ASSESSING BIOLOGICAL RECOVERY OF ACID-SENSITIVE LAKES IN ONTARIO, CANADA

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Abstract. - Information on breeding waterfowl, habitat and food chains, gathered from acid-sensitive lakes in Ontario, was used to develop a model of effects of acid deposition on waterfowl and their response to predicted sulphur dioxide (SO_2) emission reductions in eastern North America. The Waterfowl Acidification Response Modelling System (WARMS) is composed of an acidification model linked to fish and waterfowl models. WARMS uses pH, area, dissolved organic carbon, total phosphorus, and presence of fish to calculate estimates of pre-acidification, present and eventual steady-state values for pH, fish presence and waterfowl breeding parameters under proposed SO_2 emission scenarios. We used WARMS to estimate chemical and biotic responses to scenarios simulated in three regions of Ontario where biomonitoring studies are underway. For pH and fish presence, WARMS predicts the greatest improvements in the highly damaged Sudbury region, slight improvements in Algoma, and that the strongest proposed emission reductions will be required to maintain current conditions in Muskoka. For waterfowl, species-specific differences are evident among regions. We discuss implications of these assessments of biological recovery for watersheds in eastern Canada.

1. Introduction

Adverse effects of acidification on aquatic birds vary with severity of acidification and foraging habits of species (Longcore *et al.*, 1993). Fish-eating birds, such as the common loon (*Gavia immer*) and common merganser (*Mergus merganser*), are at risk due to reduced availability and quality of fish prey as pH declines in larger lakes (McNicol *et al.*, 1995a). Fish also play an important role in determining the suitability of breeding habitat (primarily small lakes and wetlands) for insectivores, such as common goldeneye (*Bucephala clangula*) and American black duck (*Anas rubripes*) (McNicol *et al.*, 1995a).

Efforts to reduce acid-causing emissions in eastern North America have been initiated, along with monitoring programs to confirm that environmental objectives to enhance or maintain aquatic biodiversity are achieved. Here, we use a computer model, the Waterfowl Acidification Response Modelling System (WARMS), to estimate response of waterfowl (including loons) and their habitats to predicted changes in acid deposition under various SO_2 emission control scenarios in three acid-sensitive regions of Ontario where long-term biomonitoring work is underway. WARMS consists of an acidification model (Marmorek *et al.*, 1990) linked to fish and waterfowl models (Blancher *et al.*, 1992), and uses lake characteristics and fish presence to estimate pre-acidification (hereafter termed "original"), present and eventual steady-state values for pH, fish presence and waterfowl breeding parameters under various scenarios. In this paper, we estimate current damage to breeding habitats of selected waterfowl species in these regions, predict eventual benefits of various emission scenarios, and assess suitability of these sites for continued monitoring work.

2. Materials and Methods

The analysis process used in WARMS is illustrated in Figure 1. The acidification model

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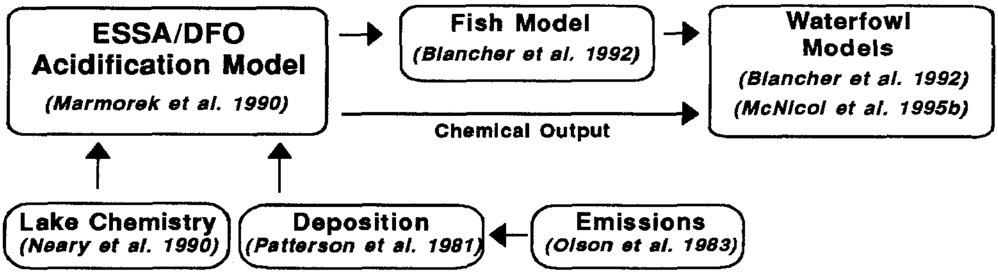

Figure 1. Schematic of WARMS Modelling Process

(ESSA/DFO; Marmorek *et al.* 1990) predicts eventual chemical status of lakes (alkalinity [Alk], pH, cations, and sulphate [SO_4]), based on watershed morphometry and runoff, current lake chemistry, observed (assumed) levels of SO_4 deposition, and assumed values of acid neutralization in watersheds (SO_4 reduction in lakes, and background or original SO_4). While similar to other cation denudation rate models (e.g. Small and Sutton, 1986), recent modifications to the model (see MacQueen *et al.*, 1995) better reflect the role of DOC in projections of Alk and pH. DOC is often a significant chemical constituent in waterbodies used by waterfowl and is especially dominant in surface waters of Atlantic Canada (RMCC 1990). The model simulates sulphur deposition only (Table I); nitrate and ammonium deposition are assumed to have no net acidifying effect.

