CLIMATOLOGICAL STUDY OF ACIDIC SNOWMELT SHOCK POTENTIAL FOR EASTERN CANADA

E.E. Wilson and L.A. Barrie
Atmospheric Environment Service
Downsview, Ontario, Canada

ABSTRACT

A hydrometeorological model of a snowpack modified to simulate the life cycle of acids deposited from the atmosphere is used to determine the occurrence, frequency, and magnitude of snowmelt acidic shocks to lakes and streams in eastern Canada. Using forty years of meteorological observations and two acid-shock indices, one for lakes and one for streams, the probability of snowmelt and acid shock on a monthly basis was determined. Neglecting seasonal variations in biological sensitivity, the model predicts that the potential for lake shock during a melt is greatest in January and February while the potential for stream shock is approximately constant throughout the winter. In March or early April, when the frequency of melts is greatest, pollutant leaching concentrates the acids in the snowmelt to a predicted minimum pH range of 3.4 to 4.1 in eastern Canada.

INTRODUCTION

The accumulation of acidic pollutants in a snowpack during freezing weather and their subsequent release to the environment during a thaw poses a potential threat to aquatic flora and fauna in streams or littoral zones of lakes receiving the runoff (Jeffries et al, 1979). One of the most spectacular manifestations of this phenomena occurred in the Tovdal River in Norway during spring 1975 (Leivestad et al, 1976), when fish kills were observed. The impact of snowmelt runoff is intensified by processes that lead to the concentration of 50-80% of the pollutants into the first 30% of meltwater (Seip 1980; Johannessen and Henriksen, 1978).

Much of eastern Canada receives acidic deposition (Whelpdale and Barrie, 1982). It is therefore important to have information on the potential magnitude and frequency of occurrence of snowmelt and snowmelt shock. An investigation of the acidic snowmelt shock potential for Eastern Canada was undertaken employing a model developed to simulate the snowmelt process. Using long-term climatological data and recent observations of acidic deposition as inputs, statistics of snowmelt parameters have been generated that may prove valuable to those interested in the effects and control of acidic deposition.

THE MODEL

General

The water and acid budgets of a snowpack were simulated using a hydrometeorological model, modified to incorporate pollutant processes. Simultations were done for 30 locations in eastern Canada (Figure 1, Table 1). Cumulative snowstore (As), snowmelt (M), total snowpack acid (Ap), the concentration of acids in meltwater (Cm) and runoff amount (RO) were calculated on a daily basis for approximately forty snow seasons using the following input information:

1. daily mean air temperature (T), snowfall (S) and rainfall (R).

2. Cp, the average precipitation acidity (Table 1) estimated from observations in 1979 and 1980 (Barrie and Sirois, 1982).

3. Dp, the daily dry deposition of acid (Table 1) estimated from measured air concentrations of sulphur dioxide, sulphate and nitrate (see, for instance, Barrie 1982).

