The Impact of Acid Rain on the Aquatic Ecosystems of Eastern Canada

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1999

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99-373

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ABSTRACT

In the past environmental management practices have been based on disparate analysis of the impacts of pollutants on selected components of ecosystems. However, holistic analysis of emission reduction strategies is necessary to justify that actions taken to protect the environment would not unduly punish economic growth or vice versa.

When environmental management programs are implemented, it would be extremely difficult for the industry to attain the targeted emission reduction in a single year in order to eliminate impacts on ecosystems. It means that targets have to be established as increments or narrowing the gap between the desired level of atmospheric deposition and actual deposition. These targets should also be designed in a way that would balance the impacts on the economy with improvements in environmental quality.

Environment Canada in partnership with other organizations has developed an Integrated Assessment Modeling Platform. This platform enables to identify an emission reduction strategy(ies) that is(are) able to attain the desired environmental protection at a minimum cost to the industry. In this study, an attempt is made to examine the impact on the industry when the level of protection provided to the aquatic ecosystems is implemented using environmental and environmental-economic goals as objectives using Canadian IAM platform.

The modeling platform takes into account sources and receptor regions in North America. The results of the analysis indicated that reductions of at least 50% of depositions of SO_2 would require complete removal of emissions from all sources. However, this is not compatible with the paradigm of balancing economy with the environment. Therefore, gradual reductions in emissions as well as depositions were found to be plausible strategy. When depositions are reduced by 80% and maximum emission reduction is set at 90%, the number of lakes with pH>6 as well as the presence of fish increased significantly compared to current level. These improvements in acidification in lakes are particularly visible for a strategy that incorporates both environmental and economic goals. Furthermore, optimization using only a single receptor at a time resulted in significantly higher reduction in emissions compared to optimization that incorporates all the twelve Canadian receptors in a single run. It implies that globally optimal emission reduction strategy (i.e., multi-receptor optimization) would not penalize the sources of emission compared to locally optimal emission reduction strategy (i.e., single receptor optimization). It is hoped that with this kind of analysis of feasible environmental targets can be put in place without jeopardizing the performance

of the economy or industry while ensuring continual improvements in environmental health of ecosystems.

1. INTRODUCTION

The primary pollutants, sulphur dioxide (SO_2) and nitrogen oxides (NO_x) can be classified as acidifying pollutants since they become acids upon contact with moisture. These gases are also transformed in the atmosphere to their corresponding acid species, sulphuric (H_2SO_4) and nitric (HNO_3) acid. These and other air pollutants can be deposited on vegetation, soils, surface or ground waters, etc. in wet and dry forms. In addition, one of the constituents of NO_x, nitrogen dioxide (NO_2) is converted to ground-level ozone (O_3) and peroxyacetyl nitrate (PAN).

Several gaseous sulphur compounds are emitted into the atmosphere through man-mad or natural processes. Of these sulphur compounds, SO_2 and hydrogen sulphide (H_2S) (which is converted to SO_2) are the most important species of environmental concern. Emission of SO_2 and its depositions as sulphate is the major anthropogenic cause of acidification of lakes, stream and terrestrial ecosystems. Man-made sources contribute to more than half of the total sulphur emissions in the Northern Hemisphere. However, total man-made sulphur emissions in the Southern Hemisphere are less than 10% of total emissions because of minimal industrial activities. In Canada, the major sources of SO_2 emissions are industrial processes (62%), fuel combustion (33%) and transportation (4%).[1,2,3,4,5]

For decades nitrogen was believed to be an essential element to the survival of aquatic and terrestrial ecosystems. Research has shown that emission of nitrogen oxides (NO_x) is increasing while emissions of sulphate are decreasing due to implementation of control programs. However, the cumulative depositions of SO_2 and NO_x have continued to threaten acidification of aquatic and terrestrial ecosystems. Excess nitrogen contributes to acidification of soil and water, eutrophication and several indirect effects through damaging habitat and altering the nitrogen cycle. Consequently, the effect of excess nitrogen is potentially more profound than earlier believed .[4,5,6]

Human activity releases ten times more nitrogen compounds to the environment than natural sources. In Canada, 95% of NO_x emissions result from combustion of fossil fuels, mostly in a form of nitric oxide (NO). Less than 10% is emitted in the form of nitrogen dioxide (NO_2), and less than 1% in a form of nitrous oxide (N_2O). Transportation, fuel combustion, power generation and industrial processes account for 60%, 20%, 12% and 5% of total NO_x emission in Canada, respectively.[2,7]

Effective control of atmospheric deposition of acidifying pollutants that would enable attainment of critical deposition loadings requires collaborative efforts among provinces and countries. Critical deposition loadings is define as: "The highest deposition of acidifying compounds that will not cause chemical changes leading to long term harmful effects on ecosystem structure and function". To this end, the Canada-U.S. Acid Rain Control Accord was signed in 1991. According to this Accord, Canada has committed to keep the total annual emission of sulphur dioxide (SO_2) to 3.2 million tones per year by the year 2000. Of this national cap, 2.3 million tones have been set to be achieved by the provinces in Eastern Canada. This cap represents a 40% reduction from the 1980 level. There is no formal commitment to extend this cap beyond the year 2000. [3,5,8]

Emissions of NO_x in eastern Canada are expected to decline by 17% in 2010. However, these reductions may be more than offset by about 40% increase in transboundary flows from Northeastern U.S.A. Furthermore, increases in emission of NO_x through a photochemical reaction with Volatile Organic

Compounds (VOCs) in the presence of sunlight produce another pollutant (ground-level ozone or smog). Thus, there are more environmental concerns with respect to increased emission of NO_x. To this end, Canada and the provinces are committed to reduce emissions of NO_x /VOCs to minimize the effect of acidification on sensitive ecosystems as well as to attain an overall ground-level ozone goal of 82 parts per billion (ppb) by 2005.[4,5]

Despite the efforts of Canada and USA to reduce acid rain, forecast of emission of SO_2 and NO_x indicated that emission for SO_2 would decline while that of NO_x will continue to rise (Figure 1). Therefore, the problem of acid rain, ground level ozone and other environmental effects associated with emissions of NO_x and SO_2 could continue for the next 20 years.

