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Aquatic effects of acidic deposition in Canada: present and predicted future situation

Effets des précipitations acides sur les écosystèmes aquatiques au Canada : situation actuelle et perspectives futures

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RÉSUMÉ

Cet article représente une évaluation de l'état actuel et des tendances observées dans les écosystèmes lacustres, ainsi que de leur état futur probable lorsque les réductions d'émissions requises dans le cadre de l'Entente Canada-États-Unis sur la qualité de l'air auront été complétées. Outre une synthèse des faits saillants de ce dossier pour l'ensemble du Canada, le présent article compile aussi l'ensemble des données physico-chimiques récentes (8 874 échantillons) observées sur 2 779 lacs de l'est canadien, ainsi que celles recueillies (1 012 échantillons) sur 252 lacs de l'ouest canadien depuis 1985. Des données biologiques (poissons, benthos, zooplankton et oiseaux aquatiques) ont également été compilées pour identifier l'ampleur des dommages biologiques.

Les nombreux lacs ayant subi une acidification anthropique récente sont situés pour la plupart dans l'est du Canada où les dépôts de SO_4^{2-} sont élevés. La sensibilité des sols influence également leur distribution spatiale. Durant la période s'échelonnant de 1981 à 1994, seulement 33 % des 202 lacs faisant l'objet d'un suivi temporel dans l'est du Canada ont montré une amélioration significative de leur acidité (réduction) en réponse à la baisse des dépôts de SO_4^{2-} (11 % des lacs ont subi une hausse d'acidité et 56 % n'ont montré aucun changement). Plus de la moitié des lacs ayant récupéré se situent à proximité de Sudbury en Ontario. Plusieurs processus biogéochimiques sont responsables du retard dans la réversibilité de l'acidification. Pour cette raison, la récupération biologique a été très faible dans l'est canadien, exception faite de la région immédiate de Sudbury.

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Trois scénarios d'émissions ont été considérés : scénario 1 : niveaux d'émission canadiens et américains de 1985 ; scénario 2 : émissions canadiennes de 1994 et émissions américaines de 1990 ; scénario 3 : réductions d'émissions américaines et canadiennes complétées. Ces scénarios de réductions d'émissions, qui ont été utilisés comme données d'entrée à des modèles stationnaires simulant la chimie des eaux de surface et qui ont été appliqués à cinq grandes zones lacustres de l'est canadien, suggèrent que la proportion de lacs « endommagés » (définis comme étant des lacs de pH < 6) diminuera conséquemment aux réductions d'émissions américaines et canadiennes.

De 11 à 49 % des lacs acidifiés le resteront après l'ensemble des réductions prévues (scénario 3). Le Québec et l'Ontario, qui reçoivent actuellement les plus fortes retombées acides, bénéficieront le plus des réductions. Les gains environnementaux seront plus faibles dans l'est et dans l'ouest du Canada. De plus faibles dépôts et une contribution naturelle à l'acidité pourrait expliquer cette moins grande récupération.

Il est maintenant reconnu que le pH est le principal facteur d'influence de la diversité spécifique du poisson, bien que d'autres facteurs comme la morphométrie du lac, l'altitude et les concentrations de COD soient aussi en partie responsables. Une réduction des dommages biologiques (*i.e.* baisse des disparitions de populations de poisson) serait donc possible, mais cette amélioration ne surviendra qu'après la hausse du pH des eaux de surface. L'importance relative des gains au plan biologique suivra un patron similaire à celui des aspects chimiques. Des dommages significatifs aux écosystèmes lacustres subsisteront néanmoins après réalisation de l'ensemble des réductions d'émissions. Des pertes de populations de poissons devraient subsister dans 6 % (Sudbury) à 15 % (Kejimkujik) des lacs. Compte tenu du grand nombre de lacs situés dans le sud-est canadien, les pourcentages précédents impliquent que les ressources piscicoles perdues pourraient être très élevées. La restauration des communautés piscicoles devra passer dans bien des cas par un réensemensement en poisson. De nouveaux programmes de contrôle visant des réductions additionnelles d'émissions seront dès lors nécessaires pour protéger adéquatement les écosystèmes sensibles.

