

TD
226
N87
No. 91-
65
c. 1

THE PREDICTED EFFECT OF SO₂ EMISSION CONTROLS
ON THE WATER QUALITY OF EASTERN CANADIAN LAKES

D.S. Jeffries, D.C.L. Lam, I. Wong
and R.M. Bloxam

NWRI CONTRICUTION 91-65

THE PREDICTED EFFECT OF SO₂ EMISSION CONTROLS
ON THE WATER QUALITY OF EASTERN CANADIAN LAKES

D.S. Jeffries, D.C.L. Lam, I. Wong

National Water Research Institute
Rivers Research Branch
P.O. Box 5050
Burlington, Ontario
Canada L7R 4A6

and

R.M. Bloxam

Ontario Ministry of Environment
Air Resources Road, East Wing
Rexdale, Ontario
Canada M9W 5L1

NWRI Contribution 91-65

Running Head: Effect of SO₂ emission controls on lake chemistry

Management Perspective

This paper presents some of the core findings from the research and data evaluation performed during preparation of the 1990 LRTAP Assessment (Parts 3 and 4). As such, most of the interpretation was released previously in the Assessment (January, 1991); however, this is the first time that a complete description of the methods and the implications of the work have been prepared for release within the general scientific literature.

Through linkage of atmospheric and water chemistry models, the paper shows that SO₂ emission control programs to be realized in Canada and the U.S. during the next decade should have a positive and observable effect on the water quality of lakes in south-eastern Canada. Lake pH and acid neutralizing capacity will increase in response to decreased sulphate deposition. Wet sulphate deposition will decline to <20 kg/ha/yr in almost all areas of eastern Canada. Southern Ontario and southwestern Quebec will exhibit the greatest improvement. Unfortunately, the Atlantic Provinces will derive lesser benefit and many lakes will still have pH values below the desired ecological threshold of 6. These results are modelling predictions and a substantive long-term monitoring program is required for verification. If future changes in sulphate deposition and lake acidity do occur as predicted, further reduction in SO₂ emissions will be needed to fully protect the aquatic ecology of southeastern Canada, and in particular, the Atlantic Provinces.

PERSPECTIVE DE LA DIRECTION

Le présent document présente une partie des principaux résultats des recherches et de l'évaluation des données effectuées au cours de la préparation du Rapport d'évaluation de 1990 sur le TGDPA (parties 3 et 4). Ainsi, la plus grande partie des interprétations a déjà été publiée dans le Rapport d'évaluation (janvier 1991); toutefois, c'est la première fois qu'une description complète des méthodes et des répercussions des travaux est préparée afin d'être publiée dans des documents scientifiques généraux.

Par combinaison de modèles atmosphériques et des propriétés chimiques de l'eau, l'auteur montre que les programmes de lutte contre les émissions de SO_2 qui seront appliqués par le Canada et les États-Unis aux cours de la prochaine décennie devraient avoir un effet positif et durable sur la qualité de l'eau des lacs du sud-est du Canada. Le pH des lacs et le pouvoir neutralisant des acides augmenteront en réponse à une réduction des dépôts de sulfates. Les dépôts de sulfates humides seront réduits à $< 20 \text{ kg/ha/année}$ dans presque toutes les régions de l'Est du Canada. La baisse la plus importante sera enregistrée dans le sud de l'Ontario et le sud-ouest du Québec. Malheureusement, les avantages seront moins évidents dans les provinces de l'Atlantique, et le pH d'un grand nombre de lacs sera encore inférieur à la valeur seuil écologique souhaitée de 6. Il s'agit de prévisions par modélisation et il faut un programme de surveillance à long terme indépendant aux fins de vérification. Si, comme on le prévoit, les dépôts de sulfates et l'acidité des lacs varient, d'autres réductions des émissions de SO_2 seront nécessaires afin d'assurer une protection complète des écosystèmes aquatiques du sud-est du Canada, et en particulier, des provinces de l'Atlantique.

RÉSUMÉ

Les modifications probables des dépôts de SO_4^{2-} en réponse à l'application des programmes de lutte contre les émissions de SO_2 , prévus au Canada et aux États-Unis, ont été utilisées comme éléments des modèles sur les propriétés chimiques de l'eau permettant par ce moyen d'estimer les changements du pouvoir neutralisant des acides (PNA) et du pH que ces programmes sont susceptible d'entraîner. L'Est du Canada a été divisé en 22 sous-régions aux fins de cette analyse. Par rapport au taux actuel (1982-1986) des dépôts de SO_4^{2-} (scénario 1), l'effet du programme canadien de lutte contre les émissions de SO_2 seul (scénario 2) est comparé à celui obtenu lorsque des mesures sont appliquées à l'échelle de l'Amérique du Nord (scénarios 3 et 4). La réduction des émissions de SO_2 diminuera le vaste champ des dépôts humides de SO_4^{2-} dans le nord-est de l'Amérique du Nord de telle sorte dans le cadre du scénario 4, il n'y aura presque plus de régions au Canada qui recevront $>20 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{année}^{-1}$. C'est dans le sud de l'Ontario et le sud-ouest du Québec que l'on enregistre la baisse la plus importante de la quantité de dépôts et le changement le plus marqué au niveau des propriétés chimiques des lacs. Les répartitions du PNA se sont déplacées vers des concentrations plus élevées et le pourcentage des lacs à $\text{pH} < 6$ diminue dans ces régions. Les provinces de l'Atlantique bénéficieront très peu des programmes de lutte, c'est-à-dire qu'elles n'enregistreront qu'une faible baisse des dépôts et une légère amélioration de la qualité de l'eau. En raison de la sensibilité élevée des terrains dans de nombreuses régions de l'Atlantique canadien, un grand nombre de lacs demeureront acides (c'est-à-dire, $\text{PNA} < 0$) et (ou) auront un $\text{pH} < 6$ (un seuil biologique important) même après l'application intégrale des plans actuels de contrôle du SO_2 au Canada et aux États-Unis.

THE PREDICTED EFFECT OF SO₂ EMISSION CONTROLS ON THE WATER QUALITY OF EASTERN CANADIAN LAKES

Dean S. Jeffries, David C. L. Lam, and Isaac Wong, National Water
Research Institute, P. O. Box 5050, Burlington, Ontario, Canada L7R 4A6
and

Robert M. Bloxam, Ontario Ministry of Environment, Air Resources Branch,
125 Resources Road, East Wing, Rexdale, Ontario, Canada M9W 5L1

Running Head: Effect of SO₂ emission controls on lake chemistry

ABSTRACT

Changes in SO₄²⁻ deposition predicted to occur in response to implementation of announced SO₂ emission control programs in Canada and the U.S.A. have been used as input to water chemistry models thereby giving an estimate of the changes in lake acid neutralizing capacity (ANC) and pH that can be expected from these programs. Eastern Canada has been divided into 22 subregions for the purpose of this analysis. Relative to the current level (1982-86) of SO₄²⁻ deposition (Scenario 1), the effect of the Canadian SO₂ emission control program alone (Scenario 2) is compared to that obtained when controls are implemented throughout North America (Scenarios 3 and 4). SO₂ emission reduction will effect a shrinkage of the high wet SO₄²⁻ deposition field in NE North America such that under Scenario 4 conditions, almost no area will remain in Canada that receives >20 kg.ha⁻¹.yr⁻¹. The greatest decrease in deposition and resulting change in lake chemistry occurs in southern Ontario and southwestern Quebec. ANC distributions shift to higher concentrations and the percentage of lakes having pH<6 decreases in these areas. The Atlantic Provinces will obtain only a minor benefit from the control programs, i.e. experiencing only a small decrease in deposition and improvement in water quality. High

sensitivity of the terrain in many parts of Atlantic Canada means that large numbers of lakes will remain acidic (i.e. $ANC < 0$) and/or have $pH < 6$ (an important biological threshold) even after full implementation of the current plans for SO_2 control in Canada and the U.S.