Measures to reduce emissions of acidifying pollutants could be classified into two categories: command-and-control and economic instruments. The traditional approach of command-and-control to implement strategies to reduce pollution has proven to be expensive. An alternative strategy is that present and future emission reduction could best be achieved with the use of markets or combination of markets and governments. Ample evidence exists regarding the feasibility of using market mechanisms to achieve environmental goals.

There has long been interest, on the part of governments and stakeholders, to explore how SO_2 and NO_x emission abatement strategies and economic instruments would result the protection of sensitive ecosystems. However, fiscal restraints and greater accountability in decision-making necessitate that the choice of strategies and instruments should also satisfy the criteria of cost-effectiveness. It is only when carefully selected strategies and instruments are implemented that it is possible to influence the release, fate and impact of pollutants on the environment. The present study is intended to examine the most efficient and less costly emission abatement strategy(ies) that would enable the attainment of the desired environmental goals, that is the protection of aquatic ecosystems in 12 receptor sites in eastern Canada.

1.1. The importance of acid rain

Acidic deposition, or acid rain, is the result of the reaction of emissions of sulfur dioxide (SO_2) and oxides of nitrogen (NO_x) in the atmosphere with water, oxygen, and oxidants to form various acidic compounds. These compounds fall to the earth in either dry form (dry deposition such as gas and particles) or wet form (wet deposition such as rain, snow, and fog). Acidic formations or compounds can be transported via wind crossing states, provinces, national and international borders.[1,3]

Acid rain causes acidification of lakes and streams and contributes to damage of trees at high elevations. Furthermore, acid rain accelerates the decay of building materials and paints, including irreplaceable buildings, statues, and sculptures that are of significant national cultural heritage. Dry deposition of acidic compounds can also dirty buildings and other structures, leading to increased maintenance costs. Prior to being deposited on earth, gaseous forms of SO_2 and NO_x as well as sulfates and nitrates contribute to reduced visibility and pose threats to human health.[1,3]

Acid rain primarily affects sensitive bodies of water, that is, those with a limited ability to neutralize acidic compounds (called "buffering capacity"). Many lakes and streams in eastern Canada suffer from chronic acidity, that is the water is characterized by a constantly low pH level. Not only acid rain has caused and/or increased acidity of lakes and streams but also several of these water bodies are sensitive to acidification. It means that they cannot tolerate additional deposition, wet or dry, above the critical load level.

It is estimated that 14,000 lakes in eastern Canada are acidic. Streams flowing over soil with low buffering capacity are equally susceptible to damages from acid rain. In some sensitive lakes and streams, not only acidification has eradicated some fish species such as trout, but also has made the chemical conditions unsuitable for the survival of sensitive fish species.[1,3]

The impact of acid rain on aquatic ecosystems is exacerbated due to a condition called "episodic acidification" (brief periods of low pH levels from snowmelt or heavy downpours). Several lakes and streams become temporarily acidic during storms and snowmelt and episodic acidification that also occurs during this period can contribute to large scale "fish kills."

Acid rain affects forest through depositions of acidic compounds on the leaves in a form of dry or wet depositions, and forest soils. In addition to stunting the growth of trees and associated components of the forest ecosystem, the run-off from forest soils has been attributed as one of the causes of acidification of soil and surface waters in eastern Canada. Percolation of acidic compounds through the soil affects nutrient movement, hence productivity of forests and forest ecosystem.

As a result of the diverse and profound impacts of SO_2 and NO_x, the governments of Canada and USA have made significant commitment toward reducing emissions of these pollutants. However, several terrestrial and aquatic ecosystems remain acidified and require a longer time to recover to their normal state of environment. The present study examines the impact of acid rain on aquatic ecosystems under two scenarios: i) using an environmental goal as the only decision criteria, and ii) using environment and economic goals as a criterion.

Controlling acid rain or reducing emissions of SO_2 and NO_x will bring substantial environmental and human health benefits. It will help improve the state of acidified lakes and streams so that they can once again support fish life. These emissions reductions will also contribute to improved visibility so that there will be an increased enjoyment of scenic sites and parks. Moreover, reductions in emissions of precursors of acid rain help revitalize forests and minimize deterioration of building and monuments, and contribute to reduce health risk by lowering particulate of SO_2 and NO_x as well as ground level ozone (smog). If status quo conditions of acidification are allowed to continue, the rate with which lakes would be acidified could increase by as high as 50% within a few decades. A significant element for reduced acidification is the reduction in emissions of SO_2. Due to national and bilateral commitments toward reducing emission of SO_2 and NO_x, it is possible that acidification can be controlled and/or reduced. However, the commulative nature of small depositions, pre-existing levels of acidity and sensitive of most lakes imply that the problem of acid rain will continue to be of significant national concern for years to come.

2. Methodology

2.1. Integrated Assessment Modeling

The methodology utilized in this study is integrated assessment modeling. Integrated Assessment Modeling (IAM) has become an important field of study over the past decade. The concept of IAM encompasses three elements: Integrated, Assessment and Modeling. IAM could be interpreted differently by different disciplines. Furthermore, the scope or coverage of the IAM could vary significantly ranging from examining an element such as sub-basin to global climate change or water supply. [9,10,11,12,13,14,15,16]

Integration refers to the incorporation of a single or chain of events into a specific framework that directly or indirectly impact a specific outcome [1,2,3,4,5] Assessment is the presentation of and drawing casual inferences from knowledge or information derived from various disciplinary researches in order to assist decision-makers in evaluating possible actions or undertaking an in-depth understanding of a problem.[1]

Due to its approach as a holistic analytic tool, the IAM is a multidisciplinary. As such an important strength of the IAM is that it can create an effective communication between basic and social scientists, and decision makers on the implications of changes in environmental health.