Mots clés : *précipitation acide, effets aquatiques, contrôle des émissions, tendances, modélisation, évaluation.*

SUMMARY

This paper is an assessment of the current status and trends of Canadian lake systems, and their likely status after the effect of the emission controls required by the Canada/US Air Quality Agreement is fully realized. Many anthropogenically acidified lakes presently occur in that part of eastern Canada where SO_4^{2-} deposition is elevated. Terrain sensitivity also influences their spatial distribution. From 1981 to 1994, only 33% of 202 lakes monitored across eastern Canada showed a statistically significant improvement (reduction) in acidity in response to reduced SO_4^{2-} deposition (11% had increasing acidity and 56% showed no change). Over half of the improving lakes are near Sudbury, Ontario. Several biogeochemical processes are delaying de-acidification. As a result, there has been little biological recovery in eastern waters, except near Sudbury. Steady-state water chemistry modelling suggests that the proportion of "damaged" lakes (defined as having pH < 6) will decline in response to both the Canadian and US emission controls. Reductions in biological damage (*e.g.* fewer lost fish populations) are expected also, but they will lag behind chemical improvement. Significant damage to aquatic ecosystems will remain after all chemical and biological improvements are realized. Further controls will be needed to protect sensitive ecosystems.

Key-words: *acid rain, aquatic effects, emission control, trends, modelling, assessment.*

1 - INTRODUCTION

Recognition of "acid rain" as an agent of regional lake acidification first occurred in Scandinavia (see papers in DRABLØS and TOLLAN 1980). As an environmental issue in Canada, surface water acidification gained prominence during the 1970s. BEAMISH and HARVEY (1972) and BEAMISH (1976) had observed losses of fish species in the La Cloche Mountain lakes of Ontario that they linked to acidification caused by atmospheric deposition of pollutants presumed to originate from the nearby smelters at Sudbury. Soon after, several studies demonstrated that lake acidification was a more wide-spread phenomenon (*e.g.* DILLON *et al.* 1978 and WATT *et al.* 1979; see also HARVEY *et al.* 1981 for a general review of the early literature). As a result, many research and monitoring projects were initiated to document the extent and magnitude of the effects of acidic deposition on Canadian surface waters (results reviewed in RMCC 1990). Concern also developed in the USA resulting in the "NAPAP" program and culminating in a comprehensive scientific review of the issue (IRVING 1991). The scientific consensus on aquatic effects obtained during this time period played a significant role in justifying the Canadian and US SO_2 emission controls specified in the 1991 Canada/US Air Quality Agreement (AQA).

Since publication of RMCC (1990) and the signing of the Canada/US AQA, study of aquatic effects in Canada has focussed on completion of specific projects and monitoring to verify that ecological improvements occur as emission controls are implemented (reviewed in JEFFRIES 1997). Canadian emission controls required by the AQA were fully implemented in 1994. Full implementation of *the US controls is expected to occur within the next decade.*

The purpose of this paper is to provide a summary of Canadian aquatic effects research and monitoring that has occurred since 1990, both in terms of the current status and predicted future situation once all SO_2 controls are implemented.

2 - METHODS

2.1 Chemical data

Data to assess both the chemical status and trends of eastern Canadian fresh waters were compiled from a number of sources. First, "recent" (1985 or later) chemical data for the provinces east of Ontario were screened from the database compiled by FRASER *et al.* (1990), and recent data for Ontario were screened from the current version of its "Acid Lakes Database" (cf. NEARY *et al.* 1990). Second, new information was added whenever possible (*e.g.* data from MCNICOL *et al.* 1996 for Ontario and Nova Scotia; from KELSO *et al.* 1992 for central Ontario; from CLAIR *et al.* 1995 for Nova Scotia, Newfoundland, and Québec; from DUPONT 1992a, b and PAPINEAU 1996 for southern Québec; and unpublished data from W. Pilgrim for New Brunswick).

The eastern Canada compilation contained 8874 samples from 2779 lakes. Sampled lakes in Nova Scotia, New Brunswick and Ontario are clustered, usually in sensitive terrain, whereas coverage in south-central Labrador and Newfoundland is fairly uniform (although sparse) and quite comprehensive in southern Québec. The database is not a statistical subset of the population of ~800,000 water bodies extant in southeastern Canada (HÉLIE *et al.* 1993), although a major component of the Québec information is from DUPONT (1992a, b) which was a statistically-based survey of the lakes ranging from 10 to 2000 ha in area. Small lakes and wetlands are greatly under-represented in the database. The database is conservative in nature; that is, conclusions derived from it tend, if anything, to under-estimate the magnitude of aquatic effects.

Chemical data for western Canadian lakes were compiled relaxing the "recent" limitation in order to maximize the information available. Data from JEFFRIES (1995) were used for Manitoba and Saskatchewan, from SAFFRAN and TREW (1996) for Alberta, and from PHIPPEN *et al.* (1996) for British Columbia. The western compilation contained 1012 samples from 252 lakes. Geographic coverage is not uniform; sampled lakes tend to occur in sensitive terrain.