INTRODUCTION

During the last 2 decades, surveys in northern Europe and northeastern North America have documented occurrences of surface waters with very low or negative acid neutralizing capacity (ANC) that are not explained by the influence of an obvious local acidifying source such as acid mine runoff (Henriksen *et al.*, 1988; Charles, in press; RMCC, 1990a). With few exceptions, these conditions have been attributed to the introduction of strong acids of anthropogenic origin based on the strong spatial correlation that exists between their occurrence and high levels of acidic deposition, or more specifically, high $SO_4^{2-}*$ deposition (the "*" implies sea salt correction, Henriksen *et al.* 1990). The $SO_4^{2-}*$ may originate from either local (e.g. Nriagu, 1984) or long range sources (RMCC, 1990a). Results of experimental acidification and deacidification of catchments (Wright *et al.*, 1988) and observations of the reversibility of acidification when $SO_4^{2-}*$ deposition decreases (Barth, 1987) lend support to this contention. While receptor liming may be a viable mechanism for preserving spatially limited and important fish stocks (Watt, 1986; Gunn *et al.*, 1990), the extent of Canadian geography means that reduction in deposition achieved by SO_2 emission control is the only long term solution.

In order to specify the degree of emission control required, the relationship between deposition and aquatic effects must be quantified so that a critical or target SO_4^{2-} load can be determined. By definition, a critical load yields no ecological damage (i.e. does not harm ecosystem structure or function; Nilsson and Grennfelt, 1988) while a target load maintains ecological damage below some politically defined level of "acceptability". By consideration of empirical evidence and application of the water chemistry models then available, U.S.-Canada (1983) suggested that "a loading of $15\text{-}20 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ wet SO_4^{2-} would maintain surface water $\text{pH} > 5.3$ on an annual basis for basins having cation concentration $\geq 200 \mu\text{eq}\cdot\text{L}^{-1}$ in areas of low runoff". In 1983, Canadian policy makers recognized a $20 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ target load and, by seeking to reduce SO_4^{2-} deposition in sensitive areas of southern Ontario and Quebec, used it to design an emission control program that has now been approved by all pertinent levels of government. Legislative action to reduce SO_2 emissions in the U.S. has been initiated recently with passage of amendments to the federal Clean Air Act (United States Congress, 1990).

The development of atmospheric deposition and lake water chemistry models leads to a profitable opportunity for linkage and prediction of the effect of SO_2 reduction on surface water ANC. Given the present state of model development and verification (e.g. verification has been performed with only limited field data; Dennis et al. 1989, Thornton et al. 1990), such predictions will be difficult to confirm in the short run. Nevertheless, the modelling analysis will provide useful information on the general magnitude and direction of changes in surface water chemistry induced by SO_2 emission control. Hence,

by using reasonable assumptions of future Canadian and U.S. SO_2 reductions to drive the models, we will assess their impact on eastern Canadian lake ANCs (regional basis) relative to the current situation. We will also consider whether such reductions achieve ecological protection.

METHODS

EMISSION CONTROL AND SO_4^{2-} DEPOSITION REDUCTION

Four Scenarios of wet SO_4^{2-} deposition will be used here. Scenario 1 reflects the current situation in eastern Canada and is taken as the average wet deposition measured over 1982-86. Deposition reductions from this base case were evaluated by application of the MOE Lagrangian trajectory puff model (Ellenton *et al.*, 1985, 1988; RMCC, 1990b) using 1980 meteorology and differing levels of emission reduction (see below). Scenario 2 reflects the effect of only the Canadian SO_2 control program to be achieved by 1994. Scenario 3 reflects the additional effect of the first half of a proposed 10 million short ton SO_2 reduction in the U.S.A., while Scenario 4 presents the outcome predicted to occur when both the Canadian and U.S. control programs are implemented in full.

Due to the uncertainties present in modelling SO_2 conversion, atmospheric transport, and the large natural between-year variability in meteorology, substantial error may be present in predicted SO_4^{2-} deposition. For example, Ellenton *et al.* (1985) showed that their deposition estimates in eastern North America in 1979 could deviate from observed values

up to a factor of two at any point in space, although the overall deposition pattern closely matched. We have attempted to minimize the impact of such error on our analysis by using only differences in model output. That is, we are using the likelihood that absolute modelling errors will remain relatively constant from one model run to another and will be cancelled by taking the difference between runs. The difference between Scenario 1 and Scenario 2 deposition at a given point in space was derived from the difference in model output between the run using 1980 North American SO_2 emission levels and the run using 1980 U.S. emissions and 1994 Canadian emissions (1980 meteorology used in all cases). Scenario 2 deposition was simply Scenario 1 (measured 1982-86 wet deposition) reduced by this between-run difference. Deposition for Scenarios 3 and 4 were obtained in a similar fashion.

The SO_2 emissions used to drive the atmospheric model were all relative to the 1980 North American inventory level. The Canadian control program will reduce SO_2 emissions by 1994 to approximately 50% of the 1980 level of 4516 kilotonnes (U.S.-Canada, 1983) for provinces east of the Saskatchewan-Manitoba border. Reduction from the 1980 base case values are distributed as follows: Manitoba - 9%, Ontario - 64%, Quebec - 24%, and the remaining eastern provinces - 3% (RMCC, 1990c). We have assumed an overall reduction of 10 million short tons for the U.S. SO_2 control program occurring in two 5 million ton phases thereby yielding Scenarios 3 and 4. The reductions were assigned on a state-by-state basis (Table I) based on the assumption that states bordering Canada would bear 60% of the control burden, south-east states 15%, western states 10%, and Ohio Valley states

15% (Canada Department of Environment, Secretariat for the Changing Atmosphere, pers. comm.). The hypothetical state-by-state assignment of emission reduction is necessary at this time and is based on the collective best judgement of the Canadian Federal-Provincial Research and Monitoring Committee (RMCC, 1990b). Until various emission trading negotiations and investigation of technological options are complete, SO₂ reduction figures for each state will remain uncertain. However, since our emphasis here is on the regional change expected to occur relative to the current situation, the detail of how much SO₂ reduction is assigned to a specific source is not as important as whether the overall magnitude of the control program is reasonable.

LAKE CHEMISTRY DATABASE

The lake chemistry database is the same as that used by RMCC (1990a) which is a compilation of several federal and provincial data sets. It contains information for 8,505 lakes in southeastern Canada of which 3,902 have sufficiently complete data records (all major ions and DOC) to permit model calculations of ANC. Details of database compilation, structure, quality assurance, etc. may be found in Fraser *et al.* (1990). The sample population represents <2% of the actual population of lakes having an area >1 ha (Table II).

Since it is a compilation, the database is not statistically representative of the overall lake population; however, it is likely that inferences made from the sample population will not overestimate the effects of acidic deposition. Support for this contention lies with the

nature of the sample collection and data compilation methods (RMCC, 1990a), and in particular, the strong bias in the sample population towards larger lakes. In a recent inventory of the lake resource, Hélie and Wickware (1990) identified 795,579 waterbodies >0.18 ha in area within the region of southeastern Canada east of 90°W longitude and south of 52°N latitude (16% of the country); nearly 54% of the lakes are ≤1 ha in size (Table II). However, of those sample lakes where surface area is recorded in the database (6,371), 84% are >10 ha in area. Smaller lakes tend to have similar (Kelso *et al.*, 1986) or lower pH and ANC (Krester *et al.*, 1988; Neary *et al.*, 1990; Dupont, 1989, 1990) compared to larger lakes. Therefore, small lakes are at least as sensitive to acidic deposition as large lakes and possibly more sensitive.