Here, we simulate three scenarios: 1) emission values remain constant at 1980 levels (hypothetical situation); 2) emissions reduced in Canada only (roughly 50% of 1980 levels); 3) emissions reduced in Canada plus the U.S. following full implementation of SO_2 control programs. We also model current conditions based on mid-1980s lake chemistries (Table II). Emission values (1980 levels) were translated into deposition values using transfer matrices from Olson *et al.* (1983) which relate emissions at 40 sites (15 in eastern Canada and 25 in the U.S.) to deposition at 9 sites (5 in eastern Canada, 4 in the U.S.). Receptor sites were not directly related to our study areas, so we interpolated wet and dry SO_4

Table I. Calculated SO_4 deposition (wet + dry) under different emission scenarios for watersheds in Algoma (A), Muskoka (M) and Sudbury (S) with corresponding number of study lakes

Watershed	Study Region	No. Lakes	SO_4 Deposition by Emission Scenario		
			1 (1980)	2 (CAN)	3 (CAN-US)
2B	A	167	19.81 + 5.16	17.16 + 4.47	11.22 + 2.92
2C	A / S	3 / 62	26.97 + 12.76	22.63 + 10.70	16.65 + 7.88
2D	M / S	18 / 120	28.14 + 13.44	20.61 + 9.84	14.76 + 7.05
2E	M	393	34.11 + 20.73	24.32 + 14.78	17.53 + 10.65
2H	M	62	36.07 + 20.70	26.10 + 14.98	18.71 + 10.74
2J	M / S	29 / 45	24.88 + 11.34	18.69 + 8.52	13.17 + 6.00
2K	M	166	31.43 + 15.73	22.97 + 11.50	16.42 + 8.22

deposition (includes background) for corresponding secondary watersheds (Table I) using equations from Patterson *et al.* (1981).

Three regions of Ontario were selected for these assessments. Algoma and Muskoka sites are defined by a 100 x 100 km block centred at 47°01'N, 83°55'W and 45°30'N, 79°06'W respectively. The Sudbury study area, defined as the zone influenced by past sulphur emissions from Sudbury smelters (Neary *et al.*, 1990), is irregularly shaped, extending southwest and northeast of Sudbury (see McNicol *et al.*, 1995a). These sites vary in current and historic levels of SO_4 deposition (RMCC 1990), as well as predicted changes under proposed scenarios (Table I). We used lake chemistries derived from provincial sampling conducted in the early to mid-1980s (Neary *et al.*, 1990). While these lakes span a broad range of characteristics (Table II), there is an obvious bias in coverage for large, gamefish lakes; small waterbodies are clearly under-represented. Some regional differences are evident with Sudbury lakes typically larger and having higher SO_4 levels than elsewhere. We use fish and waterfowl models developed for these regions (Table III; Blancher *et al.*, 1992), including a revised common loon model (McNicol *et al.*, 1995b) to predict probabilities of finding a brood of each species on each lake, based on lake characteristics. The fish model uses relationships derived for small fish species which are prey for piscivores or competitors with insectivorous waterfowl.

3. Results and Discussion

3.1 PREDICTIONS FOR CHEMISTRY

Original and eventual pH distributions under each scenario vary considerably among regions (Table IV). Using recent cation chemistry, WARMS predicted that both Muskoka and Sudbury had similar pH distributions with a relatively small pH range, whereas Algoma had a broad pH range with many naturally acidic lakes prior to acidification. Current pH distributions differ considerably. All three sites have more acid lakes than probably occur naturally, but Sudbury has experienced the most historical damage (McNicol *et al.*, 1995a).