2.2 Biological data

JEFFRIES (1997) assessed biological effects both by reviewing recent developments reported in the literature, and by compiling a database to facilitate regional analyses, to develop new biotic effects models, and/or to validate existing ones. Biological data came from a variety of sources, collection periods, and regions within eastern Canada (see DOKA *et al.* 1997 for details). Specifically, information on fish, zooplankton, benthic invertebrates and water birds was compiled along with associated information on lake location, area, depth, pH and dissolved organic carbon (DOC). Fish data were available from all eastern provinces, as were zooplankton data except for New Brunswick. Waterbird and benthos data were restricted to Ontario.

2.3 Modelling

An integrated assessment model (IAM, LAM *et al.*, 1998) was used to predict the eventual status of lake chemistry and biology after all SO_2 controls required by the Canada/US AQA are fully implemented. The IAM is an open architecture framework that allows any component model to be linked to another component model in a causal chain, *e.g.* linkage of SO_2 emission inventory data with a continental-scale atmospheric transport, source-receptor model (OLSON *et al.* 1983), steady- state water chemistry models (LAM *et al.* 1994), fisheries and zooplankton response models (DOKA *et al.* 1997), and/or wildlife response models (McNICOL *et al.* 1995a).

Three scenarios of SO_2 emission control will be used here. Scenario 1 (S1) corresponds to the situation pre-dating implementation of controls required by the Canada/US AQA by utilizing measured Canadian and US emission levels for 1985. Scenario 2 (S2) uses measured Canadian emissions for 1994 (*i.e.* after full implementation of its required controls) and measured US emissions for 1990 (*i.e.* an approximation of the equivalent time period for the US in which emissions are less than 1985 but do not yet reflect most of the controls required by the AQA). Scenario 3 (S3) corresponds to the situation after full implementation of emission controls in both Canada and the USA by using 1994 Canadian emissions and future US emissions as estimated by US EPA (1995). The relative effect of Canadian and US controls on lake chemistry and biology is approximated by the difference between S2 and S3.

Emissions for 40 North American source regions were input to the source-receptor model producing wet sulphate (SO_4^{2-}) deposition estimates at 15 receptor stations across northeastern North America (*Fig. 1*, see LAM *et al.*, 1998 for details). Since the spatial distribution of lake chemistry data is not uniform, 5 clusters of lakes that span a wide range in present SO_4^{2-} deposition were specified for Scenario modelling *(Fig. 1, Table 1)*. Average wet SO_4^{2-} deposition for each cluster *(Table 1)* and every lake within each cluster was estimated from the kriged deposition field (JEFFRIES 1997). The deposition estimates are realistic for all the clusters within the spatial domain of the 15 receptor stations. This does not include the Fort McMurray cluster in Alberta however, and it is unlikely that its lakes will experience the reduction in deposition from S2 to S3 suggested in Table 1. Nevertheless, the predicted effect on lake chemistry was calculated for the Fort McMurray cluster to illustrate what could happen under such circumstances. Finally, note that although the deposition levels estimated by the source-receptor model are expressed in terms of wet SO_4^{2-}, lake chemistry models used total SO_4^{2-} deposition (*i.e.* wet plus dry) as the driving input. The dry component of the total SO_4^{2-} deposition was assigned as in RMCC (1990).

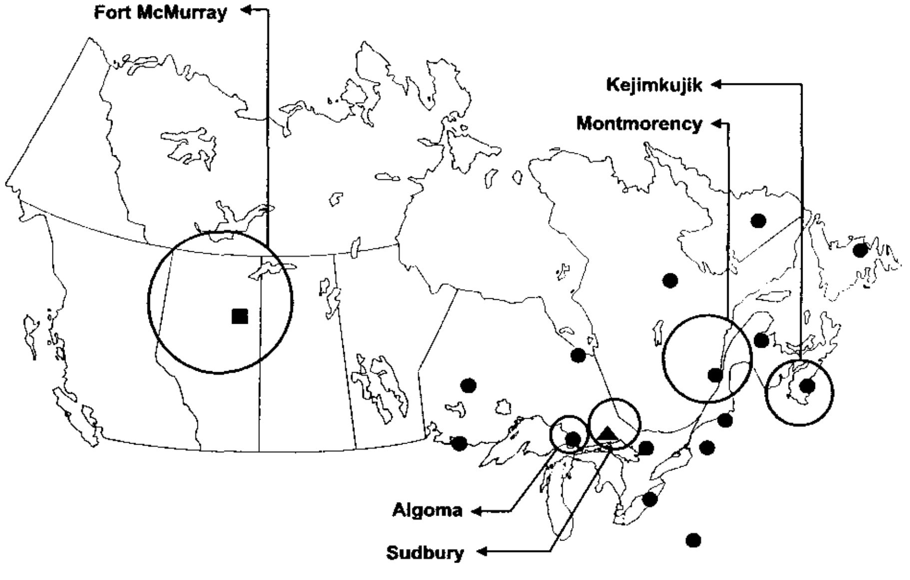

Figure 1 *Location of the 5 lake clusters used to assess "damage" related to 3 scenarios of SO_4^{2-} deposition (see* Table 1*). The spots are deposition receptor sites used by the source-receptor component of the IAM. The triangle is Sudbury and the square is Fort McMurray.*