When considering the freshwater resource on an areal basis, large lakes constitute the greatest proportion (e.g. lakes >100 ha compose >70% of the areal resource within the inventory of Hélie and Wickware, 1990). Hence, the chemical database is more representative of the areal resource than the numerical resource.

The sampled lakes present in the database fall within 324 tertiary watersheds. A "tertiary" watershed is that uniquely defined drainage basin obtained from a third level subdivision of the 4 drainage basins that compose eastern Canada. In order to obtain geographic units amenable to presentation of spatial variations across eastern Canada, the lakes were grouped into 22 aggregations of tertiary watersheds (see Figure 1 for location and numbering, and Table II for names). The Aggregates (AGs) were chosen to minimize as

far as possible the within-group variance in water chemistry and maximize between-group variance by consideration of the spatial variability in lake water specific conductance. Subjective knowledge of local variability in geology and SO_4^{2-} deposition also played a role in defining AG boundaries. The following analysis will use these geographic units, and in order to simplify the discussion, a limited number of them (i.e. those shaded in Figure 1) will be extensively used to represent southeastern Canada.

WATER CHEMISTRY MODELS

We have adopted the steady-state modelling approach in this analysis. The steady-state method is computationally simple, readily adapted to regional evaluation, and provides the answer we seek, i.e. the equilibrium chemical response to changes in deposition. While time-dependent acidification models would provide additional useful information on response times and chemical pathways, availability of the input data necessary to run them is extremely limited thereby precluding their use on a regional basis. Where time-dependent models have been used (e.g. MAGIC applied to the Turkey Lakes Watershed in central Ontario; RMCC 1990a), the time required to reach equilibrium is on the order of decades although the asymptotic nature of the curve is such that a large proportion of the overall response occurs in the first decade. Soil adsorption of SO_4^{2-} is an important factor delaying acidification of runoff waters and it is not included in the steady-state models. However, where catchment mass balances have been determined in eastern Canada, SO_4^{2-} inputs and outputs approximate steady-state conditions (Rochelle *et al.*, 1987). Rather than depending on a single steady-state model, an expert system was developed (Lam *et al.*,

1988, 1989a) and used here to predict ANC on a lake-by-lake basis. The expert system includes both the DFO-ESSA Model (a refined version of the earlier CDR model, Marmorek *et al.*, 1985, 1990) and the Trickle-Down Model (Schnoor *et al.*, 1986) with model selection controlled by data availability and a set of rule-based criteria consistent with model assumptions and performance (Lam *et al.*, 1988, 1989a, 1989b). The expert system also considers the organic anion (A^-) concentration during ANC calculation when lake DOC is $>4 \text{ mg.L}^{-1}$ or Colour is >30 Hazen units using either the A^- model of Oliver *et al.* (1983) or Lam *et al.* (1989c). DOC is assumed not to change with SO_4^{2-} deposition. Data required by the expert system to model ANC for a given lake include complete major ion chemistry, DOC, precipitation, and total SO_4^{2-} deposition for each Scenario. Total deposition was obtained by assuming that the dry component contributed 15% of the total for all AGs (RMCC, 1990b) except AG 19 (Sudbury-Noranda, 50% of total; Dillon *et al.*, 1982) and AG 2 (Mid-eastern Nova Scotia, 35% of total; Shaw, 1982).

Finally, biotic thresholds are usually expressed in terms of pH rather than ANC (RMCC, 1990a). Therefore, in order to evaluate whether the emission reduction Scenarios will achieve ecological protection, the pH distribution for each AG was calculated using the method of Small and Sutton (1986).

RESULTS

Emission reduction of SO_2 will cause shrinkage of the high deposition field presently observed in northeastern North America. Figure 2 presents the location in Canada of the

10 kg.ha⁻¹.yr⁻¹ wet SO₄²⁻* deposition contours (lines) and the 20 kg.ha⁻¹.yr⁻¹ deposition field (shading) predicted for each of the emission control scenarios.

The greatest change in the wet SO₄²⁻* deposition pattern resulting from institution of the Canadian control program (i.e. the difference between Scenario 2 and the Current situation) occurs as a contraction of the 20 kg.ha⁻¹.yr⁻¹ field in southern Ontario and southwestern Quebec. This reflects the major responsibility for SO₂ emission reduction assumed by smelters and power generation stations in these provinces. The position of the 10 kg.ha⁻¹.yr⁻¹ contour changes comparatively less. Addition of the effect of emission control in the U.S. (i.e. Scenarios 3 and 4) cause further contraction of the 20 kg.ha⁻¹.yr⁻¹ field and a more noticeable southward shift in the 10 kg.ha⁻¹.yr⁻¹ contours. After maximum reduction in SO₂ emission is achieved (i.e. Scenario 4), only 2 small areas of eastern Canada will receive >20 kg.ha⁻¹.yr⁻¹ wet SO₄²⁻* deposition and the latitude of the 10 kg.ha⁻¹.yr⁻¹ contour has shifted southwards approximately 2° (up to 5° immediately south of James Bay). Compared to Ontario and Quebec, SO₂ emission reduction effects only a small decrease in SO₄²⁻* deposition in the Atlantic Provinces.

ANC distributions for selected AGs (i.e. those shaded in Figure 1) are shown in Figure 3. The elements of each boxplot correspond to the 10th, 25th, 50th, 75th, and 90th percentile ANC concentrations as presently observed (O), or predicted under current deposition (C) or Scenario 2, 3, 4 (S2, S3, S4) deposition, respectively. The close comparability of the O and C distributions lends confidence both that the expert water chemistry model provides

a realistic ANC simulation, and that the lake waters are indeed in a near steady-state with respect to SO_4^{2-} deposition.

These boxplots show both inter-regional differences in ANC as well as the effect of reducing SO_4^{2-} deposition. Some regions have broad ANC distributions (e.g. AG 21 - Northwestern Ontario, AG 16 - Ottawa Valley, AG 3 - Northern Nova Scotia and New Brunswick) reflecting spatially variable bedrock and surficial geology, particularly the irregular occurrence of carbonate minerals. Conversely, very narrow, low concentration ANC distributions in AG 14 (Laurentide), AG 1 (Southern Nova Scotia and New Brunswick), AG 6 (Eastern Newfoundland), and AG 10 (Eastern Quebec and Southern Labrador) attest to the uniformly high terrain sensitivity present in these areas.

The effect of SO_2 emission reduction leading to SO_4^{2-} deposition reduction (compare C, S2, S3, and S4 boxplots in each AG) is apparent as a shift in lakewater ANC distributions to higher concentrations in some regions (Figure 3). The shifts are most pronounced in AG 19 (Sudbury-Noranda), AG 17 (Central Ontario), AG 16 (Ottawa Valley), and AG 14 (Laurentide) as expected, since these areas experience the greatest change in deposition (Figure 2). Aggregate 18 in extreme southern Ontario also experiences a large change in deposition; however, since this region is wholly underlain by carbonate bedrock, its few lakes normally have high ANC that will show little response to changes in SO_4^{2-} input. Little change in lakewater ANC is predicted from Scenario to Scenario for the remaining regions in Figure 3.

The percentages of acidic lakes (i.e. those having $\text{ANC} < 0 \mu\text{eq.L}^{-1}$) occurring in each AG for the four emission control Scenarios are summarized in Table III. The percentages of acidic lakes currently found in the Atlantic Provinces (AGs 1-8, column 3 in Table III) decrease only slightly in response to SO_2 controls (compare to values in column 6). For example, implementation of the full Canadian and U.S. programs reduces the proportion of acidic lakes in AG 1 from 53 to 52%, and in AG 3 from 23 to 17%. In contrast, the relatively lower percentages of acidic lakes observed in most of the southern Quebec and southern Ontario AGs exhibit a substantial decrease from the current to Scenario 4 condition (e.g. from 10 to 3% in AG 13, from 7 to 2% in AG 17, and from 31 to 6% in AG 19).