Most environmental problems have common causes, dynamics, and common impacts. The strength of the IAM as analytic tool that brings diverse disciplines, difference and commonalties in the functioning of ecosystems, in the dynamics of activities or elements of an environment-economy linkage can be examined with relatively greater degree of accuracy, defensibility and clarity. Although there are many IAM models, the he present study examines the impact of acid rain on aquatic ecosystem using Canadian IAM platform as analytic tool.

2.2. Formulation of Optimization Routine within IAM

Canada's prototype IAM is being developed to incorporate linear and nonlinear cost functions. It includes SO_2, and will incorporate NO_x and VOCs. Information such as cost functions and atmospheric inputs such as those linking sources to deposition levels, and chemical and physical processes that characterize NO_x, VOCs and SO_2 are required to run the full scale IAM platform.[17]

The cost functions are incorporated into the IAM via an optimization scheme. There are several kinds of optimization models. These models could minimize deposition levels, cost of attaining certain deposition levels, etc. Common to most models is that they are single-objective optimization schemes. That is, their objective function is either minimization of cost or deposition. Realistic assessment of pollution abatement strategies cannot be accomplished using a framework based on a single criterion or objective. Multi-objective optimization models promote appropriate roles for participants in planning and decision-making processes, enable identification of a wide range of alternatives, and provide a more realistic perception of the problem because of inclusion of many objectives. Therefore, a simple yet realistic multi-objective optimization model can be used to incorporate cost functions into the IAM. This model assumes that it may not be feasible to attain the desired critical deposition loading. Therefore, allowances are made for over or under-achieving the critical deposition levels. The optimization scheme can be called least-cost deposition-relaxed model. [17]

The mathematical formulation for least-cost deposition-relaxed model is given as: [17,18,19,20,21,22,23,24,25]

$$\text{Minimize } (z_1 + z_2 + z_3) = Z = \sum_{i=1}^{n} C_i R_i + \sum_{i=1}^{n} LC_i \lambda_i + \sum_{j=1}^{m} (W_j^u U_j + W_j^v V_j) \quad \ldots\ldots\ldots\ldots(1)$$

Subject to:

$$\sum^{n} (EC_i - R_i) T_{ij} + \sum^{o} EU_k T_{kj} + BD_j - V_j + U_j \leq (1 + \mu_j) CL_j \quad \ldots\ldots\ldots\ldots (2)$$

i=1 k=1

$$R_m = \Delta(EC_m+EU_m) \quad ....(3)$$

$$0 \leq \lambda_I \leq 1 \quad ....(4)$$

$$\sum_{i=1}^{n} R_i = EA \quad ....(5)$$

$$R_i \geq 0 \quad ....(6)$$

$$0 \leq V_j \leq \mu_j CL_j \quad ....(7)$$

$$0 \leq \mu_j \leq 1 \quad ....(8)$$

$$U_j \geq 0 , \forall j \quad ....(9)$$

Where W_j's are user-specified objective function weights for affected region j (j=1...m), C_i is the marginal cost of emission removal at controlled point source(EC) i (i=1... n), and R_i is the amount of emission removed from controlled source i (decision variable). EC_i refers to existing emission rate at controllable source i, T_{ij} is the unit transfer coefficient that relates deposition at receptor j and the rate of emission from controllable source i , EU_k is existing emission rate at non-controllable source k (k=1...o), and T_{kj} is transfer coefficient that links affected area j and uncontrollable source k. BD_j in equation 2 refers to background deposition level at affected area j, R_m refers to maximum allowable removal on rate from source m; and CL_J stands for critical deposition level at affected area j. The variables U_j and V_j refer to the magnitude of over achievement (deposition less than the critical loads) and violation (deposition exceeding critical loads) at affected area j respectively. The constant EA indicates predetermined aggregate emission reduction level and LC_i stands for employment at a point source i. The unknown parameters such as λ_i refer to the proportion of losses in employment as a result of the chosen control option at source i and μ_j indicates the proportion of violation of critical deposition level at receptor j.

Equation 3 states that the amount of pollutant removed from source m should be a certain percentage or fraction (Δ) of total unabated emission from source m. The reason for inclusion of this constraint is that some regions or sources of emission may have already implemented control strategies to satisfy the regional emission quota while others may have not. This constraint, therefore, avoids an unnecessary burden to those sources of emission that have made progress toward cleaner environment. The above formulation can be modified to include constraints specific to each affected area or sources of emission. Equation 7 sets an upper limit to the violation of deposition. Equations 1 to 9 could be simplified by dropping the underachievement variable (U) and others as may be necessitated by the availability of the data set.

A slightly different version of the above systems of equation is used to identify optimal emission reduction strategy using the IAM platform. The result emission reduction strategy will satisfy socioeconomic and environmental criteria that are included in the optimization scheme as constraints.

2.3. The Canadian IAM

IAM, in its various forms, has been in existence since the early 50s. IAM is not the only interdisciplinary or unifying research methodology or paradigm. [11,26,27] The significance and/or importance of this tool in environmental analysis, however, became more visible only over past two decades. At present, several national and international organizations utilize various forms of IAM platform for different purposes.