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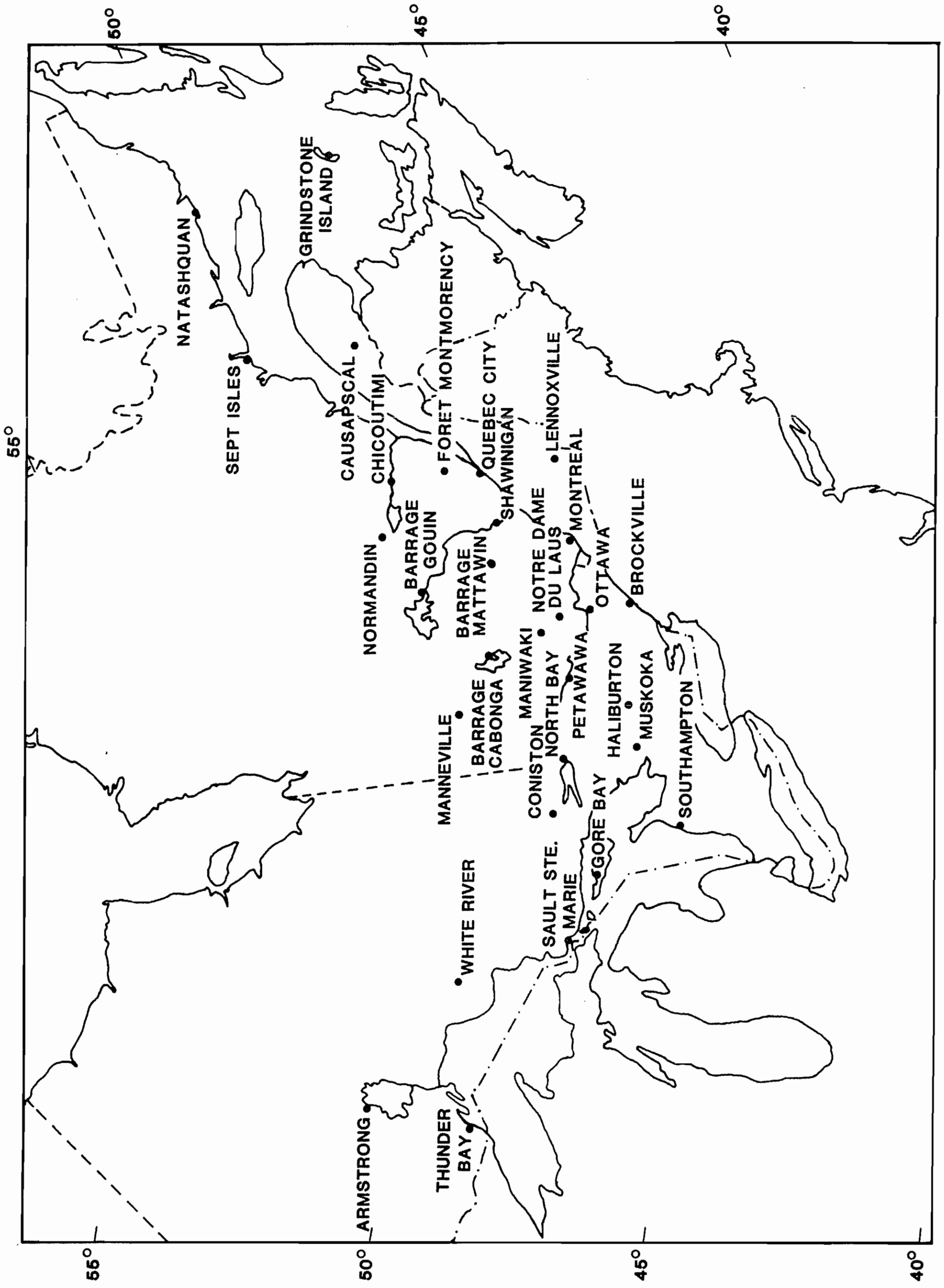

FIGURE 1: Climatological Stations - The location of 30 stations in eastern Canada for which acidic snowmelt shock potential statistics were compiled. At most stations, climatological data from 40 seasons were used.

TABLE 1: STATION DATA - SNOWMELT STUDY

STATION	LATITUDE	NUMBER OF SEASONS	DRY DEPOSITION of H^+, D_p m mole/m^2-day	PRECIPITATION ACIDITY, C_p m mole/ℓ
1. Armstrong	50.2	40	.04	.015
2. Natashquan	50.1	40	.04	.020
3. Sept Isles	50.1	34	.04	.020
4. Normandin	48.9	40	.05	.020
5. Chicoutimi	48.5	40	.05	.020
6. Barrage Gouin	48.5	40	.08	.030
7. Thunder Bay	48.5	38	.04	.015
8. White River	48.5	40	.06	.020
9. Manneville	48.5	22	.10	.050
10. Causapscal	48.4	40	.04	.020
11. Barrage Cabonga	47.4	39	.09	.035
12. Grindstone Island	47.4	40	.04	.020
13. Forêt Montmorency	47.4	14	.04	.020
14. Barrage Mattawin	46.9	40	.08	.030
15. Quebec City	46.8	36	.09	.035
16. Shawanigan	46.5	40	.09	.035
17. Coniston (Sudbury)	46.5	40	.08	.030
18. North Bay	46.5	40	.09	.040
19. Sault Ste. Marie	46.5	16	.06	.040
20. Maniwaki	46.4	26	.11	.040
21. Notre Dame du Laus	46.1	40	.11	.040
22. Petawawa	46.0	23	.18	.060
23. Gore Bay	45.8	40	.08	.040
24. Lennoxville	45.5	40	.11	.035
25. Montreal	45.5	37	.11	.035
26. Ottawa	45.5	40	.18	.060
27. Muskoka	45.0	40	.10	.050
28. Haliburton	45.0	35	.15	.061
29. Brockville	44.5	40	.18	.060
30. Southampton	44.5	40	.15	.060

Acid snowmelt shock indices for lakes and streams were chosen after consultation with freshwater lake biologists to quantitatively represent the impact of a melt period. By running the model for 40 snow seasons for a constant acid-input field, statistical parameters describing the frequency of occurrence of melts and acid shock indices were generated.

