	23,5	5,20	0,36	< 0.1	2,97	4,60	0,015		0,256	0,29	2,16	0,40
5-16	piezo 2-80	283	71	18	22,0	5,31	0,38	< 0.1	3,04	4,59	0,013		0,268	0,30	2,22	0,38
5-17	piezo 2-80	263	64	15	22,5	5,38	0,38	< 0.1	3,21	4,59	0,011		0,275	0,26	2,35	0,43
4-04	piezo A	468	44	38	21,5	5,55	0,48	< 0.1	< 0.04	5,91	0,020	0,040	0,293	0,30	1,64	0,97
4-14	piezo A	575	60	36	25,0	5,49	0,28	< 0.1	< 0.04	2,89	0,057		0,330	0,41	1,78	1,06
4-25	piezo A	500	152	80	28,0	5,05	0,70	< 0.1	< 0.04	6,26	0,054		0,289	0,43	1,64	1,07
4-29	piezo A	500			22,0	5,27	0,55	< 0.1	< 0.04	5,60	0,026		0,272	0,24	1,45	0,91
5-04	piezo A	538	128	59	23,4	5,16	0,55	< 0.1	< 0.04	5,93	0,032		0,274	0,28	1,52	0,98
5-05	piezo A	700	487	101	29,5	4,82	0,32	< 0.1	< 0.04	6,56	0,020		0,261	0,27	1,43	0,89
5-06	piezo A	630	549	153	26,6	4,56	0,64	< 0.1	0,17	4,90	0,012		0,172	0,40	0,99	0,66
5-07	piezo A	690			29,0	4,44	0,50	< 0.1	0,05	5,13	0,015		0,179	0,37	1,00	0,72
5-08	piezo A	680	801	242	31,5	4,39	0,51	< 0.1	< 0.04	6,34	0,013		0,182	0,30	1,05	0,75
5-09	piezo A	620	749	218	29,0	4,45	0,63	< 0.1	< 0.04	5,40	0,019		0,181	0,42	0,99	0,75
5-10	piezo A	690	677	240	30,0	4,56	0,80	< 0.1	< 0.04	5,22	< 0.010		0,154	0,46	0,91	0,72
5-11	piezo A	620	867	282	27,5	4,58	0,71	< 0.1	< 0.04	5,80	0,014		0,174	0,48	1,04	0,69
5-12	piezo A	630	716	257	27,5	4,50	0,52	< 0.1	< 0.04	6,09	0,013		0,178	0,39	1,03	0,74
5-13	piezo A	670	365	118	28,0	4,65	0,54	< 0.1	< 0.04	5,79	0,015		0,192	0,46	1,12	0,82
5-14	piezo A	620	383	183	36,0	4,42	0,76	< 0.1	0,42	6,97	0,123		0,330	1,33	1,48	0,87
5-15	piezo A	635	392	190	31,0	4,40	0,49	< 0.1	< 0.04	6,16	0,082		0,198	1,09	1,22	0,57
3-26	R hypo	350	244	72	62,0	4,37	2,81	< 0.1	4,47	8,33	0,335	0,025	0,372	3,30	3,12	2,40
3-31	R hypo	358	225	71	38,3	4,80	1,09	< 0.1	1,72	7,71	< 0.010	0,017	0,372	2,40	2,15	0,93
4-04	R hypo	338	175	60	26,0	4,66	0,36	< 0.1	1,37	5,48	0,042	0,010	0,268	1,62	1,69	0,27
4-10	R hypo	515			31,0	4,64	0,30	< 0.1	5,38	3,93	0,012	0,011	0,268	0,95	2,14	0,53
4-12	R hypo	720	271	64	30,0	4,74	0,34	< 0.1	5,47	3,99	< 0.010		0,252	0,37	2,15	0,55
4-14	R hypo	555	291	60	29,0	4,71	0,33	< 0.1	4,86	3,98	< 0.010		0,186	0,34	2,01	0,54
4-15	R hypo	575	251	69	28,0	4,73	0,35	< 0.1	4,71	4,09	< 0.010	0,043	0,183	0,37	1,96	0,54
4-21	R hypo	575	280	74	28,0	4,57	0,34	< 0.1	4,41	3,99	< 0.010		0,183	0,24	1,97	0,56
4-25	R hypo	575	651	147	28,0	4,74	0,37	< 0.1	4,49	4,29	< 0.010		0,183	0,29	1,93	0,56
4-29	R hypo	570	603	151	34,0	4,24	0,33	< 0.1	4,14	4,10	0,021		0,183	0,32	1,91	0,55
5-02	R hypo	525	607	138	26,5	4,79	0,31	< 0.1	4,06	4,43	< 0.010		0,183	0,32	1,92	0,54
5-04	R hypo	540	463	115	25,8	4,69	0,31	< 0.1	3,62	3,99	< 0.010		0,183	0,33	1,77	0,47
5-05	R hypo	538	553	147	24,5	4,90	0,25	< 0.1	2,60	3,92	< 0.010		0,183	0,41	1,60	0,40
5-06	R hypo	463	473	146	24,1	4,61	0,28	< 0.1	2,05	4,00	< 0.010		0,183	0,37	1,60	0,39
5-07	R hypo	515			23,5	4,71	0,26	< 0.1	1,73	3,83	< 0.010		0,183	0,36	1,47	0,36
5-08	R hypo	430	587	199	22,5	4,62	0,25	< 0.1	1,67	3,83	0,013		0,183	0,35	1,40	0,36
5-09	R hypo	430	544	200	21,0	4,61	0,24	< 0.1	1,27	3,48	0,013		0,169	0,33	1,25	0,33
154	0,35	1,23	0,31													
5-11	R hypo	468	559	252	21,5	4,64	0,23	< 0.1	1,11	3,82	0,013		0,179	0,33	1,29	0,32
5-12	R hypo	508	576	264	22,5	4,58	0,25	< 0.1	1,29	4,03	0,019		0,183	0,28	1,34	0,37
5-13	R hypo	488	285	99	22,0	4,69	0,23	< 0.1	1,18	3,94	0,023		0,179	0,31	1,31	0,36
5-14	R hypo	488	281	118	23,0	4,44	0,26	< 0.1	0,98	4,04	0,029		0,183	0,37	1,35	0,34