Under each scenario, heavily damaged Sudbury lakes would improve in response to lower deposition inputs than experienced historically. With continued 1980 emissions (Scenario 1), Algoma and especially Muskoka lakes would deteriorate. Scenario 2 (Canada only) will result in further damage at Muskoka, where deposition remains high (Table I) and many lakes are currently sensitive. A small decline in pH was noted at Algoma (Table IV); Canadian reductions would have relatively little impact on this region since most of its

Table II. Characteristics of lakes used in this study

	Algoma (n=170)		Muskoka (n=668)		Sudbury (n=228)	
	Median (SE)	Range	Median (SE)	Range	Median (SE)	Range
Area (ha)	15.6 (6.8)	1.0-663.0	22.6 (16.8)	0.2-7058	49.9 (12.9)	0.9-979
pH	6.3 (0.1)	4.5-7.5	6.1 (0.1)	4.2-7.6	5.6 (0.1)	4.2-7.6
Alk (mg/l)	2.3 (0.4)	-1.5-23.9	2.2 (0.1)	-3.3-58.8	0.3 (0.3)	-3.4-27.7
DOC (mg/l)	4.3 (0.2)	1.3-19.0	3.9 (0.1)	0.7-16.3	3.6 (0.1)	0.1-15.9
SO_4 (mg/l)	4.1 (0.1)	2.3-9.5	7.5 (0.1)	2.7-27.9	10.5 (0.3)	6.0-40.0

Table III. Logistic regression model coefficients (SE) relating fish and brood presence to lake characteristics

Species	Constant	Ln(Area)	Fish Presence	pH	DOC
Fish Presence	-10.54 (1.60)	0.39 (0.13)	N/A	1.87 (0.27)	
Common Loon	-4.19 (0.67)	0.68 (0.08)	N/A	0.23 (0.10)	
Common Merganser	-27.61 (4.23)	0.95 (0.23)	9.39	1.99 (0.61)	
Common Goldeneye	-4.07 (1.00)		-2.72 (0.37)	0.70 (0.19)	-0.16 (0.05)
American Black Duck	-4.91 (1.09)		-0.87 (0.33)	0.51 (0.19)	

deposition originates in the U.S. (RMCC 1990). Scenario 3 (Canada plus U.S.) will result in clear improvements at Algoma, and will be required to maintain current conditions at Muskoka (Table IV). However, proposed emission reductions do not return lakes to conditions predicted prior to industrialization.

3.2 PREDICTIONS FOR FISH AND WATERFOWL

In all three sites, continued emissions at 1980 levels would result in further loss of fish habitat compared to suitable habitat predicted prior to acidification (Table V), with Sudbury suffering the greatest damage. Both Scenario 2 and 3 result in increased numbers of lakes predicted to contain fish, with the greatest improvements occurring at Sudbury and the smallest change in Algoma. Even under Scenario 3, all sites are predicted to retain a 10% reduction in lakes containing fish compared to original conditions.

In this study, we model brood relationships for 4 common species which represent three ecological niches. The common merganser and common loon rely on fish as prey and fare poorly under acid conditions, while the common goldeneye, an insectivorous, diving duck, prefers lakes without fish. The black duck, although principally insectivorous during the breeding season, is a generalist species and is highly adapted to boreal conditions.

Under all scenarios, predicted effects on waterfowl broods tend to be greatest at Sudbury and lowest in Algoma (Table V). Potential effects in Muskoka are as great as Sudbury, but current conditions are not as deteriorated, and hence "real" changes are not as large. Predicted presence of mergansers and especially loons is much higher than for other species, since lakes used in the analyses are more suited to these species (Blancher *et al.*, 1992). Nonetheless, habitat for both species has deteriorated from original conditions, presumably due to declines in lake pH linked to corresponding loss of fish habitat (Table V). Minor improvements in breeding habitat are expected for loons and mergansers at

Table IV. WARMS predicted mean (SE) pH in each region
(Friedman Repeated Measures Non-Parametric ANOVA; overall comparisons significant at $P<0.001$)