It should be emphasized that we have not attempted to take into account the complex interactions of overburden, groundwater and meltwater that can occur between the base of a snowpack and a stream or lake. Consequently, meltwater acidity and shock indices predicted by the model represent the maximum possible acid insult. As it stands, the model may be applicable directly to small watersheds with very little overburden such as those occurring in southern Norway or the Killarney area of Ontario. For more general use, it should be coupled with other models that simulate the interaction of meltwater with overburden and ground water and take into account the hydrology of a watershed.

Melt Criteria

The daily amount of snowpack in millimeters of water that melts during a thaw (M) was calculated from the following equation reported by Bruce and Clark (1966).

$$M = \frac{9\bar{T}}{5} (1.88 + 0.007R) + 1.27 \qquad (1)$$

This equation yielded excellent results in studies of snowmelt runoff from sizeable drainage basins (Louie and Pugsley, 1980). It is applicable to mainly forested areas only (as reflected by the absence of wind speed in Equation 1).

An 'effective' melt was defined to occur if during a thaw the sum of daily melt and rainfall was greater than 5% of snowpack water content at the beginning of the melt. This condition is based on the observation that the maximum retention of interstitial water by a snowpack is approximately 5% (Bruce and Clark, 1966). If a thaw did not qualify as an effective melt, no runoff or pollutant depletion from the pack occurred.

During an 'effective' melt, meltwater leaves the snowpack taking pollutant with it. Based on the field and laboratory work of Johannessen and Henriksen (1978), it was assumed that the fraction of acid removed from a snowpack is a constant multiple N of the fraction of snowpack water that the sum of meltwater formed in the pack and rainwater entering the pack comprise. N was chosen to be 2.78 corresponding to a 63% removal of snowpack acid by the first 30% of meltwater. The concentrating factor C_F defined as the ratio of meltwater acidity to snowpack acidity is related to the fraction of snowpack that melts during a thaw F_S by the following equation:

$$C_F = \frac{1 - (1 - F_S)^{2.78}}{F_S} \qquad (2)$$

An effective melt episode continues until T becomes less than 0°C or the snowpack disappears. A shock period duration of Ts was defined as the number of consecutive days during an effective melt when the daily meltwater acid concentration Cm was greater than 10% of the meltwater acid concentration on the first day of the melt.

Several parameters were calculated for each effective melt. These include the arithmetic mean meltwater acid concentration for a shock period (Cm) and two acid shock indices, one for streams, I_{ST} and one for lakes, I_{LK}. The stream index is given by:

$$I_{ST} = Cm \times Ts \qquad (3)$$

I_{ST} is equivalent to the pollutant dosage at a point in a stream during the shock period. It should be emphasized that I_{ST} represents the maximum possible dosage since partial neutralization of acidic meltwater may occur before it reaches the stream by either dilution with more basic groundwater or ion exchange with the overburden or surface rock (Seip and Tollan, 1978).

The lake index is defined by:

$$I_{LK} = \sum_{i=1}^{Ts} Cm_i \; RO_i \qquad (4)$$

The subscript i denotes daily values. RO is the daily runoff (M+R). I_{LK} is essentially the total acid released per square meter during a shock period. It should be emphasized that I_{LK} represents the maximum possible flux of acid to a watershed during a melt.

RESULTS AND DISCUSSION

The Spatial and Temporal Variation of Melt Frequency and Acid Shock Indices

The seasonal variation in mean monthly melt frequency and acid shock indices is shown for ten regionally representative locations in eastern Canada in Figures 2-4. The bars on each monthly mean represent the standard deviation. In the figures, the spatial distribution of the mean seasonal value of a parameter is also depicted by plotting the calculated value for each station.

1. Melts

The seasonal mean melt frequency (Figure 2) ranges from 5.9 to 10.9 in the study area. It is usually somewhat higher (8.3 - 10.9) at locations south of a line between Montreal, Ottawa and Muskoka than at locations north of the line (5.9 - 8.6). The melt frequency is, as one might expect, highest in fall and spring and lowest in January and February. The stations in the study can be divided into two groups according to their month-to-month variation in melt frequency. Those north of latitude 48°N have less than one melt per month in December, January and February and the highest frequency of melts in April, while those south of 48°N have less than one melt per month in January and February only and the highest frequency in March. From south to north, there is a marked increase in the amplitude of the seasonal variation as well as in the number of months between fall and spring peaks. For instance, at Southampton, Muskoka and Lennoxville in the south, the monthly mean frequency of melts in February is less than a factor of two lower than the peak frequency in March, while at northern stations it is a factor of 15 to 30 times lower than the peak frequency in April.