Localisation des 5 groupements de lacs utilisés pour évaluer les « dommages » relatifs aux 3 scénarios de dépôts de SO_4^{2-} (voir *tabl. 1*). Les points représentent les sites de réception utilisés par les composantes source-réception du IAM. Le triangle représente Sudbury et le carré représente Fort McMurray.

Table 1 *Number of lakes and estimated sea-salt corrected, wet SO_4^{2-} deposition for the 5 clusters in Figure 1 and 3 SO_2 control Scenarios (Section 2.3). The estimated background component included in the Scenario depositions for each cluster is shown also. Note that the Scenario depositions for individual lakes were determined by kriging and may differ slightly from the IAM receptor values given here.*

Tableau 1 Nombre de lacs et dépôts humides en SO_4^{2-} corrigés pour les sels marins pour les 5 groupements de la figure 1 et les 3 scénarios de contrôle du SO_2 (section 2.3). La composante naturelle en SO_2 incluse dans les scénarios de dépôts pour chaque groupe de lacs est aussi présentée. Veuillez noter que les dépôts relatifs aux scénarios pour chaque lac ont été déterminés par krigeage et peuvent différer légèrement des valeurs présentées ici pour les récepteurs IAM.

Cluster	N° of Lakes	Sea-salt Corrected Wet SO_4^{2-} Deposition ($kg \cdot ha^{-1} \cdot yr^{-1}$)			
		Scenario 1	Scenario 2	Scenario 3	Background
Kejimkujik	208	14.4	13.6	12.0	5.6
Montmorency	296	21.6	18.7	16.4	4.8
Sudbury	202	25.6	21.5	17.8	3.5
Algoma	240	19.3	17.2	14.0	3.6
Fort McMurray	105	5.6	4.7	2.5	1.5

The water chemistry model calculates pH for each lake. The pH distribution for each cluster and each Scenario was evaluated relative to a threshold value. BAKER *et al.* (1990), JEFFRIES (1997) and RMCC (1990) all conclude that pH 6 is a suitable threshold for defining the onset of acidification damage in aquatic ecosystems. For the remainder of this paper, "damage" evaluated using this chemical criterion will be expressed as the percentage of lakes below the pH 6 threshold. Note however, that application of this threshold is problematic for lakes which have very low base cations and have been acidified by natural organic acids (A^-). Their original or pristine pH (pH_0) was unlikely to ever have been > 6, and application of a pH 6 assessment threshold is obviously inappropriate. We have estimated which lakes in each cluster had $pH_0 < 6$ by using background SO_4^{2-} deposition *(Table 1)* to drive the water chemistry model and specified a cluster subset for "damage" evaluation by simply excluding these lakes. For 4 of the 5 clusters, the number of lakes with $pH_0 < 6$ is small relative to the overall number of lakes, so that the damage estimate for the subset approximates that for the entire sample population. This is not the case for Kejimkujik, however, which complicates the damage evaluation for this cluster (see discussion below).

3 – RESULTS AND DISCUSSION

3.1 Chemical status

The general status of lakes in the chemistry database is shown in Table 2. The waters of Atlantic Canada are generally the most sensitive (*i.e.* low base cations, cf. very low Ca^{2+} in Table 2) and exhibit the greatest proportion of acidic systems

Table 2 *Tenth, 50th and 90th percentile values for selected variables and regions from the water chemistry database. Only the 50th percentile is presented for British Columbia due to the small number of lakes. Calcium and SO_4^{2-} data are sea-salt corrected. Sulphate statistics were calculated only for measurements made by ion chromatography or equivalent. Data for more variables and more statistics are presented in Jeffries (1997).*

Tableau 2 Valeurs des 10ᵉ, 50ᵉ et 90ᵉ centiles pour des variables et des régions données tirées de banque de données chimiques. Seul le 50ᵉ centile est présenté pour la Colombie Britannique en raison du petit nombre de données. Le calcium et le SO_4^{2-} ont été corrigés pour les embruns marins. Les statistiques relatives aux sulfates ont été calculées seulement à partir des mesures obtenues par chromatographie ionique ou l'équivalent. De plus amples données et statistiques sont présentées dans Jeffries (1997).