Several IAM models have been developed over the past decade. These models could be divided into those that examines i) the linkages between socioeconomic and environmental variables[14,15,16,28,29] , ii) only the physical environment, and iii) only the socioeconomic environment [29,30,31,32,33,34] However, emphasis is being given by policy makers to IAM as an important tool that would enable balancing economic growth with environmental protection.[10]

Canada's version of Integrated Assessment Model (IAM) evolved from a sub-basin or lake-ecosystem assessment tool called RAISON (Regional Analysis by Intelligent Systems ON a microcomputer) for windows. The IAM contains environmental models in biological or aquatic sciences, atmospheric sciences, natural resource sciences, and socioeconomic sciences. Based on inputs from these models, the IAM would facilitate the identification of a strategy that is not only least cost but also enables the protection of aquatic and terrestrial ecosystems. Unlike the policy driven IAM platforms such as RAINS of Europe, the Canadian version of IAM attempts to balance the economy with the environment or policy with science.[35,36,37]

The Canadian IAM platform has the following components: i) the biological or aquatic sciences include models such as waterfowl acidification response modeling system (WARMS), Cation Denudation rate (CDRM), Trickle down (TD), CDRLTH, and TDBO; ii) the atmospheric sciences include source-receptor relationship matrix for SO_2 and NO_x from long-range atmospheric transport model; iii) the natural sciences module is still in development but contains forestry impact model; iv) the socioeconomic sciences contain cost of emission reduction and functional specifications between costs and emission removal for SO_2; and v) emissions and deposition data for SO_2 and NO_x, and critical deposition loadings of SO_2 for sensitive aquatic ecosystems. The IAM platform also employs neural network approach to recognize patterns and fill gaps in monitoring data. Moreover, uncertainty and error propagation in models, using causal probability network and fuzzy expert system, are introduced to the platform. These modules and databases are interconnected through linear (genetic algorithms) and non-linear optimization algorithms. [35,36,37]

The optimization scheme contains an objective function and constraints to be satisfied. That is, it maximizes emissions reductions, cost minimization or both subject to the satisfaction of constraints such as non-exceedance of maximum deposition at sensitive receptors, maximum allowable reductions form source regions as well as the numbers of sources that would be examined simultaneously. The results of the non-linear optimization runs would identify a strategy that is least cost and yet enable the attainment of environmental goals.

The platform has been used for various purposes. The Canadian IAM platform has been used as a decision-support framework for basin management strategies on nutrient abatement, effluent limits, waste disposal, and dredging and other cleanup options in the Great Lakes 2000 program. Information on hydrology, water quality, geology, fisheries, forestry, transportation, urban development, socio-economics and health has been integrated in support of watershed ecosystem research studies such as the Grand River Eco-Research Project. Decision-support framework using expert system technologies to link simulation models on hydrological runoff, water quality, groundwater and river ecology for watershed management and planning have been developed (e.g., a study on the Duffins Creek Watershed). Analysis of Lake Ecosystem (e.g., lake Erie) response to climate change scenarios has been undertaken. Modeling industrial effluent transport and fate in the Athabasca River, and pathway and fate of contaminants for the Great Lakes-St. Lawrence Mixed Woods Plain have been carried out. Internationally, the RAISON system has been used for watershed modeling and Lake Hydrodynamics for the Lerma-Chapala basin (Mexico) and the Lake Caohu basin (P.R. China). [35,36,37]

The Canadian IAM platform has also been used in the assessment of ecological impacts due to sulfur and nitrogen oxides (i.e., Acid rain) for evaluation of policy options of emission control for selected sites in Canada and the United States has been conducted. In 1997, IAM was used to determine emission reduction scenario for controlling acid rain, which was then used as input into the atmospheric model.

2.4. Inputs into the Model

The Canadian IAM incorporates several sets of data and variables. These include i) gridded emissions and deposition data, ii) critical deposition loadings for sensitive receptors, iii) cost functions, iv) cost and deposition optimization algorithms, v) source-receptor relationship matrix, and vi) lake chemistry and data on aquatic ecosystems of lakes in the receptor sites. The purpose of the present study is to examine the impact of acid rain on aquatic ecosystems under two scenarios: i) using environmental goal, and ii) using environmental and economic goals in determining reductions in emission of SO_2.

The 1990 Canadian long-range transport of air pollutants and acid deposition report divided North America into 40 sources of emission and 15 sensitive receptor sites (Figures 2 and 3).[38] For the purpose of national policy making and international negotiation, the use of these large sources and few receptors may prove adequate.

3. Results of Multi-Receptor Optimization with IAM

3.1. Results When the Decision Criteria is Only Environmental Goal

The optimization routine using the IAM platform was designed in such as to obtain global optimality with respect to emission reductions and the corresponding depositions. That is rather than optimizing deposition at a single receptor at a time, all the twelve-receptor points located in eastern Canada were optimized simultaneously. Critical loads and environmental goal for the twelve-receptor points are presented in Table 1. The analysis was conducted for two scenarios: optimizing with respect to environmental goal only and with respect to environmental and economic goals. The results are presented in Table 2.

The results of the analysis indicated that reducing current deposition by 50% at all receptor sites require that emissions have to be reduced by 100% from the 1990 level. This scenario, therefore, was not feasible as it implies closing all SO_2 emitting plants in Northeastern North America that contribute to depositions in eastern Canada. After a series of runs, an environmental goal that reduces deposition to 80% of current level using a maximum emission reduction of 90% was selected as a strategy.

The results indicated that deposition optimization strategies would require a reduction in emission of SO_2 by 1968KT (64%) at a cost of 1.3 billion US$, and by 3016 kT (15%) at a cost of 1.2 billion US$ from

Canadian and USA sources respectively. In total, a reduction of 4984KT (22%) of North American emissions at a cost of 2.6 billion US$ would be required to attain the anticipated environment goal.

In a separate analysis, single receptor-optimization for the receptor site Algoma and keji showed that for the same environmental goal, the required emission reduction was 1767.3KT. The reductions from the two sites alone represent about 16% of North American emissions of SO_2. Thus, single-receptor optimization greatly penalizes the emission sources by requiring significant reduction in emissions.

3.2. Results When the Decision Criteria are Environmental and Economic Goals

The environmental-economic optimization routine results are also presented in Table 2. The findings indicate that to attain the desired environmental goal, Canada has to reduce emissions by 1520KT (49%) at a cost of close to 1 billion US$. Similarly, the USA has to reduce emissions by 3846KT (19%) at a cost of about 1billion US$. In total, SO_2 emissions have to be reduced by 5365KT (23%) at a cost of about 2 billion US$.

Single-receptor optimization for Algoma and Keji indicates that it would cost costs 600 million and 1.12 billion US$ to attain the desired environmental goal applied to all receptors. Optimization for a 50% reduction in deposition in these two sites indicates that there will be no optimal solution for Keji while it would require a reduction in emission by 30% at a cost of 11 billion US $. This means that optimization at individual receptor could be viewed as expensive, hence not a viable pollution abatement strategy.