2. Stream Acid Shock Index, I_{ST}

The seasonal mean I_{ST} (Figure 3) ranges from a minimum of 0.10 m mole ℓ^{-1}-day at Sept Iles and Grindstone Island in the northeast to a maximum of 0.67 m mole ℓ^{-1}-day at Petawawa in the Ottawa Valley. The main factors influencing the predicted spatial variability are spatial variation in the acidity of precipitation and the dry deposition rate of acidity assumed in the model (Table 1) . Both factors are a maximum in southern Ontario. However, there is also an influence of climate on the index as indicated by a comparison of I_{ST} at locations where the acid input parameters are approximately equal. For instance in eastern Quebec I_{ST} is 0.20, 0.21, 0.13, 0.10, 0.12 and 0.10 m mole ℓ^{-1}-day at Normandin, Chicoutimi, Causapscal, Sept Iles, Natashquan and Grindstone Island, respectively. Thus for constant acid input parameters, the change in climatic conditions over a distance of 500 km causes a factor of two variations in I_{ST}.

At all but the most northern stations, no significant temporal variation in I_{ST} can be distinguished because the standard deviation in the monthly mean is very large. At Armstrong in northwestern Ontario and Chicoutimi in central Quebec, there is a significant February maximum in I_{ST}. However, the probability of stream acid