Region (number of lakes)	**pH**	**Ca^{2+} $\mu eq \cdot L^{-1}$**	**SO_4^{2-} $\mu eq \cdot L^{-1}$**	**Gran Alkalinity $\mu eq \cdot L^{-1}$**	**DOC $mg \cdot L^{-1}$**
Labrador (38)	*5.9, 6.3, 6.6*	*30, 50, 81*	*13, 17, 24*	*25, 49, 79*	*3.2, 5.1, 8.5*
Newfoundland (63)	5.2, 6.1, 6.7	23, 55, 134	21, 24, 35	5, 34, 103	2.2, 5.4, 8.8
Nova Scotia (150)	4.7, 5.4, 6.4	18, 41, 135	33, 50, 96	− 15, 8, 61	2.4, 5.5, 11.1
New Brunswick (166)	5.1, 5.9, 7.3	30, 55, 184	49, 64, 89	− 3, 22, 246	2.1, 3.8, 7.9
Québec (1377)	5.3, 6.0, 6.7	50, 100, 264	31, 63, 125	14, 56, 274	2.9, 5.5, 9.7
Ontario (1037)	5.0, 6.0, 7.1	67, 120, 429	47, 110, 204	− 2, 32, 443	2.7, 5.8, 13.0
Manitoba (26)	no data	250, 374, 702	no data	280, 500, 980	no data
Saskatchewan (27)	6.3, 6.9, 7.5	42, 102, 354	no data	68, 160, 530	no data
Alberta (193)	6.5, 7.5, 8.5	100, 699, 1790	11, 63, 630	266, 1080, 2640	7.9, 22.0, 37.9
British Columbia (6)	7.0	186	no data	191	no data

(alkalinity < 0). Lakes in Ontario and Québec are generally less sensitive with lower acidic proportions relative to lakes sampled in the Atlantic provinces. Lakes in western Canada typically exhibit low sensitivity and almost no evidence of anthropogenic acidification. There are exceptions to all generalizations however. Bedrock and surficial geology is the most important determinant of terrain sensitivity, but climate and other terrain characteristics such as the occurrence of wetlands may be influential as well.

The spatial variation in lake SO_4^{2-} reflects the pattern of SO_4^{2-} deposition with local differences usually related to a within-catchment retention mechanism (*e.g.* SO_4^{2-} reduction in wetlands). Where in-lake SO_4^{2-} reduction is significant (usually lakes with long water retention times), the associated internal alkalinity generation is an important amelioration to acidic SO_4^{2-} inputs. Sulphate deposition is the primary acidifying agent in Canada. Nitrogen-based acidification is significant in < 10% of the lakes for all regions (see also JEFFRIES 1995). Natural acidification by organic anions (A^-) occurs in all provinces but is particularly important in Nova Scotia, Newfoundland and eastern Québec due to the high terrain sensitivity (cf. DOC values in Table 2). See RMCC (1990) for more detailed discussion. The importance of A^- in the Alberta data set reflects the fact that the lakes occur only in the northern half of the province where wetlands are an important landscape feature.

3.2 Chemical trends

From 1980 to 1992, eastern Canadian provinces reduced annual SO_2 emissions from 3.8 to 2.3 Mtonne, while the overall North American reduction was ~4.7 Mtonne or 16.5% (CANADA/US 1994). In both 1993 and 1994, the eastern Canada SO_2 emission control required by the Canada/US AQA was attained (2.2 and 1.7 Mtonne respectively, ENVIRONMENT CANADA 1995). Various papers have demonstrated that SO_4^{2-} deposition is declining in response to the emission reductions (*e.g.* SIROIS 1993, SUMMERS 1995). Similarly, various papers have shown that the changes in deposition caused by emission control are having an effect on surface water chemistry (*e.g.* CLAIR *et al.* 1995, COUTURE 1995, JEFFRIES *et al.* 1995, KELLER *et al.* 1992).

Within the chemical database, 202 lakes in southeastern Canada had sufficiently complete data records to permit evaluation of their acidification trends. Monotonic (*i.e.* unidirectional) trends were analysed for the 1981-1994 period using non-parametric statistical methods (CLUIS *et al.* 1989). Sulphate declined in most of the lakes in Ontario and Québec, whereas SO_4^{2-} in most Atlantic Region lakes did not change. This spatial pattern resembles the pattern of reduced SO_4^{2-} deposition resulting from SO_2 emission control. Thirty-three percent of the 202 lakes showed improvements in their acidity status (increasing pH or alkalinity); 56% showed no change; and 11% continued to acidify. Only near Sudbury, Ontario is acidity improving in the majority of lakes, a result of substantial SO_2 control at local smelters. Lakes near Rouyn-Noranda, Québec are just beginning to show improvements related to implementation of local SO_2 controls in 1989. In the remainder of Ontario, Québec, and the Atlantic region, the acidity of most lakes shows little change.