The predicted effect of reduced SO_2 emissions on lakewater pH is shown in Figure 4. A pH of 6 has been identified as an important threshold value for aquatic organisms and a suitable basis for evaluating critical and target loads (RMCC, 1990a). Accordingly, we have determined the percentage of lakes in eastern Canadian regions that have $\text{pH} < 6$ under the 4 control Scenarios. However, we also recognize that lakes in certain terrain types, particularly those with exceedingly slow weathering (or base cation supply) rates and significant A^- concentrations, may have pHs that never exceed 6, even under conditions of background deposition. The chemical criterion for a critical load for such lakes would be maintenance of the historical pH, rather than restoration to $\text{pH} > 6$. Hence, we have attempted to identify which lakes would have historical $\text{pH} > 6$ by running the models with an estimated background SO_4^{2-} deposition and assuming that A^-

concentrations do not vary with deposition. The percentages of lakes presented in Figure 4 apply only to those lakes so identified. A significant proportion of the lakes in 3 AGs likely had $\text{pH} < 6$ under background deposition, i.e. AG 1 ~ 50%, AG 4 ~ 40%, and AG 2 ~ 20%. The model predicts that approximately 10% or less of lakes in the remaining AGs historically had $\text{pH} < 6$.

Once again, the most pronounced improvement in water quality (as reflected by a reduction in the percentage of modelled lakes having $\text{pH} < 6$) occurs in southern Ontario and southwestern Quebec where changes in SO_4^{2-} deposition are also maximum. In most regions of the Atlantic Provinces, relatively high percentages of modelled lakes have $\text{pH} < 6$ due to terrain characteristics. This condition changes little from Scenario to Scenario since SO_2 emission reductions effect only small changes in deposition in this area.

In some AGs where pH changes are predicted, the Canadian emission control program (Scenario 2) causes a large reduction in the percentage of lakes with $\text{pH} < 6$. This occurs in AG 19 (Sudbury-Noranda), AG 16 (Ottawa Valley), AG 15 (Southwestern Quebec), AG 14 (Laurentide), and AG 22 (Northern Quebec; most modelled lakes are in the southwest corner of this large AG). The U.S. emission controls cause a further but lesser improvement. In other AGs (e.g. AG 17 - Central Ontario, AG 13 - Saguenay, and AG 3 - Northern Nova Scotia and New Brunswick), U.S. emission controls are as important in reducing the percentage of lakes below the $\text{pH} = 6$ threshold as those implemented in Canada.

DISCUSSION

It is difficult to comprehend the scale of the surface water resource in Canada and presentation of results in terms of percentages and distributions, as above, does not help in this regard. The sample population in our lake chemistry database is not a statistical subset of the overall population, but probably under-represents those systems most likely to be sensitive. Hence, when the percentages of acidic lakes in Table III are used to determine the numbers of lakes involved using the lake resource inventory (Table II) the numbers are, if anything, also under-estimated. Given this qualification, there are currently >14,000 acidic lakes >1 ha in area (>31,000 lakes >0.18 ha in area) within that portion of Canada south of 52°N latitude and east of 90°W longitude (16% of the country). The magnitude of these estimates seems reasonable. Neary *et al.*, (1990) estimate that the number of acidic lakes in Ontario is 7,250 based on a sample population of 6,000 lakes of which over 99% are >1 ha in size. In southern Quebec (south of 51°N latitude, north of the St. Lawrence River, and west of 62°W longitude), statistical extrapolation from an overall population of 31,800 lakes in the 10-2,000 ha size fraction gives 5,993 lakes with $\text{pH} \leq 5.5$ (J. Dupont, pers. comm.). Since the numbers of acidic lakes are extremely small in regions receiving $<10 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ wet SO_4^{2-} deposition (i.e. in western Canada, northwestern Ontario, and Labrador; RMCC, 1990a), we conclude that acidic deposition has contributed at least in part to depletion of ANC in these lakes.

Consideration of the affected resource in terms of acidic lakes is also misleading since such lakes must be deemed as the end-members of a spectrum of effect that begins when pH drops below 6. In this context, RMCC (1990a) has estimated that in the Atlantic Provinces alone (excluding Labrador), there will be approximately 47,000 lakes >0.18 ha in size having $\text{pH} < 6$ (19,000 > 1 ha in size) even after full implementation of the Canadian and U.S. SO_2 emission control programs. These large numbers indicate that a significant part of the surface water resource has been and will continue to be affected by acidic deposition. As noted above, most of the affected lakes will likely be small in size meaning that the areal proportion of the affected resource is also small. Nevertheless, small lakes are important habitat for a variety of aquatic and waterfowl species and further emission controls will be needed to ensure their protection.

Policy makers depended on information provided by U.S.-Canada (1983) when designing the Canadian SO_2 emission control program. Their intent was to reduce wet SO_4^{2-} deposition to $<20 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ throughout eastern Canada, and given that our hypothetical emission reductions in the U.S.A. will occur in the manner outlined in Table I, the above results indicate that this goal likely will be achieved. The greatest emission reductions in Canada occur in Ontario and Quebec. Coupled with the fact that the hypothetical reductions in the U.S.A. are concentrated in states bordering Canada (particularly the Great Lakes states), it is not surprising that Ontario and Quebec will be the main beneficiaries of the control programs, i.e. receiving substantially lower SO_4^{2-} deposition and improvements in the acidity status of surface waters.

The Atlantic Provinces will derive lesser benefit from the emission control programs. Even though wet SO_4^{2-} deposition will be below $20 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$, the absolute change from current levels is small, and the high proportions of acidic lakes (Table III) or lakes with $\text{pH} < 6$ (Figure 4) are reduced in only a minor way. Recall that the percentages of lakes in Figure 4 refer only to those predicted to have $\text{pH} > 6$ under conditions of background deposition and that AG 1, 2, and 4 contain significant numbers of lakes that do not meet this criterion. A contributing reason is the high sensitivity of much of the terrain in the Atlantic Provinces. U.S.-Canada (1983) noted that only waters with base cation concentrations $> 200 \mu\text{eq} \cdot \text{L}^{-1}$ would be protected when receiving $15\text{-}20 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ wet SO_4^{2-} deposition. Since most of the lakes surveyed in the Atlantic Provinces have base cation concentrations $< 200 \mu\text{eq} \cdot \text{L}^{-1}$ (median C_b levels ranged from 40 to $154 \mu\text{eq} \cdot \text{L}^{-1}$ for AG 1 to 11; RMCC, 1990a), it is expected that deposition substantially less than $15 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ (see Figure 2) will be required to effect a major improvement in lake acidity levels. In fact, for lakes that had $\text{pH} < 6$ under background deposition their critical load will be the background value, i.e. $< 8 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$. The notion of a single target deposition for all of eastern Canada is clearly faulty. In order to achieve more substantial decreases in SO_4^{2-} deposition in Atlantic Canada, the contributing sources will have to be identified more precisely and further emission controls targeted for these sites.

This paper has focused on changes in surface water chemistry that may be expected when SO_2 emission reductions are implemented in North America. This was achieved by linking atmospheric transport and deposition models with water chemistry models. In actual fact,

it is the biological response of ecosystems that is of greatest interest to policy makers. Rudimentary biological models exist (e.g. Matuszek *et al.*, 1988; Minns *et al.*, 1990) that relate fishery diversity to water pH. We will attempt to link these models with our water chemistry predictions in the future.

Overall, our linkage and application of models to predict an ecological outcome for a SO₂ emission control program has proved to be a useful assessment exercise. The critical data needs are clearly identified, e.g. a high quality, comprehensive regional deposition and water quality database. It is necessary to make some subjective decisions (e.g. selection of data aggregates and assignment of hypothetical SO₂ reductions) in order to produce a timely yet realistic evaluation that is suitable for use by policy makers. If future information shows that these subjective decisions are seriously in error, they may be altered and a new assessment prepared with relatively little effort. Our analysis presents a notion, i.e. the spatial and to some extent temporal trend, of the environmental effect expected from an anthropogenic action. The ultimate veracity of the predictions will only be established by maintenance of a long-term monitoring program.