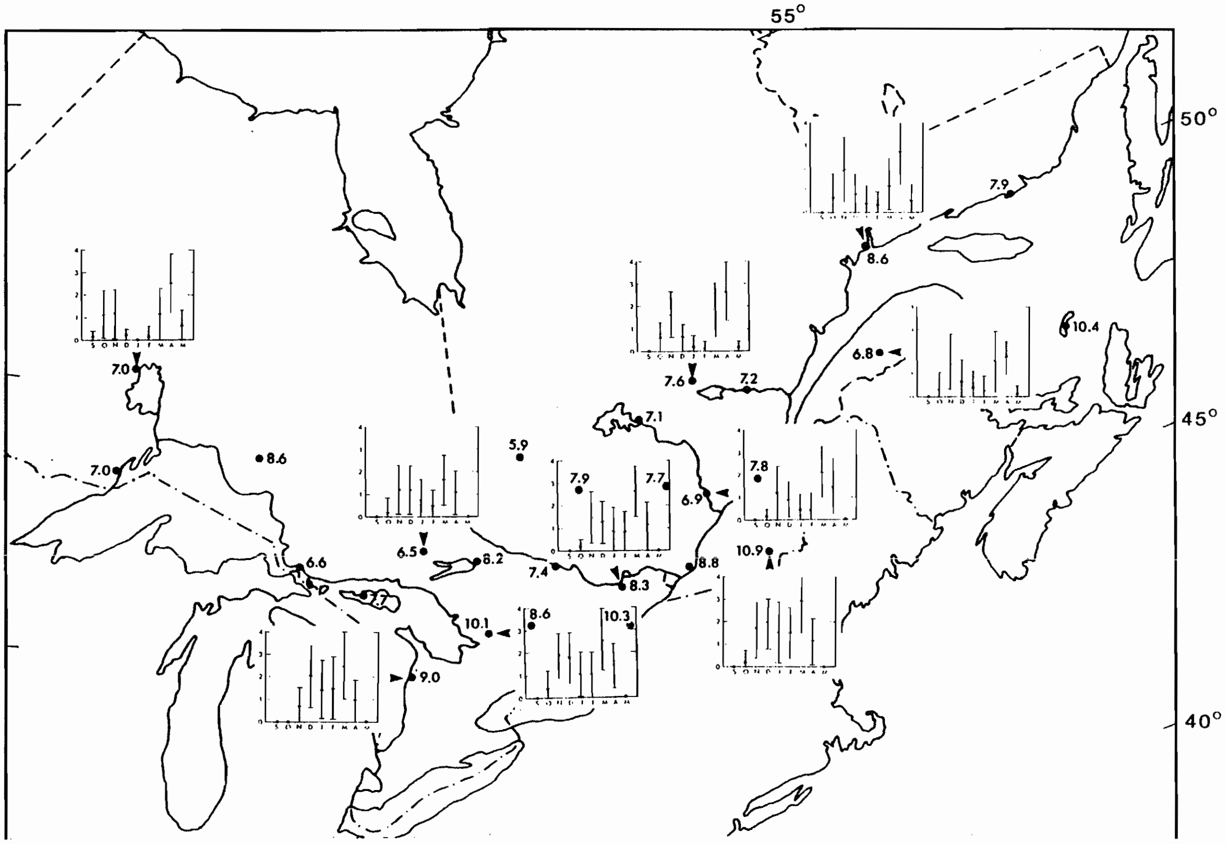

FIGURE 2: Melt Frequency - The seasonal variation of the monthly mean number of melts at 10 regionally representative stations in eastern Canada. The average number of melts in an entire winter is shown for each of 27 stations in the dataset.

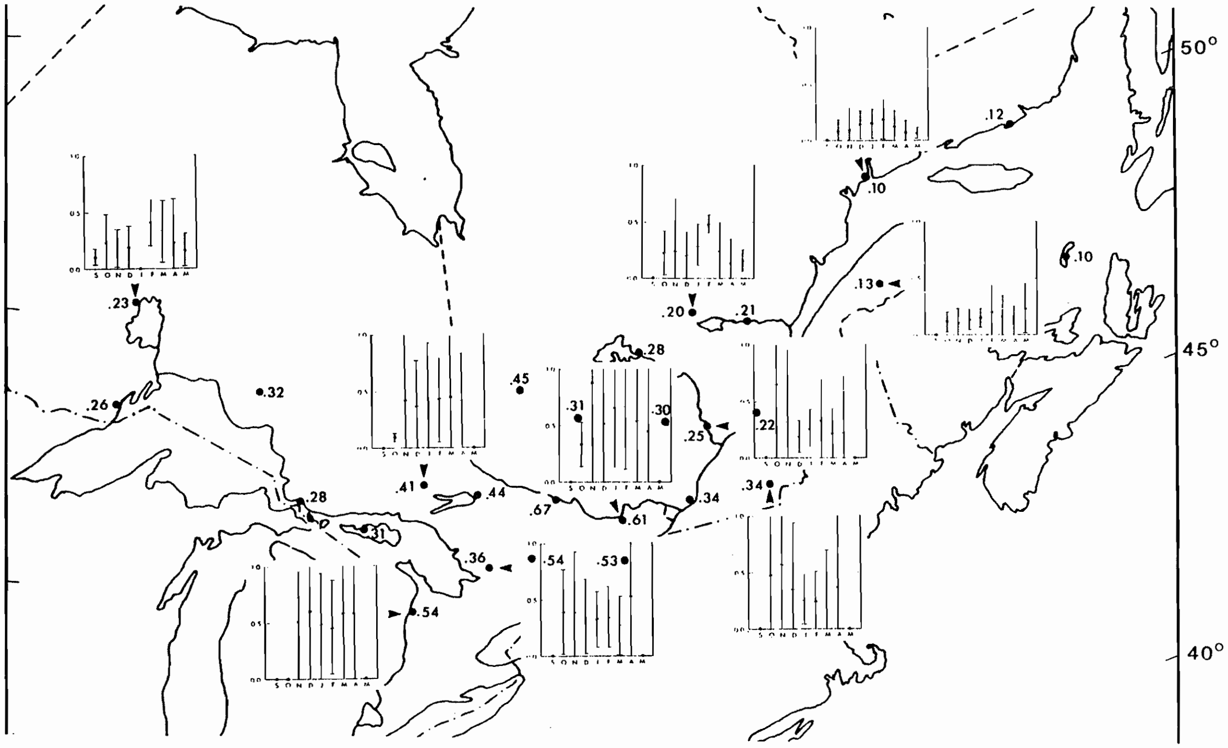

FIGURE 3: Stream Acid Shock Index, I_{ST} - The seasonal variation of the monthly mean acid shock index for streams at 10 regionally representative stations in eastern Canada. The seasonal mean values of I_{ST} are shown for 27 stations in the dataset.

shock is low since the average number of melts in this month is less than 0.2 at these locations (Figure 2). Nevertheless, should a melt occur, it is likely to subject stream life to the worst shock of the winter.