Several biogeochemical processes (*e.g.* depletion and restoration of the soil pool of base cations, LIKENS *et al.* 1996; temporary storage and release of acids in wetlands, DILLON *et al.*, 1997) and competing stressors (*e.g.* climatic variations, DILLON *et al.* in press, JEFFRIES *et al.* 1995; nitrogen deposition, COUTURE 1995) moderate the rate of response to declining SO_4^{2-} deposition. Just as it has taken several decades to reach the present state of water acidification in southeastern Canada, it will take several decades before higher pH or alkalinity is the predominating response to reduced acidic deposition. Studies of experimentally acidified lakes suggest that when lakes are acidified to pHs < 5, internal alkalinity generating mechanisms may be damaged (KELLY *et al.* 1995). This also reduces the recovery rate once acid inputs are reduced.

3.3 Biological status

Some of the earliest Canadian observations of biological effects were losses of fish species near Sudbury during the 1960s. Since then, study of most trophic levels in the region's lakes has documented biological responses to acidification, and during recent years, encouraging responses to improving chemical conditions (KELLER and GUNN 1995). Phytoplankton and zooplankton species richness increased as pH increased in Sudbury lakes. The increase was greater for phytoplankton than for zooplankton implying that the former is more resilient. However, richness is still lower than in other lakes of the area that never acidified. Studies outside the immediate Sudbury region confirm that zooplankton species richness is related to lake pH and/or alkalinity, but many other factors such as lake morphometry, nutrient status, and the presence/absence of zooplanktivorous fish also play a role (KELLER and CONLON 1994, SHAW and KELSO 1992). There have been few cases of natural recovery of fish communities in Sudbury lakes, but the improved water quality has allowed successful restocking of extinct fish species. In contrast to Sudbury, there is little evidence of regional recovery of aquatic biota in the remainder of southeastern Canada (JEFFRIES 1997).

Artificially induced changes in lake acidity have also provided information on how biological recovery may be expected to proceed. Liming a lake near Sudbury that had only acidified to pH 5.7 resulted in complete recovery of the zooplankton community within 10 years. However, liming of strongly acidified (pH ≤ 4.5), metal contaminated lakes has not caused recovery of the zooplankton community, even after 15 years (YAN *et al.* 1996). The recovery phase of whole-lake acidification experiments have corroborated Sudbury observations. While lagging (as expected) behind chemical recovery, biological recovery of a lake artificially acidified to a pH of ~5.0 did occur to a great extent over a 12-year period (MILLS *et al.* submitted); but recovery in a more strongly acidified lake (pH 4.5) has been extremely slow and the community may never return to the original structure (M.A. TURNER, pers. comm.).

Results of fish surveys and monitoring suggest that pH is the principal factor affecting fish species richness although other factors such as lake morphometry, elevation, and DOC concentrations may be influential as well (MINNS 1989, TREMBLAY and RICHARD 1993). Reductions in fish abundance and distribution linked to low pH generally occur from impaired reproduction and mortality. Acidification causes reductions in macroinvertebrate species richness (summarized by HAVAS and ROSSELAND 1995), particularly loss of calcium-rich taxa that are an important component of the food chain for higher trophic levels (*e.g.* SCHEUHAMMER *et al.* 1997). Recent studies confirm that most effects on water dependent birds accrue through changes in quality and quantity of foods (see review by LONGCORE *et al.* 1993). Aerial insectivores (*e.g.* tree swallows) have lower breeding success near acid-stressed lakes and wetlands (ST. LOUIS and BARLOW 1993). Habitat selection by waterfowl breeding on small lakes is influenced by food web alterations (McNICOL and WAYLAND 1992), and common loon breeding success is reduced on more acid-stressed lakes (McNICOL *et al.* 1995b). Overall, acidic deposition still ranks as one of the most serious threats to aquatic biodiversity (BIODIVERSITY SCIENCE ASSESSMENT TEAM 1994).

3.4 Predicted future chemical status

Modelling of steady-state lake chemistry was restricted to 5 clusters (*Fig. 1, Table 1*). The percentages of lakes damaged in each cluster in response to the 3 deposition Scenarios are presented in Figure 2. Recall that the percentages shown in Figure 2 are relative to the subsets of cluster lakes capable of attaining pH ≥ 6 (*i.e.* having estimated $pH_0 \geq 6$).