ACKNOWLEDGEMENTS

This paper draws heavily on analyses prepared to assess the current knowledge of LRTAP effects in Canada (i.e. RMCC, 1990a). We are indebted to a large number of individuals, and while it is not possible to list all who have materially contributed, A.S. Fraser, J. Jones, J. Storey, and F. Norouzian have played key roles in completing this work. We are grateful for their contribution.

Table I: U.S. SO₂ emission estimates (kilotons) used as input to the Lagrangian atmospheric model (see text for assignment rationale).

Region	SO ₂ Emissions (kilotons)		
	1980 Base Case	After 5 million kiloton reduction	After 10 Million kiloton reduction
Ohio	2884	2009	1133
Illinois	1537	1070	604
Pennsylvania	1908	1329	749
Indiana	1922	1338	755
Michigan	896	688	479
West Virginia	1150	802	452
New York	869	667	465
Wisconsin/Iowa	1186	911	635
Minnesota	273	210	146
Maine	158	121	85
Vermont/New Hampshire	120	93	64
Kentucky	1175	1004	834
Tennessee	1158	1072	986
Missouri	1295	1200	1103
Alabama	841	778	717
Virginia/North Carolina	1062	983	904
Florida	1226	1136	1044
Georgia/South Carolina	1249	1156	1064
Maryland/Delaware/ New Jersey/D.C.	778	721	663
Arkansas Louisiana/ Mississippi	905	838	771
Massachusetts/ Conn./Rhode Island	435	402	374
Western States	4763	4262	3763
Total	27790	22790	17790

Table II: Name of tertiary watershed Aggregates (AGs) and lake numbers for all lakes >0.18 ha and >1 ha within each AG (see Figure 1 also).

AG No.	Name ¹	Lake Numbers ²	
		>0.18 ha	>1 ha
1	S Nova Scotia-New Brunswick	4091	1969
2	Mid-eastern Nova Scotia	3258	1825
3	N Nova Scotia-New Brunswick	17588	5357
4	Cape Breton Highlands	352	180
5	Avalon	9295	4181
6	E Newfoundland	33650	15736
7	N&S Newfoundland	45947	17296
8	Central & W Newfoundland	42027	18071
9	Belle Isle	14524	5311
10	E Quebec - S Labrador ²	246700	108583
11	N Labrador ²	----	----
12	St. Lawrence S Shore	16920	4487
13	Saguenay ²	126097	65339
14	Laurentide	50959	28972
15	SW Quebec	45021	22737
16	Ottawa Valley	19458	7851
17	Central Ontario	57534	23649
18	S Ontario	5947	1812
19	Sudbury-Noranda	45113	19257
20	N Ontario ²	219981	106412
21	NW Ontario ²	----	----
22	N Québec ²	176165	92147
Total (excluding AG 11 and 21)		1180627	551172

¹ lakes in AG 2, 5, and 19 have local influences; AG 4, 6 and 21 have many coloured lakes.

² lake numbers and areas from the inventory of Hélie and Wickware (1990) that covers southeastern Canada east of 90°W longitude and south of 52°N latitude (16% of the country); AG 10, 13, 20 and 22 are partially outside the inventory area and the numbers have been areally prorated; AG 11 and 21 fall completely outside the inventory.

Table III: Percentage of modelled lakes predicted to have $\text{ANC} < 0 \mu\text{eq.L}^{-1}$ in tertiary watershed aggregates (AGs) under current SO_4^{2-} deposition and 3 SO_2 emission control scenarios. See text for details of the emission control scenarios.

AG No.	n	Percent ANC < 0			
		Curr.	2	3	4
1	280	53	52	52	52
2	59	22	22	22	22
3	89	23	20	18	17
4	33	61	61	61	61
6	60	20	18	17	17
7	17	29	24	24	24
8	30	23	23	20	20
10	103	21	19	18	17
11	10	0	0	0	0
12	64	2	0	0	0
13	251	10	8	6	3
14	408	7	5	4	3
15	529	2	1	1	0
16	80	1	0	0	0
17	1009	7	5	4	2
19	287	31	13	11	6
20	541	1	0	0	0
21	36	6	6	6	6
22	16	6	6	6	6

Figure 1: Location and numeric designation of tertiary watershed Aggregates (AGs) in eastern Canada used in this paper. Data from shaded AGs are presented in Figure 3.

Figure 2: Predicted location of the 10 (lines) and 20 (shading) $\text{kg. ha}^{-1} \cdot \text{yr}^{-1}$ wet SO_4^{2-} deposition contours for the 4 SO_2 emission control Scenarios.

Figure 3: Lake ANC boxplots for AGs in SE Canada. Boxplots include observed (O), and modelled under Current (C) SO_4^{2-} deposition (i.e. Scenario 1) and under 3 additional SO_2 emission reduction Scenarios (S2, S3, S4).

Figure 4: Percentage of lakes predicted to have $\text{pH} < 6$ in AGs of SE Canada under 4 SO_2 emission control Scenarios.