3. Lake Acid Shock Index, I_{LK}

The seasonal mean I_{LK} (Figure 4) ranges from 0.61 m mole m^{-2} in the extreme east to 2.87 m mole m^{-2} in the Ottawa Valley region. It seems that the main factors influencing this index are the acid input parameters. There is less influence of climatological variations as indicated by the lack of variation of I_{LK} over the area in eastern Quebec where it was shown in the previous section that despite constant acid input parameters, I_{ST} changed by a factor of two. The variation in I_{LK} between areas of maximum values and remote regions is much less (factor 3-4) than that of I_{ST} (factor 4-6). Furthermore, the difference between I_{LK} in northwestern Ontario and eastern Quebec (factor 1 - 1.4) is much less than that for I_{ST} (factor 2-3).

There is a significant temporal variation of mean monthly I_{LK} at almost all locations in eastern Canada. It is lowest in the fall and spring and greatest in January and February. The seasonal cycle is the opposite of that for frequency of melt (Figure 2). It does not vary much with location. The frequency of occurrence of the most intense lake acid shocks is low north of 48° latitude (< 1 to 2 every ten years) and high south of 48° latitude (1 to 3 per season). Whether lake life is susceptible at this time of year is a matter for biologists to consider.

The Acidity of Snowmelt

The predicted spatial distribution of the monthly mean pH of snowmelt for March is shown in Figure 5. As mentioned earlier, the model-predicted pH is a lower limit since the neutralizing influence of the overburden and groundwater is not taken into account. Furthermore, they are sensitive to the acid input parameters estimated for each location. The range of the predicted pH of snowmelt is 3.4 to 3.8 over most of the region. The lowest values of pH occur in regions where the maximum number of melts occur, that is, in central and eastern Ontario and southwestern Quebec. If one takes into account the concentrating effect of pollutant leaching, these predicted acidities are not unrealistic. For instance, consider the monthly mean fraction of snowpack that melts during a thaw (F_S) at each location in the study area (Table 2). The concentrating effect of leaching represented by C_F (the ratio of snowmelt acidity to snowpack acidity) which is related to F_S by Equation 2, is also shown in Table 2. In March, F_S and C_F range from 0.27 to 0.78 and 2.2 to 1.3, respectively. C_F values of 2.2 and 1.5 translate into a difference in pH between snowpack and snowmelt of 0.35 to 0.20 pH units.

There is observational evidence that also suggests that snowmelt can have pH values in the predicted range of 3.4 - 3.8 in March. Seip (1980), reports observations of a snowmelt pH as low as 3 in water accumulated in the snow cover just above the ice on freshwater lakes during mild periods.

CONCLUSION

A hydrometeorological model of snowpack pollutant budget has been used to conduct a climatological assessment of the potential for acid shocks to freshwater ecosystems in eastern Canada. Forty years of meteorological data ensure that statistically significant conclusions can be drawn about the most probable situation to arise. Results show that during the early spring months, northern inland regions experience almost half as many melts as southern and eastern regions. At most northern locations, pollutants accumulate in the snowpack between December and March while further south accumulation for sustained periods is restricted to January and February. Then, in March or early April, when the frequency of melts is greatest, pollutant leaching takes place concentrating acids in meltwater to a predicted minimum pH of 3.4 to 4.1.