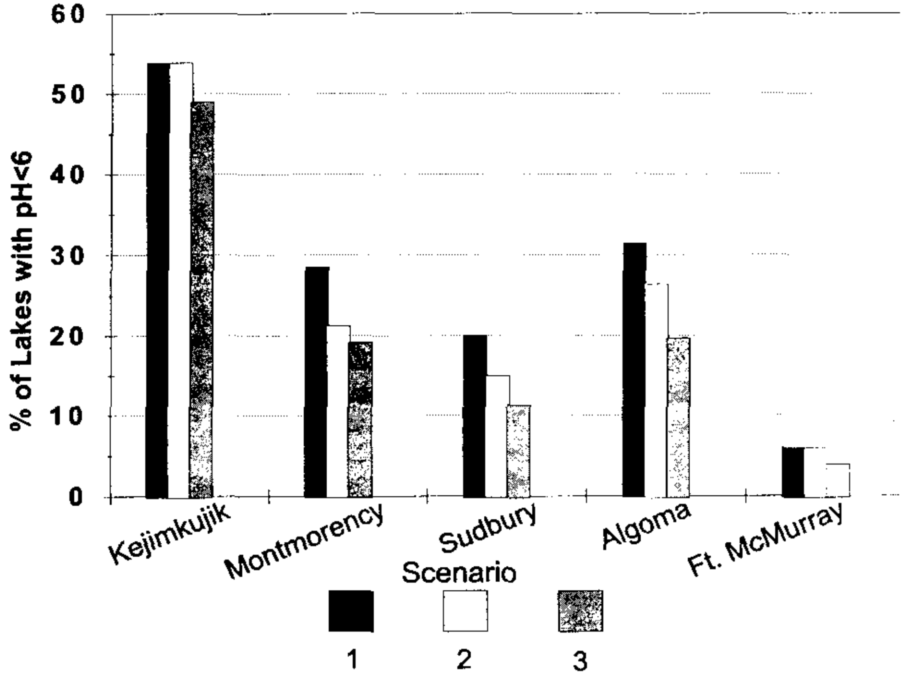

Figure 2 *Estimated percentage of lakes in the five lake clusters damaged (i.e. having pH <6) under three SO_2 emission control (or sulphate deposition) Scenarios. Damage is reported relative to the subsets of lakes with $pH_0 \geq 6$.*

Pourcentages estimés de lacs à l'intérieur des 5 groupements de lacs endommagés (*i.e.* possédant un pH < 6) en regard des trois scénarios de contrôle des émissions en SO_2 (ou des dépôts de sulfates). Les dommages sont exprimés relativement aux ensembles de lacs ayant un $pH_0 \geq 6$.

As expected, the Fort McMurray cluster in western Canada where SO_4^{2-} deposition is the lowest also shows the lowest damage (~6%, recall that S3 for Fort McMurray is unrealistic). For the eastern clusters, the percentage of damaged lakes decreases from S1 (the pre-AQA situation) to S3. Both the Canadian control program (evident from the difference between S1 and S2) and the US program (difference between S2 and S3) effect reductions in damage. However, even after full implementation of all the SO_2 controls required by the Canada-US AQA (S3), 11-49% of the lakes capable of attaining pH ≥ 6 are predicted to remain damaged (pH < 6) depending on cluster. The Québec and Ontario clusters (Montmorency, Sudbury and Algoma) show greater reductions in damage with increasing SO_2 control (Scenarios 1 to 3) than does Kejimkujik. This is as expected since the former clusters are located closer to that part of eastern North America where most of the emission controls occur.

The proportion of lakes with estimated $pH_0 < 6$ is small (0-4%) for the Montmorency, Sudbury and Algoma clusters, and thus, the damage estimates presented in Figure 2 are reasonable approximations of the damages expected for their entire sample populations. This is not true for Kejimkujik however, since 51% of its sample population had estimated $pH_0 < 6$. A large proportion of the Kejimkujik sample population is acidified by A^-. If the Kejimkujik damage percentages from Figure 2 are expressed relative to the overall number of sampled lakes (*i.e.* by including naturally acidified lakes in the percent calculation but considering them as undamaged), then the damage estimates range from 26% (S1) to 24% (S3). In reality, naturally acidified lakes are affected by SO_4^{2-} deposition also. In any case, it is clear that significant damage will remain in all eastern clusters after implementation of presently planned emission controls. Further control of North American SO_2 emissions will be needed to protect a greater proportion.