Using the maximum emission reduction level of 90% and reduction of deposition to 80% of current level, the results indicate that i) the percentage of lakes with pH<6 reduced to 15% from the intended 20%, and ii) the percentage of fish presence or richness increased by 11%. However, when deposition was reduced by 50%, i) the percentage of lakes with pH<6 reduced to 5%, and ii) the percentage of fish presence increased by 28% compared to current level.

The optimization routine that incorporated environmental and economic goals resulted in i) a 15% less in emission reduction from Canadian sources, and ii) a 4% increased in emissions reduced from sources in the USA. However, the total continental emission reduction was approximately the same (22% versus 23%). However the combined environment-economic goal optimization routine costs about half a billion less in emission abatement. Therefore, a strategy that includes both environmental and economic goals not only increased emission reductions but also costs substantially less. Furthermore, it contributed to reduced acidity and abundance of fish in more lakes in eastern Canada. Specifically, the impact of emission reduction using environmental-economic goal on water chemistry and presence of fish was that the pH was improved in about 5% of the lakes and resulted in an increase of presence of fish by about 4.2%.

The results from single optimization runs showed that for an 80% reduction in deposition, only 80% of lakes would be protected (i.e., 20% of lakes will be with pH<6). However, a 50% reduction in deposition in Algoma allowed the protection of 95% of lakes but at extremely high cost. Thus, single receptor optimizations either require greater emissions reduction at extremely high cost or would not allow greater protection of lake or aquatic ecosystems.

4. CONCLUSIONS

Environmental decision making used to rely on evidence derived from single and disparate empirical models. However, the causes of and solutions to most environmental problems tend to be interconnected. Consequently, policies that depend on disciplinary research may not be optimal with respect to balancing economic growth with environmental protection. As a result several countries, including Canada, are moving toward the use of integrated assessment modeling to bring together knowledge from various disciplines to get an in-depth understanding of environmental problems and make sound decisions.

Some IAM tools tend to be either primarily policy or science driven. Identification of trade-off between economic growth and environmental protection is crucial to attain sustainable development. In this respect, the Canadian version of IAM is well suited to give due consideration to economy and environment so that the decisions would not jeopardize the delicate balance between economy and environment.

The Canadian version of IAM incorporates several ecosystem models, economic component and scientific and socioeconomic databases. The platform was used to demonstrate the implications of environmental decision making that are based on only basic sciences and those based on both basic and social (economic) sciences. Optimal strategies were examined taking into account acid rain and inter- and intra- country emissions trading, and their implication for aquatic ecosystem.

The findings of the analysis with respect to minimizing the impact of acidification indicate that it requires long-term commitment to provide 100% protection aquatic ecosystem or lakes without hurting the economy. That is, gradually- phased emissions reduction would be required to reduce deposition in order to allow recovery and perpetuation of aquatic and other ecosystems affected by acid rain.

The incorporation of multiple objectives, that is economic and environmental goals, in developing environmental policies may contribute to faster recovery of acidified lakes compared to strategies that consider only environmental goals because the former approach allows the removal of a large percentage of current emissions. It means that this strategy will help reduce the percentage of lakes acidified as well as improves the presence of fish species in Canadian lakes. Furthermore, the study indicated that these large reductions could be achieved at costs that are less than or equal to those incurred when policy development tools take into account only environmental goals. It means that strategies that incorporate economic and environmental goals would make the polluters, society and the environment better-off. Furthermore, the analysis indicated attainment of environmental goals in Canadian sensitive receptors require major emissions reductions from the USA.

The principle of sustainable development requires that there must be a balance between economy and the environment. The study has demonstrated that radical and stricter environmental goal may hurt the economy. Therefore, gradual emission and deposition reduction strategies may enable the attainment of improved environmental quality and yet inflict less economic cost on the industry.

5. REFERENCES

1. Legge, A.H., and Krupa, S.V. (eds)., 1990. Acidic Deposition: Sulphur and Nitrogen Oxides. Lewis Publishers, Inc. Michigan, U.S.A..
2. Environment Canada., 1995. Air Emissions: Baseline Forecast, 1990-2010, Pollution Data Branch. March.
3. Environment Canada., 1990. The 1990 Canadian Long-Range Transport of Air Pollutants & Acid Deposition Assessment report: Part 1, Executive Summary; & Part 4, Aquatic Effects.
4. Mariam, Y., 1994a. Analysis of the socioeconomic implication of environmental pollution from emission of NO_x . mimeo. Economic Analysis Branch, Environment Canada. May.
5. Mariam, Y., 1994b. Trend analysis of energy use and emission of NO_x for eastern Canada. Mimeo. Economic Analysis Branch, Environment Canada. December.
6. Morgan, M.G. and H. Dowlatabadi, 1996. Climatic Change, 34, 3-4, 337-368.
7. Wareham, D.G., McBean, E.A., and Byrne, J.M., 1988.Water, Air and Soil Pollution, 40, 157-175.
8. Perrings, C., Folke, C. and Maler, K.G., 1992. Ambio, 21,3, 201-210.
9. Canadian Council of Ministers of the Environment, 1990. Management plan for NO_x /VOCs, Nov.
10. Parson, E.A. and K. Fisher-Vanden, 1995. Searching for Integrated Assessment: A Preliminary Investigation of Methods, Models, and Projects in the Integrated Assessment of Global Climatic Change. Consortium for International Earth Science Information Network (CIESIN).University Center, Mich..
11. Risbey, J., M. Kandlikar, and A. Patwardhan., 1996. Climatic Change, 34, 3-4, 369-395.
12. Rotmans, J., Van Asselt, M., 1996. Climate change, 34, 3-4, 327-336.
13. Rotmans, J., M. Hulme, and T.E. Downing., 1994. Global Environmental Change, 4,2, 97-124.
14. Alcamo, J., G.J.J. Kreileman, M. S. Krol, and G. Zuidema., 1994. "Modeling the Global Society-biosphere-climate System: Part 1: Model Description and Testing." In IMAGE 2.0: Integrated Modeling of Global Climate Change, ed. J. Alcamo. Dordrecht, The Netherlands: Kluwer Academic Publishers.
15. Alcamo, J., R. Shaw, and L. Hordijk, eds., 1990. The RAINS Model of Acidification: Science and Strategies in Europe. Dordrecht, The Netherlands: Kluwer Academic Publishers.
16. Ball, M., and H. Dowlatabadi., 1995. "The Role of Aerosols in Climate Change: Results from an Integrated Assessment Model (ICAM 2.0)." Pittsburgh, Pa.: Carnegie Mellon University, Department of Engineering and Public Policy.
17. Mariam, Y., 1995. Review and Selection of Modeling Methods in Pollution Abatement with Inclusion of Uncertainty. Mimeo. Economic Analysis Branch, Environment Canada, May.
18. Cohon, J.L., 1978. Multiobjective programming and planning. Academic Press, Inc., NY, NY .
19. Alcamo, J., and Bartnicki, J., 1990. Atmospheric Environment, 24A:2169-2189.