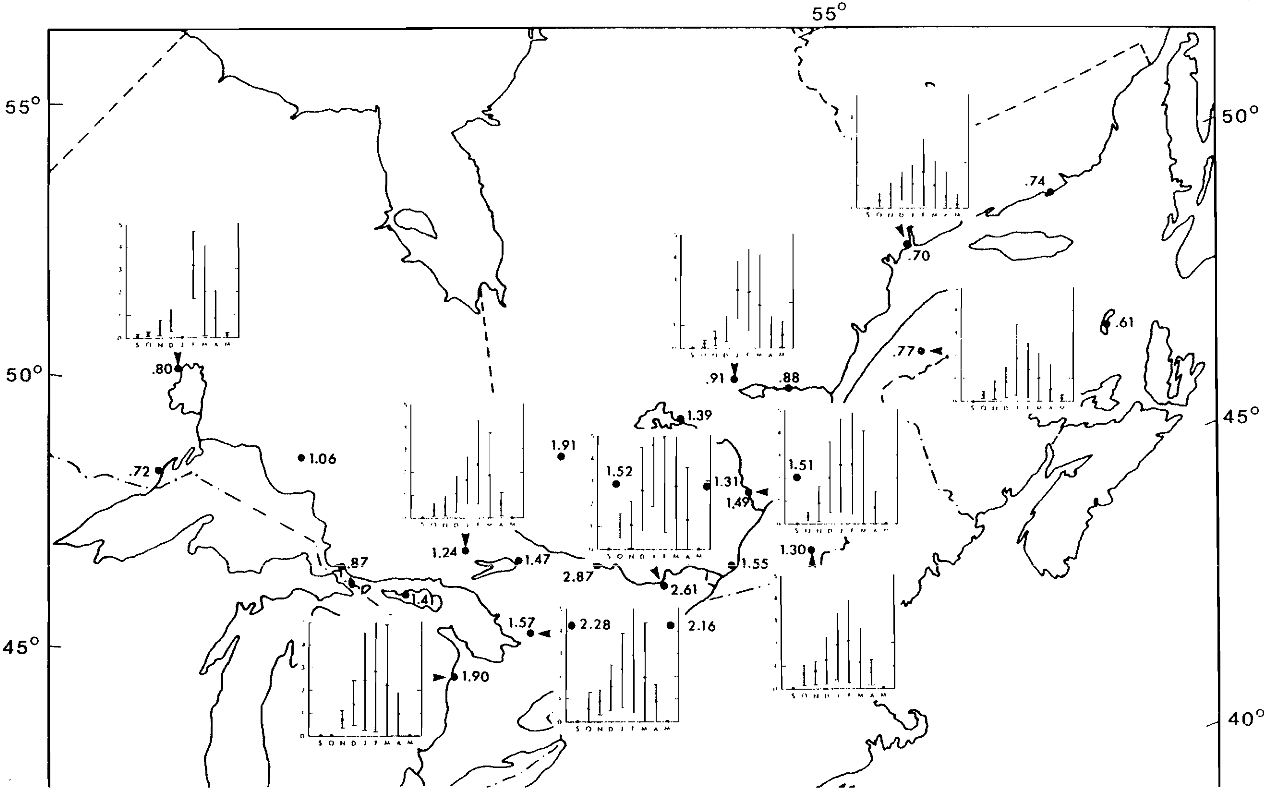

FIGURE 4: Lake Acid Shock Index, I_{LK} - The seasonal variation of the monthly mean acid shock index for lakes at 10 regionally representative stations in eastern Canada. Seasonal mean I_{LK} values are shown for 27 stations in the dataset.