3.5 Predicted future biological status

The IAM predicts biological responses to reductions in SO_2 emissions by linking various empirical models to the water chemistry models. Results from a fish damage analysis are reported here, although JEFFRIES (1997) also presents results for zooplankton and loons. The approach differs from that quantifying chemical damage (above) since it does not employ a threshold criterion. Using the biological database, DOKA *et al.* (1997) developed an empirical model for southeastern Canada that predicts the number of fish species present in a lake as a function of lake area and various chemical variables. The model was used to quantify biological "damage" for a lake cluster in terms of the percentage of fish populations lost relative to the original condition *(Fig. 3)*. The original number of fish populations was estimated using background SO_4^{2-} deposition to drive the IAM. Hence we have quantified a potential damage. Since not all cluster lakes had all the necessary input data, population estimates were calculated for subsets of lakes as indicated in Figure 3.

As expected, the between-Scenario differences in fish population losses *(Fig. 3)* mirror the differences in chemical damage *(Fig. 2)*. Kejimkujik shows the least reduction in fish populations lost from S1 to S3, while Sudbury and Algoma show the greatest improvement. Clearly, both the Canadian SO_2 control program (reflected in the difference between S1 and S2) and the US program (difference between S2 and S3) are influential in reducing the percentage of lost fish populations. Nevertheless, even after full implementation of the controls required by the Canada/US AQA (S3), the estimated fish population losses will range from 6% (Sudbury) to 15% (Kejimkujik). The damage estimates are conservative for all clusters except possibly Montmorency, where the occurrence of sympatric brook trout populations may mean that the estimates are biased high (JEFFRIES 1997).

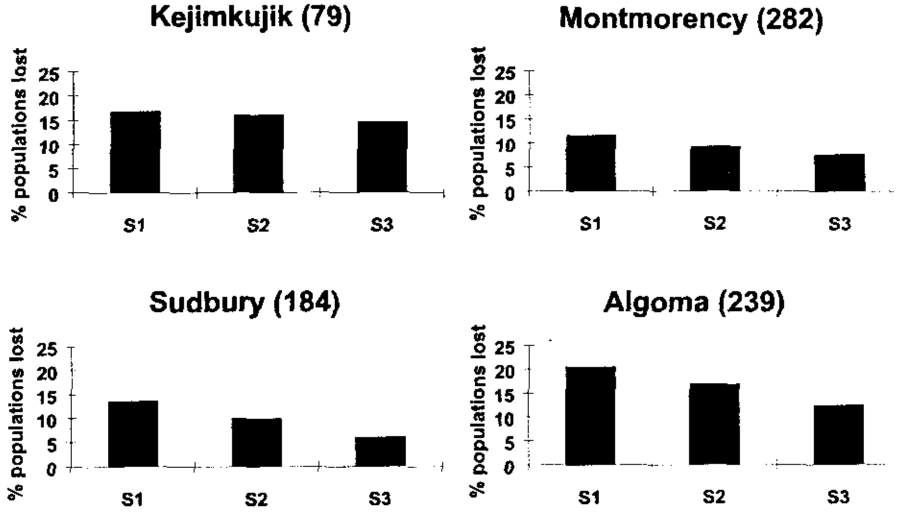

Figure 3 *Estimated percentage loss of fish populations (relative to the estimated original condition) in four lake clusters from southeastern Canada (see* Fig. 1*) for the 3 Scenarios of SO_4^{2-} deposition. The number of lakes in each cluster with sufficient data to apply the model is shown in brackets.*

Pourcentages estimés des pertes de populations de poissons (relatif aux conditions d'origine) dans quatre groupements de lacs du sud-ouest du Canada (voir *fig. 1*) pour les 3 scénarios de dépôts en SO_4^{2-}. Le nombre de lacs dans chaque groupement possédant un nombre de données suffisant pour l'application du modèle est présenté entre parenthèses.

A disadvantage of the percent loss estimates in Figures 2 and 3 is that they do not give a good impression of the actual magnitude of resource losses. For S3, the model predicts a loss of approximately 250 fish populations from the 784 cluster lakes, relative to their original state. If this sample population is indicative of the thousands of lakes in southeastern Canada, then the overall resource loss is clearly huge.

4 – CONCLUSIONS

Effects of acidic deposition on Canadian aquatic ecosystems have been visible for over thirty years. The Canada/US AQA was established in 1991 requiring large reductions in SO_2 emissions which were realized in Canada in 1994 and will be realized in the US within the next decade. An assessment of lake chemistry shows that many acidified lakes occur in southeastern Canada where deposition levels are highest. Emission controls have resulted in reduced SO_4^{2-} deposition, but corresponding reductions in lake acidity lag behind (*i.e.* are observed in only a limited number of cases). Steady-state modelling of water chemistry predicts that the percentage of damaged lakes (pH < 6) will decline as the full effects of emission controls are felt. Similarly, declines in biological damage are expected. Nevertheless, significant aquatic effects will remain after full implementation of all planned SO_2 controls in North America, and further controls will be needed to achieve lower damage levels.

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