20. Battermann, S., and Amann, M., 1991. Environmental Management, 32,57-72.

21. Ellis, J.H., 1988. European J. Operations research, 35,365-377.

22. Ellis, J. H., 1990. European J. Operations research, 46,313-321.

23. Ellis, J. H., and Bowman, M.L., 1994. J. of Environmental Engineering, 120,273-290.

24. Ellis, J.H., McBean, E.A., Farquhar, G.J., 1985. Atm. Env., 19,925-937.

25. Ellis, J.H., McBean, E.A., Farquhar, G.J., 1986. Atm. Env., 20,501-511.

26. Forrester, J.W., 1971. World Dynamics.Wright-Allen Press, Cambridge, Mass.

27. Brunner, R.D., 1996. Climate Change, 32,121-147.

28. Consortium for International Earth Science Information Network (CIESIN), 1995. Thematic Guide to Integrated Assessment Modeling of Climate Change. University Center, Mich.

29. Rubin, E.S., 1991. J.of the Air and Waste Management Association, 41, 914-21.

30. Edmonds, J.A., M.A. Wise, and C. MacCracken., 1994. Advanced Energy Technologies and Climate Change: An Analysis Using the Global Change Assessment Model (GCAM). PNL-9798, UC-402. Richland, Wash.: Pacific Northwest Laboratory.

31. Maddison, D. 1994. "A Cost-Benefit Analysis of Slowing Climate Change." Center for Social and Economic Research on the Global Environment (CSERGE). London: University College London.

32. Hulme, M., S.C.B. Raper, and T.M.L. Wigley., 1994."An Integrated Framework to Address Climate Change (ESCAPE) and Further Development of the Global and Regional Climate Modules (MAGICC)." In Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change, ed. N. Nakicenovic, W.D. Nordhaus, R. Richels, and F.L. Toth. International Institute for Applied Systems Analysis (IIASA) Collaborative Paper, CP-94-9. Laxenburg, Austria: IIASA.

33. Nordhaus, W.D., and Z. Yang., 1995. RICE: A Regional Dynamic General Equilibrium Model of Optimal Climate-Change Policy. New Haven, Conn.: Yale University and Massachusetts Institute of Technology.

34. Energy Modeling Forum., 1995. Second Round Study Design for EMF 14: Integrated Assessment for Climate Change. Palo Alto, Calif.: Stanford University.

35. Environment Canada., 1990. The 1990 Canadian Long-Range Transport of Air Pollutants & Acid Deposition Assessment report: Part 1, Executive Summary; & Part 4, Aquatic Effects.

36. Lam, D.C.L., C.W. Mayfield, D.A. Swayne and K. Hopkins., 1994. J. Biol. Systems, 2,499-517.

37. Lam, D.C.L., W.G. Booty, W.G., Wong, I., Kay, D., and Kerby, J., 1995. The RAISON decision support system: examples of applications. National Water Research Institute, Environment Canada, Burlington, Ontario, Contribution No. 95-151.

38. Lam, D.C.L., Puckett, K.J., Wong, I., Moran, M.D., Fenech, G., Jefferies, D.S., Olson, M.P., Whelpdale, D.M., McNicol, D., Mariam, Y.K.G., and Minns, C.K., 1998. Water Quality Res. J. Canada, 33, 1, 1-17.