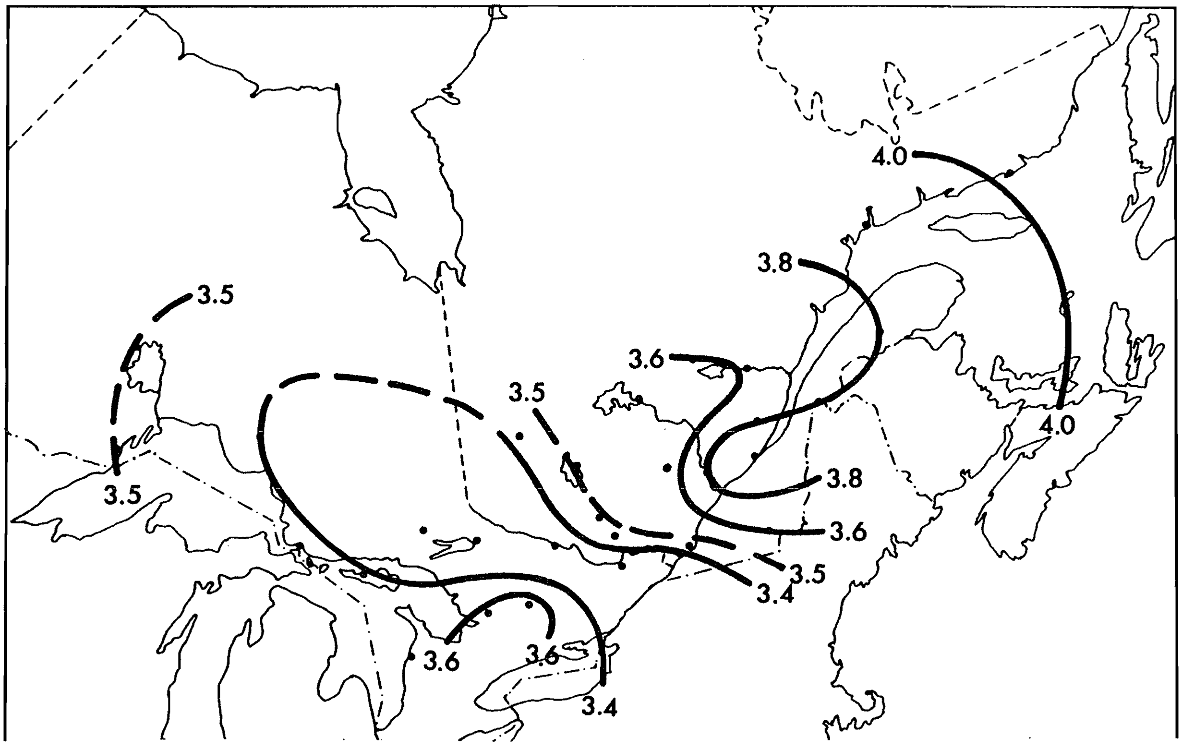

FIGURE 5: Estimated Mean pH of Snowmelt in March - The spatial distribution of the estimated mean snowmelt pH in March. These pH values are a lower limit since neutralizing influences of overburden and groundwater are not considered in the model. Analysis is based on approximately 40 seasons of climatological data at 30 stations in eastern Canada.

TABLE 2: A summary of the mean fraction of snowpack to melt F_S and the concentrating influence of snowmelt leaching on the pollutant burden C_F (from Equation 2) for February, March and April.

		FEBRUARY		MARCH		APRIL	
	STATION	F_S	C_F	F_S	C_F	F_S	C_F
1.	Armstrong	.49	1.73	.46	1.78	.79	1.25
2.	Natashquan	.15	2.42	.33	2.03	.47	1.76
3.	Sept Isles	.30	2.09	.26	2.18	.54	1.64
4.	Normandin	.22	2.26	.33	2.03	.62	1.50
5.	Chicoutimi	.37	1.95	.62	1.50	.89	1.72
6.	Barrage Gouin	.16	2.40	.49	1.73	.74	1.31
7.	Thunder Bay	.61	1.52	.66	1.44	.86	1.16
8.	White River	.41	1.88	.58	1.57	.81	1.22
9.	Manneville	.48	1.75	.54	1.64	.73	1.33
10.	Causapscal	.38	1.93	.50	1.71	.70	1.38
11.	Barrage Cabonga	.31	2.08	.43	1.84	.77	1.28
12.	Grindstone Island	.44	1.82	.27	2.16	.56	1.60
13.	Forêt Montmorency			.29	2.2	.52	1.67
14.	Barrage Mattawin	.38	1.93	.56	1.60	.80	1.24
15.	Quebec City	.18	2.76	.36	1.97	.70	1.38
16.	Shawanigan	.27	2.16	.38	1.93	.65	1.46
17.	Coniston (Sudbury)	.59	1.55	.63	1.49	.87	1.15
18.	North Bay	.42	1.86	.52	1.67	.81	1.22
19.	Sault Ste. Marie	.24	2.22	.58	1.57	.85	1.17
20.	Maniwaki	.46	1.78	.65	1.46	.83	1.20
21.	Notre Dame du Laus	.28	2.14	.48	1.75	.79	1.25
22.	Petawawa	.36	1.97	.66	1.44	.83	1.20
23.	Gore Bay	.35	1.99	.53	1.66	.77	1.28
24.	Lennoxville	.49	1.73	.68	1.41	.94	1.06
25.	Montreal	.43	1.84	.47	1.76	.78	1.26
26.	Ottawa	.44	1.82	.49	1.73	.70	1.38
27.	Muskoka	.51	1.69	.54	1.64	.87	1.15
28.	Haliburton	.43	1.84	.55	1.62	.80	1.24
29.	Brockville	.56	1.60	.73	1.33	.95	1.05
30.	Southampton	.61	1.52	.78	1.26	.96	1.04

While acidic deposition may be larger in southern regions than in northern areas, northern snowpacks accumulate pollutants for a longer period from December to February. Furthermore little pollutant is lost from the pack during a melt in these cold months since the average pack melted is less than that further south throughout most of the winter and early spring. Consequently, potential acidic impact is as significant in areas of north central Ontario and Quebec as it is further south.

In all regions, the acidic shock of a lake is most intense in late winter (February) when the very first melts generally occur and the first fractions of pollutant accumulated in the pack are released. However, throughout Ontario and western Quebec, acidic melt values remain relatively high in southern areas in March and in northern areas in April when significant melts take place in these regions.

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