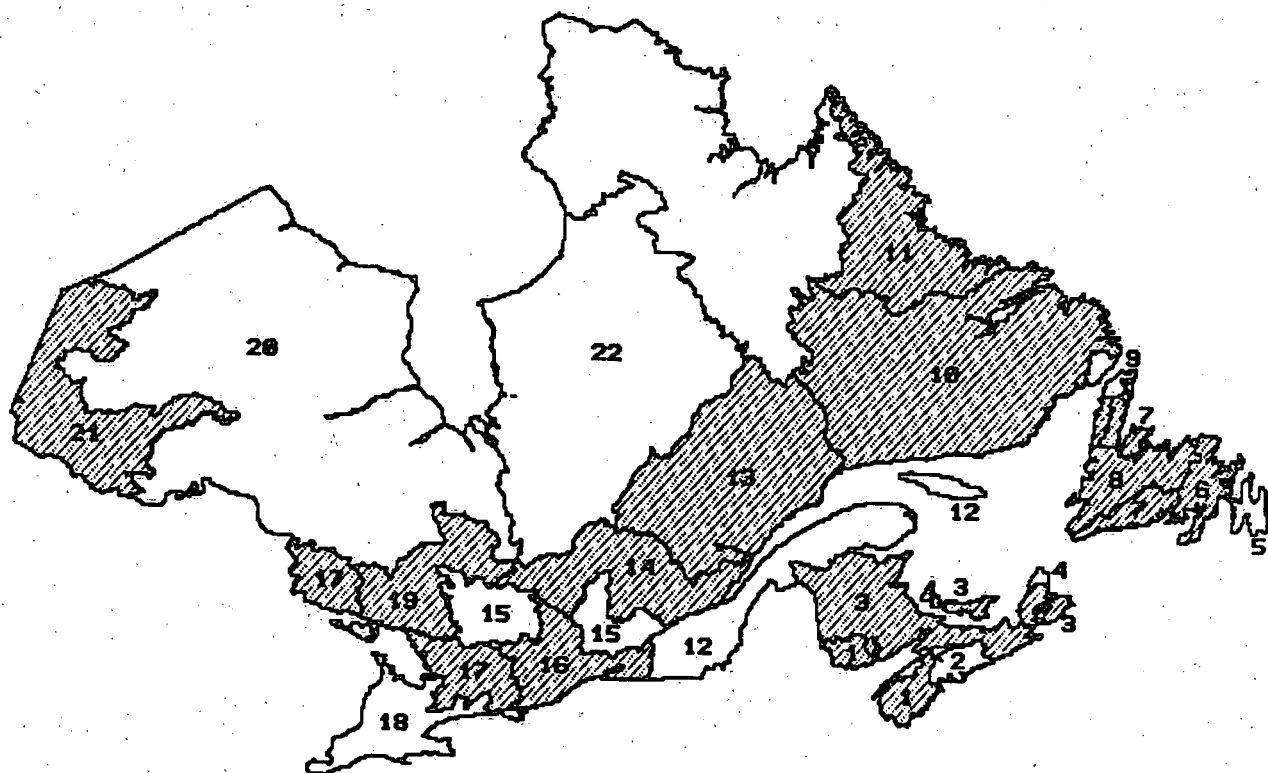


Figure 1

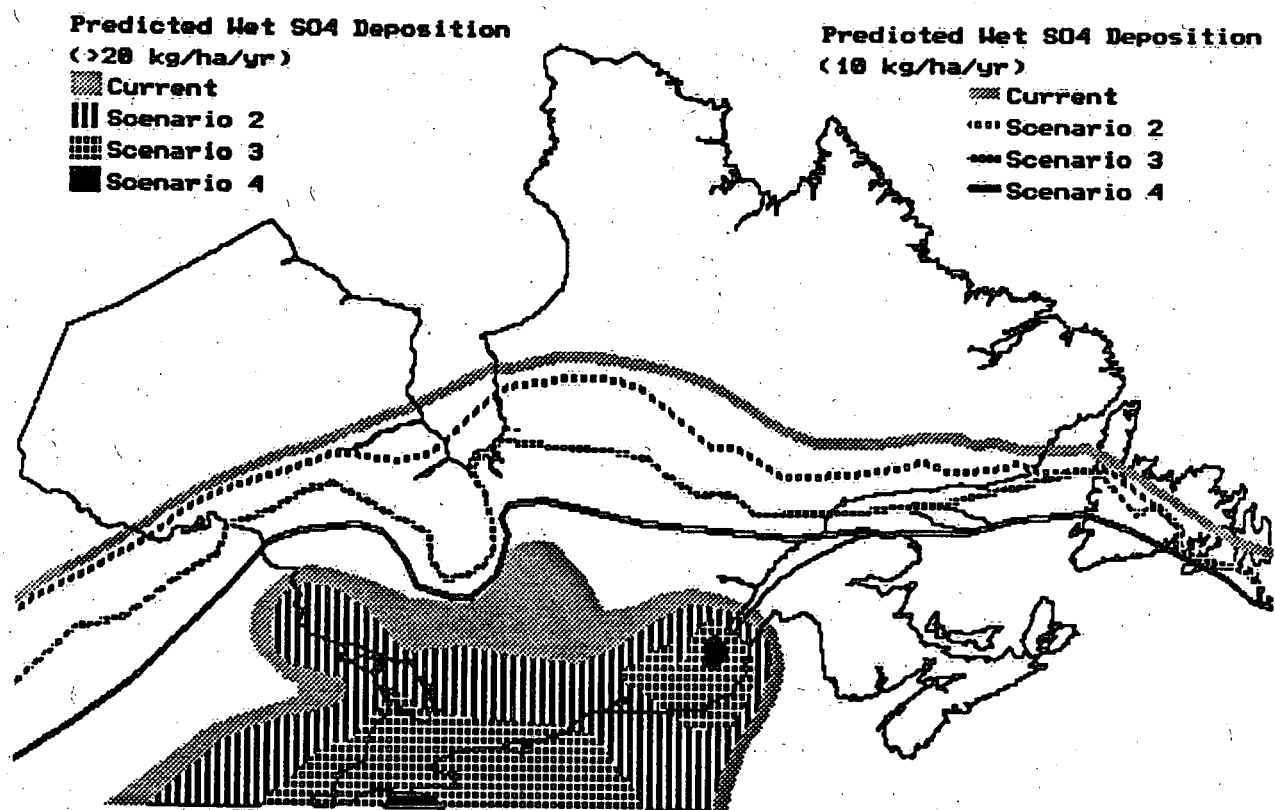


Figure 2

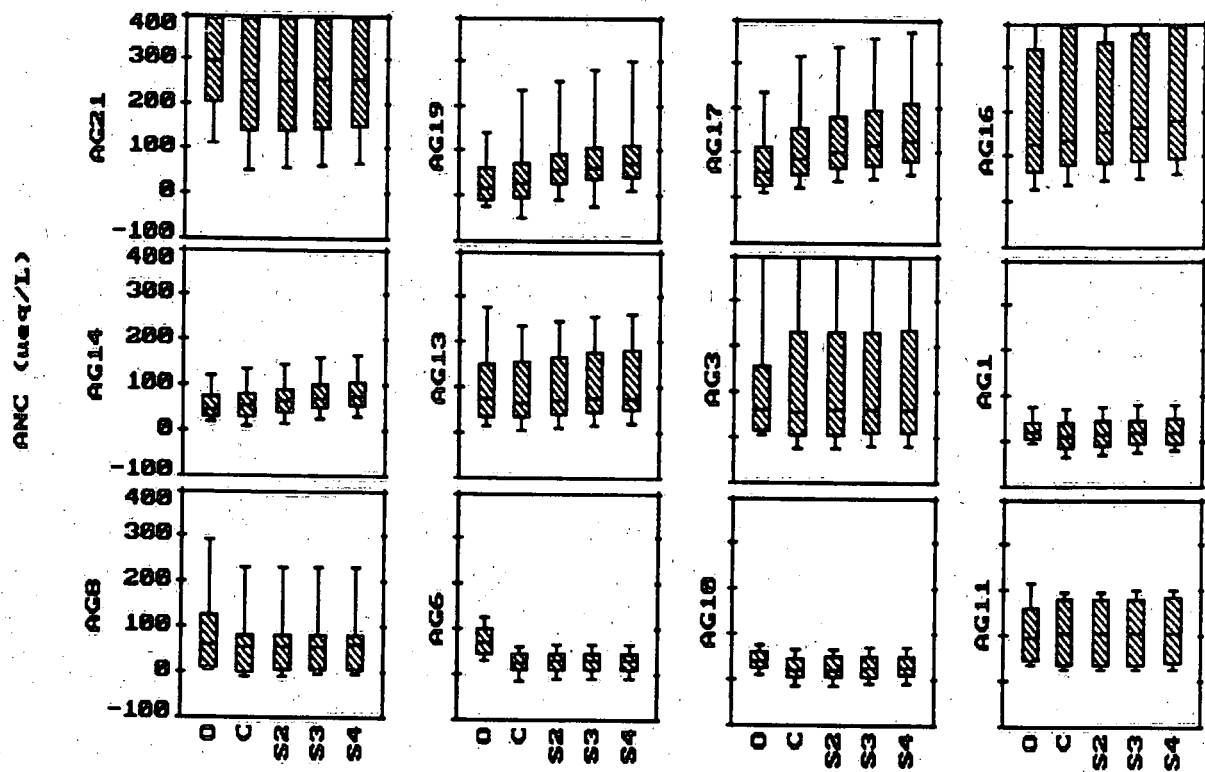


Figure 3

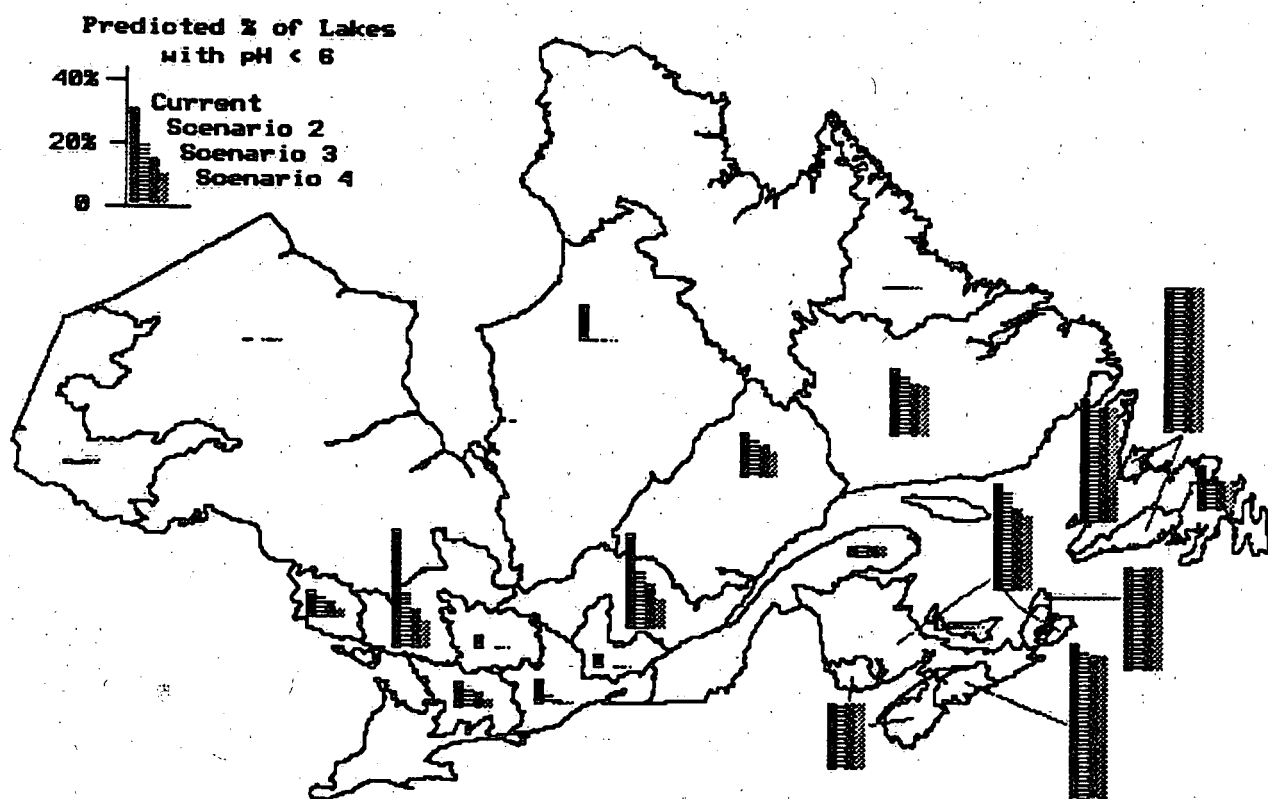


Figure 4

REFERENCES

- Barth, H. (ed): 1987, Reversibility of Acidification, Elsevier Applied Science Publ. Ltd., New York, 175 p.
- Charles, D.F. (ed): in press, Acid Deposition and Aquatic Ecosystems: Regional Case Studies, Springer-Verlag.
- Dennis, R.L., Barchet, W.R., Clark, T.L., Seilhop, S.K. and Roth, P.M.: 1989, 'Evaluation of Regional Acidic Deposition Models', NAPAP SOS/T Rep. 5, National Acid Precipitation Assessment Program, Washington, D.C.
- Dillon, P.J., Jeffries, D.S., and Scheider, W.A.: 1982, 'The use of calibrated lakes and watersheds for estimating atmospheric deposition near a large point source', Wat. Air Soil Pollut. **18**, 241.
- Dupont, J.: 1988, 'Etat de l'acidité des lacs de la région hydrographique de l' Outaouais', Québec Ministry of the Environment, Report No. PA-13, 74p.
- Dupont, J.: 1989, 'État de l'acidité de lacs de la région hydrographique de la Maurice', Québec Ministry of the Environment, Report No. Pa-38. 131p.
- Ellenton, G., Ley, B., and Misra, P.K.: 1985, 'A trajectory Puff Model of Sulfur Transport For Eastern North America', Atmos. Environ. **19**, 727-777.
- Ellenton, G., Misra, P.K., and Ley, B.: 1988, 'The Relative Role of Emission Change and Meteorological Variability in Variation of Wet Sulfur Deposition: A Trajectory Model Study', Atmos. Environ. **22**, 547-556.
- Fraser, A.S., Jones, J.L., Jeffries, D.S.: 1990, 'Long Range Transport of Atmospheric Pollutants Eastern Canada Database Characteristics', NWRI Contribution #90-61, National Water Research Institute, Burlington, Ontario.