			Emission Scenario		
Region	Original	Current	1(1980)	2 (CAN)	3 (CAN/US)
Algoma	6.16 (0.04)	5.87 (0.06)	5.72 (0.07)	5.77 (0.07)	5.95 (0.06)
Muskoka	6.29 (0.01)	5.95 (0.02)	5.52 (0.03)	5.78 (0.02)	5.99 (0.02)
Sudbury	6.24 (0.03)	5.33 (0.06)	5.37 (0.06)	5.62 (0.06)	5.86 (0.05)

Table V. WARMS predictions for fish and broods in each region
(Friedman Repeated Measures Non-parametric ANOVA; overall comparisons significant at $P < 0.001$)

Species	Mean Probability of Presence				
			Emission Scenario		
	Original	Current	1 (1980)	2 (CAN)	3 (CAN-US)
ALGOMA					
Fish Presence	0.824	0.715	0.656	0.675	0.745
Common Loon	0.316	0.304	0.300	0.301	0.308
Common Merganser	0.086	0.080	0.079	0.080	0.082
Common Goldeneye	0.060	0.067	0.070	0.069	0.065
Black Duck	0.078	0.074	0.073	0.074	0.075
MUSKOKA					
Fish Presence	0.923	0.816	0.666	0.758	0.828
Common Loon	0.395	0.380	0.361	0.374	0.385
Common Merganser	0.102	0.077	0.060	0.068	0.079
Common Goldeneye	0.058	0.060	0.067	0.062	0.059
Black Duck	0.077	0.071	0.066	0.069	0.071
SUDBURY					
Fish Presence	0.897	0.620	0.633	0.716	0.794
Common Loon	0.470	0.433	0.432	0.445	0.454
Common Merganser	0.169	0.088	0.091	0.106	0.128
Common Goldeneye	0.071	0.083	0.083	0.078	0.073
Black Duck	0.075	0.062	0.063	0.066	0.070

Algoma, whereas large improvements should occur in Sudbury, due to expected recovery of fish in many lakes (McNicol *et al.*, 1995a). Scenario 3 is required to maintain current habitat suitability for piscivores in Muskoka; hence, habitat suitability for piscivores may decline in Muskoka over the next decade despite existing SO_2 reductions in Canada.

In contrast to piscivores, habitat for goldeneyes is expected to decline at all sites under all scenarios towards original levels (Table V). This species behaves as a "negative indicator" in acidification studies, that is, goldeneyes appear to do well on acid lakes where fish populations have been lost and acid-tolerant invertebrates thrive, and thus may be more abundant or successful under acid conditions than following emission reductions (McNicol *et al.*, 1995a). Even so, WARMS predicts that the "ideal" habitat for goldeneye broods are high pH, fishless lakes (Blancher *et al.*, 1992).

For the black duck, continued emissions at 1980 levels would have resulted in a 7% decline in habitat at Algoma and 15% declines in Muskoka and Sudbury (Table V). Under all scenarios, little change is expected at Algoma, and some decline may occur in Muskoka prior to full implementation of the U.S. program, but improvements over current conditions should occur at Sudbury (Table V).

4. Conclusions

While there is no direct means of predicting the nature and extent of aquatic ecosystem recovery from acidification, WARMS was developed to estimate responses of waterfowl, loons and their breeding habitats to predicted changes in acid deposition following SO_2 emission reductions. Here, various control scenarios were simulated in three regions of Ontario; WARMS predicts improvements at Algoma and Sudbury, and that the strongest proposed emission reductions will be required to maintain present conditions in Muskoka. Predicted responses by waterfowl to emission reductions are achieved primarily through changes in the fish status of lakes. Fish-eating species suffer when fish are reduced, while insectivores often benefit in the absence of fish but suffer under low pH due to the progressive reduction in the diversity of invertebrate prey as pH declines. In the future, species-specific waterfowl and fish relationships will be validated on watersheds elsewhere in eastern Canada prior to undertaking regional assessments of waterfowl responses to predicted emission reductions.

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