RESULTATS D'ANALYSE - INRS-EAU - HIVER 1988 - JONES/ENV. CANADA

Rapport en date du 14 fevrier 1989

DATE	ECHANTILLON	Al diss (ug/L)	Al-CV (ug/L)	Al-CVR (ug/L)	Cond (umho)	pH	Cl (mg/L)	PO4 (mg/L)	NO3 (mg/L)	SO4 (mg/L)	NH4 (mg/L)	F- (mg/L)	Mg (mg/L)	K (mg/L)	Ca (mg/L)	Na (mg/L)
5-15	R hypo	518	261	102	22,0	4,55	0,26	< 0.1	1,24	4,19	< 0.010		0,183	0,35	1,34	0,36
5-16	R hypo	518	302	102	22,5	4,54	0,26	< 0.1	1,28	4,17	0,026		0,183	0,35	1,35	0,38
5-17	R hypo	475	307	105	22,5	4,64	0,26	< 0.1	1,29	4,19	0,014		0,183	0,31	1,30	0,37
5-18	R hypo	518	305	107	22,5	4,57	0,24	< 0.1	1,21	3,99	0,018		0,183	0,34	1,28	0,35
3-28	sangamo A	85	87	69	97,0	4,19	1,50	< 0.1	1,00	16,15	0,186	0,014	1,875	3,78	3,12	0,96
3-28	sangamo B	13	17	< 10	13,3	4,88	0,45	< 0.1	0,39	1,24	0,037	0,008	0,051	0,32	0,40	0,32
4-04	sangamo B	10	10	< 10	40,0	4,13	0,27	< 0.1	1,50	3,71	0,258	0,006	0,051	0,19	0,27	0,14
4-05	sangamo B				22,5	4,35		< 0.1								
4-21	sangamo B	12	41	< 10	23,5	4,35	0,24	< 0.1	1,69	1,54	0,142		0,048	0,08	0,15	0,17
4-25	sangamo B	5	17	< 10	14,0	4,71	0,35	< 0.1	0,48	1,03	0,064		0,013	0,23	0,10	0,18
4-29	sangamo B	10	26	< 10	21,5	4,41	1,14	< 0.1	1,68	1,69	0,287		0,024	0,16	0,12	0,10
5-02	sangamo B		80	19	18,5	4,53	0,28	< 0.1	0,43	1,84						
5-14	sangamo B	63	46	12	39,0	4,10	0,74	< 0.1	1,76	4,45	0,333		0,113	0,83	0,80	0,41
5-18	sangamo B	22	< 10	< 10	25,5	4,20	0,21	< 0.1	1,44	2,80	0,282		0,051	0,17	0,31	0,08

TOTAL