Figure 1. Trends Emissions of NO2 and SO2 in Canada and USA

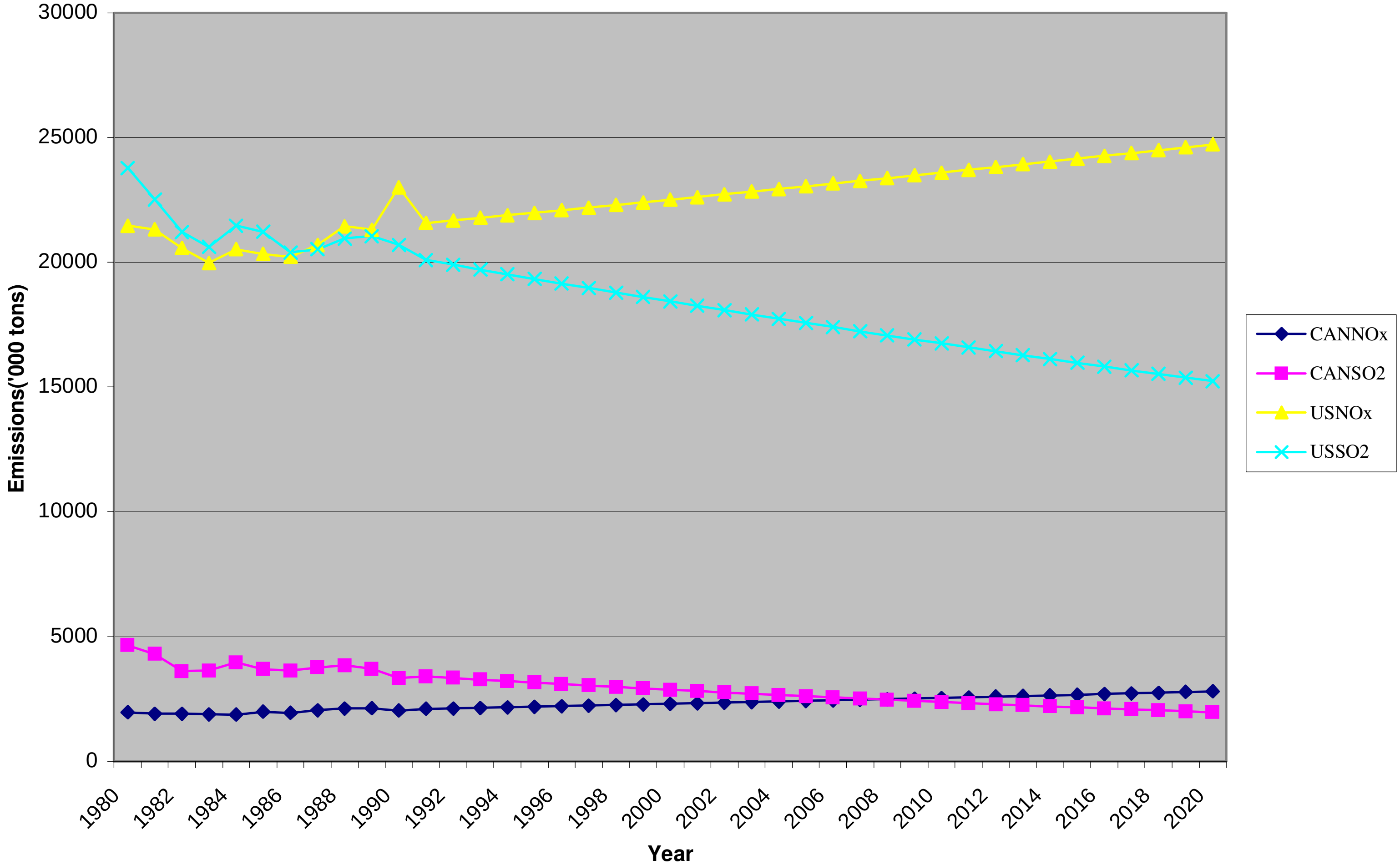


Figure 2. Map of Forty Emission Regions Used for Acid Rain Assessment

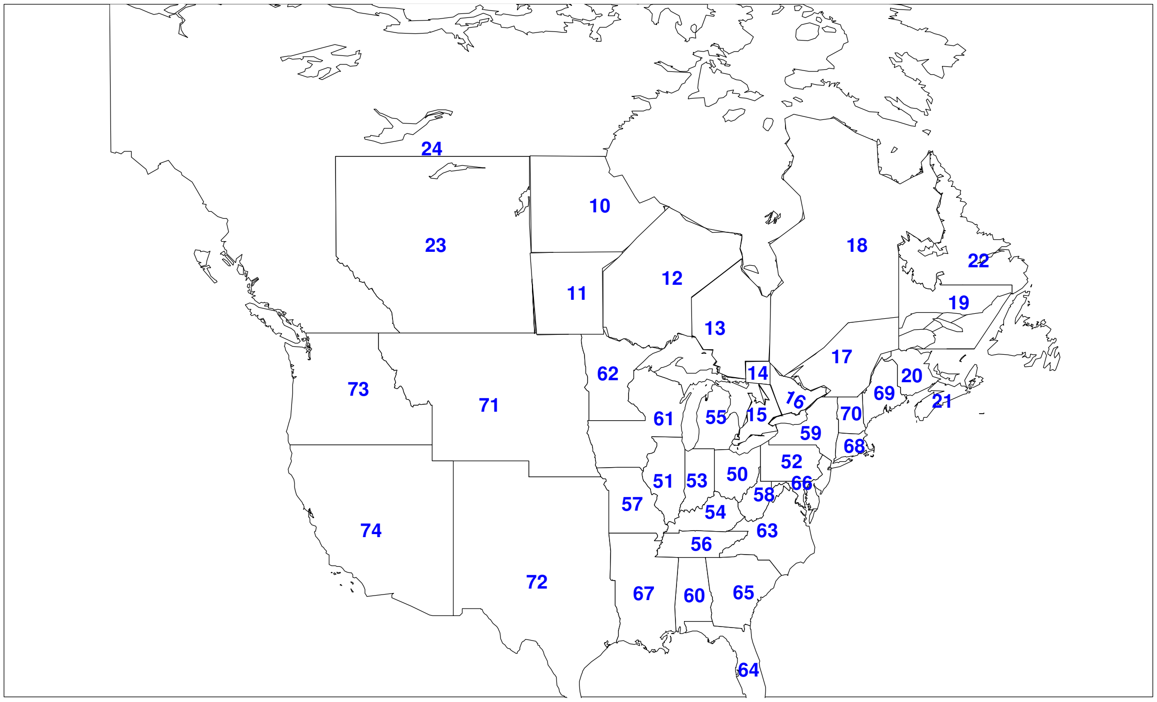
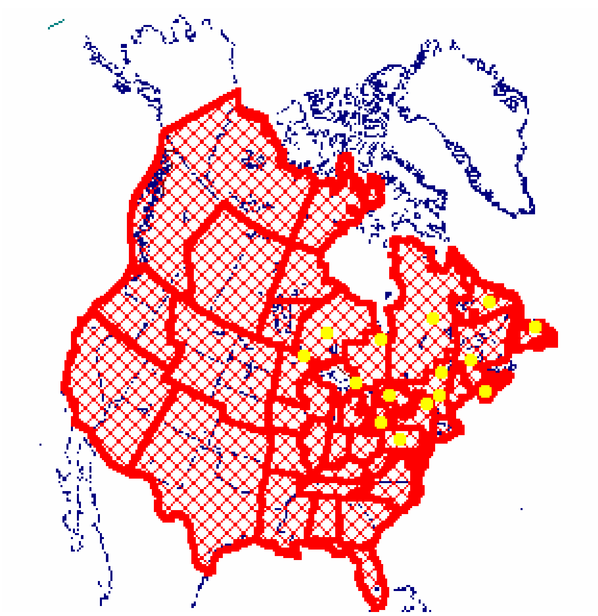


Fig. 3. Map of Forty Source Regions and Fifteen Receptor Sites in North America



Note: Points identified with yellow circles are receptor sites while the emission regions delineated with red lines are similar to those in fig.2.