- Gunn, J.M., Hamilton, J.G., Booth, G.M., Wren, C.D., Beggs, G.L., Rietveld, H.J., and Munro, J.R.: 1990, 'Survival, growth, and reproduction of lake trout (Salvelinus namaycus) and yellow perch (Perca flavescens) after neutralization of an acidic lake near Sudbury, Ontario', Can. J. Fish. Aquat. Sci. **47**, 446.
- Hélie, R.G., and Wickware, G.M.: 1990, 'Quantitative assessment of surface water resources at risk due to acidification in eastern Canada'. Discussion Paper No. 1, Sustainable Development Branch, Environment Canada, Ottawa.
- Henriksen, A., Lien, L., Traaen, T.S., Sevaldrud, I.S., and Brakke, D.F.: 1988, 'Lake Acidification in Norway - Present and Predicted Chemical Status', Ambio **17**, 259-266.
- Henriksen, A., Lien, L., and Traaem, T.S.: 1990, "Critical Loads For Surface Waters - Chemical Criteria for Inputs of Strong Acids, Report 22/1990, Norwegian Institute for Water Research, Oslo, Norway.
- Kelso, J.R.M., Minns, C.K., Gray, J.E., and Jones, M.L.: 1986, 'Acidification of surface waters in eastern Canada and its relationship to aquatic biota', Can. Spec. Publ. Fish. Aquat. Sci. **87**, 42.
- Krester, W., Gallagher, J., and Nicoletter, J.: 1989, 'Adirondack Lakes Study 1984-1987: An evaluation of fish communities and water chemistry'. Adirondack Lakes Survey Corporation, Ray Brook, New York.
- Lam, D.C.L., Swayne, D.A., Storey, J., Wong, I., and Fraser, A.S.: 1988, 'Regional Analysis of Watershed Acidification using the Expert Systems Approach', Environ. Software **3**, 127.
- Lam, D.C.L., Swayne, D.A., Storey, J., and Fraser, A.S.: 1989a, 'Watershed acidification models using the knowledge-based systems approach', Ecol. Modelling **47**, 131.