Table 1. Current, Background, objective and critical deposition loadings (kg SO_4/ha/yr)

Receptor Site	Original Deposition (KG/HA-SO4)	Background Deposition (kg/ha-SO4)	Objective Deposition (kg/ha-SO4)	Critical Deposition (KG/HA-SO4)	Gap1 (objective less original)	Gap2 (objective less critical)
ALGO	17.45	3.6	13.96	16.00	3.49	-2.04
CHAR	13.42	4.2	10.74	8.00	2.68	2.74
ELA	6.73	2.7	5.38	8.00	1.35	-2.62
GAND	6.29	4.7	5.03	8.00	1.26	-2.97
GOOS	8.08	3.8	6.46	8.00	1.62	-1.54
KEJI	13.97	5.6	11.17	8.00	2.79	3.17
LONG	30.85	3.8	24.68	20.00	6.17	4.68
MOOS	8.23	2.8	6.58	20.00	1.65	-13.42
MUSK	22.97	4	18.38	16.00	4.59	2.38
NICH	8.11	3.3	6.49	16.00	1.62	-9.51
PICK	6.51	2.9	5.21	20.00	1.30	-14.79
QUEB	18.83	4.8	15.06	9.00	3.77	6.06

Where

ALGO- refers to Algoma Receptor site in Ontario

CHAR- refers to Charlo Receptor site in New Brunswick

ELA- refers to Ela Receptor site in Ontario

GAND- refers to Grander Receptor site in Newfoundland

GOOS- refers to Goose Bay Receptor site in Newfoundland

KEJI- refers to Kejimkujik Receptor site in Nova Scotia

LONG- refers to Long Point Receptor site in Ontario

MOOS- refers to Moosonee Receptor site in Ontario

MUSK- refers to Muskoka Receptor site in Ontario

NICH- refers to Nitchequon Receptor site in Quebec

PICK- refers to Pickle Lake Receptor site in Ontario

QUEB- refers to Monmorency Receptor site in Quebec

Table 2. Optimized Emission Reduction to achieve 80% reductions in Depositions of sulphate at 12 Canadian Receptor Sites using a maximum of 90% reduction in emissions of SO_2

Source Region	Original SO_2 Emission (kT/Yr.)	Final SO_2 Emission (kT/Yr.)	Abated SO_2 Emission (kT/Yr.)	% Emission Reduction	Cost of Emission Reduction (US$M)	Original SO_2 Emission (kT/Yr.)	Final SO_2 Emission (kT/Yr.)	Abated SO_2 Emission (kT/Yr.)	% Emission Reduction	Cost of Emission Reduction (US$M)
10	530	187	343	65	78	530	425	105	20	24
11	12	1	11	89	0	12	12	0	0	0
12	10	1	9	89	36	10	1	9	88	35
13	50	9	41	81	11	50	46	4	7	1
14	688	77	612	89	142	688	70	618	90	143
15	216	25	191	88	79	216	134	82	38	34
16	30	3	27	89	5	30	24	6	20	1
17	184	20	165	89	116	184	150	35	19	24
18	162	18	144	89	35	162	18	145	89	35
19	46	5	41	90	9	46	5	41	90	9
20	176	19	157	89	254	176	28	148	84	239
21	182	18	164	90	297	182	37	145	80	263
22	72	7	65	90	268	72	33	39	54	160
23	610	610	0	0	0	610	468	142	23	22
24	110	110	0	0	0	110	109	2	1	0
Canadian	**3078**	**1110**	**1968**	**64**	**1329**	**3078**	**1558**	**1520**	**49**	**991**
50	2318	1533	785	34	89	2318	1490	828	36	94
51	1124	1023	101	9	13	1124	808	316	28	42
52	1274	1274	0	0	0	1274	941	333	26	85
53	1658	1658	0	0	0	1658	1351	307	19	47
54	952	952	0	0	0	952	952	0	0	0
55	454	54	401	88	0	454	454	0	0	0
56	938	938	0	0	0	938	938	0	0	0
57	796	796	0	0	0	796	396	401	50	108
58	1024	1024	0	0	0	1024	828	196	19	50
59	536	314	222	41	84	536	411	125	23	48
60	688	688	0	0	0	688	508	180	26	0
61	612	130	482	79	502	612	273	339	55	354
62	124	26	98	79	226	124	51	73	59	168
63	790	790	0	0	0	790	790	0	0	0
64	744	744	0	0	0	744	610	134	18	1
65	1088	1088	0	0	0	1088	732	356	33	30
66	584	62	522	89	88	584	464	121	21	20
67	710	710	0	0	0	710	683	27	4	2
68	314	33	281	89	191	314	275	39	12	27
69	70	7	63	89	0	70	70	0	0	0
70	70	7	63	89	23	70	48	22	32	8
71	470	470	0	0	0	470	425	45	10	7
72	1698	1698	0	0	0	1698	1694	4	0	0
73	216	216	0	0	0	216	216	0	0	0
74	658	658	0	0	0	658	658	0	0	0
USA Total	**19910**	**16894**	**3016**	**15**	**1216**	**19910**	**16064**	**3846**	**19**	**1090**
Grand Total	**22988**	**18004**	**4984**	**22**	**2546**	**22988**	**17623**	**5365**	**23**	**2081**