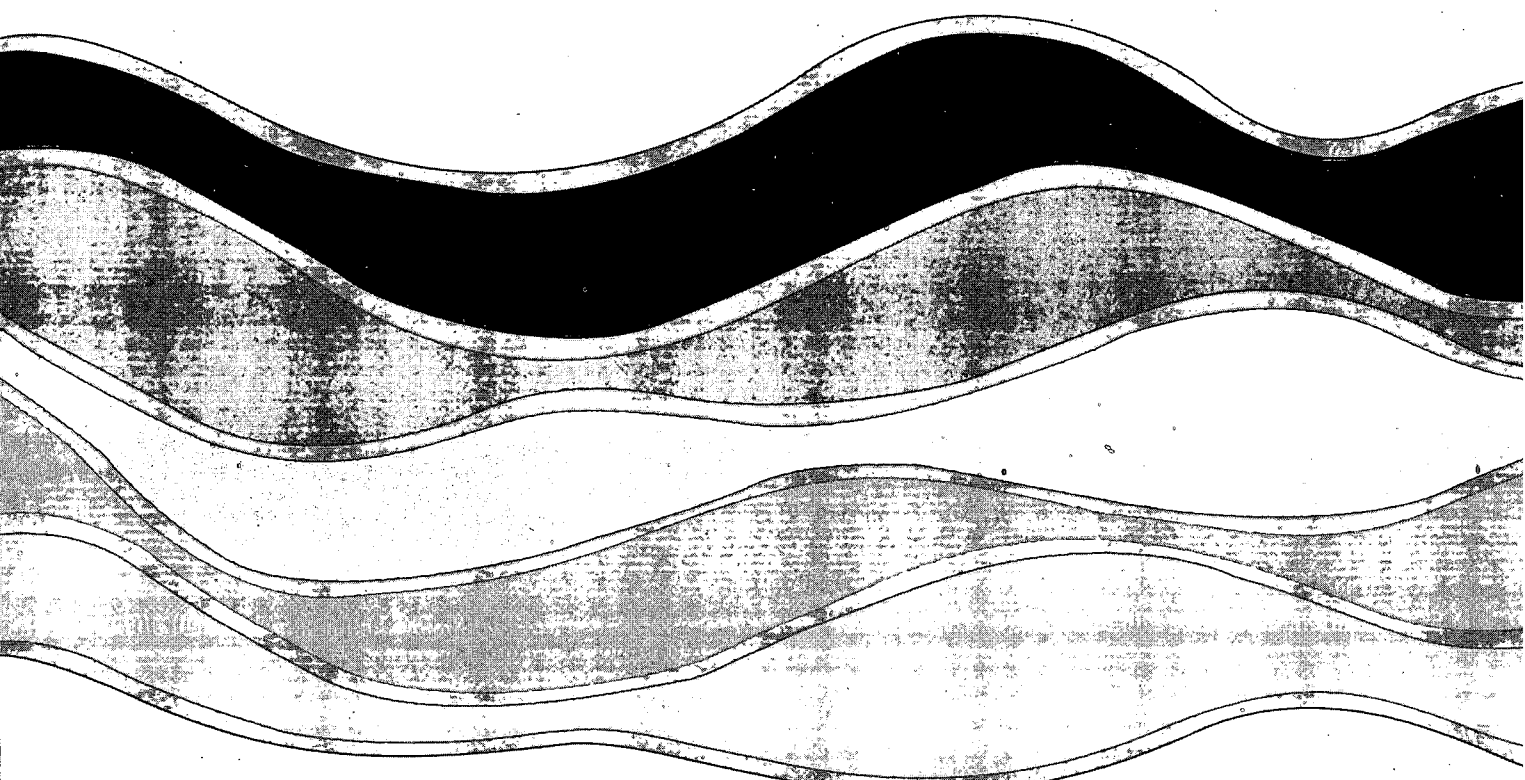
- Lam, D.C.L., Swayne, D.A., Fraser, A.S., Story, J., and Wong, I.: 1989b, 'A knowledge-based approach to regional acidification modelling: a case study of New Brunswick, Canada', in Kamari *et al.* (eds), Regional Acidification models: geographic extent and time development, Springer-Verlag, Berlin pp. 213-226.
- Lam, D.C.L., Bobba, A.G., Bourbonniere, R.A., Howell, G.D., and Thompson, M.E.: 1989c, 'Modelling organic and inorganic acidity in two Nova Scotia rivers', Wat. Air Soil Pollut. **46**, 277.
- Marmorek, D.R., Jones, M.L., and Minns, C.K.: 1985, 'A simple model to predict the extent of damage to inland fisheries due to acidic precipitation', Environmental and Social Systems Analysts Ltd., Toronto, Canada.
- Marmorek, D.R., Jones, M.L., Minns, C.K., and Elder, F.C.: 1990, 'Assessing the potential extent of damage to inland lakes in Eastern Canada due to acidic deposition, I, Development and evaluation of a simple "site" model', Can. J. Fish. Aquat. Sci. **47**, 55.
- Matuszek, J.E., Goodier, J., and Wales, D.L.: 1988, 'The occurrence of cyprinids and other small fish species in relation to pH in Ontario lakes', Ontario Fisheries Acidification Report Series, No. 88-14, Ontario Ministry of Natural Resources, Toronto, Ont., 109 p.
- Minns, C.K., Moore, J.E., Schindler, D.W., and Jones, M.L.: 1990, 'Assessing the potential extent of damage to inland lakes in Eastern Canada due to acidic deposition. IV, Predicting the response of potential species richness in several taxa of aquatic biota', Can. J. Fish. Aquat. Sci. **47**, 821.

- Neary, B.P., Dillon, P.J., Munro, J.R., and Clair, B.J.: 1990, 'The Acidification of Ontario lakes; an assessment of their sensitivity and current status with respect to biological damage', Ontario Ministry of Environment Report, Dorset Research Centre, Dorset, Ontario, 170 p.
- Nilsson, J., and Grennfelt, P.: 1988, 'Critical loads for Sulphur and nitrogen', Proc. UN ECE Workshop on Critical Loads, Skoskloster, Sweden.
- Niragu, J.O., (ed): 1984, Environmental Impacts of Smelters, John Wiley & Sons, Toronto, 608 p.
- Oliver, B.G., Thurman, E.M., and Malcolm, R.L.: 1983, 'The contribution of humic substances to the acidity of colored natural waters', Geochim. Cosmochim. Acta 47, 2031.
- Rochelle, B.P., Church, M.R., and David, M.B.: 1987, 'Sulfur retention at intensively studied sites in the U.S. and Canada', Wat. Air Soil Pollut. 33, 73.
- RMCC: 1990a, 'The 1990 Canadian long-range transport of air pollutants and acid deposition report, Part 4: Aquatic Effects', Federal-Provincial Research and Monitoring Committee, Ottawa, Ontario.
- RMCC: 1990b, 'The 1990 Canadian long-range transport of air pollutants and acid deposition report, Part 3: Atmospheric Sciences', Federal-Provincial Research and Monitoring Committee, Ottawa, Ontario.
- RMCC: 1990c, 'The 1990 Canadian long-range transport of air pollutants and acid deposition report, Part 2: Emissions and Controls', Federal-Provincial Research and Monitoring Committee, Ottawa, Ontario.

- Schnoor, J.L., Lee, S., Nilolaidis, N.P., and Nair, D.R.: 1986, 'Lake resources at risk to acidic deposition in the eastern United States', Wat. Air Soil Pollut. **31**, 1091.
- Shaw, R.: 1982, 'Deposition of atmospheric acid from local and distant sources at a rural site in Nova Scotia', Atmos. Environ. **16**, 337.
- Small, M.J., and Sutton, M.C.: 1986, 'A regional pH - alkalinity relationship', Wat. Res. **20**, 335-344.
- Thornton, K., Marmorek, D., Ryan P.F.: 1990, 'Methods for projecting future changes in surface water acid-base chemistry', NAPAP SOS/T Rep. 14, National Acid Precipitation Assessment Program, Washington, D.C.
- U.S.-Canada: 1983, 'Memorandum of intent on transboundary air pollution.' Report of the Impact Assessment Working Group 1, Section 3-Aquatic Effects, 259 p.
- United States Congress: 1990, '1990 Clean Air Act Amendments, Public Law 549 of the 101st Congress', House Document Room, Washington, D.C.
- Watt, W.D.: 1986, 'The case for liming some Nova Scotia salmon rivers', Wat. Air Soil Pollut. **31**, 775.
- Wright, R.F., Lotse, E., and Semb, A.: 1988, 'Reversibility of acidification shown by whole-catchment experiments,' Nature **334**, 670-675.



3 9055 1017 0340 2



NATIONAL WATER RESEARCH INSTITUTE
P.O. BOX 5050, BURLINGTON, ONTARIO L7R 4A6

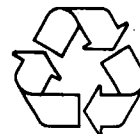


Environment Environnement
Canada Canada

Canada

INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX
C.P. 5050, BURLINGTON (ONTARIO) L7R 4A6

Think Recycling!



Pensez à recycler!